INVESTIGATION OF UNDERGRADUATE STUDENTS' MENTAL MODELS ABOUT THE QUANTIZATION OF PHYSICAL OBSERVABLES

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submitted by **NİLÜFER DİDİŞ** in partial fulfillment of the requirements for the degree of **Doctor of Philosophy in Secondary Science and Mathematics Education Department, Middle East Technical University** by,

Prof. Dr. Canan Özgen ________
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Ömer Geban ________
Head of Department, **Secondary Science and Mathematics Education**

Assoc. Prof. Dr. Ali Eryılmaz ________
Supervisor, **Secondary Science and Mathematics Educ. Dept., METU**

Prof. Dr. Şakir Erkoç ________
Co-Supervisor, **Physics Department, METU**

Examining Committee Members:

Prof. Dr. Ali Azar ________
Secondary Science and Math. Educ. Dept., Bülent Ecevit University

Assoc. Prof. Dr. Ali Eryılmaz ________
Secondary Science and Math. Educ. Dept., METU

Prof. Dr. Edward Frederick (Joe) Redish ________
Physics Department, University of Maryland, MD, USA

Assoc. Prof. Dr. Esen Uzuntiryaki ________
Secondary Science and Math. Educ. Dept., METU

Assist. Prof. Dr. Ömer Faruk Özdemir ________
Secondary Science and Math. Educ. Dept., METU

Date: 24.04.2012

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last Name : Nilüfer DİDİŞ

Signature :

ABSTRACT

INVESTIGATION OF UNDERGRADUATE STUDENTS' MENTAL MODELS ABOUT THE QUANTIZATION OF PHYSICAL OBSERVABLES

Didiş, Nilüfer

Ph.D., Department of Secondary Science and Mathematics Education
Supervisor : Assoc. Prof. Dr. Ali Eryılmaz
Co-Supervisor: Prof. Dr. Şakir Erkoç

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The purpose of this research is to investigate undergraduate students' mental models about the quantization of physical observables. The research was guided by ethnography, case study, and content analysis integrated to each other. It focused on second-year physics and physics education students, who were taking the Modern Physics course at the Department of Physics, at Middle East Technical University. Wide range of data was collected by interview, observation, test, diary, and other documents during 2008-2 academic semester. The findings obtained from the qualitative analysis of the data indicated the following conclusions: (1) Students displayed six different mental models, defined as Scientific Model, Primitive Scientific Model, Shredding Model, Alternating Model, Integrative Model, and Evolution Model, about the quantization of physical observables. (2) Students' models were influenced by the external sources such as textbooks (explanations in textbooks, bringing textbook into the classes, and the use of one or both textbooks), instructional elements (explanations in instruction, taking notes in classes, and studying before and after the classes+taking notes in classes+attending classes regularly), topic order, and classmate; they were influenced by the internal sources such as meta-cognitive elements, motivation, belief (the nature of science and the nature of quantum physics concepts), and familiarity and background about the concepts. (3) The models displayed by students developed with the contribution of these sources in different proportions. Furthermore, although upgrading in models was observed within the cases of quantization, students' mental models about the quantization of physical observables are context dependent, and stable during the semester.

Keywords: Physics Education, Mental Models, Quantization.

ÖZ

LİSANS ÖĞRENCİLERİNİN GÖZLENEBİLİR FİZİKSEL BÜYÜKLÜKLERİN KUANTİZE OLMASI HAKKINDAKİ ZİHİNSEL MODELLERİNİN İNCELENMESİ

Didiş, Nilüfer

Doktora, Orta Öğretim Fen ve Matematik Alanları Eğitimi Bölümü
Tez Yöneticisi : Doç. Dr. Ali Eryılmaz
Ortak Tez Yöneticisi: Prof. Dr. Şakir Erkoç

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Bu araştırmanın amacı lisans öğrencilerinin gözlenebilir fiziksel büyüklüklerin kuantize (kuantumlu) olması hakkındaki zihinsel modellerini incelemektir. Araştırma birbirine entegre edilmiş etnografi, durum çalışması, ve içerik analizi ile yürütülmüştür. Araştırma, Orta Doğu Teknik Üniversitesi Fizik Bölümü'nde Modern Fizik dersi alan fizik ve fizik öğretmenliği ikinci sınıf öğrencilerine odaklanmıştır. 2008-2 akademik dönemi süresince görüşme, gözlem, test, günlük, ve diğer belgeler yoluyla çeşitli veriler toplanmıştır. Verilerin nitel analizinden elde edilen bulgular şu sonuçları göstermiştir: (1) Öğrenciler gözlenebilir fiziksel büyüklüklerin kuantize olmasına ilişkin Bilimsel Model, İlkel Bilimsel Model, Dilimleme Modeli, Dalgalı (Değişken) Model, Birleştirici Model, ve Evrim Modeli olarak tanımlanan altı farklı zihinsel model sergilemişlerdir. (2) Öğrencilerin modelleri ders kitapları (ders kitaplarındaki açıklamalar, derslere ders kitabı getirmek, ve ders kitaplarından biri ya da her ikisini kullanmak), öğretime ait elementler (öğretimde yapılan açıklamalar, derslerde not tutmak, ders öncesi ve sonrası çalışmak+derslerde not tutmak+derslere düzenli olarak katılmak), konu sıralaması ve yakın sınıf arkadaşı gibi dış kaynaklardan; üst-bilişsel elementler, motivasyon, inanış (bilimin doğası ve kuantum fiziği kavramlarının doğası) ve kavramlara aşinalık ve altyapı gibi iç kaynaklardan etkilenmiştir. (3) Öğrenciler tarafından sergilenen modeller bu kaynakların farklı oranlarda katılımı ile gelişmiştir. Ayrıca, kuantumlanma durumları içinde modellerde iyileşme gözlenmesine rağmen, öğrencilerin gözlenebilir fiziksel büyüklüklerin kuantize oluşuna ilişkin zihinsel modelleri bağlam bağımlı ve dönem süresince durağandır.

Anahtar Kelimeler: Fizik Eğitimi, Zihinsel Modeller, Kuantize (kuantumlu) olma.

I dedicate this dissertation to my sister

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LIST OF ABBREVIATIONS

SM	Scientific Model
PSM	Primitive Scientific Model
ShM	Shredding Model
AM	Alternating Model
IM	Integrative Model
EM	Evolution Model
NM	No Model
NE	No Element
NA	No Answer

CHAPTER 1

INTRODUCTION

1.1 Physics Education in the World

Science is like a tripod standing on the disciplines of biology, chemistry and physics. Among these disciplines, physics tries to put forward some explanations about all of nature, from micro to macro, from the living to the nonliving, by using mathematical expressions, theories and laws. We know the roots of first explanations about physics date back to early civilizations on the earth. For example, with the invention of the wheel, early people observed nature and used some ideas of physics without being aware of physics. With this simple tool, they minimized the applied force to carry their load. In 350 B.C., Aristotle was the first person who developed common sense beliefs about physical phenomena such as force and motion (Halloun & Hestenes, 1985a).

As the roots of ideas about physics are so old, scientific explanations and research on physics also date back several centuries. Comparing "research on physics" and "research on physics teaching and learning", the latter is far younger. The first ideas and scientific research on "physics education" were started in 1980s. Physics education firstly aims to identify students' problems in physics in detail and tries to develop some pedagogical tools and techniques to help students to understand physics at any level, such as secondary school, college, university etc. Many students have problems with physics and they think that physics is a collection of facts and formulas; they cannot connect physics with daily life, and they cannot solve physics problems (Hammer & Elby, 2003). Students also think that physics is difficult to understand. Although they get good grades, they have misconceptions, poor problem solving skills, and they have difficulty in interpreting physical laws (Reif, 1995). Many students also think that being successful while studying in physics is an innate ability and/or depends on hard work (Prosser, Walker, & Millar, 1996). These negative experiences, ideas, beliefs, expectations, as well as students' knowledge of physics, might be caused by many different sources. However, as physics educators, we may start from the most available source to convert them from negative to positive by revising physics instructions. For example, Redish and Steinberg (1999) explained one of the sources of difficulty in the nature of introductory physics courses. The approach of these courses is explaining many topics superficially to provide a context for later physics studies, as well as emphasizing mathematical manipulations and structures that are basis for advance studies (Redish & Steinberg, 1999). McDermott (1991, 1993, 1997, p.139) showed that there is a mismatch between what instructors taught and what students learned. In traditional instruction, many instructors have a tendency to think of students as younger versions of themselves, and are unaware of how students' perceptions and readiness cause trouble in learning physics. For these reasons, she (1993) put forward some suggestions for physics instructors:

- Instructors should ask questions which require students to use qualitative reasoning and verbal explanations,
- Students' own construction of qualitative models to understand relationships and differences among concepts is important,
- Conceptual difficulties should be addressed in different contexts,
- Students' scientific reasoning skills should be cultivated,
- Practice in interpretation of physical formalism and relating it to a real world is necessary for students,
- Being intellectually active is necessary for students to develop functional understanding.

It is very important to be aware of what students bring into classroom, because this interferes with new information presented in the class. Halloun and Hestenes (1985a, 1985b), and Hestenes, Wells and Swackhamer (1992) mentioned that many students had a "well-established system of common sense beliefs" about the physical world which had an important role in learning physics. Therefore, the researchers suggested that instruction should take these preconceptions into account, and conceptual learning must be encouraged to facilitate effective physics instruction (Dykstra, Boyle, & Monarch, 1992).

Another consideration for physics instructors is being aware of the past issues in physics and knowing what students expect from physics. Heilbron (1983) stressed the importance of historical events in physics lectures to not only explain the content of physics, but also to show its nature and methods, and indicate the development of concepts to students (as cited in Bevilacqua & Giannetto, 1998). Therefore, after having the idea of students' expectations, it is important for physics instructors to take them into account, since these expectations affect students' selection of activities when constructing their own knowledge (Redish, Saul, & Steinberg, 1998).

Another important issue in physics instructions is about "knowledge organization". Reif (1995, 1997, p.187) indicated the importance of knowledge organization in physics learning and drew attention to the requirement of hierarchical knowledge organization, because incoherent-disconnected knowledge did not provide a good basis for problem solving in physics. In the light of previous research on physics education, the theoretical framework of this dissertation is based on "knowledge organization". Although students think that physics requires the memorization of many facts and formulas, being a good physicist requires having organized knowledge, which permits remembering and inferring the details (Reif, 1995).

One of the theories about knowledge organization is "mental modeling". The roots of the "mental model" term date back quite some time in physics. For example, Lord Kelvin mentioned the importance of the construction of mechanical models (Johnson-Laird, 2004). Also, Maxwell's models of electromagnetic theory and Feynman's models of quantum electrodynamics (Johnson-Laird, 2004) are other examples of models of scientific thinking. A mental model is "an internal representation which acts out as a structural analogue of situations or processes. Its role is to account for the individuals' reasoning both when they try to understand discourse and when they try to explain and predict the physical world behavior" (Greca & Moreira, 2002).

1.2 Learning Quantum Physics and Mental Modeling

Many students have difficulty in understanding the concepts of the quantum theory because of its abstract nature and its requirement of complex mathematical formalism (Sadaghiani, 2005). Also, instructors have difficulty while teaching quantum physics because it introduces a new philosophy which is different from classical physics, the concepts are abstract, and it is lack of analogies and metaphors (Wattanakasiwich, 2005). Pedagogical research on students' quantum physics learning conducted with diverse number of data collection techniques and students in different countries showed that students had *conceptual problems* (Budde, Niedderer, Scott, & Leach, 2002a, 2002b; Çataloğlu, 2002; Didiş, Eryılmaz, & Erkoç, 2007, 2010; Gardner, 2002; Ireson, 2000; Ke, Monk, & Duschl, 2005; Müller & Wiesner, 1999, 2002; Olsen, 2002; Özcan, Didiş, & Taşar, 2009; Singh, 2001; Singh, Belloni, & Christian, 2006; Styer, 1996; Wattanakasiwich, 2005), *mathematical problems* (Gardner, 2002; Ireson 2000; Ke et al., 2005; Pospiech, 2000; Sadaghiani, 2005; Sauer, 2000; Strnad, 1981; Wattanakasiwich, 2005), and *visual problems* (Çataloğlu, 2002; Çataloğlu & Robinett, 2002; Mashhadi & Woolnough, 1999) while learning quantum physics. In addition, they have *difficulty in discriminating classical and quantum concepts* (Bao, 1999; Budde et al., 2002a, 2002b; Mannila, Koponen, & Niskanen, 2002; Müller & Wiesner, 2002; Olsen, 2002; Pospiech, 2000; Sadaghiani, 2005; Strnad, 1981).

Identification of students' mental models about scientific phenomena is an important issue to be able to understand students' learning of scientific concepts. In physics education, many research examined students' mental models in various physics concepts (Bao, 1999; Bao & Redish, 2006; Borges & Gilbert, 1999; Chiou & Anderson, 2010; Corpuz, 2006; Corpuz & Rebello, 2005, 2011a; Hrepic, 2002, 2004; Hrepic, Zollman, & Rebello, 2010; Hubber, 2006; Itza-Ortiz, Rebello, & Zollman, 2004; Redish, 1994; Scherr, 2007; Vadnere & Joshi, 2009; Wittmann, Steinberg, & Redish, 1999). Most of the research about identification of mental models was conducted with university students.

University of Maryland (UMD) Physics Education Research Group (PERG) has great importance in the development of mental modeling research by integrating "cognitive science" into physics education research. One of the pioneer of these studies in UMD PERG is the study of Bao's (1999) dissertation. He examined students' mental models of quantum concepts. He classified students' models into three categories such as classical models, hybrid models, and mixing models. Also, Wittmann's (1998) dissertation, which was conducted in UMD

PERG, examined students' models of mechanical waves. Following studies of Wittmann et al. (1999) explained models in terms of other knowledge elements i.e. p-prims, resources, facets etc. Kansas State University (KSU) PERG also conducted some research about students' mental models. One of the pioneers is Hrepic's (2002) research for master thesis. He investigated students' mental models of sound propagation via qualitative research. He identified that students had hybrid mental models as they had pure mental models. There are some other studies about the investigation of mental models of sound propagation in KSU PERG (Hrepic, 2004; Hrepic et al., 2005, 2010). Corpuz and Rebello's (2005, 2011a, 2011b) studies and Corpuz's (2006) dissertation in KSU PERG examined also university students' mental models of friction. One of the results of their studies was how students' mental models of microscopic concepts were affected from macroscopic experiences.

1.3 Research Questions of the Dissertation

Investigation of mental models provides a theoretical framework to investigation of students' understanding of physics concepts. In the light of literature, I focused on how students organize their quantum physics knowledge. At this point, my research design uses mental models as theoretical framework to identify students' understanding quantum physics. For this reason, the aim of this research is to examine second-year physics and physics education students' mental models of some concepts in quantum theory. So, in the first and second research questions, students' mental models and the characteristics (the nature and context dependency of models with the role of cues, model construction approach i.e. on the spot or previously thought out, model construction source i.e. common sense, recalling, or reasoning, and degree of certainty) of these mental models were examined by asking;

- What are the second-year physics and physics education students' mental models of the quantization of physical observables (i.e. electromagnetic radiation /light, energy and angular momentum)?
- What are the characteristics of second-year physics and physics education students' mental models of the quantization of physical observables?

Since we live in a social environment, some factors have a critical role on students' model construction. Students might be aware of these sources or not while constructing their models since sources may be internal or external for students. In the third research question, these factors were examined by asking;

- What are the external and internal sources that influence students' mental models of the quantization of physical observables?

Modern physics course is the only course that lays the foundations of the quantum theory in students' minds. For this reason, to explain students' model development is as important as to explain students' models. For this aim, in the last research question, the development of students' mental models in modern physics course by the influence of some internal and external sources was examined by asking;

- How do the second-year physics and physics education students' mental models of the quantization of physical observables develop by the influence of internal and external sources?

1.4 Research Approach of This Study towards the Identification of Mental Models

Identification of mental models is not a simple process, since mental models can be in a complex form. Also, it is difficult to distinguish fragmented elements and coherent structures by using a single question, but the research can offer indications by in-depth questioning and getting responses over time and context (Taber, 2008). With this aim, this dissertation had some basic considerations while examining students' mental models. These are:

- We cannot see students' mental models directly in their minds. However, while investigating students' mental models, we make some inferences based on what they explained to us in the interviews, tests, classroom environment etc.

- Mental models are coherent knowledge structures that allow explaining physical phenomena and reasoning in qualitative physics problems.

- They include the organization of the concepts related to phenomena.

- Coherency is required to specify a mental model.
- “They may not have firm boundaries and their elements might be confused with each other” (Norman, 1983, p.8).
- More than one model can be hold together at the same time, and can be used inconsistently (Gentner, 2002).
- They allow qualitative reasoning (Gentner, 2002) about the explanation of experienced and hypothetical situations.
- They may exist by the organization of fragmented elements (Bao, 1999; Hrepic, 2002, 2004; Itza-Ortiz et al., 2004; Wittmann, 1998; Wittmann et al., 1999). If the fragmented elements are not organized, i.e. if they are disconnected or incoherently used, an unorganized structure is called “no model” (Hrepic, 2002).
- As students develop their own mental models of the phenomena during a time-period, previously gained fragmented and memorized structures might be organized in-situ, and then students might develop mental models of the phenomena by answering the questions immediately.
- Quantization is not an independent single concept, but it is the whole and basic idea of the quantum theory causing paradigm shift from classical physics with the interpretation of new experimental results. So, students’ mental models about quantization of light, energy and angular momentum in the photoelectric experiment, blackbody radiation and ultraviolet catastrophe, energy levels and atomic spectra, particle in a box, harmonic oscillator, the Bohr atom and the quantum atom contexts can explain students’ understanding of quantum physics.
- Finally, since quantum physics does not allow “intuition”, students’ previous conceptions and linking of the related concepts about the quantization phenomenon are important for the explanation of mental models of the quantization of physical observables.

With these considerations, this study follows previous mental model research (Bao, 1999; Bao & Redish, 2006; Corpuz, 2006; Corpuz & Rebello, 2005, 2011a; Hrepic, 2002, 2004; Hrepic et al., 2010; Itza-Ortiz et al., 2004; Redish, 1994; Scherr, 2007; Wittmann et al., 1999) in terms of the basic ideas about the mental modeling framework. So, there are some methodological similarities i.e. more than one context examination, including large number of students. However, this study differs from previous research on mental models in physics education in terms of research design, examined physics concepts, detailed explanation of data analysis with coding, inter-coding, and constructing themes. These issues were emphasized in the current study.

1.4.1 Definitions of Sources Influencing Students' Mental Models

Textbook: The book(s) used in PHYS 202 Modern Physics course that students interact with in and out of the classroom setting. Textbook is an actively used course material.

Instruction and the elements related with instruction: Modern physics classes, the attitude and motivation of the instructor towards to course and students, and activities that students engage in and out of the modern physics classes such as preparation before and after modern physics classes, attendance, taking notes in the classes, doing homework, studying for examinations.

Topic order: Arrangement of the modern physics concepts while teaching.

Classmate: Friends whom students interact with in and out of the classroom setting.

Extra sources for learning: The additional sources such as books, internet etc. that are used for learning modern physics concepts.

Belief: Fishbein and Ajzen (1975) defined belief as "person's subjective probability judgments concerning some discriminable aspects of his world; they deal with the person's understanding of himself and his environment" (p.131). It is one's stable subjective knowledge (Lavonen, Jauhiainen, Koponen, & Kurki-Suonio, 2004), so beliefs can be accepted as an internal cognitive element and interact with students' learning (Boz & Uzuntiryaki, 2006). In this study, "acceptance of an idea as true" is defined as belief. Two different beliefs are explained for this study. These are: (1) *Nature of science.* Students' beliefs about scientific knowledge, scientific methods, and nature of facts/formulas, and (2) *Nature of quantum physics concepts.* Students' beliefs about the structure (abstractness, counter-intuitiveness, mathematical formalism etc.) of quantum concepts.

Meta-cognition: Meta-cognition is one of the elements interacting with individuals' knowledge on a topic (Gredler, 2001, p.211). Therefore, it plays an important role in learning. It can be defined as "act of thinking about students' own mental process". Three important elements of meta-cognition are considered in this study. These are: (1) *Awareness.* Being aware of what individual knows and does not know, how s/he thinks etc., (2) *Satisfaction.* Feeling frustration or satisfaction of own knowledge, and (3) *Regulation.* Strategies to regulate own cognitive process.

Motivation: Motivation is an affective variable, which is defined as "the process whereby goal directed behavior is instigated and sustained" (Schunk, 1990, p.3). So it is the willingness for learning. Since the individuals direct their energy through attention, concentration and imagination when they are motivated, they constantly learn (Wlodkowski, 1999, p.8). For this reason, it is an important element in education. Two elements are considered in this study. These are: (1) *Interest.* It is the enjoyment in an activity while learning, and (2) *Utility.* It is the consideration of future needs for learning.

Familiarity of the concepts: Being familiar or unfamiliar with some concepts from classical mechanics.

Background knowledge: Having information about some physics concepts discussed in the contexts (i.e. energy, angular momentum etc.).

1.5 Significance of the Study

As physics educators, our expectation from students is to develop robust knowledge structures, not a patchwork of ideas (Redish et al., 1998), and understand and apply the developed well-defined coherent models of physics (Wittmann et al., 1999). For this reason, students' having coherent knowledge structures- mental models- for physics phenomena is important. Identification of students' mental models is also important since mental models are the minimum organized knowledge that shows understanding. In addition, organized knowledge permits retrieval process systematically and easily (Reif, 1995). It is also important for the use of information in new situations (Isabella, 1999) by selecting the useful resource in the given situations (Redish, 2004).

Identification of the mental models of students for quantum mechanical concepts is important for physics educators who teach quantum theory because mental models show students' approaches to scientific knowledge and how students organize their cognitive resources (for example selecting, coordinating, combining, and transforming) in order to learn physics (Redish, 2004). In addition, learning is facilitated when new information is consistent with existent models (Gentner, 2002; Gentner & Whitley, 1997). Also, physics education aims to "have students build the proper mental models for doing physics" (Redish, 1994). This includes students' correct qualitative reasoning to explain physical events, using the existent mental structures coherently, and knowing how to apply it while doing physics (Redish, 1994). By this way, this dissertation suggests approaches for meaningful learning of the quantum theory in universities. Therefore, courses teaching quantum theory (i.e. modern physics course, quantum physics course) can be developed in order to help students to connect more scientific concepts and develop more scientific mental models about quantization. In addition, while developing courses, the findings about external and internal sources influencing students' mental models might be taken into consideration to facilitate students' scientific knowledge organizations.

This research fills some gaps in physics education literature in terms of researched concepts and research design. First, this research is both descriptive and explanatory in stating students' mental models about quantization. It stands on three different science branches; physics, cognitive psychology, and anthropology from the qualitative perspective and by using diverse number of data collection techniques. Because of the mathematical, complex, counter-intuitive and abstract nature of the quantum theory, the construction of more scientific mental models of quantum phenomena is important for teaching and learning this theory. The examination of mental models during a period of time and in different cases in a real learning setting by ethnographic manner together with the other research methodologies acts as a window to look at human cognition by means of physics phenomena.

Pedagogical research in quantum physics with mental modeling is limited in worldwide. Students' understanding of "quantization" phenomenon was not researched before by mental modeling framework. In addition, both mental modeling and pedagogical research in quantum physics are new for physics education research in Turkey. Because of these missings in literature in worldwide and Turkey, current study aimed a pedagogical research in quantum physics learning by using the mental modeling framework. While explaining students' mental models about quantization, the current study discussed some sources influencing students' model development. Therefore, this research is different from previous research in terms of research design, examined physics concepts, detailed explanation of data analysis.

1.6 Research Assumptions

As a researcher, I studied in a natural setting - Modern Physics course- for four and half month period. Social environment, previous experiences and previous knowledge may affect students' learning, especially their mental models about quantum phenomena. The design of the study presumes the "socially constructed knowledge claim" as Creswell (2003, pp.8-9) stated. The assumptions are:

- Initially, students do not have mental models of the quantization phenomenon since the idea of quantization was not taught in high schools to students. However, students might have conceptions about quantum concepts.
- Instruction provides a convenient environment to develop models, and there might be factors which influence students' model development.
- How students can achieve organized knowledge can be revealed by using Gentner's (2002) method of "not asking directly their mental models" but by in-depth questioning and getting responses *over time* and *context* (Taber, 2008).

1.7 Summary of the Research and Organization of the Chapters

This is a qualitative research that uses three research methodologies interwoven together in order to find explanation to research questions. Quantization of physical observables (i.e. energy, angular momentum) were the cases of this study, since these are the core ideas of the quantum theory. The focus was second-year physics and physics education students who were taking the modern physics course at the Department of Physics, at Middle East Technical University (METU). The research was conducted during the academic semester 2008-2. A range of different data was collected by interviews, observations, test, diary, and other documents (two textbooks of the course, notebooks of students, and examination- homework- quiz papers). Figure 1.1 summarizes the main issues in the chapters and how the dissertation was organized.

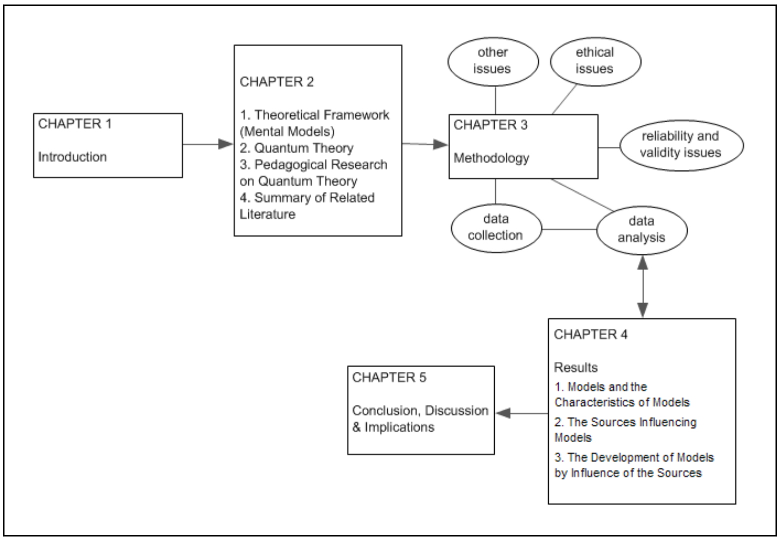

Figure 1.1 Organization of the chapters.

CHAPTER 2

CONCEPTUAL CONTEXT

This chapter presents the conceptual context of the study in four parts. First, the theoretical framework of the study; second, the quantum theory; third, the pedagogical research on quantum theory, and; last, the summary of the chapter.

Section 2.1, theoretical framework, is composed of two main sections such as "mental models" and "fragmented structures". First part of this section (2.1.1) explains what mental modeling was, the methods of identification of students' mental models, and some research on students' mental models of physics concepts. Second part of this section (2.1.2) is composed of the explanation of primitives and facets since the organization of these fragmented elements play a role in the construction of mental models (Bao, 1999; Hrepic, 2002, 2004; Itza-Ortiz et al., 2004; Wittmann, 1998; Wittmann et al., 1999). Section 2.2 provides brief explanations about the quantum theory before the explanation of pedagogical research in quantum theory in Section 2.3. So, in Section 2.3, pedagogical research is explained in two parts, which are student difficulties in learning quantum theory (2.3.1) and new approaches and remedies in teaching quantum theory (2.3.2). Last section, 2.4, concludes with a summary of the chapter that focuses on previous research on students' mental models and learning quantum theory.

2.1 Theoretical Framework of the Study

2.1.1 Mental Models

Models are the basic elements for explaining scientific ideas. They are "key tools" for scientists, science teachers and science learners (Coll, France, & Taylor, 2005). A model can be defined as "a surrogate object, a conceptual representation of a real thing" (Hestenes, 1987, p.441), which means they are conceptual representations of physical systems and processes (Wells, Hestenes, & Swackhamer, 1995). Conceptual models are scientifically accepted models;

however, people have some personal models in their minds, called *mental models* (Duit & Glynn, 1996), which they use to express ideas and explain events.

Craik (1943) can be accepted as the pioneer of the theory of mental models. In his book, which is called “The Nature of Explanation”, he stated that human thought had the power to predict events (p.50) and it provided small-scale models to explain processes (p.59). After forty years, the mental model term was used in two different books with the same name, which were Johnson-Laird’s (1983) and Gentner and Stevens’s (1983) books named “Mental Models”. While Johnson-Laird’s (1983) book explained the theory from the perspective of psychology, Gentner and Stevens’s (1983) book clarified it from the perspective of “science education” by editing the different researchers’ studies identifying students’ mental models of science concepts.

The use of the mental modeling theory is wide-ranging. It is examined by many different disciplines, so the approaches of different researchers to mental models differ. A mental model can be defined by several ways with stressing the different points. Some of the descriptions, which originated from both science education and psychology are like that;

- A mental model is “an internal representation which acts out as a structural analogue of situations or processes. Its role is to account for the individuals’ reasoning both when they try to understand discourse and when they try to explain and predict the physical world behavior” (Greca & Moreira, 2002, pp.108-109).
- Williams, Hollan and Stevens (1983) defined a mental model as “a collection of connected autonomous objects” (p.133).
- van der Veer, Kok and Bajo (1999) considered mental models as knowledge structures and processes that were relatively permanent.
- Vosniadou’s approach to mental models was that they were temporal representations constructed on the spot with the purpose of solving the problem or answering questions (van der Veer et al., 1999; Vosniadou & Brewer, 1992, 1994; Vosniadou et al., 1999).

- Gentner (2002) described her approach to mental model research as "knowledge-based," which means it is used "to characterize the knowledge and processes that support understanding and reasoning in knowledge-rich domains" (p.9683).

In their explanations about mental models, while these perspectives focus on their representation of reality and permanence, physics education researchers mainly focus on coherently organization of small knowledge elements. Some other descriptions of mental models that are from the perspective of physics educators, are:

- Bao (1999) put forward his model definition by considering the other mental model definitions in the literature. According to him, mental models are "productive mental structures that can be applied to a variety of different physical contexts to generate explanatory results" (p.13).
- Corpuz and Rebello (2005) defined a mental model as "students' way of understanding a certain physical phenomenon", these physical phenomena may be an unseen physical phenomena (Corpuz & Rebello, 2011a).
- Bao and Redish (2006) explained that a mental model is a knowledge element or a strongly associated set of knowledge elements, and it has a robust and coherent characteristic.
- Hrepic et al. (2010) explained how they perceived a mental model with these words: "A mental structure built of more fundamental cognitive and knowledge elements, e.g., p-prims or conceptual resources" (p.1). In addition, the researchers stressed the "coherent" organization of these elements to form a mental model.

Mental models are the elements used to explain the relation between cognitive process and the world (Borges & Gilbert, 1999). They are dynamic and generative representations that can be manipulated mentally while making predictions and causal explanations about physical phenomena (Greca & Moreira, 2000, 2002; Johnson-Laird, 1983; Vosniadou et al., 1999). Individuals' mental models may contain contradictory, erroneous and unnecessary concepts (Norman, 1983). They sometimes contradict with scientific models; namely, they are "coherent but incorrect" (Chi, 2008). In order to make explanations or predictions for events, students may use incorrect mental models - flawed models- in a consistent way (Chi, 2008).

Mental models represent parts of reality; although they imitate reality, just certain aspects resemble reality, and, they do not have to resemble reality pictorially (Craik, 1943, p.51; Johson-Laird, 2004). In addition, they do not need to be technically accurate; however, they must be functional (Norman, 1983). Then, they can facilitate problem solving and reasoning (Gentner, 2002; Gentner & Whitley, 1997). However, they might still not be explicitly verbalized or consciously used (Wittmann et al., 1999).

Johnson-Laird (1983, p.10) expressed that understanding occurs with working models in the mind, and understanding of a scientific theory requires the construction of mental models in the mind. Therefore, learning occurs during the active construction of mental models. When the material being learned is consistent with the existent mental models, learning is facilitated (Gentner, 2002; Gentner & Whitley, 1997). Some of the other determining characteristics of mental models are stated by Norman (1983);

- "Mental models are incomplete.
- People's abilities to 'run' their models are severely limited.
- Mental models are unstable: People forget the details of the system they are using, especially when those details have not been used for some period.
- Mental models do not have firm boundaries: similar devices and operations get confused with one another.
- Mental models are 'unscientific': People maintain 'superstitious' behavior patterns even when they know they are unneeded because they cost little in physical effort and save mental effort.
- Mental models are parsimonious: Often people do extra physical operations rather than the mental planning that would allow them to avoid those actions; they are willing to trade-off extra physical action for

reduced mental complexity. This is especially true where the extra actions allow one simplified rule to apply to a variety of devices, thus minimizing the chances for confusions." (p.8).

Gentner (2002) added some other characteristics for mental models:

- Reasoning due to mental models is qualitative relations.
- Mental models permit mental simulation (running a mental model and observing the outcome).
- People can hold two or more "inconsistent" mental models together in the same domain.

Redish (1994) indicated another characteristic for mental models as the following:

- "They consist of propositions, images, rules of procedure, and statements as to when and how they are to be used" (p.797).

According to diSessa's (diSessa, 1996 as cited in diSessa, 2002) - also stated in Hrepic (2002, 2004) and Hrepic et al. (2010)- mental models require some characteristics. These are:

- "Mental models should (1) involve a strong well developed 'substrate' knowledge system, such as spatial reasoning, (2) allow explicit hypothetical reasoning, and (3) involve only a small, well defined class of causal inferences" (pp.53-54).

Therefore, we understand from the literature that mental models are very useful elements that people construct in their minds. The development of mental models occurs through learning and it depends on some factors such as previous knowledge, previous experiences, the structure of the information processing system, ability to learn, culture, how the new information presented during teaching, and interaction with the system or domain (Collins & Gentner, 1987; Norman, 1983; van der Veer et al., 1999). Humans construct their own mental models by interacting with their social environment through discourse. During this interaction, meaning is central to models since sentences, background knowledge and knowledge of human communication are important for the construction of mental models in discourse (Johnson-Laird, 2004). They evolve during interaction until to get a workable result. The models, which are constructed by experience, may be resistant to instruction (Gentner, 2002). Since students' knowledge does not mainly depend on their experiences in the atomic world, students' development of incorrect ideas may be interpreted as being "mis-taught" or being caused by the "misinterpretation of information" based on culture, books, instruction etc. (Taber, 2008).

Vosniadou et al. (1999) mentioned two important elements in the development of mental models. These are framework theories, which consist of ontological and epistemological presuppositions, and specific theories, which consist of beliefs generated through observation and information coming from the culture. Mental models are mainly based on "systems of long-standing beliefs" (Gentner & Whitley, 1997). Norman (1983) explained individuals' mental models contain "degree of certainty" statements about their knowledge due to his studies of human error and human –machine interaction. Therefore, mental models may include "knowledge or beliefs that are thought to be of doubtful validity (Norman, 1983). Moreover, incorrect or flawed mental models may contain correct and false beliefs (Chi, 2008). Since they are the elements of human cognition, they cannot be experienced directly (Coll et al., 2005).

Ontology of mental models is important since it explains the components that constitute a mental model and collection of the properties used for describing these components (Schwamb, 1990). It specifies the kind of information, which is available for reasoning (Greeno, 1983, p.228). Therefore, ontological beliefs about the phenomena provide some information about mental models (Reiner, Slotta, Chi, & Resnick, 2000; Slotta & Chi, 2006). For example, in the examination of students' understanding of force, heat, light and electricity, it was identified that some students had some materialistic (substance-like) mental models rather than process-like (Reiner et al., 2000; Slotta & Chi, 2006). From the "ontological beliefs" perspective, students' unscientific mental models, or alternative conceptions, or misconceptions are explained students' commitment to inappropriate ontologies (Slotta & Chi, 2006), since ontology divide individuals' knowledge into conceptually different categories (Chi, 1992).

Constructed mental models are based on what a person already knows about the "words" (Greca & Moreira, 2002). The "words" used by students while explaining the concepts are very important for us. In addition, use of these words are important to explain physics concepts correctly. Putting different meanings into words, which is called as "language degeneracy" (Hrepic, 2002), has a role in the construction of mental models as it was identified in the Bao's (1999) and Hrepic's (2002) studies. In the examination of students' mental models, both of the researchers identified that although students use same words (terminology), they displayed putting different meanings into the words. By this way, as mental models were shaped around the meaning of the words, they are also the determinants of the perception of the phenomenon (Greca & Moreira, 2002).

2.1.1.a Identification of students' mental models

Identification of mental models can be classified into two fundamental groups such as qualitative and quantitative investigation of mental models; however, they are not alternative of each other. While qualitative investigations focus on sequenced interviews by in depth questioning and getting responses over time and context (Taber, 2008), quantitative investigations focus on development of a test to identify mental models. So, quantitative investigations needs "a qualitative examination" before the development of mental model test. For this reason, they are used after or together with a qualitative research. Table 2.1 summarizes the research in terms of research methodologies. Detailed information about the research presented in Table 2.1 are given in next section 2.1.1.b.

Table 2.1 Summary of mental model research in physics in terms of model investigation approach.

Research	**Examined concepts**	**Research approach**	**Used techniques**
Wittmann et al. (1999)	Mechanical waves	First qualitative and then quantitative	Individual demonstration interviews, pretests (short, ungraded quizzes that accompany tutorials), examination questions, and specially designed diagnostic tests.
Borges and Gilbert's (1999)	Electricity	Qualitative	Semi-structured interviews based on simple experiments by "predict-observe-explain" technique.
Hrepic (2002), Hrepic et al. (2010)	Sound propagation	Qualitative	Interviews before and after the instruction about sound from different contexts.
Hrepic (2004), Hrepic et al. (2005)	Sound propagation	Quantitative based on Hrepic (2002, 2004)	Conducting Linked Item Model Analysis (LIMA) on Formative Assessment of Mental Models of Sound Propagation (FAMM-Sound).
Bao (1999)	Potential energy diagrams, probability	First qualitative and then quantitative	Tutorials, interviews, conceptual quizzes, homework/exams. Conducting "Model Analysis" technique on the developed multiple-choice test.
Itza-Ortiz et al. (2004)	Newton's second law in mechanics and electricity	First qualitative and then quantitative	Series of interviews in two semesters by using some FCI (Hestenes et al., 1992) questions. Development of a multiple choice test (with four- five options) with two dimensions in mechanics and three dimensions in electromagnetism.
Corpuz (2006), Corpuz and Rebello (2005, 2011a),	Microscopic friction	Qualitative	Interviews with two sessions from different contexts by "Model Eliciting Activities"
Scherr's (2007)	Special relativity	Qualitative	Interviews, tutorials

Table 2.1 (continued)

Hubber (2006)	Nature of light	Qualitative	Longitudinal study prior to, and following 12th grade
Vadnere and Joshi's (2009)	Heat transfer, electromagnetic radiation, blackbody radiation, Wien law etc.	Quantitative	Conducting "Model Analysis" technique on the developed multiple-choice test.
Chiou and Anderson (2010)	Heat conduction	Qualitative	Interviews

Each type of examination has different contributions. For example, while it is possible to see how students organize their knowledge in a period of time by qualitative investigations, the examination of many students' mental models at the same time in a limited period is possible with quantitative investigations. However, both types of investigations need carefully planned designs.

There is no "unique" qualitative design for investigation of mental models. So, physics education researchers use several different designs by focusing on some issues, such as:

- the examination of models in a course context (mainly in university level),
- the examination of models in a long period (such as one or two semester(s)),
- the examination of models by following interviews with in depth questioning,
- the examination of models in multiple contexts.

2.1.1.b Research on students' mental models in physics

There are many research investigating students' mental models on various phenomena. As their investigation approaches and common characteristics were discussed in previous section (2.1.1.a), their findings about students' mental models were stated in this section.

One of the pioneers in mental model research in physics education is research of Bao (1999) that is also base for the current research. Bao studied university physics students' mental models about probability concept for classical and quantum mechanics. He developed his "Model Analysis" tool to make quantitative explanations of students' models. This tool included two algorithms in order to examine students' mental models quantitatively. With Model Analysis tool, by using students' answers in the test with multiple-choice questions, he identified students' model-based responses. In addition, by using these model-based responses, he constructed density matrices including the information about students' model states. Five force and motion questions of FCI (Hestenes et al., 1992) were used to determine physical models as "correct", "incorrect" and "null" models. After the analysis, Bao explained the superiority of this analysis to the score-based (measurement with multiple-choice tests) analysis by indicating the loss of information in score-based analysis. He implemented this analysis to examine students' mental models in quantum mechanics. He first developed tutorials and implemented in the quantum physics courses. He conducted interviews, conceptual quizzes and homework/exam questions. Then he developed a multiple-choice test to construct matrices. By the experience about students' difficulties in the classes, he examined students' conceptions of "potential energy diagrams" and "probability" topics. In his study, Bao identified three types of mental models of students for quantum mechanical concepts. These are: (1) strong classical mechanical models, (2) hybrid models, which included correct information about quantum mechanical concepts by using classical mechanical reasoning and (3) mixing models, which included both quantum mechanical and classical mechanical models at the same time.

Another important study and one of the pioneer studies examining students' mental models belongs to Wittmann et al. (1999). The researchers examined university physics students' mental models on mechanical waves. They collected data by individual demonstration interviews, and the interviews were videotaped. In addition, "pretests (short, ungraded quizzes that accompany tutorials), examination questions, and specially designed diagnostic tests" (p.15) were used for collecting the data. In the analysis, various types of wrong reasoning were identified on wave propagation and wave superposition. All of the reasoning revealed that students had a Particle Pulses Mental Model, which was constructed by making analogies between waves and rigid objects by thinking about the Newtonian particle model.

Borges and Gilbert’s (1999) study was different from the previous research on mental models in terms of diversity of participants. The researchers examined the mental models about the electricity. 56 participants of that study was different since participants were composed of 15-17 year-old Brazilian secondary school students, technical school students, teachers, engineers and practitioners (electricians and school laboratory assistants) dealing with the electricity. The researchers used semi-structured interviews to collect data. The interviews were based on simple experiments by “predict-observe-explain” technique to answer the questions. Since the interviews were independent from grade level, the researchers used only “simple circuits” in the interviews. After the analysis of audio recorded interviews to transcriptions, the researchers identified four types of models such as electricity as “Flow, Opposing Currents, Moving Charges, and a Field Phenomenon”.

Hrepic et al. (2010) examined students’ mental models of sound propagation. Twenty-three concept-based physics course students participated in the study, and the interviews were conducted with the participants. Sixteen of the interviews were before and after the instruction, one of them was just before the instruction, and six of them were just after the instruction (totally 39 interviews). They considered sixteen students (whom interviewed before and after the instruction) as a main sample. In the interviews, the questions were asked about sound from different contexts. The researchers carried out phenomenographic analysis. In the study, it was identified that students had a scientific model- a wave model- and an unscientific model- an entity model. In addition to these pure models, the researchers identified hybrid (or, sometimes called as “blend”) models, which were new composite models like Bao mentioned (1999). These hybrid models were: Shaking model, Longitudinally Shaking model, Propagating Air model, Vibrating Air model, Ether model, and Ether and Compression model. The researchers also observed some students used disconnected knowledge. In addition to students’ mental models, the researchers examined students’ model states. This examination revealed that some of the students had pure model state (that is holding just one type of model and using it over the contexts), some of them had mixed model state (that is holding more than one type of model and using them inconsistently over the contexts), and some of them had hybrid (blend) state (that is constructing just one type of hybrid model and using hybrid model over the contexts). This study is important in terms of both explaining mental models and their nature, and students' model states.

Based on identified mental models in Hrepic (2002, 2004) developed a multiple choice test, which is Formative Assessment of Mental Models of Sound Propagation (FAMM-Sound) to identify students' mental models in a classroom setting. The researchers discussed the Linked Item Model Analysis (LIMA) as "a novel method for eliciting and representing mental models in areas where hybrid models play a role in students' learning" of sound propagation (Hrepic, 2004; Hrepic et al., 2005). LIMA works by comparing students' answer combinations to questions sets with the model elements stated in the choices of multiple-choice questions in the test. If there is a match between students' answer set and set of the elements given in the alternatives, students' model states can be determined as pure model; if there is not match, so students are determined as in the mixed state in addition to examination of students' mental models.

Itza-Ortiz et al. (2004) examined students' mental models of Newton's second law in mechanics and electricity. They aimed to develop a multiple choice test in order to investigate students' mental models. However, before this, they explored students' models by interviews in two semesters. They started to conduct interviews with sixteen students from engineering areas, physics and mathematics. Since the researchers conducted series of interviews like three of the interviews in the first semester for classical mechanics topics, and three of them in the second semester. Some of the students left the study, and the study was completed with ten students. Some questions from Force Concept Inventory (FCI) of Hestenes et al. (1992) were used in the interviews. Models examined over contexts, and the researchers identified three mental models developed in the mechanics contexts and transferred to the electromagnetic contexts. These are: Aristotelian model, Newtonian model and a hybrid model, which is formed by the elements of these models. At the end of the study, they developed a multiple choice test (with four-five options) based on two dimensions in mechanics and three dimensions in electromagnetism. Number of questions in each survey changes between five to eight, and each alternative of a question corresponded to a mental model that students possibly use. By this way, teachers can use them in the classes to correct students' wrong models.

Corpuz and Rebello (2005, 2011a), and Corpuz (2006) examined students' mental models of microscopic friction by conducting interviews with students. Eleven students from different majors (engineering, marketing, computer science etc.) participated in the study. The interviews were with two sessions that discuss different contexts. In the interviews, the researchers used some activities that were called "Model Eliciting Activities". The researchers followed phenomenographic research methodology and they categorized students explanations (quotes and excepts). The agreement (inter-coder reliability coefficient) was obtained 0.80 by two independent coders. Then, the researchers combined the categories and constructed the themes. The researchers identified two basic categories as models of "Mechanical Interactions" (i.e. intertwining or interlocking, rubbing or sliding, skimming over the top, getting smoother, oil as bearing, floating and reduction of bums and valleys), and "Bonding" (i.e. breaking of bonds, fewer bonds, weaker bonds). Moreover, it was explained that these models constructed on the spot while answering the questions in the interviews.

Scherr's (2007) followed two theoretical frameworks to identify students' understanding of special relativity concepts. In addition, examined students' ideas in terms of both "framework of ideas", which were called misconception model, mental model, alternative model etc. and "pieces model", which were called p-prims, facets, resources etc. In her study, by considering the true or false determinacy of theories, she called the false ideas as "misconception model". However, she still considers coherently structured ideas for false frameworks. In the analysis, which the determinacy, coherency, context dependency, variability, and malleability were discussed, she identified that students' ideas about the theory of special relativity favor both of the theories. In other words, she concluded that some aspects of the students' ideas can be described by misconception model, and some of the others can be described by pieces model. More specifically, students' ideas about "simultaneity" is consistent with misconception model, "nature of reference frame" is consistent with knowledge in pieces, or pieces model.

Hubber (2006) examined students' mental models about the nature of light by a longitudinal study. Six participants of the study were examined in three years (from 10th year to 12th year). Namely, the researcher examined students' mental models prior to, and following 12th grade. The research was classroom based, and the role of the researcher in his research was both teacher and the researcher. He implemented methods of constructivist perspective due to his teaching experience. In order to provide some validity issues, triangulation, member checks, and peer examination were undertaken. Data were collected by interviews, classroom observations and questionnaires. In the research, three types of models emerged early in Year 12. These are: Standard Ray Model incorporating Wave Model, Beam Ray Model and Particle Ray Model. However, the researcher indicated he got some evidences that students had views of "beams" and "rays" in Years 10 and 11. During Year 12, students presented a range of models about the nature of light. Students also constructed hybrid models. The researcher identified a change in students' "thinking of rays as actual constituents of light" in three years. The researcher explained that students presented naïve realist epistemology in Years 10 and 11. Three students presented ray scientific model of light at the beginning of Year 12. The researcher concluded that the reason of persistency of understanding "ray" was the ontological difference between "ray as a physical entity" and "ray as a graphical representation".

Vadnere and Joshi's (2009) study is considerably new study using the tool of Bao (1999) that he developed in his dissertation to examine students' mental model; however, their design differed from Bao (1999). The researchers examined students' mental models of some physics concepts with a weak experimental design. The researcher implemented a pre-test to 119 volunteer Standard 12 (corresponding K-12) students. Then, a software used for students' learning of the physics concepts including heat transfer, electromagnetic radiation, Wien law etc. Then, the students were post-tested. In the analysis, the researchers used the "density matrix", which was used in mental model identification by Bao (1999). They firstly defined three probabilities for students' mental models such as expert model (E), misconception model (M), and null model (N) by considering students' answers. In the examination of the development of students' mental models, the researchers identified that the increase in the probability of triggering expert state, and the decrease in the null state were higher in the post-test then in the pre-test. By this way, they explained this media is successful in the development of students' mental models. They suggested the tools of quantum mechanics, which are the mathematical expressions used in the definition of quantum particles i.e. density matrix, could be used to analyze students learning.

Chiou and Anderson (2010) examined college students' mental models about heat conduction by considering students' ontological beliefs. They conducted interviews with 30 undergraduate physics students in Taiwan. Each interview was video recorded. The researchers coded the data. They compared the different data such as verbal, drawing, writing etc. obtained from participants, and they obtained 0.92 agreement on the categorization of ontological beliefs, and 1.00 agreement on the categorization of process analogies. Then, by discussion the discrepancy the researcher got the total agreement. At the end of the data analyses, the researchers identified three ontological beliefs for heat that are substance, calorie and molecule; and five process analogies as marching, flooding, gradient, gradient-marching, and gradient-flooding. Then, by combination of these issues, they identified seven mental models about heat conduction. These are: Calorie-Marching, Molecule-Flooding, Substance-Gradient, Calorie-Gradient, Molecule-Gradient, Molecule- (Gradient-Marching), and Calorie- (Gradient-Flooding). By considering these two aspects, the researchers suggested that examination of mental models by combination of these two aspects could be better.

2.1.2 Fragmented Structures

There are some knowledge structures, which are smaller than mental models. Redish (2003, p.24) and Scherr (2007) stated that it was not necessary to form coherent frameworks using knowledge pieces such as primitives, facets, and resources. However, it might be possible to organize fragments to construct a coherent framework, and many researchers such as Bao (1999), Hrepic (2002, 2004), Itza-Ortiz et al. (2004), Wittmann (1998), Wittmann et al. (1999) explained that mental models consist of some cognitive and some knowledge elements such as p-prims, resources, facets etc. For example, Wittmann (1998) explained "mental model" in terms of primitives. He used a "guiding executive" term that "guides students to use and interpret particular primitives in particular situations". So he considered this guiding executive as "a mental model" when it was "structured" and “coherent”. In addition, Chinn and Brewer (1998) mentioned there could be observed a shift from fragmented knowledge to more structures knowledge as a global change of knowledge.

In physics education, the p-prims of diSessa (1983, 1993), the resources of Hammer (2000), and the facets of Minstrell (1992) are the most examined fragmented elements. Wittmann (1998) defined the term “pattern of associations” between primitive elements and mental models. Pattern of associations could be thought of as “a linked web of primitives and facets associated with a topic,” and he considered them “more fluid and less precise” than mental models. A pattern of associations may be also “incomplete” and “self-contradictory” as with mental models; however, he stressed its “incoherency” to distinguish it from a mental model. Since the aim is not to examine such type of fragmented structures, I mentioned only two of the knowledge pieces that are widely examined. These are: P-prims of diSessa (1983, 1993), and facets of Minstrell (1992).

2.1.2.a Primitives

Students might not always have coherent structures in their mind. They may have “fragmented” structures. One of the theories, which draws attention to students’ fragmented knowledge structure is the “phenomenological primitives (p-prims) theory” of diSessa (1983). In contrast to the coherent characteristics of mental models, according to p-prims theory knowledge is made up smaller, more fragmentary structures in the mind (Hammer, 1996; Ueno, 1993). P-prims are like “conceptual atoms” to form complex cognitive structures (Taber, 2008). They are not only elements of knowledge, they also are used in combination with other elements in cognition (diSessa, 1993).

P-prims operate at a preconscious level (Taber, 2008) since they are too abstract, general and oversimplified (Bao, 1999). They do not need explanation (Ueno, 1993), however, they explain the events. After they are obtained in one context, they may be transferred to other contexts by over-generalizing the events. Therefore, it is also meaningless to classify p-prims as correct or wrong. However, it should be discussed whether the “use of p-prims” are appropriate or not in a specific context. Wittmann (1998) showed that many students did not have the ability to determine the appropriate p-prims to use for the “wave” concept, so they used them inappropriately.

P-prims are socially shared (Ueno, 1993) and they are activated in specific contexts (diSessa, Gillespie, & Easterly, 2004). People construct their stable conceptual structures from primitive elements through repeated use (Taber, 2008). The students who do not have stable and coherent knowledge structures may construct their answers in-situ from fragmented elements, so they can give inconsistent answers influenced by contextual features (Taber, 2008).

2.1.2.b Facets

Another type of fragmented elements is the "facet" of Minstrell (1992). He defined a facet as a "convenient unit of thought, a piece of knowledge or a strategy seemingly used by the student in addressing a particular situation" (p. 112). So, they can be considered as context-specific interpretations of primitives (Bao, 1999; Wittmann, 1998). One of the other differences between p-prims and facets can be seen in their involvement in mental operations. For example, involvement of p-prims is often implicit; however, involvement of facets is often explicit in mental operations (Bao, 1999).

2.2 Quantum Theory

Two important synchronic studies in 1900's affected the framework of physics differently. One of these studies is "Max Planck's introduction of quantized energy to explain the spectrum of Blackbody Radiation" (Ke et al., 2005), and the other is the "relativity theory of Albert Einstein". These studies specialized physics into relativistic physics and quantum physics. While the theory of relativity was changing the idea of space and time, the quantum theory introduced indeterminism, probability and non-locality into physics (Müller & Wiesner, 2002).

Quantum physics can be defined briefly as the physics of very smalls. It explains one of the most successful theories in physics- *quantum theory*. The quantum theory is a physical theory which is constructed out of physical ideas, and it is expressed mathematically (Erkoç, 2006, p.XIII). Quantum mechanics provides mathematical tools to explain the physical events of quantum theory. Merzbacher (1998) defined it as a "theoretical framework within which it has been found possible to describe, correlate, and predict the behavior of a vast range of physical systems, from particles through nuclei, atoms and radiation to molecules and condensed matter" (p.1). It is regarded as probabilistic physical theory with probabilistic nature (Busch, Lahti, & Mittelstaedt, 1996).

Quantum mechanics was independently explained by two young physicists almost at the same time. In 1925, German physicist Heisenberg's "Matrix Mechanics", and in 1926, Austrian physicist Schrödinger's "Wave Mechanics" were understood as independent theories. However, the big interrelation between these theories was comprehended, and they were combined by English physicist Dirac in an extensive theory, which was *"Quantum"* (Penrose, 1997, p.103). 1926 is considered as the golden age of physics with a new quantum theory. Although, Einstein did not accept the quantum theory by saying "the god does not play with dice" referring to the probabilistic explanations of the theory, his "photoelectric experiment" is one of the most important experiments in this theory that indicates the particle nature of light. The nature of atoms and quantum particles, wave particle duality and Heisenberg uncertainty relations, probability, wave- functions, the Hilbert space, the Schrödinger equation, quantization, and matrix representations are the main elements and concepts of this theory.

The quantum theory is accepted as a successful theory in the history of science. It allows scientists to calculate many experiments, and creates new technology based on the behavior of atomic objects (Faye, 2002). The explanations of the forces, which compose matter and the physical properties such as colors of matter, freezing and boiling etc. require the knowledge of quantum theory (Penrose, 1997, p.96). So, it has great importance in physics. For this reason, learning of the quantum theory by students is as important as quantum theory itself.

Until the beginning of the study of quantum physics, scientists were interested in the physical behaviors of macro systems described by classical physics. However, passing from the macro-world to the micro-world with the quantum theory changed all measurement techniques, in addition to interpretations in some parts of physics. "Quantization" is (first) one the important phenomena considered in the new paradigm "quantum theory". It allowed Planck and Einstein having Nobel prizes in 1918 and 1921, respectively. Or, another example, the first postulate of the quantum theory explains that any self-consistently and well-defined observable (such as energy, linear momentum etc.) in classical physics corresponds an operator in quantum mechanics (Liboff, 1998, p. 67). It should be acted on some functions, and the calculations of mathematical expressions that are the measurement process gives us the behavior of the particle. This change is sometimes considered a paradigm shift in physics, from classical physics to quantum physics because of the deep changes on the explanation of behaviors of small particles. It coerced physicists "to reshape their ideas of reality, to rethink the nature of things at the deepest level, to revise their concepts of position and speed, their notions of cause and effect" (Kleppner & Jackiw, 2000, p.893).

2.3 Pedagogical Research on Quantum Theory

In 1990s, the amount of educational research on students' understanding of quantum mechanical concepts has increased. The great proportion of this research has been conducted in cognitive domain, and the research in affective domain has just been conducted recently, mainly focusing on achievement motivation (Didiş & Eryılmaz, 2007; Didiş & Özcan, 2007, Didiş & Redish, 2010).

Figure 2.1 presents the map of pedagogical research on quantum mechanics. The pedagogical research on quantum mechanics examines both upper level high school and university physics students' understanding, and provides new methodologies about quantum mechanics instruction (Budde et al., 2002a, 2002b; Cuppari, Rinaudo, Robutti, & Violino, 1997; Çataloğlu, 2002; Çataloğlu & Robinett, 2002; Didiş et al., 2007, 2010; Didiş, Özcan, & Abak, 2008; Dobson, Lawrence, & Britton, 2000; Escalada, 1997; Frederick, 1978; Gardner, 2002; Hadzidaki, Kalkanis, & Stavrou, 2000; Ireson, 2000; Kalkanis, Hadzidaki, & Stavrou, 2003; Ke et al., 2005; Kwiat & Hardy, 2000; Michelini, Ragazzon, Santi, & Stefanel, 2000; Morgan, 2006; Müller & Wiesner, 1999, 2002; Olsen, 2002; Özcan et al., 2009; Sadaghiani, 2005; Shadmi, 1978; Singh, 2001; Singh, Belloni, & Christian, 2006; Strnad, 1981; Styer, 1996; Wattanakasiwich, 2005; Vandegrift, 2002).

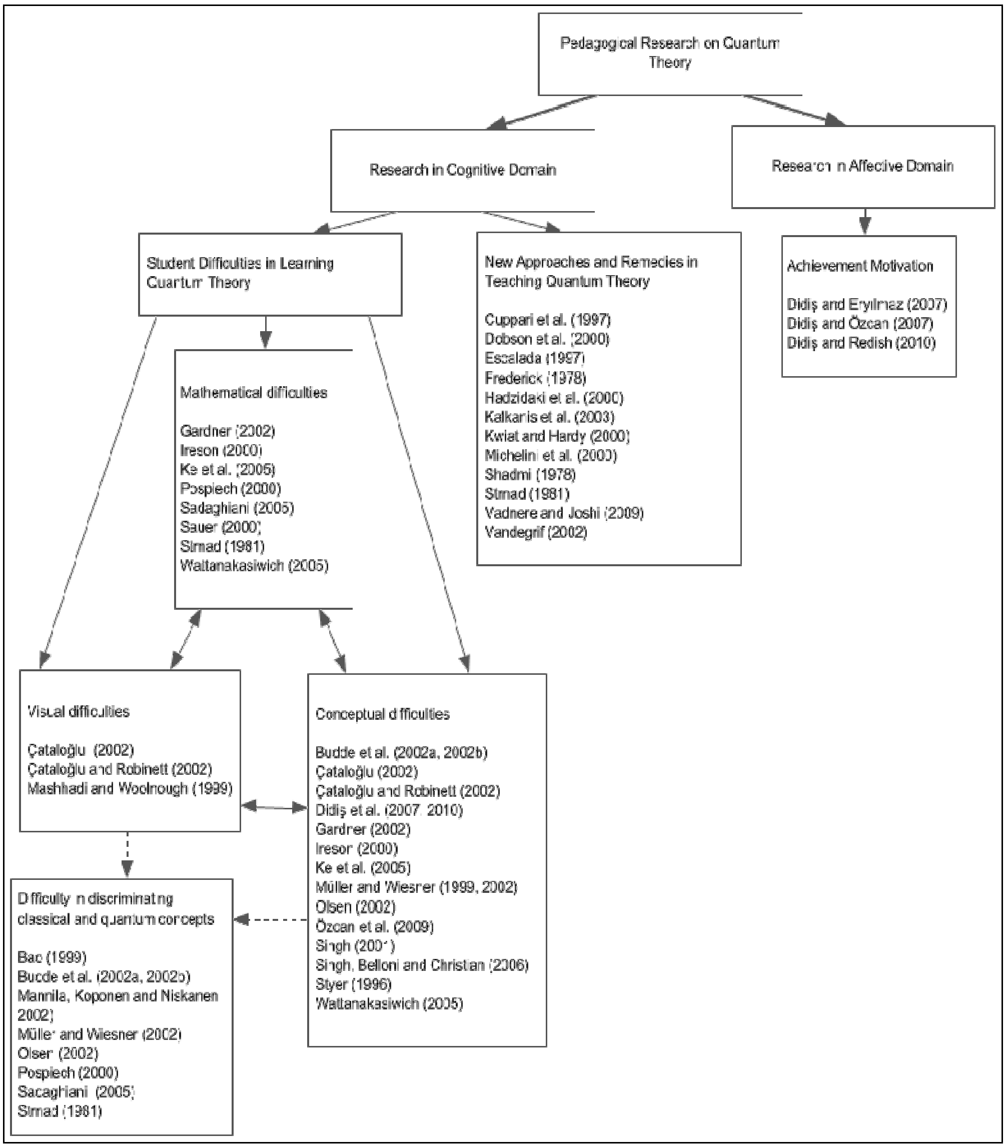

Figure 2.1 Map of pedagogical research on quantum mechanics.

The research in the cognitive domain focuses on student difficulties and new approaches and remedies to overcome these difficulties, since students have mainly four types of difficulty in learning quantum theory: (1) *Conceptual difficulty* (Budde et al. 2002a, 2002b; Çataloğlu, 2002; Didiş et al., 2007, 2010; Gardner, 2002; Ireson, 2000; Ke et al., 2005; Müller & Wiesner, 1999, 2002; Olsen, 2002; Özcan et al., 2009; Singh, 2001; Singh et al., 2006; Styer, 1996; Wattanakasiwich, 2005), (2) *mathematical difficulty* (Gardner, 2002; Ireson 2000; Ke et al., 2005;

Pospiech, 2000; Sadaghiani, 2005; Sauer, 2000; Strnad, 1981; Wattanakasiwich, 2005), (3) *visual difficulty* (Çataloğlu, 2002; Çataloğlu & Robinett, 2002; Mashhadi & Woolnough, 1999), and (4) *difficulty in discriminating classical and quantum concepts* (Bao, 1999; Budde et al., 2002a, 2002b; Mannila et al., 2002; Müller & Wiesner, 2002; Olsen, 2002; Pospiech, 2000; Sadaghiani, 2005; Strnad, 1981). In addition to the identification of these difficulties, new materials were developed by the researchers and previous instructions were revised (Cuppari et al., 1997; Dobson et al., 2000; Escalada, 1997; Frederick, 1978; Hadzidaki et al., 2000; Kalkanis et al., 2003; Kwiat & Hardy, 2000; Michelini et al., 2000; Shadmi, 1978; Strnad, 1981; Vadnere & Joshi, 2009; Vandegrift, 2002).

2.3.1 Student Difficulties in Learning Quantum Theory

2.3.1.a Conceptual difficulties

One of the reasons of students' "misconceptions" is the difficulty of abstract concepts in quantum physics (Singh et al., 2006; Styer, 1996). Misconceptions are stable, unscientific concepts of individuals. It is difficult to understand the abstract concepts by reading their definitions, so misconceptions are unavoidable in understanding quantum physics. PERGs study for the same goal of providing conceptual learning for every concept of physics. For this reason many researchers tried to understand students' conceptions about quantum mechanical concepts (Budde et al., 2002a, 2002b; Çataloğlu, 2002; Çataloğlu & Robinett, 2002; Didiş et al., 2007, 2010; Gardner, 2002; Ireson, 2000; Ke et al., 2005; Müller & Wiesner, 1999, 2002; Olsen, 2002; Özcan et al., 2009; Singh, 2001; Styer, 1996; Wattanakasiwich, 2005).

Misconceptions in quantum mechanics are not considered as "pre-conceptions" because students have almost no chance to gain experience about quantum theory in their daily lives. For this reason, unscientific, coherent and robust explanations of the concepts, which may be gained from textbooks, teachers and the language in lesson, were explained as misconceptions. Styer's (1996) listed some misconceptions in quantum mechanics based on his observation of students, colleagues etc. He emphasized conceptual difficulties and suggested these misconceptions should be taken into consideration in order to combat them. He classified these misconceptions into three major classes. They are: "(1)

misconceptions regarding the idea of quantal states (about wavefunctions, energy eigenstates etc.), (2) misconceptions regarding measurement, (angular momentum measurements, wave packets etc.), and (3) misconceptions regarding identical particles" (pp.31-33).

After the identification of the general misconceptions of students, Müller and Wiesner (1999, 2002) investigated German students' ability to distinguish between classical and quantum objects and overview the common conceptions of quantum objects. They researched pre-service physics teachers' conceptualizations of "atoms, permanent localization, [and the] Heisenberg uncertainty principle". They focused on students whose major was not physics, who never have a chance for learning concepts in quantum physics conceptually. The study of Müller and Wiesner (1999) can be accepted as the first study on pre-service physics teachers. So it is very important for both its design and results.

In Ireson's (2000) study, a 40- item questionnaire was given to 342 pre-university students in England to determine the students' understanding of quantum phenomena. These items were with five point scale, and 29 of the 40 items were directly related with the "quantum phenomena". The results of the cluster analysis of the post- study revealed three clusters about students' understanding of the quantum theory. These were: "(1) Quantum thinking, (2) Conflicting quantum thinking, and (3) Conflicting mechanistic thinking". The study showed that students could not interpret the quantum theory (the problematic ones were second and third clusters) by conflicting some quantum ideas with each other and attributing conflicting mechanistic properties to some basic ideas of the quantum theory.

Gardner (2002) aimed to understand students' perspectives about learning quantum mechanics in his dissertation. He conducted a qualitative research by getting data by range of techniques. He conducted interviews with large number of students, and made observations in undergraduate (Classes A, B, and C) and graduate (Class D) quantum mechanics classes in physical chemistry curriculum. He got artifacts, which were 3x5 cards that students wrote their comments about the class at the end of each class. He identified that students had conceptual difficulties on waves, harmonic oscillator, angular momentum, Hamiltonian, energy levels and transitions, wave particle duality and uncertainty concepts. He concluded the reasons of these difficulties were difficulty in physical concepts and difficulty in mathematical ideas.

Morgan (2006) studied undergraduate physics students' conceptions of "energy, probability and barriers" by conducting surveys and interviews. He used the research results to develop tutorials about these concepts. After the development of the tutorials, they were used in the quantum mechanics courses. The results of his experiment showed that the students using the tutorials learned the basic ideas of quantum physics and answered tunneling questions as well or better than the advance undergraduate physics students.

Sadaghiani (2005) studied both conceptual and mathematical difficulties of university physics students with basic concepts such as probability, operators, wave functions, and the uncertainty principle. Many students showed that they did not have functional understanding of probability and related concepts. Students had problems with terminology and they confused some terms such as "expectation value" and "probability density", "probability density" and "probability amplitude" with each other.

Wattanakasiwich (2005) also examined university physics students' conceptions about the probability concept. She explained the reason for students' difficulties in conceptual understanding as having a lack of physics knowledge. For this reason, they do not understand the mathematical solutions" conceptually, and memorize the solutions.

Singh (2001) examined advanced undergraduate students' difficulties in some quantum mechanics concepts such as measurements, time development. She implemented a test to 89 students from six different universities and conducted interviews with nine students. She identified that although students had different background, teaching style and textbook, most of them presented same difficulties such as unsureness about their responses, difficulty in discriminating concepts and conflicting justifications. She identified some misconceptions about operator, expectation value, eigenstate, and time evolution. Students' difficulties were summarized in three categories as "(1) lack of knowledge related to a particular concept, (2) knowledge that is retrieved from memory but cannot be interpreted correctly, (3) knowledge that is retrieved and interpreted at the basic level but cannot be used to draw inferences in specific situations" (p.892).

Didiş et al. (2010) examined two pre-service physics teachers' understanding of some quantum concepts such as operator, observable, eigenvalues and interrelated concepts. The researchers collected data with the interviews. They identified that (1) students had insufficient conceptions that influence their descriptions and discriminations, (2) students' comprehension contained correct and wrong ideas simultaneously, and their indefinite comprehension influenced the use of different concepts interchangeably, and making explanations and discriminations by intuitive reasoning, and (3) some of the conceptions of students were totally unscientific. In addition, students' comprehension allowed translation only from mathematical to verbal.

As a summary of this section, although the designs and the samples of the studies were different, the results indicate that students had conceptual problems in understanding quantum mechanics. And, from my personal experience, students' conceptual difficulties create problems in solving mathematical problems.

2.3.1.b Mathematical difficulties

Mathematical formalism is one of the prominent characteristics of the quantum theory. While Pospiech (2000) explained that mathematical formalism often hides the philosophical issues, Ireson (2000) claimed that the mathematical formalism of quantum mechanics is not the problem, but the problem is interpretation. Gardner (2002) supported this idea in his dissertation by indicating that students' problems were not related to the calculation of the mathematical problems, but they are related with the lack of mathematical skills and calculus background, lack of transfer of mathematical knowledge to quantum mechanics course, and difficulty in notations. By considering these different explanations, researchers may ask these questions to understand the reasons of students' mathematical difficulties: What is the main problem in quantum mechanics about mathematics? Is the problem because of its highly mathematical structure (and also requiring the solving of mathematical problems, including advanced calculus) or not being able to interpret these mathematical expressions?

There are some studies in literature about the mathematical difficulty of students (Ke et al., 2005; Sadaghiani, 2005; Strnad, 1981; Wattanakasiwich, 2005) helping to find answers to these questions. Strnad (1981) explained that the reasons for the difficulty in teaching quantum mechanics in secondary school are an "unsatisfactory mathematics background" in addition to students' classical mechanics usage. The exams require strong mathematical skills to solve problems. However, the ability of students to solve mathematical equations in quantum mechanics does not show students' conceptual understandings (Ke et al., 2005).

Sadaghiani (2005) also studied the mathematical difficulties of students in quantum mechanics. She indicated that students' achievement in quantum mechanics was related to their mathematics backgrounds. They had difficulty in differentiating the wave function and recognizing the mathematical symbols. She recommended instructors emphasizing in quantum mechanics lectures that "quantum mechanics is a mathematical theory" (p.82).

2.3.1.c Visual difficulties

The statement of Eddington (Eddington, 1928, p.xvii as cited in Mashhadi & Woolnough, 1999, p.511) "When I think of an electron there rises to my mind a hard, red, tiny ball" is a good example that shows us that not being able to experience the quantum mechanical concepts in micro-levels brings different visuals to our minds about them. Mashhadi and Woolnough researched students' imaginations about electrons and photons in England and Wales upper secondary school students. Students gave many different representations of visuals in their minds about electrons and photons. The variation in students' responses was categorized by the researchers. For example the most probable responses for electrons and photons were that "electrons are very small spherical objects that move very fast (23%)", and "photons are bright spherical balls (38%)" respectively. The results showed that majority of students made abstract concepts concrete by unscientific visual images in their mind.

Another study about the visualization of quantum mechanical concepts belongs to Çataloğlu (2002). The researcher aimed to develop a valid and reliable multiple choice test in quantum mechanics. He developed 24-questioned Quantum Mechanics Visualization Instrument (QMVI) by the participation of 213 undergraduate and graduate students. By this test, students' understanding of visual representations was also investigated. Instead of limited data on visualization, it was indicated that students could connect their mathematical and conceptual knowledge with visual representations in quantum mechanics. That means, some results showed that students could use their knowledge on quantum mechanics by manipulating the information given in visual representations.

2.3.1.d Difficulty in discriminating classical and quantum concepts

Pospiech (2000) claimed in her study that the reasons for difficulty in understanding quantum mechanics started with classical mechanics. A similar study, Budde et al. (2002a, 2002b), added the reasons for difficulty in learning atomic models were the differences between the quantum physics and classical physics views. For this reason, “Electronium” atomic model was suggested by the researchers. In this model, all the quantities such as energy, angular momentum, charge, and the field were considered as substantial fluid whose density varying from center to surface. After teaching the probability atomic model, Electronium was introduced to students in order to remove the classical mechanics interpretations in quantum mechanics for the atomic model. That means, they aimed to change students’ electron perspective that is “particle” into the “substance”.

Strnad (1981) explained another difficulty arising from students’ classical physics background in addition to an unsatisfactory mathematics background. Müller and Wiesner (2002) stated that because of traditional instruction and counter intuitiveness of quantum mechanics, students confused classical and quantum notions, so their misconceptions were not surprisingly occurred.

The study of Mannila et al. (2002) was about students’ conceptions of the wave- and particle-like properties of quantum entities. The researchers examined two groups of students’ qualitative problem solving from two intermediate quantum mechanics courses. One of the groups contained eight students who were educated to get physics teachers degree. The other group contained 21 students from physics majors. The students were shown some figures and with eight questions were asked. The analysis of the interviews revealed that students’ responses formed four major classes as quasi-classical (particle ontology based), trajectory-based, statistical (probabilistic) and quasi-quantum. It was stressed that students persistently used classical models and students understood quantum mechanical concepts by using classical conceptions. The main difficulty for students was to construct a new ontology for a conceptual shift. In many studies, it was recommended that classical mechanical concepts should be avoided in quantum mechanics courses.

Sadaghiani (2005) found that students used classical mechanical models to interpret quantum mechanical events. Olsen (2002) also reported that students poorly understood wave-particle duality in his study with 230 high school students. He indicated some students clearly demonstrated misconceptions due to their classical physical background. In contrast, Bao (1999) explained that students could interpret the situations in quantum mechanics if there were traces from classical mechanics; otherwise they could not make any physical interpretation, and quantum mechanics became just a composition of mathematical equations.

To summarize students' difficulties, the literature indicated that these difficulties are not independent from each other. They are linked with each other and they cause interrelated problems (Bao, 1999; Budde et al., 2002a, 2002b; Çataloğlu, 2002; Çataloğlu & Robinett, 2002; Didiş et al., 2007, 2010; Gardner, 2002; Ireson, 2000; Ke et al., 2005; Mannila et al., 2002; Mashhadi & Woolnough, 1999; Müller & Wiesner, 1999, 2002; Olsen, 2002; Özcan et al., 2009; Pospiech, 2000; Sadaghiani, 2005; Wattanakasiwich, 2005). In other words, all conceptual, mathematical and visual difficulties interact with each other. The sources of these difficulties are understood differently by the researchers. Although some of the researchers thought that the source of them was the nature of the quantum theory, others thought the source of problems was related to the students' background and instruction.

2.3.2 New Approaches and Remedies in Teaching Quantum Theory

Due to students' these four types of difficulty in understanding quantum mechanics, some researchers proposed new approaches, in other words "remedies", to these difficulties in several ways (Cuppari et al., 1997; Dobson et al., 2000; Escalada, 1997; Frederick, 1978; Hadzidaki et al., 2000; Kalkanis et al., 2003; Kwiat & Hardy, 2000; Michelini et al., 2000; Shadmi, 1978; Strnad, 1981; Vadnere & Joshi, 2009; Vandegrift, 2002). These approaches can be classified into basically into two categories. First one can be considered as a remedy for the whole of the instruction. That means, in order to develop conceptual understanding, quantum mechanics instructors need to design new courses. For example, Hadzidaki et al. (2000) and Kalkanis et al. (2003) strongly believed that a qualitative approach to quantum mechanics should be designed following the historical development of the concepts. They proposed a simple, sufficient and relevant teaching approach towards quantum mechanics into pre/in-service teachers. Hadzidaki et al. (2000) and Kalkanis et al. (2003) suggested lectures imply the independent conceptual systems of classical mechanics and quantum mechanics. Escalada (1997) tried to develop activity-based quantum mechanics lessons for high school students who have a limited mathematical and physics background. He studied the solids and light unit in the Visual Quantum Mechanics Project of Kansas State University. The research showed that students learned the related topics about solids and light. It was also indicated that the training of teachers for activity-based quantum mechanics lectures was very difficult, although the lectures were designed well. Vadnere and Joshi (2009) identified that use of a multimedia package for learning of early quantum concepts such as blackbody radiation, Wien's Law etc. promoted construction of scientifically accepted models. That means, it was helpful for learning.

The other approach is "not standardizing the methods used for teaching concepts". That means instructors applied different approaches to teach different concepts (Cuppari et al., 1997; Dobson et al., 2000; Frederick, 1978; Kwiat & Hardy, 2000; Michelini et al., 2000; Shadmi, 1978; Strnad, 1981; Vandegrift, 2002). For example, tutorials were developed and applied to instruction as course materials. Michelini et al. (2000) proposed introducing Dirac formalism without requiring an advanced mathematics and physics background in polarization of photons. These researchers believed students could learn the basic ideas of the quantum theory without an advanced mathematics background. Cuppari et al. (1997) proposed a different idea about the usage of classical mechanical traces in quantum mechanics lessons. They proposed that an introduction to quantum mechanics course should consider the action of classical mechanics. This allows students to investigate the limits of classical mechanics to explain quantum mechanical events. When the studies about remedies are considered, these remedies change due to the researchers' epistemologies about quantum mechanics.

2.4 Summary of the Related Literature

This is not a narrative summary of previous research. By showing the whole picture in worldwide and Turkey, it aims to state the last status of related literature.

- Previous research showed that students had great problems in learning quantum physics (Bao, 1999; Budde et al., 2002a, 2002b; Çataloğlu, 2002; Çataloğlu & Robinett, 2002; Didiş et al., 2007, 2010; Gardner, 2002; Ireson, 2000; Ke et al., 2005; Mannila et al., 2002; Mashhadi & Woolnough, 1999; Müller & Wiesner, 1999, 2002; Olsen, 2002; Özcan et al., 2009; Pospiech, 2000; Sadaghiani, 2005; Sauer, 2000; Singh, 2001; Singh et al., 2006; Strnad, 1981; Styer, 1996; Wattanakasiwich, 2005).
- These problems are not only visual and mathematical, but the most important one is "conceptual". At this point, how students organize their knowledge is important. One of the theories about knowledge organization is "mental modeling" and in physics education literature, large number of studies (Bao, 1999; Bao & Redish, 2006; Borges & Gilbert, 1999; Chiou & Anderson, 2010; Corpuz, 2006; Corpuz & Rebello, 2005, 2011a; Hrepic, 2002, 2004; Hrepic et al., 2010; Hubber, 2006; Itza-Ortiz et al., 2004; Redish, 1994; Scherr, 2007; Vadnere and Joshi, 2009; Wittmann et al., 1999) identified students' mental models on various physics concepts. By this way, the researchers had idea about what was happening in students' minds, and they explained students' understanding of various physics concepts by means of mental modeling framework. Common characteristics of the mental modeling research in physics education can be summarized as the examination of models in a course context, examination in a long period (such as a semester) and by following interviews, examination in multiple contexts, and examination of university level students' mental models. However, although they focus on common issues, the research design of each study strictly differs from each other.
- Other common characteristic of these studies is giving limited information about the "determination of a mental model" (i.e. coding procedure, codes etc.). Thick description of coding procedure is not stated much in these studies. Therefore, we have limited information about the components of mental models and the characteristics of these elements.

- In addition, the examination of students' mental models in various physics concepts provides great advantages to understand the function and characteristics of mental models. However, there is no strict methodology to identify mental models, and each design has strong and weak points.
- To sum up, Table 2.2 and Table 2.3 summarize the previous research and present the need for current study by reflecting previous research in worldwide and Turkey, respectively. In these tables, I could not integrate all of the related studies although I have read some other related studies. So, the studies explained in the boxes are most related research in this dissertation and I called the unstated ones with "*" in the boxes.

Table 2.2 Whole picture of related literature in worldwide.

	Quantization	Quantum Physics	Other Physics Domains
With mental modeling framework		Bao (1999), Vadnere and Joshi (2009).	Bao and Redish (2006), Borges and Gilbert (1999), Chiou and Anderson (2010), Corpuz (2006), Corpuz and Rebello (2005, 2011a), Hrepic (2002, 2004), Hrepic et al. (2010), Hubber (2006), Itza-Ortiz et al. (2004), Redish (1994), Scherr (2007), Wittmann et al. (1999), *
Without mental modeling framework		Budde et al. (2002a, 2002b), Cuppari et al. (1997), Çataloğlu (2002), Çataloğlu and Robinett (2002), Dobson et al. (2000), Gardner (2002), Escalada (1997), Frederick (1978), Hadzidaki et al. (2000), Ireson (2000), Ke et al. (2005), Kalkanis et al. (2003), Kwiat and Hardy (2000), Mannila, Koponen and Niskanen (2002), Mashhadi and Woolnough (1999), Michelini et al. (2000), Müller and Wiesner (1999, 2002), Olsen (2002), Pospiech (2000), Sadaghiani (2005), Sauer (2000), Shadmi (1978), Singh (2001), Singh, Belloni and Christian (2006), Strnad (1981), Styer (1996), Vadnere and Joshi (2009), Vandegrift (2002), Wattanakasiwich (2005), *	**NOT IN MY INTEREST**

* represents other research that could not be integrated into the table.

- As it is seen in Table 2.2, although there is great amount of pedagogical research in quantum physics and mental models separately, there is limited research in quantum physics with mental modeling in worldwide. In addition, these studies have some limitations. Finally, first column of the table also shows that "quantization" phenomenon is not studied anyway by mental modeling framework. Table 2.3 indicates the status of the literature with these domains in Turkey. Both of mental modeling and pedagogical research in quantum physics and quantization are new research areas for physics education research in Turkey.

Table 2.3 Whole picture of related literature in Turkey.

	Quantization	**Quantum Physics**	**Other Physics Domains**
With mental modeling framework			
Without mental modeling framework		Didiş et al. (2007, 2008, 2010), Özcan et al. (2009), *	**NOT IN MY INTEREST**

* represents other research that could not be integrated into the table.

- Because of some missing in the literature in worldwide and Turkey, this study aimed a pedagogical research in quantum physics learning by using the mental modeling framework. While explaining students' mental models about quantization, it discussed some sources influencing students' model development. Therefore, by taking into consideration the strong points of previous research and by constructing a new design, this study differed from previous research in terms of research design, examined physics concepts, detailed explanation of data analysis (coding, inter-coding, constructing themes).

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

This is a qualitative research aimed to examine second-year physics and physics education students' mental models about some quantum physics concepts. So, the research questions are:

1. What are the second-year physics and physics education students' mental models of the quantization of physical observables?
2. What are the characteristics of second-year physics and physics education students' mental models of the quantization of physical observables?
3. What are the external and internal sources that influence students' mental models of the quantization of physical observables?
4. How do the second-year physics and physics education students' mental models of the quantization of physical observables develop by the influence of internal and external sources?

These questions were examined in three parts such as (1) Models and the characteristics of models (with the first and second questions), (2) The sources influencing models (with the third question), and (3) The development of models by influence of the sources (with the fourth question). As it is presented in Figure 3.1, the qualitative research in this dissertation was guided by three research methodologies that each methodology is fundamental and inseparable to explain each part constructing the dissertation. These methodologies are: (1) Case study, (2) ethnography, and (3) content analysis.

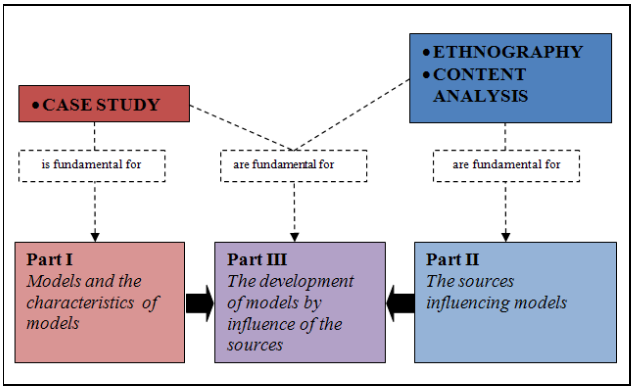

Figure 3.1 Research design of the dissertation.

Although these methodologies are seen separate, they are interwoven to each other by using the data emerged from specific methodologies. The fundamental research methodology to explain Part I was called as "case study". This part includes sequenced measurements (interviews, test). Part II is almost unobtrusively examined by "ethnography" and "content analysis". Ethnography is a type of qualitative research methodology that documents the everyday experiences of individuals by observing and interviewing them (Fraenkel & Wallen, 2000, p.541). It is widely used in educational settings from pre-schools to institutions of higher and adult education (Beach, Gobbo, Jeffrey, Smyth, & Troman, 2004). In this research, students' natural setting, course content, course requirements and instructor's methodology etc. were not manipulated, and students' artifacts and course materials were examined through the study. So, the fundamental research methodologies for Part II were called as ethnography and content analysis, respectively. Finally, for Part III, findings of Part I and II were interpreted together to explain students' model development.

Figure 3.2 presents an overview of the research starting from the data collection and up to the integration of results. This figure is independent of research questions just focusing on the data collection and analysis processes of the dissertation.

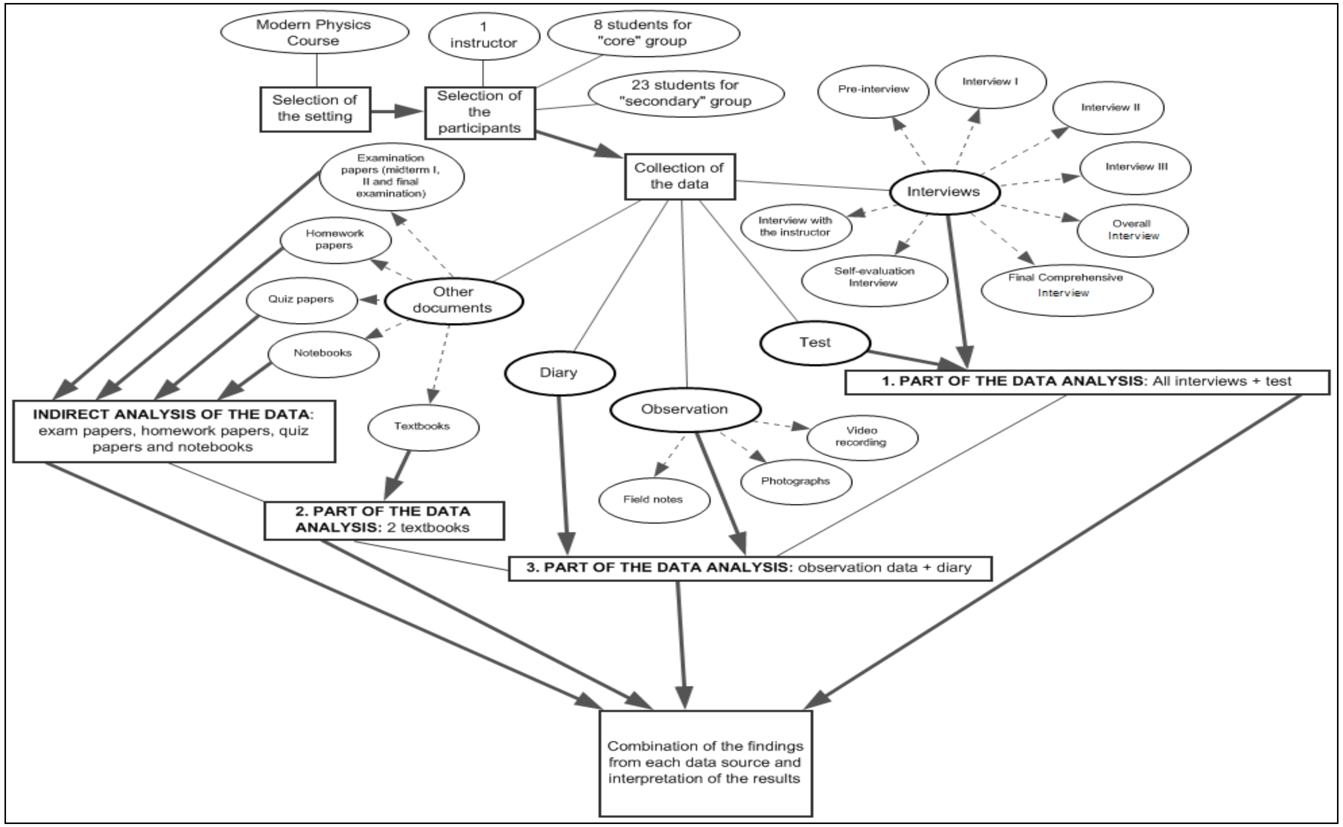

Figure 3.2 Summary of the research.

3.2 Description of the Key Issues in This Research

This research was conducted in the Modern Physics (PHYS 202) course given in the Department of Physics. In this section, I describe five key issues important for this study. These are: (1) Modern Physics course, (2) the participants of the study, (3) the instructor, (4) the course setting, and (5) the cases and contexts that were examined in this study.

3.2.1 Description of the Modern Physics Course

Concepts of the quantum theory are taught to physics and physics education students in three related compulsory courses: Modern Physics (PHYS 202), Quantum Physics (PHYS 300) and Quantum Mechanics (PHYS 431) in the Department of Physics at METU. The first course - Modern Physics - includes two fundamental physics topics: Relativistic Physics and Quantum Physics. In this course the "special theory of relativity, particle properties of waves, wave properties of particles, atomic structure, elementary quantum mechanics, many electron atoms, nuclear structure and radioactivity" (Department of Physics, 2010) are introduced to students. Appendix A shows the details of the course content and objectives that were written by the researcher, and revised and approved by the instructor of the course at the beginning of the semester. The objectives of the course were not stated to the students taking the course, but they were presented in Appendix A for the reader of the dissertation to make the course content clear.

Modern Physics (PHYS 202) is a pre-requisite course for the Quantum Physics (PHYS 300) and Quantum Mechanics (PHYS 431). It is very important for students to make sense of the quantum theory, because it introduces the primary ideas of the quantum theory before taking PHYS 300 and PHYS 431. This course constructs students' conceptual background about the quantum theory. So it is more conceptual than PHYS 300 and PHYS 431. In addition, it examines "the quantization of physical observables" in the atomic systems. Since students did not learn this phenomenon in high school physics classes, so this course was selected as a setting.

Modern Physics course is given to students in the second semester of the second academic year in the physics program. Before this course, students complete some science and mathematics courses in the first three semesters of the physics and physics education programs. These courses are: Mechanics (PHYS 109), Electromagnetism (PHYS 110), General Chemistry I (CHEM 101), General Chemistry II (CHEM 102), Calculus with Analytic Geometry (MATH 119), Calculus for Functions of Several Variables (MATH 120), Introductory Electronics I (PHYS 203), Mathematical Methods in Physics I (PHYS 209), Optics and Waves (PHYS 221), Basic Linear Algebra (MATH 260)" (Department of Physics, 2010) courses.

It is a four-credit compulsory course for each physics and physics education student. The language of the course is "English", since this is the official language of education at METU. In the 2008-2 semester, the classes were held in one of the large lecture halls of the Department of Physics. The total length of the course was almost fifteen weeks per academic semester. The duration of a class was fifty minutes, and four classes of modern physics were taught each week.

In this course, two midterms, quizzes, homework and a final examination were the assessment methods. Norm-referenced evaluation was the main approach for evaluation of the students.

3.2.2 Description and Selection of the Participants

The participants of this study were selected from undergraduate second-year physics and physics education students who were taking the Modern Physics course. In the setting, there were basically two kinds of student profiles. These are: Physics students who were from the Faculty of Arts and Sciences, and physics education students who were from the Faculty of Education. Although students enrolled to different departments, they took the same Modern Physics (PHYS 202) course given by the Department of Physics.

In Turkey, in order to enroll a college or a university, each student must take University Entrance Examination. The students in this course took this examination in 2006. Table 3.1 drawn by information published by ÖSYM (2006) presents the University Entrance Examination base scores for the Department of Physics Education and the Department of Physics. As it is seen in Table 3.1, score range of the Department of Physics was larger than the score range of the Department of Physics Education. However, the score ranges of the departments overlapped, and the mean of the scores were similar. Although students were from different departments, their University Entrance Examination scores -their general competency- in order to enroll the departments at METU were similar.

Table 3.1 Base scores about the departments for the students who took University Entrance Examination in 2006.

					GENERAL QUOTA		QUOTA FOR THE STUDENT GRADUATED WITH THE FIRST RANK OF HIGH SCHOOL	
CODE	DEPARTMENT NAME	QUOTA	USED	SCORE TYPE	MIN.	MAX.	MIN.	MAX.
MIDDLE EAST TECHNICAL UNIVERSITY (ANKARA)								
	Faculty of Education							
1421032	Physics Education	31	31	Sci/Math 2	316.847	332.109	-	-
	Faculty of Arts and Sciences							
1421101	Physics	82	82	Sci/Math 2	305.053	345.138	-	-

This table is constructed from the data exist in the document presented by ÖSYM (2006).

Again as it is seen in Table 3.1, the quota (82) of the Department of Physics was more than twice of the quota (31) of the Department of Physics Education. This had affected the homogeneity of the students in the class. In the 2008-2 semester, a total of 98 students took the Modern Physics course. 70 (45 males, 25 females) of them were physics students, and 28 (17 males, 11 females) of them were physics education students.

Physics backgrounds of the students in this course were the same. Physics and physics education students take exactly same physics courses (excluding Statistical Thermodynamics, PHYS 430, which must be taken in the last semester of their program) during their education. These are: Mechanics (PHYS 109), Electromagnetism (PHYS 110), Introductory Electronics I (PHYS 203), Mathematical Methods in Physics I (PHYS 209), Mathematical Methods in Physics II (PHYS 210), Optics and Waves (PHYS 221), Optics and Waves Laboratory (PHYS 222), Modern Physics (PHYS 202), Applied Modern Physics (PHYS 307), Classical Mechanics (PHYS 311), Quantum Physics (PHYS 300), Electromagnetic Theory (PHYS 334), Quantum Mechanics I (PHYS 431), Special Problems in Physics (PHYS 400) and three elective courses from the Department of Physics (Department of Physics, 2010). All course settings, instructor and laboratory sessions are common for physics and physics education students. In addition, there is no restriction in the selection of elective courses for physics education students from the Department of Physics. Physics and physics education students can work in collaboration with each other in many different elective physics courses. Their physics competencies were also similar to each other, but a difference occurs in students' physics background by the selection of three departmental elective physics courses. The ages of the students were also similar (between 20 and 23 years old). Figure 3.3 presents a scene just before a modern physics class that physics and physics education students exist in the same setting.

Figure 3.3 A scene from the classroom environment.

In contrast to all the similarities between the two student profiles, one main difference originates from the aim of the departments. A physics education student is educated to be a "physics teacher" at secondary schools. Physics education students complete all physics courses at the Department of Physics in three and half years. Then, they take pedagogy courses by the Department of Secondary Science and Mathematics Education (SSME) in almost one and half years. However, a physics student is educated for four years to be "physicist" in research and industrial area. So, students' future expectancies were different.

Of all 98 students taking Modern Physics course, totally thirty-three participants were purposively selected in order to get more information about students' understanding. So, by determining the number of students, I aimed to access large number of students. The aim was not representativeness, but the "diversity" of the participants. For this reason, almost 1/3 of the total number of the students in the class were determined as the participants of the study. However, two of the participants (a female physics education student and a male physics students) left the study at the mid of the study because of not having enough time to participate in the interviews regularly. For this reason, these students were omitted from the study.

Although my aim in the selection of the participants was diversity, I took "gender" and "department" variables in my consideration in order to prevent accumulation of the participants into a category of a variable. For this reason, Table 3.2 presents the number of participants in each "gender" and "department" categories.

Table 3.2 Department and gender of the students who participated in the study.

Participants	# of physics students (total # students taking the course)	# of physics education students (total # students taking the course)	Total # of participants (total # students taking the course)
Females	9 (25)	4 (11)	13(36)
Males	11 (45)	7 (17)	18(62)
Total # of participants (total # students taking the course)	20 (70)	11(28)	31(98)

While selecting the participants for the interviews, students' physics achievement and interest were my considerations. First eight weeks of the semester, I got information about students in and out of the classes. I examined students via Cumulative Grade Point Averages (CGPAs), Midterm-I results, and answers to conceptual questions in the quizzes. In addition, due to my observations in the class, I determined the students asking questions to the instructor in and out of the classes, answering the instructor's questions in the classes, discussing on modern physics concepts in the breaks, and seating at the front/ back of the lecture hall (and chatting with each other) in the classes. They were my considerations for diversity. Then, I determined the specific criteria to provide "diversity" also in these characteristics. Although these characteristics were separated from each other exactly, selected participants might have different characteristics at the same time. So during selection of the participants, I just focused on a specific characteristic of a participant. I determined almost 2/3 of the participants by considering their physics achievements. Finally, Table 3.3 presents the number of participants considered in sampling criteria.

Table 3.3 Selected participants due to purposive selection criteria.

Selection domains	Selection Criteria	# of students
By considering students' physics achievement	CGPA > 2.80	2
	2.20 < CGPA <2.80	2
	CGPA< 2.20	2
	Grade of Midterm-I above the average	4
	Grade of Midterm-I below the average	4
	Satisfactory explanations in the quizzes	3
	Unsatisfactory explanations in the quizzes	2
By considering students' physics interest	Asking questions to the instructor during/ end of the classes	3
	Answering the instructor's questions in the classes	3
	Discussing modern physics with each other in the breaks	3
	Sitting at the front of the lecture hall	1
	Sitting at the back of the lecture hall and not interested in the classes	2
	Total # of selected students	31

First, I determined a group of students by considering their CGPA's up to taking the course. By my experience, I determined three categories in this group as the students' CGPAs <2.20 (poor academic performance), 2.20<CGPAs<2.80 (average academic performance), and CGPAs>2.80 (good academic performance). It was my consideration of students' physics achievement in general. Then, I considered more specific criterion. That was students' Midterm-I examination results. I categorized them into two groups as students above the average, and the students below the average. Although it was more specific information about students' physics achievement than their CGPAs, it was still in general since Midterm-I included the concepts of the theory of relativity. I determined my final criterion as explanations in the "quizzes". By omitting the explanations in the first quiz that was about the concepts of theory of relativity, I focused on students' second and third quizzes that were asking questions about early ideas of the quantum theory. So, I categorized the explanations as satisfactory explanations in the quizzes and unsatisfactory explanations in the quizzes. My second basic consideration was students' physics interest. I determined "asking questions to the instructor during/ end of the classes", "answering the instructor's questions in the classes", "discussing modern physics with each other in the breaks", "sitting at the front of the lecture hall", and "sitting at the back of the lecture hall and not interested in the classes" as the criteria giving cues about students' interests. I selected almost 1/3 of the participants by considering these criteria. By this way the participants were selected for this study.

3.2.3 Description of the Instructor

The instructor of the course was a full time professor at the Department of Physics at METU. He had specialized in astrophysics and he had several books and articles on his research area.

He was a middle aged, student friendly, smiling and enthusiastic professor. He always provided students a relax environment to ask him questions if they need. He gave several physics courses for several years, and he has given the Modern Physics course last five years. In addition to success in research, he was a good physics teacher. He had upper level teaching certificate. He believed that the importance of having pedagogical knowledge to teach physics. He always used pedagogy knowledge in the classes to create effective learning environment.

3.2.4 Description of the Course Setting

As it is mentioned before, 98 students were taking Modern Physics course in 2008-2 semester. In contrast to previous 5-6 years, the course was given by a professor in one section having capacity for 120 students. For this reason, the classes were held in a large lecture hall. Figure 3.4 presents a scene from this lecture hall.

Figure 3.4 Lecture hall.

Its heating and lightening were appropriate. Its acoustic was also good. Because of locating in the second floor, there was no external noise affecting the classes. There was no unfavorable element for students.

Figure 3.5 shows students' attendance to the classes. Two 50-minute lectures were on Mondays, and the other two were on Thursdays. Both of them were at the same time period of a day that was between 10.40- 12.30. At least 70% attendance to the classes during the semester is an obligation for each student to pass the course.

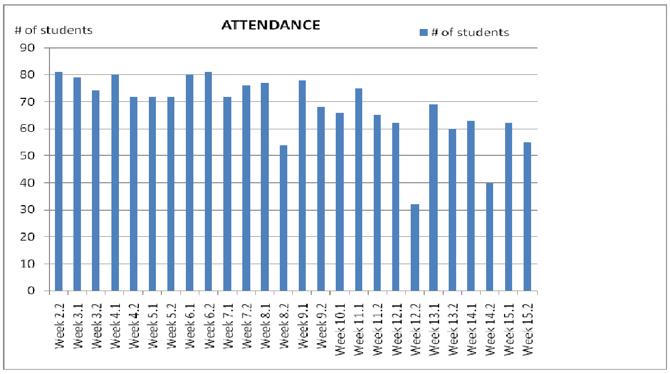

Figure 3.5 Attendance of students during the semester.

As it is seen in Figure 3.5, the overall attendance of the students was around 60%-70% during the semester. Two sharp decreases occurred in the course attendance after the exams (Midterm-I in Week 8, Midterm-II in Week 12).

Instructional methodology of the course was mainly instructor centered. However, the instructor enriched the instructions by using several instructional techniques such as analogy, role play, questioning, and examples from daily life. In addition, he was telling the stories related with the concepts and he mentioned scientists and history of science in the classes. He used them for different aims such as gaining students' interest, to provide motivation to learn and to facilitate their understanding. When the instructor encouraged students to participate to the classes, their participation was high. Especially, while using questioning technique, students were very enthusiastic to answer the questions.

3.2.5 Cases and Contexts for Quantization

Quantization of physical observables such as light, energy and angular momentum in quantum theory were the cases of this study. The examination of the literature and my personal experience revealed that students had problems with quantum physics concepts. "Quantization" is an important phenomenon for quantum theory since its explanation brought a new interpretation to the experiment results. It caused a paradigm shift from classical perspective to quantum. So, it is the heart of the quantum theory. Learning of it correctly by students is important since correct conceptions of quantization facilitate students' understanding of other concepts of the quantum theory easily.

Quantization explains the nature of light, energy and angular momentum in atomic worlds. It is not just a single concept taught in a modern physics or other quantum physics courses. Since it is the whole and basic idea of the quantum theory, it cannot be reduced under only a specific topic and a title. Figure 3.6 presents the examination of the quantization phenomenon in different contexts for Modern Physics (PHYS 202) course.

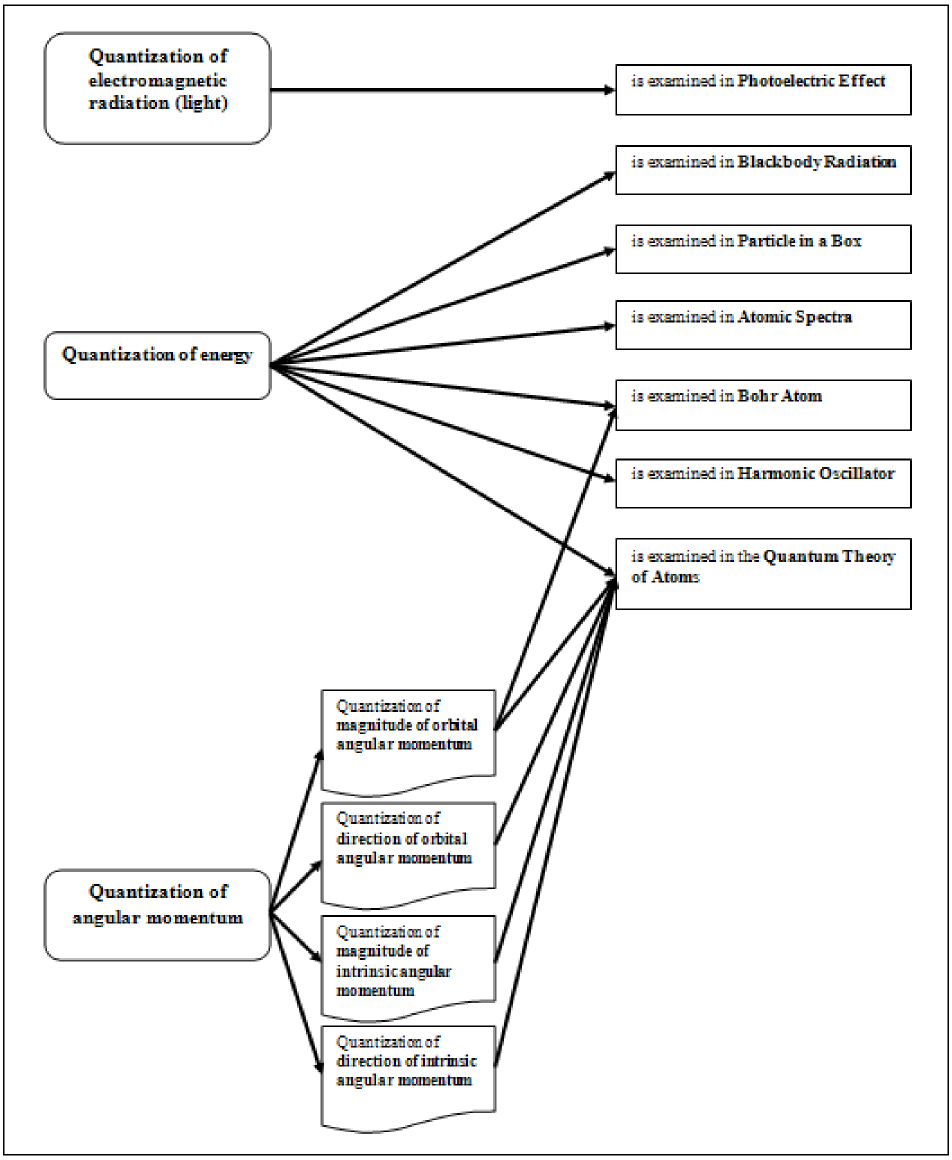

Figure 3.6 Examination of the quantization phenomenon in different contexts.

For this reason, in this study the contexts, which quantization was explained in during the semester, were selected to identify students' mental models about quantization. So, the contexts are:

- Context 1: Photoelectric experiment *(for the quantization of light)*
- Context 2: Blackbody radiation and ultraviolet catastrophe *(for the quantization of energy)*
- Context 3: Energy levels and atomic spectra *(for the quantization of energy)*
- Context 4: Particle in a box *(for the quantization of energy)*
- Context 5: Harmonic oscillator *(for the quantization of energy)*
- Context 6: Atom (6.a for Bohr, and 6.b for quantum mechanical model of an atom) *(for the quantization of energy and angular momentum)*

3.3 Data Collection Methodology and Recording of the Data

The data of this study were collected by using a variety of data collection methods such as interview, observation, test, diary, and other documents (two textbooks of the course, notebooks of students, and examination- homework- quiz papers). Table 3.4 presents which data collection techniques were used to get the data for each research question.

In this study, the interviews with students provide data to all research questions. Although the research questions were not exactly independent from each other, different interviews were planned to get the data of different research questions at the beginning of the data collection. However, some of them were still "probable" data source for each other. In the data analysis, I experienced some interviews provided data for other research question. For this reason, this situation was discriminated in Table 3.4 by representing the "planned and main data source" by (√), and "probable data source" by (*) for each research question. In addition to the interviews, the test was one of the other main sources providing information for first, second and fourth research questions. Finally, textbooks, observation, diary, interview with the instructor, and other documents provide mainly data for the third and fourth questions examining sources influencing students' mental models and their model developments. As it was explained at the beginning of this chapter, the third part (research question 4) was exactly composed of the use and execution of data in the first (research questions 1 and 2) and second parts (research question 3).

Table 3.4 Data sources for each research question.

DATA COLLECTION TECHNIQUES	Research Questions			
	1	**2**	**3**	**4**
Pre-interview			√	√
Interview I	√	√		√
Interview II	√	√	*	√
Interview III	√	√	*	√
Test	√	√		√
Overall interview	√	√	*	√
Final Comprehensive Interview	√	√	*	√
Self-Evaluation Interview			√	√
Interview with the Instructor			√	√
Observation (classroom video records, field notes)			√	√
Diary			√	√
Textbooks			√	√
Notebooks, examination-homework- quiz papers of the participants	**		√	√

(√) represents the data source for each question,
(*) represents the probable data source for each question,
(**) used just as a remedy for undetermined situations in data analysis.

3.3.1 Observation

Marshall and Rossman (1999) defined observation as “the systematic noting and recording of events, behaviors and artifacts (objects) in the social setting chosen for study” (p.107). It is an important fundamental data collection method in qualitative studies and widely used in educational settings to observe the classroom environment (Marshall & Rossman, 1999, p.107). In this study, modern physics course setting, students and the instructor in the setting were observed by me during the academic semester 2008-2 by ethnographic manner. Four modern physics classes were held each week, and each class took 60 minutes with breaks (50-minute class and a 10-minute break). Observation data were recorded by taking field notes, video records and photographs. Appendix B.1 presents the information about observation dates and duration. In this study, almost 2760 minutes (46 hours) classroom observation video recorded between 4^{th} week- and 15^{th} week.

As a researcher, my role was an overt participant observer in the research. All students in the course setting knew “me” as an observer. They had the information about the course was being researched, and that they were the participants of the study. The role of a participant observer is linking all the data which were gained by various methods, so obtaining a “unique kind of information” which cannot be obtained by other methods (Wilson, 1977). So also by taking notes, I aimed to link the data obtained from different sources.

In the observations, there were two dynamic information sources. First one is the instructor. The instructor was observed by focusing the contexts that quantization was explained, the instructional techniques that were used him, the stress of “quantization” term, the links among concepts and contexts, comparisons between quantum and classical physics. Second source was the students in the setting. They were observed by focusing firstly the attendance to the classes, participation to the class activities, interactions with the instructor in the classes and breaks, interactions with each other to discuss quantization, extraordinary events, students’ questions to the instructor in and out of (in the breaks) the class, students’ with each other out of the class etc.

3.3.1.a Field notes

Bogdan and Biklen (1992) defined field notes as the writing of “what the researcher hears, sees, experiences, and thinks in the course of collecting and reflecting on the data in a qualitative study” (p.107). When research is in an educational setting, they are usually notes of the researcher taken in the classes or schools (Fraenkel & Wallen, 2000, p.546). In this study, the written data obtained by me in the classes during observation is accepted as field note. In each observation in the class, field notes were taken regularly. Taking field notes during the observation was done by using the outline in Appendix B.2. By this way, the notes about two dynamic data sources- the instructor and students- were taken. In addition, some important events in the setting were recorded every ten-minute period in each class.

3.3.1.b Video records and photographs

Considering the trustworthiness of a video camera, it is a powerful data recording instrument. It allows saving the data for a long period of time. In this study, video records and photographs were obtained. For this reason, a small portable video camera was used. It had a hard disk with both recording and photograph taking characteristics. Having a small size video camera was an advantage for not disturbing students’ attention in the course setting. The portable characteristic of the video camera was an advantage for both observations in and out of the course setting. In addition, the hard disk of the video camera allowed recording of a large amount of video and photographs, and the data were transferred to a computer easily, where it would be saved.

Video recording was used for both the observations and interviews. All classroom observations were also recorded by the same video camera. The video camera and related setup were prepared in the lecture hall before the lectures by me. By examining several places in the lecture hall in terms of appropriateness before starting the data collection, the video camera was always located in the same place during the data collection period. In addition, in case of not getting the voice with video camera, I used a voice recorder by locating it on the instructor’s table.

I made a great effort to avoid distracting students, and so I always sat the same place in the back of the lecture hall, where students did not see me and the video camera. The issues mentioned in observation checklist were focused also while recording by video camera. These were instructor's instructional techniques, explanations about quantization, interactions between students and the instructor (i.e. asking-answering the questions, role plays etc.), extraordinary situations in lecture (i.e. discussion and disagreement with instructor), participation to the class activities, and interactions between students (discussion with each other about quantization) etc. were recorded by me manipulating the angle of video camera and using its zoom in/ out properties.

In addition to the course setting, I used video camera to record interviews. All interviews were conducted in the same setting shown in Figure 3.7.

Figure 3.7 Interview setting for the participants.

The points (a), (b), and (c) describe the basic elements of the setting. All student interviews were recorded by placing the video camera top of the tripod on the table in my office in the Department of Physics (point a). The direction of the video camera was arranged by me during the interviews by focusing the interviewee and her/his interview protocols to capture both verbal and written answers of the interviewee. The interviewees and the interviewer always sat the same places by the arrangement of chairs on the points (b) and (c) shown in the picture, respectively. Finally, the interview with the instructor was also recorded by video camera.

Pole and Morrison (2003) stressed that “what appears on the photographic print is not arbitrary” (p.64). Photographs were taken only in the classroom observation period. While taking photographs, the specific situations that were focused such as interactions between students- instructor, student-student, instructional techniques, and other issues to explain quantization. One of the examples was presented in Figure 3.8.

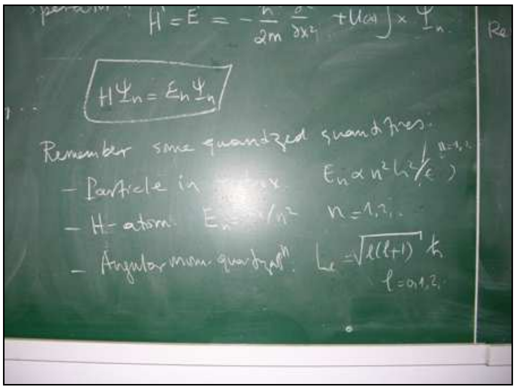

Figure 3.8 A photograph from the class in Week 11, Lecture 20 (27.04.2009).

Figure 3.8 shows that the instructor recalls students some contexts that quantization was observed. While he was recalling verbally, he also noted them on the board.

3.3.2 Interview

An interview is a way of getting a large amount of data in a short period of time (Marshall & Rossman, 1999, p.108). In this study, semi-structured interviews were conducted with the participants and the instructor.

3.3.2.a Interview with students

Totally thirty-one students were interviewed regularly during the study. At first I specified the appropriate week to start conducting each type of interview, then students determined regularly the appropriate time period for themselves to interview in that week. That means, after each interview, each student determined the time of the next interview by considering the specified week, and recorded his/her interview date into the weekly-prepared draft tables. By this way, interview dates were organized. Strict specification of the week to conduct each type of interview but flexibility in students' determination of the best time period for themselves to interview facilitated great proportion in students' participation to the interviews. By this way, the interview schedules were determined for each week up to the end of the final exam.

Before the interviews, pilot interviews were conducted with students to check the communication in order to control the loss of data, determine students' trust to the researcher, and make students relax and feel confident about the interviews.

Semi-structured interviews were conducted out of the classroom setting and they were recorded by video camera. In the first three weeks of the semester, the theory of relativity was taught, then the ideas of the quantum theory started to be explained. After three weeks from the beginning of the semester, the first interview (Pre-interview) was started in 9^{th} week, and other interviews followed the Pre-interview. In the interviews, while students were thinking aloud and answering questions, they had their own copy of interview protocols and papers to provide written explanations, drawings etc.

All interview questions were prepared both for English and Turkish. The first reason of this was students learn the concepts in English; however, they were difficulty in making explanations in English and tend to explain in Turkish. Second reason was the probability of misinterpreting of the questions written in English. So, in order to remove probable threats about understanding the questions, students were allowed to use the best way to answer the questions. In addition, they were allowed to explain their ideas however they want (i.e. in terms of stating their ideas in written, drawn or verbal format) by using multiple representations. During the explanations, students were also requested think aloud as possible and they were requested to explain the sources of their answers.

I had basically two groups for the interviews: The core group and the secondary group. Basic consideration of the determination of the group members among thirty-one participants was students' "wish and convenience for spending extra time". That means, in order to be able to conduct three basic interviews during the semester, the core group students would have three extra interviews by comparison with the secondary group students. Then, as similar with the selection of thirty-one participants of the study, my another basic consideration was again "diversity" in the determination of these groups among the selected participants. My final consideration was representativeness for diversity. In order to represent the diversity that was considered in the selection of participants, I determined the number of participants in each group as almost 7-9 students for the core group and 22-24 for the secondary group. By doing this, "my convenience about coping with the interviews" was considered at the same time because the number and detail of the conducted interviews within these two groups differed. Conducting three following long interviews with each participant in the core group during the semester would take extreme amount of time. Finally, by considering these three criteria, and using the information presented in Table 3.3, I determined eight participants of the core group and twenty- three participants of the secondary group.

The core group was composed of eight students; four of them were physics students and four of them were physics education students. The reason of creating this group was the examination of mental models and development of models in detail. So this group was observed in a step by step process in which the detailed interviews were conducted topic by topic and in an inductive way. The other group was the secondary group, which was composed of twenty-three students; sixteen of them were physics students and seven of them were physics education students. As it was presented the characteristics in Table 3.3, this group covered the wide range of achievement status of the students from low achievers to high achievers. The data of this group was also important for evidence for the categories of examination since the models firstly identified in the core group, then the secondary group was examined whether the same models existed or not. The secondary group was also examined during the semester, but in a deductive way, which excluded step by step examination of concepts.

Figure 3.9 presents the timetable for regularly conducted interviews. Both of the groups started the series of interviews with Pre-interviews; however, while the core group was interviewed throughout the semester (by Interviews I- II- II and Overall, Final comprehensive and Self-Evaluation interviews), the secondary group was interviewed almost at the end of the semester (by Overall, Final

Comprehensive and Self-Evaluation interviews). So each participant in the core group had seven interviews, and each participant in the secondary group had four interviews. Questions asked in all interviews were presented in Appendix C.

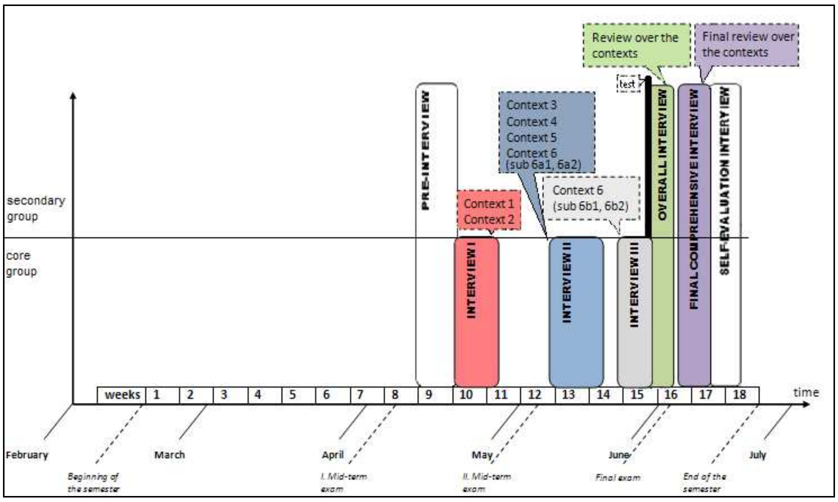

Figure 3.9 The timetable for the interviews.

Pre-interview: As it is seen in Figure 3.9, Pre-interviews were started at the mid of April (Week 9) and they were completed in one week with including all participants. The Pre-interviews aimed to learn more about the participants; their feelings, beliefs, ideas about the course, the classroom environment. The data of the Pre-interview were also important to discuss some sources influencing students' mental models. The questions asked in Pre-interview were given in Appendix C.1. Twenty minutes was the planned time for a Pre-interview with each of the students, but Pre-interview duration for each student was almost fifteen minutes.

Interview I, II, and III: After the Pre-interview, three interviews (Interview I, II, and III) were conducted with the core group over six weeks. These interviews included questions to examine students' understanding about the quantization of physical observables in the quantum theory.

Interview I started after one and half week from the first midterm, and conducted with eight students during one and half weeks (Weeks 10-11). In Interview I, the quantization of energy and light was examined in blackbody radiation and photoelectric effect contexts (Contexts 1 and 2). The questions asked in Interview I were given in Appendix C.2.

Interview II started at the first half of May (Week 13). In Interview II, the quantization of energy was examined in atomic transitions-spectra, the particle in a box, and the harmonic oscillator (Contexts 3, 4, and 5); also, the quantization of energy and angular momentum was examined for the Bohr atom contexts (Contexts 6.a1 and 6.a2). The questions asked in Interview II were given in Appendix C.3.

Interview III was conducted at the end of May (Week 15) and continued a week. In Interview III, the quantization of energy and angular momentum was examined in terms of quantum numbers in a quantum mechanical model of an atom context (Contexts 6.b1 and 6.b2). The questions asked in Interview III were given in Appendix C.4. The average time spent for each Interview I, II, and III was almost fifty minutes.

Overall Interview: The Overall Interview was again a common interview both for the core and secondary groups. A test was implemented in the last week of the semester. That means, after all topics about the quantization of physical observables were covered in the course. Then, the Overall Interview was conducted. It had the same questions with the test. The questions asked in the Overall Interview were given in Appendix C.5.

In the Overall Interview, one of the aims was to get detailed information about what was written in the test, and to examine the consistency of students' explanations whether there was a change or not. In the interview period, the test answered by each interviewee was examined, and prepared for the interviewee before the interview. It was presented to interviewee at the beginning of the interview. After the examination of student's own answers in the test, s/he gave details about her/his own explanations in the test, or added new ones if s/he did not answer a question, or changed her/his explanations. After the examination of the questions in the test, students were asked to state whether there was a quantization in the physical events by giving some of the cases from Interviews I, II, and III. In this way, students discussed the physical events and examined quantization case by case. A total of forty-five minutes was the planned time for the Overall Interview, and it took almost thirty minutes for each student.

Final Comprehensive Interview: This interview was conducted after the final examination (Week 16) of the modern physics course. The same questions asked in the Overall Interview were used. Since Norman (1983) explained the “instability” of mental models, the aim was to examine the “consistency” in the development of the models for some period of time. Lack of environments for students testing and changing their mental models, and studying for final examination were the situations to discuss about the stability of mental models. Each Final Comprehensive Interview took almost fifteen minutes. The questions asked in this interview were given in Appendix C.6.

Self- Evaluation Interview: Finally, the Self- Evaluation Interview was conducted (Weeks 17-18). This interview was important to understand some external and internal sources influencing students’ mental models. For this reason, students were asked meta-cognitive questions to reflect their understanding in this interview. Thirty-minute time period was recommended for each interview, and each interview was almost twenty minutes. The questions asked in the Self-Evaluation Interview were given in Appendix C.7.

3.3.2.b Interview with the instructor

At the end of the semester, a semi-structured interview was conducted with the instructor in order to get his opinions and experiences about students’ understanding of the quantization of physical observables, the sources that shape their models, and the overall evaluation about students’ motivation during the semester. The interview took almost thirty minutes. The questions asked in this interview were given in Appendix C.8.

To summarize, totally 141 interviews were conducted with thirty-one students, and an interview was conducted with the instructor. In Appendix D, the information about which interviews were conducted with each student was presented in detail.

3.3.3 Test

After all of the topics about the quantization of physical observables were covered in the class (at the end of Week 15) during the semester, the test was implemented to all of the students in the class in the last week of the semester. This test was aimed to get the general information about students' understanding of the quantization of physical observables. The other aim was also to provide a base for the Overall Interview while identifying models. It was implemented in a class hour within thirty minutes. The questions asked in the test were given in Appendix E.

3.3.4 Diary

A diary provides "particular, parochial and time bound" data (Pole & Morrison, 2003, p.58). The data which cannot be obtained by other ways could be obtained by diaries. Diary was used for external events related with context of the study, occurring in and out of the course setting. Mainly personal ideas, feelings and extra information given by the participants were recorded in the diary by me. For example, students' comments about their understanding of the concepts related with the research aim, and ideas about some questions in the exams that related with etc. were recorded. For this reason, the data in the diary were highly subjective, but it revealed some hidden links among other data obtained with other ways. Some sample notes from the diary were presented in Appendix F.

3.3.5 Other Documents

In addition to the data obtained by observation, interview, test, and diary, some other documents provided data for this study. These documents are: Two textbooks of the course, notebooks, examination, homework, and quiz papers of the participants. As it was presented in Table 3.4, among these obtained documents, two textbooks were directly integrated to data analysis, but other were integrated indirectly. The reason of this was the artifacts created for different expectations such as getting good grade might not represent the natural responses of students. So, the notebooks, examination, homework, and quiz papers of the participants were used only when needed.

3.3.5.a Textbooks

Two textbooks of the course (Beiser, 2003; Krane, 1996) were reviewed to be able to explain the sources influencing students' mental models and model development. In the textbooks, two issues were focused. These are: The explanation of quantization and the methodologies to explanation quantization. By this way, how students use the information, and make sense the statements, notifications, formulas, visual elements etc. could be examined. For these aims, in Textbook 1 (Beiser, 2003), Chapters 2, 3, 4, 5, 6, and 7, and in Textbook 2 (Krane, 1996) Chapters 3, 4, 5, 6, and 7 were examined. Unit of analysis in the data analysis was "a minimum meaningful chunk of a sentence/ figure/ formula indicating quantization".

3.3.5.b Notebooks

Although twenty-four students were taking notes during the semester, twenty notebooks were obtained at the end of the semester. Eleven notebooks could not be obtained since seven students stated they did not take notes in the class, and other four students stated they lost their notebooks in the mid of the semester. Obtained notebooks were copied. Notebooks of student were examined for extra notes to reflect their understanding of the concepts, and comparing the similarity with the instructor's explanations in the class. In Appendix G.1, some sample pages from the students' notebooks were presented.

3.3.5.c Homework

In a semester, seven assignments were given to students. Homework questions were prepared by the instructor, but they were evaluated by me and other teaching assistants of the course. In Appendix G.2, a sample homework paper of a student was presented.

3.3.5.d Quizzes

In this course, five quizzes were implemented to students in the class. They were implemented at the beginning of the lectures in first ten minutes. Quiz questions were prepared by the instructor; however, they were evaluated for grading by me because I was one of the teaching assistants of the course. In addition to grading quizzes, I examined some of the quizzes (second and third ones) to select participants for interviews. I focused on providing both satisfactory and unsatisfactory information in the quizzes in the selection of participants for the aim of diversity. In Appendix G.3, a sample quiz paper of a student was presented.

3.3.5.e Examinations

Students in Modern Physics course took three exams during the semester. These were Midterm I, Midterm II, and Final examination. There were conceptual and mathematical questions in the exams. As a researcher, as I did not manipulate anything in the course setting, I had no effect in the preparation of examination questions. All questions were prepared by the instructor, and all papers were evaluated by the instructor. The examination papers of three students were used to have a final conclusion about students' models for some contexts (i.e. Contexts 3 and 6).

3.4 Data Analysis of the Interviews and Test

Data analysis is "the process of systematically searching and arranging" the data (Bogdan & Biklen, 1992, p.153). The analysis of the data mainly consisted of three stages: (1) data reduction, (2) data display, and (3) conclusion/verification" mentioned by Miles and Huberman (1984, pp.21-23). This was done because coding the data provides a formal representation of analytic thinking (Marshall & Rossman, 1999, p.155).

3.4.1 Coding of the Interview and Test Data: Codes and Themes

All types of data were analyzed by coding. I started to the data analysis from the interview data. In the data analysis, the issues mentioned in Miles and Huberman (1984, pp.60-63) were considered. The following steps were taken: (1) the codes were named by considering the closeness of the concepts, (2) definitions of the codes were made in detail, and (3) double coding was done by different researcher (external coder). Coding required engaging in the data for a long time at different times.

In the analysis, I used a qualitative data analysis program (NVIVO 8) because of;

- its ability to keep a huge amount of data in order,
- the easiness of the coding process in the program,

- the easiness of the manipulation of the codes during the analysis, and,
- the ability for letting the researcher make matrix comparisons among participants.

3.4.1.a Steps of data coding

Transcription. All of the interview data were transcribed by the researcher, and converted into the written format. In addition, all artifacts (written and drawn data) that were produced in the interviews and other artifacts (tests, examinations, homework, quiz papers, notebooks, etc.) were scanned, and transferred into the computer medium.

Uploading the data into the program. "Cases" created in the program for each student, and all prepared data transferred into the computer medium as well. By this way, for each student I got a case matched with his/her own data.

Reading. In spite of being familiar with the data in the transcription period, I have read all interview data of each participant two times after transcription.

Determination of the codes (concepts). A draft code lists were constructed in the light of my previous quantum physics knowledge and the obtained data.

Control of the code lists by the experts. Constructed code list used in the examination of the quantization phenomenon in the interviews (which is also common list for the analyses of textbook and observation data) was examined three physicists (2 physics professors and 1 Ph.D student) and three physics educators (3 professors). The experts examined the codes in terms of "mutually exclusiveness" and "definition", and "appropriateness" of the codes for research aims. Finally, required revisions on the code list were done. Final version of the code list was presented in Coding Booklet 1 that exists in Appendix H.1.

The code lists that were constructed for the analysis of external and internal sources influencing students' mental models were checked and revised by two physics education professor and a physics professor. Final version of these code lists were presented in Coding Booklet 2 that exists in Appendix H.2.

Coding. Interview data were analyzed by means of final coding booklets. Unit of analysis for the investigation of models and sources influencing models was "word(s)" that was "a minimum meaningful chunk of a sentence/ figure/ formula indicating quantization". So, the "content" of a "chunk" was determined as appropriate for the investigation of mental models, since each word and link among the words were the determiners for mental models. Therefore, it was considered that although there might be more than one "chunk" corresponding to a code, there exists maximum one type of code in a sentence. In other words, a sentence can be coded maximum one time with the same code. In conclusion, each type of code may appear once per a sentence, figure or formula.

By using Coding Booklets 1 and 2 in Appendices H.1. and H.2 respectively, I started the coding of interviews with my core group (8 students). After students' interviews were transcribed, the test and written/drawn materials from the interviews were matched, coding was started by examining each student in the core group context by context. That means, the quantization phenomenon was examined by starting from Context 1 (Photoelectric experiment), and by ending Context 6 (Bohr and Quantum mechanical model of an atom). For each context, students' explanations about the concepts of the quantization of physical observables were identified and named. After the completion of this process for the core group students, the same process was followed for each student for the secondary group students.

3.4.1.b Constructing the models

In this research, I followed some steps while specifying students' mental models about the quantization of physical observables. In the determination of models, students' definition of what quantization means was important, but it was not in my focus. Their understanding of the phenomenon, and linking of the phenomenon with other physics concepts were considered as the main focus together with their definitions of quantization. Coherency, which is having single conceptual framework was the most important issue in the determination of a model among students' explanations. So, the links stated among the concepts were considered for coherency. In other words, it was not just a check of the existence of the elements in a model, but meaningful and organized use of them as a framework. That means, the knowledge structure that is composed of the coherently use of these elements to explain the phenomenon was called as "mental model". For example, three elements "discreteness or/and discreteness characteristics, natural characteristic and only bound particle" were the elements of scientific model. So, the coherent use of these elements had role in the indication of scientific model. As the identification of scientific models, the unscientific models constructed by the inappropriate use of the codes (concepts) were identified. Finally, mental models were identified by considering coherency.

In addition to the model structures that students had, there are some fragmented structure that cannot be considered as mental models. The characteristic of this type of structure was students' use of the concepts inconsistently. In this study, this type of fragmented structures was called as "No Model (NM)" because of lack of coherency, they did not have a framework constructing a model. Since I just focused on mental models, I did not examine fragments in the current study. Different from NMs, the explanations of students that did not provide any code or physical concepts were coded as "No Element (NE)". These were the irrelevant explanations about quantization like "everything in quantum mechanics is probabilistic…". When students did not give explanations to the questions, and passed to the next question, they were coded with "No Answer (NA)".

3.4.1.c Specific examples explaining the determination of a mental model

In this section, I explain how I specify whether a student displays a model or not by considering coherency among the codes and using the specific examples from the data. Figure 3.10 presents the codes exist in students' explanations. Numbered links indicate the construction of models with these elements.

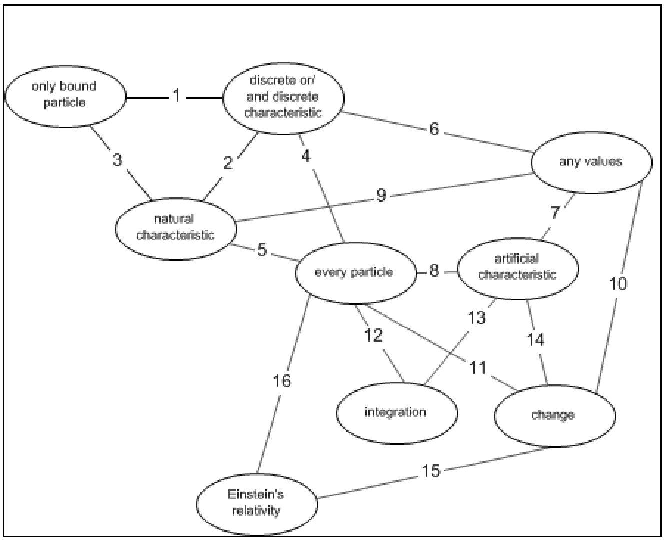

Figure 3.10 Links among the model elements required for the coherency of models.

These minimum conceptual elements were coherently used in models. For example, the elements "only bound particle, discreteness or/and discreteness characteristic, and natural characteristic" were accepted minimum scientific elements in the construction of scientific mental model (with Links 1-2-3) about the quantization of physical observables. The other elements identify from other models, "any values, artificial characteristic, Einstein's relativity, change, integration, and every particle" were designated at "not unscientific" but "irrelevant" elements in the construction of scientific mental model about the quantization of physical observables (see Appendix H.1 for the definitions of these elements). However, these elements were the main elements for the construction of other mental models (unscientific ones) rather than scientific models. By this way, in addition to the Scientific Model, I identified five unscientific models that I called as Primitive Scientific Model (with Links 2-4-5), Shredding Model (with Links 4-6-7-8), Alternating Model (with Links 5-9-10-11), Integrative Model (with Links 8-12-13) and Evolution Model (with Links 8-14-15-16). That means each model presented a composite of the ideas by linking some elements to form a coherent idea. Although mental models do not have firm boundaries, students' mental models of quantization develop with these elements. Therefore, these elements provide extension and refinement of the mental models. In addition to the minimum elements, the "links" among the elements represent coherency of the conceptual framework. Table 3.5 presents the sample codes to explain determination of "mental model" and "no model" structures in the contexts.

Table 3.5 Sample codes and frequencies to explain specification of models.

CONTEXTS Students	1	2	3	4	5	6.a1	6.a2	6.b1	6.b2
St1			OBP 2 D/DC 10 AV 3 C 5		AV 1 C 2				
St2							OBP 3 D/DC 11 NC 4		
St4									D/DC 11 NC 3 AC 4 I 3 EP 2

St2 and St4 presented two different examples for the specification of mental models in this study. For example, St2 had some codes in Context 6.a2. In this context, student explains the quantization of angular momentum in Bohr context by using OBP, D/DC and NC codes by 3, 11 and 4 times, respectively. In this context, the codes were meaningfully linked to construct a framework by this student. All these coherently used codes indicate the scientific mental model. I determined such type of coherent structures including only elements of a framework as a mental model. However, there were some other structures that include additional codes that did not belong to a specific framework. The explanations of St4 in Context 6.b2, which was the examination of the quantization of angular momentum in the quantum atom, was a good example for this type of structure. In this context, although St4 used AC, I, and EP (with 4, 3 and 2 times, respectively) coherently, he also used D/DC and NC. However, they were the explanations like scattering the words without making a meaning. That means some concepts did not belong to the coherent structure. As it is seen in this example, I focused on the coherently use codes (i.e. AC, I, and EP) to specify models by omitting the disconnected codes (i.e. D/DC, NC) in the determination of mental models in this type of explanations

St1 presented another example about the determination of models. In Context 3, students used four types of codes such as OBP, D/DC, AV, and C with 2, 10, 3, and 5 times, respectively to explain the quantization of energy. Although this student used more type of codes with several times, her explanations does not construct a framework to explain quantization. She has just used the words by scattering. That means, the existence of some codes did not mean having a coherent structure. So, such type of structures that the codes were incoherently used, were called as "No Model". As similar with Context 3, there were two types of codes (AV and C) that were incoherently used. This one had the simpler structure than the previous example. Some of specifications as No Models included only one type of a code. All these type of structures were discriminated from mental models because of lack of coherency they were specified as No Model in this study.

3.5 Data Analysis of the Textbooks

3.5.1 Content Analysis and Coding

Content analysis is "unobtrusive" and "nonreactive" research (Marshall & Rossman, 1999, p.117). In this study, two textbooks of the Modern Physics course were analyzed by content analysis via the Coding Booklets in Appendix H.1 and H.3. In the analysis of the documents, some steps stated (Forster, 1995 as cited in Yıldırım & Şimşek, 2005, pp.193-201) were followed.

3.5.1.a Obtaining documents

Two textbooks of the course were obtained at the beginning of the study. The analysis of the textbooks was important in specifying the sources influencing students' mental models and their influences on model development.

3.5.1.b Analysis of the data

Textbooks were analyzed by following these steps:

Selection of the sample. Both of the textbooks were selected to be analyzed. However, not all chapters of the books were taken into consideration in the data analysis. Table 3.6 presents the information about the chapters that were analyzed.

Table 3.6 Analyzed chapters of the textbooks.

Textbooks	Examined Chapters	Number of Pages
Textbook 1 (Beiser, 2003)	2, 3, 4, 5, 6, 7	241
Textbook 2 (Krane, 1996)	3, 4, 5, 6, 7	171

Development of the categories. The categories were developed from the data. "mutually exclusive" characteristic of the codes was also an important consideration in the development of categories. Textbooks provided data in two dimensions. First dimension was the physical explanation of quantization. Second, dimension was the methodologies that were used to explain quantization. The code list in Coding Booklet 2 was composed and controlled by two experts (1 physics professor and 1 physics education professor).

Determining the unit of analysis. Unit of analysis in coding of knowledge organization (in Coding Booklet 1 in Appendices H.1) and method of explanation (in Coding Booklet 3 in Appendices H.3) were again "word(s)". That means "a minimum meaningful chunk of a sentence/ figure/ formula indicating quantization" considered in the analysis. So, the "content" of a "chunk" was determined as appropriate for the analysis of the textbooks. As similar with coding of interview data, it was considered that although there might be more than one "chunk" corresponding to a code, there exists maximum one type of code in a sentence, figure or formula. In other words, a sentence, figure or formula can be coded maximum once with the same code. In conclusion, each type of code may appear once per a sentence/ figure or formula. Although "quantization" word was scanned in the texts, how it was used and how presented in the textbooks were very important. By using the coding booklets in Appendices H.1 and H.3, I coded two textbooks of the course.

Quantification. Although quantification was not a requirement, some information with frequencies and percentages were presented.

3.6 Data Analysis of the Observation and Diary

First video records, photographs and field notes matched with each other for each class. In the analysis of observation data, video records of the classes were not transcribed. The same procedures with the analysis of textbook were followed for observation data. The code lists for the analysis of observation data were presented in Coding Booklets 1 and 4 in Appendix H.1 and H.4, respectively.

Selection of the sample. The data including the explanation of quantization was determined for the data analysis.

Development of the categories. Again, "mutually exclusive" codes were developed from the data. As similar with the textbooks, observation provided two dimensional data of both explaining quantization and methodologies to explain quantization. The code list in Coding Booklet 4 in Appendix H.4 was composed and controlled by two experts (1 physics professor and 1 physics education professor).

Determining the unit of analysis. Unit of analysis in coding of observation data was also "word(s)". That means "a minimum meaningful chunk of a sentence/ figure/ formula indicating quantization" was considered in the analysis. So, the "content" of a "chunk" was determined as appropriate for the analysis of observation data. As similar with the coding of interview data and textbooks, it was considered that although there might be more than one "chunk" corresponding to a code, there exists maximum one type of code in a sentence, figure or formula. In other words, a sentence, figure or formula can be coded maximum one time with the same code and other type of codes may also appear once. In addition, the use and stress of "quantization" term was in my consideration during the coding process since how it was used and presented in the classes were important for model development. By using the Coding Booklets in Appendices H.1 and H.4, I coded the video data. One difference during the coding was not having a written document of huge amount of video data. So, I transcribed only the analyzed units for this part of the analysis.

Quantification. Some information was presented with frequency/percentage tables and graphs to make understanding the findings easier.

3.7 Reliability and Validity Issues

Reliability and validity issues of quantitative research are studied using different terms in qualitative research because of the differences in researchers' epistemologies. Table 3.7 presents these issues and naturalistic techniques to provide evidence.

Table 3.7 Establishing trustworthiness for qualitative research.

Criterion	Conventional Term	Naturalistic Term	Naturalistic Techniques
Truth value	Internal validity	Credibility	Prolonged engagement
			Persistent observation
			Peer debriefing
			Triangulation
			Referential adequacy
			Member check
			Quasi statistics
Applicability	External validity	Transferability	Thick description
			Purposive sampling
Consistency	Reliability (Internal reliability)	Dependability	Dependability audit
Neutrality	Objectivity (External reliability)	Confirmability	Confirmability audit

This table was adapted from Erlandson, Harrison, Skipper, and Allen (1993).

In this study, most of the techniques mentioned in Table 3.7 were used to provide validity and reliability, and also the precautions stated by LeCompte and Goetz (1982) and Yıldırım and Şimşek (2005) were considered.

3.7.1 Credibility

Credibility indicates the internal validity of a study. This issue was addressed by prolonged engagement, peer debriefing, triangulation, member checking, and quasi statistics for this study.

3.7.1.a Prolonged engagement

Prolonged engagement is related with the duration of the data collection. The data of this study was saturated at the end of the semester, so the duration of data collection was determined as one semester (from the mid of February to end of June).

3.7.1.b Peer-debriefing

Peer-debriefing is one of the important issues for credibility, in other words, for the internal validity of the study to remove bias. In this study, peer debriefing was done by two ways: (1) By a physics education researcher who participated from the beginning to the end of the study, and (2) by different physics and physics education researchers who participated at the key points of the study with valuable feedback.

For the first way, I call the researcher whom I met for peer-debriefing aim as the “external coder”. In addition to giving feedback from the beginning to the end of the study, this researcher existed at the inter-coding process to examine inter-coder agreements. The external coder was one of the key elements in the research, so the determination of external coder was not random. The external coder in this study has two years physics research background, and Ph.D degree on physics education. The external coder teaches physics actively in a physics education program of a university. In addition, the external coder gives some pedagogy courses in the same program of the university. This coder had knowledge about qualitative research, and did qualitative research about university students’ quantum physics learning. From beginning to the end of the study, we approximately spent thirteen hours together by discussing on data collection (~4 hours), data analysis and results (~9 hours). In addition, the external coder spent extreme amount of time individually in the examination of the materials used in the data collection and analysis required for the validity and reliability issues.

For the second way, some other experts who were in the physics and physics education research areas were actively participated in some key points of the research in the different steps such as the validation of the materials, analysis and discussing the results of the study.

In the preparation of interview questions. Preparation for data collection took almost seven months from the last four months of 2008 to first three months of 2009. In this period, my focus was the preparation of the interview questions. Interview questions prepared not by a single step, but developed by the feedback of five physicists (4 physics professors, and 1 Ph.D student) and three physics educators (3 professors) in terms of content and format by using the checklist in Appendix I.1. By their suggestions, content and presentation of some questions were revised. For example, second question in Interview I (see Appendix C.2) was revised, and seventh question in Interview II (see Appendix C.3) was added to the interview questions in order to examine the quantization phenomenon better.

For validating the codes. Development of code list was a tiring process. Since the lack of information about the codes to examine students' mental models in previous research, and not existence of similar studies in terms of examined physics concepts, all coding booklets were constructed by me. Draft codes were emerged basically from the data in the light of my knowledge on quantum mechanics. Constructed draft code lists were developed by the valuable feedback of some experts on physics and physics education. As it was mentioned before, three physicists (2 physics professors and 1 Ph.D student) and three physics educators (3 professors) examined the codes for interview data in terms of "mutually exclusiveness", "definition" and "appropriateness" of the codes for research aim (in Appendix H.1). The codes for sources influencing models were examined by two physics educators and a physics professor (in Appendix H.2). The codes for the method of explanation for textbooks and observation data were examined by two experts (1 physics professor and 1 physics education professor) (in Appendices H.3 and H.4, respectively). After the improvement of draft code list, the final code lists in the coding booklets were obtained.

For validating the coding. Validating the coding process was not a long and tiring process like the development and validation of the codes. Sample coding procedures were discussed with three experts (1 physics professor and 2 physics education professors). They were not familiar with the data at first; however, they were familiar with quantum mechanical concepts and qualitative research. This was done by using the document in Appendix I.2. Sample excerpts were coded and presented to the experts. They controlled the appropriateness of the coding with the excerpts from the students' interviews. In conclusion, they validated that the coding was appropriate.

For validating the identified mental models. This was the last part of the validation about coding. In this part, some sample results were also validated by three experts (1 physics professor and 2 physics education professors) as previous coding procedures. For this aim, the document presented in Appendix I.3 was used. Identified mental models were given to the experts with their definitions and they were requested to match them with the excerpts from students' interviews. Since they were familiar with codes and coding, they examined the excerpts easily, and they stated the appropriateness of model excepts with the definitions of each corresponding model.

3.7.1.c Triangulation

Triangulation is "collecting information from a diverse range of individuals and settings, using a variety of methods" (Maxwell, 1996, p.93). Since it decreases bias or other risks of associations occurred by chance in a research project (Maxwell, 1996, p.93), for this study data triangulation was done by using different types of data collection techniques. As it was mentioned in Table 3.4, each research question was examined by collecting data by at least two techniques. In addition, triangulation for results was done for a limited type of results that was about the identification of mental models of students. The documents that were used for the triangulation in Appendices I.3, and J.1-3. The results of the examinations of other experts were almost same with my results.

3.7.1.d Member checking

Member checking is getting the approval of the participants for what a researcher records about them. In this study, member checking is important for interviews. In order to record what a participant wanted to say, member checking was done by requesting from each participant to paraphrase her/his statement at the end of each question in the interviews as possible. In addition, by paraphrasing the participant's statements in a question format and asking "I understand..., am I right?" (almost 5-6 times per-interview) in each interview, I got participant's agreement about her/his explanations. By this way, the participants provided an assurance about what they mean in their verbal and written explanations.

3.7.1.e Quasi statistics

Quasi statistics is "the use of simple numerical results that can be readily derived from the data" (Maxwell, 1996, p.95). In this study, some descriptive statistics were used to present results. That means, frequency of the codes, frequency and percentage about the findings about displayed models were presented in tables and figures as possible.

3.7.2 Transferability

Transferability can be explained as the extension of the findings to different settings. Thick description and purposive sampling were considered for transferability of the study.

3.7.2.a Thick description

Thick description is the description of what a researcher sees and hears in a specific context. In this study, all course settings, participants and other important issues for this section were described in detail between Sections 3.2- 3.11. In addition, some samples clarifying these sections were also presented in related appendices.

3.7.2.b Purposive sampling

Purposive sampling is a non-random sampling, which selects the participants by aiming to get maximum specific information about the context. First, Modern Physics course was purposively selected since students learned the concepts of quantum theory in this course and they construct models about the quantum phenomena (see Section 3.2.1). As it was explained in detail in Section 3.2.2, the participants were determined purposively to be able to find answers to research questions of the study. Detailed description of purposive sampling is important to compare the results of this study with the studies which have similar considerations and characteristics.

3.7.3 Dependability

LeCompte and Goetz (1982) explained the internal reliability by indicating the importance of "inter-rater or inter-observer reliability" as "the extent to which the sets of meanings held by multiple observers are sufficiently congruent so that they describe phenomena in the same way and arrive at the same conclusions about them" (p.41).

3.7.3.a Inter-coding

As LeCompte and Goetz (1982) defined, an inter-coder (inter-rater) reliability test is a way of determining the reliability of coded data. It indicates the reliability of coding data by showing the agreement among different researchers in the coding of data. Inter-coder reliability (R) was calculated as; $R = \frac{N_a}{N_a + N_{da}}$

Where, "N_a" represents "number of agreements", and "N_{da}" represents "number of disagreements. If there is no disagreement between two coders, the reliability coefficient will be 1/1. That means, there is 100% (full agreement) correlation between two codings. Miles and Huberman (1984, p.63) mentioned while researchers examining inter-coder reliability, they should not expect agreement for 5-10 pages of transcribed data better than 70%. However, they suggested getting inter-coder reliability around 90%.

In this study, I examined inter-coder reliability for the analysis of interviews, textbooks and observations separately. At the beginning of the data analysis, the external coder, whom I defined in Section 3.7.1.b, coded the sample data belong to each type of data. Although the main procedure was similar with each other, there were little changes in some parts of the examination of inter-coder reliability for each type of data.

At first, I and the external coder looked through some interview data without calculating a coefficient, and examined together by randomly selected 10-15 pages. In the second stage, the external coder examined a sample interview data with 5-6 pages and we discussed on the codes again without calculation of inter-coder reliability coefficient. In the third stage, first inter-coder reliability calculation for interview data was done by using the first document (Peer Review Checklist for Inter-coding I) presented in Appendix J.1. In the first part of this document for inter-coder reliability, there was a randomly selected transcript of a student among the data. In the second part of the same document, there were sample excerpts from different students and different interviews. The reason of mine to prepare a sample data with two parts was whether the diversity of codes might be limited in randomly selected data. So, to minimize the probability of accumulation of the codes in the same codes, and to see the coding of external coder on different codes, I arranged different excerpts from different students for the second part of the document. While doing this, I randomly selected the excerpts indicating students' models. Then, the document including the sample data was given to the external coder together with the coding booklet in Appendix H.1. The external coder coded the data individually and we met and got 74.3% agreement by comparing the codes in this inter-coding. We discussed on the disagreements in order to be able to reach almost full agreement. In the second step, the data (Peer Review Checklist for Inter-coding II) in the second part of Appendix J.1 were presented to the external coder. This checklist was also prepared with the same procedure with the previous one. The external coder coded the new document by considering the issues in previous discussion after the first try of inter-coder reliability examination. In the second try for inter-coding, we finally got 90.7% agreement.

Getting inter-coder reliability coefficient for textbook and observation data were same with the examination of interview data. In one of the meetings on coding, we first examined a randomly selected textbook page together. For the examination of inter-coding, as it was presented in Appendix J.2, I prepared sample data from the textbooks to the external coder. I considered the contexts in the selection of sample data. I randomly selected Context 3 from Textbook 1 (6 pages) and Context 6.2b from Textbook 3 (5 pages) and copied, then I gave the external coder together with related coding booklets. After his coding the data individually, we met and discussed on codes. Our agreement was 70.6% in the first try. Then we met and discussed on the disagreements. For the second try, I again prepared a sample data from the textbooks. For this one, I did not select the sample data randomly; however, by crossing the chapters, I prepared a sample data with Context 6.2b from Textbook 1 (5 pages) and Context 3 from Textbook 2 (5 pages). The external coder coded this material by considering the issues in previous discussions. In the second try on this sample, we got 86.4% for the textbook coding.

In one of our meetings at the beginning of the data analysis, we examined a randomly selected ten-minute period of a video record together. For the first try of inter-coding reliability examination, a video among 23 video records from the list in Appendix B.1 was randomly selected. The video, whose information was presented in Appendix J.3, was given to the external coder together with the coding booklets. Then, the external coder coded the sample video data by watching the video individually without transcription. The external coder noted the “coded units” from the video. In the examination of the coding, we got 66.7% agreement in our first try. As similar with inter-coding for interview and textbook data, we discussed on the disagreements. Then, for the second try I randomly selected a video from the same list. By the same procedure, the external coder coded the sample thirty minutes of video data by considering the previous discussions. Finally, we got 79.1% agreement in our second try of inter-coder reliability for video data.

We got inter-coder reliability coefficient around 0.9 for the interview data after several tries. One of the reasons of getting high degree of agreement can be explained with the similarity of the research interest (quantum physics learning) and qualitative research knowledge of the external coder with me, and spending extreme amount of time together at the key steps of study (i.e. discussion on interview questions, definition of the codes, code lists etc.). However, for the other types of data (textbook and video), we got quite smaller agreements than the interviews. The reason of this might be the external coder's familiarity with interview coding too much but not with the others.

3.7.3.b Intra-coding

Miles and Huberman (1984, p.63) suggested intra-coding to the researchers to examine their consistency in coding. That means, by this way consistency of a researcher through time can be examined. In this study, I examined a sample data with 5-6 pages twice waiting for almost a month. By using the same formula stated in Section 3.7.3.a, I calculated intra-coder reliability coefficient as 0.94 at first. Then, after the examination of disagreements with my previous coding, I got full agreement with my previous coding.

3.7.3.c Precautions for internal reliability

LeCompte and Goetz (1982) and Yıldırım and Şimşek (2005, pp.262-264) suggested that some precautions for internal reliability should be considered. By following the suggested precautions, in this study, these precautions were considered:

Presentation of obtained data in a descriptive approach. The data were presented with direct quotations- episodes- without interpretation in the explanation of findings in Chapter 4.

Multiple researchers should be included to the study. In this study a external coder, who was expert on physics education, existed. In addition, other experts, who were physics and physics education professors provided feedbacks and discussions during the development of the study. By this way, agreement among the different experts obtained to increase the acceptance of the results of study by other researchers.

Using multiple data collection techniques. Observation, interview, test, diary, and other artifacts were used for the data collection in this study. As it was presented in Table 3.4, at least two techniques for each research question were used to collect data. This is important for comparison of different type of data to get a conclusion.

Peer examination. The external coder, who was described in Section 3.7.1.b, was included in the data analysis period of the study. The results from external coder were discussed. So, it was important for the reliability of findings.

Explanation of the theoretical framework and data analysis. In Sections 3.4, 3.5 and 3.6, the data analysis procedures for each data from different sources were explained in detail. Especially, in the identification of mental models, how I constructed models after coding were explained in detail by considering the theoretical framework in Section 3.4.1.c. In addition, all coding booklets and related documents were presented for other researchers.

Using mechanical devices. The use of mechanical devices increases the internal reliability in case something is forgotten (LeCompte & Goetz, 1982). A video camera and a voice recorder were used for data recording. In addition, a computer was used for the transfer of data, and finally external hard disks were used to save huge amount of data.

3.7.4 Confirmability

Confirmability is about the replication of the study by other researchers and obtaining similar results in similar conditions.

3.7.4.a Precautions for external reliability

The precautions for external reliability that were defined by LeCompte and Goetz (1982) and Yıldırım and Şimşek (2005, pp.260-262) were considered for this study:

Explanation of researcher's status and position. The role of the researcher was described in Sections 3.2, 3.3 and 3.9. In this study, I had different positions as being overt participant observer, interviewer etc. during the different parts of the research.

Selection of informant choices. The participants in the study were selected and described in detail in Section 3.2.2. In similar studies, researchers may consider these characteristics while selection of their samples (Yıldırım & Şimşek, 2005, p.261).

A good description of social status and conditions. Since social environment affected human behavior and perception, the data obtained from different social environments may depend on social conditions (Yıldırım & Şimşek, 2005, p.261). In this study, the characteristics of course and course setting were explained in detail in Sections 3.2.1 and 3.2.4.

A good description of analytic constructs and premises. Replication of the study requires explicitly defined assumptions and theories that underlie the choice of terminology and methods of analysis. In Section 1.6 of Chapter 1, 2.1 of Chapter 2, the assumptions and the theoretical framework of the study were explained for other researchers in detail.

A good description of data collection and data analysis techniques. All techniques about data collection and data analysis were explained between Sections 3.1- 3.5. How the observations and interviews were done, how the test was implemented, and how the data were recorded and analyzed were explained in detail as a precaution for confirmability.

3.8 Ethical Issues

Three ethical issues were considered in this study. These are: (1) informed consent, (2) harm, and (3) privacy (Fraenkel & Wallen, 2000, pp.43-45). As presented in Appendix K.1 and K.2, required permissions were obtained from the Rectorship, the Graduate School of Natural and Applied sciences, the Ethical Committee, the Department of Physics and the instructor of the course. Students were the main elements of this study, so the ethical issues were mentioned to them verbally in the 3rd week (in 5th class on 05.03.2009). Then, the consent forms presented in Appendix K.3 were distributed to students to inform them about the details of the research, and to get their written permission by signing the last part of the consent form. At the same time, by respecting to participants (Fraenkel & Wallen, 2000, p.551), being an overt participant observer in the classes was explained to the students by not deceiving them. The permissions of 74 students in the class were obtained by signing the related part of the consent form. In the 4th week, the same explanations were done for absent students in the 3rd week, and their permissions were obtained. The other two ethical issues, which were harm and privacy, were mentioned to the participants in detail. The probable harm might be physical or psychological; however, this study did not construct a new setting or not manipulated the existing one, no physical harm existed in students' natural setting. A probable psychological harm (i.e. anxiety) was prevented by locating the video camera at the back of the hall in the classes. That means, I did my best to ensure there would not be any harm. Students' trustworthiness was provided by detailed explanations and answering students' questions about the research. A relax environment for them was provided by preventing seeing and feeling the existence of video camera, and the researcher in the setting. In addition, all interviews were recorded by video camera with participants' consents. Finally, for interviews and observation, video records, written materials etc. were kept private. The confidentiality issue was strongly stressed and carefully explained to the students.

3.9 Description of the Researcher

Researcher's background is an important issue in qualitative research for how to collect data, how to analyze data and how to present and interpret the findings. As a researcher, I took a qualitative research course from the Department of Secondary Science and Mathematics Education (SSME) in Faculty of Education titled as "SSME 701 Writing Qualitative and Quantitative Research in Education" during my Ph.D, and I passed the course with success. In the course, qualitative data collection techniques were taught, the perspectives of qualitative and quantitative research were compared, and a qualitative research proposal was prepared. I had a chance to learn the pioneers of qualitative research and to read their books explaining qualitative research techniques.

I joined a seminar to learn data analysis with a software (NVIVO 8). In this seminar, I also had a chance to discuss the issues of qualitative research with the researchers from different research areas. Finally, I followed (without registration) a course at University of Maryland (UMD) when I was a visiting researcher at UMD PERG. The course was "EDCI 792 Qualitative Research II: Analysis and Interpretation of Data" from the Curriculum and Instruction Department of College of Education. In the course, we had focused on data analysis, and important issues for qualitative research. In the boundary of this course, I gave a "qualitative data analysis seminar with a software" to Ph.D students taking the course and other faculty members who were interested in qualitative research.

Finally, I did qualitative research in my research area and the research articles (of mine and my collaborators'), whose methodology were qualitative research were published in journals (Didiş et al., 2008; Didiş et al., 2010; Didiş & Özcan, 2009; Özcan et al., 2009).

3.10 Delimitations

This study was delimited to:

- A Modern Physics course in a physics department of a government university to understand students' knowledge organization in detail.
- An academic semester for data saturation.
- Thirty-one participants to be interviewed in order to get diverse range and deep data.

3.11 Procedure

3.11.1 Researched Databases and Keywords

Many databases, which were accessed at METU and UMD were examined. These databases are: "American Institute of Physics (AIP), Dissertations and Thesis, Ebrary, Eric, Institute of Physics (IOP), ISI, JSTOR, PsycARTICLES, ScienceDirect, Taylor and Francis Online Journals, Web of Science SSCI, and Web of Science SCI Expanded".

In addition, I used many library sources for Chapters 2 and 3. Also, some reliable web materials were used after the checking reliability of the pages. Basic key words for this research while searching are: Ethnography, ethnography in education, qualitative research, qualitative data analysis, mental model, model, science education and modeling, physics education and modeling, learning quantum physics/mechanics, quantum physics, and teaching quantum mechanics etc.

3.11.2 Time Schedule of the Study

Time is one of the important considerations of this qualitative research. As a researcher, I spent considerable amount of time to construct a conceptual context, collect data, prepare data for data analysis, and analyze the data as it was presented in Appendix L. Before starting the research of this dissertation, I was interested in pedagogical research on quantum theory and mental models, so I had some background for this research. After I started to research, I updated conceptual context (the theoretical framework, explanation of quantum theory, and pedagogical research on quantum theory) by including the recent studies up to the end of writing dissertation. Preparation of data collection and collecting data period took almost a year. While organization of the data took more than a year, analysis of the data took more than two years. Up to the end of data analysis period, the results and conclusions were written, and they were revised regularly after feedback almost in a year. That means, while writing this dissertation, I focused on the different parts in different time periods. For example, while I considered some parts at the end of the study by updating, I completed some of them in a period without updating. By this way, overall of this research took almost five years.

CHAPTER 4

RESULTS

As we know, it is impossible to see students' mental models in their minds, and it is not functional to ask students what their mental models were (Gentner, 2002). Investigation of mental models requires making inferences from the data based on what and how students responded to the questions about the phenomenon. For this reason, some quotes from students and the instructor explanations are given by translating (the underlined ones are direct quotes without translation).

Students' mental models were examined over time and over context, and then all data were interpreted together. In this chapter, I present the results by considering the research questions. So they are grouped in three categories:

I. Models and the characteristics of models including Research Questions 1 and 2,

II. The sources influencing models including Research Question 3, and

III. The development of models by influence of the sources including Research Question 4.

4.1 Models and the Characteristics of Models

In this part, I focused on the first two research questions:

- What are the second-year physics and physics education students' mental models of the quantization of physical observables?
- What are the characteristics of second-year physics and physics education students' mental models of the quantization of physical observables?

As I stated in Table 3.4, I use interviews, test, and other documents in order to find the answer for these research questions. In spite of these three different sources, "interview" is the primary source for this part. Then, students' explanations in the test are integrated into data analysis and students' mental models are determined. Finally, the examination papers of the students, whose models are undetermined, are reviewed and some models of students are concluded in the determination of mental models. Figure 4.1 summarizes how I reached the findings for this part after the use of different sources.

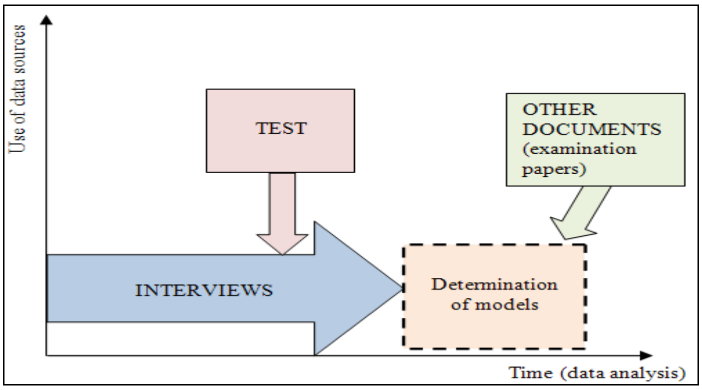

Figure 4.1 Integration of data sources to explain students' mental models.

I examine students' mental models in basically six contexts. They are:

- Context 1: Photoelectric experiment *(for the quantization of light)*
- Context 2: Blackbody radiation and ultraviolet catastrophe *(for the quantization of energy)*
- Context 3: Energy levels and atomic spectra *(for the quantization of energy)*
- Context 4: Particle in a box *(for the quantization of energy)*
- Context 5: Harmonic oscillator *(for the quantization of energy)*
- Context 6 (a1, a2, b1, and b2): Atom (Bohr and quantum mechanical model of an atom) *(for the quantization of energy and angular momentum)*

In this part, in addition to identifying mental models over these contexts, I examine the characteristics of models. That means, I interpret the findings in terms of the nature of models (pureness & hybridness), and context dependency (existence of model states) of models with role of cues (key concepts), model construction approach (i.e. on the spot or previously thought out), model construction source (i.e. common sense, recalling, or reasoning), and degree of certainty (comfort) to explain the characteristics of mental models identified in this study. Identification of students' mental models and model characteristics also indicates students' conceptual difficulties such as difficulty in making sense of the quantum concepts, difficulty in discrimination of the concepts, difficulty in linking the concepts, and difficulty in putting the physical meaning into mathematical explanations.

Table 4.1 presents the summary of the mental models that students displayed about the quantization of physical observables. Table 4.1 also shows the common and distinguishing elements constructing the mental models. Each identified mental model in this study was named by me due to the characteristics of each conceptual framework explained with operational definitions in Sections 4.1.1- 4.1.6.

Table 4.1 Summary of mental models of quantization.

Models	Only bound particle	Discreteness (1) or/ and Discreteness characteristic (2)	Natural characteristic	Any values	Artificial characteristic	Einstein's relativity	Change	Integration	Every particle
Scientific Model (SM)	√	√	√						
Primitive Scientific Model (PSM)		√	√						√
Shredding Model (ShM)		√		√	√				√
Alternating Model (AM)			√	√			√		√
Integrative Model (IM)					√			√	√
Evolution Model (EM)					√	√	√		√

In the table, the left part of the bold solid bar contains the scientific elements about the quantization of physical observables; and the right part of the bold solid bar contains the unscientific elements about the quantization of physical observables.

Each mental model seen in Table 4.1 is a specific composite of the codes explained in Section 3.4.1.c. The frequency and percentage of all codes composing mental models identified in students' explanations are presented in Appendix M.1. In addition, Appendix M.2 presents the frequency of the codes for each student over the contexts. Therefore, by counting the models and other structures that are composed of the codes in Appendix M.2, Table 4.2 was constructed. Table 4.2 summarizes the frequency of students' models and other structures over contexts.

Table 4.2 Summary of the frequency of mental models and other structures over the contexts.

CONTEXTS MODELS and OTHER STRUCTURES (MOS)	1	2	3	4	5	6.a1	6.a2	6.b1	6.b2	Total # of MOS
MODEL 1: **SM**	2	0	5	8	0	5	6	1	2	29
MODEL 2: **PSM**	5	1	6	0	0	0	0	0	3	15
MODEL 3: **ShM**	2	2	1	1	1	0	0	0	0	7
MODEL 4: **AM**	1	0	2	5	0	1	1	0	1	11
MODEL 5: **IM**	2	0	0	1	0	1	0	0	1	5
MODEL 6: **EM**	2	0	0	0	0	0	0	0	0	2
NO MODEL: **NM**	13	11	14	11	8	15	10	15	17	114
NO ELEMENT: **NE**	3	17	3	4	8	9	9	15	6	74
NO ANSWER: **NA**	1	0	0	1	14	0	5	0	1	22
Total # of students	31	31	31	31	31	31	31	31	31	279

In the following sections, I discuss mental models that are displayed by students to explain the quantization phenomenon and the characteristics of models. So, I explain students' models starting from scientific to unscientific. The aim of starting with the scientific mental model is to show clearly how students' knowledge structure diverge from the scientific one to unscientific ones by the change of mental models.

4.1.1 Model 1: Scientific Model (SM)

Model 1, which I call "Scientific Model (SM)", is the scientifically accepted model. I identify students having this model when they display the minimum concepts for scientific explanation of quantization such as "only bound particle, discreteness or/and discreteness characteristic, and natural characteristic", and use them coherently in the explanation of the quantization of physical observables. The operational definitions of this model can be stated as:

- The student who uses this model mentions that the quantization of physical observables such as energy, angular momentum is seen when a particle is confined in a region.
- The student mentions that the values of physical observables are restricted. The physical observables can have only discrete values and these values are only certain (allowed) values.
- The student mentions that it is natural for the atomic systems.

Figure 4.2 summarizes the use of SM over the contexts to explain the quantization of light, energy and angular momentum.

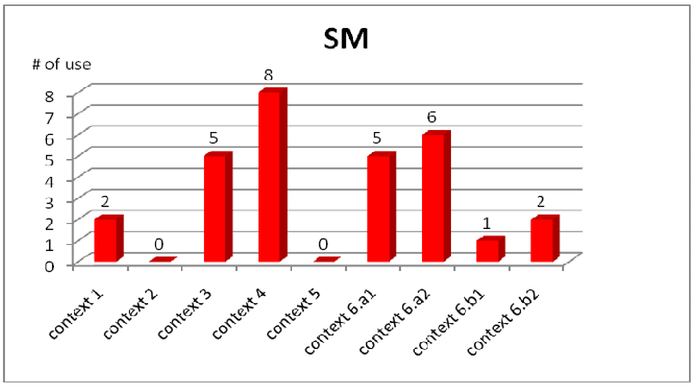

Figure 4.2 The use of SM over the contexts.

Among thirty-one students, only two of them use the SM in Context 1 (photoelectric effect). In Context 4 (particle in a box), number of students who use the SM is maximum (eight students). On the contrary, in Context 2 (blackbody radiation and ultraviolet catastrophe), and Context 5 (harmonic oscillator), none of the students uses SM. We see this graph implies that although the students have scientific mental model to explain the quantization of physical observables, its usage is so limited for thirty-one participants.

For the first case, the quantization of light is examined in the photoelectric context. One of the examples for the SM is from Student 18's (St18's) interviews. He is a physics student. He is very enthusiastic about becoming a physicist in the future, and he is interested in every discussion about physics. He explains the quantization of light by linking with the quantization of energy. The important thing for my identification of a mental model is that in the student's explanation of light, the energy is carried in a specific amount- hν. St18 could link both cases and concepts together.

... text continues before the excerpt...

I (Interviewer): For example, what can you say about the photoelectric experiment?

St18: Is there quantization in the photoelectric experiment? Umm...

I : Yes, can you explain that there is a situation for quantization or not?

St18: In the photoelectric experiment... We need a certain amount of energy to remove the electron. It is like what I said before. There is an electron around the nucleus, and it has a certain amount of energies while on the specific orbits. For example, I need to give a certain amount of energy to remove it from the bound structure. Neither less nor more amount of this energy. In classical physics, it is OK to remove it with more energy. For example, the moon is orbiting around the earth. If I send a beam of light, actually I cannot do that with a beam of light, it cannot remove the moon. Anyway, if a meteor crashes into the earth, its energy is enough to remove the moon from its orbit. That means, much more amount of energy could do that. However, here, it is not like that. It must be an exact amount of energy.

I : But I should clarify this point: Is it excitation or ionization for this situation? In addition, do we use a photon here?

St18: Yes, photon. Here, the situation is for ionization, but the photon's energy must be an exact amount of energy like the amount of energy between the energy levels.

I : Therefore, must the energy of photon correspond with exactly with this amount for excitation of an atom, right?

St18: Yes. It must be exactly "hν" *(between two energy levels).*

I : You told "it is like what I said before".

St18: Yes.

I : You mention a certain amount of energy.

St18: Yes... Quantized energy.

... text continues after the excerpt...

Other Contexts 2, 3, 4, 5, 6.a1, and 6.b1 are the contexts for the examination of the quantization of energy. As it is understood from the graph in Figure 4.2, most of the use of this model is seen "particle in a box" context (Context 4). One of the examples for the use of SM in energy levels and atomic spectra belongs to a physics student-St15. St15 is also very enthusiastic to learn modern physics and she regularly attends modern physics lectures and enjoys them.

... text continues before the excerpt...

I : All right, now, let's look at this situation *(by looking at the interview questions)*: Here there is an emission spectrum, and an absorption spectrum for mercury atom. *(by examining the 1. question)* "In an emission spectrum, what do the (colored) lines explain (for the visible region), or in an absorption spectrum what do the dark lines explain? Why do the lines occur? Why do they have different colors (for the visible region) for emission spectra; why are they dark for absorption spectra?" Do you have any idea about this issue?

St15: Yes, I have. This is like… Umm… *(By showing the emission spectrum)* An atom emits a photon when an atomic electron changes its orbit while jumping from upper orbit to lower orbit. These are *(by showing the spectral lines)* the photons. The energy is not continuous; a certain amount of energy. For example in the electron's movement from third orbit to second orbit, a photon can take the amount of energy between these energy levels that the electron has. Therefore, these lines occur.

I : OK. What do "dark" parts mean in an emission spectrum?

St15: Dark parts… Umm… That means an atom cannot emit a photon having that wavelength *(by showing the dark part)*. Therefore, it is dark. In the absorption spectrum, it is opposite. That means, if an atom absorbs a photon, this part seems dark *(by showing the dark part)*, the others seem colored.

I : All right, let's look at this *(by looking at the interview questions)*: Suppose the electron in the Hydrogen atom obeys classical mechanics rather than quantum mechanics. What would you expect to observe in the spectrum? Why?

St15: It cannot behave as a classical particle! If it behaves classically, it must stick to the nucleus after turning and turning. But we do not see this. If it occurs, I would expect "light colors" here *(by showing the spectrum)*. Umm… That means, I do not expect discrete lines like these ones *(by showing the spectrum figures in interview protocol)*.

I : Can you clarify the "light colors" more?

St15: Not discrete colored lines. The photons with any wavelength could be emitted.

I : Do you mean something like is continuous?

St15: Yes. At that time, energy could not be quantized in classical physics. It could be continuous. However, for example, here *(by showing the spectrum)* energy is quantized since it has only certain values, not for every value.

... text continues after the excerpt...

I found other examples for the explanation of the quantization of energy during the particle in a box context. Both of the excerpts are from the participants who are physics students. St7 is a very inquisitive student who tries to understand every physics concept when she hears or reads, tries to make sense. Another student (St10) is also inquisitive and he likes to discuss physics concepts with his friends and to teach them physics. He explains quantized energy by means of an analogy. Some excerpts from students' interviews are:

... text continues before the excerpt...

I : All right, what is "quantized energy" exactly?

St7 : Quantized energy... Distinct energies, having only certain values... Umm... For example, I remember it from there, the instructor derived its formula. There is a particle in the box. When we examine a particle in the box whose wavelength is DeBroglie wavelength, when we use these information, we see there is an "n" term in its energy formula. We see the "quantum number" and when we examine the formula, we see that it is possible just for certain energy levels. The reason is that the particle cannot have any wavelength because it is confined in a box. Either this one or this one *(by drawing "energy levels" on particle in a box figure).* It cannot have any wavelength. This is the reason. Because of not have every wavelength, it restricts the energy of the particle in a box.

... text continues after the excerpt...

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... text continues before the excerpt...

I : Is it *(quantization)* considered just for the energy?

St10 : I know it is for the energy, but energy is considered for many things also. I know it is for the electron energy. I understand that confinement of a particle in a box is a basis for the "quantization of energy". I imagine it like that: For example, one of my friends from the physics department of X university asked me "Why do they *(scientists)* use a box?". I answered "I think they cannot explain it otherwise; it is just to be able to explain better". Here, the quantization of energy is explained better in this box. For the quantization of energy in a box, energy levels are observed. Then we say "quantized energy". Energy of the confined particle cannot have any value. It can have certain energies.

I : To summarize, you say "energy of the particle observed in the box is quantized", right?

St10 : Yes. Energy is quantized.

I : Can you explain more what you mean by quantization?

St10 : Quantization... Umm... Just certain values. For example, it is just like an apartment building. Each floor in the building can be considered as a certain value. However, there is a difference here. You can arrange a ratio between each floor for the apartment building, however, in the box the energy levels depend on the width of the box. The width changes the levels. The energy of the particle in a box that we observed is quantized. Its behavior is determined, its energies are determined naturally… They can only have certain values. They are not allowed for any values.

... text continues after the excerpt...

A third case I examine where a student displays the SM of quantization is "quantization of angular momentum". In the examination of quantization of angular momentum in Contexts 6.a2 and 6.b2, my aim was to discuss the quantization of the magnitude of orbital angular momentum in the context of the Bohr atom. This model, which was proposed by Niels Bohr, lets us discriminate his model of an atom from Rutherford's classical planetary model. In addition, I aimed to discuss the magnitude and direction of orbital angular momentum, and the magnitude and direction of intrinsic angular momentum (spin) for a quantum mechanical model of atom part of this context.

St5, a physics education student, tries to explain the quantization of angular momentum for the Bohr atom. St18 also tries to explain the quantization of angular momentum in a similar way. Although students explain more, the following excerpts reflect students' models.

... text continues before the excerpt...

I : All right, do you know any other quantized observables?
St5: I know angular momentum *(smiling)*. The instructor explains it like "$L=n\hbar$" *(by writing the equation)*. Its magnitude... Umm... I don't think it gets every value. This "n" can get 1, 2, 3 etc. I know it. "$L=n\hbar$" shows the quantization of angular momentum when an electron orbiting around the nucleus in Bohr atom.

... text continues after the excerpt...

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... text continues before the excerpt...

I : OK. You said "angular momentum must be quantized". What is your evidence?
St18 : Yes... Because *(by writing $L=n\hbar$)* n is an integer, ħ is also an integer.
I : How is it quantized? What does "n is an integer" mean?
St18 : Bohr explained it as the electron orbiting around the proton. For each different orbit, it can just have a certain angular momentum values. For example, angular momentum cannot have $\pi\hbar$ value. It has just $1\hbar$, $2\hbar$, $3\hbar$ values.

... text continues after the excerpt...

Another student (St25), who is a physics education student, explains the quantization of angular momentum for intrinsic angular momentum (spin).

... text continues before the excerpt...

**I : ** What do you know about spin?
St25: It's turning around itself!
**I : ** What is turning around itself?
St25: Here, this is an electron inside the atom.
**I : ** You wrote something like that "angular momentum of e^- orbiting the nucleus and spinning around itself" for quantized physical observables on the test! What do you mean?
St25: Umm... It has only two directions while turning around itself. For example, upward and downward. "ms" is +1/2 and -1/2... Now, electrons are also orbiting around the nucleus also. Direction of spin can have two values. +1/2 and -1/2, not other values. This is quantization.
**I : ** OK, you just tell direction of an electron spin is quantized in an atom. Can you explain magnitude of spin?
St25: Was it $\sqrt{\frac{3}{2}}$? Actually, I did not think it before...
**I : ** How can you say $\sqrt{\frac{3}{2}}$?
St25: Umm... $S = \hbar\sqrt{s(s+1/2)}$ *(by writing the equation).* s is 1/2 for electrons.
**I : ** Can you conclude your statements about magnitude of electron spin?
St25: It should be quantized as its direction is quantized.

... text continues after the excerpt...

Having SM is important to explain physical events correctly because the students displaying the SM recognize that quantization is for bound systems and it is the characteristic of nature's itself. This issue is important for students' discrimination of classical and quantum physics. Although it is good to see students have scientific models, this research show that the SM usage over the contexts and the number of students, who use the SM, is limited.

4.1.2 Model 2: Primitive Scientific Model (PSM)

Primitive Scientific Model (PSM) is an unscientific model. However, this model also contains some scientific elements together with an unscientific (irrelevant) one to explain the quantization of physical observables. It contains the "discreteness or/and discreteness characteristic, and natural characteristic" elements of SM, but the unscientific one of "every particle". In this model, the students' conceptual framework is constructed around these definitions:

- The student mentions that the values of physical observables are restricted. The physical observables can have only discrete values and these values are only certain (allowed) values.

- The student mentions that the quantization of physical observables is observed for all atomic particles, not for only bound particles.
- The student mentions that it is natural for the atomic systems.

The difference of this model from the scientific one is students' inappropriate application of "bound structure". That means, boundedness is an important element that should be considered in the quantization of physical observables such as energy, and angular momentum. This part of the model discriminates itself from the SM in that the association of quantization with boundedness is not applied.

Because this unscientific model seems the closest model to SM, if this part of the model is recovered, students can make coherent scientific explanations about the phenomenon. Figure 4.3 represents the distribution of this model over the contexts.

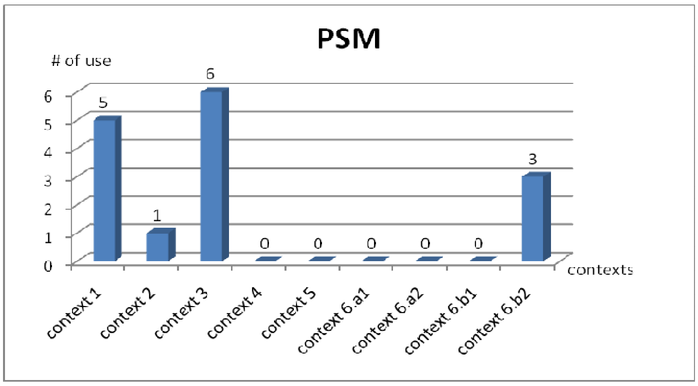

Figure 4.3 The use of PSM over the contexts.

As it is seen in Figure 4.3, this model is identified totally fifteen times. To summarize: For the quantization of light, it is used five times; for the quantization of energy, it is used seven times; for the quantization of angular momentum, it is used three times. It is interesting to explain quantization of energy by this model only in Contexts 2 and 3, not in Contexts 4, 5, 6.a1 and 6.b1. The excerpt below shows a student's explanations about the quantization of light.

... text continues before the excerpt...

I : Can you explain the photoelectric experiment?

St17: Umm… There is a material with a threshold. If I give an energy exceeding the threshold, it emits an electron.

I : What do you expect for an electron to be emitted? In other words, can you explain what happens for the electron to be emitted?

St17: Umm… How can it be *(by asking himself)*? There are different orbits of electron and also different energy levels. If you give a certain energy, it jumps to upper orbit. The system is a jumping system. We can mention about the quantized energy here. If you give more energy exceeding the total energy, the electron is emitted and it becomes free.

I : For which particles do you mention about quantized energy?

St17: All particles.

I : For example…

St17: For example electrons, photons.

I : Why photons?

St17: Umm… The energy that is sent to material is related with the frequency of light. For a certain frequency, a certain energy exists. They carry the certain energy.

I : Is light quantized?

St17: Yes.

I : Can you summarize your explanations?

St17: We see quantization in the atomic systems.

... text continues after the excerpt...

Since the quantization of light is not independent of the quantization of energy, St17 explains combining them. Quantization of light is a result of quantized energy-frequency connection as explained by Einstein and is a different phenomenon. At this point, since the student's consideration of a photon is a free particle and it carries the quantized energies of light, he generalizes "quantization" to all particles. Another student, who is a physics student, explains quantization of energy in blackbody radiation and ultraviolet catastrophe context in the following excerpt.

... text continues before the excerpt...

I : How did Planck solve this problem?

St3: Umm… Planck… In his theory… He mentioned about quantized energy. Umm… Like energy blocks or energy packets. But I could not understand it well.

I : What is the reason of quantized energy?

St3: Particles… Umm… We know energy is quantized. This quantized energy is carried by photons, with energy packets… It is like that… Planck said energy and frequency are related. Einstein also said energy is quantized and it is carried by packets. They say similar things.

... text continues after the excerpt...

Another student, St10, who uses the SM in particle in a box and atom (only the Bohr atom part) contexts, uses the PSM in the energy levels context. In contrast to scientific explanations in particle in a box context, it is seen that this student does not indicate boundedness in the following excerpt.

... text continues before the excerpt...

St10: I remember that the instructor explained "quantum" was a Latin word. The energy was in the packets. Light transmits the energy packet by packet. I know quantized energy is "energy is in packets". I understand something like that. Umm... For example, if I lend some money to one of my friends, I can get my money with little amounts, such as 3 liras or 5 liras. I say "I am a physicist, I must get my money with little amounts" by kidding him. It is something like that.

I : OK. You said "energy is in packets". What can you say about the "energy levels"?

St10: Umm… Energy levels. The electrons in the atom have energy levels. Certain energies.

I : I want to turn back to your analogy. Your analogy was from the macro world. What can you say about…? Umm… What is your consideration to explain quantization?

St10: Particles in the atomic systems. Here, photons.

... text continues after the excerpt...

St11 is a student, who mainly uses fragments in the explanations of quantization over the contexts. In the quantization of intrinsic angular momentum, he has explanations by using the PSM.

... text continues before the excerpt...

I : Yes… Let's talk about spin!

St11: Spinning of a car in Formula 1 races *(smiling)*.

I : Now, here, we will talk about electron spin!

St11: Yes... I know it has two directions to rotate.

I : Who has two directions?

St11: Electron… +1/2 and -1/2.

I : What are the plus and minus signs?

St11: Direction! It must be the direction.

I : Do you know why it is 1/2?

St11: Umm… I have no idea!

I : OK, you will learn it later. Let's talk about spin more. You mentioned about two directions. What kind of motion does the electron have?

St11: Something like rotating itself.

I : For which electrons do you explain this behavior?

St11: All electrons. Am I right? *(Smiling)*.

I : We will discuss it later. Well. You told "It is something like electron rotates itself". Therefore it could have an angular momentum. You know angular momentum is also a vector quantity.

St11: Yes. Its direction is quantized. It can rotate itself only in two directions.

... text continues after the excerpt...

Although this model is the closest model to SM, students associate the quantization phenomenon not for bound particles but for every particle. In Scattering Theory plane waves of free particles can be expanded as a superposition of spherical harmonics (Erkoç, 2006, pp.374-375). In other words, for scattered particles (free particles) wave functions are expressed in terms of angular momentum quantum numbers. However, this does not mean that free particles show space quantization. For this reason, in order to explain space quantization, boundedness should be considered as it is considered in the quantization of energy. This model seems a transition model from unscientific to scientific one. So explicit stress on boundedness might be useful for students' recognizing their conceptions and revising them to have SMs.

4.1.3 Model 3: Shredding Model (ShM)

Another unscientific model identified in students' explanations of the quantization of physical observables is the "Shredding Model (ShM)". This model is called as "shredding" since students' conceptual framework is constructed with the idea something like "cutting a cake into the slices". This model can be defined as;

- The student mentions that the physical observables are divided into quantum and have discrete values. This is just like dividing into little particles.
- Therefore, the values of the physical observables are not restricted, and quanta can take any value as the amount of a cake slice.
- The student mentions that the quantization of physical observables is observed for all atomic particles, not for only bound particles.
- The student mentions that the quantization is not a natural characteristic for atomic systems, so it is an external manipulation of the values of the physical observables.

This model has even more unscientific elements that the PSM model. It is observed in all of the explanations totally seven times. Figure 4.4 shows the use of ShM over the contexts.

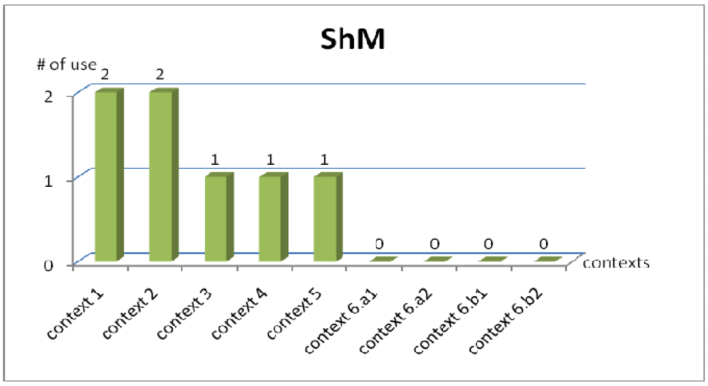

Figure 4.4 The use of ShM over the contexts.

As it is seen in Figure 4.4, although the students use this model in the first five contexts, it is not observed in the "atom" context (Context 6). In addition, it also shows that students do not use this model for quantization of angular momentum. This model is only used by four students (all of them females) to explain the quantization of light and energy. Two of these four students use the ShM once over the contexts, the other two students use the ShM more than once.

St27, who is a physics student and using only the ShM. She associates the quantization of light with "dividing". The following except is:

... text continues before the excerpt...

I : Well, do you remember photoelectric experiment?
St27: Yes. I think I remember it.
I : What was happening? Can you explain it for me?
St27: A photon comes and crashes to the surface, and it causes an electron emission from the surface.
I : Does every photon break off an electron?
St27: No, there is a limit for it, limit for the energy.
I : Do you say "every energy cannot break off the electron"?
St27: Yes.
I : Is it related with incoming light?
St27: Yes, its frequency affects it.
I : All right, can you mention about quantization here? Is it in consideration?
St27: It is the disintegration of the energy, isn't it? That means the disintegration of the total energy… Umm… That means, not to take a constant value.
I : How does it happen? You explained "dividing particles into their smallest components" here *(in the test) (by looking at the test paper).*
St27: Yes, yes. We mention for the energy. For example, here, we take the energy of the photon by dividing, this is quantization.

... text continues after the excerpt...

As it is seen in student's explanations, the student puts a different meaning to “discreteness”. Another student, St29, who is also a physics student and only uses the ShM over the contexts, explains quantization of energy with this model. The sample excerpts are from student’s explanations in Contexts 1 and 4.

... text continues before the excerpt...

I : In addition to what you wrote in the test, what would you like to say any other things about quantization?

St29: Quantization *(by speaking aside)…*

I : You wrote “if we think about for light” but you did not continue to explain here *(by looking at her test paper).*

St29: Yes. We can think about light, and in addition, we can think about for packets also.

I : What do they mean?

St29: It is something like packaging the light after dividing into little particles… Umm *(thinking)*... Something like that.

I : Ok, let’s explain it more. What do you mean by quantization exactly?

St29: We cannot quantize anything in classical physics, because the results were too silly and meaningless. In quantum, we quantize light, energy, velocity. That means, we could quantize the light *(saying quietly)*. In addition, we divide energy into smaller components, we quantize them.

... text exists here...

I : OK, can you say something about the physical situation of the particle in a box?

St29: I know that when the energy of the electron is not enough it behaves as a particle in a box.

I : Do you mean “it may be free particle when it has enough energy”?

St29: I think so, but I am not sure. I know there are free electrons in conductors.

I : OK, you told we quantize energy, velocity etc. before. Now what can you say about them?

St29: They are quantized. I think energy must be quantized.

I : Why it is quantized?

St29: Because we always see the energy in discrete units in quantum physics. We divide the energy into little components and examine it like dividing light. I think here energy must be divided for the electron to exceed that energy and to go out the box. I guess quantization is required.

... text continues after the excerpt...

Student’s explanations of the quantization of light and energy show that the students displaying this model have difficulty in conceptual understanding about both the phenomenon and the related concepts. They use only “discreteness”, which is scientific element, but puts a different meaning it like dividing, disintegrating, slicing etc. Also, other elements are irrelevant to explain the quantization of physical observables. In addition, three students using the ShM in a particular context do not use other models. Therefore, this model seems robust for the construction of other models.

4.1.4 Model 4: Alternating Model (AM)

The next observed model is "Alternating Model (AM)". This is called as Alternating Model since students' conceptual frameworks about the quantization of physical observables are constructed around the "change" element. This change is a natural change seen in physical observables of every particle. The operational definitions for this model are:

- The student mentions that the quantization occurs as any kind of change. It is like spontaneous change of the values.
- The student mentions that there is not restriction for the values of the physical observables, and so they can have any values.
- The student mentions that it is observed for all atomic particles, not for only bound particles.
- The student mentions that it is a natural characteristic for the atomic systems.

This change may depend on the other physical observables. Therefore, the students having this model focus on continuity in the variables, and they perceive physical observables by taking of any values as "alternating". By alternating conception, students explain physical observables do not have stable values because of a dynamic system that is in the effect of external forces. Figure 4.5 shows the use of AM over the contexts.

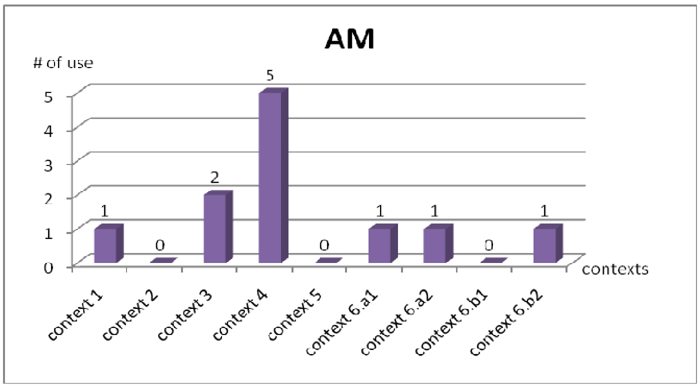

Figure 4.5 The use of AM over the contexts.

As it is seen in Figure 4.5, this model was identified totally eleven times. This model was mostly observed (five times) in the particle in a box context (Context 4).

The following excerpts indicate how the students having this model explain the quantization phenomenon. St9 is a physics student. She uses this model six times over the contexts, and she does not use any other models. Although she is robust in her use of this model, she is nervous about her answers and she has difficulty in remembering what she wrote on the test. St9's some explanations about quantization of light are presented below.

... text continues before the excerpt...

I : All right, let's look at what you explained about quantization *(by looking at her test paper).* You wrote "The values might be similar to each other, but they are different".

St9: I compared with classical physics there. Why did I say that?

I : No, you compared with classical physics below. "Quantized"… You said we haven't seen anything like that in classical physics *(by looking at her test paper together).*

St9 : *(Smiling)…*

I : You wrote "It is in quantum physics… There is not quantization in classical physics"… Yes… You also wrote "particle" *(by looking at her test paper).* Now, here, let's talk about "quantization". Explain verbally what you want to say here *(in the test)* exactly!

St9 : Quantization… *(Silence).* Umm… Mass was changing.

I : How?

St9 : That means, for example, I remember it only from mass. Or, like that… How can I say? It seems like… Mass gets a value when it already had, this seems to me it is quantized. I do not know it is correct or not exactly… It is also same for light… I don't know… *(Silence)… (Smiling).*

I : OK, well… You say "the values are similar to each other but they are different", right?

St9 : That means, for example, mass is 10 kg. But when it is quantized, we see it nine, or eight. I guess I wanted to say something like that here…

... text exists here...

I : OK, you gave an example for mass, but you told that "it is similar for light". When we say "light", let's continue with light. Do you remember photoelectric experiment? What was happening in photoelectric experiment?

St9 : Light was coming, and then it was hitting, and reflecting.

I : What was happening when it hits?

St9 : It breaks off an electron.

I : Yes. If it has enough energy, it breaks off an electron from the surface. You know the photoelectric experiment is the experiment of Einstein. Can we mention about quantization here? Is there anything something like that? What would you like to say?

St9 : Here… Umm… Yes, I think it shows quantization. Because, for example, an electron stays at rest, and a light beam comes, then it *(electron)* breaks away, it changes its motion and creates a current. I think this shows an example to quantization.

... text continues after the excerpt...

Her explanations about quantization of energy in the energy levels and atomic spectra contexts continue similar with the previous ones. In both of the explanations, the student focuses on a "change" in the values of variables that naturally occurs.

... text continues before the excerpt...

I : What does it show that the quantized energy here?
St9 : Umm… The particle does not keep in its normal state. It does not stay same as we have known. It does not keep its' values. It changes. Actually, everything is not same as we see. Its energy changes... It gets different values, it becomes more different. Anything else *(by telling herself)*… Umm… Like that… *(Smiling).*
I : You say this change shows quantization of energy, don't you?
St9 : Yes. The energies are not constant, they are not same…

... text continues after the excerpt...

Other examples of this model are from the particle in a box context. St9 still continues using this model. Also, St21 and St22 state explanations in this context that are similar to hers (St9).

... text continues before the excerpt...

I : Ok, what can you say about the energy of this particle?
St9: I think, its speed changes when it is moving inside the box. Then its energy changes, because its energy depends on its speed.
I : What do you think about is energy quantized everywhere and for every particle?
St9: This is quantum physics, so I think energy is quantized everywhere for every particle. But I am not sure.

... text continues after the excerpt...

St21 still focuses on change while explaining quantization in particle in a box with these explanations:

... text continues before the excerpt...

I : OK. Well. What do you think about the physical meaning of "particle in a box"?
St21: *(Silence).*

**I : ** What do we mean by "particle in a box"?

St21: Umm… The particle moves as a wave… DeBroglie wave. Wavelength is related with the length of the box in order to keep the particle inside it.

**I : ** Well, do you think it is just theoretical box or it has a physical meaning?

St21: I think it is theoretical. It is impossible to see such a thing.

**I : ** OK, what do you want to say about this theoretical particle inside the box? What is it?

St21: Most probably it is electron… Or, it may be a photon.

**I : ** Well, what do you think about the energy of this particle? Because you said "it may be an electron, or a photon" as a particle. Is the energy of that particle quantized?

St21: I think no. Energy is not quantized here!

**I : ** Why it is not quantized?

St21: Because its energy is constant, it does not change. The particle just goes back and forth inside the box, so it is not quantized.

... text continues after the excerpt...

As it is seen in student's explanation, this student associates quantization with "change". So, St21 says "there is not quantization" in the absence of a change. St22 also focuses on "change" and explains as the following:

... text continues before the excerpt...

**I : ** All right, what do you understand from "particle in a box"?

St22: It is a theoretical stuff. I guess it has some applications. What can I say for this particle *(by asking himself)*? Umm… Maybe, it is done by using light.

**I : ** OK, then, what might be the particle in it?

St22: If we use light, it may be a photon. Or, if we use a magnetic field, it may be an electron, or other particles…

**I : ** OK, well, what do you want to say about the energy of this particle? Let's talk about its energy. We were discussing about quantization, is the energy quantized?

St22: Umm… The energy… It may be quantized.

**I : ** Why do you think so?

St22: The motion of the particle changes. For example if we consider its behavior as a wave, its energy will change with the frequency of the light. The motion of the particle will change. It will change the energy… The energy changes.

... text continues after the excerpt...

St9 also explains the quantization of angular momentum in the Bohr atom context by using this model again. Some excerpt from her explanations like that:

... text continues before the excerpt...

**St9 : ** Here *(in the Bohr atom)* again we actually do the same thing. Again quantization. Umm… With the same way.

**I : ** What do you mean exactly?

St9: Actually I am not sure but again there is a change. When the length changes, its angular momentum changes. It is quantized. It was as same as in classical physics.

... text continues after the excerpt...

In her description of the quantum atom, her explanations still continue to robustly use AM. She still appears to consider change to be the critical element for the quantization of physical observables.

... text continues before the excerpt...

St9: The location of electrons. The number of electrons always changes. Their locations change due to “n”, “l” changes, “ml” changes. Yes… Umm… We can say that angular momentum is quantized.

... text continues after the excerpt...

This model is displayed by six of thirty-one participants. While a student (St9) is using it over the contexts robustly, the other five students use the AM in one of the contexts (Context 4). Students’ use of this model especially in this context may be because of an element indicating “change” for quantization in particle in a box.

4.1.5 Model 5: Integrative Model (IM)

Another model that I have identified is the “Integrative Model (IM)”. As with other unscientific models, this model includes students’ use and link of unscientific elements to explain the quantization of physical observables. Three students of thirty-one students use this model. Their conceptual framework about quantization is composed of quantization is a mathematical idea. That means, instead of making sense of the quantization of physical observables as a physical event, they consider it is a mathematical event done by means of integrals, or integrating. Operational definitions for the IM are:

- The student mentions that quantization is an integration process to make the values of the physical observables continuous.
- The student mentions that the quantization of physical observables is observed for all atomic particles, not for only bound particles.
- The student mentions that quantization is not a natural characteristic for atomic systems, so it is an external manipulation of the values of the physical observables.

This model is also used limited. Figure 4.6 shows students' use of this model over the contexts.

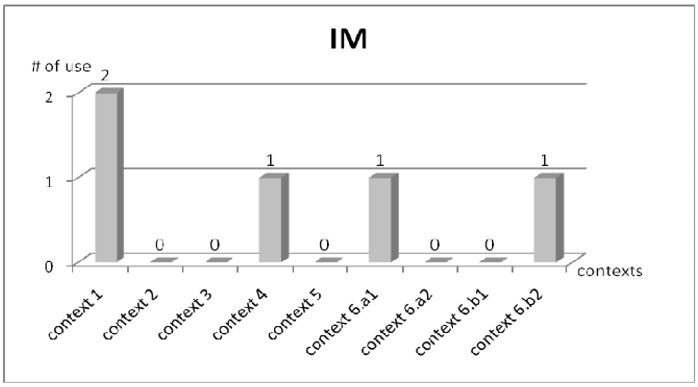

Figure 4.6 The use of IM over the contexts.

As it is seen in Figure 4.6, this model is identified totally five times by three students (males). Two of the three students use another model (SM) and fragments in different contexts, but one of the students (St28) uses only this model and fragments while explaining the quantization of physical observables.

Some excerpts from the explanations of St4 are presented below. He explains quantization of light as:

... text continues before the excerpt...

I : Let's look at your test. You say "we quantize little particles in order to examine them. Because they are very little particles to examine and we are talking with some probability. So we need to examine these little particles in the packets" in your test *(by looking at his test paper).* Would you like to add anything here?

St4: *(Smiling)*… Umm… We are talking about the probabilistic situations in quantum physics. We cannot determine the location of a particle exactly. It is difficult to examine a single particle, so we consider a group of particles instead of a single particle. I understand "quantization" like that. I say "quantization" to this integration of particles. Am I right?

... text continues after the excerpt...

St28 makes similar explanations. He mentions some discrete quantities; however, his understanding about quantization is different from the scientific one. He tries to explain the quantization of energy as making the pieces of energy a continuous energy by using some mathematics.

... text continues before the excerpt...

I : Now, let's overview what you wrote in the test.

St28: OK. After the quiz, actually before it I examined the textbook about what quantum means. Actually, I examined the dictionary. It means "how much" as I understand. But probably what you wanted to ask is not it exactly. Physically, as I understand energy was in pieces, wasn't it? For example, photons are similar, there is not a unity. In any kind of quantization, we try to make it continuous. I understand like that reading after the quiz.

I : What do you mean by "making it continuous"? Why do we not accept as it exists? In other words, why do we not accept that the structure as discrete and try to make it continuous? What is the reason of this idea?

St28: Now, when we think about the wave function, we don't know where the electron is. We calculate that it is in somewhere with some probability. It is between plus infinity and minus infinity, it is certainly in there… *(Thinking)* This does not show a clear result to us. Actually, I cannot explain it exactly. So it wants to get the whole. It is something like that. Actually, I could not state it better.

I : Umm… You say "by making the discreteness continuous" *(silence).*

St28: Yes. By making it continuous.

I : To summarize, "we are trying to make it continuous".

St28: Yes.

I : OK. Well, you especially mentioned about the energy. Actually we asked to you which physical observables are quantized, and where and how we observed them here *(in the test)*. And, we requested that you give some evidence. While you were explaining quantization, you stated the energy first.

St28: Yes.

I : Yes… You started your explanation by the discreteness of energy, would you like to continue for the energy? Then, state again what you understand from quantization of energy, and let's talk about it again. What do you mean?

St28: Umm… Quantization. That means, by making the discrete energy wave continuous, we can understand something there, and reach a conclusion.

I : OK, discreteness… That means a discontinuous situation.

St28: Yes, making the discontinuous situation "continuous". As I understand, quantization means making discontinuous energy or wave continuous.

... text exists here...

St28: That means, for example, protons and neutrons in the nucleus, and electrons around them move by vibrating in a modern model model of the atom. We do not know the exact location, do we? Namely, while finding its location, we quantize.

I : OK. Well, you said "quantizing the discreteness" before…

St28: Making it continuous…

I : All right, where did we see it? That means, you said quantization. How did we make it continuous?

St28: It is too long… By writing the boundary conditions. For example, there is something in the particle in a box also. Let's say writing boundary conditions between plus and minus infinity, we made it continuous.

I : OK, let's overview what we mean by continuity again. If you explain to me by using graph or mathematics, how do you make discontinuity "continuous"? How do you do exactly?

St28: By integrals… I could write the boundaries for the integral, I could write sine function for wave function and I even up it to 1. We can quantize by means of integrals like that.

... text continues after the excerpt...

St4 continues with the same conceptual framework. He tries to explain the quantization of intrinsic angular momentum (spin). While explaining, he gets confused and by keeping to use same model, he regrets the quantization of spin direction because of there is not "integration" there. An excerpt is given below:

... text continues before the excerpt...

St4 : Spin is quantized… This is the quantization of spin. Actually, I couldn't make sense of it exactly… *(Smiling)*… But we are always talking about it.

I : OK, let's understand what you mean by quantization. In your previous explanations, you said "we need to quantize little particles in order to examine them". What does that mean exactly?

St4: According to me, it is integrating. Because we cannot examine it as a single piece, because it is too small, we examine it with packets in a body.

I : Well, you told "spin is quantized". You know spin is a vector quantity. Let's talk about its direction and magnitude separately. Let's look at the direction first.

St4 : Is the direction of spin quantized *(by asking himself)* ? Umm… Is it quantized also *(by asking himself again)*? It has just 2 directions. It can never be quantized! Because, the direction must be this one or another one. So, we can't say the direction of spin is quantized. It takes just 2 values. So why it is quantized? Actually, we cannot make out the meaning of the particle itself exactly, we examine it inside the packet. I say, if it is determined, we cannot talk about the quantization of spin.

... text continues after the excerpt...

By explaining quantization associated with "integration", the students using this model consider quantization as a mathematical issue rather than a physical phenomenon.

4.1.6 Model 6: Evolution Model (EM)

Another model that I have seen students use is an unscientific model that I call the "Evolution Model (EM)". This model is also inappropriate model for quantum systems. This model is the only model that is not observed in the core group. There are only two students (males) in the secondary group who used this model. The operational definitions are:

- The student mentions that quantization is a phenomenon of Einstein's theory of relativity.
- The student mentions that it occurs as any kind of change.
- The student mentions that the quantization of physical observables is observed for all atomic particles, not for only bound particles.
- The student mentions that it is not a natural characteristic for atomic systems, so it is an external manipulation of the values of the physical observables.

Figure 4.7 shows that these students only use this model in a single context which is the photoelectric experiment context (Context 1).

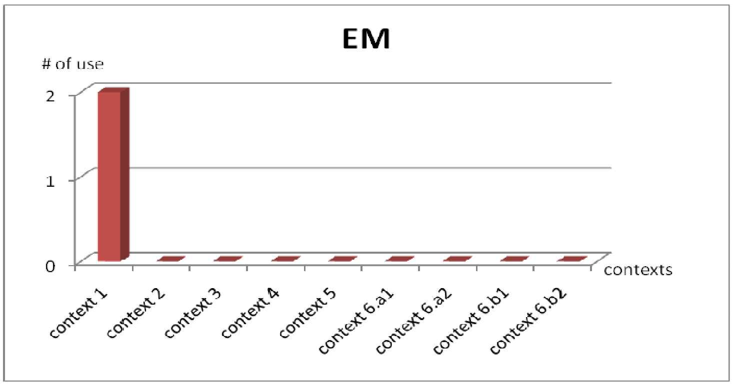

Figure 4.7 The use of EM over the contexts.

As it is seen in Figure 4.7, this model was identified two times in the explanations of the quantization of light. In the explanation of the quantization of energy and angular momentum, EM was not used any more.

This model stresses a structural change in physical observables such as mass, energy etc. For this property, it is also different from AM. In AM, the change occurs in the values of physical observables. However, in EM, change occurs in the characteristics of physical observables. This change seems as evolving to a different observable. The long excerpt from St21, reflects how this student understands the quantization of physical observables.

... text continues before the excerpt...

I : OK… Let’s look at what you wrote about quantization. *(By reading from his test paper)* You said, “quantization is the energy of a particle”, didn’t you? You defined it in terms of the energy.

St21: Yes.

I : You also said, “quantization is the change of mass into energy when the material has the speed of light” *(by looking at his test paper).*

St21: Is it correct?

I : *(Silence)…*

St21: Not correct! *(Smiling).*

I : Now, let’s explain what you mean here exactly. That means, you wrote quantization for energy in the test, you also wrote for mass might be quantized. You said, “it is the energy of a particle” also. That means, what do they mean? Could you explain?

St21: Actually, I do not know exactly teacher *(smiling).* That means…

I : All right, if you consider the energy for classical and quantum physics, is quantization in consideration?

St21: I should look at what I wrote there *(by looking at his test paper).*

I : *(By looking at what he wrote in the test)* You said energy equals to mechanical energy that is composed of kinetic and potential energies in classical physics. You defined the kinetic energy. In quantum physics, you wrote “when the material is quantized, the energy is mc^2”, didn’t you?

St21: Yes.

I : You also wrote the “kinetic energy changes due to the relativistic mass”.

St21: Yes *(by shaking his head).*

I : All right, what was your reason to say like that? That means, this phenomenon- quantization- have you seen it in relativity topics?

St21: I know like that… *(Silence)*… Umm… Yes, in the relativity chapter. I guess it was 2nd chapter including mass, relativistic mass. They come to my mind. I know quantization like that, so I wrote them.

I : OK, well, let’s look at the last question in the test now. Here, we asked which physical observables were “quantized”. For example, you wrote “mass is quantized” and you continued to write with other explanations. What do you mean here by “mass is quantized” exactly?

St21: By quantization, I mean the change of mass due to speed.

I : Do you say “a change due to speed”?

St21: Yes. I think energy becomes mass.

I : Could you explain more? I could not understand well.

St21: Every mass has an energy. Energy of the rest mass is mc^2. When it has the speed of light, it has that energy.

I : Well, how does this particle have the speed of light? You mentioned about the energy of the particle!

St21: *(Thinking)…* We do this by accelerating.

I : OK, by this way is the energy quantized now?

St21: It is quantized.

I : Actually, you say “we do quantize the energy by accelerating!”.

St21: Yes.

I   : All right, would you like to add any other things here?
St21: No.

... text continues after the excerpt...

Other student says similar things by explaining the change of energy to a mass. St11 explains it in the photoelectric experiment context to explain how the electron is emitted.

... text continues before the excerpt...

St11: Quantization of energy… It is the change of energy to a mass. Here it is. The energy of light transforms to mass because of quantization. The energy passes to the electron, and it breaks off the electron by quantization.

... text continues after the excerpt...

By comparison with other models, the use of this model is very limited in terms of number of usage and number of contexts that was used in. In addition, this model is not observed in the core group students but identified in secondary group students.

4.1.7 No Model (NM)

In contrast to having coherent structures, students have some fragmented knowledge, which cannot be called as a mental model. So, I call this type of knowledge structure “No Model (NM)” in this study. These are disconnected knowledge elements, in other words, the incoherent use of fragmented elements such as p-prims, resources, facets etc. (Hrepic, 2002). They also include the direct recall (without strong physically interpretive associations) of memorized elements.

NMs were discriminated from “No Element (NE)” and “No Answer (NA)”, since, NMs include students’ making incoherent and unstructured explanations, whereas, NAs show that a student does not give explanation to the question. NE means a student tries to answer the questions but states his/her ideas about quantum physics, the course and examination grades, feelings about being a physicist/a physics teacher candidate etc. without providing any physical (scientific or unscientific) explanation. Figure 4.8 shows that students’ use of fragments over the contexts without constructing mental models.

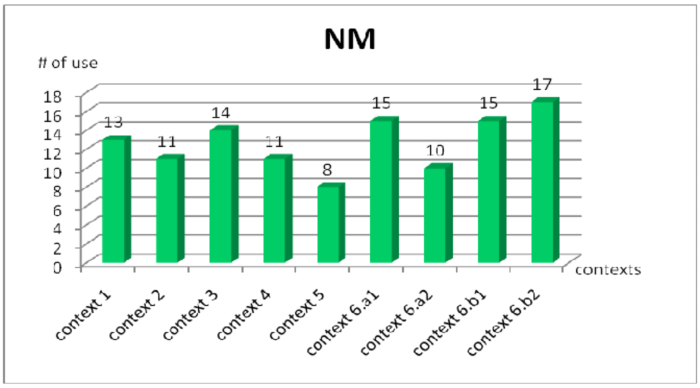

Figure 4.8 The use of NM over the contexts.

As it is seen in the Figure 4.8, in all of the contexts some students use fragments. NMs are used totally 114 times in 279 instances. This is very large number, since it constitutes almost half of the instances. Figure 4.9 shows the comparison of NMs with the total number of all models over the contexts.

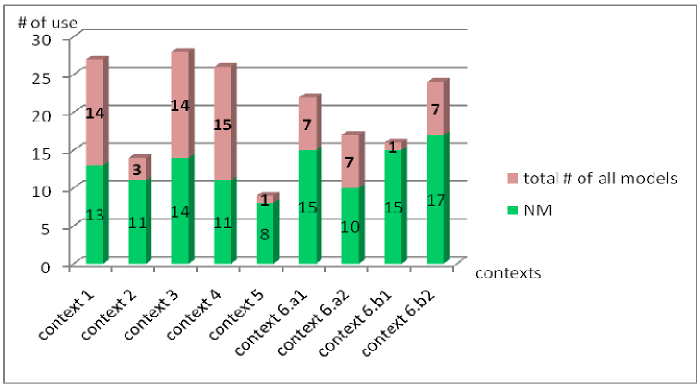

Figure 4.9 Comparison of NMs with the total number of all models over the contexts.

Figure 4.9 summarizes that the use of fragments is greater than total use of models. This result is not surprising, since models are coherent structures that require having conceptual frameworks to explain the phenomena, whereas, the fragments are unlinked primitive elements. In majority of the instances, I observed students were more likely to respond with disconnected, one step reasoning based on poorly in each of the context.

While students using fragments, they think that they could explain the quantization phenomenon with a single physical term, which is mainly "discreteness or/and discreteness characteristic". However, in this way, they could only at most offer a definition of "quantization". Therefore, they simplify the phenomenon, and confine it to its definition without providing a more structural and procedural was to use the concept. Since students do not link the concepts related with phenomenon, their explanations are sometimes only memorized elements residue of the classes, or textbooks etc.

When students use NM in a context, they mainly over generalize the quantization of physical observables for a context. They use some statements such as "it is quantized", "quantization of …" without expressing how the physical observables were quantized. For example, St2, is a student who mainly uses the SM and PSM. When he uses NM in the other contexts, his explanations are like that:

I : Can you explain "energy" for a harmonic oscillator?
St2: Umm… I understand… Energy must have discrete values.
I : Why is it so?
St2: Because we are accustomed to it. Everything is discrete, for example in Bohr atom, and the others. There is no continuity. So I guess, energy is discrete for harmonic oscillator.

... text exists here...

St2: Planck explains Planck constant, the quantization of energy, etc. While learning Planck, you see "energy is quantized", but you do not think that it is quantized in the atom. Then, the quantization of angular momentum comes. At the beginning, I did not recognize that it was so general. But now, I think that for an atom, everything is quantized.

Another student, who use NM for the quantization of angular momentum in the Bohr atom and the quantum atom gives the explanations below:

St31: I do not know Bohr is correct or not, but he says that angular momentum is quantized. We did not check it with the experiments, but we say it quantized also in a quantum atom due to L= $\sqrt{l(l+1)}\hbar$.

The other students (St30, St20 and St5) just say with shortcut explanations that quantization is used in quantum physics. Their explanations are:

St30: I don't know a term "n" in classical physics. I think that it is specific for quantum physics. So I guess it must show a quantization… We started to explain "quantization". For this reason, I think everything seems to be quantized after then.

***

St20: I think "quantization" is just for quantum physics, not for the others.

***

St5 : It *(quantization)* is just as a step to enter to the quantum physics.

St13 and St16 also give similar explanations. While St13 generalizes "quantization of energy" to quantum physics, the second one indicates only "energy" as a quantized physical observable.

St13: If this is quantum physics, I think the energy is quantized for all of the situations.

***

St16: We mainly work with the "energy". So I have directly written *(in the test)* as "energy" is quantized … I don't know… Just the energy comes to my mind at fist.

As it is seen in the examples, although students use some physical elements to explain the phenomenon, the explanations do not show a conceptual framework. These explanations are mainly "flashlight" explanations, which cannot be paraphrased by the student in the second time when it is asked for. So, one of the reasons of using models is more parsimonious than using fragments. Or, it may be run away from the unknown concepts by using shortcuts. One of the shortcut elements was "Planck Constant *(h)*". For example, St22 states "quantization" by using the Planck constant as soon as he sees *h* in any formula.

St22: I think the most of the formulas that contain "Planck's Constant" indicate quantization.

"Just recalling" issues are dominant when students use NM instead of mental models. For example, all of St13, St20, and St31 used NM while explaining the quantization of angular momentum. All their explanations are superficial without reasoning and based on just recalls from the instruction or textbook etc.

St13: The instructor told us that the direction of angular momentum is quantized in the quantum atom. I just remember this, and I don't know the others.

***

St20: There were some formulas about it in the textbook. Also the instructor mentioned it. I guess I remember them and I wrote "angular momentum is quantized" *(in the test)*.

***

St31: As I remember from the textbook… Umm… Angular momentum is quantized. I remember its direction and magnitude are quantized.

4.1.8 Characteristics of Mental Models

In previous sections (Sections between 4.1.1- 4.1.6), I have discussed some characteristics about students' model structures by giving operational definitions. In this section, by using the findings in these sections, some other characteristics of mental models are discussed. I focus on two characteristics of mental models such as "nature" and "context dependency". After I explain the nature of identified models in this study in Section 4.1.8.a, I explain how students' models are context dependent in Section 4.1.8.b.

4.1.8.a Nature of mental models

Six mental models were identified about the quantization of light, energy and angular momentum. Each model has a unique conceptual framework for quantization that is composed of scientific or unscientific elements. So, one of the models is scientific, which is composed of only scientific elements; and other five are unscientific, which are composed of the combination of scientific and unscientific elements, or only with unscientific elements. Table 4.3 shows pure and hybrid nature of mental models that students displayed for the quantization phenomenon.

Table 4.3 Pure or hybrid nature of models.

Model	# of scientific elements in model structure	# of unscientific (irrelevant) elements in model structure	Nature of Models
SM	3	0	Pure scientific model
PSM	2	1	Hybrid unscientific model
ShM	1	3	Hybrid unscientific model
AM	1	3	Hybrid unscientific model
IM	0	3	Pure unscientific model
EM	0	4	Pure unscientific model

Hybrid (blend) model means getting some characteristics of two parental models and forming a new composite model that is different from the parental models (Bao, 1999; Hrepic, 2002, 2004). In the determination of the pure, or hybrid nature of mental models in this study, I consider "scientific" and "unscientific" elements. Therefore, I determine pureness or hybridness of the models by considering only "scientific nature" as a reference.

SM is a pure scientific model. This model is used mainly by some specific students who are enthusiastic to learn more modern physics. They mainly give explanations that they have thought through before the interviews, such as while studying, doing homework etc. In addition to students' reasoning by linking the concepts, students using this model state how the instructor explained the phenomenon in the class. Also, students are sure about what they explained when they are using this model. When students use the SMs, they state clear ideas about the discrimination of relativistic and quantum physics. Finally, this model is observed when students have a correct understanding of the contexts. Students having SM use on the spot and previously thought out ideas together since they use recall and reasoning together while answering the questions. For example, St18 states his reasons by indicating his explanation based on previously thought out ideas:

St18: I have written them by thinking of the nature of light *(in the test)*. The light contains packets, quanta… So I have written all of them by thinking these packets.

PSM is a hybrid unscientific model. It is constructed by the coherent use of two elements from the scientific set and one element from the unscientific set. It is the closest model to the SM because of composition; however, it still contains unscientific elements. The PSM model is constructed by the ignorance of "boundedness" and overgeneralization to the physical observables of every particle. At this point, students seem to have some conceptual difficulty understanding the quantization phenomenon. This point also shows that students' have some conceptual problems about the physical explanations of the contexts. Students using this model are not confident about their learning. One of the examples is from St20. He stresses about his confidence about his explanations:

St20: I think that my answers are not correct…

ShM is a hybrid unscientific model. It contains one scientific element and three unscientific elements. The students, who use this model, have very different understanding of the quantization phenomenon. Their understanding the quantization of physical observables is shaped around the idea that the quantization of physical observables as "slicing a cake". Students' explanations give some cues to their on the spot explanations as Vosniadou and Brewer (1992) explained. These cues were "stopping during the interview to think", "smiling by asking like *'am I right?'*" etc. In addition, students' degrees of certainty shows that they are mainly are not sure about their explanations. One of the examples belongs to St27. She seems very reluctant to examine the phenomenon over the contexts. She is so unsure about her statements.

St27: I think we should not discuss for the other situations.
I : Why?
St27: *(Smiling)* Because I think all of my previous answers are wrong. I cannot be sure about them.

In addition, their discomfort about their on the spot explanations are identified. The explanations of St27 and St29 are like that:

St27: Umm… I need to think… Umm… Quantization… Discrete energies… It is so complex… I will leave to work in physics *(by showing discomfort)*!

***

St29: I don't know… I just feel that I talk nonsense the same things *(with dissatisfied manner).*

The most important issue for this model is that students have some problems about the discrimination of the concepts of classical, quantum and relativistic physics, and their concepts and the contexts.

AM is a hybrid unscientific model. It also contains one scientific and three unscientific elements to explain the quantization of physical observables. As similar with ShM, students' model of quantization diverges significantly from the SM. The students' model is developed around the idea of "change". In addition, students make on the spot explanations more and they are nervous about their answers while using this model. For example, St24 states that:

St24: I do not know my answers correct or not. I never be sure about them. Maybe they are correct, maybe not… When I see this concept *(quantization)*, I cannot be sure about my knowledge.

They have conceptual difficulty with the concepts of the contexts. In AM, it is also observed that students make mainly on the spot explanations. One of the students, who uses the AM regularly over the contexts, gives explanations showing on the spot explanations and shows conceptual difficulty on some concepts.

St9: Umm… I don't know… I haven't thought it before.

***

St9: I have no ideas about why I explained there like that…

***

St9: I don't know exactly it is quantized or not.

***

St9: I am not sure but I feel that I cannot construct the concepts. I do not feel I understand it well. Maybe, I am guilty because I did not study too much.

IM is a pure unscientific model. It only contains the three elements from the unscientific set. This model also diverges from the scientific one. Students' understanding about the quantization of physical observables is shaped around the idea of "the integration of small parts". One of the different characteristics of this model is students' mathematical interpretation of the physical phenomenon. In contrast to other models, in this model, students think that quantization is a mathematical way of using integrals. Students who use this model are also not sure about their explanations. As with the other unscientific models, students using this model have conceptual difficulty with the concepts of the contexts.

EM is a pure unscientific model. It contains four elements from the unscientific set. This model was only used by the students in the secondary group, and it was used only twice in Context 1 to explain the quantization of light. Students who use this model also have a different way of understanding the quantization of physical observables. Students' models are developed around the idea of "evolving". Students' key concept while using this model was the "speed of light". They use some ideas of the theory of relativity while explaining the phenomenon. Students have problems discriminating Einstein's relativity and the ideas of quantum theory. In addition, they are also not sure about their explanations. The excerpt below belongs to the St21 who uses EM. He states his guess before his explanations, then he explains the phenomenon. This also indicates his on the spot thinking during giving explanation. St11 also gives similar explanations.

St21: It is quantized…
I : How do you explain it?
St21: I just guess with the 50% probability *(smiling).*

***

St11: More speed means more energy… But I want to remind that all of my explanations are "based on my mind". That means 90% is wrong *(smiling).*

My last important finding is about the use of SM and unscientific models. The findings show that students who use the SM in one or more than one contexts, used mainly NMs when they do not use models; however, the students who use unscientific models (PSM, ShM, AM, IM and EM) use mainly NEs when they do not use models, and sometimes they do not answer the questions (NAs).

4.1.8.b Context dependency of mental models

Studying students' mental models in different contexts is important to see the context dependency of mental models. As it is identified in the previous studies

(Bao, 1999; Bao & Redish, 2006; Hrepic, 2002, 2004; Hrepic et al., 2010; Wittmann et al., 2003), students' mental models are context dependent in the current study. That means students may use different models in the different contexts of the phenomenon. I examine it especially in the explanation of the quantization of energy. This is shown in Table 4.4.

Table 4.4 Context dependency of the models.

		CONTEXTS	*1*	*2*	*3*	*4*	*5*	*6.a1*	*6.a2*	*6.b1*	*6.b2*
CODE – GENDER - DEPT											
ST1	F	PHED	NM	ShM	NM	AM	NM	NM	NM	NE	NM
ST2	M	PHED	PSM	NM	PSM	SM	NM	NM	SM	NM	SM
ST3	M	PHYS	PSM	PSM	NM	SM	NM	SM	SM	NM	NM
ST4	M	PHYS	IM	NM	NM	NM	NE	NM	SM	NE	IM
ST5	M	PHED	NM	NM	NM	NM	NE	IM	SM	NE	NM
ST6	M	PHYS	NM	NM	SM	SM	NM	NM	NM	NM	NM
ST7	F	PHYS	PSM	NM	PSM	SM	NM	SM	NM	SM	NM
ST8	M	PHED	NM	NE	NM	NE	NM	SM	NM	NM	NM
ST9	F	PHYS	AM	NE	AM	AM	NE	AM	AM	NM	AM
ST10	M	PHYS	NM	NE	PSM	SM	NA	SM	SM	NM	NM
ST11	M	PHYS	EM	NE	NM	NM	NA	NM	NM	NM	PSM
ST12	F	PHED	NM	NE	PSM	NE	NA	NM	NA	NM	NM
ST13	F	PHYS	NM	NE	NM	NE	NE	NM	NE	NE	NM
ST14	F	PHYS	NM	NE	NM	NE	NE	NE	NE	NE	NE
ST15	F	PHYS	NM	NM	SM	SM	NM	SM	NM	NE	NM
ST16	F	PHED	NM	NE	NM	NM	NE	NM	NM	NE	NE
ST17	M	PHYS	PSM	NM	NM	NM	NE	NM	NE	NE	PSM
ST18	M	PHYS	SM	NM	SM	SM	NA	NM	SM	NM	NM
ST19	M	PHYS	NM	NE	PSM	NM	NA	NM	NM	NM	NE
ST20	M	PHYS	NE	NE	PSM	NM	NA	NM	NE	NM	NM
ST21	M	PHYS	EM	NE	NM	AM	NA	NE	NE	NE	NE
ST22	M	PHED	SM	NM	NM	AM	NA	NE	NE	NM	PSM
ST23	F	PHYS	NM	NM	NE	AM	NA	NE	NA	NE	NE
ST24	F	PHED	NA	NM	AM	NA	NA	NE	NA	NE	NM
ST25	M	PHED	PSM	NE	SM	SM	NA	NM	NM	NM	SM
ST26	M	PHED	NE	NE	NM	NM	NA	NE	NA	NE	NA
ST27	F	PHYS	ShM	ShM	NE	NM	NA	NE	NA	NE	NM
ST28	M	PHED	IM	NE	NE	IM	NE	NE	NE	NE	NM
ST29	F	PHYS	ShM	NE	ShM	ShM	NA	NE	NE	NE	NE
ST30	F	PHYS	NE	NE	NM	NM	ShM	NM	NE	NM	NM
ST31	M	PHYS	NM	NE	SM	NM	NM	NM	NM	NM	NM

For example, Contexts 2, 3, 4, 5, 6.a1 and 6.b1 are the contexts for the quantization of energy. It is identified that while students explaining the quantization of energy with SM in a context, they use some unscientific model (PSM) in the other contexts (St2, St3, St7 and St10). One of the students (St1) uses different unscientific models (ShM-AM) in different contexts. These findings indicate the discussion of model states.

We know that people can hold two or more "inconsistent" mental models together in the same domain (Gentner, 2002). More specifically, students may use different models for the different contexts of phenomenon. I call this as "mixed state" as Bao (1999), Hrepic (2002, 2004), and Hrepic et al. (2010) called. Since if a model is used robustly over the context, then students' model state is called pure state (Bao, 1999; Hrepic 2002; Hrepic et al., 2010). In mixed model state, students hold different mental models for a situation at the same time, and using them inconsistently (Bao, 1999; Hrepic, 2002; Hrepic et al., 2010). In this study, students use different models at the same time over the contexts. For example, we see in Table 4.4, St1, St2, St3, St7 and St10 have mixed model states since St2, St3, St7 and St10 use the SM and PSM together. In addition, St1 uses two different unscientific models, which are the ShM and AM. Both of these models are hybrid unscientific models. Since they are different hybrid models, her model state is also a mixed state.

In addition, we see that none of the students uses models in each context. They may sometimes use models, and sometimes fragments. They sometimes do not answer the questions and they do not state any physical explanations. In the examination of their model usage, we see nineteen students have pure model states in the quantization of energy case. Last seven students do not use any model to explain the quantization of energy.

In Table 4.4, we also see that students' robustness of their ideas. For example, St9 uses the AM in three contexts of the quantization of energy. She uses the same knowledge structure robustly. Also, another example, St15 uses the SM in also same three contexts. She states scientific explanations about the quantization of energy. These robust models seem stable and they might be context independent after a time.

4.1.9 Reconsideration of This Section

To summarize, second-year physics and physics education students display six different mental models about the quantization phenomenon. Among the identified mental models, most used model is the SM (totally 29 times). Although having SM more than the unscientific ones is a wanted situation, this is quite small number by considering 279 instances. As Figure 4.10 presents the use of all models over the contexts.

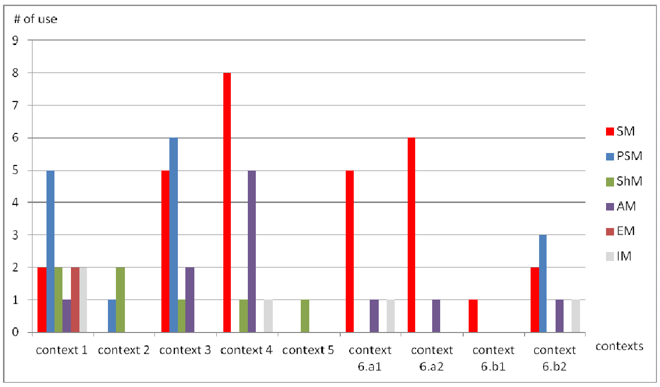

Figure 4.10 Comparison of the frequency of mental models over the contexts.

Figure 4.10 shows that the diversity of the displayed models is maximum in Context 1 (six different models), and minimum in Contexts 5 and 6.b1 (one type of model). This might be interpreted with the familiarity of students to photoelectric effect context more than harmonic oscillator and the quantum atom contexts. Figure 4.11 summarizes the distinct comparison of the frequency of each model and other issues (NM, NE, and NA).

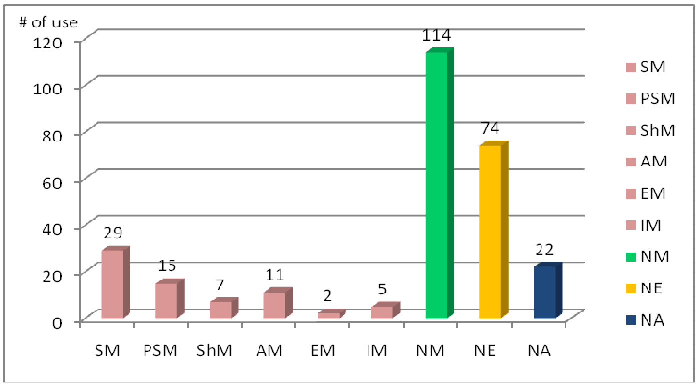

Figure 4.11 Comparison of the frequency of each model with other issues.

Among 279 instances, the most dominant one is the use of NM. Since mental models are complex and coherent structures, students sometimes prefer to use fragments consciously or unconsciously. Figure 4.12, presents the comparison of the total number of all models with other issues.

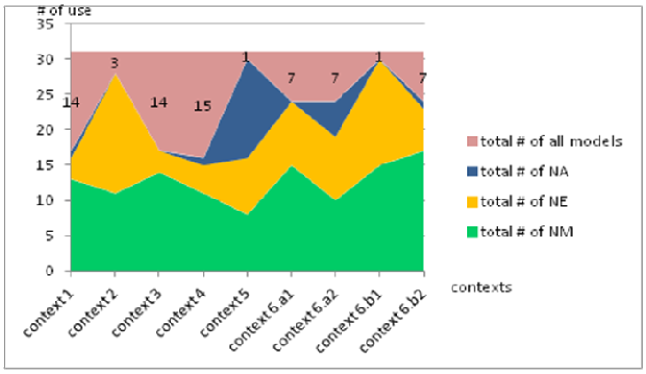

Figure 4.12 Comparison of the total number of all models with other issues.

We see the dominant use of fragments again (~40.9%). The percentage of the use of models (~24.7%) is close to the percentage of not to use none of the fragments (~26.5%).

In addition to the identified models, the instructor explains his ideas about students' understanding of the quantization phenomenon. The instructor thinks that the richness of a student's explanations vary due to their models. The following excerpts present the ideas of instructor.

> **Instructor:** This *(quantization)* is not such an easy concept for students to understand. Its comprehension is difficult. They got some good grades in the exams, however they have some mis- or missing conceptions bring from high school physics classes related with the phenomenon. These previously learned conceptions make students' understanding the phenomena difficult. In previous lessons, students learned "continuous physics". But now, when we pass to "quantized observables", new concepts are seen difficult to students. If they do not discuss the new concepts in their minds, the concepts are not learned easily. I do not say "they learned quantization completely", but I believe they learned the basic ideas about it. They have learned the energy levels of a Hydrogen atom is quantized, angular momentum is quantized etc. Then I think they could construct the other ideas of quantum physics on this knowledge. I think they got the main ideas.

***

Instructor: Students' explanations vary. A student, who understands well can model quantization better and explain it better. For example, in the class, I made an analogy that was the flow of water drops from a tap to indicate the discreteness. When you let the water flow fast, we cannot see the discreteness at that point. This point can be considered as Newtonian physics. I think that the students, who understand quantization correctly, can remember this analogy or construct other analogies, and explain quantization correctly.

4.2 The Sources Influencing Students' Mental Models

Norman (1985, pp.316-317) stresses that the study of cognition requires consideration of external and internal parts of the entire system. In this part, external and internal sources influencing students' mental models are explained with the question:

- What are the external and internal sources that influence students' mental models of the quantization of physical observables?

In this section, I focus on which sources are in action in the development of models. Since it is impossible to study everything as a source, in this research I focus on some elements by considering the cognitive science literature and the data I obtained. I basically classify the sources as "external" come out from students' environment, and as "internal" come out from students' own personality. Textbook, instruction and the elements related with instruction, topic order, classmate, and extra sources for learning (internet, books) are discussed in terms of the external sources influencing students' mental models. In contrast to these sources, meta-cognition, motivation, beliefs, familiarity of the concepts and background knowledge are considered as the internal sources influencing students' mental models.

Diverse number of data sources contributes in the explanation of these sources. Figure 4.13 shows which data were used to explain this section. Although there is a time order in the analysis of data, there is no specific time order in the interpretation of the data constructing this section. That means external and internal sources identified in the data analysis were integrated regardless of time.

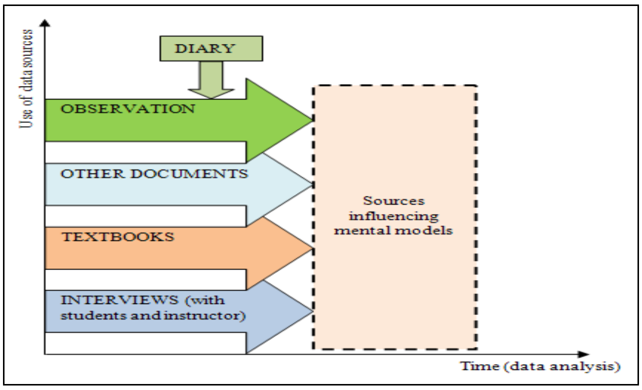

Figure 4.13 Integration of data sources to explain sources influencing students' mental models.

As I classify the sources external and internal, I explain them basically in two sections. In Sections 4.2.1 and 4.2.2, external and internal sources are explained, respectively. While explaining these sources, each source is considered as independent from each other.

4.2.1 External Sources Influencing Students' Mental Models

Textbook and instructional elements were probable sources mentioned in literature; however, classmate, and extra sources were determined at the beginning of the study. In addition, topic order was identified in the data analysis of the study. Therefore, in the following sections I present the evidences about how those sources influence students' mental models.

4.2.1.a Textbook

In this section, textbook is explained as an external source by two ways. First, by using students' explanations in the interviews, their use of textbooks actively in and out of the classes, preferences of textbooks, ideas about the effectiveness of textbooks are focused. By the analysis of the interviews, I got explicit evidences about the influence of textbook(s). Second, the analysis of textbooks in terms of scientific explanations and method of explanations are important in the explanation of textbook as an external source influencing students' mental models. By content analysis of two textbooks, I got implicit evidences about the influence of textbook(s) on students' mental models. Then, I combined the findings obtained explicitly and implicitly, and interpreted them together. By the examination of the relationship between implicit and explicit evidences qualitatively, I explain the influence of textbook on students' mental models.

To start with the interviews, all of the students use textbooks actively. Although students use different textbook(s) (Beiser's or Krane's book) for some different reasons, the interviews show that all participants of this study use textbook(s) as a main resource. Seventeen of the students state that they use only Textbook 1 actively, and four students state that they used Textbook 2. However, ten students explain that they use both of the textbooks at the same time.

Students have different reasons about textbook usage. For example, three of the students who use Textbook 2 state that they like the style of Textbook 2 while explaining the concepts, one of the students (St23) states that she has not any idea about why she uses that book. Some examples for students' reasons of selecting and using Textbook 1 are like that;

St12: Everybody in the class uses Beiser, so I use it also.

***

St13: I use Beiser, because it explains the concepts in an easy way.

The students, who use both of the textbooks at the same time, explain their reasons like that:

St22: I use Beiser while studying on the topics since it just gives the main ideas without expressing the details, and I use Krane while doing homework.

St29: I mainly study on Beiser to learn the concepts, but the exam questions are similar with the questions asked in Krane, so I solve problems in Krane before the exam.

In the examination of students' interviews, eleven students state that they never bring modern physics textbook (whichever they used) into the classes; eight students state that they always bring their textbooks; and twelve students state that they sometimes bring their textbooks while coming to the classes. When the percentage of students bringing textbook into the classes is examined, 82.35% of the students who use Textbook 1 bring their textbooks to the classes. This ratio is 50% for the students who use Textbook 2. This is a bit low (40%) for the students who use both textbooks. The students bringing their textbooks to the classes explain their reasons as the following: (1) easiness of the following taught concepts from the textbooks; (2) not to take notes to a notebook and just marking the important points on the textbook, (3) reading the textbook when not understanding what the instructor explained; and (4) for preparation before the quizzes. A sample excerpt belongs to St4 shows his reasons like that:

> **St4:** When I bring my textbook into the classes, I can follow what the instructor explained easily, I can understand the concepts easily, Umm… I feel that I had the power to learn.

In the conceptual interviews, students were requested to state the reasons of their answers. In other words, they were asked to explain the sources (i.e. textbooks, instruction, friends etc.) of explanations in each context. Figure 4.14 presents attributions of the core group students (n=8) in each context.

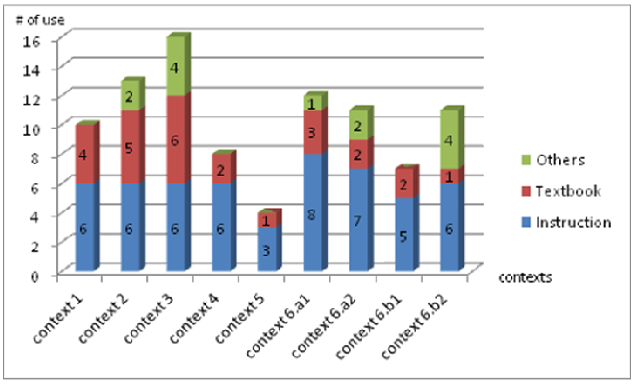

Figure 4.14 The core group students' attributions about textbook as a source of their explanations in the conceptual interviews.

Context by context explanations of students' attributions indicate that textbook is considered as a source at least one time in each context. No matter they are used together with the other sources (i.e. instruction), this result shows that students feel some influences of using textbooks in their learning of modern physics concepts in each context as they feel similar for bringing their textbooks into the classes. In addition to explanations given in the conceptual interviews, some students also have some attributions about the methodology of textbooks influencing their learning. For example St25, who is a physics education student and having scientific model in energy quantization, states the importance of use of analogy and figures in the book like that:

I **:**What are the most influencing elements on your understanding in this situation *(Context 3)*?

St25 : Umm... I think the figures in the textbook… To make the concepts more concrete. Also, there was a comparison of energy levels with the steps of ladder, you cannot stand between the steps. That was helpful for energy quantization.

In the Self-Evaluation Interview at the end of the semester, students were asked which factors influenced their understanding of quantization. Figure 4.15 presents the perceptions of twenty-nine (two students lack Self-Evaluation interview) students about the source of understanding quantization.

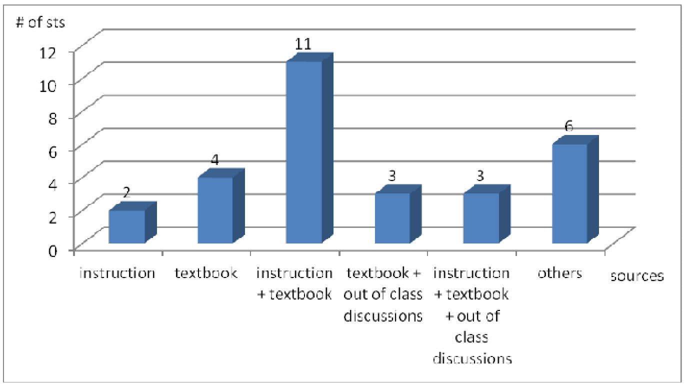

Figure 4.15 Students' attributions about the sources influencing their understanding of quantization.

Only four students attribute to textbook as a main element in understanding of the quantization phenomenon. However, excluding two students saying only "instruction", and six students saying "other sources", twenty-one of twenty-nine participants explain that textbook is the source of their understanding of the quantization of physical observables. This is quite great number to occur by chance.

Another interesting explanation belongs to St5. He is a physics education student and he has the IM and SM in the Bohr atom context (Contexts 6.a1 and

6.a2). The excerpt below shows that how this student interprets the quantization phenomenon in the textbook, and the role of the textbook in his construction of model about quantization.

> **St5:** Quantization... Umm… There are some explanations in the textbook but I do not understand them. I know the textbook use integrals while "quantizing", and it sums up all probabilities in a specific volume. This is quantization.

In addition, in some of the contexts, students use "memorization" elements coming from the textbooks. For example, St4 is a physics student and he uses both SM and IM in different contexts. However, when he does not use any of these models, he gives explanations about the quantization of energy in the particle in a box context like that:

> **St4:** It is quantized!
> **I :** What is quantized? And, how is it?
> **St4:** Energy! Particle in a box. The textbook says that "the energy is quantized"!

Another student is a physics student. St20 uses the PSM in the energy level context but he does not use any model for quantization of angular momentum. He indicates the influence of textbook in the same manner:

> **I :** You said that "I have a different way to explain quantization of angular momentum", right? How do you explain it? Or, do you already accept quantization of angular momentum?
> **St20 :** I saw it in the textbook. I read it there. There was something about it.
> **I :** Well, let's talk about it! Angular momentum! How is it quantized? What tell us it was quantized?
> **St20:** I remember its' formula in the textbook. I just remember they were in the textbook. So, I told it was quantized.

The limited data also show that although students do not use mental models in some contexts, they state that textbook is a source for their understanding. One of the example for this situation belongs to St14. She is a physics student who does not have any model and she just uses fragments, explains her reasons about why the textbook is important in her understanding like that:

> **St14:** The main factor was the textbook. Because, I have attention deficit in the classes. So, I cannot concentrate to the lesson and I cannot listen to the instructor. So, I studied from the textbook, I understand by studying the textbook.

In conclusion, no matter students have scientific or unscientific models, the interviews indicate that "textbook" is important for students' models. In the interview with some of the students, they explain their ideas about the influence of textbooks in their understanding directly. For example, St6 is a physics student and has the SM of energy quantization. He explain that:

> **St6:** I think the textbook is the main factor in my understanding. It explains all concepts in a logical way very well. This is Beiser's book.

Another student, St30 who is a physics student and having ShM, attributes her poor understanding not to study on the textbook too much as:

> **St30:** I know, if I studied on textbook, I could understand well. But this semester was too busy for me and I could not study on the textbook much. But in the summer vacation, I will study on quantization from the textbook. I will read it to improve my understanding.

St3, who is a physics student and having SM about quantization of energy, explains his reasons about the effects of textbooks in his understanding like that:

> **St3:** I believe the classes have effect on my understanding of quantization, but the textbook focuses it more than the classes. For example, if the textbook explained the quantization of energy only in the blackbody radiation topic, I could not understand it well. However, it states quantization was an important concept and focuses it in many different topics. It makes concrete by giving many examples, then I can make sense better.

Because students use textbooks so actively, the explanation of quantization of physical variables in the textbooks is so important. For this reason, the examination of the textbooks (context by context) in terms of "what" and "how" is explained the phenomenon provide some information about the influence of textbook on students' mental models of quantization. The tables in Appendix M.3 and M.4 were obtained after the content analysis of the textbooks. While Appendix M.3 presents the frequency of the codes explaining the quantization of physical observables in the textbooks, M.4 presents the frequency of the codes about the methodology of the textbooks explaining the quantization phenomenon.

Figure 4.16 presents the distribution of students' knowledge structures due to their use of textbooks. Since the number of students in each group varies, the results are given in percentages by standardizing the numbers in order to interpret better.

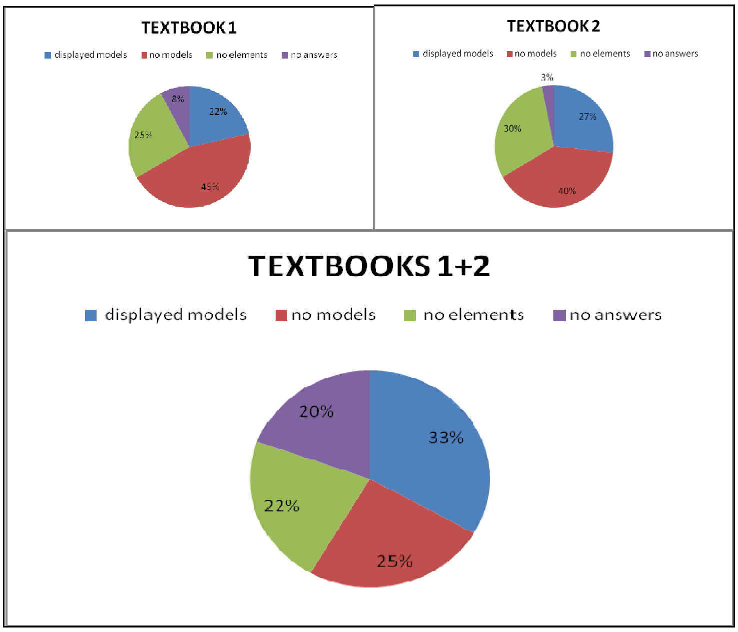

Figure 4.16 Students' knowledge structures due to the use of the textbook(s).

As Figure 4.16 presents, while percentage of displayed models is 22% for students who use only Textbook 1 and 27% for the students who use only Textbook 2, respectively, this percentage increases to 33% for the students who used both of the textbooks. In addition, "No Elements" and "No Models" which indicate unphysical and scattered ideas, are considerably decreased for this group. In addition, this figure indicates an increase in the percentage of students who do not answer the questions (NAs). This might be the because of meta-cognitive elements that students are aware of their knowledge. That means, if students know the phenomenon, they answer with coherent structures by using models; if they do not know, they do not answer the questions. Figure 4.17 shows the distribution of each model due to the use of textbook.

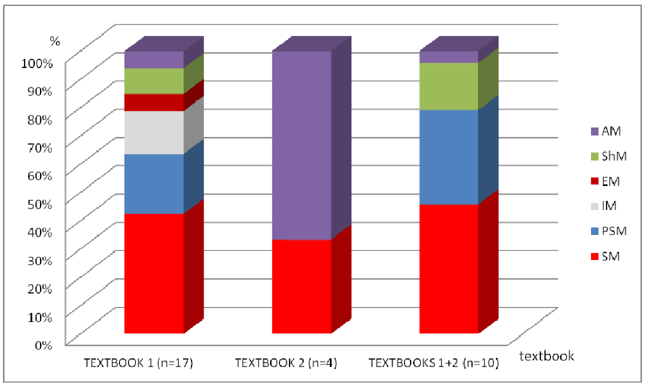

Figure 4.17 Percentage of each model displayed due to the use of different textbook.

Variety in the displayed models might be because of the number of students in each group; however, more than half of the students who use only Textbook 1 and all of the students who use Textbook 2 have "pure" model states about the quantization phenomenon regardless of scientific/unscientific nature. That means students are consistent with their explanations over the contexts. In addition to increase in the percentage of the use of models for students using both textbooks, this figure indicates the increase in the percentage of the use of SM for students using both of the textbooks.

Percentage of the students who explain "textbook" as a source of their understanding of quantization differs for these groups. This percentage is 76.4% for the students who use Textbook 1, 50% for the students who use Textbook 2, and 80% for the third group using both textbooks.

While examining textbook as a source influencing students' models or not, I have used the content analysis. So with the examination of the textbooks via content analysis, I got implicit evidences about textbook is an external source. These findings were tabulated in Appendices M.3 and M.4 as mentioned before. I executed these findings by using other findings that was modified version of the table given in Table 4.4. This table was a new table that was separated in to three categories by considering students' use of textbooks. Then three tables that showing students' model structures were obtained from Table 4.4. By comparing students' mental models for each group (using a specific textbook) in each context together with the findings presented in M.3 and M.4, I constructed new tables for each group indicating relationship qualitatively. By using the information in tables that indicating a pattern about model usage, use of scientific models, or the robustness of the SMs etc., I determine "textbook" is an external source influencing students' mental models.

By the examination of influence of using Textbook 1, Textbook 2, and Textbook 1 and 2 together in each context, the following tables (Tables 4.5, 4.6 and 4.7) indicate why "textbook" is an influencing source on students' mental models.

Table 4.5 The influence of using Textbook 1 on students' mental models (n=17).

Contexts	1	2	3	4	5	6.a	6.b
Frequency of displayed models	7	3	7	7	0	6	3
Frequency of the SMs	0	0	4	4	0	5	1
Stress to quantization	1	2	4	5	1	1	15
Frequency of the codes about quantization	51	25	117	77	35	29	141
Frequency of the codes OBP+NC	20	10	32	39	3	5	50
Explicit explanation of OBP/NC	-	√	√	√	√	-	√
Diversity of the methodologies to explain quantization	6	5	7	7	7	4	7
Frequency of the codes of methodology to explain quantization	P :4 T: 32 M:15	P:1 T: 20 M:4	P:6 T: 75 M: 36	P:4 T: 53 M:20	P:4 T: 21 M:10	P:2 T: 18 M:9	P:9 T: 100 M: 32

P: pictorial, T: textual, M: mathematical explanations.

The table providing some evidences about the influence of Textbook 1 on students' models indicates that,

- The *diversity of the methodologies to explain quantization* + *frequency of the codes about quantization* might have influence on number of models (plus sign means considering the elements together). For example, with increase in these elements together, the number of models used in Contexts 1, 3, and 4 is high; with decrease in these elements together, the number of used models in Contexts 2 and 5 is low. However, I could not observe this pattern for Context 6.
- The use of SM seems to be influenced by the *stress to quantization* + *frequency of the codes about quantization* + *explicit explanation of OBP/NC*, together. For example, with increase in these elements together, the SM is used more Contexts 3 and 4; with decrease in these elements together, the SM is used few in Contexts 1 and 5. However, I could not observe this pattern for Context 6.

Table 4.6 The influence of using Textbook 2 on students' mental models (n=4).

Contexts	1	2	3	4	5	6.a	6.b
Frequency of displayed models	2	0	3	3	0	3	1
Frequency of the SMs	1	0	1	1	0	1	0
Stress to quantization	0	1	0	2	0	3	5
Frequency of the codes about quantization	70	24	42	47	14	120	182
Frequency of the codes OBP+NC	18	13	3	23	5	38	56
Explicit explanation of OBP/NC	√	√	-	-	-	-	√

Table 4.6 (continued)

Diversity of the methodologies to explain quantization	7	3	6	6	5	6	6
Frequency of the codes of methodology to explain quantization	P:1 T: 44 M:25	P:0 T: 21 M:3	P:3 T: 24 M:15	P:2 T: 37 M:8	P:1 T: 5 M:8	P:3 T: 82 M:35	P:15 T: 137 M:30

P: pictorial, T: textual, M: mathematical explanations.

The table providing some evidences about the influence of Textbook 2 on students' models indicates that,

- The *diversity of the methodologies to explain quantization* + *frequency of the codes about quantization* might have influence on number of models. For example, with increase in these elements together, the number of models used in Contexts 1, 3, 4 and 6.a is high; with decrease in these elements together, the number of used models in Contexts 2 and 5 is low. However, I observe this pattern for Context 6.b as the existence of a model with the use of these elements more.
- The *diversity of the methodologies to explain quantization* + *frequency of the codes about quantization* might have influence on the number of displayed the SMs. However, it does not provide information about increase, it just shows existing once. For example, we see the SM in Contexts 1, 3, 4 and 6.a when these elements are used together more; we do not see the SM in Contexts 2 and 5 when these elements are used together few. I also could not observe this pattern for Context 6.b.

Table 4.7 The influence of using both Textbooks students' mental models (n=10).

Contexts	1	2	3	4	5	6.a	6.b
Frequency of displayed models	5	0	4	5	0	5	4
Frequency of the SMs	1	0	0	3	1	5	2
Stress to quantization	1	3	4	7	1	4	20
Frequency of the codes about quantization	121	49	159	124	49	149	323
Frequency of the codes OBP+NC	38	23	35	62	8	43	106
Explicit explanation of OBP/NC	√	√	√	√	√	-	√
Diversity of the methodologies to explain quantization	7	5	7	7	7	7	7
Frequency of the codes of methodology to explain quantization	P:5 T: 76 M:40	P:1 T: 41 M:7	P:9 T: 99 M:51	P:6 T: 90 M:28	P:5 T: 26 M:18	P:5 T: 100 M:44	P:24 T: 247 M:62

P: pictorial, T: textual, M: mathematical explanations.

The table providing some evidences about the influence of using both Textbook 1 and 2 together on students' models indicates that,

- The *diversity of the methodologies to explain quantization* + *frequency of the codes about quantization* + *the ratio of the codes OBP+NC to OBP+NC+D/DC* might have influence on number of models. For example, with increase in these elements together, the number of models used in Contexts 1, 3, 4, 6.a and 6.b is high; with decrease in these elements together, the number of used models in Contexts 2 and 5 is low.

- The use of SM seems to be influenced by the *diversity of the methodologies to explain quantization + frequency of the codes about quantization + the ratio of the codes OBP+NC to OBP+NC+D/DC + stress to quantization* together. For example, with increase in these elements together, the SM is used more in Contexts 4, 6.a and 6.b more; with decrease in these elements together, the SM is used few in Contexts 1, 2, 3, and 5.

By using the information in these three tables, I can summarize the commonalities of the influence of using textbook.

- In the explanation of number (percentage) of model usage, the *diversity of the methodologies to explain quantization + frequency of the codes about quantization* is common for these three groups,
- In the explanation of number (percentage) of SM usage, the *frequency of the codes about quantization* is common for these three groups; and the *stress to quantization* is common for using Textbook 1, and Textbook 1 + 2.

In conclusion, although using different textbooks has an influence on students' models separately, they also have common influences. Therefore, I can state that textbook is an external source on students' models. The following paragraphs explain why a textbook is an external source influencing students' models in detail. To start with the stress of the "quantization" in the textbooks identified by content analysis, Figure 4.18 presents the frequency of use of the terms such as "quantization of…", "…quantized", "quantized …" etc. in the textbooks over the contexts. The frequencies of the terms are not the total number of use of these terms in the textbooks. That means, the terms also used context independent or in the omitted sections are not focused in this study.

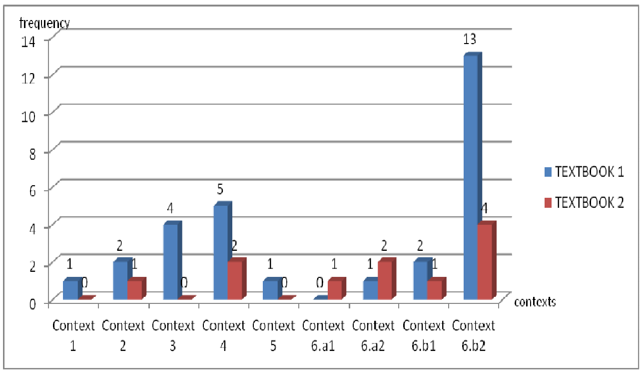

Figure 4.18 Frequency of the use of "quantization/quantized" terms in the textbooks over the contexts.

Although textbooks use these terms with different frequencies that is presented in Figure 4.18, their direct usage to stress phenomenon is important. In addition to differences. In the frequency of stress of quantization, the methodologies of the textbooks stressing these terms also differ. For example, while Textbook 1 indicates quantization in Context 3 with the title "Quantization in Atomic World" (Beiser, 2003, p.136), Textbook 2 indicated it in Context 2 with a history of science text stressing its natural characteristic as "quantization property is not an accident arising from the analysis of one particular experiment, but is instead of a property of the electromagnetic field itself" (Krane, 1996, p.82). In addition, both of the textbooks mainly stress quantization over the context explicitly.

As the frequency and methodology to stress quantization differ, frequency and methodology of the codes to explain quantization differ for both Textbook 1 and Textbook 2. Context 1 is the "Photoelectric Experiment". In this context, quantization is stressed by Textbook 1 by explaining Einstein's interpretation of Planck's formula about the energy quantization (Beiser, 2003, pp.63-64). Scientific elements OBP, D/DC and NC are indicated by both of the textbooks several times. While Textbook 1 indicates discreteness or/and discreteness characteristic explicitly, only bound particle and natural characteristic are used implicitly. However, Textbook 2 presents some evidences about using all of them explicitly. When the methodologies of these textbooks are examined, Textbook 2 differs from Textbook 1 by mainly using classical and quantum comparisons, and frequency of exemplification. In this context, all models are used totally fourteen times by students (SM-two times, PSM-five times, ShM-two times, AM-one time, EM-two times, and IM-two times). When students' models are examined in this context due to the preference of a textbook, model usage is 41.2%, 50% and 50% for the students using Textbook 1, Textbook 2, and both textbooks, respectively. All models used by the students using Textbook 1 are unscientific. In spite of the explicit statement of quantization, implicit explanation of the core elements (only bound particle and natural characteristics) may be the reason of these models.

Context 2 is the "Blackbody radiation and ultraviolet catastrophe" to examine the quantization of energy. While Textbook 1 uses regular sentences more, it stresses quantization two times; and Textbook 2 uses history of science elements more, it stresses quantization one time in this context. This is good starting to introduce "quantization" to gain students' attention. To give scientific ideas, both textbooks do not use boundedness as the main element of quantization idea explicitly, but they use it implicitly. They use "oscillator" term, but this term is implicit for students to indicate boundedness. Natural characteristic that is one of the elements of scientific explanations is given explicitly by both of the textbooks. Textbook 1 states "it is an element of physical reality" (Beiser, 2003, p.62), and Textbook 2 explains it stressing the experiment results. However, most of the sentences indicate that quantization is a natural characteristic in quantum physics implicitly, and main emphasis of the books is on the "discreteness or/and discreteness characteristic" terms. By comparison with the number of the codes with previous context, frequency of the codes is almost half of the previous contexts in spite of almost same number of pages. Both textbooks use almost same number of codes and their methodologies to explain quantization are also similar. Both of them mainly use regular sentences and history of science elements.

By the examination of students' models in this context overall, two models are observed only (two times ShM and one time PSM). None of the models are displayed by the students, who are using Textbook 2 and both of the textbooks. The reason of students not to display models might be the use of few number of codes by comparison with the other context. When the number of codes are few, indication of boundedness and natural characteristic is also few. None of the students also uses the SM to explain the quantization of energy. One of the reasons may be implicit explanation of quantization for only bound particles. In the examination of models due to the preference of a textbook, all of three unscientific models are used by the students who are using Textbook 1.

Context 3 is the "Energy levels and atomic spectra" to examine the quantization of energy. Although Textbook 1 uses "quantization of…, quantized…" terms for four times by notifications/titles and uses in the texts, Textbook 2 does not use any way. In addition, by considering the frequency of codes, Textbook 1 explains the quantization of energy for almost three times longer than Textbook 2. In this context, while three fundamental elements of quantization are explained both explicitly and implicitly in Textbook 1, boundedness is not observed in Textbook 2. But, boundedness of the particles is explicitly emphasized in Textbook 1 including such type of statements: "An atomic electron", "confinement of an electron to a region" etc. In addition, natural characteristic is used implicitly.

In the explanation of quantization in this context, both textbooks use some common methodologies; however, Textbook 1 uses also classical quantum comparison, analogy and notification/title elements. For example, the use of analogy is also differed from the previous contexts. Textbook 1 uses analogy with the explanation of *a person who stands on the steps of ladder, and does not stand in between the ladder steps* to stress the quantization of energy. Although it just stresses the "discreteness or/and discreteness characteristic", it might be helpful students to make sense of the quantization of physical observables. In addition, since the number of codes in Textbook 1 is almost three times larger than Textbook 2, this difference also reflects the frequency of use of regular sentences in the textbooks. This ratio is also 3/1 for Textbook 1 over Textbook 2.

Almost half of the students use models in this context. Large number of these models are the SM (five times) and PSM (six times) in the overall examination of models. However, when the models of students due to preference of textbooks are examined, it is observed that all SMs are displayed by the students who are using one of the textbooks. This is interesting since using both textbooks seems not facilitating the use of the SM in this context. This might be explained by focusing on one kind of textbook might be better in this context. For the students using Textbook 1, stress of quantization four times, and explicit explanation of bound particle, discreteness or/and discreteness characteristic, and natural characteristic might be the reasons of using more SM (57.1%) by comparison with PSM (42.9%).

Context 4 is “Particle in a box” to examine the quantization of energy. Again, “quantization of, and quantized” terms are used by both of the textbooks (five times by Textbook 1, and two times by Textbook 2). While both of the textbooks using the fundamental elements of quantization, the frequency of these elements and total number of them are different for both of the textbooks (two times greater in Textbook 1 than Textbook 2). “Boundedness” of the particle is explicitly indicates while explaining the quantization of energy in both of the textbooks with the statements “completely trapped within the box”, “trapped particle”, “the particle restricted to a certain region of space”, “any particle confined to a certain region”, “atomic electron” etc. Textbook 2 also makes comparison of energy of a free particle and bound particle to stress “boundedness”, and it concludes this comparison with “energy is not quantized for free particles”. The ratio of stating boundedness is almost 2/1 for Textbook 1/Textbook 2. However, in spite of much stress on the boundedness, the textbooks still explain the quantization is a natural characteristic of atomic systems implicitly.

Both textbooks explain the quantization of energy with almost same methodology. In other words, since the frequency of the codes is larger in Textbook 1, the use of regular sentences, mathematical formulas and examples are more used than Textbook 2. For example, although “regular sentence” is the main explanation methodology for both textbooks, “exemplification” is preferred also by Textbook 1 to stresses the “boundedness” and “discreteness or/and discreteness characteristics”. A difference between these textbooks is also observed. In Textbook 1, quantization of energy is explained explicitly and step by step.

By the examination of displayed models, the dominant model used in this context is the SM (eight times). However, the AM is also used by many students (five students) in contrast to the IM (one student) and ShM (one student). The students who use models the AM, IM and ShM indicate “quantization for every particle”. It is an interesting result in spite of the stress of bound particle, these students stress the energy quantization for every particle. In the examination of students’ models due to the used textbook, the dominant model in the groups using

Textbook 1, and Textbooks 1 + 2 is the SM (57.1%, and 60%, respectively).

Context 5 is the “Harmonic oscillator” to examine the quantization of energy. While both of the textbooks are using boundedness, discreteness and natural characteristics, the frequency of the use of them differs too much for Textbook 1 and Textbook 2 (i.e. four times larger in Textbook 1 than Textbook 2). Both of the textbooks state boundedness implicitly by giving examples for a harmonic oscillator as “diatomic molecule”, “an atom in crystal lattice”, “a vibrating diatomic molecule” etc. Natural characteristic is also explained implicitly, in contrast to explain discreteness explicitly. In addition, similar with the previous contexts, natural characteristic is explained implicitly in the textbooks. The methodologies to explain quantization have common elements; however, Textbook 1 uses also classical quantum comparison and reminders by comparing energy levels for H atom and particle in a box, and uses notifications and pictures more dominant than Textbook 2.

When students’ models are examined in overall, most of the students (fourteen out of thirty-one) do not answer the questions about the quantization of energy of a harmonic oscillator and eight of the rest of the students (seventeen students) state irrelevant explanations. Only one student (St30) uses a model (ShM) and the rest the eight students use fragments in this context. When students’ models are examined due to the preference of textbook, the students who are using only Textbook 1 and Textbook 2 do not use models, but the student using both textbooks displays the ShM. In spite of the use of similar methodologies with previous context, I explain decrease in use of models, and increase in “No answers” by the decrease in frequency of the codes of fundamental elements as similar with Context 2.

Context 6 is the “Atom” to examine both the quantization of energy and angular momentum. In this context, Context 6.a discusses the Bohr atom, and Context 6.b discusses the quantum atom. In Context 6.a, both textbooks stress the quantization phenomenon (Textbook 1 one time, Textbook 2 three times). While Textbook 1 indicating quantization of angular momentum, Textbook 2 indicates both energy and angular momentum by using “… quantized” term. While both of the textbooks using boundedness and natural characteristic implicitly in contrast to use of discreteness explicitly, the frequency of the codes diverges too much.

Textbook 2 uses these elements almost four times larger than Textbook 1 (Textbook 2 explains in almost two times more pages than Textbook 1). While boundedness and natural characteristics are indicated in both textbooks, discreteness is also explained almost two times than these elements in this context in overall.

When the methodologies of the textbooks are examined, there are four times greater codes in Textbook 2, and it uses classical quantum comparisons, title/notifications and mathematical examples different from Textbook 1. In addition, although they use regular sentences, Textbook 2 uses them five times greater than Textbook 1. Textbook 1 uses history of science element as a different methodology from Textbook 2.

In the examination of students' models in the Bohr atom context for energy and angular momentum in overall, although students display limited number and diversity of models, the use of SM is greater (78.6%) than the other display models. When these models are examined due to the preference of textbooks, most of the students using Textbook 1 and having models display the SMs; and and all of the students using both textbooks and having models display the SMs.

In the second part of Context 6, the quantization of energy and angular momentum is examined for the quantum atom. Context 6.b is discussed in both of the textbooks almost 2-3 times larger than the previous contexts. So the stress of quantization and frequency of the codes both for fundamental elements and methodology to explain the phenomenon are considerably great in this context. For example, quantization is stressed by Textbook 1 for fifteen times and Textbook 2 for five times in this context (by omitting the other concepts related with the quantum atom). In addition, almost 1/3 of all codes are used in this context for both of the textbooks. This context is the context that all fundamental elements are explicitly explained by both of the textbooks. Methodologies of these textbooks to explain quantization are also similar to each other ignoring the frequency of the regular sentences. In addition, in both of the textbooks, the quantization of angular momentum is discussed more than the quantization of energy since the explanation of the quantization of angular momentum is given more detailed with the explanation of magnitude and direction of orbital angular momentum and spin (intrinsic angular momentum).

When the models of students using Textbook 1 or Textbook 2 are examined, it is observed that students display limited number of models in this context. This percentage increases a bit for the students using both textbooks. In addition although number of used models is few, these students present more SMs than the other students using one of the textbooks. Not to develop more models in this context is interesting, it might be because the influence of other sources on students' models might be more dominant than textbooks in this context.

To summarize the results of the influence of textbook on students' models:

- The use of both textbooks facilitate to use of any kind of models and use of SMs in overall of the quantization phenomenon. However, context by context examinations indicate focusing of a textbook might be better for some of the contexts.
- The students who use both textbooks indicate that textbook as a source of understanding of quantization more than the others who use one of the textbooks.

The comparison of the results from content analysis of the textbooks, the analysis of students' conceptual interviews, and the analysis of the interviews about students' own evaluations show that textbooks influence students' models by several ways. With these results, I can state that the textbook(s) that students interact in and out of the classroom setting is an external source having influence on students' models of the quantization phenomenon.

4.2.1.b Instruction and the elements related with instruction

I explain this section in two parts. First part is the discussion of explanations in instruction together with the elements related with instruction (attending the classes, taking notes in the classes, preparation before and after modern physics classes), and the second part is the discussion of instructor's attitude and motivation.

First, by using students' explanations in the interviews, I got some explicit data. Then, I used the data obtained from observation by video recording of the classes during the semester. After the analysis of this data in terms of scientific explanations and method of explanations, I got some implicit information about the influence of all these instructional elements. Finally, as similar with the followed procedure in previous section (4.2.1.a), I combine both implicit and explicit data in order to explain the influence of instructional elements on students' models.

To start with the interviews, students were requested to state the sources of their explanations in the conceptual interviews. As Figure 4.14 presented the all type of attributions about the sources influencing students' explanations, Figure 4.19 presents the distribution of core group students' attributions to "instruction" over the contexts. That means, instruction is stated at least one time alone or together with other sources.

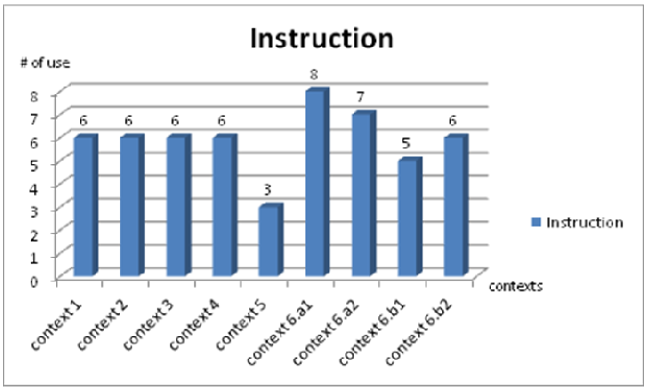

Figure 4.19 The core group **s**tudents' attributions about instruction as a source of their explanations in the conceptual interviews.

Figure 4.19 indicates that almost all of the core group students state that instruction is one of the sources of their explanations in each context. That means, students feel some influences of instruction in their learning of modern physics concepts. In addition, as it was presented in Figure 4.15 in previous section, students were asked which factors influence their understanding of quantization in the Self-Evaluation Interview. The results show that sixteen of twenty-nine students explain the instruction as a source of their understanding. Two of these sixteen students state the instruction as the only element in their understanding of quantization.

Before explaining why the instruction is a source in students' model construction, brief description of instructional environment in terms of instructional techniques might be helpful. The instructional methodology of the course is direct (teacher centered) teaching enriched by different teaching techniques. Since the instructor has pedagogical knowledge, he integrates many teaching techniques into modern physics instruction. These are history of science story, real life story, inquiry, role play, daily life example, analogy etc. By this way, instructor keeps students' attention fresh by encouraging them into the classes. In the interview with the instructor, he explains his reasons about role plays like that:

> **Instructor:** In the classes, I generally make students to be active and to participate physically. For example, in the explanation of quantization, I jumped from an upper step to lower step in the lecture hall to show discrete values. I stated that I cannot stand between the steps, this was similar with quantization. This type of techniques may be helpful for students' understanding, because students enjoy the class with these activities. They are excited. I believe that this excitement also contributes students' understanding.

He integrates his verbal statements into written statements very well while he is explaining the concepts. For example, while he is writing mathematical expression, he does not just write on the board by himself; however, he explains all unknown terms, and the physical meanings of the mathematical expressions. He asks students the meanings of the abbreviation of the terms, and then he clarifies their meanings. This is also same for drawing the figures. He always explains the parts of the figure while he is drawing and process the information to teach step by step.

One of the other important characteristics integrated into the instructional methodology is recalling the previous issues and linking the new information with the previous ones. In addition, at the beginning of each chapter, the instructor summarizes the previous chapter and links the previous concepts with new concepts.

Another issue about the instructional methodology is the instructor's notification of confused concepts such as ionization and excitation, radiation, and decay etc. He stresses the differences and makes clarification about these concepts.

He also uses his voice very well. He modifies his tone of voice to take students attention, to motivate students, to stress the important terms. In addition, he also integrates body language into his speeches. For example, while stressing the important points such as "discreteness" in energy, in most of the explanations he states that he mentions about not a continuous energy, but the energy levels by showing the discreteness by his hands. Or, in the space quantization of electron spin, he also uses his hands to make the concepts concrete, etc.

Another strong point in the instruction is linking the concepts in historical manner (chronological order), and what is done before and after the specific date. For example, in the explanation of the quantum atom, semi-classical model of atom- Bohr- was recalled and the new understanding of atom was expressed. In addition, in this historical manner, comparison and discrimination of classical and quantum issues are also important techniques used by the instructor.

About the "quantization" phenomenon, the strongest point of the instruction is linking the quantization with how a physical observable is quantized. For example, after he tells "quantization of energy", he explains the energy quantization by stressing the scientific elements such as discreteness or/and discreteness characteristic, boundedness of the particle and natural characteristics for the atomic systems. The instructor gives the information so "pure" that is direct and clear. This is one of the instructional profits, which might not be obtained in the textbooks.

Another important point is the instructor's reminder of some classical concepts learned in freshman physics. For example, before explaining the angular momentum, harmonic oscillator etc., he fist reminded students the classical explanations, then he taught their quantum explanations.

Students are aware of the instructor's methodology influencing their understanding. So they state that they like the instructional techniques of the instructor. For example, St29 stresses the instructor's linking of concepts by historical and daily life stories:

> **St29:** The instructor constructs very good analogies. He tells historical stories. This show us "who made the concepts? Who did the experiment? How did they do the experiments? etc.". These are effective it is because showing time order. In addition, I think these parts are the most wondered parts . We cannot see them in the textbooks. For example "Why did he do this experiment? What did he find? What did he wonder?" We wonder them. So the instructor's explanation of them is so good.

Some other students focus on the "questioning" technique of the instructor. They stress the positive effect of this technique on their understanding.

St26: The instructor always focuses on inquiry. He requests us to find the answers and he keep our interest fresh. I think this effects positively.

***

St27: The technique of the instructor that I liked most is asking questions. These questions covers all learned concepts. This is so good.

Another student stresses the step by step approach of the instructor influencing their understanding.

St15: We are lucky since the instructor writes all formula step by step. So I think it is effective for our understanding better.

In the examination of students' models, it is observed that students who use the SM have some attributions about the instruction. That means, students give some explanations like i.e. "*St7: … the instructor derived its formula…", "St5: … the instructor explains it like "$L=n\hbar$"…"* etc. And the excerpts from some of the students show the influence of instructor on students:

St5: I think that reading the textbook does not always mean understanding the concepts. Students need information presented in a simple way, like a summary of the concepts. This is what the instructor explained. So, I think instructor's explanations are so precious.

***

St2: I think, if I did not attend the classes and then try to understand the concepts by reading the textbook only, it wouldn't be useful for me by itself. I cannot make sense the concepts exactly without attending the lectures. Classes are so helpful for my understanding. I believe both of them- classes and studying on textbook- reinforced my understanding about quantization.

In the examination of the instruction by observation data, I also got implicit evidences about the instruction as an external source. While examining it is a source influencing students' models or not, I used the analysis findings of the observation data. These findings were tabulated in Appendices M.5 and M.6. Appendix M.5 presents the frequency of the codes explaining the quantization of physical observables while teaching modern physics in the classes during the semester. Appendix M.6 also presents the frequency of the codes about the methodology (i.e. verbal regular sentences, on the board mathematical formulas etc.) while teaching modern physics in the classes. I executed these findings by using the other findings presented in Table 4.4. By comparing students' mental models in each context with the findings presented in M.5 and M.6, I constructed a new table indicating relationship between them qualitatively. By using the information in table indicating a pattern about model usage, use of scientific models, or the robustness of the SMs etc., I determine "instruction" is an external source influencing students' mental models.

By the examination of influence of instruction on each context, the following table indicates that why it is an influencing source on students' mental models.

Table 4.8 The influence of instruction on students' mental models.

Contexts	**1**	**2**	**3**	**4**	**5**	**6.a**	**6.b**
Frequency of displayed models	14	3	14	15	1	14	8
Frequency of the SMs	2	0	5	8	0	11	3
Stress to Quantization	0	0	12	6	0	20	78
Frequency of the codes about quantization	23	55	97	82	22	67	228
Frequency of the codes OBP+NC	5	20	28	26	4	27	37
Diversity of the methodologies to explain quantization	4 verbal, 3 on the board= 7	6 verbal, 2 on the board, 1 body lang.=9	4 verbal, 6 on the board, 1 body lang.=11	6 verbal, 4 on the board, 1 body lang.=11	3 verbal, 3 on the board=6	6 verbal, 4 on the board, 1 body lang.=11	6 verbal, 6 on the board, 1 body lang.=13
Frequency of the codes of methodology to explain quantization	Verbal: 17 On the board:6 Body lang.:0	Verbal: 48 On the board:6 Body lang.:1	Verbal: 66 On the board:28 Body lang.:3	Verbal: 56 On the board:23 Body lang.:3	Verbal: 14 On the board:8 Body lang.:0	Verbal: 45 On the board:18 Body lang.:4	Verbal: 157 On the board:65 Body lang.:6

The table providing some evidences about the influence of instruction on students' models indicates that,

- The *diversity of the methodologies to explain quantization* + *frequency of the codes about quantization* + *the proportion of the use of verbal elements to other elements* together might explain together the use of models. As it is seen in Contexts 1, 3, 4, 6a and 6b, more models are used with the increase of these elements; and few models are used with the decrease of these elements seen in Contexts 2 and 5.
- In addition to the *diversity of the methodologies to explain quantization* + *frequency of the codes about quantization* + *the proportion of the use of verbal elements to other elements* explaining the use of models together, the contribution of the *stress to quantization* + *the use of body language, verbal notifications and mathematical formulas, and pictorials on the board* into previous elements might explain the use and number of SMs together. As it is observed in Contexts 3, 4 and 6a, with increase of percentage of the new elements in each context, the use of SM increases; and with the decrease of the percentage of the new elements (i.e. Context 1 and 5), the use of SM decreases.

To conclude, these findings show that the explanations in instruction as a source influencing students' mental models. The following paragraphs explain why instruction is an external source for students' mental models in detail.

To start with the stress of quantization in the classes, "quantization of…, …quantized etc." are used in the classes several times. Figure 4.20 presents the frequency of these terms for each context.

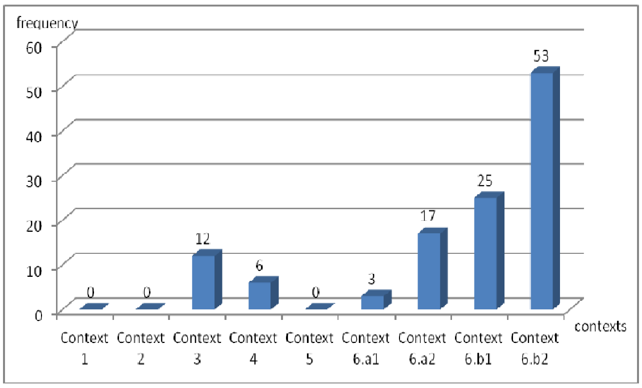

Figure 4.20 Frequency of the use of "quantization/quantized" terms in the classes over the contexts.

As it is seen in Figure 4.20, quantization is stated over the contexts. In Context 1, which is Photoelectric Experiment, the instructor mainly explains the quantization of light by means of history of science. As it is known, Planck's explanations are before Einstein's explanations, the instructor prefers to explain linking how their explanations are related. He explains in the class like that:

> **Instructor:** Einstein brings a very drastic understanding more drastic than Planck's understanding… Up to Planck, it is seen continuous like a wave. No! It does not continue like that, but small energy packets constitute the wave. Or, energy must be ported on the wave by small packets of energy. This is drastic… According to Einstein, light is not only emitted in the form of quanta, energy is concentrated in quanta as the wave propagates…

In this context, while the instructor uses three fundamental elements of quantization, main stress is on the discreteness or/and discreteness characteristic. The instructor mainly uses written and verbal statements. When students' models are examined, I observe various number of models. Almost half of the students use models, and two of them are scientific. Among these models, the PSMs and SMs are dominant models that are used by students in this context, since the students stress the discreteness more.

However, when the students attending the classes around 75%, not studying before and after the classes and not taking notes in the class are examined, I observed only one student having these four characteristics. This student (St25) presents the PSM in this context.

In Context 2, which is the "Blackbody radiation and ultraviolet catastrophe", the instructor starts to teach "quantization" phenomena with a historical story. He explains:

> **Instructor:** "Natura non facit saltos" *(by reading the book)*. What does it mean? Did you understand anything? "Natura non facit saltos". What is salto *(somersault)*? Did you do a somersault? Nature never jumps! Natura! "Doğa", non facit! "asla", Saltos "sıçramaz". It was so before… Before 1900s... It was told that nature never jumps. After 1900, after Planck's experiment, natura jumps! Now after 1900s, nature jumps! That's what we have learned.

In addition to the use of diverse number of methodology to explain quantization, he stresses the paradigm shift by saying "*This is a moment of changing physics*" for the introduction of quantization issue by history of physics elements. In addition, he constructs analogy for students to make sense of quantization. The analogy is:

> **Instructor:** It is just like a tap. What is tap? "Musluk". Water just flows drop by drop, like "pıt, pıt, pıt, pıt". And every drop is a quantum, just like hv. These quanta may be large or small. The emission of quanta is like dropping "pıt, pıt, pıt". If you increase "pıt-pıt-pıt-pıt *(by saying fast)*", and if you increase more "pıt-pıt-pıt-pıt *(by saying faster than the previous ones)*, it appears continuous.

Frequency of the codes is almost two times greater than the previous context. By this way, without using "quantization" term, the instructor explains the discreteness and the characteristic of discreteness (allowedness). In addition, he explains it is the nature of energy and just seen for only bound particles by explaining the harmonic oscillation of electrons. However, the results show that although the instructor uses such diverse explanations to explain the quantization of energy in the blackbody radiation and ultraviolet catastrophe context, none of the students has the SM. In addition, the PSM (one student) and ShM (two students) are also used very limited. Most of the students do not make relevant expressions (seventeen students) and eleven of them are used fragments. This is interesting result and the reason might be the students' familiarity with these concepts, and not make sense of the relevant concepts (i.e. a blackbody, blackbody radiation, emission etc.). When St25's knowledge organization is examined, this student does not use a model in this context.

Context 3 is the "Energy levels and atomic spectra". The frequency of the codes considerably increases in this context by explaining boundedness, discreteness and natural characteristic. The instructor stresses the discreteness by stating "discontinuous" term many times (69 times) and showing energy levels by using body motion by drawing levels in the air by his right hand. He also explicitly stresses the "boundedness" of the particle indicating the quantized energy. Finally, the instructor uses the "quantization of energy, energy is quantized" statements twelve times by explaining the quantization of energy in this context. When the models of students are examined, almost half of the students mainly present models, and great proportion of these models is composed of models indicating discreteness. In this context, five students use the SM and six students use the PSM. This result is better than the previous ones, since there is an increase in students' use of scientific explanations. In the examination of St25 to see the influence of classes, this student uses the SM in this context.

Context 4 is the "Particle in a box" to explain the quantization of energy. As similar with the previous context, great number of codes is identified explaining boundedness, discreteness and natural characteristic. In addition to stressing discreteness or/and discreteness characteristic, the instructor explicitly explains "boundedness" condition for a particle to have quantized physical observables. He also implies its' natural characteristic explicitly. In the explanation of energy quantization, the instructor uses "quantization/quantized" terms six times. Most of the explanations of the instructor is verbally explained regular statements, stress of the mathematical elements verbally, and exemplifications of the board. As similar with the previous context, he also uses body language. In addition to these methodologies to explain quantization, the instructor also uses "instructional methodology" that is inquiry. After writing the energy condition for the particle in a box, he requests students interpreting the equation. By this way, students arrive at the discrete nature of energy for a bound particle and these energy values are only allowed values. Possibility of the physical existence of "particle in a box" is discussed with students. Again, he uses analogy by considering *particle as a human being obeying the laws of state and doing only allowed behaviors* as similar with having allowed values in the quantization. When students' models are examined in this context, almost half of the students use models and eight of thirty-one students display SM. The results show that students' making sense of quantization more facilitates the development of mental models. When St25's model is examined, he uses the SM in this context.

Context 5 is the examination of quantization in "Harmonic Oscillator". In this context, by comparison with Contexts 3, 4 and 5, there is considerable decrease in the use of scientific elements indicating boundedness, discreteness and natural characteristic. Although the instructor explicitly stresses the boundedness of an electron having harmonic motion, the instructor never uses the quantization of energy, quantized energy, energy is quantized" terms while explaining the quantized energy for quantum harmonic oscillator. When the instructor's methodology to explain quantization is examined, he mainly uses verbal and written statements on the board, and diversity of the methodologies used in this contexts is decreased. In the teaching of the quantized energies of harmonic oscillator, the instructor firstly reminds students about its classical explanation. However, the results show that students still do not make sense harmonic motion in quantum systems. When the models of the students' are examined, it is observed that just one of thirty-one students uses a model (ShM) to explain the quantization of energy. Almost half of them do not give answer and eight of thirty-one students gave irrelevant answers. St25 also does not answer this question. This is the most problematic context in terms of model usage so it might indicate the influence of some other elements in this context.

Context 6 is the last context to discuss the quantization phenomenon in the atom. As similar with the examination in the textbooks, atom is also examined for both the Bohr model and quantum model in this section. This context is important in terms of examination of the quantization of both energy and angular momentum. In the first part of this context that is Context 6.a, the instructor uses "quantization/quantized" terms more than the previous ones. For example, in the Bohr atom he uses three times for the energy quantization, and seventeen times for the quantization of angular momentum. The frequency of the codes is great to explain boundedness, discreteness and natural characteristic. In addition, the instructor uses all these elements explicitly while teaching the phenomenon. While using mainly regular statements verbally, he also uses body language in this context. The models displayed by students are examined, it is observed that five students can explain the energy quantization by using the SM; and six students can explain the quantization of angular momentum by using the SM in this context. In addition, great proportion of used models is composed of SM. In contrast, when St25's explanations are examined in this context, he never uses a model in this context.

In Context 6.b, the stress of quantization term increased more. These terms are used for the quantization of energy totally twenty-five times; and they are use fifty-three times for the quantization of angular momentum. This is parallel with the textbooks since the quantization of angular momentum is discussed for both magnitude and direction of the orbital and intrinsic angular momentum (spin). The frequency of the codes for this context considerably increases since almost 2/5 of all codes belong to this context. While the explanation of discreteness element increases too much, the statement of boundedness and natural characteristic are almost used with same amount. However, the instructor strongly stresses "natural characteristics" in addition to "boundedness, discreteness or/and discreteness characteristic". Verbal notifications indicating quantization increase in the methodology of explanation of the phenomenon. Body language is also used more in this context. When students' model usage in this context is examined, limited number of models are used (for quantization of energy one student, and for angular momentum two students). Most of these models are unscientific. This result is interesting because, although these issues are discussed longer than the previous contexts, students do not display more models (by also including SM more). On the contrary, they give irrelevant answers, and use fragments to be able to answer the questions. This might be the result of another source influencing model usage more in this context.

After the determination of instruction as an external source influencing students' mental models, the other elements related with instruction are examined. These are: Attending the classes, note taking in the classes, preparation for modern physics before and after the classes, doing homework, studying for examinations. Specification of these elements as a source influencing students' mental models, my approach was the same with the previous ones. By executing the information obtained with the interviews by students and the findings presented in Table 4.4, I got some patterns about the change in the number of model usage, percentage or robustness of SMs etc. Then I determine which of these sources have influence on students' models.

In the interviews, eleven students state that they prepare for modern physics before the classes, and twenty of them state that they do not. In addition, eleven students (different eleven) state that they study after the classes regularly; fourteen students state that they rarely study; and six students state that they never study after the modern physics classes. They state different reasons about preparation before and after the classes. When students' models are examined, all of the students (four students) who never use models in the contexts explain they never study before the classes, and two of them also state they never practice after the classes. I do not have clear evidences about the influence of studying before and after the classes on students' models. So, these findings indicate it is not a single element influencing models; however, it might influence together with others.

In the examination of students' attendances in the classes, twenty-five participants among thirty-one participants attend to the classes regularly (more than 75%) and the rest of them state that they attend around 75%. In the examination of the influence of physically attending the classes, it is identified that twenty-one of twenty-five students construct "coherent structures", that means they develop mental models, no matter they are scientific or unscientific. However, four students do not have models in spite of attending the classes regularly. In addition, an interesting result is belong to the students who do not attend classes regularly. The students who do not attend the classes regularly present model structures more. The number of models used by these six students who attend the classes around 75% vary from 2 to 5, and most of the used models are SMs. In conclusion, attendance is not an "independent" source for students' models; however, it may influence other elements, and has an influence with other elements related with the instruction.

Twenty-four of thirty-one students take notes on their notebooks during the course. Twenty of students taking notes state that they took notes exactly the same with what the instructor wrote on the board. In addition, they state that they do not query what is written while they are taking notes, and they explain that they write without interpretation what they wrote. In the examination of students' explanations in three groups over the contexts, I observe that while model usage of the students who take notes exactly same with the instructor and a bit different from the instructor are, 23.3% and 22.2%, the students, who never take notes display more models (30%). The percentage of SM for the students who never take note is 52.6%. In addition, four students who never use models in the contexts are the students taking notes as exactly same with the instructor. Taking notes without interpreting might prevent students' organization of their knowledge by sticking to what the instructor told. In conclusion, note taking might be a source influencing students' models.

In addition to the independent analysis of these elements related with the instruction, Figure 4.21 presents the models of students who attend the classes regularly, study before and after the classes, and take notes in the classes.

CODE	*GENDER*	*DEPT*	*context 1*	*context 2*	*context 3*	*context 4*	*context 5*	*context 6.a1*	*context 6.a2*	*context 6.b1*	*context 6.b2*
ST1	F	PHED	NM	ShM	NM	AM	NM	NM	NM	*NE*	NM
ST6	M	PHYS	NM	NM	SM	SM	NM	NM	NM	NM	NM
ST10	M	PHYS	NM	*NE*	PSM	SM	NA	SM	SM	NM	NM
ST12	F	PHED	NM	*NE*	PSM	*NE*	NA	NM	NA	NM	NM
ST22	M	PHED	SM	NM	NM	AM	NA	*NE*	*NE*	NM	PSM
ST24	F	PHED	NA	NM	AM	NA	NA	*NE*	NA	*NE*	NM
ST29	F	PHYS	ShM	*NE*	ShM	ShM	NA	*NE*	*NE*	*NE*	*NE*
ST30	F	PHYS	*NE*	*NE*	NM	NM	ShM	NM	*NE*	NM	NM

Figure 4.21 Models of students who attend the classes regularly, study before and after the classes, and take notes in the classes**.**

As it is seen in Figure 4.21, each student has a model at least one time. Since the instruction provides pure information about the quantization of physical observables, attending the classes, and taking notes and getting this information and making it "knowledge" by studying prior and after the classes might facilitate knowledge organization requiring for model development.

In the interviews, most students state that they do homework regularly. They explain doing homework is effective (1) to show different examples about concepts, (2) to make them to interpret and discuss about the concepts, (3) to recognize their mistakes, (4) for preparation for exams, and (5) to make them study for modern physics. However, they never explain doing homework and studying for the examination contribute their understanding of quantization. Since homework questions are mainly mathematical, they explain that they tend to focus just to solve mathematics without interpreting the physical event. Although students explain doing homework is helpful for their understanding, I cannot observe a direct influence of doing homework on students' models.

In addition, students take two midterms and a final examination. Although the students explain that study for the exam much, most of them explain they do not ask questions to the instructor and the assistants before the exams. Students believe that studying for the exam contributes their understanding modern physics overall. However, students explain they mainly focus on problem solving when they study for the exams. Their explanations in the Self-Evaluation Interview and their robustness to change their models after the final exam show that studying for final exam does not influence students' mental models about the quantization of physical observables. As similar with homework, I do not interfere to the setting and do not ask quantization specific questions in the examinations and homework, I do not have direct evidences to talk about the details of the influences of doing homework and studying for the examinations to mental models. In conclusion, I cannot explain their influences on students' models.

Second issue about the instruction is "the attitude of the instructor". The attitude of the instructor towards the course and students is positive. And he is a motivated instructor, and he always tries to motivate students when they are unsuccessful (in the exams) or cannot answer the questions asked in the classes. For example, in a class that the instructor requests students to explain "space quantization". None of the students answers, and the instructor tells:

> **Instructor:** Pay attention! The most important thing for you as I understand that you do not understand what you read. So this shows you do not pay attention to what you listen and what you read! We can classify the reading into three parts. I do not mean just reading the book, I mean understanding an event, a text etc. First one is "reading with discussing". What is reading with discussing? Discussing what you read, what you see or what you listen. Discussing and making sense in your mind. Second one is "reading with obeying". It is taking information without discussing, just like dogmas. You do not ask the reasons, and you say "I believe it". This is the second one. And the third one is "reading with refusing". You read and then refuse. I understand that, your reading seems in the third category while you were reading the exam questions. You read the questions and refuse to understand. You do not try to understand. However, you must read with discussing! You should not read as second and third ones. Please discuss the meaning of the terms in your mind. You are physicists! You must do this.

Another example is about motivating the students who cannot answer the question asked in the classes. The instructor encourages students by saying:

> **Instructor:** Try, try, and succeed! Don't give up! Don't give up anything! Try, try, and try!

The feedback of the instructor is constructive. When a student cannot succeed to explain a physics concept, the instructor tells that:

> **Instructor:** Some of you try to explain, try to open folders in your minds, but cannot reach the files inside the folders exactly.

The instructor also states about meta-cognitive issues implicitly. He motivates students about being aware of themselves by saying:

> **Instructor:** Being aware of yourself, and evaluating yourself are one of the important things. You should evaluate yourself, and value yourself!

He also implies the importance of linking the concepts and transferring the knowledge into another context. After the announcement of the results of second exam, the instructor warns students about these issues by saying:

> **Instructor:** Dear students! You remember we solved a question in the class similar to the question in the exam. However, in the class we asked square of x, but we asked cube of x in the exam. In the exams, we do not just want see your knowledge. We would like to see your linking the concepts in different contexts and use them. You should learn linking the concepts. For example, in the exam, most of you told that there was no information about the atomic mass number of oxygen atom. But there was information about the atomic number of the oxygen. We want you that you should find atomic mass number by using the information about atomic number...

Again, after the exam, he motivates students by trying to understand the reasons of problems in their modern physics learning. He also gives feedback about students' exam performances.

> **Instructor:** Examine yourself! Maybe you are making a mistake somewhere. Maybe you do not listen carefully. Or, you are not studying the textbook, you don't fill in the gaps in previous lectures. Or, something wrong with your studying. It is not maybe a regularly studying. You just study one day before the exam. This makes students unsuccessful. I do not know... You should look into yourself. You must be careful! Another thing, you may be difficulty in

> understanding the questions. Mostly it happens. You don't solve different type of questions, or, you don't try to solve question by your own. If you don't understand, please come and ask. You do not ask much questions in the class. Then I think that you understand, and I expect successful exam result. But there is an unfortunate result. However, never give up! You must always be optimistic, not pessimistic. So you get succeed, you get still good grades if you explore where the mistake is. So you have another midterm, final, homework, quizzes. I give you many chances. You have to create your own chances. How you create your chances? "By studying". Is it OK?

He also gives importance to students' recognition of their mistakes in homework, and learning from the correct ones by checking their homework papers. Therefore, he commonly reminds students to check their papers. While the instructor provides extremely positive attitude and motivation toward the course and students taking the course, I cannot see its direct influence on students' model usage. However, this might contribute indirectly by facilitating students' attendance to the classes, their enjoyment in the classes and doing requirements of the course etc. as the attendance.

In conclusion of overall of these results about instruction and the elements related with instruction, I can state that the explanations in instruction and some elements related with instruction together (note taking, prior and after study + note taking+ attending the classes regularly) have influence on students' use of models. While taking notes by attending the classes and doing prior and after practices independent explanations in the classes facilitate the knowledge organization explicitly, omitting the existence of these activities and explaining what and how explained in the classes show the influence of elements on models implicitly.

4.2.1.c Topic order

Topic order is examined as another external source influencing students' mental models. I define it as the arrangement of modern physics concepts while teaching both in the textbook and the classes". In order to explain topic order, the transition from the theory of relativity to the quantum theory is examined both for the instruction and textbooks. In addition, students' explanations in the conceptual and Self-Evaluation interviews are interpreted together. One main consideration of topic order is the presentation of the quantum theory just after the theory of relativity chapters both in the textbooks and the classes. Although this issue is considered by the authors of the textbook and the instructor, students cannot recognize the discrepancy between these theories because of considering the continuity among the chapters.

In Textbook 1, the quantum theory starts with Chapter 2 after the theory of relativity (Chapter 1). However, the author explains that new chapter is also central for modern physics as the first chapter in the introduction part of the chapter. In Textbook 2, the quantum theory starts with Chapter 3, after the theory of relativity chapter (Chapter 2) again. As similar with Textbook 1, Textbook 2 says the "wave mechanics" is the second theory in modern physics in the first sentence of the introduction part of the chapter. In the instruction, sixth class starts with the introduction of the quantum theory, and the instructor stresses it by stating:

Instructor: This is a general introduction to waves that you already know even from freshman, from optics or from high school. The title of the chapter is particle properties of waves. Now we are advancing in history. Time was nineteen century, all belongs to nineteen century. Now we come to twentieth century which is extremely important for everybody. So this bring us to discussion of blackbody radiation… Quantum! Beginning of quantum physics.

However, in spite of the notifications of the textbooks and instructor, conceptual and Self-Evaluations interview reveal that some students have problems about discriminating these theories.

In the conceptual interviews, students were requested to state their reasons of explanations. In addition, at the end of the semester, students were asked "In the Modern Physics course, how often did you hear the terms 'quantization' and 'quantized'? In which topics have you heard them?" in the Self-Evaluation Interview. The results show that out of twenty-nine students, twenty-one of them explain they heard or see the quantization term in quantum physics topics that is after the theory of relativity chapter. However, two of them state they do not heard it in the classes; and four of them state they heard it in the theory of relativity chapter. Figure 4.22 presents the models of these two groups of students.

	CODE	GENDER	DEPT	context 1	context 2	context 3	context 4	context 5	context 6.a1	context 6.a2	context 6.b1	context 6.b2
in the relativity chapter	ST9	F	PHYS	AM	*NE*	AM	AM	*NE*	AM	AM	NM	AM
	ST11	M	PHYS	EM	*NE*	NM	NM	NA	NM	NM	NM	PSM
	ST21	M	PHYS	EM	*NE*	NM	AM	NA	*NE*	*NE*	*NE*	*NE*
	ST23	F	PHYS	NM	NM	*NE*	AM	NA	*NE*	NA	*NE*	*NE*
I have not heard it												
	ST24	F	PHED	NA	NM	AM	NA	NA	*NE*	NA	*NE*	NM
	ST26	M	PHED	*NE*	*NE*	NM	NM	NA	*NE*	NA	*NE*	NA

Figure 4.22 Models of students who have problems in discrimination of the concepts of the theory of relativity and the quantum theory.

Figure 4.22 indicates that the students who cannot discriminate these two theories mainly have unscientific models. The reasons of influencing use of mainly EM and AM might be the result of the inappropriate transfer of the codes (concepts) “Einstein Relativity” and “Change” that are considered in the theory of relativity, respectively. In contrast, among the thirteen students having SM, twelve of them are aware of the difference between the theory of relativity and the quantum theory. For example, the following two students having SM -St8 is a physics education student and St15 is a physics students- imply that they heard or see “quantization” term in the classes several times.

I : In the Modern Physics course, how often did you hear the terms ‘quantization’ and ‘quantized’? In which topics have you heard them?
St8 : Many times. It started with quantization of energy. Umm… It was already not in the relativity. It started after it. That means, I think in the atomic structure.

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I : Well, in the Modern Physics course, how often did you hear the terms ‘quantization’ and ‘quantized’? In which topics have you heard them?
St15: Several times, especially in the last topics.
I : Towards to end… All right.
St15: Yes, it does not exist in relativity… It is after relativity.
I : What is the reason you did not hear or see this term in the relativity?
St15: Umm… Actually, the beginning of the textbook and the beginning of the semester are so different from the last concepts we learned. They are different.

The following excerpts present the explanation of students who cannot discriminate these two theories. For example, St9 is also physics student and she displays the AM in all cases of the quantization of physical variables. She mentions this issue in both Overall and Self-Evaluation interviews. The excerpts from her interviews below:

I : Can you tell me the experiments showing us the quantization of energy?
St9 : Umm... In the relativity? *(by speaking aside).* Umm… How was it? Actually energy is not quantized, isn't it?
I : Why do you think so?
St9 : Umm...
I : Why are you not sure?
St9: I really do not know *(smiling)*!

... text exists here...

I : All right, in the Modern Physics course, how often did you hear the terms 'quantization' and 'quantized'? In which topics have you heard them?
St9: I heard that a few times.
I : Do you remember where they were?
St9: I remember I heard that at the beginning of the semester so much... Umm... Mostly I heard at the beginning...
I : Beginning!
St9: Yes… Mostly I heard in the relativity topics.

Next student is a physics student, and he displays the EM and AM. He states the reasons of his explanations like that:

I : All right, what was the reason of your explanation is like that? That means, let's say "quantized", did you see this term especially in the relativity topics?
St21: It comes to my mind like that... *(Waiting a minute)...* Yes, in the relativity. Probably in Chapter 2, there were mass, relativistic mass. They came to my mind. I remembered something like that about quantization, so I wrote like that *(in the test).*

For example, St23 is a physics student and she has the AM about the quantization of energy.

I : OK, in the Modern Physics course, how often did you hear the terms 'quantization' and 'quantized'? In which topics have you heard them?
St23: I have not heard it in the class… Maybe the instructor told but I missed it. I remember I told that velocity and other things were quantized in the previous interviews. Umm… May I show them by using the textbook?
I : Sure, these are the textbooks *(by presenting textbooks to student).*
St23: *(Student is scanning the textbook).* Umm… Relativity! Actually I am not sure but, it *(quantization)* is especially considered here. Because there are a lot of variables here. Especially "velocity". Because "time", "velocity" were here. This was the starting.

With these results, I can conclude that students' discrimination of these two theories has roles on the development of their mental models. While the discrimination of these two different theories facilitates SMs; not discriminating them seems causing inappropriate knowledge transfer, and facilitating the use of unscientific models. Therefore, topic order in modern physics course is an external source influencing students' mental models of quantization.

4.2.1.d Classmate

Social environment provides media to students develop mental models. One of these social environment is emerged with a peer, or a friend in educational setting. I call "classmate" as the friend(s) whom students interact with in and out of the classroom setting. Main consideration of this property is "long term" engagement with each other. That means, students whom I call as classmates have spent time together for at least three semesters, which is from the beginning of the first year in the department. In my data, there are three groups with this characteristic. While two of these groups are composed of two students from the same department (physics), the other group is a composite of three students, two of them are from the physics education department, and the last one is from the physics department.

In this section, I aim to examine whether there is an interaction between/among the students in each groups. As similar with the previous examination of the sources, I examine the influence of a classmate implicitly and explicitly. For example, after the identification of the models for each student, I compare the models of students in each pair. This is the implicit way of the examination. However, by asking students directly how they were interacted with their classmates, I also got some data about how students were influenced from each other. Then I decide classmate is a source influencing students' models or not.

By considering all participants of the study, students' explanations in the interviews provide an overall perspective about students' ideas about classmates while doing homework, or studying for the exam etc. In addition, many students state that they discuss on modern physics concepts with their classmates in and out of the classes. Students mainly express that they enjoy about the discussions, and by this way, they could make sense some physics concepts easily.

In this study, I examine each three groups as "classmate". While the first pair displays mainly scientific model, the second one displays unscientific model. Third group is partially different from them, since it displays almost scientific with the use of both PSM and SM. Figure 4.23 presents the models of students who are considered as classmates.

	CODE	GENDER	DEPT	context 1	context 2	context 3	context 4	context 5	context 6.	context 6.a2	context 6.b1	context 6.b2
First group	ST6	M	PHYS	NM	NM	SM	SM	NM	NM	NM	NM	NM
	ST15	F	PHYS	NM	NM	SM	SM	NM	SM	NM	NE	NM
Second group	ST29	F	PHYS	ShM	NE	ShM	ShM	NA	NE	NE	NE	NE
	ST30	F	PHYS	NE	NE	NM	NM	ShM	NM	NE	NM	NM
Third group	ST2	M	PHED	PSM	NM	PSM	SM	NM	NM	SM	NM	SM
	ST8	M	PHED	NM	NE	NM	NE	NM	SM	NM	NM	NM
	ST20	M	PHYS	NE	NE	PSM	NM	NA	NM	NE	NM	NM

Figure 4.23 Mental models of students who were considered as classmates.

First pair is composed of St6 and St15. Both of the students are physics students, and they are enthusiastic students to learn physics much. St6 is a male student and St15 is a female student. St6 is one of the students examined in the core group, and St15 is from the secondary group. These two students are always in interaction with each other, for example they do homework together, study for the exams together, sit in the classes together, and spend time out of the classes together.

In the examination of students' models, it is seen that both of them display SMs about the quantization of energy. It is interesting to see that their scientific explanations are in the same contexts- energy levels and particle in a box (Contexts 3 and 4). In addition, both of them do not use models for the quantization of light and angular momentum. Another common point of these students is that students have pure model states which are scientific. In other words, they do not use other models at the same time over the different contexts of same domain, so they have just use SM.

They also think that a classmate might have an influence on learning. St6 explains this issue in the interviews like that:

> **St6:** I mainly go to the classes with my best friend *(St15)*, we sit together, we discuss on physics, we do homework together. As similar, we are together in the laboratory sessions. It is because we have a good dialog with each other. We discuss on everything together, because people can only discuss with the people that they know well. If you know a person, you can know his/her mental structure, his/her way of thinking. In addition, if you know him/her for a long time, you can be sure about he/she was a reliable source when you

asked a question. I know her *(St15)* for two years. I hang with her *(St15)* at the beginning of the first semester of freshman. So I know how she thought and I trust on her knowledge. So, I can ask questions to her easily with no doubt. So, we can discuss with each other.

***

St6: We discuss physics concepts like that: For example, "If the situation occurs like that, what happens then? This one or this one?" We discuss on physics topics like that.

***

St6: Sometimes, while walking with my friends together, they might be a source for learning physics. For example, they may joke and then we try to understand the joke, and try to make physical explanations.

***

St6: Doing homework together *(with St15)* is always better than to do by myself. Because I am not an expert on physics, so sometimes I cannot recognize some important points of the concepts. If you get the idea of another person that you trust on, producing an idea is very pleasant feeling. I like it too much.

St15 uses almost same statements about the influence of the discussion with St6.

St15: Discussion with each other is very useful for me. Discussion on physics is better than to think about the concepts by myself. We *(St 15 and St6)* try to do homework together. We open the textbook and we discuss about for example what the physical explanation of the question was, which formula would be used for the questions etc. We discuss on all process.

Second pair is composed of two girls. They are also physics students. This pair is composed of St29 and St30. Both of the students are physics students. They are enthusiastic students to learn physics, but these students are too anxious students about learning physics. So, they are mainly unsure about their answers in the interviews. Both of the students are secondary group participants of this study. As similar with the first pair, these two students are always in interaction with each other. For example, they do homework together, study for the exams together, sit in the classes together, and spend time out of the classes together.

In the examination of the second pair's models, it is seen that both of them have the ShM about the quantization of energy and they do not have any model in the quantization of angular momentum. However, in contrast to first pair, these students use the ShM different from each other by using in the different contexts of energy quantization. These students have pure unscientific model state which are unscientific. More specifically, they only use the ShM over different contexts. They also do not use other unscientific models. Having pure model state is an interesting result common for both pairs.

St29 and St30 explain their discussion with each other about modern physics concepts. The following excerpts reflect students' ideas:

> **St30:** We *(with St29)* discuss on some topics. We have discussed especially on the concepts at the beginning too much. We discuss on homework questions and I learn too much by discussing together. I also learned in the classes but I understand by the discussion on the examples more, I learned more.
>
> ***
>
> **St29:** I studied with my best friend *(St30)*. You can understand better by discussions, then you can fill the blanks in your understanding easily.

Third group that is considered as the classmate is composed of St2, St8 and St20. St2 and St8 are physics education students, and St20 is a physics student. All of the members are males. The difference of this group from the previous ones is that these students are more independent from each other than other two groups. That means, these students spend time with each other mainly to discuss on modern physics topics. In this group, all of three students present a great success in the first mid-term. They are hardworking and calm students. St8 explain that he likes discussing on modern physics topics with his friends like that:

> **St8:** Yes, we discuss. There are many topics to be discussed. I like it.
> **I :** For whom do you discuss?
> **St8:** X *(St2)*… I discuss with Y *(St20).*

St2 presents mixed model state in the explanation of the quantization phenomenon. Similar characteristic with the previous pairs is displaying pure model state of other group members. That means, St20 has the PSM in Context 3 as similar with St2, and St8 has the SM in Context 6.a as similar with St2. This also might be an evidence for the influence of St2 on St8 and St20 separately.

To summarize, for the pairs called as "classmate", it can be interpreted that the students who are in interaction mainly with their pairs have pure model states no matter the models are scientific or unscientific. When the groups are in more complex nature including more than two students, one of the students might also be a source for other two students having pure model states again. In conclusion, I conclude that classmate has influence on students' mental models, especially on model states of students.

4.2.1.e Extra sources for learning

In addition to the environments emerging in the boundary of the course, students may interact with other sources that are not determined by the course. I call this type of sources as extra sources that are determined by the preference of students. By the examination of students' interviews, I identify basically two extra sources such as "internet" and "other books" that students use for learning modern physics concepts. Figure 4.24 presents the frequency of use of extra sources together with the textbooks.

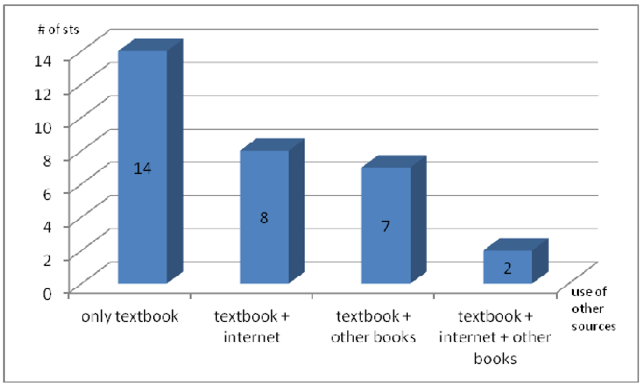


Figure 4.24 Students' use of other sources for learning.

Although extra sources are not basic sources like "textbooks", results show that seventeen of thirty-one students use extra sources such as internet and other books to understand modern physics concepts more. In the examination of models of students who use extra sources, fifteen of them display models. However, in the examination of students' answers to the question "What are the most effective sources that shape your understanding of the quantization phenomenon?", none of the students states that the extra sources are the only sources for their understand quantization. In addition, in the examination of students' answers in the conceptual questions, I do not have direct evidences about students' use of the information from extra sources such as different notification, pattern of explanation, etc. Based on students' answers in the Self-Evaluation and explanations in conceptual interviews, my data do not give me explicit or implicit evidences indicating the direct influences of extra sources on students' mental models.

4.2.2 Internal Sources Influencing Students' Mental Models

As similar with external sources, internal sources might have roles in development of students' mental models. In contrast to external sources, internal sources are "student dependent" sources. In other words, students have a power to control their learning by manipulating these internal sources. In this section, I mainly focus on four basic internal sources. First three of them were emerged from previous literature examining students' physics learning by influence of them. They are meta-cognition, motivation, and beliefs that are meta-cognitive, affective and cognitive elements, respectively. The last one (familiarity and background about the concepts) was emerged from the data and it is specific for a modern physics course case.

Because of the nature of my research, in this part I do not examine meta-cognition motivation, and belief, by using questionnaires and inferential statistics. However, by examining students' explanations, I make some inferences about the sources and I try to understand the influence of these sources on mental models by qualitative claims.

4.2.2.a Meta-cognition

Meta-cognition is examined as an internal source. In this section, I examine students' meta-cognitive ideas in three parts: (1) awareness about cognitive process and knowledge, (2) satisfaction about knowledge, and (3) regulation of cognition. While doing this, I focus on students' explanations of the questions in the Self-Evaluation interview "When you consider your learning, did you ask questions such as 'What am I doing? How do I learn? Why do I learn?' to yourself? Do you have any idea about your knowledge (what you know and do not know) and your cognitive process? Do you have some strategies about how you obtain the knowledge better? Do you believe you understand the quantization of some physical observables?". By this way, students provide explicit evidences about their meta-cognitive states.

About the first issue "awareness", Figure 4.25 summarizes students' meta-cognitive evaluations about themselves.

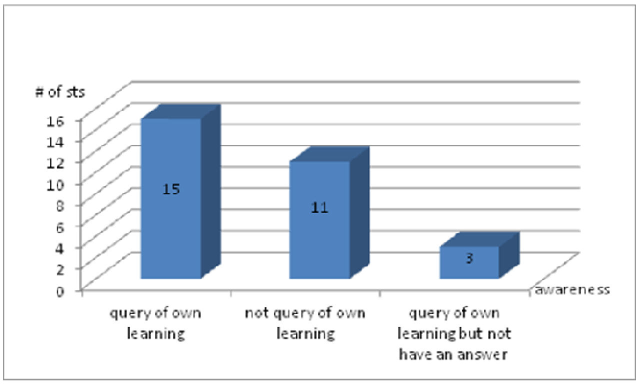


Figure 4.25 Students' meta-cognitive evaluations about themselves.

As it is seen in Figure 4.25, almost half of the students ask some meta-cognitive questions to themselves about their learning. Moreover, others are not aware of their learning. The examination of students' awareness and their models show that the percentage of displayed models by students who are aware of their learning is 27.1%. This ratio for the students, who do not inquiry themselves, is a bit low (21.2%). Two of the students, who never display a model, state they are aware of their learning, and last two explain they are not. For example, St16 is a student who does not use any model in her explanations. She explains her reasons of why she does not query her learning.

St16: No… I did not ask to myself… *(Smiling)*. Actually, I told myself "I should learn them", and then I learned.

Another example is from St24. She is a student who uses an unscientific model (AM) in one context, and she mainly does not answer the questions.

St24: No, I never queried myself *(smiling)*. I mainly do not think that why I took the courses. I never think why they would be useful for me or not.

In contrast to St16 and St24, another example belongs to St17 who is aware of his knowledge. He has the PSM for the quantization of light and angular momentum. He expresses how he queries himself like that:

> **St17:** Yes, I query myself too much.
> **I :** Do you examine what you know and do not know?
> **St17:** Sure. I always think about it. While I am studying physics, everything seems to me so meaningless.
> **I :** Then, do you give up querying yourself?
> **St17:** *(Smiling).* Physics is so exciting, and it captures me and I feel good while learning.

Although I observed that the students who are aware of themselves present more organized knowledge structures than others, this information does not provide extra information about the use of specific models.

At first, we can talk about the “awareness of knowledge” is important for the organization of scientific elements. However, in addition to querying themselves to be aware of their knowledge, we see that “satisfaction” about this knowledge is also important. Among eighteen students who inquiry their learning, eight of them are satisfied about their knowledge. By comparison with the percentage of the model usage of related with the awareness of knowledge, the percentage of model usage of students who are both aware and satisfied about their knowledge is 30.6%. That means there is an increase in the percentage of displayed models. When their models are examined, these students display only three type of models such as the the SM, PSM and ShM, and almost half (54.5%) of them are SMs. The increase in model usage indicates that satisfaction of knowledge facilitates knowledge organization. In addition, increase in the use of the SMs indicates iterative relation between satisfaction and scientific knowledge. That means, when students are satisfied, they construct scientific knowledge; when they scientifically organize their knowledge, they satisfy about their knowledge.

One of the examples from the students who are both aware and satisfied about their learning belongs St6. He states that he understands the quantization of physical observables.

> **St6:** Umm… I think that I understand it. I can explain it but I am not sure about whether I can solve the problems about it or not. But, I made sense it. We saw "quantization" in the classes, in the textbook too much. Its physical meaning is logical to me.

The students, who are aware but not satisfied about their knowledge display mainly unscientific models. For example, St21, having EM and AM, also is not satisfied about his understanding. He explains it by stating his displeasure while making explanations like that:

> **St21:** I could not give good answers to your questions. I guess I have a problem with my learning, or I forget what I learned.

The excerpt below belongs to the student who has the ShM. This also indicates her dissatisfaction about her knowledge.

> **St30:** I think my understanding is not enough because, I understand the concrete concepts better. However, it is so abstract, and I cannot visualize quantization in my mind much.

The last excerpt is from St9, who uses the AM robustly over the context. Although she makes robust explanations, she is still unsure about her knowledge. Dissatisfaction about understanding the quantization of physical observables is seen in her explanations.

> **St9:** I am not sure but I feel that I cannot construct the concepts. I do not feel I understand it well. Maybe, I am guilty because I did not study too much.

The final issue about meta-cognition is "regulation" that can be defined as the "strategies to regulate own cognitive process". Individuals could control their cognitive activities to reach a goal by regulation of cognition. After students' awareness and satisfaction about the knowledge of the quantization of physical observables, their self-regulative behaviors were examined. The results show that out of eight students who are aware and satisfied of their learning, six of them stated that they have some methodologies for learning. That means, these six students have self regulative behaviors. Figure 4.26 presents the models of these students over the contexts.

CODE	GENDER	DEPT	context 1	context 2	context 3	context 4	context 5	context 6.a1	context 6.a2	context 6.b1	context 6.b2
ST2	M	PHED	PSM	NM	PSM	SM	NM	NM	SM	NM	SM
ST3	M	PHYS	PSM	PSM	NM	SM	NM	SM	SM	NM	NM
ST6	M	PHYS	NM	NM	SM	SM	NM	NM	NM	NM	NM
ST7	F	PHYS	PSM	NM	PSM	SM	NM	SM	NM	SM	NM
ST29	F	PHYS	ShM	*NE*	ShM	ShM	NA	*NE*	*NE*	*NE*	*NE*
ST31	M	PHYS	NM	*NE*	SM	NM	NM	NM	NM	NM	NM

Figure 4.26 Models of students who are aware, satisfied and regulated their learning.

The percentage of displayed models increases for these students (aware + satisfied+ regulated their learning). When knowledge organizations over the contexts are examined for these students, the percentage of model usage is 38.9%. By comparison with the percentages of model usage of the students who are only aware of their knowledge and the students who are aware and satisfied about their knowledge, there is a great increase in students' model usage in this group. Figure 4.26 presents the distribution of the models of students presenting three meta-cognitive behaviors together.

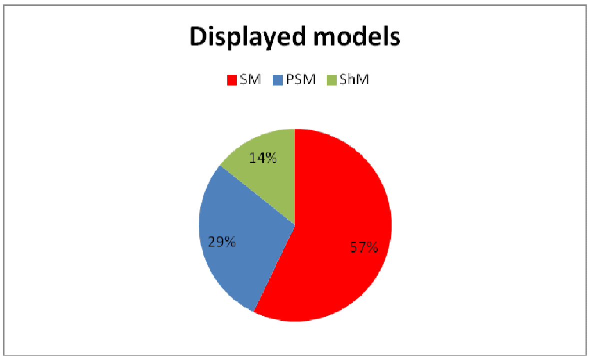


Figure 4.27 Distribution of the models of students who are aware, satisfied and regulated their learning.

As Figure 4.27 presents, the use of SM among other models increases from 54.5% (for aware and satisfied) to 57% (for aware + satisfied+ regulated). In addition, when the total instances (use of any kind of knowledge structures) are considered for each group, students' use of SMs increases from 16.6% (for aware and satisfied) to 22.2% (for aware + satisfied+ regulated). The following excerpts are from the students having three basic meta-cognitive behaviors. St2 explains his strategies like that:

> **St2:** I got it. Actually I know I had a style to study. In the first exam, I studied modern physics topics every day. I increased to study step by step until the exam date. I studied whole day in the library just before the exam day. I can say that if I have enough time to study, I feel relax. I really give importance to "understand" concepts. Just 1-2 hours practices in everyday are very helpful. It also gives pleasure. For this reason I study regularly by taking pleasure. That means, for this course, I study like that.

As it is mentioned before, St7 is a student who tries to understand the nature of the concepts, and spends too much time for this issue. She also states that she is exactly aware of her knowledge, cognitive process etc. She has the PSM and SM about the quantization phenomenon. She explains her meta-cognitive control with these words:

> **St7:** I have a characteristic valid for my daily life. I must learn the "reasons" of a something. I must understand it well. If I cannot understand the reasons well, I cannot go forward. Then I cannot construct the other concepts. I cannot learn the whole of the topic… I must imagine it. I wonder the reasons of events too much. However, sometimes I think the opposite such as "scientists constructed the knowledge for long years. I cannot learn the reasons of everything in a short time, it is not easy, and my expectation about learning the reasons of everything is wrong. It is wrong to try to understand everything". Then, I try to understand how the scientists thought about as possible. It seems so interesting to me. I wonder "how" they thought, explained and then I learn.

As a final statement about meta-cognition, in the interview with the instructor, he indicates the importance of meta-cognitive issues with these words:

> **Instructor:** At the beginning of the semesters, I always advice to my students about learning modern physics: "You should learn to learn".

In conclusion, we see some evidences about awareness, satisfaction and regulation elements of meta-cognition are important for students' mental models. While being aware of learning increasing the percentage of model usage, satisfaction with awareness both increase the percentage of model usage and the use of SM. Most of the students, who are aware and satisfied about their knowledge used SM. In addition, variety in students' models decreases. Finally, the use of all models and the use of SM among models are increased with awareness+ satisfaction + regulation of learning. As a final statement, these findings indicate us the importance of meta-cognitive issues on students' knowledge organization.

4.2.2.b Motivation

Motivation is examined as an another internal source influencing students' models. Motivation might direct students learning quantization in or out of classroom environment and it might provide a wish for them to understand the concepts. For this reason, motivation is considered as a probable affective internal source influencing the development of students' models. In this section, I consider two of motivational elements such as "interest" and "utility".

While students answered the questions about motivation, they also gave explanations indicating their motivation in the conceptual interviews. All these explanations were examined to determine motivation is a source influencing students' mental models or not. Figure 4.28 shows students' feelings about being in the modern physics classes.

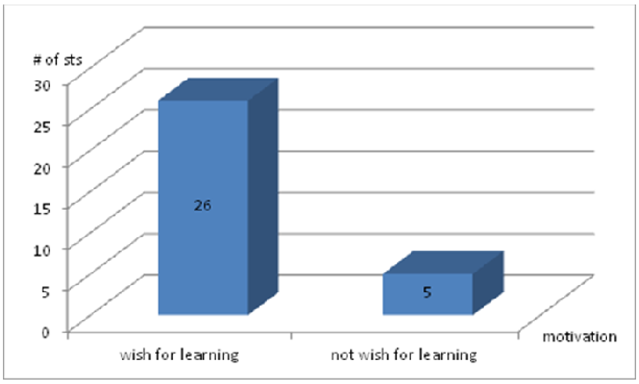


Figure 4.28 Students' feelings about being in the modern physics classes.

Twenty-six of thirty-one participants state that they like modern physics because they have wish for learning modern physics for different reasons. These students explain that they feel that they learn physics when they are in the modern physics classes. For this reason, they state that they feel good and they wish to learn modern physics more. However, four students state that being in modern physics is just as a procedure to be completed for graduation. One student also states she does not want to come to the classes. She explains that she feels too much anxiety when she is in the modern physics classes. This student explains her reasons about anxiety like that:

> **St14:** It makes me anxious, because I have a prejudice about learning quantum concepts. So, I do not want to come to the classes.

In the student's explanations, we see that prejudice about learning quantum physics creates anxiety, then the anxiety might influence students' motivation to learn modern physics. In the examination of students' physical explanations in the contexts, this student never displays a model. In other words, her knowledge about the quantization of physical observables is not organized, and it is mainly composed of not physical explanations (NEs).

I examined the reasons of these twenty-six of thirty-one students having wish of learning about modern physics. Their reasons vary due to their "interest" and "future needs". Some of the students state that really feel enjoyment while learning physics. However, some of them state that they learn modern physics by considering the future.

Interest. Interest provides some information about students' intrinsic motivation, because motivation is provided with the enjoyment in the activities. Among twenty-six students, seventeen give explanations about their interest of learning modern physics. The students who are motivated to learn explain that they enjoy while learning modern physics. The following excerpts from students' explanations indicate their interest for modern physics learning:

> **St2:** I really feel that I learn modern physics not to get good grades, I just want to learn because I enjoy. The topics are so interesting and the instructor explains them very well. I really enjoy while learning that means I come to the classes not for attendance requirement.

***

> **St5:** It *(learning modern physics)* is not an obligation, it is just an "curiosity". Every physics student or everyone who likes physics wonders, and then want to learn.

***

St7: The concepts of modern physics are very interesting. I like modern physics too much. I also like the instructor's teaching methodology, then I enjoy. That's all.

***

St10: I learn a lot of new concepts in modern physics course. We *(students)* learn the concepts that only physicists learned. This is important for me because I will be a physicist. These concepts are also important for other physics major courses. So, I take pleasure to learn it.

***

St18: Modern physics includes so many concepts. While I am attending the classes, this issue is always in my mind. I am very enthusiastic to learn modern physics. It is also more conceptual and less mathematical. While I am coming to the classes, I think about it. I like it.

Utility. Utility can be considered as an external motivation element since students who are motivated to learn just consider their future profits. Nine students provide explanations stating wish of modern physics learning for future. The following excerpts shows students' utility values:

St13: I want to learn modern physics, but not to get good grades affect my wish of learning negatively. Getting good grade from the courses is important for applications master's program of physics.

***

St20: If I continue to learn physics in the master program after my graduation, this knowledge will be useful for me. Because, in order to learn advance physics, you should construct the base for it first.

These two students, who are physics students, mention about the usefulness of knowing modern physics is important for master's program. Next excerpts belong to the physics education students:

St16: It is a new perspective. It makes me more knowledgeable as a physics teacher candidate.

***

St22: I really come to the classes by my wish. I believe it enhance my physics knowledge too much. I will be a physics teacher and this is important for my personal development.

These two students, who are physics education students, mention about its usefulness for their subject matter knowledge in the future.

In the examination of students' models in terms of interest and utility, I cannot observe a pattern about each element influencing models. However, when I examine the models of students who have wish for learning modern physics (twenty-six), and not wish for physics learning (5 students), the latter group provides limited number of models. Figure 4.29 presents the tendency of model usage and the models displayed by these students.

CODE	*GENDER*	*DEPT*	*context 1*	*context 2*	*context 3*	*context 4*	*context 5*	*context 6.a1*	*context 6.a2*	*context 6.b1*	*context 6.b2*
ST11	M	PHYS	EM	*NE*	NM	NM	NA	NM	NM	NM	PSM
ST14	F	PHYS	NM	*NE*	NM	*NE*	*NE*	*NE*	*NE*	*NE*	*NE*
ST17	M	PHYS	PSM	NM	NM	NM	*NE*	NM	*NE*	*NE*	PSM
ST19	M	PHYS	NM	NE	PSM	NM	NA	NM	NM	NM	*NE*
ST31	M	PHYS	NM	*NE*	SM	NM	NM	NM	NM	NM	NM

Figure 4.29 Models of the students who are unmotivated.

When displayed models of these students are examined, the patterns seem so strange because the use of models is considerably low. The percentage of model usage is just 13.3%. That means, the students who are not motivated to learn modern physics resist to organize their knowledge, and they mainly use disconnected elements by scattering. In conclusion, I cannot discriminate the influence of interest and utility elements on students' models; however, motivation for learning is observed a source influencing students' models.

4.2.2.c Beliefs

While quantum physics causing important discussions conflicting with the previous physics explanations, it is also a probable discussion topic among physics and physics education students. Since the ideas of quantum physics are too new for students, most of them need to state their beliefs about quantum physics while explaining the concepts of quantum physics. That means, students' explanations indicating their beliefs were emerged in the interviews naturally without asking a specific question. By this way, I implicitly identified two types of beliefs influencing students' models in their explanations about "quantization" in this study. These are (1) beliefs about nature of science, and (2) beliefs about nature of quantum physics concepts.

Nature of science. Students' beliefs about nature of science are important for their learning. If these students are physics and physics education students, their beliefs about nature of quantum physics gain more importance. Nature of science includes students' beliefs about scientific knowledge, scientific methods, and nature of theories, facts or formulas.

When I examine students' beliefs of nature of science, I observe that several types of different explanations indicate students' perspective towards to science. Because of classifying them as correct or not, positive or negative etc. is meaningless, I do not examine students' mental models varying due to their beliefs. However, I examine the beliefs of two groups of students (1) the students who use models (mainly scientific models) in the contexts, and (2) the students who use limited number of models. In addition, I got some explicit evidences about students' beliefs emerging from their direct explanations. More specifically, students explain that they accept or not an idea related with quantization.

In the first group, St18 is a student who presents only SMs. He uses the SM four times in the contexts. He indicates the difficulty of believing, accepting and understanding quantum physics. Moreover, he explains that he spends extra effort.

> **St18:** Perspective of quantum physics is different from the classical physics. Therefore, our *(students')* perspective was different until meeting with quantum physics. It is the result of why we have difficulty in understanding the concepts. There are very different explanations in quantum physics that we have never seen before anywhere. I still think that our perspective is in the effect of classical physics. We approach to the classical physics by thinking it classically. We try to explain by using classical physics. Actually, quantum physics is so abstract. It is so far from the daily life so it is difficult to understand. Therefore, you cannot accept its ideas easily… Making sense of it is difficult… It is difficult to believe it. Its perspective crosses with my perspective and I need more time, and more effort to understand…

St10, who uses the SM three times and uses the PSM one time, give some evidences about how his models are influenced from firstly the nature of science, and then what the instructor explained.

> **St10:** Actually, we cannot produce new things in quantum physics. We just need to understand what the instructor explained. It is difficult to produce new information.

These beliefs indicate "why" individuals organize their knowledge. Although students' beliefs about quantum physics are similar to each other, these beliefs influence their knowledge organization processes differently. For example, in the first one, St18 stresses that because of the difficulty of acceptance of the ideas of quantum physics and he explains he spends more effort to make sense. However, the second one gives explanations showing the "acceptance" of what authority told us. That means, this student organizes his knowledge, by accepting the explanations of authority in contrast to first one.

In the second group of students, who use limited number of models, I examine the beliefs of a student having SM (St8) and two students having unscientific models. St8 is a physics education student, who uses the SM in one context and explains mainly by fragments in other contexts. He indicates his difficulty in imaging.

> **St8:** I still cannot visualize anything in my mind.
> **I :** What do you want to expect? Is something like a real picture?
> **St8:** I do not know… Maybe I am wrong, but I still think it is just a theory. A theory that examines everything by dividing into small particles. It also includes classical physics. Maybe another theory may understand this theory well. However, I believe this *(quantum)* is a theory, which can be falsified.

St19 is the student having radical ideas about science. He uses the PSM just one time, and makes explanations mainly with fragments. As it is seen in his explanations, the student's beliefs have great importance for his learning of physics.

> **St19:** Although passing from classical physics to quantum physics, I still believe that there are many missing explanations. None of the ideas is settled down. There are always "assumptions, exceptions" etc. I also believe that "uncertainty" will be solved in the next years… As physicists, we cannot determine its position and momentum at the same time. I believe someone will do that later…
>
> ***
>
> **St19:** I think, science is oversimplification of the world into the books. It is so arrogant. It is not needed. Therefore, although I am a physics student, I do not want to be a physicist. I dislike the idea "I will know everything". I think this is the reason.

St27, who uses the ShM in two instances, explains why she cannot be sure about her explanations.

> **St27:** Why am I not sure? Because, there is not only one explanation for the physical situations in quantum physics. Different explanations may exist. It is abstract and provides different explanations to us.
>
> ***
>
> **St27:** I believe there is not only one true explanation. If we are in quantum physics, I am sure that there is not one true explanation, there are some others.

The common influence of these different beliefs is the students' resistance towards knowledge organization. These students inquiry the nature of quantum physics and they do not accept its explanations. So, without accepting the ideas, they might resist to understand and integrate the information into their knowledge systems.

In addition to the implicit links examined between students' beliefs and models, I also got some other implicit evidences about students' models and beliefs. Following two examples present how students' explanations in the conceptual interviews are influenced from their beliefs.

St17, who uses the PSM in two times, indicates "discreteness" in his explanations. This student's explanations in the conceptual interviews reveals that why he gives explanations stressing discreteness.

> **St17:** I believe there is no infinite smallness… It should be discrete. *(Smiling)*. I do not believe infinite smallness, so everything should be discrete…
>
> ***
>
> **St17:** I do not believe infinite smallness…There is just undiscovered explanations, not infinite smallness… It is not perception; it is the nature of quantum physics… Discreteness is absolutely nature of atomic systems.

St11, uses the EM and PSM in two contexts; however, he mainly explains with fragments (NMs). In the explanation of the quantization of energy and angular momentum, he uses the "discreteness" fragment. However, he states this idea seems absurd to him.

St11: Actually, this discreteness, these jumps for Bohr or other systems are so absurd to me. Quantum is always absurd. This is my opinion.

In conclusion, beliefs about nature of science might have implicit role on students' mental models.

Nature of quantum physics concepts. Quantum physics is abstract and counter intuitive by comparison with the classical physics. Therefore, learning of quantum concepts might be influenced both from the nature of quantum physics concepts, and students' beliefs about nature of quantum physics concepts. This part examines the beliefs about the structure (abstractness, counter-intuitiveness, mathematical formalism etc.) of quantum concepts. As similar with the previous part (beliefs of nature of science), in this part I examine the beliefs of two groups of students. Because students present more different beliefs together, I do not classify their beliefs. In the first group, I examine the beliefs of students' who use limited number of models or not use models.

For example, St1 is a student, who uses two unscientific models to explain the quantization of energy. She also has some conceptual problems about quantum concepts. Her beliefs about the quantum concepts are:

St1: When I understand the concepts, I can solve the problems easily. However, in the quantum physics part, I have difficulty to understand the concepts. The concepts are so abstract and it is difficult to make sense of them.

St14, is a student, who does not use models in none of the contexts. Although she is a physics student, she does not want to be a physicist after graduation. Her beliefs about quantum concepts are like that:

St14: I think I do not like quantum physics. At the first, I felt that I do not want to be a physicist while everybody was impressed from quantum physics. It is not appropriate to my way of understanding. It is so abstract. I do not know too much thing about the quantum. Do I study? Not much.

St28, who uses the IM, stresses its mathematical nature as it is considered in IM.

St28: It is so mathematical. Many complex mathematical expressions exist. Each of them has an important meaning.

St24 is also a physics education student and she uses the AM in one context. Although she uses some fragments, she mainly does not answer the questions in the interviews. She explains her reasons like that:

> **St24:** Modern physics is so abstract to me. In modern physics, we generally solve questions without knowing the meaning of events. I want to explain conceptually, but I think that I cannot explain the concepts that you asked. It is difficult to understand quantum ideas conceptually.

In the second group, St6 is a student, who uses the SM in the explanation of quantization of energy. He believes his understanding is affected from the nature of quantum concepts. He explains his beliefs like that:

> **St6:** I feel that I learned the concepts at the beginning of the quantum chapter well. Because there were not too much mathematics. However, in the middle, we engage in mathematics too much. I think mathematics must be just a way to learn.

With these evidences about relation between students' models and beliefs, I conclude that beliefs about nature of quantum physics concepts might have influence on students' models no matter the models are scientific or not. But, I observe students who mainly display unscientific models state that they are influenced by the abstract, counter-intuitive and mathematical nature of quantum concepts.

In conclusion of the examination of students' beliefs about nature of science and nature of quantum concepts, "belief" is specified as a source influencing students' models.

4.2.2.d Familiarity of the concepts

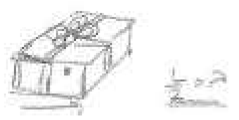
Familiarity with something may provide a great contribution to understand another thing. In this section the influence of being familiar with some concepts from classical mechanics is examined under the title of familiarity of concepts. Since "quantization" caused a paradigm shift in physics, new concepts were emerged together with it. In the examination of students' models, familiarity was the potential element influencing students' make sense of the concepts, linking the concepts, and constructing a conceptual framework (mental model). In order to examine the influence of familiarity of the concepts/contexts to students' mental models, there was not a specific question in the interviews that students answered. However, students' explanations in the conceptual interviews provide some implicit evidences about the influence of familiarity on students' mental models.

One of the unfamiliar concepts for students is the "space quantization". The interviews show that two students consider "aerospace" in the space quantization instead of considering the quantization of direction of angular momentum. In other words, I observe "language degeneracy" that is the students' use of same terminology with different meanings (Hrepic, 2002) by the unfamiliarity of some concepts. St30 does not have a mental model in the quantization of angular momentum context (Context 6.b2); however, she tries to give some explanations about space quantization like that:

St30: I know the quantum numbers "n" and "l" from the last topic. I am not sure but I remember that they *(quantum numbers)* were quantized in the aerospace. That is space quantization.

Another example is about "particle in a box" that is examined in Context 4. One of the interesting explanations of a student, who does not have any model in the particle in a box context, is like that:

I : What do you understand about the "particle in a box" term in physics?
St5: Umm… When I see particle in a box, I imagine something like that *(drawing the following figure)*:



I : Is it something like a gift box? *(Smiling)*
St5: For me, this is "Particle in a box".
I : What does the ribbon on the box mean?
St5: *(Smiling).*
I : What do you mean by this?
St5: I don't know. But whenever I heard "particle in a box", that comes to my mind.
I : Why? What is the meaning of it in physics? Do we have such type of boxes in physics? Is it a physical box?
St5: I think there was not such a box in physics, and then someone gave it to physics this box as a gift *(smiling).*
I : Does it mean someone gave it to examine?
St5: Yes. What is hidden in a gift box is always wondered. So, we wonder that what this particle was. This is the particle in a box.

The other unfamiliar concept is “Spin”. St8, who does not use any model in the quantization of angular momentum, shows the strangeness of “spin” concept for him like that:

I : About this issue, have you heard “electron spin” concept before?
St8: Spin? Not yet. Could you remind me?
I : Maybe you remember “spin” word from Formula 1 races!
St8: Is it “tumbling down over the car”?

Harmonic oscillator (Context 5) is another unfamiliar concept for students. As similar with the previous examples, one of the students, who does not have any model about harmonic oscillator context, states the strangeness of harmonic oscillator. He explains it also by showing the strangeness of particle in a box like that:

I : Have you heard “harmonic oscillator” concept before?
St31: Yes, I have heard it.
I : What do you understand from it? Could you explain by considering for atomic systems?
St31: I think that it is a closed box something like particle in a box.

Contexts 2, 5 and 6.b are the problematic contexts that students display limited number of models.

“Blackbody” term is also new for students. In Context 2, two types of models (PSM and ShM) are observed. The most important thing is not the type of models but the construction of models since only three students use models in this context. Moreover, none of the models is SM. In addition to not to construct coherent knowledge structures, students mainly give irrelevant answers (NEs).

In Context 5, I observe only one model (ShM). None of the students uses the SM to explain the quantization of energy. In addition to the unfamiliarity of the harmonic oscillator, students’ background about it might be the reason of limiting the type and number of displayed models in this context.

Last unfamiliar concept is the quantum atom (Context 6.b). In the examination of students’ models, we see that number and diversity of models are larger in the Bohr atom sub-contexts than the quantum atom sub-contexts. More important one is the number of SM is larger in the Bohr atom sub-contexts than the quantum atom sub-contexts. Therefore, as similar with the previously discussed concepts, we see that students' unfamiliarity to this concept may have influence of students' mental models. Since the Bohr atom is taught in high schools, students are a bit familiar with it. This success on having SMs can be explained by familiarity. St9, who has the AM about the quantization of angular momentum in this context, explains the quantum atom model like that:

St9: If we think about the atom in three dimension, there are some ledges of the atom. These ledges change over time. And the locations of the ledge changes.
I : What are these ledges? What do they mean?
St9: I don't know...

Since the student is unfamiliar with the quantum atom, she interprets the electron probability density as the "ledges of the atom" in the picture of atom, which is obtained by a computer program due to the different states of electrons. Following figure shows students' use of models over the contexts. Figure 4.30 examines the contribution of each context on students' mental models.

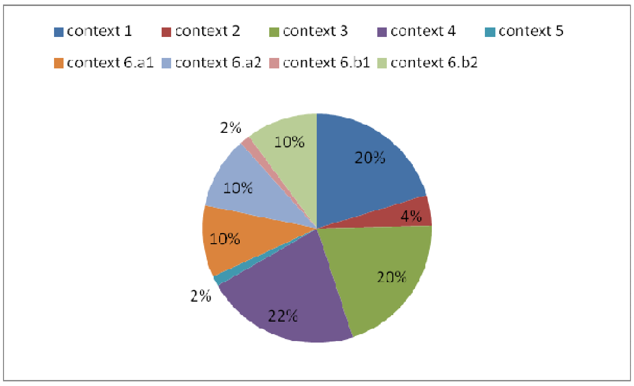


Figure 4.30 Distribution of displayed models over the contexts.

As Figure 4.30 displays, Context 2, Context 5 and Context 6.b1 contribute only with 4%, 2% and 2% to the use of models. That means, the use of models in these contexts is considerably few. To conclude, being familiar with the concepts has important roles in making sense and linking of the concepts. That means, students firstly need to know the concepts well, and then they link them correctly to construct a coherent framework. The contexts and concepts in the contexts that students are not familiar might prevent the development of students' mental models in related contexts. Therefore, familiarity can be explained as an internal source that influencing students' mental models.

4.2.2.e Background knowledge

In order to have scientific models about the quantization of physical observables, background knowledge has an important role for the connection of concepts with each other. This issue is considered separately from the familiarity of the concepts. Because the familiarity of the concepts indicates new concepts emerged from quantum physics, background shows students' understanding the common concepts of both classical and quantum physics such as energy, angular momentum etc.

In order to examine the influence of background knowledge on models, there was no specific question in the interviews. However, students' explanations in the conceptual interviews provide some implicit evidences about the influence of having background knowledge about the concepts (either classical or quantum) to make sense of the quantization of physical observables.

Having the minimum concepts is important for students develop mental models. Because of the lack or weak background about the concepts, students have problems about linking them to construct coherent structures. For example, in the quantum atom context by excluding St7, none of the students uses models to explain the quantization of energy. This might be the result of insufficient background about the quantum atom. As I explained before, St7 can be accepted as an extreme student, who would like to understand every word mentioned in the course. Therefore, she also has satisfied background about the freshman physics. So, while this student uses a model, the other do not.

One of the students (St18), who has pure scientific model state about quantization, explains the importance of background knowledge about concepts like that:

St18: While I am learning a new subject, if I heard about it a little, in spite of very little fragments, it is very beneficial for my learning. This is because these fragments locate into our minds with some blanks and we fill these blanks in the classes. All these blanks are filled in the class. It is very enjoyable to see that. I feel I understand. Therefore, I like to listen what the instructor explain, to understand the concepts in the class too much.

In addition, in contrast the extremely limited number of model usage for the quantization of energy in the quantum atom context, other results show that students' models are mainly constructed about the energy quantization case. By comparison with energy, angular momentum and light cases, this might be because of students having more background about energy from classical physics rather than angular momentum and light. In the interview with the instructor, he also makes the similar explanations about the importance of background knowledge.

Instructor: I would like to state the importance of making the abstract concepts "concrete" before teaching the advance concepts about it. I believe it is so useful. For example, understanding the precession of angular momentum in the space is a bit hard. If it is explained before the explanation of the quantization of angular momentum by a demo setup, it will help students' understandings.

With this implicit examination, I conclude that background is an internal element contributing students' mental models.

To summarize, as it is understood from the findings, different sources have influence on students' models. As a very brief summary of the sources influencing students' mental models, in the interview, the instructor explains some sources on students' understanding from his perspective like that:

Instructor: At the beginning of the semesters, I always advice to my students about learning modern physics: "You should learn to learn". Because learning is not an isolated process. It includes a lot of things. "Learning" and "forgetting" are neck to neck. Mainly, the reason of unsuccessfulness of a student is not "not to learn", it is "not to remember what is learned". What does "learning" include? First one, students should use "senses". It requires attending the classes regularly. They should see what is written on the board, should hear what is explained, should ask questions to the instructor. This is first requirement. Second, learning requires "practice". It is not "memorizing" but practicing what is learned in the classes in the evening. 5-10 minutes are enough for this. Practice! I always advice it. Review and repeat what you have learned! You should examine your textbooks. You should read the textbooks and write your missing to your notebooks. I always advice that it enhanced learning. Third, students should not write everything what the instructor wrote, they should select and note shortly. These contribute to learn. We can mention about other things about learning. For example, students should use extra books to learn in addition to the textbooks. They should link the concepts learned in past and present. I would like to say previous learning has great contribution to students' new learning. All of them are environmental

> factors. These are the factors enhancing learning. If students care about these issues, they will affect successfulness positively. For this reason, there is not "one" factor influencing learning. I think, all of the combination of these factors influences students' success and scientific approach.

In conclusion, I examined some probable sources influencing students mental models. By using implicit or explicit evidences, or sometimes implicit and explicit evidences together, I identified the sources influencing students' mental models qualitatively. Therefore,

- Textbook;
  - Explanations in textbook,
  - Bringing textbook into the classes,
  - The use of textbook (Textbook 1, Textbook 2 or both of them).
- Instructional Elements;
  - Explanations in instruction,
  - Taking notes as same as with the instructor,
  - Studying before and after the classes + taking notes in the classes + attending the classes regularly.
- Topic order;
- Classmate

are the external sources influencing students' mental models.

- Meta-cognitive issues;
  - Awareness of knowledge,
  - Awareness + satisfaction of knowledge,
  - Awareness + satisfaction + regulation of learning.
- Motivation;
- Belief;
  - Nature of science,
  - Nature of quantum physics concepts.
- Familiarity of the concepts,
- Background knowledge

are the internal sources influencing students' mental models.

4.3 The Development of Models by Influence of the Sources

"Incompleteness" characteristic of mental models indicates that models can develop in time. In addition, we also know that models may be forgotten if they are not used or for some reasons models can be totally revised. In this part, development of students' mental models of quantization by the influence of external and internal elements is examined with the question:

- How do the second-year physics and physics education students' mental models of the quantization of physical observables develop by the influence of internal and external sources?

As Figure 3.4 presents, I use all data sources (i.e. interviews with students and the instructor, observation, textbooks, diary and other documents) in order to find answers to this question. This section is composed of the execution and reinterpretation of findings in Sections 4.1 and 4.2. After the identification of mental models in Section 4.1, and the sources (external and internal) influencing students' mental models in Section 4.2, the development of mental models is discussed in this section. As similar with the analysis of textbooks and observation provide implicit interpretation, the analysis of the core group interviews (Interviews I, II, and III, Overall Interview and Final Comprehensive Interview) also let me interpret the development of models implicitly. However, examination of the Self-Evaluation Interview provides explicit information about model development. In addition, comparison of the evidences also allowed validation of findings.

I examine "model development" in two ways. First, I explain how a student's model develops with the influence of some sources that were examined in the previous section. Then, I consider "all kind of change" as development of mental models and examine model development with time order, within the cases of quantization, and student by student.

4.3.1 Development of Mental Models Displayed in This Study

In Section 4.2, textbook, some instructional elements, classmate, topic order are specified as the external sources, and meta-cognition, motivation, belief, familiarity and background of the concepts are specified as the internal sources influencing students' mental models. In this part, I firstly examine how these sources have roles in students' model development. Then, I discuss the influences of them on each model.

4.3.1.a Development of a coherent structure

In this part, by using the information obtained from all sources in the data analysis, I constructed a framework shown in Figure 4.31. I preferred to use a rectangular prism to show the relation among the sources, contexts, students, and students' models. The reason of mine to display in a rectangular prism is the interaction of some sources (explanations in instruction, explanations in textbook, familiarity of the concepts, topic order, background knowledge) with the contexts, and some of them (bringing textbook into the classes, use of textbooks, taking notes as same as with the instructor, studying before and after the classes + note taking in the classes + attending classes regularly, classmate, meta-cognitive issues, motivation, belief) with students' characteristics. For this reason, some of the boxes in the surface of the prism are empty. By using this prism, with the information on "students" versus "context" plane (Plane 1), students' models can be obtained; with the information on "students" versus "sources" plane (Plane 2), students' characteristics specific for modern physics course can be obtained; and with the information in "context" versus "sources" plane (Plane 3), characteristics of the contexts can be obtained. So, only the surfaces of rectangular prism provide information. That means, inside of a unit cube (by a unit context, student and source) is meaningless. While interpreting the prism, combination of the elements in Planes 2 and 3 should be interpreted as the specific sources influencing the development of students' mental models of quantization in specific contexts.

T: Explanations in Textbook; T+: Contributes -- **UT**: Use of Textbook; T1: Use of one of the textbook, T1+2: Use of both of the textbooks -- **BT**: Bringing of Textbook to the classes; BT+: Bring, BT-: Not to bring -- **I**: Explanations in instruction; I+: Contributes-- **NT**: Note taking in the classes; NT+: Take notes, NT-: Not to take notes -- **4el**: Studying before and after the classes + note taking in the classes + attending the classes regularly; 4+: Exists, -: Does not exist -- **TO** : Topic order; TO+: Contributes -- **C**: Classmate; C+: Exists, -: Does not exist -- **M-C**: Meta-cognitive elements; ASR: Awareness+ satisfaction+ regulation, A: Awareness, -: None -- **MOT**: Motivation; M+: Contributes -- **BEL**: Belief; Bnos: Nature of science beliefs, Bnqc: Beliefs of nature of quantum concepts, B2: Nature of science beliefs + beliefs of nature of quantum concepts -- **FAM** : Familiarity of the concepts; F: Familiar, uF: Unfamiliar -- **BG**: Background knowledge; Ben: Background about energy needed, Bang: Background about angular momentum needed.

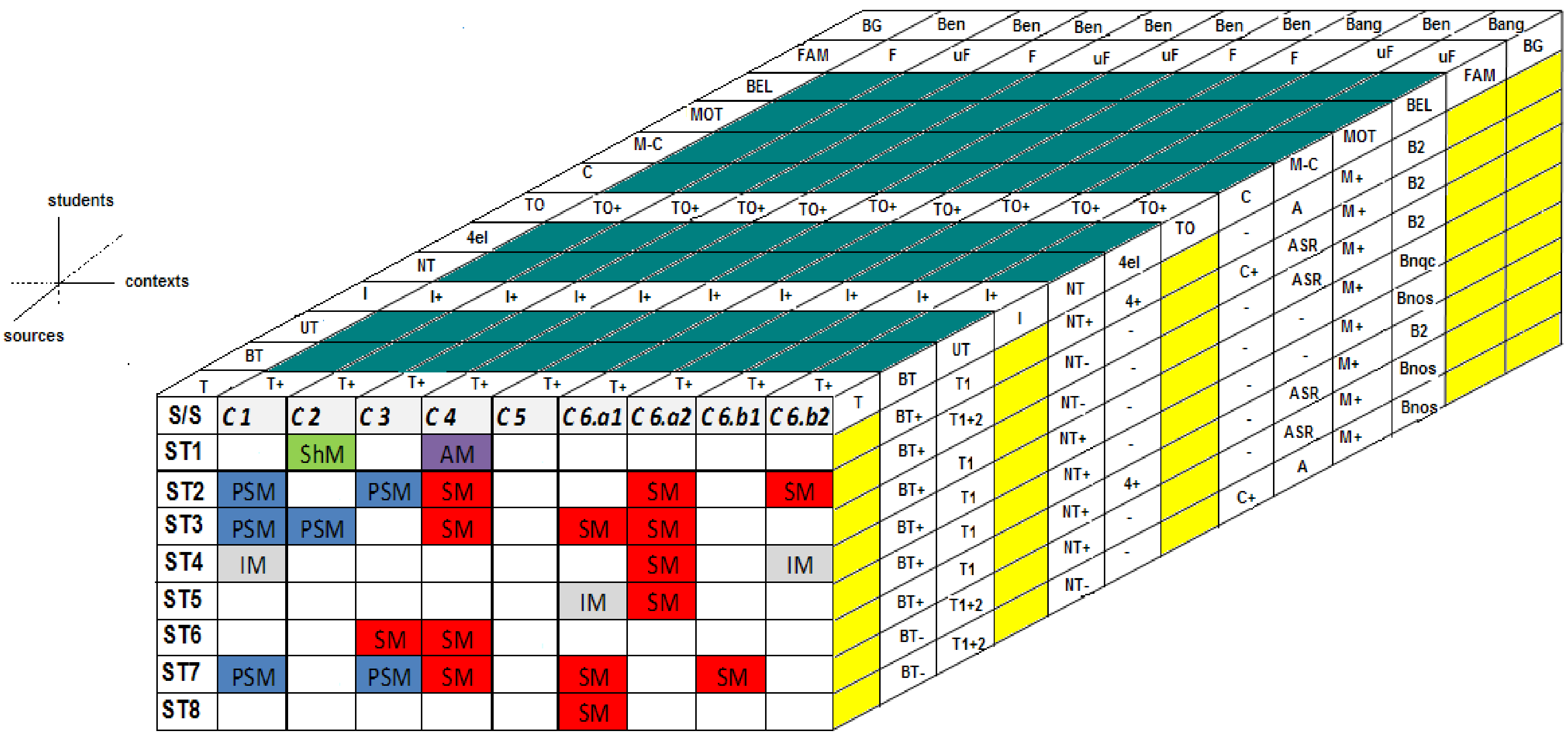


Figure 4.31 A framework for the influence of sources on students' model development.

There might be other student specific characteristics for develop and use of models; however, the following interpretations are based on only the sources examined in the current study. For the following paragraphs, I explain how a source has an influence on students' models by using the information in the prism. I first examine Plane 2, and then Plane 3, and I interpret them together to explain development of models presented in Plane 1.

When the sources influencing models are examined, first I focus on St2, St3 and St7 because these students develop more models than the others. The pattern for these three students is a bit interesting since the PSM and SM are close models; however, the PSM, including unscientific element, is unscientific. These students first develop the PSM and then SM. By the examination of Plane 2, the most dominant sources are identified as "motivation" and "meta-cognitive awareness + satisfaction + regulation". In addition, "bringing textbook", "use of both textbooks", "not to take notes", and "beliefs of nature of science" are seen probable sources for the development of more models. In addition, by the examination of Plane 3 it is seen that most of these models are in the familiar contexts. So, this shows the importance of familiarity in the construction of the links among the concepts. Although Context 4 is not a familiar context, development of the SM by three students in this context might be explained with the explanations in the textbooks, instruction and students' background of energy concepts.

I examine the sources for using of limited number of models. For this reason, I focus on the information provided from St5, who uses both SM and IM two times. There are some discriminating elements using limited number of models from the use of more models. "Not become aware of knowledge" is the most explicit one. In addition, "taking notes" and "using only one textbook" might be other elements influencing students' use of limited number of models. With this interpretation, use of both textbooks and not to take note in the classes may become more probable in the use of more models. In conclusion, with these patterns I can conclude that "meta-cognitive awareness + satisfaction + regulation" is very important for the use of more models.

4.3.1.b Development of each coherent structure

In this section, I explain the influence of each source in the development of each model. Again by using Figure 4.31, I use the same technique with the previous section.

To start with SM, the characteristics coming from students' themselves and specific for modern physics course such as "motivation", "meta-cognitive awareness + satisfaction + regulation", "bringing textbook into the classes", "classmates" and "beliefs of nature of science" are seen as the sources influencing development of SMs (in Plane 2). With the examination of Plane 3, "background" is seen as a source having influence on development of SMs. In addition, "explanations in textbook" and "explanations in instruction" have influence on each context; however, it is seen that most of SMs are seen in the contexts that students are "familiar" and "having background". For example, half of the students display the SM in Context 4 that students are unfamiliar but they need background about energy concept. Or, Context 6.a2 is the Bohr atom context that students are familiar but they need background of angular momentum. Again, half of the students present SMs. In conclusion, one of these elements might have more dominant influence together with other elements (i.e. explanations in the textbook). In the "atom" context (Context 6), familiarity and background are needed for the development of SM.

PSM is an unscientific model including two scientific elements. With the examination of Plane 2, "motivation" and "meta-cognitive awareness + satisfaction + regulation" are identified as the main sources for this model, and "use of both textbooks", "not to take notes", and "beliefs of of both nature of science and nature of quantum concepts" are seen probable sources. The examination of this model contains some elements specific for SMs. So, removing some elements by comparing with St6, the sources for the PSM might be explained better. "Using both textbook", "not taking notes", and "beliefs of both nature of science and nature of quantum concepts" gain importance when eliminating probable influence of the SM (purely used two times). When the examination of the roles of the characteristics arising from the contexts (Plane 3), although the textbooks and instruction are basic elements, background is needed to explain the number of use of PSM; familiarity is needed to explain the development of this model. For example, these students develop the PSM in the contexts that they have background more (Contexts 1, 2 and 3)

IM is another unscientific model. By using the information in Plane 2, “use of only one textbook”, “note taking”, “not to be meta-cognitively aware of knowledge”, “motivation”, and “bringing textbooks to the classes” are seen as the sources for the development of this model. In the examination of Plane 3, I cannot explain more about the influence of “familiarity” and “background”; however, they can be considered as probable sources.

ShM and AM are the unscientific models that are used by only one student, so influence of the sources arising from other students are too limited to find a pattern. So the sources such as “bringing textbook”, “using one of the textbooks”, “note taking”, “studying before and after the classes + note taking in the classes + attending to classes regularly”, “meta- cognitive awareness”, “motivation” and “beliefs of both nature of science and quantum concepts” might be probable sources for the development of these models. In addition, both of the models are developed in the contexts that students are not “familiar”. In addition, while “explanations in textbook” and “explanations in instruction” are common for these models, the ShM needed “familiarity” in the second context.

For the last model EM, that I explain in Section 4.1.6, I cannot explain about model development by student specific characteristics. This model is the only model that is not observed in the core group students. In addition, that model is only developed in Context 1. I can conclude that context specific sources might be more dominant than student specific sources on the development of this model.

These findings indicate the importance of the “meta-cognitive awareness + satisfaction + regulation” together to develop SMs, and develop more models over the contexts. In addition, not develop any model in Context 5 indicates the influence of “familiarity” more than explanations in the textbooks and instruction. Because, in spite of the stress of quantization, explicit explanations, using diverse type and amount of codes, being unfamiliar for the quantum harmonic oscillator is dominant by preventing students’ model development in this context.

4.3.2 Reconsideration of Model Development as Change

By considering the development as a change, I examine the development of a mental model first "context by context" with the time order. Then, I examine the development "case by case (over physical observables)" for the quantization of light, energy and angular momentum separately. Finally, I examine the model development of students.

4.3.2.a Context by context examination

In order to see the change of models in time, I examine the development context by context. In Chapter 3, Figure 3.9 showed the time order for the interviews to examine students' models. For the core group, which is set to examine development of models, models were examined in the interviews I, II and III in detail. In the Overall and Final Comprehensive Interviews what students stated were discussed again, and they were allowed to change/revise the previous explanations (if need). Figure 4.32 shows that variation of models over the contexts.

CODE	*GEND.*	*DEPT.*	*context 1*	*context 2*	*context 3*	*context 4*	*context 5*	*context 6.a1*	*context 6.a2*	*context 6.b1*	*context 6.b2*
ST1	F	PHED		ShM		AM					
ST2	M	PHED	PSM		PSM	SM			SM		SM
ST3	M	PHYS	PSM	PSM		SM		SM	SM		
ST4	M	PHYS	IM						SM		IM
ST5	M	PHED						IM	SM		
ST6	M	PHYS			SM	SM					
ST7	F	PHYS	PSM		PSM	SM		SM		SM	
ST8	M	PHED						SM			

Figure 4.32 Development of the core group students' models over the contexts.

In the first time period (Interview I), which is examination of the quantization of light and energy in Contexts 1 and 2, three types of unscientific models are used. These are the PSM, IM and ShM. Although Context 1 is the most diverse context among the other contexts in terms of models by considering the core and secondary group students, only the PSM and IM are observed in the core group in this context. In this time period, development of the PSM as a mental model can be accepted as better starting than the others since it includes two important scientific elements and it is the closest model to SM. By considering the core and secondary group, Context 2 is very poor in terms of used models. Just the PSM and ShM are used for the quantization of energy. Two students also use these models in the first period. One of the reasons of using limited number of models might be explained by the problems in the conceptual understanding of the blackbody radiation.

In the second time period (Interview II), which is examination of the quantization of energy and angular momentum in Contexts 3, 4, 5 and 6 (sub 6.a1 and 6.a2), students display four types of mental models. However, the dominant model is the SM in the overall. It was good to see students' development of the SM for the quantization of energy. As similar, in Context 4 half of the core group students (4 students) use SM. One of the reasons may emerge from the explanations in the textbooks or instruction showing the requirements of the quantization of physical observables. In Context 5, the result is very interesting, because none of the models are used. The reason may be students' conceptual difficulty in harmonic oscillator in order to apply their models to explain phenomenon. Another interesting result is in the atom context (Bohr part). Half of the students in the core group make scientific explanations about the quantization of angular momentum by using the SM again. This indicates the influence of familiarity with the concepts since students are familiar with the Bohr atom model from high schools, so they can construct scientific models easier. However, quantum harmonic oscillator is new for them, so they might not develop a model in this context because of unfamiliarity.

In the third time period (Interview III), which is examination of the quantization of energy and angular momentum, only three students use models. One of them use the SM for the quantization of energy and, other two use the SM and IM to explain quantization of angular momentum. For the third time period, it is expected that more students having SM about quantization. However, there is again a decrease in the use of SM. This also shows students' conceptual difficulties about quantum mechanical model of atom and related concepts. Because in the second time period, although students have the SM about the quantization of energy and angular momentum in the Bohr atom contexts (Contexts 6.a1 and 6.a2), they do not continue to use the SM in the quantum mechanical model of atom contexts (Contexts 6.b1 and 6.b2) in this time period. One of the reasons may be that the quantization of angular momentum is explained just as quantization of orbital angular momentum in the Bohr model of atom. However, some other concepts about the angular momentum exist in the quantum model of atom. These are the quantization of direction and magnitude of both orbital angular momentum and intrinsic angular momentum (spin). They might cause students having confusion. In addition, students are again unfamiliar with the quantum atom. In addition they might have limited background about angular momentum. This might be in action on students' model development in the third time period.

In the fourth (Overall Interview) and fifth (Final Comprehensive Interview) time periods, which are the reviews of the quantization of light, energy and angular momentum over the contexts, students are stick to their previous explanations. Maybe the time period between these interviews is short, or lack of experiences or other student specific situations, students might not reorganized their knowledge. So there are not radical changes in students answers.

In addition to identified models presented in the contexts, students also interpret the development of their understanding of the quantization phenomenon at the end of the semester. Although the students believe that they feel development of the quantization phenomenon over the semester, they think that studying for the final examination do not change their understanding at the end of the semester. This finding corresponds with students' not revising their explanations in the fourth and fifth time periods (just before and after the final examination).

Each of the students in the core group explains own reasons. First excerpt belongs to students shows the beliefs about the contribution of studying for the final examination to understanding the quantization phenomenon. So the question of the interviewer was "Did studying for the final exam contribute to your understanding of this phenomenon?". The second excerpt of the students shows the student' beliefs about the development of understanding of the quantization phenomenon over the semester. So the questions were "What can you say about the conceptual development of these concepts when you first heard about it? Do you feel a development in your understanding about these concepts? Do you believe you understand the quantization of some physical observables?".

St1: I do not think that I understand the quantization well after the final examination.

St1: At first *(at the beginning of the semester)*, I did not understand quantization. Umm... When I saw “quantization”, I just thought about some figures something like spin, etc. But now, I think I had some ideas of quantization.

***

St2: I just practiced the “spin” issue after the final examination. I had known but, I practiced much by means of final examination.

St2: While quantization was explaining first, you see “Planck constant” was important to show quantization. It shows quantization of energy. I just thought like that “yes, energy is quantized”, but I never thought that I could see quantization in the atom. Then we saw quantization of angular momentum. Then I understand that it is really important. Finally, I generalized it as a phenomenon for “atom”.

***

St3: Still spin *(smiling)*! I still did not understand the spin! I understand angular momentum but I try to understand spin, but still I could not.

St3: When I heard “quantization” first, I thought that we would discuss about “probability”, but we did not. We learned $E=h\nu$, and I thought that “this is quantization”. Then we discussed too many issues about it. I think I understand it.

***

St4: For quantization? No... It *(studying to final exam)* did not change anything. I mainly focused on problem solving for final exam.

St4: I feel the development. I always wondered “what is quantum mechanics”, because a lot of students were talking about quantum mechanics. But now, I know what quantum mechanics was. I learned it conceptually. I learned quantization much.

***

St5: No. I think I still did not understand “quantization” while I was studying for final exam. It is the same with how I understand at the beginning.

St5: How much I read and whatever I do, I don’t understand quantization. I just remember the word “quantization”. I cannot make sense it *(smiling)*.

***

St6: Not too much change. Maybe some contribution to angular momentum part.

St6: I heard quantum physics too much and I always thought that it was something like “particle physics”. Then we introduced with quantum physics in modern physics. We learned quantization was starting of it. We learned energy in atom was discrete, there are restrictions. Then we learned angular momentum is quantized and I understood that quantum physics was different than the classical physics. Since there are restrictions in quantum physics, you cannot do everything in quantum physics as you did in classical physics. I understand “quantization” well with these restrictions. When I understand quantization, I made sense all other concepts. I can say that I understand quantization and other quantum concepts.

***

St7: I can say that it helped a bit.

St7: Absolutely I feel development. At first, it *(quantization)* was so abstract. It was so different than the other concepts. I could not understand. But then, after I studied and I became more familiar with it, I understand. I see too much development in my understanding. It was settled in my mind exactly.

***

St8: I learned the meaning of ml, l and ms by studying with final exam.

St8: Maybe I heard "quantization" term before the course, but I understand it well in the classes during the semester.

Explanations of secondary group students are also reviewed in the Final Comprehensive Interview. They were also asked to evaluate themselves about the development of the phenomenon and contribution of studying for the final examination in understanding the quantization. Some excerpts from the secondary group students are presented below. Students explain why they do not change their ideas in the review interview after the final examination.

St22: Umm… I do not want to revise what I explained before. Since I think that there won't expect some conceptual questions in the exam, I did not study on quantization much while studying the exam. I mainly study on the mathematical problems, I solved sample problems. So my ideas about quantization did not change…

***

St29: Actually, we do not give importance to understand the concepts in the textbook while studying the exams. We just underline the statements, and pass to the next topic. So there is no change in my understanding of quantization after the final examination. All we have talked are same.

As similar with the core group, secondary group students focus to problem solving to be successful in the exams. So they resist to reorganize their knowledge.

4.3.2.b Case by case examination

Figure 4.33 shows the change of students' models in the different cases of the quantization phenomenon.

CODE	GEND.	DEPT.	LIGHT	ENERGY		ANGULAR MOMENTUM	
ST1	F	PHED		ShM	AM		
ST2	M	PHED	PSM	PSM	SM	SM	
ST3	M	PHYS	PSM	PSM	SM	SM	
ST4	M	PHYS	IM			SM	IM
ST5	M	PHED		IM		SM	
ST6	M	PHYS		SM			
ST7	F	PHYS	PSM	PSM	SM		
ST8	M	PHED		SM			

Figure 4.33 Change of students' models in the different cases the quantization phenomenon.

In addition to context dependency, the models vary due to the smaller parts of the same phenomenon as it is seen in Figure 4.33. For example, although St2 and St3 use the PSM for the quantization of light, they use the PSM and SM together for the quantization of energy and also they only use the SM for the quantization of angular momentum. Or, St6 and St8 only display the SM for the quantization of energy, but they use none of the models for light and angular momentum. In this energy case, the reason of students' having more models might be explained with the large number of contexts in the examination of energy. As similar, St5 uses an unscientific model (IM) for the quantization of energy but the SM for the quantization of angular momentum independent of time.

It is seen that students' models vary case by case in addition to variation context by context (see Figure 4.15). As it is seen in Figure 4.16, St4 is a good example for the fluctuation of students' ideas. For example, in the atom context, to explain quantization of angular momentum, student uses the SM in the Bohr atom. However, again in atom context- in the quantum atom- this student uses the IM for angular momentum. This shows the fluctuation of his models in the atom context.

All of these examples show that mental models are smaller coherent and working structures to explain the phenomena. With removing the time order in the contexts, this figure represents students' development of different models at the same time for the cases (light, energy and angular momentum) of quantization.

4.3.2.c Student by student examination

In this part, I examine the development of models about the quantization phenomenon student by student by combination with cases and contexts.

St1, in the core group, is a physics education student. In the first time period, she presents the ShM about the quantization of energy. At first, her ideas about the quantization of energy are based on discreteness of the energy like the slices of a cake. In the second time period, she uses different model for the quantization of energy in the particle in a box context. And she does not use any model in the third time period. For her, it is observed that she holds two unscientific model together for the energy case. But she does not develop any model for the quantization of light and angular momentum cases.

St2, St3, and St7 show almost similar development patterns about their mental models of the quantization of physical observables. St2 is a physics education student, and St3 and St7 are physics students. One of the common characteristics of them is "enthusiasm about learning physics". All of the students state the importance of learning physics conceptually in the interviews.

St2, St3 and St7 develop the PSM model in the first time period. At the beginning, students do not consider "boundeness" of the particle for the quantization of physical observables. But all of them correctly apply the discreteness/discreteness characteristics and natural characteristics elements. So, students' development of the PSM is important to reach the SM at the end, since it is the closest model to SM. For these students, it can be considered as case by case development. Students develop the PSM to explain the quantization of light, then they hold the PSM and SM together in the explanation of energy. Excluding St7, others have the SM for the quantization of angular momentum at the end. That might be considered as "upgrading" over the cases.

St4 is a physics student. His first model is the IM for the quantization of light in the first time period. He uses the SM in the Bohr atom context to explain the quantization of angular momentum. However, he uses the IM again in the quantum atom context to explain the quantization of angular momentum in the third time period. The use of different models almost similar contexts is interesting. In the case by case examination of students' models, it is seen that he has the IM for the quantization of light, and the IM and SM for the quantization of angular momentum. The interesting one is he is the only student in the core who does not develop any model for the quantization of energy.

St5 is a physics education student. In the case by case examination, he has the IM for the quantization of energy, and the SM for the quantization of angular momentum. In the first time period, he does not develop any model and in the second time period, he uses models only for the Bohr atom context for the quantization of energy and angular momentum. This result is also interesting since he uses different models to explain the quantization of energy and angular momentum in the parts of the Bohr atom context. Then he does not use any model in the third time period discussing the energy and angular momentum in the quantum atom (see Figure 4.32). This result is also interesting, since he does not transfer his models from the Bohr atom to to quantum atom. These examples also indicate that the context dependency of mental models and the importance of use of more than one contexts in the examination of mental models.

St6 and St8 present similar development patterns. In the first time period, both of them do not develop a model to explain quantization. However, in the second time period, they use the SM to explain the quantization of energy, and finally they do not use any model in the third time period. Although they use the SM for the quantization of energy, each of them use it in different context. This result indicates also importance of the elements of different contexts to activate mental models. In the examination of students' mental models case by case, both students have only a model for the quantization of energy, but not for light and angular momentum. Having a pure model state with the SM for the quantization of energy is good and important for students' understanding the whole of the phenomenon.

CHAPTER 5

CONCLUSION, DISCUSSION, AND IMPLICATIONS

5.1 Conclusion and Discussion

This study was designed to investigate undergraduate (second-year) physics and physics education students' mental models about the quantization of light, energy and angular momentum. As the results of the study were presented in three parts in Chapter 4, in this chapter the results are discussed in three parts by comparison with previous research in the literature, and conclusions are drawn for each part. Then, the implications and other issues for further research are explained at the end of the chapter.

In Section 5.1.1, conclusion and discussion of models and the characteristics of models are presented. This section puts new information to the literature by explaining the models displayed by students for the quantization phenomenon, and discussing context dependency of mental models in some contexts of quantum physics. In Section 5.1.2, conclusion and discussion of the external and internal sources influencing models and their influences on models are presented. This section puts new information to the literature by integration of these theoretical elements into research design and examining qualitatively. In Section 5.1.3, development of models by influence of the sources is presented. This section also puts new explanations drawn from the reinterpretation of the sources in model development. In addition, it explains the conclusions about model development by time order, light- energy- angular momentum cases, and student by student.

The implications, limitations of the study and controlling the threats, strengths of the study, and the suggestions for further research are presented in Sections 5.2, 5.3, 5.4, and 5.5, respectively. In the interpretation of the results, these issues should be considered.

5.1.1 Conclusion and Discussion of Models and the Characteristics of Models

In this section, conclusions are drawn about students' mental models and model characteristics due to the results of the analysis of the data sources presented in Figure 4.1. The conclusions and discussions are organized by considering direct and explicit information emerging from the study.

Conclusion 1: Second-year physics and physics education students display six different mental models about the quantization of physical observables. These are: Scientific Model (SM), Primitive Scientific Model (PSM), Shredding Model (ShM), Alternating Model (AM), Integrative Model (IM), and Evolution Model (EM).

"Quantization" is an important phenomenon allows passing from classical physics to quantum physics. It is the "precious result" of different experiments caused "paradigm shift" in physics. Therefore, the investigation of students' mental models about the quantization of physical observables (Sections between 4.1.1-4.1.6) shows that how students construct and organize their knowledge about the quantum theory. For example, SM indicates the coherent structure that contains scientific elements and links, which are scientifically constructed. The other models (PSM, ShM, AM, IM, and EM) indicate also coherent structures, but they include scientific and unscientific concepts together, or totally unscientific concepts, and with wrong and missing connections. Therefore, out of SM, other identified mental models are unscientific models to explain quantization of physical observables. As Norman (1983) explained, mental models may be unscientific. Because in order to save mental energy, superstitious behavior patterns can be hold by people. In addition, as Itza-Ortiz et al. (2004) implied in their study, unscientific models of students are not considered as "errors", but they are students' "own internal consistencies".

Conclusion 2: Identification of unscientific mental models show that students have difficulty with quantum concepts.

This study with large number of students over large number of contexts and concepts show (Sections between 4.1.2- 4.1.6) that students have (1) difficulty in making sense of the quantum concepts, (2) difficulty in discrimination of the concepts, (3) difficulty in linking the concepts, and (4) difficulty in putting the physical meaning into mathematical explanations. This result is compatible with the previous research (Bao, 1999; Didiş et al., 2010; Ireson, 2000; Ke et al., 2005; Müller & Wiesner, 1999, 2002; Olsen, 2002; Özcan et al., 2009; Sadaghiani, 2005; Singh, 2001; Styer, 1996; Wattanakasiwich, 2005), because many studies identified such type of problems in students' understanding quantum concepts. One of the reasons might be the nature of quantum concepts (abstractness, counter-intuitiveness and mathematical). The other reason might be students' epistemological and ontological beliefs about the quantum theory. For example, students stick to classical interpretations if a quantum variable had a classical counterpart; if the quantum concepts were not similar with classical concepts, students did not build physical understanding of the mathematics (Bao, 1999). In this study, it is observed that students consider quantum physics as a total contrast of classical physics. Therefore, while making explanations they use such a pattern like "if … in classical physics, it must be … in quantum physics".

Conclusion 3: Students' mental models about the quantization of physical observables are context dependent.

Investigation of knowledge structures is a complex action. So in this study, students' explanations about physics concepts over the contexts were examined (Section 4.1.8.b). As Table 4.4 presents, a change in the use of models is observed. That means, students use different models in different contexts of the same phenomenon, and models vary due to the contexts. Sabella (1999) explained that students' answers to questions might be varied due to contexts. By the use of many contexts in this study, it is identified that students' mental models about the quantization of physical observables are context dependent as Bao (1999), Bao and Redish (2006), Hrepic (2002, 2004), Hrepic et al. (2010), Itza- Ortiz et al. (2004), and Wittmann et al. (2003) identified the context dependency of mental models. Context dependency of mental models is meaningful since mental models are the minimum coherent structures to explain phenomena. Therefore, if a scientific model is constructed and improved, and then used "robustly" over the contexts, then "scientific understanding" might be more probable in learning. However, if an unscientific model is constructed and used "robustly" over the contexts by wrong organizations, then unscientific conceptions might be more probable learning. And, if they are not modified, students might have unscientific understanding about the phenomena. It is not expected as the outcome of physics learning, because physics education aims to have students building the proper mental models for doing physics (Redish, 1994).

Conclusion 4: Students use limited number of models over the contexts.

As it was summarized Figure 4.12 (Section 4.1.9), students use models in only 69 of 279 instances to explain the quantization phenomenon. The ratio of using models over contexts was almost 25%. This ratio may explain students' difficulty in developing models about the quantization of physical observables, because mental models are coherent structures, and they require the organization of knowledge to have a single conceptual framework. Although the students use the SM to explain the quantization of physical observables twenty-nine times in total, it is also limited by considering 279 instances for thirty-one participants. The ratio explains us students' use of the SM over the contexts is almost 10% of all students. The smallness of the ratio of using the SM also indicates that students' understanding of the quantization of the physical observables is limited.

Conclusion 5: Students hold scientific and unscientific fragments together in order to develop mental models.

Students' explanations reveal that they hold scientific and unscientific fragments together, and these elements are linked with each other (Sections between 4.1.1- 4.1.6) to develop mental models. This finding supports Norman's (1983, p.8) finding that is "individuals' mental models might contain contradictory, erroneous and unnecessary concepts". By this way, students develop hybrid unscientific models in addition to pure scientific/unscientific models in this study. SM is a pure scientific model, and the IM and EM are pure unscientific models. However, the PSM, ShM, and AM are hybrid unscientific mental models that students hold about the quantization of physical observables, because hybrid models contain scientific and unscientific elements together. By this way, with the coherent combination (Bao, 1999; Hrepic, 2002, 2004; Hrepic et al. 2010; Itza-Ortiz et al., 2004) of these elements, a "new coherent structure"- mental model- is developed which is called as hybrid model. Hrepic et al. (2010) explained hybrid models were complex models. Since construction of a hybrid model requires the use and organization of the elements from different domains (in this study, scientific and unscientific domains) to construct knowledge.

In this study, I interpret the reason of hybrid unscientific models by the explicit stress of "discreteness or/and discreteness characteristic"; and, implicit expression of "boundedness" in the textbooks and instruction for the construction of the PSM and ShM. This is because, in these models students do not use boundedness for quantization appropriately. As a result, students incorporate "discreteness" with inappropriately use of "boundedness" to develop these hybrid unscientific models.

> **Conclusion 6:** Students may hold more mental models together. In other words, some students have mixed model states by holding different mental models about the phenomenon at the same time. They use their models inconsistently.

This result is compatible with Gentner's (2002) study explaining that people can hold two or more "inconsistent" mental models together in the same domain (Section 4.1.8.b). As Bao (1999), Bao and Redish (2006), Hrepic (2002, 2004), and Hrepic et al. (2010), Itza- Ortiz and Rebello (2002), and Itza- Ortiz et al. (2004) found that students had mixed model states about some physics phenomena, some of the undergraduate second year physics and physics education students have mixed model states about the quantization phenomenon in this study. That means, students use different models in different contexts by holding different models together about the phenomenon. This might be the result of activation of different mental models by triggering elements in each context, because these elements may activate specific models as Bao (1999) explained that different physics questions might trigger different models.

Since the number of contexts to identify mental models is large, this allows to us to be able to examine students' mental model states. These model states may vary in terms of closeness of the frameworks that allow understanding. That means, for example, four students have a mixed state with the PSM and SM, which have more common concepts, or one student has the ShM and AM at the same time about the quantization of energy. Or, another student has the SM and IM at the same time for the quantization of angular momentum. Although the SM and IM do not have common elements that means they are completely different frameworks, no matter the closeness of the models students may hold them together. Chi (2008) explained that students might use incorrect models inconsistently to make explanations or predictions for events. In this study, since students have mixed model states, they tend to use the models inconsistently over the contexts. Physics and physics education students' use of their models inconsistently is compatible with the results of Bao's (1999), Hrepic's (2002), and Hrepic et al.'s (2010) findings. Again, this might be explained by a result of the contextual elements that activate students' models differently in the different contexts of the same phenomenon.

Conclusion 7: Students use fragments when they do not use models.

Construction of a mental model is a complex process. Students sometimes do not make explanations based on models, but they make explanations based on fragments that are disperse or unorganized (Gardner, 2002), unlinked or disconnected or incoherently used (Hrepic, 2002) (Section 4.1.7). In this study, since students construct their mental models by organizing with memorized elements and the fragments- especially facets-; in the absence of some these elements and links, students cannot form a coherent framework, and then they try to use these elements independent and inconsistent way. Students also use memorized elements without stating their explanations. This type of physics knowledge is explained as "nominal" and "not functional" (Reif, 1995). The students, who have incoherent knowledge organization and confuse the concepts, are accepted as in transitional phase (Perret-Clerment, 1980 as cited in Chinn and Brewer, 1998). Moreover, having fragmented knowledge prevents the benefits (such as remembering and inferring the details) of having coherent structure result by knowledge (Reif, 1995). Because the examination of the nature of fragmented elements is out of the research aims, they were not explained in this study.

Conclusion 8: Construction of the SM is based on "on the spot" and "previously thought or experienced" explanations, and the students using the SM trust on their knowledge more than other students. However, unscientific models are mainly constructed "on the spot" when the questions are asked.

In this study, it is observed that while students having SM make explanations both on the spot and previously thought, the students having PSM, AM, ShM, IM, and EM present mostly on the spot explanations (Section 4.1.8.a). As Vosniadou and Brewer (1992) explained "on the spot" construction of mental models, in addition Hrepic (2004) identified that students constructed some mental models of sound on the spot while answering the questions. As similar, Corpuz and Rebello (2005) investigated students' mental models of friction could be constructed "on the spot", but students' macroscopic experiences have influenced their mental models at the atomic level. These findings are surprising since "sound" and "friction" are everyday phenomena, and students constructed models on the spot. In this study, students do not have any physical experience from daily life about the concepts. They might experience the cases of quantization in the laboratories by conducting experiments, or they experience in the instruction by interpreting what is explained. For this reason, it is reasonable to construct all types of models on the spot. However, by considering the SMs, students construct SMs based on mathematical elements in the quantization of angular momentum (both in the Bohr and quantum atom). This result is also compatible with the studies of Itza-Ortiz and Rebello (2002) and Itza-Ortiz et al. (2004). They identified that in order to explain physical situations in magnetic field contexts, students relied on equations more than before.

Norman (1983) explained that individuals sometimes feel uncertain about their knowledge, and individuals' mental models contained some "degree of certainty" elements. By the examination of students' mental model characteristics in terms of "assurance level", the students who use the SM are more certain than the other students while making explanations. This might be because of the awareness of their scientific knowledge, and then trusting on the scientific knowledge that they got from the instruction and textbooks etc.

Conclusion 9: Language degeneracy is identified in students' explanations.

Hrepic (2002) mentioned the language degeneracy that is students' use of the same terminology with experts, textbooks i.e. using same words, expressions, but putting different meanings to these items. Therefore, they may use some concepts interchangeable. In this study, as explained in Section 4.2.2.d, some students put different meanings to "space quantization" and "particle in a box" terms. As Greca and Moreira (2002) explained, constructed mental models are based on what a person already know about the words. If there are no concepts, students cannot construct models; however, if there are concepts, which are known “wrong”, students could construct models by using the wrong knowledge. For this reason, language degeneracy might be considered in construction of models.

Conclusion 10: Some models are used more probable than the others.

As it is presented in Figure 4.11 (Section 4.1.9), it is identified that the SM and PSM are used by many different students in the examination of used models over contexts. However, other models -ShM, AM, IM and EM- are used by small number of students. The common property of these local models is that these models are unscientific models. This pattern is important in order to understand students' knowledge organization about the quantum theory. It may explain that there might be some other personal factors about the locality of unscientific models.

Conclusion 11: Limited number of students (just three students) could transfer their mental models into a similar context.

St2 and St9, who use the SM and AM in the explanation of quantization of angular momentum in the Bohr atom context respectively, transfer their models (that means, they use the same model in a similar context) to explain the quantization of angular momentum in the quantum atom (Section 4.1.8.b). As similar, St7, who uses SM, in the explanation of quantization of energy in the Bohr atom context, transfer her model to explain the quantization of energy in the quantum atom. This result is compatible with the results of Itza-Ortiz et al. (2004) which they investigated that students could transfer their models from classical mechanics to electromagnetism concepts. They explained that it is done when students faced with abstract contexts. As these researchers explained, the explanations are more likely based on the experience in the classes. We have already known that quantum concepts are abstract in this study. Among twenty-seven students who use models, most of them by (exclude three students) do not transfer their models from the Bohr atom to the quantum atom to explain the quantization of energy and angular momentum.

5.1.2 Conclusion and Discussion of the Sources Influencing Students' Mental Models

Previous studies in literature mentioned about some factors affecting students' mental models (Chi, 2008; Collins & Gentner, 1987; Gentner, 2002; Gentner & Whitley, 1997; Greca & Moreira, 2002; Hrepic, 2004; Johnson-Laird, 2004; Norman, 1983; Taber, 2008; van der Veer et al., 1999; Vosniadou et al., 1999). After the analysis of data sources shown in Figure 4.13, I got some evidences about external and internal sources influencing students' models of the quantization of physical observables. Conclusion and discussion of the results in this section are presented in the same order with Chapter 4. Therefore, Conclusions 12, 13, 14, and 15 are about the influence of external sources; Conclusions 16, 17, 18, 19, and 20 are about the influence of internal sources. All these elements in the examination of students' mental models are specific for this study.

Conclusion 12: Textbook is an external source influencing students' mental models.

As Taber (2008) stated "books" have importance in students' mental models, in this study I identify that textbook is a source influencing students' mental models (Section 4.2.1.a) about quantization. Great majority of the students explain the influence of textbook on their understanding of quantization. In addition to the influences of explanations in textbooks, bringing textbook into the classes, and use of one or more than one (both) textbooks are implicitly and explicitly identified as a source which has influence on students' models. These findings imply that implicit or explicit presentation of information, stress to main terms, and use of diverse number of methods to explain concepts are important for students' knowledge organization in quantum physics.

Conclusion 13: Instruction is an external source influencing students' mental models.

As similar with textbook, "instruction" is a source influencing students' models. In addition, many students explain the influence of the instruction on their understanding of quantization. Identification of some instructional elements such as note taking and prior and after study + attending to the classes + note taking indicate the importance of these elements on models.

Lecture hall is also a social environment that students could interact with the instructor. That means "human communication" is important for the construction of mental models (Johnson-Laird, 2004). During with this interaction, "meaning" is central for the construction of mental models (Johnson-Laird, 2004). Attending the classes is not a source by itself, however when students attend to the classes with prior and after study and then take notes, this might be helpful for their development of coherent knowledge organization. As it was examined in Section 4.2.1.b, contribution of each element individually differs. For example, while taking note in the classes is examined individually, it is seen that four students, who do not use model anyway, take notes in the classes regularly. The reason of such type of structures might be students' keeping the obtained information during a short period of time without converting to knowledge. By this way, some residue of information caused wrongly constructed concepts or memorized elements, and wrong or missing links among these concepts in the organization of knowledge. The interesting one is the students, who do not take notes, present more coherent and scientific structures. This indicates that the students may lose their attention and miss some important elements facilitating their models during the classes. That means, this might be an element determining the gain of the instruction.

I observe a development in some of the students' understanding in the core group during the semester. This might be the result of instruction focuses on the phenomena step by step. This result is also compatible with the results of Gentner's (2002) study, since the researcher explains the resistance to instruction may be observed when students construct mental models by experience. Since students do not have chance to experience the quantization phenomenon and related concepts in daily life, students could improve their models over the cases. This result indicates us students' learning sometimes might be easier for the abstract and counter intuitive quantum concepts in the classes.

> **Conclusion 14:** Arrangement of the physics topics during teaching has some influence on students' models.

As it is examined in previous research (Chi, 1992; Chiou & Anderson, 2006; Greeno, 1983; Reiner et al., 2000; Slotta & Chi, 2006), ontology is important for students' knowledge construction. One of the interesting findings of this study is students' problems in the discrimination of two different theories (the theory of relativity and the quantum theory). Although, the difference between these theories is explicitly explained in the classes and textbooks, I got some evidences in students' mental models including "relativistic" conceptions about the quantization of physical observables. This indicates us, students' recognition of the differences between the theories might be obtained by rearrangement of the topic order that has some influence on students' understanding.

Conclusion 15: Classmate has some influence on students' mental models and model states.

Johnson-Laird (2004) explained that "human communication" was important for the construction of mental models. In the current study, classmate is observed as a source influencing students' models (Section 4.2.1.c). More specifically, in addition to the use of similar (mainly same) models, classmates influence students' mental models states. The examination of social interaction with environment, especially with the nearest person whom interacted, shows that students present the same mental models for the same cases of the phenomenon. In addition, the students who are in interaction with their pair in and out of the classroom have "pure" mental states no matter the models are scientific or unscientific. That means they use only one type of mental model over the contexts. This may be the result of their "unconscious persuasion" of each other. By this way, students might construct the concepts and links among the concepts by influencing each other.

Conclusion 16: Meta-cognitive elements have influence on the development of models.

As we have known, meta-cognitive strategies may enhance learning (Gredler, 2001, p.211). As it was explained in Figure 4.26 (Section 4.2.2.a), the students, who are aware and satisfied their knowledge and self- regulated, mainly present models, and these models are mainly scientific models. Although students may not consciously use their mental models (Wittmann et al., 1999), dis/satisfaction of knowledge provides some feedback to students to revise their knowledge. Having these three elements of meta-cognition at the same time is important for the development of SMs, and making explanations mainly with models over the contexts.

Conclusion 17: Motivation for learning has influence on students' models.

Most of the participants (twenty-six) explain their wish of learning modern physics during the semester. As it was explained in Figure 4.29 (Section 4.2.2.b), the students who are not motivated to learn physics concepts use limited number of models and these models are mainly unscientific. They mainly (more than 80%) use unorganized fragments while making explanations. In addition to the model usage, motivation is important for model development and use of models (Sections 4.3.1.a and 4.3.1.b).

Conclusion 18: Students' understanding is influenced by their beliefs about nature of science and nature of quantum concepts.

Bao (1999), Corpuz and Rebello (2005), Gentner and Whitley (1997) explained the effect of beliefs on students' mental models. Bao (1999) also identified similar results about the students' models on quantum concepts and beliefs. He explained that as the aspects of the quantum theory, abstract, counter-intuitive (not allow intuition anyway), mathematical nature and lacking of daily life examples had influence on students' model construction. As similar with the previous research, I observe that beliefs about both nature of science and nature of quantum concepts are important for students' models in this study (Section 4.2.2.c). Different beliefs about the quantum theory influence models different by triggering students' acceptance of information different.

Conclusion 19: Familiarity of the contexts influences the number and diversity of displayed models.

New concepts emerged with the paradigm shift from classical to quantum understanding. These concepts are both ontologically different and they are abstract and counter-intuitive concepts. Bao (1999) identified that understanding the "probability" concept significantly affected how students understand other quantum concepts. In this study, it is identified that unfamiliarity of new concepts cause students having language degeneracy in some concepts such as space quantization, particle in a box, harmonic oscillator, spin etc. (Section 4.2.2.d). In the contexts that students are unfamiliar (i.e. blackbody radiation, quantum harmonic oscillator), they present mainly unorganized knowledge structures and use some unscientific models. In addition, I also observe the use of SM differs in two parts of the atom context (as presented in Table 4.4). For example, large number of SMs (11 times) are used in the Bohr atom (Contexts 6.a1 and 6.a2) contexts that is familiar to students (since it is semi-classical), and other models are used in limited diversity (IM and AM). However, in the totally new model of atom that is the quantum atom (Contexts 6.b1 and 6.b2), students present limited number of SMs (3 times), and more diversity other models than the Bohr atom context (PSM, IM and AM). This finding explains Bao's (1999) findings about students' interpretation of quantum concepts better when they find some traces from classical physics.

> **Conclusion 20:** Background knowledge about the classical concepts of a phenomenon influences students' mental models.

Previous research explained that the importance of previous learning for students' mental models (Bao, 1999, Chinn & Brewer, 1998; Gardner, 2002; Hrepic, 2004; Johnson-Laird, 2004). Although students are familiar with some concepts in classical physics, their insufficient background about the concepts might influence their mental models. Knowledge allows individuals to draw conclusions about the events by influencing the reasoning process (Johnson-Laird, 2004). Gardner (2002) identified that the students who had strong understanding of physics were very comfortable while learning quantum mechanics. As Chinn and Brewer (1998) explained, both enrichment of prior conceptions and quality of background knowledge are the factors for knowledge change. Bao (1999) stressed that some of the classical concepts are crucial for learning of quantum concepts although they are different from each other. In this study, I observe that although students have background about both energy and angular momentum concepts in the classical physics, they explain the energy quantization better than the angular momentum quantization (Section 4.2.2.e). That means, students' problems about linear and angular momentum in classical physics, in other words, their lack of conceptual learning of these concepts affect how they organize their knowledge in quantum physics.

In addition, students' not constructing any SMs or/and developing limited number of unscientific models might be explained with the influence of background in students' model development. In some contexts, students mainly use unstructured knowledge elements, since they mainly cannot construct any concepts related with the quantization phenomenon. Therefore, what individuals know about the words before is important for mental models (Greca & Moreira, 2002).

5.1.3 Conclusion and Discussion of the Development of Models by Influence of Sources

In this section, the results presented in Section 4.3 are discussed and conclusions are drawn. Three main conclusions and discussions about the development of models by influence of the sources exist for this section.

Conclusion 21: Each source contributes model development differently.

As the external and internal sources explained in Section 4.2 have influence on models, each source contributes model development differently. So each model developed by the influence of different sources in different proportions. For example, while the development of some models are explained by more sources, some of them develop by the contribution of few elements (Section 4.3.1.b). This indicates us model development is a complex process under the influence of many sources contributing with different properties and proportions. This conclusion shows us by manipulating these sources, we can facilitate students' knowledge organization and revise their unscientific knowledge structures. For example, based on the findings of this study, by improving students' meta-cognitive behaviors, the probability of having SM may be increased.

Conclusion 22: Upgrading in models is observed within the cases (over the physical observables) of quantization.

For two students among eight students, it is observed that students present upgrading in their models in Interviews I, II, and III (Section 4.3.2.a). These students explain the quantization of light with the PSM, they continue to explain the quantization of energy with the PSM and SM, and finally, they explain the quantization of angular momentum with the SM (Section 4.3.2.a). By considering the time order in the development of these models, an additional student (totally 3 students) present a development from the PSM to SM. Norman (1983) implied the influence of "interaction with the system" during model development. Hrepic et al. (2010) also explained models could be upgraded through experience and formal instruction. This finding is compatible with the previous studies, since the students present the development while they are continuing to learn the quantization phenomenon. During this period, they recover their ideas, and they could use the SM at the end. The reason of recovery of PSM also might be the closeness of it with SM, since the main difference of these models is inappropriate use of "boundedness". Therefore, students' appropriately use of this discriminating element and modifying their knowledge might be the reasons of such type of development.

I did not observe the development from other unscientific models to SM. The reason might be the difficulty in the construction of the scientific concepts and links by radical changes, since most of the unscientific models diverge from the SM too much in terms of concepts and framework.

> **Conclusion 23:** Students' models about the quantization of physical observables are quite stable up to the end of the semester.

Corpuz and Rebello (2011a) explained that learners tested their models in the light of new experiences, and modified/reorganized their models by this way. Scherr (2007) also identified that the change in understanding was difficult and learning was more permanent. In this study, students also do not have chance to test their models in new experiences, so it might be difficult to change them (Section 4.3.2.a). Therefore, "not to have new experiences" should explain the stability of the models for some period of time. At the beginning, this conclusion seems in contradiction with Norman's (1983) conclusion that he stated "Mental models are unstable: People forget the details of the system they are using, especially when those details have not been used for some period." (p.8). However, he explained he got this conclusion based on general observations of a variety of people (p.8), and he did not explain "certain" duration for the durability of mental models (p.8). By this way, the similar conclusion may be observed in the future i.e. in the next grade. For this study, the time period is one semester. Students develop their models while they are learning the phenomenon (during Interviews I, II and III), and they keep them at the end of the semester. At the end, they do not change their models before and after the final examination. One of the other reasons of students' stability of models may be their expectation of mathematical questions in the exam. Therefore, most of the students consider studying for final examination is not helpful for their understanding of the quantization phenomenon, and then they focus on solving mathematical problems without recovering or reorganizing their knowledge structures.

5.2 Implications

The following sections present some implications of the current study. The findings of this study indicate some points that should be considered by modern physics instructors/teachers, the students who are taking modern physics course, and modern physics textbook authors.

5.2.1 Implications for Modern Physics Instructors or Teachers

Implication 1: Links among the different physics concepts or different contexts should be constructed in the classes.

In this study, it was identified that students hold many incoherent unscientific ideas together with the unscientific mental models. Incorrect ideas must be changed with the correct ones (Scherr, 2007) for scientific knowledge. In addition to the unscientific conceptions, students sometimes had correct ideas but they used them inconsistently. Being a good physicist requires having organized knowledge, which permits remembering and inferring the details (Reif, 1995), so constructing links among the concepts should be facilitated by concept mapping and summary. Physics concepts are not isolated, and they are the elements of a coherent framework, so “meaning” should be constructed with linking the concepts coherently. This might help students’ knowledge organization better.

Implication 2: Scientific concepts and elements, which are fundamental for scientific models, should be explained explicitly and stressed in the classes.

In modern physics classes, explicitly explanation of the scientific elements should be considered in the classes, because students may be unable to recognize these elements although they are stated in the classes. By this way, students’ cognitive development while learning physics should be supported. When students develop cognitively, they would adopt more sophisticated and powerful mental models (Glynn, 2007).

Implication 3: Mental model of the instructor should allow predicting students' probable knowledge structures.

Instructor's mental model about the quantization of physical observables is important to shape instruction. Having complex scientific mental models with integration of advance level concepts may allow instructor predicting how students approach towards the concepts, and how they organize knowledge. By this way, instructors might predict students' inappropriate use of some concepts and construction of unscientific models. Then, they can consider some precautions preventing students' organization of knowledge wrongly, manipulate their unscientific models, and recover them by manipulating the instruction.

Implication 4: Instructor should pay attention to use body language in the classes together with other explanations for students' knowledge organization.

Quantum concepts that students are not familiar before bring some difficulties while teaching them. In this study, the use of body language to indicate "discreteness" might be more helpful for students' recognition of basic scientific elements of quantization easily. By this way, students might be stimulated better for making sense of the concepts by experiencing in physical environment.

Implication 5: Some activities making concepts concrete should be facilitated.

Since students do not have a chance for daily experience about the quantization phenomenon, it might be better to show some demonstrations or simulations in the classes. Sometimes computer generated models shown in pictures, or some drawings or mathematical explanation might be useful for students' making sense of the concepts. By this way, students can make sense some abstract concepts by experiencing them in the instruction.

Implication 6: Handouts or lecture notes should be provided to students in the classes in order to get students' attention.

In this study, my findings about students' note taking indicated that students who do not take notes with different reasons displayed more coherent and scientific knowledge structures. This might explain that these students might focus just to understand what the instructor explained in the classes without only recording them. For this reason, students' knowledge organization might be facilitated by showing the focus concepts that students should take into consideration more with lecture notes or handouts provided in the classes. The existence of the important terms in these notes might gain students focus and direct them to integrate these elements into their knowledge organizations.

Implication 7: While selecting the textbooks for students, instructors should consider the way of explanations, and the diversity of the methodologies explaining the concepts in the textbooks.

Due to the findings of this study, the instructors should select textbooks that using diverse methodologies explaining concepts, because it was observed that this issue was important for the development of coherent knowledge structures. In addition, the stress and explicit explanations of the concepts are important for scientific and coherent structures.

Implication 8: Topic order should be stressed in the classes explicitly to discriminate different theories (the theory of relativity and the quantum theory). Or, the theory of relativity chapters may be explained/taught after the concepts of the quantum theory.

In order to construct scientific knowledge of quantum phenomena, students' understanding of "quantization" should be known well since it is "key" for passing from classical to quantum ideas. However, while students trying to understand the new concepts of the quantum theory, they integrate the concepts of relativity and classical physics to their knowledge organization about quantum theory. When quantum concepts are explained in the classes, the differences among relativistic physics, classical physics and quantum physics should be stressed more. The change in teaching order of these theories might also be helpful for students' making sense of the quantum concepts better without integrating the others. For example, because these theories are not prerequisite for each other, theory of relativity should be taught after the quantum theory that students constructed the quantum concepts well.

Implication 9: The variables such as meta-cognition and motivation should be taken into consideration in the instructions.

The findings indicate that this is one of the most important issues for students' use and development of scientific models of the quantization phenomenon. Some activities that showing students' affective status should be followed by instructors. This might be done at the beginning of the semester by examining these issues. Then the instruction might be redesigned in the light of the findings about students. For example, short reports in some periods of the semester might be included into the instruction. By this way, students' reflections about themselves and course might be re-shaped iteratively. Although what must be taught is stated in the academic catalog, students who are taking the course change each semester. So, students' characteristics should be taken into consideration at the university level to enhance their knowledge organization.

Implication 10: Students' prior knowledge should be identified by the instructor.

In the instructions, instructors should expect diverse types of students' ideas (Scherr, 2007) whether organized or unorganized. Students' knowledge structures should be identified because having background no matter classical and quantum concept is important for coherent knowledge organizations. Moreover, in the classes, students should be helped to use knowledge elements correctly. As this study indicates the importance of background knowledge on mental models, the "persistency" of SMs should be provided for a long period of time for students' use their models (PHYS 307) in the Applied Modern Physics course in the next semester.

5.2.2 Implications for Modern Physics Students

Implication 11: Students should bring their textbooks into the classes and use them effectively by facilitating note taking.

Taking notes in the classes as same as exactly what the instructor explained might not be as helpful as students thought. In addition, bringing textbook into the classes and using them in the classes might be more helpful for students than they thought. These two elements should be taken into consideration, because having more coherent knowledge first needs making sense of what is explained. This might be obtained by interpreting more what the instructor explained than writing exactly what the instructor wrote on the board. Bringing textbook into the classes and use of it in the classes promote development of coherent structures. So, students should learn to use textbooks effectively as (1) an advance organizer before the classes, (2) for following the instructor's explanations and highlight the important parts of the concepts during the classes, and (3) for summarizing the topics with the help of explanations on the textbooks by noting instructor's verbal explanations at the end of the classes.

Implication 12: Students should learn to ask questions about their learning.

Meta-cognitive inquiry of a student is important both knowledge organization by having any kind of model, and having SMs. Students should inquiry themselves about their learning, and they should develop the easier ways of understanding quantum concepts by regulating their learning.

Implication 13: As students attend the classes regularly, they should spend time before and after the classes.

The results of this study indicate that studying before and after the modern physics classes with note taking and attending the classes facilitate coherent knowledge organizations. This might be helpful for familiarity with the concepts and having background about them. This also allows students focusing what the instructor explained more and catching the key points in the classes. By this way, they might develop more coherent knowledge structures easily.

Implication 14: Students should force themselves to develop mental models.

Having mental models about the concepts fosters the development of complex organized knowledge about phenomena. It also permits retrieval process easier. For this reason, students should link the concepts in coherent way for better understanding; and they should push themselves to organize their knowledge.

5.2.3 Implications for Modern Physics Textbook Authors

Implication 15: Scientific ideas should be stated in the textbooks explicitly; important concepts should be stressed; and diverse number of methodologies should be used to explain scientific concepts. In addition, frequency of using these elements is important.

Textbook is also identified one of the influencing elements on students' mental models of the quantization phenomenon. Since students engaged the textbooks for many instances, it should be given importance explaining and stressing the basic concepts explicitly with the use of different number and diversity of the methodologies. It might make students recognizing scientific issues.

Implication 16: Some advance organizers such as concept maps, brief summaries should be used to foster linking the concepts.

Links among the concepts should be constructed while explaining the concepts. This might be possible with the repetition of the previous concepts to connect new learning and the previous ones. In addition, by concept maps, important concepts might be stressed and the construction of links among the concepts might be fostered. In addition, the summaries at the end of the sections and chapters might keep the concepts fresh, and they might facilitate students connecting the concepts in an easy way in the following sections and chapters.

5.3 Limitations of the Study and Controlling the Threats

Although this was a qualitative research, some limitations and threats are discussed in this section. For example, observer bias, reactivity, limiting students to use a specific language (Turkish or English) while explaining physics concepts can be considered as some threats for this study. In Section 5.3.1, how these probable threats handled are explained. In addition, limitation in the examination of interaction among the sources, limitation in the examination of knowledge elements directly, and limitation in the generalization of results are discussed in Section 5.3.2.

5.3.1 Controlling the Threats

Observer bias (highly subjective interpretation) can be considered a threat. In this study, observer effect (Fraenkel & Wallen, 2000, pp.538-539) was controlled by video recording,. In addition, this threat was tried to be controlled with the examination of a sample data and findings by different experts.

Reactivity is “the influence of the researcher on the setting or individuals studied” (Maxwell, 1996, p.91). By being a participant observer in natural setting, reactivity was controlled (Maxwell, 1996, p.91) for observation data. In the interviews, it was avoided exciting students about the quantization phenomenon in order to prevent their preparation for regularly conducted interviews. So, the “quantization” word was carefully used in the interviews. In the implementation of test, students were not allowed to interact with each other. In the production other artifacts by students such as homework papers, examination papers etc. were not interfered by me anyway by considering the examination of students’ mental models in their natural settings. By these ways, reactivity threats were tried to be controlled.

In addition, in order to prevent students misunderstanding the questions, all materials were provided in Turkish and English. Students were also allowed to make explanations by using both of the languages. This was important in order to get maximum information about students’ understanding. Students learn the concepts in English; however, they sometimes may be in difficulty with explaining the phenomena in English because of their poor English grammar knowledge or difficulty with wording. In contrast, students’ limited knowledge about the Turkish counterparts of the physics concepts learned in English was another limitation for the requirement of getting only Turkish explanations. For these reasons, by allowing students’ use both the languages - since language is just a device for communication-, students provided rich data by using both languages - English and Turkish. At the end, the threat caused by language was minimized by this way. Using this type of explanations also made students inquiry and learn the Turkish counterpart of the concepts learned in English for their physics knowledge.

5.3.2 Limitations

In this study, I did not examine the interaction of the sources influencing students' mental models since it was out of my research aims. Not to diverge from research aims, the sources were examined as independent from each other. Not to examine the interaction among the factors qualitatively might be considered as a limitation for this study.

We have known that mental models are not directly observable- or measurable (Bao, 1999; Gentner, 2002). For this reason, the research investigation of students' mental models is limited with "what students explained" and "how the researcher interpreted". In addition, the students' ability of accessing and using their mental models (Reif, 1995) also limits mental model studies.

Finally, my aims were to "understand" and "explain" students' mental models about the quantization of physical observables. Although I did not aim to generalize my conclusions over the population, the locality of the conclusions might be considered as a limitation from the quantitative research perspective.

5.4 Strengths of the Study

This study has some strength as well as some limitations. The strength of this study can be summarized as:

Strength 1: In this study, a wide range of data was collected from the setting without manipulating the setting as ethnographic manner. The collection of huge amount of data from different sources provided comparison of the data from different sources. In addition, it allowed examining mental models in more dimensions. For example, examination of the influences of external and internal sources on mental models is specific for this study. In addition, discussion of these issues in model development also brings new explanations to the literature about model development.

Strength 2: Quantization phenomenon is examined during the semester. So, in the examination of students' models, the use of multiple contexts is one of the strengths of this study.

Strength 3: I worked with thirty-one participants during the study. Although it was difficult to organize the qualitative data from large number of students, working with large number of students in the study was important in the recognition of some patterns about the mental models, the sources influencing mental models and model development.

Strength 4: Although I followed the previous physics education literature in terms of the examination of mental models, the design of this study is specific for this study. In addition, the explanation of methodological issues in detail is one of the strengths of this study.

Strength 5: This study examining students' understanding of quantum concepts is a new perspective for the physics education research in Turkey. And the contribution of the study by its sample, methodology, examined physics concepts, theoretical framework, results, and conclusions, find a room in physics and science education literature about mental models in worldwide.

Strength 6: This study combines the different domains such as physics, educational sciences, cognitive science, and anthropology. Standing in the intersection of different sets gains more importance as an interdisciplinary study.

5.5 Suggestions for Further Research

The findings imply McDermott's (1991) explanation once more that is what we teach is different from what students understand. Since, in spite of the scientific explanations in the classes and textbooks, some students really cannot make sense of the concepts as we expect. With this research, I suggest the following issues for further research:

Suggestion 1: Construction of scientific mental models is important for both physics and physics education students. In this study, I examined students' mental models about quantum physics concepts that were highly abstract. The results indicated students' difficulty in organizing these concepts. For further research, students' mental models about other advance-level physics concepts should be examined.

Suggestion 2: In this study, I did not examine the influence of students' ontologies on their mental models. However, the findings indicated that some ontological issues might have roles on model development. For further research, contribution of students' ontologies should be studied.

Suggestion 3: In this study, I identified some traces about the influence of language degeneracy on models. For further research, its action in model development might be examined with new research designs.

Suggestion 4: In this study, I did not examine the influence of "gender" on students' mental models. However, some findings indicated "gender" having some roles on displayed models by females and males, and the use of SM (males use SM more than females). However, there might be other reasons interacting with gender to explain the influence on models. For further research, contribution of "gender" to students' development and use of models should be examined.

Suggestion 5: In this study, although I worked with a large number of participants, I identified six unscientific elements contributing students' mental models. For further research, including more students into the study might identify some other probable unscientific elements contributing model structures.

Suggestion 6: I did not develop a test based on the results of this study. For further research, a test might be developed to investigate students' mental models, and inferential statistics may be used by the implementation of the test to large number of students. Then, some generalizations can be drawn for populations.

Suggestion 7: In this study, fragmented structures are not explained because of exceeding the research aims. So for the future research, students' fragmented elements about quantization of physical observables might be examined.

Suggestion 8: In this study, the direct influence of instruction on students' models was identified. By using this information, new experimental designs facilitating model development in quantum concepts might be developed and tested.

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APPENDIX A

PHYS 202 COURSE CONTENT AND OBJECTIVES

PHYS 202-MODERN PHYSICS COURSE

(2008-2)

NOTIFICATIONS:

- There are four modern physics classes per week (2 x 2 hours).
- First 3 weeks are omitted from the list because of focusing on the theory of relativity that is irrelevant for the research aims.
- Abbreviations for Cognitive Domain of Bloom taxonomy: **K**= Knowledge, **C**= Comprehension, **Ap**= Application, **An**= Analysis, **S**= Synthesis, and **E**= Evaluation.

WEEKS	DATES	TOPICS	SPECIFIC OBJECTIVES
1	**The theory of RELATIVITY concepts**		
2			
3			
4	09.03.2009	▪ *ELECTROMAGNETIC WAVES* ▪ *BLACKBODY RADIATION*	▪ To describe electromagnetic waves (K). ▪ To describe the characteristics of blackbody (K). ▪ To explain the blackbody radiation (C). ▪ To distinguish blackbody and black object (C). ▪ To explain the Planck's postulates (C). ▪ To explain the ultraviolet catastrophe (C). ▪ To interpret the energy density versus frequency of electromagnetic radiation (light) graph of blackbody radiation (C). ▪ To recognize the quantization of energy (An).

APPENDIX A (continued)

	12.03.2009	▪ *PHOTOELECTRIC EXPERIMENT* ▪ *WHAT IS LIGHT?* ▪ *X-RAYS* ▪ *X-RAY DIFFRACTION*	▪ To explain workfunction (C). ▪ To explain the photoelectric experiment showing light as a particle (C). ▪ To draw the current versus potential graph for different intensities at constant frequency (S). ▪ To draw the current versus potential graph for same intensities at different frequencies (S). ▪ To solve the mathematical problems about photoelectric effect (Ap). ▪ To identify the quantization of light (An). ▪ To define X-rays (K). ▪ To give examples from daily life about X-rays (C). ▪ To explain the X-Ray diffraction (C). ▪ To recognize the inverse of photoelectric effect same with X ray production (An).
5	16.03.2009	▪ *COMPTON EFFECT* ▪ *PAIR PRODUCTION* ▪ *PHOTONS AND GRAVITY*	▪ To explain the Compton Effect this is another experiment about light as a particle (C). ▪ To solve the mathematical problems about Compton Effect (Ap). ▪ To explain the pair production that is another experiment showing light as a particle (C). ▪ To differentiate the photoelectric effect, Compton Effect, and pair production by considering the λ of incident wave (An). ▪ To explain the gravitational behavior of light (Gravitational red shift) (C).

APPENDIX A (continued)

	19.03.2009	▪ *DEBROGLIE WAVES* ▪ *WAVES OF PROBABILITY*	▪ To explain the wave properties of particles (C). ▪ To explain the DeBroglie wavelength (C). ▪ To describe the matter waves (K). ▪ To explain the measurable quantity in a wave (probability) (C).
6	23.03.2009	▪ *DESCRIBING WAVE* ▪ *PHASE AND GROUP VELOCITIES*	▪ To describe wave (K) ▪ To explain wave propagation (C) ▪ To distinguish the group and phase velocity (C). ▪ To distinguish wave packet and wave group (C). ▪ To solve the mathematical problems about wave velocities (Ap).
	26.03.2009	▪ *PARTICLE DIFFRACTION* ▪ *PARTICLE IN A BOX*	▪ To explain the wave behavior of particle (C). ▪ To explain the standing waves in a box (C). ▪ To explain the behavior of standing waves in a box (C). ▪ To identify the energy quantization of the particle in a box (An). ▪ To solve the mathematical problems about particle in a box (Ap).
7	30.03.2009	▪ *UNCERTAINTY PRINCIPLE*	▪ To explain uncertainty principle (C). ▪ To solve the mathematical problems about uncertainty principle (Ap).
	02.04.2009	▪ *APPLYING UNCERTAINTY PRINCIPLE*	▪ To state uncertainty relation for different considerations (C). ▪ To solve the mathematical problems about wave velocities (Ap).

APPENDIX A (continued)

8 *1. Midterm week* *08.04.2009*	06.04.2009	▪ *THE NUCLEAR ATOM* ▪ *ELECTRON ORBITS* ▪ *ATOMIC SPECTRA*	▪ To explain the history of atom (C). ▪ To list the atomic models (K). ▪ To explain the nuclear size (C). ▪ To explain the planetary motion (an atom with electrons orbiting) (C). ▪ To infer the failure of classical physics and start of new hurdles (An). ▪ To explain the formation of spectral lines (C). ▪ To distinguish emission and absorption spectra (C).
	09.04.2009	▪ *THE BOHR ATOM* ▪ *ENERGY LEVELS AND SPECTRA*	▪ To infer the semi classical theory of Bohr (An). ▪ To infer the failure of Bohr Theory (An). ▪ To infer the quantization of atomic energy levels (An). ▪ To predict the allowed and forbidden transitions (C).
9	13.04.2009	▪ *CORRESPONDENCE PRINCIPLE* ▪ *NUCLEAR MOTION*	▪ To explain the relation between classical and quantum physics (C). ▪ To calculate the motion of electrons by considering the moving nucleus (Ap).
	16.04.2009	▪ *ATOMIC EXCITATION* ▪ *THE LASER*	▪ To describe the laser (K). ▪ To explain the characteristics of laser light (C). ▪ To give example to the daily applications of lasers (C).

APPENDIX A (continued)

10	20.04.2009	▪ *INTRODUCTION TO QUANTUM MECHANICS (QM)* ▪ *THE WAVE EQUATION*	▪ To explain wave function (C). ▪ To state wave equation (K). ▪ To explain the importance of wave function in quantum mechanics (C). ▪ To state the Schrödinger's time independent wave equation (K). ▪ To relate the Schrödinger equation with Newton's 2. Law (C). ▪ To define operator (K). ▪ To define observable (K). ▪ To distinguish operator and observable (C).
	23.04.2009	**No classes (National Holiday)**	**No classes (National Holiday)**
11	27.04.2009	▪ *SCHRÖDINGER' TIME DEPENDENT WAVE EQUATION* ▪ *LINEARITY AND SUPERPOSITION* ▪ *EXPECTATION VALUES* ▪ *EIGENVALUES, EIGENFUNCTIONS*	▪ To state the Schrödinger's time dependent wave equation (C). ▪ To interpret the physical meaning of Schrödinger's time dependent wave equation (An). ▪ To explain expectation value (C). ▪ To explain its physical meaning (C). ▪ To distinguish the eigenvalue and eingenfunction (C).
	30.04.2009	▪ *PARTICLE IN A BOX* ▪ *FINITE POTENTIAL WELL*	▪ To interpret the particle in a box problem (An). ▪ To explain the behavior of a particle in a finite well (C). ▪ To solve the mathematical problems about potential wells (Ap). ▪ To explain the energy for particle in a box in quantum mechanics (C). ▪ To recognize the quantization of energy (An).
12 *2. Midterm week 06.05.2009*	04.05.2009	▪ *TUNNEL EFFECT*	▪ To explain the tunnel effect (C). ▪ To give examples about tunnel effect behavior (C). ▪ To describe the harmonic

APPENDIX A (continued)

			oscillator for classical and quantum systems (C). ▪ To solve the mathematical problems about tunnel effect (Ap).
	07.05.2009	▪ *HARMONIC OSCILLATOR* ▪ *SCHRÖDINGER EQUATION FOR HYDROGEN ATOM* ▪ *QUANTUM NUMBERS* ▪ *PRINCIPLE QUANTUM NUMBER*	▪ To explain the energy for a harmonic oscillator in quantum mechanics (C). ▪ To solve the mathematical problems about harmonic oscillator (Ap). ▪ To recognize the quantization of energy (An). ▪ To explain the principle quantum number (C). ▪ To state the partial differential equation for wave function of the electron in Hydrogen atom by spherical coordinates (C).
13	11.05.2009	▪ *ORBITAL QUANTUM NUMBER* ▪ *MAGNETIC QUANTUM NUMBER*	▪ To explain the orbital quantum number (C). ▪ To infer the quantization of orbital angular momentum (An). ▪ To explain the magnetic quantum number (C). ▪ To infer the quantization of direction of orbital angular momentum (An). ▪ To solve the mathematical problems about harmonic oscillator (Ap).
	14.05.2009	▪ *ELECTRON PROBABILITY DENSITY* ▪ *RADIATIVE TRANSITIONS* ▪ *SELECTION RULES* ▪ *ZEEMAN EFFECT*	▪ To explain the quantum model of atom (C). ▪ To state electron probability density equation (C). ▪ To relate wave function and probability density (C). ▪ To state Born interpretation for probability density (C). ▪ To state allowed and forbidden transitions (C). ▪ To calculate the allowed and forbidden transitions (Ap).

APPENDIX A (continued)

			▪ To explain the Zeeman Effect (C). ▪ To solve the mathematical problems about harmonic oscillator (Ap).
14	18.05.2009	▪ *ELECTRON SPIN* ▪ *EXCLUSION PRINCIPLE* ▪ *SYMMETRIC AND ANTI-SYMMETRIC WAVEFUNCTIONS*	▪ To explain the spin (C). ▪ To explain the Pauli Exclusion Principle (C). ▪ To distinguish the field used in Zeeman and Stern Gerlach experiments (C). ▪ To infer the quantization of the magnitude of electron spin (intrinsic angular momentum) (An). ▪ To infer the quantization of the direction of electron spin (An). ▪ To differentiate symmetric and anti-symmetric wave functions (C).
	21.05.2009	▪ *SPIN-ORBIT COUPLING*	▪ To explain the spin-orbit coupling (C).
15	25.05.2009	▪ *NUCLEAR COMPOSITION* ▪ *SOME NUCLEAR PROPERTIES* ▪ *STABLE NUCLEI* ▪ *BINDING ENERGY*	▪ To define the binding energy (K). ▪ To solve the mathematical problems about binding energy (Ap). ▪ To explain stability of nucleus (C).
	28.05.2009	▪ *RADIOACTIVE DECAY* ▪ *HALF-LIFE*	▪ To explain radioactive decay (C). ▪ To explain the radioactive decay with alpha, beta and gamma rays (C). ▪ To explain half-life (C). ▪ To solve the mathematical problems about half-life (Ap).

APPENDIX B

OBSERVATION INFORMATION

B.1 Observation Dates and Duration

Observation Record

Week	Lecture No	Date	Observation No	Observation Duration
Week 4	Lecture 6	09.03.2009	1	~120 minutes
Week 4	Lecture 7	12.03.2009	2	~120 minutes
Week 5	Lecture 8	16.03.2009	3	~120 minutes
Week 5	Lecture 9	19.03.2009	4	~120 minutes
Week 6	Lecture 10	23.03.2009	5	~120 minutes
Week 6	Lecture 11	26.03.2009	6	~120 minutes
Week 7	Lecture 12	30.03.2009	7	~120 minutes
Week 7	Lecture 13	02.04.2009	8	~120 minutes
Week 8	Lecture 14	06.04.2009	9	~120 minutes
Week 8	Lecture 15	09.04.2009	10	~120 minutes
Week 9	Lecture 16	13.04.2009	11	~120 minutes
Week 9	Lecture 17	16.04.2009	12	~120 minutes
Week 10	Lecture 18	20.04.2009	13	~120 minutes
Week 10	Lecture 19	23.04.2009	14	*No classes*
Week 11	Lecture 20	27.04.2009	15	~120 minutes
Week 11	Lecture 21	30.04.2009	16	~120 minutes
Week 12	Lecture 22	04.05.2009	17	~120 minutes
Week 12	Lecture 23	07.05.2009	18	~120 minutes
Week 13	Lecture 24	11.05.2009	19	~120 minutes
Week 13	Lecture 25	14.05.2009	20	~120 minutes
Week 14	Lecture 26	18.05.2009	21	~120 minutes
Week 14	Lecture 27	21.05.2009	22	~120 minutes
Week 15	Lecture 28	25.05.2009	23	~120 minutes
Week 15	Lecture 29	28.05.2009	24	~120 minutes

B.2 Outline for Observation

Outline for Observation

Week:
Date:

Observation of the Instructor

No	Focus Points	Explanations
1	In which context does the instructor explain the quantization of physical observables?	
2	What are the instructional techniques used by the instructor while explaining the quantization of physical observables?	
3	How many times does the instructor stress quantization?	
4	Does the instructor link the quantization of physical observables with each other? (i.e. energy- angular momentum)	
5	Does the instructor link the quantization of physical observables in different contexts? (i.e. particle in a box and harmonic oscillator)	
6	Does the instructor compare “quantization” for quantum and classical physics?	
7	Others	

Observation of the Students

No	Focus Points	Explanations
1	How is the attendance in the class?	
2	Do the students join the class activities?	
3	Instructor- student interactions (i.e. during questioning, discussion)	
4	Extraordinary events in the class	
5	Do the students ask questions to the instructor in the class?	
6	Do the students ask questions to the instructor out of the class? (i.e. in the break, before or after the class)	
7	Do the students discuss quantization with each other out of the class? (i.e. in the break)	
8	Others	

Notes for each ten minutes

Time	Events
10.30	Students come to the lecture hall.
10.40	The lecture starts.
10.50	
11.00	
11.10	
11.20	
11.30- 11.40	Break
11.40	
11.50	
12.00	
12.10	
12.20	The lecture ends.
12.30	Students leave the lecture hall.

APPENDIX C

INTERVIEW QUESTIONS

C.1 Questions for Pre-Interview

QUESTIONS FOR PRE- INTERVIEW

The aim of this study is to examine second-year physics and physics education students' mental models about some quantum physics concepts.

Interviewer :
Interviewee (name or pseudonym) :
Interview Date :
Interview Duration :
Interview Data Recorders :
Department : □ Physics □ Physics education
Gender : □ Female □ Male
Number of taking this course : □ First time □ Second time or more

DIRECTIONS: Dear student, the following questions will be asked to you to describe your opinions, behaviors, and what you learned in the Modern Physics (PHYS 202) course. If you do not want to answer a question, you can skip it. There are both English and Turkish versions of each question. To express the answers in English is not compulsory; if you prefer, you can explain in Turkish. Recommended duration for this interview is 20 minutes.

YÖNERGE: Değerli öğrenci, sizin Modern Fizik (PHYS 202) dersine yönelik fikirlerinizi, davranışlarınızı, ve öğrendiklerinizi tanımlamak için aşağıdaki sorular sorulacaktır. Cevaplamak istemediğiniz soruyu geçebilirsiniz. Her sorunun İngilizce ve Türkçe versiyonu bulunmaktadır. Cevapları İngilizce açıklamak zorunlu değildir, isterseniz Türkçe açıklayabilirsiniz. Bu görüşme için öngörülen süre 20 dakikadır.

QUESTIONS

1. Do you study new topics prior to the Modern Physics classes?
Modern Fizik dersinden önce yeni işlenecek konulara çalışıyor musunuz?

2. Do you attend the Modern Physics classes regularly?
Modern Fizik derslerine düzenli olarak devam ediyor musunuz?

3. Do you bring Modern Physics textbooks to the classes?
Modern Fizik derslerine ders kitaplarını getiriyor musunuz?

4. What does “being in the Modern Physics class” mean to you?
Modern Fizik dersinde olmak sizin için ne anlam ifade ediyor?

5. What are the factors, which affect your understanding in the lecture hall?
Sınıfta anlamanıza etki eden faktörler nelerdir?

6. Do you take notes on what mentioned in the Modern Physics classes?
Modern Fizik derslerinde anlatılanları not alır mısınız?

7. What is your favorite aspect in the Modern Physics classes?
Modern Fizik derslerinde en sevdiğiniz şey nedir?

8. Do you practice after the Modern Physics classes?
Modern Fizik derslerinden sonra tekrar yapar mısınız?

9. How do you solve the homework questions (individually, discussing with your friends etc.)? Do you check your homework after the homework grades are announced?
Ödev sorularını nasıl çözersiniz (bireysel, arkadaşlarınızla tartışarak vs.)? Ödev notları açıklandıktan sonra ödevinizi kontrol eder misiniz?

10. How do you study for the exams (individually, discussing with your friends etc.)? Do you question the assistants or the instructor? Do you examine your exam after the exam grades are announced?
Sınavlara nasıl çalışırsınız (bireysel, arkadaşlarınızla tartışarak vs.)? Asistanlara ya da dersi veren öğretim üyesine soru sorar mısınız? Sınav notları açıklandıktan sonra sınav kağıdınızı inceler misiniz?

11. Do you use textbooks actively to understand the topics? Do you use other external sources to understand Modern Physics topics?
Ders kitaplarını aktif olarak kullanıyor musunuz? Modern Fizik konularını anlamak için başka kaynaklar kullanıyor musunuz?

12. Do you discuss about Modern Physics topics with your friends?
Modern Fizik konuları hakkında arkadaşlarınızla tartışır mısınız?

13. Do you have problems understanding Modern Physics concepts? If yes, which topics?
Modern Fizik kavramlarını anlamakta problem yaşadınız mı? Evet ise hangi konularda yaşadınız?

14. What does “grade of the Modern Physics exam” mean for you?
Modern Fizik sınavından aldığınız not sizin için ne anlam ifade eder?

C.2 Questions for Interview I

QUESTIONS FOR INTERVIEW I

The aim of this study is to examine second-year physics and physics education students' mental models about some quantum physics concepts.

Interviewer :
Interviewee (name or pseudonym) :
Interview Date :
Interview Duration :
Interview Data Recorders :
Department : □ Physics □ Physics education
Gender : □ Female □ Male
Number of taking this course : □ First time □ Second time or more

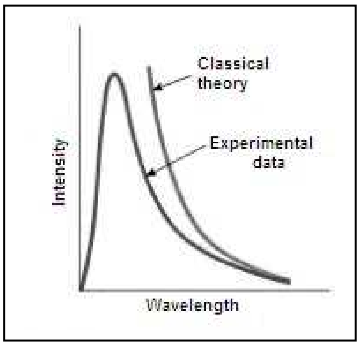
<u>DIRECTIONS:</u> Dear student, the following questions are about the topics we have learned in the Modern Physics (PHYS 202) course. You can answer the questions however you want (i.e. verbally, drawings, mathematical expressions etc.). While answering the questions, think aloud if possible. Please state your reasons for your answer; in other words, explain what shaped your answers (books, classes, friends etc.). If you do not want to answer a question, you can skip it. There are both English and Turkish versions of each question. To express the answers in English is not compulsory; if you prefer, you can explain in Turkish. Recommended duration for this interview is 60 minutes.

<u>YÖNERGE:</u> Değerli öğrenci, aşağıda Modern Fizik (PHYS 202) dersinde öğrendiklerimize ilişkin sorular bulunmaktadır. Soruları isteğiniz şekilde yanıtlayabilirsiniz (mesela sözlü, çizimler, matematiksel ifadeler vb.). Soruları cevaplarken mümkün olduğunca sesli düşününüz. Lütfen cevabınızın sebeplerini, yani cevaplarınızı nelerin şekillendirdiğini (kitaplar, dersler, arkadaşlar) belirtiniz. Cevaplamak istemediğiniz soruyu geçebilirsiniz. Her sorunun İngilizce ve Türkçe versiyonu bulunmaktadır. Cevapları İngilizce açıklamak zorunlu değildir, isterseniz Türkçe açıklayabilirsiniz. Bu görüşme için öngörülen süre 60 dakikadır.

<u>QUESTIONS</u>

1. a) What do "blackbody" and "blackbody radiation" mean? Explain.
"Karacisim" ve "karacisim ışıması" nedir? Açıklayınız.

2.



In this figure, you see a disagreement after a point between experimental data and classical theory.
Figürde deney verileri ile klasik teori arasında bir noktadan sonra uyumsuzluk görüyorsunuz.

a) What was the problem?
Problem neydi?

b) How did Planck solve this problem?
Planck bu problemi nasıl çözdü?

c) What is the importance of this finding?
Bu bulgunun önemi nedir?

3. a) We have discussed Planck's explanation of radiation. What is the meaning of "Planck's constant (h)" in the explanation of radiation?
Planck'ın ışımaya ilişkin açıklamalarını tartıştık. Işımanın açıklanmasında "Planck sabiti" nin anlamı nedir?

b) What is the importance of this constant for quantum theory?
Bu sabitin kuantum teorisi için önemi nedir?

4. a) For a photoelectric experiment, assume we have a photon with 2.4 eV energy, and the work function of the metal is 4.8 eV. When we send the photon to this metal, do you think the metal will emit any electron? If yes, how many electrons will be emitted?
Fotoelektrik deneyi için, elimizde 2.4 eV enerjili bir foton ve iş fonksiyonu 4.8 eV olan bir metal olduğunu varsayalım. Bu fotonu metal yüzeye gönderdiğimizde metal elektron salar mı? Evet ise kaç tane elektron salınır?

b) Well, now, if we send two photons to that metal, with each photon having 2.4 eV energy, will the metal surface emit an electron?
Peki, şimdi bu metale her biri 2.4 eV enerjili iki foton gönderdiğimizde metal yüzey elektron salar mı?

c) If these two photons are sent to an another metal with a work function of 4 eV, will it emit electron? If yes, how many electrons will be emitted?
Eğer bu iki foton iş fonksiyonu 4 eV olan başka bir metal yüzeye gönderilirse, bu metal elektron salar mı? Evet ise kaç tane elektron salınır?

5. a) What does the "photoelectric experiment" explain about nature of light? Why do the results suggest this conclusion?
Fotoelektrik deneyi ışığın doğası ile ilgili ne açıklar? Bulgular neden bu sonucu önerir?

b) Why is it an important experiment for quantum physics?
Kuantum fiziği için neden önemli bir deneydir?

6. What did Planck and Einstein mention about quantization? Is there any difference between their explanations about quantization? If yes, explain the difference(s).
Planck ve Einstein kuantize olma (kuantumlanma, kuantumlu olma) durumuna ilişkin ne söylediler? Kuantize olma durumuna ilişkin açıklamalarında bir fark var mıdır? Evet ise açıklayınız.

Probing Procedure:
- Getting the student into the context,
- Discuss the physics of the context,
- Then discuss the quantization of physical observables depending on student's explanations in the context.

C.3 Questions for Interview II

QUESTIONS FOR INTERVIEW II

The aim of this study is to examine second-year physics and physics education students' mental models about some quantum physics concepts.

Interviewer :
Interviewee (name or pseudonym) :
Interview Date :
Interview Duration :
Interview Data Recorders :
Department : □ Physics □ Physics education
Gender : □ Female □ Male
Number of taking this course : □ First time □ Second time or more

<u>DIRECTIONS:</u> Dear student, the following questions are about the topics we have learned in the Modern Physics (PHYS 202) course. You can answer the questions however you want (i.e. verbally, drawings, mathematical expressions etc.). While answering the questions, think aloud if possible. Please state your reasons for your answer; in other words, explain what shaped your answers (books, classes, friends etc.). If you do not want to answer a question, you can skip it. There are both English and Turkish versions of each question. To express the answers in English is not compulsory; if you prefer, you can explain in Turkish. Recommended duration for this interview is 60 minutes.

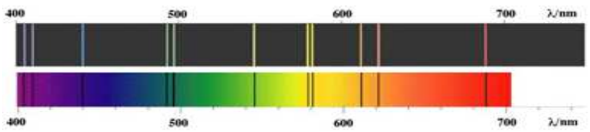
<u>YÖNERGE:</u> Değerli öğrenci, aşağıda Modern Fizik (PHYS 202) dersinde öğrendiklerimize ilişkin sorular bulunmaktadır. Soruları isteğiniz şekilde yanıtlayabilirsiniz (mesela sözlü, çizimler, matematiksel ifadeler vb.). Soruları cevaplarken mümkün olduğunca sesli düşününüz. Lütfen cevabınızın sebeplerini, yani cevaplarınızı nelerin şekillendirdiğini (kitaplar, dersler, arkadaşlar) belirtiniz. Cevaplamak istemediğiniz soruyu geçebilirsiniz. Her sorunun İngilizce ve Türkçe versiyonu bulunmaktadır. Cevapları İngilizce açıklamak zorunlu değildir, isterseniz Türkçe açıklayabilirsiniz. Bu görüşme için öngörülen süre 60 dakikadır.

<u>QUESTIONS</u>

1. In an emission spectrum, what do the (colored) lines explain (for the visible region), or in an absorption spectrum what do the dark lines explain? Why do the lines occur? Why do they have different colors (for the visible region) for emission spectra; Why are they dark for absorption spectra?
Emisyon spektrumu için görünür bölgedeki renkli çizgiler ya da absorbsiyon spektrumundaki siyah çizgiler ne açıklar? Çizgiler neden oluşur? Emisyon spektrumu neden renkli çizgilere sahiptir ya da absorbsiyon spektrumu çizgileri neden siyahtır?

Emission spectrum

Absorption spectrum



2. Suppose the electron in the Hydrogen atom obeys classical mechanics rather than quantum mechanics. What would you expect to observe in the spectrum? Why?
Varsayalım ki Hidrojen atomundaki elektron kuantum mekaniğine değil de klasik mekaniğe göre davranıyor. Spektrumunda ne gözlemeyi beklersiniz? Neden?

3. a) What did Bohr state about the atom, in other words what are the Bohr Postulates?
Bohr atomla ilgili olarak neler söyledi, diğer bir deyişle Bohr Postülaları nelerdir?

b) What are the failures of the Bohr Postulates about the quantum theory?
Bohr Postülaları'nın kuantum teorisi açısından eksiklikleri nelerdir?

4. What do the "energy levels" mean?
"Enerji seviyeleri" ne demektir?

5. a) What do you understand about the "particle in a box" term in physics?
Fizikte "Kutudaki parçacık" teriminden ne anlıyorsunuz?

b) What can be considered a particle in a box?
Bu parçacık ne olabilir?

c) Can you give an example from a physical situation about particle in a box?
Kutudaki parçacık durumuna fiziksel bir durumdan örnek verebilir misiniz?

d) Explain the "energy", "wavelength", and "velocity" for a particle in a box.
Kutudaki parçacık için "enerji", "dalga boyu" ve "hız" ı açıklayınız.

6. a) What do you understand about the "harmonic oscillator" term?
"Harmonik salınıcı" teriminden ne anlıyorsunuz?

b) Explain "energy" for a harmonic oscillator.
Bir harmonik salınıcı için "enerji" yi açıklayınız.

7. Did Bohr postulate the quantization of energy? What did he postulate about the quantization?
Bohr enerjinin kuantize olmasını (kuantumlanmasını, kuantumlu olmasını) önerdi mi? Kuantize olmaya ilişkin ne önerdi?

8. Compare Planck's and Bohr's explanations about quantization.
Planck ve Bohr'un kuantize olmaya ilişkin açıklamalarını karşılaştırınız.

Probing Procedure:
- Getting the student into the context,
- Discuss the physics of the context,
- Then discuss the quantization of physical observables depending on student's explanations in the context.

C.4 Questions for Interview III

QUESTIONS FOR INTERVIEW III

The aim of this study is to examine second-year physics and physics education students' mental models about some quantum physics concepts.

Interviewer :
Interviewee (name or pseudonym) :
Interview Date :
Interview Duration :
Interview Data Recorders :
Department : □ Physics □ Physics education
Gender : □ Female □ Male
Number of taking this course : □ First time □ Second time or more

<u>DIRECTIONS:</u> Dear student, the following questions are about the topics we have learned in the Modern Physics (PHYS 202) course. You can answer the questions however you want (i.e. verbally, drawings, mathematical expressions etc.). While answering the questions, think aloud if possible. Please state your reasons for your answer; in other words, explain what shaped your answers (books, classes, friends etc.). If you do not want to answer a question, you can skip it. There are both English and Turkish versions of each question. To express the answers in English is not compulsory; if you prefer, you can explain in Turkish. Recommended duration for this interview is 60 minutes.

<u>YÖNERGE:</u> Değerli öğrenci, aşağıda Modern Fizik (PHYS 202) dersinde öğrendiklerimize ilişkin sorular bulunmaktadır. Soruları isteğiniz şekilde yanıtlayabilirsiniz (mesela sözlü, çizimler, matematiksel ifadeler vb.). Soruları cevaplarken mümkün olduğunca sesli düşününüz. Lütfen cevabınızın sebeplerini, yani cevaplarınızı nelerin şekillendirdiğini (kitaplar, dersler, arkadaşlar) belirtiniz. Cevaplamak istemediğiniz soruyu geçebilirsiniz. Her sorunun İngilizce ve Türkçe versiyonu bulunmaktadır. Cevapları İngilizce açıklamak zorunlu değildir, isterseniz Türkçe açıklayabilirsiniz. Bu görüşme için öngörülen süre 60 dakikadır.

<u>QUESTIONS</u>

1. By considering the quantum theory of a hydrogen atom, what does the "*n*" term mean? What does it describe? Explain.
Bir Hidrojen atomu için kuantum teorisini göz önüne aldığımızda, "n" terimi ne anlama gelir? Neyi açıklar? Açıklayınız.

2. By considering the quantum theory of a hydrogen atom, what does the "*l*" term mean? What does it describe? Explain.
Bir Hidrojen atomu için kuantum teorisini göz önüne aldığımızda, "l" terimi ne anlama gelir? Neyi açıklar? Açıklayınız.

3. By considering the quantum theory of a hydrogen atom, what does the "m_l" term mean? What does it describe? Explain.
Bir Hidrojen atomu için kuantum teorisini göz önüne aldığımızda, m_l" terimi ne anlama gelir? Neyi açıklar? Açıklayınız.

4. Explain "*n*"," *l*", "m_l" terms for the Bohr atom? Compare with quantum mechanical model of atom.
Bohr atomu için "n"," l", "m_l" terimlerini açıklayınız. Kuantum mekaniksel atom modeli ile karşılaştırınız.

5. What do you understand about the "quantum mechanical model of an atom"?
"Kuantum mekaniksel atom modelinden" ne anlıyorsunuz?

6. By considering the quantum theory of an atom, what does the "m_s" term mean? What does it describe? Explain.
Bir atom için kuantum teorisini göz önüne aldığımızda, m_s" terimi ne anlama gelir? Neyi açıklar? Açıklayınız.

Probing Procedure:

- Getting the student into the context,
- Discuss the physics of the context,
- Then discuss the quantization of physical observables depending on student's explanations in the context.

C.5 Questions for Overall Interview

QUESTIONS FOR OVERALL INTERVIEW

The aim of this study is to examine second-year physics and physics education students' mental models about some quantum physics concepts.

Interviewer :
Interviewee (name or pseudonym) :
Interview Date :
Interview Duration :
Interview Data Recorders :
Department : □ Physics □ Physics education
Gender : □ Female □ Male
Number of taking this course : □ First time □ Second time or more

<u>DIRECTIONS:</u> Dear student, the following questions are about the topics we have learned in the Modern Physics (PHYS 202) course. You can answer the questions however you want (i.e. verbally, drawings, mathematical expressions etc.). While answering the questions, think aloud if possible. Please state your reasons for your answer; in other words, explain what shaped your answers (books, classes, friends etc.). If you do not want to answer a question, you can skip it. There are both English and Turkish versions of each question. To express the answers in English is not compulsory; if you prefer, you can explain in Turkish. Recommended duration for this interview is 45 minutes.

<u>YÖNERGE:</u> Değerli öğrenci, aşağıda Modern Fizik (PHYS 202) dersinde öğrendiklerimize ilişkin sorular bulunmaktadır. Soruları isteğiniz şekilde yanıtlayabilirsiniz (mesela sözlü, çizimler, matematiksel ifadeler vb.). Soruları cevaplarken mümkün olduğunca sesli düşününüz. Lütfen cevabınızın sebeplerini, yani cevaplarınızı nelerin şekillendirdiğini (kitaplar, dersler, arkadaşlar) belirtiniz. Cevaplamak istemediğiniz soruyu geçebilirsiniz. Her sorunun İngilizce ve Türkçe versiyonu bulunmaktadır. Cevapları İngilizce açıklamak zorunlu değildir, isterseniz Türkçe açıklayabilirsiniz. Bu görüşme için öngörülen süre 45 dakikadır.

<u>QUESTIONS</u>

1. What does “quantum” mean in physics?
Fizikte “kuantum” ne anlama gelir?

2. What does “quantization” mean in physics?
Fizikte “kuantize olma (kuantumlanma, kuantumlu olma)” ne anlama gelir?

3. Compare “quantization” for classical physics and quantum physics?
Klasik fizik ve kuantum fiziği için “kuantize olma” durumunu karşılaştırınız.

4. What are the quantized physical observables that you have learned in this course? Explain where and how this quantization occurs, and give some evidence.
Bu derste öğrendiğimiz hangi gözlenebilir fiziksel büyüklükler kuantizedir? Hangi durumlarda (nerede) ve nasıl kuantize olduğunu açıklayınız, ve deliller gösteriniz.

5. Interpret the following physical events by considering quantization:

- Blackbody radiation and ultraviolet catastrophe
- Photoelectric experiment
- Energy levels and atomic spectra
- Particle in a box
- Harmonic oscillator
- Atom (the Bohr atom and the quantum mechanical model of an atom)

Aşağıdaki fiziksel olayları kuantize olma durumu açısından yorumlayınız:

- *Karacisim ışıması ve morötesi felaket*
- *Fotoelektrik deneyi*
- *Enerji seviyeleri ve atomik spektra*
- *Kutudaki parçacık*
- *Harmonik salınıcı*
- *Atom (Bohr atomu ve kuantum mekaniksel atom modeli)*

C.6 Questions for Final Comprehensive Interview

QUESTIONS FOR FINAL COMPREHENSIVE INTERVIEW

The aim of this study is to examine second-year physics and physics education students' mental models about some quantum physics concepts.

Interviewer :
Interviewee (name or pseudonym) :
Interview Date :
Interview Duration :
Interview Data Recorders :
Department : □ Physics □ Physics education
Gender : □ Female □ Male
Number of taking this course : □ First time □ Second time or more

DIRECTIONS: Dear student, the following questions are about the topics we have learned in the Modern Physics (PHYS 202) course. You can answer the questions however you want (i.e. verbally, drawings, mathematical expressions etc.). While answering the questions, think aloud if possible. Please state your reasons for your answer; in other words, explain what shaped your answers (books, classes, friends etc.). If you do not want to answer a question, you can skip it. There are both English and Turkish versions of each question. To express the answers in English is not compulsory; if you prefer, you can explain in Turkish. Recommended duration for this interview is 45 minutes.

YÖNERGE: Değerli öğrenci, aşağıda Modern Fizik (PHYS 202) dersinde öğrendiklerimize ilişkin sorular bulunmaktadır. Soruları isteğiniz şekilde yanıtlayabilirsiniz (mesela sözlü, çizimler, matematiksel ifadeler vb.). Soruları cevaplarken mümkün olduğunca sesli düşününüz. Lütfen cevabınızın sebeplerini, yani cevaplarınızı nelerin şekillendirdiğini (kitaplar, dersler, arkadaşlar) belirtiniz. Cevaplamak istemediğiniz soruyu geçebilirsiniz. Her sorunun İngilizce ve Türkçe versiyonu bulunmaktadır. Cevapları İngilizce açıklamak zorunlu değildir, isterseniz Türkçe açıklayabilirsiniz. Bu görüşme için öngörülen süre 45 dakikadır.

QUESTIONS

1. What does "quantum" mean in physics?
Fizikte "kuantum" ne anlama gelir?

2. What does "quantization" mean in physics?
Fizikte "kuantize olma (kuantumlanma, kuantumlu olma)" ne anlama gelir?

3. Compare "quantization" for classical physics and quantum physics?
Klasik fizik ve kuantum fiziği için "kuantize olma" durumunu karşılaştırınız.

4. What are the <u>quantized physical observables</u> which you have learned in this course? Explain where and how this quantization occurs, and give some evidence.
Bu derste öğrendiğimiz hangi gözlenebilir fiziksel büyüklükler kuantizedir? Hangi durumlarda (nerede) ve nasıl kuantize olduğunu açıklayınız, ve deliller gösteriniz.

5. Interpret the following physical events by considering quantization:

- Blackbody radiation and ultraviolet catastrophe
- Photoelectric experiment
- Energy levels and atomic spectra
- Particle in a box
- Harmonic oscillator
- Atom (the Bohr atom and the quantum mechanical model of an atom)

Aşağıdaki fiziksel olayları kuantize olma durumu açısından yorumlayınız:

- *Karacisim ışıması ve morötesi felaket*
- *Fotoelektrik deneyi*
- *Enerji seviyeleri ve atomik spektra*
- *Kutudaki parçacık*
- *Harmonik salınıcı*
- *Atom (Bohr atomu ve kuantum mekaniksel atom modeli)*

C.7 Questions for Self-Evaluation Interview

QUESTIONS FOR SELF-EVALUATION INTERVIEW

The aim of this study is to examine second-year physics and physics education students' mental models about some quantum physics concepts.

Interviewer :
Interviewee (name or pseudonym) :
Interview Date :
Interview Duration :
Interview Data Recorders :
Department : □ Physics □ Physics education
Gender : □ Female □ Male
Number of taking this course : □ First time □ Second time or more

DIRECTIONS: Dear student, the following questions aim to identify evaluation of yourself (i.e. awareness of your knowledge, your performance during the semester etc.). If you do not want to answer a question, you can skip it. There are both English and Turkish versions of each question. To express the answers in English is not compulsory; if you prefer, you can explain in Turkish. Recommended duration for this interview is 30 minutes.

YÖNERGE: Değerli öğrenci, aşağıdaki sorular sizin kendinizi değerlendirmenizi (bilginizden haberdarlığınız, dönem süresince performansınız vs.) tespit etmeyi amaçlamaktadır. Cevaplamak istemediğiniz soruyu geçebilirsiniz. Her sorunun İngilizce ve Türkçe versiyonu bulunmaktadır. Cevapları İngilizce açıklamak zorunlu değildir, isterseniz Türkçe açıklayabilirsiniz. Bu görüşme için öngörülen süre 30 dakikadır.

QUESTIONS

1. When you consider your learning, did you ask questions such as "What am I doing? How do I learn? Why do I learn?" to yourself?
Öğrenmenizi göz önüne aldığınızda, kendinize "Ben ne yapıyorum? Nasıl öğreniyorum? Niçin öğreniyorum?" gibi sorular sordunuz mu?

2. Do you have any idea about your knowledge (what you know and do not know) and your cognitive process? Do you have some strategies about how you obtain the knowledge better?
Bilginiz (neyi bilip bilmediğiniz) ve bilişsel süreçleriniz hakkında bir fikriniz var mı? Bilgiye daha iyi nasıl ulaşacağınıza dair stratejileriniz var mı?

3. In the Modern Physics course, how often did you hear the terms "quantization" and "quantized" ? In which topics have you heard them?
Modern Fizik dersinde "kuantize olma" ve "kuantize" terimlerini hangi sıklıkta duydunuz? Hangi konularda duydunuz?

4. What can you say about the conceptual development of these concepts when you first heard about it? Do you feel a development in your understanding about these concepts?
Bu kavramları ilk duyduğunuzdan itibaren sizdeki kavramsal gelişimi hakkında ne söylersiniz? Bu kavramları anlamanızda bir gelişim hissettiniz mi?

5. Did studying for the final exam contribute to your understanding of this phenomenon?
Final sınavına çalışmak bu olgunun anlaşılmasına katkı sağladı mı?

6. Do you believe you understand the quantization of some physical observables?
Bazı gözlenebilir fiziksel büyüklüklerin kuantize (kuantumlu) yapıda olmasını anladığınıza inanıyor musunuz?

7. What are the most effective factors that shape your understanding of the quantization phenomenon?
Bu olguyu anlamanızı *şekillendiren en etkili faktörler nelerdir?*

8. Would you like to say any other things to explain about quantization and your understanding of this phenomenon?
Kuantize olma ve bu olguyu anlamanıza ilişkin belirtmek istediğiniz başka şeyler var mı?

C.8: Interview with the Instructor

INTERVIEW WITH THE INSTRUCTOR

The aim of this study is to examine second-year physics and physics education students' mental models about some quantum physics concepts.

Interviewer :
Interviewee :
Interview Date :
Interview Duration :
Interview Data Recorders :

<u>**DIRECTIONS:**</u> **Dear professor, the following questions aim to identify your evaluation of the Modern Physics course in this semester in general manner. If you do not want to answer a question, you can skip it. There are both English and Turkish versions of each question. To express the answers in English is not compulsory; if you prefer, you can explain in Turkish. Recommended duration for this interview is 30 minutes.**

<u>YÖNERGE:</u> Sayın profesör, aşağıdaki sorular sizin bu dönemki Modern Fizik dersini genel anlamda değerlendirmenizi tespit etmeyi amaçlamaktadır. Cevaplamak istemediğiniz soruyu geçebilirsiniz. Her sorunun İngilizce ve Türkçe versiyonu bulunmaktadır. Cevapları İngilizce açıklamak zorunlu değildir, isterseniz Türkçe açıklayabilirsiniz. Bu görüşme için öngörülen süre 30 dakikadır.

<u>**QUESTIONS**</u>

1. What do you think about the success of the students in the Modern Physics course in this semester?
Öğrencilerin bu dönemki Modern Fizik dersindeki başarıları hakkında ne düşünüyorsunuz?

2. What do you think about students' understanding about the quantization of some physical observables? If they did not understand, what can you say about its' reasons?
Öğrencilerin bazı gözlenebilir fiziksel büyüklüklerin kuantize (kuantumlu) yapısını anlamalarına ilişkin ne düşünüyorsunuz? Eğer anlamamışlar ise bunun sebepleri hakkında ne söylersiniz?

3. What do you think about the similarity of models used by students and the models used by you in the classes? Are they parallel? How are the models in terms of scientific rigor?
Öğrencilerin kullandığı modeller ile sizin sınıfta kullandığınız modellerin benzerliği hakkında ne düşünüyorsunuz? Bunlar paralel midir? Bilimsel açıdan bu modeller nasıldır?

4. According to you, how do external sources shape students' models used while explaining concepts?
Sizce dış kaynaklar öğrencilerin kavramları açıklarken kullandığı modelleri nasıl etkiler?

APPENDIX D

THE INTERVIEWS CONDUCTED WITH EACH PARTICIPANT

CODE	GROUP	GENDER	DEPT.	Pre-interview	Interview I	Interview II	Interview III	Overall Interview	Final Compr. Int.	Self-Evaluation Int.
ST1	CORE	F	PHED	☺	☺	☺	☺	☺	☺	☺
ST2	CORE	M	PHED	☺	☺	☺	☺	☺	☺	☺
ST3	CORE	M	PHYS	☺	☺	☺	☺	☺	☺	☺
ST4	CORE	M	PHYS	☺	☺	☺	☺	☺	☺	☺
ST5	CORE	M	PHED	☺	☺	☺	☺	☺	☺	☺
ST6	CORE	M	PHYS	☺	☺	☺	☺	☺	☺	☺
ST7	CORE	F	PHYS	☺	☺	☺	☺	☺	☺	☺
ST8	CORE	M	PHED	☺	☺	☺	☺	☺	☺	☺
ST9	SECONDARY	F	PHYS	☺				☺	☺	☺
ST10	SECONDARY	M	PHYS	☺				☺	☺	☺
ST11	SECONDARY	M	PHYS	☺				☺	☺	☺
ST12	SECONDARY	F	PHED	☺				☺	☺	☺
ST13	SECONDARY	F	PHYS	☺				☺	☺	☺
ST14	SECONDARY	F	PHYS	☺				☺	☺	☺
ST15	SECONDARY	F	PHYS	☺				☺	☺	☺
ST16	SECONDARY	F	PHED	☺				☺	☺	☺
ST17	SECONDARY	M	PHYS	☺				☺	☺	☺
ST18	SECONDARY	M	PHYS	☺				☺	X	☺
ST19	SECONDARY	M	PHYS	☺				☺	X	X
ST20	SECONDARY	M	PHYS	☺				☺	☺	☺
ST21	SECONDARY	M	PHYS	☺				☺	X	☺
ST22	SECONDARY	M	PHED	☺				☺	☺	☺
ST23	SECONDARY	F	PHYS	☺				☺	☺	☺
ST24	SECONDARY	F	PHED	☺				☺	X	☺
ST25	SECONDARY	M	PHED	☺				☺	☺	☺
ST26	SECONDARY	M	PHED	☺				☺	☺	☺
ST27	SECONDARY	F	PHYS	☺				☺	X	X
ST28	SECONDARY	M	PHED	☺				☺	☺	☺
ST29	SECONDARY	F	PHYS	☺				☺	☺	☺
ST30	SECONDARY	F	PHYS	☺				☺	☺	☺
ST31	SECONDARY	M	PHYS	☺				☺	☺	☺

and an interview (☺) with the INSTRUCTOR

DESCRIPTIONS		
☺	Interview exists	18 Male students participated in the study
X	Interview does not exist	13 Female students participated in the study
PHYS	Students from Physics Department	20 Physics students participated in the study
PHED	Students from Physics-Education Department	11 Physics education students participated in the study
M	Male students	
F	Female students	
DEPT	Department	

APPENDIX E

TEST ABOUT THE QUANTIZATION OF PHYSICAL OBSERVABLES

TEST (PHYS 202)

Name Surname :
Year :
Department : □ Physics □ Physics education
Gender : □ Female □ Male
Age : □ 18-20 □ 21-24 □ >24

DIRECTIONS: Dear student, the following questions are about the topics we have learned in the Modern Physics (PHYS 202) course. You can answer the questions however you want (i.e. verbally, drawings, mathematical expressions etc.). If you do not want to answer a question, you can skip it. There are both English and Turkish versions of each question. To express the answers in English is not compulsory; if you prefer, you can explain in Turkish. Recommended duration for this test is 30 minutes.

YÖNERGE: Değerli öğrenci, aşağıda Modern Fizik (PHYS 202) dersinde öğrendiklerimize ilişkin sorular bulunmaktadır. Soruları isteğiniz şekilde yanıtlayabilirsiniz (mesela sözlü, çizimler, matematiksel ifadeler vb.). Cevaplamak istemediğiniz soruyu geçebilirsiniz. Her sorunun İngilizce ve Türkçe versiyonu bulunmaktadır. Cevapları İngilizce açıklamak zorunlu değildir, isterseniz Türkçe açıklayabilirsiniz. Bu test için öngörülen süre 30 dakikadır.

QUESTIONS

1. What does "quantum" mean in physics?
Fizikte "kuantum" ne anlama gelir?

2. What does "quantization" mean in physics?
Fizikte "kuantize olma (kuantumlanma, kuantumlu olma)" ne anlama gelir?

3. Compare "quantization" for classical physics and quantum physics?
Klasik fizik ve kuantum fiziği için "kuantize olma" durumunu karşılaştırınız.

4. What are the quantized physical observables which you have learned in this course? Explain where and how this quantization occurs, and give some evidence.
Bu derste öğrendiğimiz hangi gözlenebilir fiziksel büyüklükler kuantizedir? Hangi durumlarda (nerede) ve nasıl kuantize olduğunu açıklayınız, ve deliller gösteriniz.

APPENDIX F

SAMPLE NOTES FROM THE DIARY

8. Hafta 06/04/2009

14. Ders

I. sınavdan önceki son dersti. Bu ders kuantumlu enerjinin vurgulanması ve klasik ve kuantum fiziği için kuantize durumların karşılaştırılması açısından çok önemliydi.

Atomda elektronun her enerji değerini alamadığını kürsünün basamakları ile analoji kurularak verilmesi de kavramın öğrenciler tarafından daha kolay anlaşılması açısından önemliydi.

15. Hafta 28/05/2009

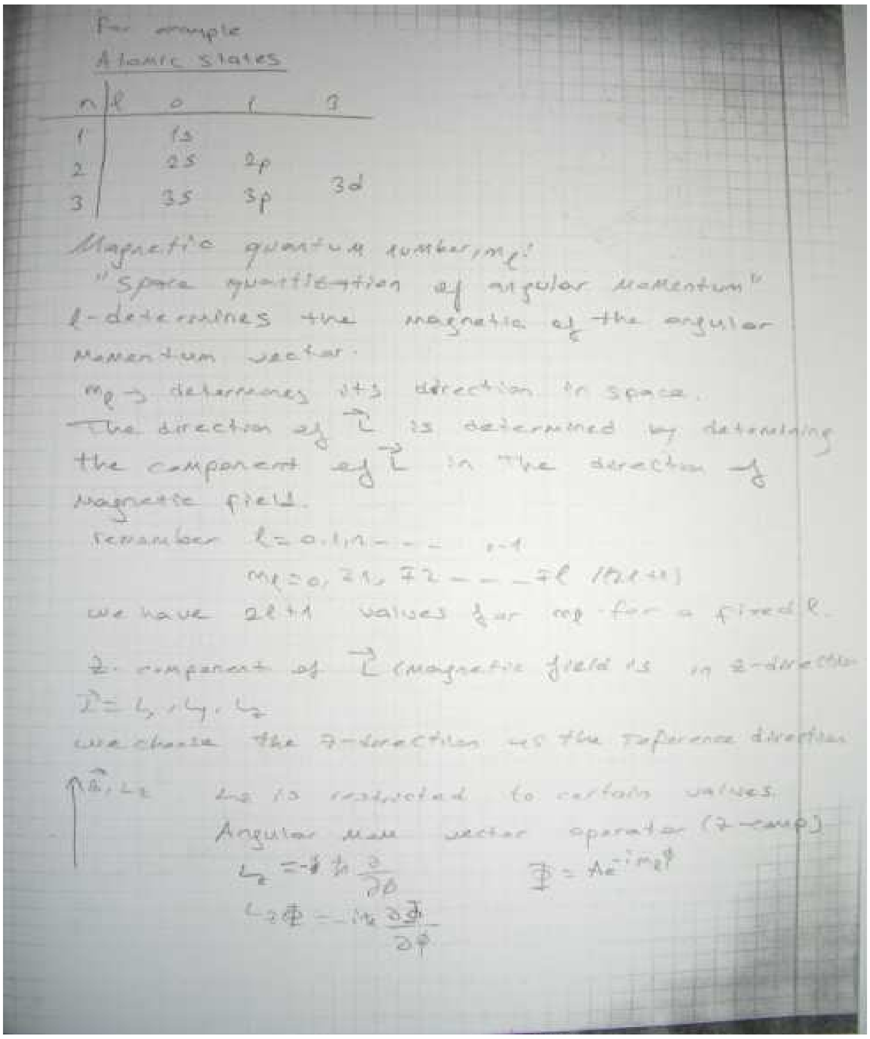
29. Ders

St2, St 8 ve St 20 ders arasında modern atom modelinde açısal momentumun yönünün kuantumlu olması durumunu tartışıyorlar. St2 açıklama yapıyor, St 8 ve St 20 emin olamadıklarını belirtiyorlar

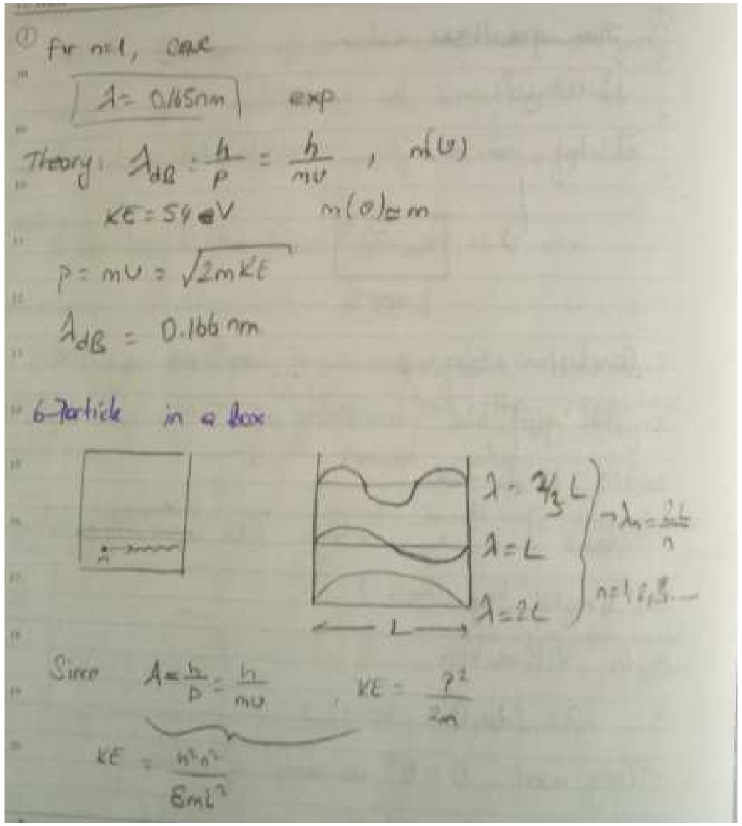
APPENDIX G

SOME SAMPLES FROM OTHER DOCUMENTS

G.1: Sample Pages from the Students' Notebooks



From the notebook of St4 (notes about Context 6.b2: Quantum Atom)



For n=1, CRR

$\lambda = 0.165nm$ exp

Theory: $\lambda_{dB} = \frac{h}{p} = \frac{h}{mv}$, m(v)

$KE = 54\ eV$ $m(0) \cong m$

$p = mv = \sqrt{2mKE}$

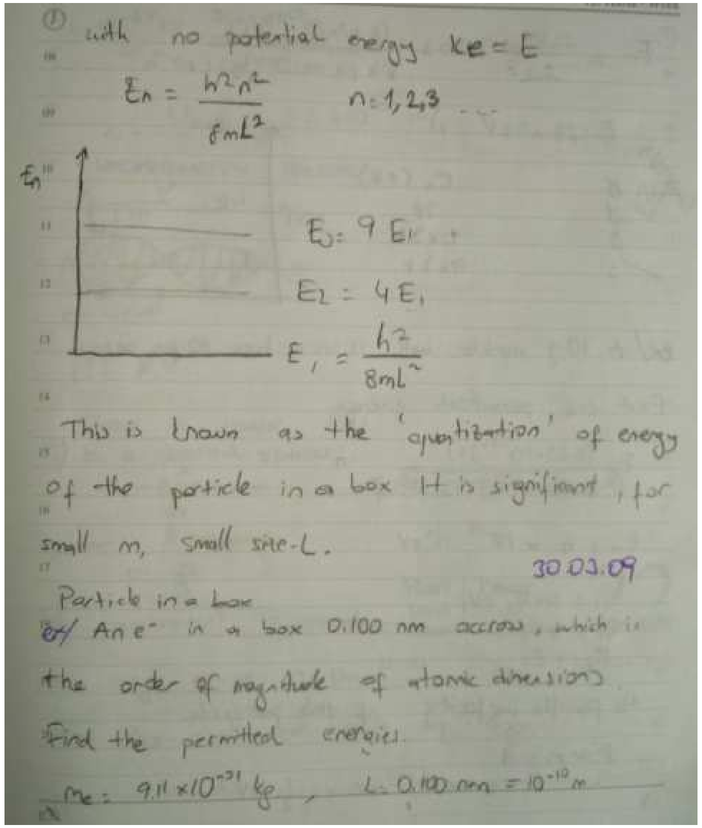
$\lambda_{dB} = 0.166\ nm$

6- Particle in a box

$\lambda = \frac{2}{3}L$, $\lambda = L$, $\lambda = 2L$ → $\lambda_n = \frac{2L}{n}$, $n = 1, 2, 3 \ldots$

Since $\lambda = \frac{h}{p} = \frac{h}{mv}$, $KE = \frac{p^2}{2m}$

$KE = \frac{h^2 n^2}{8mL^2}$



with no potential energy KE = E

$E_n = \frac{h^2 n^2}{8mL^2}$ $n = 1, 2, 3 \ldots$

$E_3 = 9E_1$

$E_2 = 4E_1$

$E_1 = \frac{h^2}{8mL^2}$

This is known as the 'quantization' of energy of the particle in a box. It is significant, for small m, small size-L.

30.03.09

Particle in a box

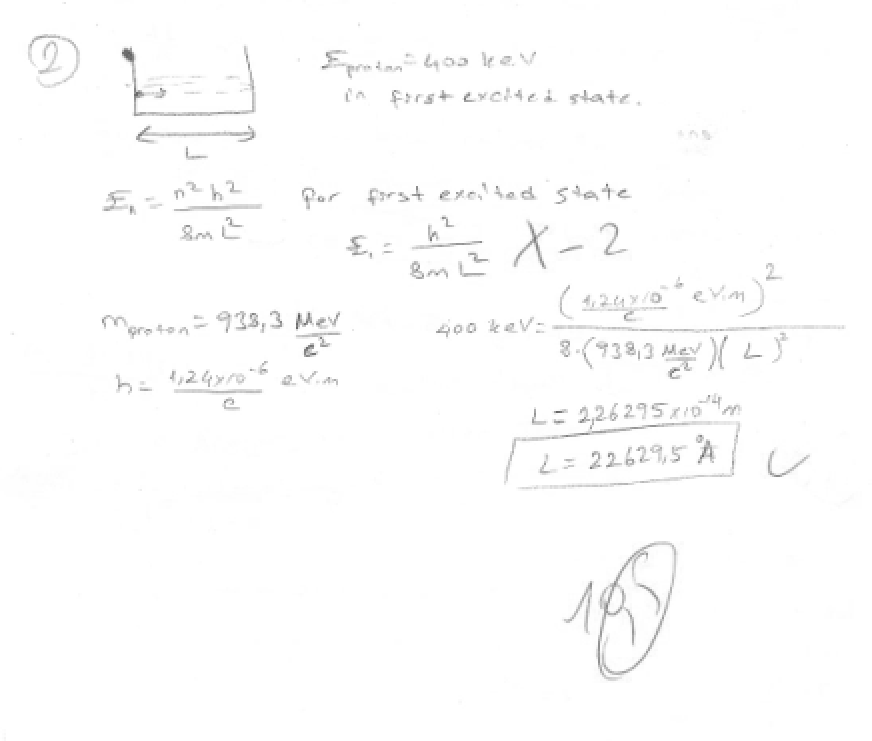
ex/ An e^- in a box 0.100 nm across, which is the order of magnitude of atomic dimensions. Find the permitted energies.

$m_e = 9.11 \times 10^{-31}\ kg$, $L = 0.100\ nm = 10^{-10}\ m$

From the notebook of St1 (notes about Context 3: Energy levels and atomic spectra)

G.2: A Sample Homework Paper

Question 2: A proton in a one-dimensional box has energy of 400 keV in its first excited state. How wide is the box?



(2)

$E_{proton} = 400$ keV in first excited state.

$E_n = \frac{n^2 h^2}{8mL^2}$ For first excited state $E_1 = \frac{h^2}{8mL^2}$ X − 2

$m_{proton} = 938,3 \frac{MeV}{c^2}$

$h = \frac{1,24 \times 10^{-6}}{c}$ eV.m

$400 \text{ keV} = \frac{\left(\frac{1,24 \times 10^{-6}}{c} \text{ eV.m}\right)^2}{8 \cdot (938,3 \frac{MeV}{c^2})(L)^2}$

$L = 2,26295 \times 10^{-4}$ m

$L = 22629,5$ Å ✓

185

From the 4th Homework of St11

G.3: A Sample Quiz Paper

QUIZ 2

1. The work function of a tungsten surface is 5.4 eV. When the surface is illuminated by a light of wavelength 175 nm, the maximum photoelectron energy is 1.7 eV. Find Planck's constant form these data.

$KE_{max} = h\nu - \phi$

$1{,}7\ eV = \frac{hc}{\lambda} - 5{,}4\ eV \qquad \frac{hc}{\lambda} = 7{,}1\ eV$

$h = \frac{175 \times 10^{-9}\ m \times 7{,}1 \times 1{,}6 \times 10^{-19}\ J}{3 \times 10^{8}\ m/s}$

$h = 6{,}627 \times 10^{-34}\ Js$

2. What can you say about (1) the physical meaning and (2) the importance of Planck's constant?

1) The photon energies are quantized.

2) with the help of this constant, Plank could explain the ultraviolet catastroph.

From the Quiz Paper of St25

APPENDIX H

CODING BOOKLETS

H.1 Coding Booklet for Investigation of Knowledge Organizations

Coding Booklet for Investigation of Knowledge Organizations

CODING INSTRUCTIONS:

This Coding Booklet is a common for the interview, textbook and observation data to investigate of knowledge organizations.

For Interview Data

1. A sentence/figure/formula can be coded maximum one time with the same code although there might be more than one “chunk” corresponding to a code.
2. Student’s repetition of the question by him/herself, and statement of the chunk of a question that corresponds to a code will not be coded.

For Textbook data

1. A sentence/figure/formula can be coded maximum one time with the same code although there might be more than one “chunk” corresponding to a code.
2. Related sentences connected with “;” and “:” will be accepted as separate sentences and coded separately.
3. Explanations in the parentheses will be coded as a part of a sentence.
3. “Title”, “figure legend”, “table title”, “the explanation following a formula” will be coded, but “running head of the chapters/sections” will not be coded.
4. The sections and chapters that are not covered in the course will not be included.
5. If the formulas following each other are called with different numbers, they will be considered as different formulas.
6. The chunks of mathematical explanations (i.e. numerical examples) stated in the text will be coded as a part of a sentence, they will not be coded as separate formulas.

For Observation Data

1. A sentence/figure/formula can be coded maximum one time with the same code although there might be more than one “chunk” corresponding to a code.
2. The statements expressed by a different type of method of explanation (i.e. both verbal and on the board explanations) at the same time will be coded separately.
3. Body language accompanying with verbal explanations will be coded separately.

The Codes for Investigation of Knowledge Organizations

NO	CODE	ABBR.	DEFINITION OF THE CODE
1	**Only bound particle**	OBP	Specificity of the quantization of physical observables for only the particle confined in a region.
2	**Discreteness[(1)] or/and Discreteness characteristic[(2)]**	D/DC	[(1)] For the physical observables such as energy, angular momentum, having only discrete values. [(2)] Restriction of the values of the physical observables, and so having only certain (allowed) values.
3	**Natural characteristic**	NC	Specificity of the quantization of physical observables for the nature of atomic systems.
4	**Any values**	AV	No restriction of the values of the physical observables, and having any values.
5	**Artificial characteristic**	AC	Externally manipulation of the values of the physical observables.
6	**Einstein's relativity**	ER	Considering the quantization of physical observables as a phenomenon of Einstein's theory of relativity.
7	**Change**	C	Considering the quantization of physical observables as any kind of change.
8	**Integration**	I	Considering the quantization of physical observables as an integration process to make the values of the physical observables continuous.
9	**Every particle**	EP	Considering the quantization of physical observables is observed for every atomic particle.

H.2 Coding Booklet for Investigation of the Sources Influencing Mental Models

Coding Booklet for Investigation of the Sources Influencing Mental Models

CODING INSTRUCTIONS:

This Coding Booklet is specific for the interview data to investigate the sources influencing students' mental models.

1. A sentence/figure/formula can be coded maximum one time with the same code although there might be more than one "chunk" corresponding to a code.
2. Student's repetition of the question by him/herself and "statement of the chunk of a question that corresponds to a code" will not be coded.

External Sources (The sources that come out from students' environment)

NO	CODE	ABBR.	DEFINITION OF THE CODE
1	**Textbook**	ES-T	The textbooks that students interact with in and out of the classroom setting.
2	**Instructional elements** ***2.1*** *Instruction* ***2.2*** *Instructional activities* ***2.3*** *Instructor*	ES-(I)INS ES-(I)IAC ES-(I)I	Course setting that modern physics concepts are taught in. **(2.1)** The instructional issues considered in the modern physics classes. **(2.2)** All activities that students engage in and out of the modern physics classes such as preparation before and after modern physics classes, attendance, taking notes in the classes, doing homework, studying for examinations. **(2.3)** The attitude and motivation of the instructor towards to course and students.
3	**Topic order**	ES-TO	Arrangement of the modern physics concepts while teaching.
4	**Classmate**	ES-C	Friends whom students interact with in and out of the classroom setting.
5	**Extra sources for learning**	ES-ESL	The additional sources such as books, internet etc. that are used for learning modern physics concepts.

Internal Sources (The sources that come out from students' own personality)

NO	CODE	ABBR.	DEFINITION OF THE CODE
1 Meta-cognitive	**1.1 Meta-cognition** ***1.1.a*** *Awareness* ***1.1.b*** *Satisfaction* ***1.1.c*** *Regulation*	 IS- (MC)A IS-(MC)S IS-(MC)R	**(1.1)** Act of thinking about students' own mental process. **(1.1.a)** Being aware of what individual knows and does not know, how s/he thinks etc. **(1.1.b)** Feeling frustration or satisfaction of own knowledge. **(1.1.c)** Strategies to regulate own cognitive process.
2 Affective	**2.1 Motivation** ***2.1.a*** *Interest* ***2.1.b*** *Utility*	 IS-(MOT)I IS-(MOT)U	**(2.1)** Willingness for learning. **(2.1.a)** Enjoyment in an activity while learning. **(2.1.b)** Consideration of future needs for learning.
3 Cognitive	**1.1 Belief** ***3.1.a*** *Nature of science* ***3.1.b*** *Nature of quantum concepts*	 IS-(B)NOS IS-(B)NQC	**(3.1)** Acceptance of an idea as true. **(3.1.a)** Beliefs about scientific knowledge, scientific methods, and nature of facts/formulas. **(3.1.b)** Beliefs about the structure (abstractness, counter-intuitiveness, mathematical formalism etc.) of quantum concepts.
4 Others	**4.1 Familiarity**	IS-F	**(4.1)** Being familiar or unfamiliar with some concepts from classical mechanics.
	4.2 Background Knowledge	IS-BK	**(4.2)** Having information about some physics concepts discussed in the contexts (i.e. energy, angular momentum etc.).

H.3 Coding Booklet for the Methodology of the Textbooks

Coding Booklet for the Methodology of the Textbooks to Explain Quantization

CODING INSTRUCTIONS:

This Coding Booklet is specific for the textbook data to investigate the methodology of the textbooks while explaining the quantization phenomenon.

For Textbook data

1. A sentence/figure/formula can be coded maximum one time with the same code although there might be more than one "chunk" corresponding to a code.
2. Related sentences connected with ";" and ":" will be accepted as separate sentences and coded separately.
3. Explanations in the parentheses will be coded as a part of a sentence.
3. "Title", "figure legend", "table title", "the explanation following a formula" will be coded, but "running head of the chapters/sections" will not be coded.
4. The sections and chapters that are not covered in the course will not be included.
5. If the formulas following each other are called with different numbers, they will be considered as different formulas.
6. The chunks of mathematical explanations (i.e. numerical examples) stated in the text will be coded as a part of a sentence, they will not be coded as separate formulas.

The codes for method of explanation

NO	***CODE***	**ABBR.**	***DEFINITION OF THE CODE***
1	**Pictorial**	mthd- P	Pictorial elements such as real pictures, graphs, drawings to explain the quantization of physical observables.
2	**Textual** **2.1** *Regular sentences* **2.2** *Comparison of classical and quantum physics* **2.3** *History of science* **2.4** *Analogy* **2.5** *Notification/title* **2.6** *Reminder*	mthd- (T)RS mthd- (T)C&Q mthd- (T)HOS mthd- (T)A mthd- (T)N/T mthd- (T)R	Textual explanation of the quantization of physical observables. **(2.1)** Explanation with regular sentences. **(2.2)** Explanation by comparing the classical and quantum events. **(2.3)** Explanation by explaining scientists' life and contributions to science, development of science etc. **(2.4)** Making comparison with familiar knowledge domain to explain unfamiliar concepts. **(2.5)** Explanation with warnings. **(2.6)** Explanation by recalling the previous ideas.
3	**Mathematical** **3.1** *Mathematical relations* **3.2** *Exemplification*	mthd- (M)MR mthd- (M)E	Symbolic explanation of the quantization of physical observables. **(3.1)** Explanation with formulas. **(3.2)** Explanation with numerical calculations.

H.4 Coding Booklet for the Methodology used in the Classes

Coding Booklet for the Methodology used in the Classes to Explain Quantization

CODING INSTRUCTIONS:

This Coding Booklet is specific for the observation data to investigate the methodology used in the modern physics classes to explain the quantization phenomenon.

For Observation Data

1. A sentence/figure/formula can be coded maximum one time with the same code although there might be more than one "chunk" corresponding to a code.
2. The statements expressed by a different type of method of explanation (i.e. both verbal and on the board explanations) at the same time will be coded separately.
3. Body language accompanying with verbal explanations will be coded separately.

The codes for method of explanation

NO	*CODE*	ABBR.	*DEFINITION OF THE CODE*
1	**Verbal** **1.1** *Regular sentences* **1.2** *Comparison of classical and quantum physics* **1.3** *History of science* **1.4** *Story* **1.5** *Analogy* **1.6** *Notification/title* **1.7** *Reminder* **1.8** *Mathematical*	 mthd-(V)RS mthd-(V)C&Q mthd-(V)HOS mthd-(V)S mthd-(V)A mthd-(V)N/T mthd-(V)R mthd-(V)M	Verbal explanation of the quantization of physical observables. **(1.1)** Explanation with regular sentences. **(1.2)** Explanation by comparing the classical and quantum events. **(1.3)** Explanation by explaining scientists' life and contributions to science, development of science etc. **(1.4)** Explanation with the stories from daily life. **(1.5)** Making comparison with familiar knowledge domain to explain unfamiliar concepts. **(1.6)** Explanation with warnings. **(1.7)** Explanation by recalling the previous ideas. **(1.8)** Explanation with formulas.
2	**On the Board** **2.1** *Pictorial* **2.2** *Mathematical relations* **2.3** *Exemplification* **2.4** *Regular sentences* **2.5** *Notification/title* **2.6** *Reminder*	 mthd-(OB)P mthd-(OB)MR mthd-(OB)E mthd-(OB)RS mthd-(OB)N/T mthd-(OB)R	Explanation of the quantization of physical observables on the board. **(2.1)** Explanation with pictorial elements such as figures, graphs. **(2.2)** Explanation with formulas. **(2.3)** Explanation with numerical calculations. **(2.4)** Explanation with regular sentences. **(2.5)** Explanation with warnings. **(2.6)** Explanation by recalling the previous ideas.
3	**Body Language**	mthd-BL	Explanation of the quantization of physical observables by body language such as using hand motion, stepping etc.

APPENDIX I

VALIDITY ISSUES

I.1 A Checklist for Content Related Evidence for Validity

Checklist for Interview Questions

The aim of this study is to examine second-year physics and physics education students' mental models about some quantum mechanical concepts.

EXPERT INFORMATION
Name - Surname :
Title :
Area of Expertise :
Date :

DIRECTIONS: Dear professor, there are two parts in the checklist. First part is about content of the questions, and the second part is about the format of the questions. After examining the questions, please mark relevant boxes for each item in the checklist. At the end of the checklist, please make comment and express your suggestions in order to make the questions better in terms of content and format.

YÖNERGE: Sayın profesör, kontrol listesinde 2 bölüm yer almaktadır. Birinci bölüm soruların içeriği, ikinci bölüm ise soruların biçimi ile ilgilidir. Lütfen her soruları inceledikten sonra kontrol listesindeki her ifade için ilgili kutuyu işaretleyiniz. Soruları içerik ve biçim bakımından daha iyi yapabilmek için kontrol listesinin sonunda lütfen yorumlarınızı ve önerilerinizi belirtiniz.

CONTENT OF THE QUESTIONS				
item no	**items**	**weak**	**should be developed**	**strong**
1	Each question is appropriate with the aim.			
2	Each question is comprehensive.			
3	Content of each question is appropriate with the topic.			
4	Each question represents the central idea.			
5	Each question requires students to engage in reasoning.			

FORMAT OF THE QUESTIONS				
Item no	**Items**	**Weak**	**Should be developed**	**Strong**
1	Readability of each question is appropriate for students' grade level.			
2	Drawings in the questions are appropriate.			
3	Language of each question is clear.			
4	Instructions are clear.			
5	Clarity of printing is good.			
6	There is adequate workspace for solution.			
7	Difficulty level of each question is appropriate for students.			
8	Time for solution is enough.			
9	Each question has only one meaning.			
10	There is no clue about the answer.			

YOUR COMMENTS AND SUGGESTIONS ABOUT THE QUESTIONS

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I.2 Peer Review Document for Validation of Coding

Peer Review Checklist I

The aim of this study is to examine second-year physics and physics education students' mental models about some quantum mechanical concepts.

EXPERT INFORMATION
Name - Surname :
Title :
Area of Expertise :
Date :

DIRECTIONS: Dear expert, this checklist requests you to examine the appropriateness of the coding on students' explanations by using the coding booklet developed in this study. Please check the coding and state your changes when needed. Please find the related coding booklet in the attachment.

YÖNERGE: Sayın uzman, bu kontrol listesi bu araştırmada geliştirilen kodlama kitapçığını kullanarak öğrencilerin açıklamaları üzerindeki kodlamaların uygunluğunu incelemenizi istemektedir. Lütfen kodlamayı kontrol ediniz ve gerektiğinde değişikliklerinizi belirtiniz. İlgili kodlama kitapçığı ekte yer almaktadır.

A SAMPLE CODING

Excerpt Information	Excerpts	Codes
The explanations of St15 in the Overall Interview	***... text continues before the excerpt...*** **St15:** Evet var. Bu şey gibi… Iıı… *(Emisyon spektrumunu göstererek)* Atomdaki elektron üst yörüngeden alt yörüngeye geçip orbitini değiştirince atom foton yayıyor.	OBP
	Bunlar *(spektrum çizgilerini göstererek)* foton. Enerji sürekli değil, belli bi miktar enerji.	D/DC
	Mesela, elektronun üçüncü yörüngeden ikinci yörüngeye geçişiyle foton elektronun bu enerji seviyelerinde[1] sahip olduğu[2] enerjiler arasındaki fark kadar[3] enerji alabilir. O yüzden bu çizgiler oluşur. *** ***... text exists here...*** ***	[1,3]D/DC, [2]NC
	St15: ***(paragraph continues)…*** Ama mesela burada *(spektrumu göstererek)* enerji kuantize çünkü sadece belli değerlere[1] sahip[2], her değere sahip değil[3]. ***... text continues after the excerpt...***	[2]NC, [1,3]D/DC

The explanations of St29 in the Overall Interview	***... text continues before the excerpt...*** **St29:** Evet. Işığı düşünebiliriz ve ayrıca paketler için de düşünebiliriz. **I:** Ne demek bu? **St29:** Işığı küçük küçük[1] parçalara[2] böldükten[3] sonra paketlemek gibi bişey… Iıı *(düşünüyor)*… Böyle. **I:** Tamam, biraz daha açıklayalım. "Kuantize olma" dan tam olarak ne kastediyorsun? **St29:** Klasik fizikte hiç bişeyi kuantize edemiyoruz, çünkü sonuçlar çok saçma ve anlamsız. Kuantumda ışığı, enerjiyi, hızı kuantize ederiz. Yani ışığı kuantize edebiliriz *(sessizce söyleyerek)*. Ayrıca enerjiyi küçük[1] parçalara[2] böleriz[3], kuantize ederiz[4]. *** ***... text exists here...*** *** **I:** Neden kuantizedir? **St29:** Çünkü kuantum fiziğinde enerjiyi hep ayrık birimlerde[1] görüyoruz. Enerjiyi küçük[2] birimlerine[3] bölüyoruz[3] ve ışığı böldüğümüz gibi[4] inceliyoruz… ***... text continues after the excerpt...***	EP [1]AV, [2]D/DC, [3]AC AC AC AC [1]AV, [2]D/DC, [3,4]AC, [1]D/DC [1]AV, [2]D/DC [3,4]AC
The explanations of St9 in the Overall Interview	***... text continues before the excerpt...*** **I:** Burada kuantize enerjiyi gösteren ne? **St9:** Iıı... Parçacık[1] normal durumunu koruyamıyor[2]. Bizim bildiğimiz gibi aynı kalmıyor[1]. Değerlerini koruyamıyor. Farklılaşıyor. Herşey gördüğümüz gibi değilmiş aslında yani. Enerjisi falan faklılaşıyor... Farklı değerler[1] alıyor[2], çok daha farklı oluyor[3]. Başka *(kendi kendine söyleyerek)*... Iıı… Bu şekilde… *(Gülümseme).* **I:** Bu değişimin enerjinin kuantize olmasını gösterdiğini söylüyorsun, değil mi? **St9:** Evet, sabit değil enerjiler, aynı değiller. ***... text continues after the excerpt...***	[1]EP, [2]C C C, C C [1]AV, [2]NC, [3]C C

I.3 Peer Review Document for Validation of Models

Peer Review Checklist II

The aim of this study is to examine second-year physics and physics education students' mental models about some quantum mechanical concepts.

EXPERT INFORMATION
Name - Surname :
Title :
Area of Expertise :
Date :

DIRECTIONS: Dear expert, this checklist requests you to match the sample excerpts with identified mental models by using the list containing model characteristics. Please read the model characteristics; and mark the related box for matching in the table at the end of the excerpts. Please find the related list in the attachment.

YÖNERGE: Sayın uzman, bu kontrol listesi model özelliklerini içeren listeyi kullanarak örnek alıntılar ile tespit edilen zihinsel modelleri eşleştirmenizi istemektedir. Lütfen model özelliklerini okuyunuz; ve eşleştirme için alıntıların sonunda bulunan tabloda ilgili kutucuğu işaretleyiniz. İlgili liste ekte yer almaktadır.

SAMPLE EXCERPT 1

... text continues before the excerpt...

I: Peki, fotoelektrik deneyini hatırlıyor musun?
St27: Evet hatırlıyorum galiba.
I: Ne oluyordu, olayı anlatabilir misin bana?
St27: Bi foton geliyor, bir yüzeye çarpıyor ve o yüzeyden bir elektron kopmasına neden oluyordu.
I: Her foton elektron kopartabiliyor muydu peki?
St27: Hayır, belirli bir sınırı var onun, enerji sınırı.
I: Her enerji bir elektron kopartamıyor mu diyoruz?
St27: Evet.
I: Gelen ışık ile bir ilgisi var mı?
St27: Evet, frekansı etkiliyordu.
I: Peki burada kuantumlanmadan bahsedebilir miyiz? Söz konusu mu?
St27: Enerjinin parçalanması değil mi? Hani bütün bir enerjinin parçalanması... Iıı... Yani sabit bi değer almaması.
I: Bu nasıl oluyor? Burada da *(testte)* "parçacıkları küçük parçalara bölmek ve analiz etmek" demişsin *(teste bakarak).*

(öğrencinin testte yazdığı ifadesi)

quantization means dealing with the dividing particles into their smallest components and analyzing them.

St27: Evet, evet. Enerji için bahsediyoruz. Mesela burada fotonun enerjisini bölerek alıyoruz, bu kuantize.

... text continues after the excerpt...

<u>SAMPLE EXCERPT 2</u>

... text continues before the excerpt...

I: Tamam, peki kuantize olmayla ilgili ne söylemişsin bakalım *(testte yazdığına bakarak)*. "Değerler birbirine yakın olabiliyorlar, ama farklı" yazmışsın.

St9: Orada klasik fizikle karşılaştırmışım. Niye öyle demişim?

I: Hayır, klasik fizikle aşağıda söylemişsin. “Kuantize”… Klasik fizikte böyle bi şey görmediğinizi söylemişsin *(test kağıdına beraber bakarak).*

St9: *(Gülümseme)*…

I: "Kuantum fiziğine giriyormuş… Klasik fizikte kuantize olmuyor" yazmışsın… Evet… Hem de "parçacık" yazmışsın *(testte yazdığına bakarak)*. Şimdi burada, "kuantize olma” üstünde konuşalım. Sen burada *(testte)* tam olarak söylemek istediğini birde sözlü olarak ifade et.

St9: Kuantize olma… *(Sessizlik)*. Iıı... Hani kütle değişiyordu.

I: Nasıl?

St9: Yani mesela ben burada aslında sadece kütleden hatırlıyorum. Ya da böyle… Nasıl anlatsam? Sanki… Ya işte kütle, normalde durduğu değerden farklı bir değer alıyor, o kuantize olmuş gibi geliyor bana. Doğru mu yanlış mı bilemiyorum tam… Işık için de aynı şey... Ya bilmiyorum… *(Sessizlik)*… *(Gülümseme).*

I: Tamam, peki, "değerlerin birbirine yakın olması ama farklı olması…" diyorsun değil mi?

St9: Yani işte mesela kütledir, 10 kg’dır. Ama kuantize olunca biz onu dokuzmuş gibi görüyoruz, ya da işte sekizmiş. Onun gibi bi şey demeye çalışmışım herhalde.

... text exists here...

I: Tamam peki, kütleye örnek verdin ama "ışık için de aynı şey" dedin. Işığa değinmişken, ışıkla devam edelim. Fotoelektrik deneyini hatırlıyor musun? Ne oluyordu fotoelektrik deneyinde?

St9: Işık geliyordu, sonra oradan çarpıyordu, yansıyordu.

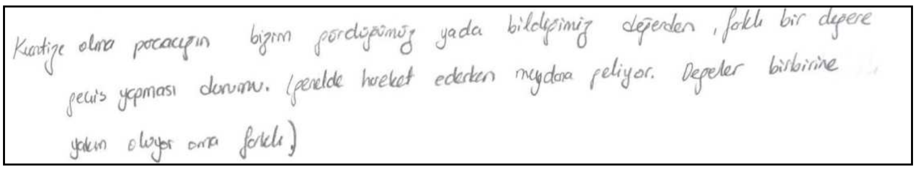
I: Çarptığı zaman ne oluyordu?

St9: Elektron kopartıyordu.

I: Evet, yeterli enerjisi varsa yüzeyden elektron kopartıyordu. Fotoelektrik deneyi Einstein'a ait bir deneydi biliyorsun. Burada acaba kuantize bi durumdan bahsedebilir miyiz? Böyle bir durum var mı? Ne söylemek istersin?

St9: Burada… Iıı... Evet, bu kuantumlanma gösteriyor bence. Çünkü mesela elektron durduğu yerden bir ışık gelerek oradan kopup hareket değiştirip akım oluşturuyor. Bence bu kuantize örneği gösteriyor evet.

(öğrencinin testte yazdığı ifadesi)



... text continues after the excerpt...

<u>SAMPLE EXCERPT 3</u>

... text continues before the excerpt...

I: Mesela fotoelektrik deneyine baktığımızda ne söylersin?

St18: Fotoelektrik deneyinde kuantize olma durumu var mı? Iıı...

I: Evet, açıklayabilir misin var mı kuantize bir durum?

St18: Ya şey var fotoelektrikte... Tabii elektronu koparabilmemiz için belli bir enerjide şey yapmak. Yani ilk dediğim şeye geliyor orda. Çekirdek etrafında dönen elektron var bir tane ve bunun farklı enerjileri var belli yörüngelerde dönerken. Ben bunu buradan, mesela bound'dan koparabilmek için belli bir enerji vermem gerekiyor. Onun bir aşağısı, bir yukarısı falan filan değil. Klasikte olsa biraz üstünden göndersen tak diye kopar. Mesela ay şeyin etrafında dönüyor dünyanın etrafında dönüyor. Şimdi bir tane ışık göndersem, aslında ışıkla olmaz tabii de, ışık koparmaz ayı. Neyse ya da meteor gelse çarpsa mesela enerjisi şeyi koparabilecek şekilde ayı yörüngeden çıkarabilecek şekilde kopartır. Yani o değerin üstünde bile olsa kopartır. Ama burada öyle değil. Burada enerjinin tam o değeri olmak zorunda.

I: Şuna açıklık getirelim yalnız. Burada “excitation” mı? “Ionization” mı? Bir de burada foton ile mi bi şeyler yapıyoruz?

St18: Evet foton. Burada kopartmak “ionization” oluyor, ama uyarmak için de tam o enerji seviyelerinin farkı kadar olmak zorunda foton enerjisi.

I: O zaman atomu uyarmak için de mi "fotonun enerjisi tam denk gelmesi lazım, ne altı ne üstü olmaz" böyle?

St18: Evet. O “hv” de olması lazım.

I: "İlk dediğime geliyor" dedin?

St18: Evet.

I: Yani belli bi enerjiden bahsediyorsun...

St18: Evet, kuantize enerji.

... text continues after the excerpt...

<u>SAMPLE EXCERPT 4</u>

... text continues before the excerpt...

I: Şimdi şu testte yazdıklarının üstünden geçelim.

St28: Tamam. Ben “quiz”den sonra, ya bundan da önce kitaptan bakmıştım kuantum ne demek diye. Hatta sözlüğe falan da bakmıştım. "How much" anlamına geliyor anladığım kadarıyla. Ama herhalde burada tam sizin sormak istediğiniz o değildi. Fiziksel ifade olarak anladığım kadarıyla enerji parça parça idi değil mi? Mesela fotonlar falan da, tam bir bütünlük yok. Herhangi bir kuantumlanmada onu sürekli hale getirmeye çalışıyoruz. Böyle bi şeyler anladım “quiz”den sonra okuyunca.

I: "Sürekli hale getirmeye çalışıyoruz" derken ki kastın ne? Yani niye biz onu öyle kabul etmiyoruz? Yani kesikliyse biz o yapıyı niye kabul etmedik de “continuous” hale getirmeye çalışıyoruz? Bunu düşünmene sebep olan şey ne?

St28:Şimdi dalga fonksiyonunu düşününce hani şeyin elektronun nerede olduğunu bilmiyoruz. Arada bir yerde olduğunu olasılık ile hesaplayabiliyoruz. Artı sonsuzla eksi sonsuz arasında var, kesin arada bir yerde… *(Düşünme)* Bu bize net bi sonuç vermez. Onu aslında tam ifade edemiyorum. O yüzden onun tamamını almayı düşünüyor. O şekilde bi şey. Güzel ifade edemedim ama…

I: Iıı... “O kesikliliği ‘continuous’ yaparak” diyorsun... *(Sessizlik).*

St28: Evet, sürekli hale getirerek.

I: Özetlersek, "Sürekli hale getirmeye çalışıyoruz".

St28: Evet.

I: Tamam, peki, özellikle enerjiden bahsettin. Aslında şurada *(testte)* size hangi fiziksel büyüklüklerin kuantize olduğunu, ve nerede nasıl biz bunları gözlediğimizi sormuştuk.

Ve deliller göstermenizi istemiştik. Sen de zaten kuantumlanmayı açıklarken ilk etapta "enerji" dedin.

St28: Evet.

I: Evet… Açıklarken enerjinin kesikliliği diye başladın ifadene, devam ettirmek istiyor musun enerji için? O zaman, kuantize enerjiden ne anlıyorsun tekrar anlat ve onun üzerine tekrar konuşalım. Tam olarak kastın ne?

St28: Iıı… Kuantize olma. Yani, o kesikli enerji dalgasının tam sürekli hale getirip oradan bi şeyler çıkartabiliyoruz, bi sonuca ulaşabiliriz.

I: Tamam… Kesiklilik, yani "discontinuous" bir durum.

St28: Evet "discontinuous" bir durumu continuous duruma geçirmek. Kuantize benim algıladığım kadarıyla, "dicontinuous" enerji ya da işte dalgayı continuous hale getirmek.

... text exists here...

St28: Yani kullandığımız modern atom modelinde, çekirdekte protonlar nötronlar, etrafında dönen elektronlar titreşim hareketi yaparak dönüyorlar. Onun tam yerini bilmiyoruz, değil mi? İşte onun yerini bulurken, kuantize ediyoruz.

I: Tamam… Peki, daha önce "kesikliliği kuantize etmek" demiştin…

St28: Sürekli hale getirmek.

I: Peki, bunu nerelerde gördük? Yani kuantize durumu dedin ya. Onu sürekli hale nasıl getirdik?

St28: Çok uzun bi şey... Belli bir sınırlar alarak. Yani mesela "particle in a box" ta bu vardı. Artı ve ya eksi sonsuz arası, yani bi sınırlar koyarak onu sürekli hale getirdik diyelim.

I: Tamam, o zaman süreklilikteki kastımızı tekrar gözden geçirelim. Bana böyle bi grafiksel ya da matematiksel bi şey ile anlatacak olsan o "discontinuous" şeyi nasıl "continuous" hale getirirsin? Tam olarak nasıl yaparsın onu?

St28: İntegralle belirtirdim… İntegralin sınırlarını çizerdim, dalga fonksiyonu için sinüs fonksiyonu verirdim, o arada 1'e eşitlerdim onu. Bu şekilde kuantize edebiliriz integralle.

... text continues after the excerpt...

<u>SAMPLE EXCERPT 5</u>

... text continues before the excerpt...

I: Şimdi burada yazdıklarına bakalım *(öğrencinin testte yazdığına bakarak)*

St21: Hı hıı *(evet anlamında onaylama)*, tamam.

I: Kuantum nedir diye sormuştuk. Fizikte "kuantize olmak" ne anlama gelir demiştik, klasik fizik ve kuantum fiziği için "kuantize olma" durumunu karşılaştırmanızı istemiştik. En son soruda da hangi fiziksel büyüklüklerin kuantize olduğunu, bize nerede ve nasıl kuantize olduklarını söylemenizi istemiştik.

St21: Evet.

I: Senin şimdi burada yazdıklarına eklemek istediğin var mı? Detaylandıralım.

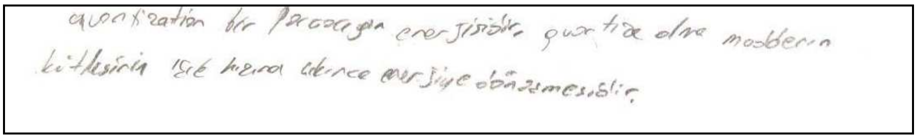
St21: *(Öğrenci kağıdını okuyor).* Aslında bilmiyorum yani hala tam olarak.

I: Tamam... Şimdi bakalım "quantization" ile ilgili ne söylemişsin. *(Öğrencinin testte yazdığını okuyarak)* "Kuantize olma bir parçacığın enerjisidir" demişsin değil mi? Enerji cinsinden tanımlama yapmışsın.

St21: Evet.

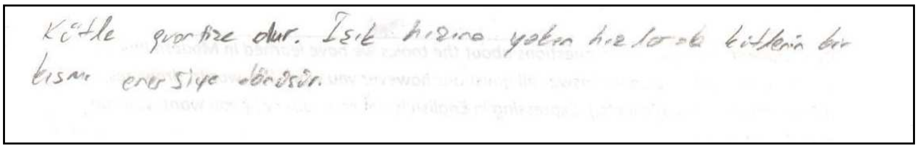
I: Ayrıca "Kuantize olma maddenin kütlesinin ışık hızına çıkınca enerjiye dönüşmesidir" demişsin *(öğrencinin testte yazdığına bakarak).*

(öğrencinin testte yazdığı ifadesi)


quantization bir parçacığın enerjisidir, quantize olan maddenin kütlesinin ışık hızına ulaşınca enerjiye dönüşmesidir.

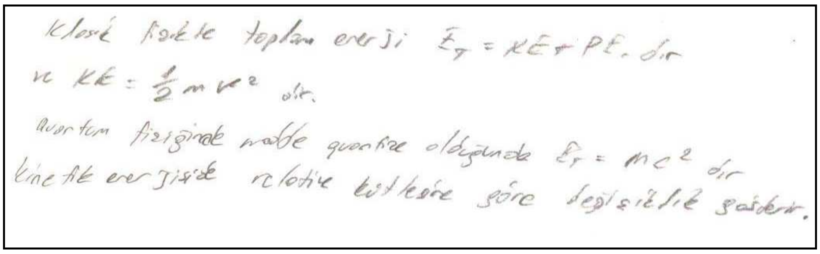
St21: Doğru mu?
I: *(Sessizlik)*…
St21: Değil! *(Gülümseme).*
I: Şimdi tam olarak ne kastettin bunu açıklayalım. Yani "quantization" durumunu testte enerji için yazdın, ayrıca kütle için de yazmışsın kütlenin kuantize bir büyüklük olabileceğini. Ayrıca “Bir parçacığın enerjisidir” diyorsun. Yani ne demek bunlar? Anlatır mısın?

(öğrencinin testte yazdığı ifadesi)


Kütle quantize olur. Işık hızına yakın hızlarda kütlenin bir kısmı enerjiye dönüşür.

St21: Aslında doğru mu tam bilmiyorum hocam *(gülümseme).* Yani…
I: Peki, klasik fizik ve kuantum fiziği için enerjiyi düşünecek olursan kuantize durum söz konusu mudur?
St21: Şurada yazdıklarıma bi bakayım *(test kağıdına bakarak).*
I: *(Öğrencinin testte yazdıklarına bakarak)* Klasik fizikte enerjiyi mekanik enerji eşittir kinetik artı potansiyel enerji olarak söylemişsin. Kinetik enerjinin de tanımını yapmışsın. Kuantum fiziğinde ise “madde kuantize olduğunda, enerji "mc^2" olur diye bahsetmişsin değil mi?

(öğrencinin testte yazdığı ifadesi)


Klasik fizikte toplam enerji $E_T = KE + PE$ dir ve $KE = \frac{1}{2} m v^2$ dir.
Kuantum fiziğinde madde quantize olduğunda $E_T = mc^2$ dir kinetik enerjisi de relative kütlelere göre değişiklik gösterir.

St21: Evet.
I:"Kinetik enerji de relative kütlelerine göre değişiklik gösterir" demişsin.
St21: Evet *(başını sallayarak).*
I: Peki bunu bu şekilde söylemenin sebebi neydi? Yani hani kuantumlu olma durumu diyelim, bu kavramı relativite konularında mı gördünüz özellikle?
St21: Öyle biliyorum… *(Sessizlik)*... Iıı... Evet, relativitenin içinde. “2. Chapter” da galiba kütle, relativistik kütle falan vardı. Onlar yani aklıma geldi. Öyle bi şey biliyorum kuantize ile ilgili, öyle yazdım o yüzden.
I: Tamam peki şimdi testte sorduğumuz son soruya bakalım. Burada da hangi fiziksel büyüklükler "kuantizedir" diye sormuştuk. Sen de mesela “kütle kuantize olur” yazıp başka açıklamalarla devam etmişsin. Tam olarak ne demek istedin burada "kütle kuantize olur" derken?
St21: Kuantize olur derken kütlenin değişmesi hıza göre.

I: “Hıza göre değişim oluyor” mu diyorsun?
St21: Evet. Enerji herhalde oluyor kütle.
I: Biraz daha detaylandırır mısın? Tam anlayamadım.
St21: Her kütlenin bir enerjisi oluyor. Durağan bir kütlenin bi enerjisi oluyor “mc^2” işte. Işık hızına çıktığında o enerjiye sahip oluyor.
I: Işık hızına nasıl çıkıyor peki bu parçacık? Parçacığın enerjisinden bahsetmiştin!
St21: *(Düşünme)*... Biz çıkartıyoruz hızlandırıp.
I: Tamam, şimdi bu şekilde kuantize mi olmuş oluyor enerji?
St21: Olmuş oluyor.
I: Daha doğrusu “biz yapıyoruz enerjiyi kuantumlu hızlandırıp!” diyorsun.
St21: Evet.
I: Peki burada başka eklemek istediğin var mı bunlara?
St21: Yok.

... text continues after the excerpt...

Matching Table

EXCERPTS	MODELS					
	SM	PSM	ShM	AM	IM	EM
EXCERPT 1						
EXCERPT 2						
EXCERPT 3						
EXCERPT 4						
EXCERPT 5						

Attachment of the checklist: *Descriptions of the identified mental models about the quantization of physical observables.*

MODEL NAME (MODEL ABBREVIATION)	MODEL DESCRIPTION
Scientific Model **SM**	▪ Quantization of physical observables such as energy, angular momentum is seen when a particle is confined in a region. ▪ The values of physical observables are restricted. The physical observables can have only discrete values and these values are only certain (allowed) values. ▪ It is natural for the atomic systems.
Primitive Scientific Model **PSM**	▪ The values of physical observables are restricted. The physical observables can have only discrete values and these values are only certain (allowed) values. ▪ Quantization of physical observables is observed for all atomic particles, not for only bound particles. ▪ It is natural for the atomic systems.

Shredding Model **ShM**	▪ The physical observables are divided into quantum and have discrete values. This is just like dividing into little particles. ▪ Therefore, the values of the physical observables are not restricted, and quanta can take any value as the amount of a cake slice ▪ Quantization of physical observables is observed for all atomic particles, not for only bound particles. ▪ Quantization is not a natural characteristic for atomic systems, so it is an external manipulation of the values of the physical observables.
Alternating Model **AM**	▪ Quantization occurs as any kind of change. It is like spontaneous change of the values. ▪ There is not restriction for the values of the physical observables, and so they can have any values. ▪ It is observed for all atomic particles, not for only bound particles. ▪ It is a natural characteristic for the atomic systems.
Integrative Model **IM**	▪ Quantization is an integration process to make the values of the physical observables continuous. ▪ Quantization of physical observables is observed for all atomic particles, not for only bound particles. ▪ Quantization is not a natural characteristic for atomic systems, so it is an external manipulation of the values of the physical observables.
Evolution Model **EM**	▪ Quantization is a phenomenon of Einstein's theory of relativity. ▪ It occurs as any kind of change. ▪ Quantization of physical observables is observed for all atomic particles, not for only bound particles. ▪ It is not a natural characteristic for atomic systems, so it is an external manipulation of the values of the physical observables.

APPENDIX J

RELIABILITY ISSUES

J.1 Inter-coding Document for Interviews

Peer Review Checklist for Inter-coding I

The aim of this study is to examine second-year physics and physics education students' mental models about some quantum mechanical concepts.

EXPERT INFORMATION
Name - Surname :
Title :
Area of Expertise :
Date :

DIRECTIONS: Dear expert, this checklist is composed of 2 parts. Please follow the checklist by reading the directions for each part.

YÖNERGE: Sayın uzman, bu kontrol listesi 2 bölümden oluşmaktadır. Lütfen bu kontrol listesini her bölümdeki yönergeleri okuyarak takip ediniz.

PART 1: A SAMPLE TRANSCRIPT OF A STUDENT

Directions for Part 1: Part 1 requests you to code the interview transcripts of a student by means of the coding booklet developed in this study. Please find the related coding booklet in the attachment.

1. Bölüm Yönergesi: 1. Bölüm, bu araştırmada geliştirilen kodlama kitapçığını kullanarak bir öğrencinin görüşme çözümlemelerini kodlamanızı istemektedir. İlgili kodlama kitapçığı ekte yer almaktadır.

INTERVIEW II

Interviewer	**:** *N. Didiş*
Interviewee (name or pseudonym)	**:** *ST7*
Interview Date	**:** *18.05.2009, between 13.00- 13.42*
Interview Duration	**:** *42 minutes*
Interview Data Recorders	**:** *Video camera, interview protocol, paper, pencil.*
Department	**:** ■ Physics □ Physics education
Gender	**:** ■ Female □ Male
Number of taking this course	**:** ■ First time □ Second time or more

¶1: **I:** İlk sorumuza bakalım, bir spektrum var *(1. Soru)* "**1.** In an emission spectrum, what do the (colored) lines explain (for the visible region), or in an absorption spectrum what do the dark lines explain? Why do the lines occur? Why do they have different colors (for the visible region) for emission spectra; Why are they dark for absorption spectra?" *Emisyon spektrumu için görünür bölgedeki renkli çizgiler ya da absorbsiyon spektrumundaki siyah çizgilerin ne açıklar? Çizgiler neden oluşur? Emisyon spektrumları neden renkli çizgilere sahiptir ya da absorbsiyon spektrumu çizgileri neden siyahtır?*

¶2: **St7:** Iıı... "Emission"da hani belirli dalga boylarında dalgaların verildiği. Bunu anlatıyor. "Absorption"da da bildiğim kadarıyla yine aynı şekilde belirli "stateler"de dalga boylarındaki dalgaların absorbe edildiği. Çizgiler bunları gösteriyor bildiğim kadarıyla.

¶3: **I:** Tamam, peki 2. soruya bakalım. *(2. Soru)* "**2.** Suppose the electron in the Hydrogen atom obeys classical mechanics rather than quantum mechanics. What would you expect to observe in the spectrum? Why?" *Varsayalım ki Hidrojen atomundaki elektron kuantum mekaniğine değil de klasik mekaniğe göre davranıyor. Spektrumunda ne gözlemeyi beklersiniz? Neden?*

¶4: **St7:** Klasik mekaniğe göre hareket etmek istiyor... Iıı… Bu durumda saptayabilirdik, tam kesinlikle bulunduğu yeri ve momentumunu, herhangi bir belirsizlik olmadan saptayabilirdik. Yani belirsizlik olmazdı ve parçacık şeklinde hareket ederdi, yani dalga gibi olarak değil de klasik parçacık… Şimdi kuantuma göre belli matematiksel olarak formülünü elde ettiğimiz zaman görüyoruz ki belli dalga boylarında, belli "state"lerde "emission" ve ya "absorption" oluyor. Klasik mekaniğe göre davransaydı, herhalde biz böyle bir spektrum elde etmezdik, onun yerine galiba bütün dalga boylarını, ya bilmiyorum hani, herhalde böyle belli "state"ler çıkmazdı ortaya gibi düşünüyorum.

¶5: **I:** Yani çizgileri mi görmezdik? Yani nasıl bir şey olurdu?

¶6: **St7:** Iıı... Galiba çizgileri görmezdik, çünkü sadece bir parçacık olarak kabul ettiğimiz için, klasik mekaniğe göre düşündüğümüzde DeBroglie'yi göz önüne almayacağız, bu durumda bir şey görmezdik galiba.

¶7: **I:** Tamam, peki Bohr bir atom tanımlıyor, nasıldır bu Bohr atomu?

¶8: **St7:** Bohr atomu dediği... Bohr atom modeli 1 elektronlu atomlar, Hidrojen ve Hidrojene benzer 1 elektronu olan atomlar için geçerli bir model. Bohr atom modeline baktığımız zaman belirli "state"lerde belirli spektrumları görüyoruz. Belli dalga boyları belli enerji seviyeleri, yani bunlar.

¶9: **I:** *(3. soru a kısmı)* "**3. a)** What did Bohr state about the atom, in other words what are the Bohr Postulates?" *Bohr atomla ilgili olarak neler söyledi, diğer bir deyişle Bohr Postülaları nelerdir?*

¶10: **St7:** Mesela şeyden bahsediyor, şu an formülünü tam hatırlayamamakla beraber bu açısal momentumun kuantizasyonundan bahsediyor.

¶11: **I:** Nasıl bir şey bu?

¶12: **St7:** Iıı... Bu... Açısal momentumun *(duraksama)*… Ya içeriğini tam olarak hatırlayamıyorum onu, unuttum biraz... Daha sonra belirli "enerji state"lerinde, elektronlar sadece belirli enerji "state"lerine sahip olacağından bahsediyor kuantum "number"larına göre, başka, Iıı... Bu kadar.

¶13: **I:** Açısal momentumun dışında başka bir şeyden bahsediyor mu acaba?

¶14: **St7:** Enerji "state"lerinden bahsediyor dedik bir de... Iıı... Başka aklıma gelmiyor. Bu kadar.

¶15: **I:** Peki *(3. soru b kısmı)* "**b)** What are the failures of the Bohr Postulates about the quantum theory?" *Bohr Postülaları'nın kuantum teorisi açısından eksiklikleri nelerdir?*

¶16: **St7:** Iıı... Spinlerden bahsetmiyor, sadece 1 elektronlu atomlar için geçerli. Iıı... Diğer yani çok fazla eksikliklerini bilmiyorum Bohr atom modelinin.

¶17: **I:** "Orbit", yörünge diye bir şey duydun mu? Bohr modelinde acaba "orbit" bize ne açıklıyor?

¶18: **St7:** Bohr modelinde "orbit" bize enerji seviyelerini açıklıyor. Yani elektron hangi enerji seviyesinde bulunuyorsa ona göre bir orbit üzerinde hareket ediyor.

¶19: **I:** Peki enerji seviyesi dedin, ben de sana tam sonu soracaktım, ne demek enerji seviyesi? *(4. Soru)* "**4.** What do the "energy levels" mean?" *Enerji seviyeleri" ne demektir?*

¶20: **St7:** Enerji seviyesi deyince bi elektronun sahip olduğu enerjiler. Her enerjiye sahip olamıyor. Belirli "state"lerde.

¶21: **I:** Ne demek o her enerjiye sahip olamıyor?

¶22: **St7:** Iıı... Mesela onun çıkardığımız zaman formülünü matematiksel olarak, görüyoruz ki "quantum number"ına göre belirli seviyelerde belli enerjiye sahip oluyor. Mesela her değerdeki enerjiye sahip olamıyor. Bunu görüyoruz. Enerji seviyeleri bu sahip olabildiği enerjiler... Enerji seviyeleri, bu galiba elektronun dalga boyu ile DeBroglie dalga boyu ile ilgili bir şey. Yani her işte, onun yaydığı dalga boyuyla ilgili olduğu için enerjisi ve onun yaydığı dalga boyunu göz önüne aldığımızda işte sadece belirli "state"lerde enerjisi olabiliyor. Bu kadar yani. Iıı.. Mesela bir dalga boyu veriliyor, elektron yüksek enerjiden düşük enerjili bir duruma geçtiğinde bir enerji yayıyor. Bir foton yayıyor doğal olarak, belli dalga boyunda olan, "characteristic" dalga boyları. Bunlarında işte daha üstlerden 1. seviyeye geçiş Lyman serisi, daha üstlerden 2. seviyeye geçiş Balmer, veya daha üstlerden 3. enerji seviyesine geçiş Pashen serisi olarak.

¶23: **I:** Tamam, buradan buraya *(kağıtta iki yörüngede, üst yörüngeden alt yörüngeye geçişi göstererek)* geçiş için ne söyleyebilirsin mesela? Ne oluyor burada?

¶24: **St7:** Elektron buradan buraya *(üst yörüngeden alt yörüngeye geçtiğini göstererek)* geçiyor.

¶25: **I:** Evet, yani...

¶26: **St7:** Evet, dolayısıyla bir enerji vermiş oluyor. Iıı... Şöyle, mesela enerji farklarının fazla olduğu çok yüksek bir enerji "state"inden daha alt bir enerji "state"ine geçerken aradaki fark ne kadar olursa yayılan fotonun dalga boyu da aynı o kadar küçük oluyor. Yani frekansı büyük oluyor.

¶27: **I:** Tamam, peki diğer soruya bakalım *(5. Soru)* "**5. a)** What do you understand about the "particle in a box" term in physics?" *Fizikte "Kutudaki parçacık" teriminden ne anlıyorsunuz?*

¶28: **St7:** Iıı... Particle in a box... Şöyle, bi küçük bir "particle"ın aynı zamanda bir DeBroglie dalgası olduğu için de kutunun genişliğine göre farklı dalga boylarında olabilme ihtimali var, bunu anlıyorum. Bu da bize aslında şunu gösteriyor, Iıı... Mesela çekirdeğin çevresinde dönen bir elektronu "particle in a box" gibi düşünebiliriz, kutu içinde bir "particle" gibi. Belirli bir sınırlama oluyor. Belli bir sınırlanmış alan oluyor. Onu aşamıyor çekirdeğin çekim kuvvetinden dolayı. Ona benzetebiliriz.

¶29: **I:** Peki, elektron dışında başka bir parçacık olabilir mi acaba? *(5. Soru devam)* "**b)** What can be considered a particle in a box?" *Bu parçacık ne olabilir?*

¶30: **St7:** Iıı... Başka bir parçacık? Iıı... Olabilir yani başka da, ama şu an aklıma gelmiyor, ama olabilir tabii ki, bi alanda kısıtlanmış parçacık olabilir.

¶31: **I:** Peki "particle in a box" gerçekten fiziksel bir şey mi yoksa hani mesela dedin fizikte böyle bir şey varsa o da elektron'un atom içinde bulunmasıdır, hani bir yaklaşım falan mı yapıyoruz? Kutunun içindeki bir parçacığa mı benzetiyoruz? Yani "particle in a box" gerçek bir kavram mı, yoksa bir yaklaşım mı bişeyler açıklayabilmek için? *(5. Soru devam)* "**c)** Can you give an example from a physical situation about particle in a box?" *Kutudaki parçacık durumuna fiziksel bir durumdan örnek verebilir misiniz?*

¶32: **St7:** Bence bir yaklaşım... Benzetme gibi düşünüyorum daha çok. Gerçek kavramdan ziyade.

¶33: **I:** Peki, bu parçacık bir elektron ise, sen elektron olabilir demiştin, *(5. Soru devam)* "**d)** Explain the "energy", "wavelength", and "velocity" for a particle in a box." *Kutudaki parçacık için "enerji", "dalga boyu" ve "hız" ı açıklayınız.*

¶34: **St7:** Önce dalgaboyu ile ilgili konuşalım. Dalga boyu sınırlı bir bölge içinde olduğu için sahip olacağı dalga boyunun ihtimalleri var kutunun genişliğine göre. Dalga boyu değişebilir farklı dalga boylarına sahip olma ihtimali var. Bununla bağlantılı olarak da enerjisi de değişir. E tabii dalga boyunun da kutunun genişliğine göre ona baktığımızda belli değerleri var, alabileceği belli değerler. Dolayısıyla enerjide dalga boyu ile bağlantılı olduğu için bakıyoruz. Enerjinin de alabileceği belli değerler oluyor oradan, sonra hız, hızına bakarsak o da, Iıı... Hızı, c, c aslında DeBroglie dalga boyu yanlış hatırlamıyorsam.

¶35: **I:** c? Işık hızı mı?

¶36: **St7:** Işık hızı.

¶37: **I:** Elektron hareketi ama?

¶38: **St7:** Bi saniye... Doğru, evet, hı hıı *(evet anlamında onaylama)*, bu durumda ışık hızı olmaz. Iıı... Hızı da dalga boyuna göre değişir.

¶39: **I:** Tamam, birbirlerine bağlı olduğunu söylüyorsun.

¶40: **St7:** Evet birbirlerine bağlı.

¶41: **I:** Peki diğer soruya bakalım, *(6. Soru)* "**6. a)** What do you understand about the "harmonic oscillator" term?" *Harmonik salınıcı" teriminden ne anlıyorsunuz?*

¶42: **St7:** Fizikte klasik mekanikten aklıma gelen şey, mesela yay- kütle sistemi olabilir bu, sonra "pendulum" olabilir bi sarkaç. Bu tür örnekler geliyor. Harmonik hareket yapan örnekler geliyor.

¶43: **I:** Peki bunların enerjisi hakkında ne söyleyebilirsin? Alabileceği enerjinin yapısı diyebiliriz. *(6. Soru devam)* "**b)** Explain "energy" for a harmonic oscillator." *Bir harmonik salınıcı için "enerji" yi açıklayınız.*

¶44: **St7:** Iıı... Enerjisi hakkında... *(Düşünme).*

¶45: **I:** Yani enerjileri nasıldır? Klasik sistemlerdeki harmonik salınıcıların enerjisi hakkında ne söyleyebilirsin?

¶46: **St7:** Aslında normalde buna mikro boyutta, "nano" boyutta baktığımızda belli değerler aldığını görüyoruz yine. Peki bu klasik mekanikte doğru değil mi? Klasik mekanikte de doğru fakat, klasik mekanikte daha büyük sistemlerde diyelim, onlarda da doğru fakat orda boyut çok değiştiği için ihmal edilebilecek ölçülere geliyorlar, yani aslında yine belli değerleri var ama biz onları algılayamıyoruz.

¶47: **I:** Tamam, bunlar "klasik ile kuantum arasında fark ediyor" diyorsun!

¶48: **St7:** Hı hıı (evet anlamında onaylama), evet.

¶49: **I:** Peki, bi sonraki soruya bakalım *(7. Soru)* "**7.** Did Bohr postulate the quantization of energy? What did he postulate about the quantization?" *Bohr enerjinin kuantize olmasını (kuantumlanmasını, kuantumlu olmasını) önerdi mi? Kuantize olmaya ilişkin ne önerdi?*

¶50: **St7:** Enerjinin kuantize olduğunu gösterdi. Tabii, yani bişeyler söyledi, hani belli bir formülü var onun ama formülü hatırlayamıyorum şu anda.

¶51: **I:** Ama formülde bize enerjinin kuantize olduğunu gösterdi diyorsun?

¶52: **St7:** Evet, hı hıı *(evet anlamında onaylama)*, gösterdi.

¶53: **I:** Başka kuantize büyüklüklerden bahsetti mi? Açıklayabilir misin?

¶54: **St7:** Galiba açısal momentumun kuantize olmasından bahsetmişti, başka... Iıı...

¶55: **I:** Formülü var demiştin, formül hatırlıyor musun bununla ilgili?

¶56: **St7:** Hı hıı *(evet anlamında onaylama)*, evet var, ama onu da tam hatırlayamıyorum maalesef.

¶57: **I:** Peki o formülü hatırlayamasan da bunun böyle olduğunu gösteren şey neydi? Kuantize olduğunu düşündüren şey, bir sembol ya da başka bi şey olabilir. Neden kuantize dedin? Formülün tamamını hatırlayamadın ama "evet şu sebepten dolayı ben kuantize olduğunu söyledim" diyebilir misin enerji ve açısal momentum için?

¶58: **St7:** Şöyle yani, şuradan bağlantı kurabiliyorum sadece. Elektronun mesela "particle in a box" düşünürsek aynı şekilde belli dalga boylarına sahip olabiliyor sadece. Buradan da belli dalga boylarına sahip oldukça sınırlı bir alan da belli bir enerji seviyesine sahip oluyor. Bu sebepten dolayı enerjisi kuantizedir. Açısal momentum ile ilgili bir şey söyleyemeyeceğim sebep olarak, çok iyi anlamadım onu.

¶59: **I:** Peki, *(8. Soru)* "**8.** Compare Planck's and Bohr's explanations about quantization." *Planck ve Bohr'un kuantize olmaya ilişkin açıklamalarını karşılaştırınız.*

¶60: **St7:** Planck'ın "blackbody radiation"ı hatırlayamıyorum yani kuantizasyonuna dair söylediği şeyi hatırlayamıyorum.

¶61: **I:** Kuantize bir durumdan bahsediyor mu peki?

¶62: **St7:** Onu da hatırlayamıyorum, yani "blackbody radiation"a dair pek bir şey hatırlayamıyorum!

¶63: **I:** Tamam peki Bohr'un postülalarını bi toparlayalım, ne oluyordu tam olarak?

¶64: **St7:** Bohr'un açıklamaları, hı hıı tamam. Elektron atomda belirli yerlerde, belli enerji seviyelere sahip olabilir. Her enerjiye sahip olamaz. İşte bu enerji seviyelerinde geçişler olabilir. Açısal momentumda da, yine aynı şekilde. Belirli açısal momentum değerlerine yine sahip olabilir. Bütün değerlere sahip olamaz. Bu şekilde.

¶65: **I:** Tamam, biz bu duruma ne diyoruz?

¶66: **St7:** “Quantized”.

¶67: **I:** Peki bu onun doğasına has bi şey mi?

¶68: **St7:** Onun doğasına has bi şey. Ya incelediğimizde hani bizimle bir alakası yok. Doğadan kaynaklanan bi şey. Tabiatından kaynaklanan bi şey enerjinin.

¶69: **I:** Tamam peki, enerjinin kuantize olması tam olarak ne anlama geliyor?

¶70: **St7:** Enerjinin kuantize olması… “Distinct” şeylerde olması, belirli değerler alması. Iıı... Mesela şeyde hani formül çıkarımını göstermişti hoca, oradan hatırlıyorum. Parçacık kapalı bir kutuda. İşte kapalı bir kutuda bir dalga boyu, DeBroglie dalga boyu olan bir “particle” ı ele aldığımız zaman oradan işte bu temel bilgileri kullandığımız zaman çıkan enerji formülüne baktığımızda içinde “n”, olduğunu görüyoruz. “Quantum number” olduğunu görüyoruz ve formüle göre çıkardığımızda belli enerji seviyelerinde olabildiğini görüyoruz. Şöyle, bunun sebebi de hani belli bir kutunun içinde olduğu için rastgele bir dalga boyuna sahip olamıyor parçacık. Ya şu olur, ya şu olur *(kutudaki parçacık figürü üzerinde “enerji seviyeleri” çizerek)*… Her dalga boyuna sahip olamıyor. Bu yüzden. Her dalga boyuna sahip olamadığı için de, kapalı bir kutunun içinde olunca enerjiyi sınırlıyor.

¶71: **I:** Peki o kapalı kutudan ne anlıyorsun? Neye benzetebiliriz demiştik o kapalı kutuyu?

¶72: **St7:** Şeye benzetebiliriz, çekirdeğin çevresinde belli bir alan içinde dolanan elektrona benzetebiliriz. Hani çıkamıyor dışına belli bi alan içinden kuvvetler sebebiyle.

¶73: **I:** Tamam, peki burada yaptığın açıklamalara eklemek istediğin var mı?

¶74: **St7:** Yok.

¶75: **I:** Peki, bu açıklamalarını şekillendiren şeyler neydi genel olarak?

¶76: **St7:** Derste dinlediklerim ve çalıştıklarıma dayanarak söyledim. Zaten hani dersten dinlediklerim ve kitaptan çalıştıklarım genelde, bazen derslere devam edemiyorum. Bu durumda kitaptan çalıştıklarımla söyleyebiliyorum.

PART 2: SAMPLE EXCERPTS FROM THE INTERVIEWS

Directions for Part 2: Part 2 requests you to code the excerpts from the interviews of different students by using the same coding booklet.

2. Bölüm Yönergesi: 2. Bölüm, aynı kodlama kitapçığını kullanarak farklı öğrencilerin görüşmelerine ait alıntıları kodlamanızı istemektedir.

<u>SAMPLE EXCERPT 1</u>

... text continues before the excerpt...

I: *(Kuantize olma)* sadece enerji için mi göz önüne alınır?
St10: Enerji için diye biliyorum ama enerji bi çok şey için göz önüne alınır. Elektron enerjisi olarak biliyorum. Parçacığın kutuya hapsolması enerjinin kuantize olmasının temeli diye anladım ben. Ben şöyle düşünüyorum: Mesela X üniversitesinin fizik bölümünden bir arkadaşım bana “neden kutu kullanıyorlar *(bilim adamları)*?” diye sordu. Ben de “Bence öbür türlü açıklayamıyorlar, sadece daha iyi açıklayabilmek için” dedim. Burada enerjinin kuantize olması bu kutuda daha iyi açıklanıyor. Kutuda enerjinin kuantize oluşunda enerji seviyeleri görülüyor. Ondan sonra “enerji kuantizedir” diyoruz. Sınırlandırılmış parçacığın enerjisi her değeri alamıyor. Sadece belli enerjilere sahip

olabiliyor.

I: Özetlersek, “kutuda gözlemlediğimiz parçacığın enerjisi kuantizedir” diyorsun, değil mi?

St10: Evet. Enerji kuantize.

I: “Kuantize” derken neyi kastettiğini biraz daha açabilir misin?

St10: Kuantize olma… Iıı... Sadece belli değerler. Mesela, bi apartman gibi. Apartmanın her bir katı belli bir değer olarak düşünülebilir. Fakat burada bi fark var. Apartmanda katlar arasına bir oran verebilirsin ama kutuda enerji seviyeleri kutunun genişliğine bağlı. Seviyeleri genişlik değiştirir. Kutuda gözlemlediğimiz parçacığın enerjisi kuantizedir. Parçacığın davranışı, enerjileri belirlenmiş kendiliğinden… Enerjiler sadece belli değerlere sahip olabilir. Her değere izin verilmez.

... text continues after the excerpt...

SAMPLE EXCERPT 2

... text continues before the excerpt...

I: Fotoelektrik deneyini açıklayabilir misin?

St17: Iıı… Eşik seviyesi olan bi materyal var. Bu materyale eşik seviyesini aşan bi enerji gönderdiğimde materyal elektron salıyor.

I: Elektron salınabilmesi için ne olmasını bekliyorsun? Yani, elektronun salınması için ne olması gerektiğini açıklayabilir misin?

St17: Iıı… Nasıl olabilir *(kendi kendine sorarak)*? Elektronun farklı yörüngeleri ve farklı enerji seviyeleri var atomda. Belli bir enerji verirseniz elektron üst yörüngeye geçer. Sistem atlamalı bir sistem. Burada kuantize bir enerjiden bahsedebiliriz. Toplam enerjiyi aşan daha çok enerji verirseniz, elektron salınır ve serbest kalır.

I: Hangi parçacıkların enerjisi için kuantize enerjiden bahsediyorsun?

St17: Bütün parçacıklar.

I: Mesela…

St17: Mesela elektronlar, fotonlar.

I: Neden fotonlar?

St17: Iıı… Materyale gönderilen enerji ışığın frekansıyla alakalı. Belli frekansta belli bi enerji var. Fotonlar belli enerji taşıyorlar.

I: Işık kuantize mi?

St17: Evet

I: Açıklamalarını özetleyebilir misin?

St17: Atomik sistemlerde kuantizasyonu görüyoruz.

... text continues after the excerpt...

SAMPLE EXCERPT 3

... text continues before the excerpt...

St4: Spin kuantize… Bu spinin kuantize olması. Kuantizeyi tam oturtamadım aslında kafamda… *(Gülümseme)*… Sürekli aslında onun üstünde konuşuyoruz ama.

I: Tamam, kuantizeden tam anlamıyla kastının ne olduğunu anlayalım. “Biz küçük parçacıkları kuantize edelim ki inceleyebilelim” demiştin daha önceki açıklamalarında. Ne demek tam olarak bu?

St4: Bence birleştirmek bana göre. Çünkü zaten onu tek parça halinde inceleyemediğimiz için, çok küçük olduğu için, paket halinde falan inceliyoruz ki toplu halde.

I: Peki “spin kuantizedir” dedin. Biliyorsun ki spin vektörel bir büyüklük. Yönü ve büyüklüğü ile ilgili ayrı ayrı konuşalım. Yönü için bakalım önce.

St4: Spin in yönü kuantize mi *(kendi kendine sorarak)* ? Iıı… O da kuantize mi olmuş oluyor *(tekrar kendisine sorarak)* ? 2 yönü var zaten. Asla kuantize olamaz bu! Çünkü yönü ya o’dur ya öbürü. Bu yüzden kuantizeden bahsedemeyiz ki spinin yönü için. Zaten aldığı 2 değer var. O zaman neden kuantize olsun ki? Parçacığın tek başına anlamı zaten tam kestiremiyoruz, paket içinde inceliyoruz. Bu belli ise zaten kuantizesinden bahsedemeyiz spinin diyorum.

... text continues after the excerpt...

SAMPLE EXCERPT 4

... text continues before the excerpt...

I : Peki, "particle in a box" tan ne anlıyorsun?

St22: Teorik bi şey. Sanırım bazı uygulamaları olabilir. Parçacık için ne söyleyebilirim *(kendi kendine sorarak)*? Iıı… Işık kullanılarak yapılıyor olabilir.

I: Tamam, o zaman içindeki parçacık ne olabilir?

St22: Eğer ışık kullanırsak, foton olabilir. Ya da manyetik alan kullanırsak, elektron olabilir. Ya da başka parçacıklar.

I: Tamam, peki, bu parçacığın enerjisi hakkında ne söylemek istersin? Enerjisi üzerinde konuşalım. "Kuantize olma" üzerinde tartışıyorduk, enerji kuantize midir?

St22: Iıı… Enerji… Kuantize olabilir.

I : Neden öyle düşündün?

St22: Parçacığın hareketi değişir. Mesela davranışını dalga olarak alırsak, enerjisi ışığın frekansı ile değişecek. Parçacığın hareketi değişecek. Bu da enerjiyi değiştirir... Enerji değişir.

... text continues after the excerpt...

Peer Review Checklist for Inter-coding II

The aim of this study is to examine second-year physics and physics education students' mental models about some quantum mechanical concepts.

EXPERT INFORMATION
Name - Surname :
Title :
Area of Expertise :
Date :

<u>DIRECTIONS:</u> **Dear expert, this checklist is composed of 2 parts. Please follow the checklist by reading the directions for each part.**

<u>YÖNERGE:</u> Sayın uzman, bu kontrol listesi 2 bölümden oluşmaktadır. Lütfen bu kontrol listesini her bölümdeki yönergeleri okuyarak takip ediniz.

PART 1: A SAMPLE TRANSCRIPT OF A STUDENT

Directions for Part 1: Part 1 requests you to code the interview transcripts of a student by means of the coding booklet developed in this study. Please find the related coding booklet in the attachment.

1. Bölüm Yönergesi: 1. Bölüm, bu araştırmada geliştirilen kodlama kitapçığını kullanarak bir öğrencinin görüşme çözümlemelerini kodlamanızı istemektedir. İlgili kodlama kitapçığı ekte yer almaktadır.

INTERVIEW III

Interviewer : *N. Didiş*
Interviewee (name or pseudonym) : *ST3*
Interview Date : *25.05.2009, between 13.40- 14.07*
Interview Duration : *27 minutes*
Interview Data Recorders : *Video camera, interview protocol, paper, pencil.*
Department : ■ Physics □ Physics education
Gender : □ Female ■ Male
Number of taking this course : ■ First time □ Second time or more

¶1: **I: 1.** By considering the quantum theory of a hydrogen atom, what does the "*n*" term mean? What does it describe? Explain. *Bir Hidrojen atomu için kuantum teorisini göz önüne aldığımızda, "n" terimi ne anlama gelir? Neyi açıklar? Açıklayınız.*

¶2: **St3:** Bunun zaten öncesinde, burada da sormuştunuz. Hangi büyüklüklerin kuantize olduğunu sormuştu *(testte)*. Böyle bir durumda direkt “principle quantum number” ı düşünebiliriz. “Energy quantization” ı *(diyerek kağıda yazarak açıklıyor).*

¶3: **I:** Bu “energy quantization” ı direkt olarak söyler diyorsun değil mi?

¶4: **St3:** Hı hıı *(Evet anlamında onaylama).*

¶5: **I:** İsmini nasıl adlandırmıştın “n” nin?

¶6: **St3:** “Principle quantum number”.

¶7: **I:** Evet, böyle kullanıyoruz. Nasıl peki bize gösteriyor enerjinin kuantize olduğunu, nasıl anlıyoruz? Nerede gösteriyor?

¶8: **St3:** Sürekli bir “energy distribution” ı olmadığını görmüştük. Bunu da sadece “discrete” olarak, sürekli olmayan bazı değişim gireceğini söylüyorduk. İşte “1. Level” da “hv”, “2. Level” da “2hv” böyle artan “energy distrubution” ları. Farklı olan enerjiler için “hv” nün daha katları şeklinde. Sürekli artmayan, sürekli olmayan bir enerji.

¶9: **I: 2.** By considering the quantum theory of a hydrogen atom, what does the “*l*” term mean? What does it describe? Explain. *Bir Hidrojen atomu için kuantum teorisini göz önüne aldığımızda, “l” terimi ne anlama gelir? Neyi açıklar? Açıklayınız.*

¶10: **St3: “**l”, bu da şey, momentum *(kağıda yazıyor)*. Dün bunlara çalıştım, bunları tamam görmüştük “Bohr postulate” olarak, 3.sü vardı bir de açısal momentum vektörünün yönü kuantize olması

¶11: **I:** Nasıl gösteriyor?

¶12: **St3:** Bunu formülün öncesinde bir yerde görmüştük, “Bohr postulate” de. Bunu bir kere sormuştunuz herhalde, çok şeydi böyle, neydi? *(kendi kendine sorarak)*. Açısal momentumu böyle bir şeye bölüyordu *(kağıda yazarak)*. Şimdi Bohr’un da momentumun kuantize olduğuna dair şeyi var, öyle söylüyordu, göstermişti hatta. Orada ben böyle bir şey *(kağıda kendisi yazdığı denklem gibi olduğunu kastederek)* çıktığını, “derive” ettiğini fazla düşünmüyorum yani. Sadece göstermişti o bölümde yani. Ama orada daha değişik böyle, direkt formülasyonlarını yerine koymalarını, direkt bunu değil de başka bir şey çıkmıştı.

¶13: **I:** “n” ye bağlı olarak bir şey mi çıkmıştı?

¶14: **St3:** Evet. “nħ”dı. O zaman “n”i niye burada *(formülde)* vardı *(kendi kendine sorarak)*?

¶15: **I:** Bohr “n” cinsinden açıklamıştı, “l” den bahsetmemişti değil mi?

¶16: **St3:** Yani şöyle bir şey çıktı *(hala yazdığı denkleme bakıyor)*, orada da yazmıştım yani bu şeydeki “nħ”. Böyle bir şey çıkmıştı. Şuan mesela açısal momentumun kuantize olması konusunda iyi bir şey olarak çıkmıştı ama şu anda yeni bir şey var mesela “n” den farklı olarak “l” var. “Orbital quantum number”. Onu tanımlayabiliriz. Onu yerine koysam mesela “l” e göre nasıl değiştiğini görmem gerekir.

¶17: **I:** Şimdi burada açısal momentumun kuantize olması ile ilgili bir şey gösterir dedin hani “l” ye ve Planck sabitine bağlı bir değer olarak bunu söyledin. Nasıl peki? Nasıl gösteriyor?

¶18: **St3:** *(sessizlik)*

¶19: **I:** Tamam onu düşün o zaman, şu soruya geçelim, **3.** By considering the quantum theory of a hydrogen atom, what does the “*ml*” term mean? What does it describe? Explain. *Bir Hidrojen atomu için kuantum teorisini göz önüne aldığımızda, ml” terimi ne anlama gelir? Neyi açıklar? Açıklayınız.*

¶20: **St3:** Iıı… “Magnetic quantum number”. Açısal momentum vektörünün yönünün kuantize olduğunu.

¶21: **I:** Ne demek bu?

¶22: **St3:** Yani bunu ben şu an, en son böyle bir şey soruyordu arkadaşlar, yani ondan gelmişti ilk başta.

¶23: **I:** Peki bu vektörel bir büyüklük mü açısal momentum?

¶24: **St3:** Vektörel bir büyüklük olması lazım.

¶25: **I:** Yönünün kuantize olması açıklayan bu mu *(ml)* en başta demiştin?

¶26: **St3:** Yönünü anladım da, yönünün kuantize olmasını, bunu anlamadım. Üç boyutlu uzayda yönün aynı şekilde sürekli değişmesi mi? Yani şeyi bulacağız “orbit”, “rotation” lar var ya orada mesela bir yön tanımlayabilirim ben açısal momentum için. Bu yönünün kuantize olması için yönünün sabit olduğunu düşünüyorum.

¶27: **I:** Nerede biz buna bakıyoruz, görüyoruz?

¶28: **St3:** Şimdi bir “rotation” var elektronların, manyetik alanı var. Buradan şu açısal momentumun kuantize olması ile ilgili bir şey kullanacağımı düşündüm mesela bu manyetik alana göre kuvvetlerden falan bir açısal momentum tanımlayacağım. Onun mesela nasıl kuantize olduğunu o formülden çıkaramam, o yüzden bunun “proof" u şey geldi yani, fiziksel olarak düşünmedim.

¶29: **I:** Tamam peki, **4.** Explain “*n”,” l”, “ml*” terms for the Bohr atom? Compare with quantum mechanical model of atom. *Bohr atomu için “n”,” l”, “ml” terimlerini açıklayınız. Kuantum mekaniksel atom modeli ile karşılaştırınız.*

¶30: **St3:** Bohr zaten enerji seviyesi olarak “n” üzerinden bir şey tanımlamıştı mesela. Tam olarak yazamayacağım *(kağıda yazmayı deneyerek)* “E” nin mesela sırf “n” e bağlı olarak. Bu yarıçapın mesela diyelim, yarıçapın da dediğim gibi, “$h_o n^2$” miydi öyle bir şeydi. Böyle “n” e bağlı olarak tanımladığı bir enerji kavramı mesela, öyle bir şey yapmıştık. Bu öngörülen şeylerden bir tanesi de zaten açısal momentumun kuantize olması. Böyle işte “nħ” olduğu için söylemişti, buradaki “magnetic quantum number” ı ilk defa Bohr’un söylemediğini ama, kuantum mekanik modelde yeni tanımlanan bir terim olduğunu düşünüyorum.

¶31: **I:** Diğerleri için *(“n”ve “l” yi kastederek)*?

¶32: **St3:** Diğerleri için Bohr’un zaten bunları göz önünde bulundurduğunu, “n” için atomdaki enerji seviyeleri için belli, kuantum mekanikte açısal momentumun kuantize olduğunu tanımını zaten Bohr da söylemişti. Ama kuantum modelde de bunun yanı sıra açısal momentum vektörünün kuantize olması başka bir terim.

¶33: **I:** Tamam peki **5.** What do you understand about the “quantum mechanical model of an atom”? *“Kuantum mekaniksel atom modelinden” ne anlıyorsunuz?*

¶34: **St3:** Kuantum atom modelinden yani hiç direkt yani bir ihtimal, olasılık üzerinden değerlendirilen bir atom modeli var. Bu öncesinde yapılan atom modellerini düşünüyoruz. Yani Bohr atom modelini hani tamam böyle bir şeyin gerçekliği vardır ama kuantum atom modelinin bunların hepsini içeren kapsayan bir niteliği olduğunu düşünüyorum mesela. Zaten olasılıklar üzerinden gittiği için mesela bir çok, yani herhangi bir, şey de vardı mesela biz bir “r” *(kağıda yazıyor)* şey bulduk. Bohr atom modelinde, yarıçap bir değer yaklaşık. Ha bunun şey sonrasında da kuantum modelinde de zaten bu şey Bohr’un bulduğu yarıçap, kuantum modelinin olasılıklarından bir tanesi olabilir. Diğer birçok olay düşündüğümüz zaman mesela diğer atom modellerinde bu güne kadar mantıklı olan atom modelleri Bohr olduğunu düşünüyorum mesela. Bohr’un kuantum mekanik modele daha yakın olduğunu düşünüyorum ve diğerlerinin biraz sığ. Ama Bohr modelinin kuantum modeline yakın, en yakın model olduğunu düşünüyorum, ama tam olarak atomun nasıl olduğunu tanımlamıyordu. Kuantum modeli bir ihtimal üzerinden değerlendiren atom modelidir. Bohr da bunun bir şeyi yani, ihtimallerinden bir tanesi. Yani Bohr'un bulduğu değerleri kullanıyor.

¶35: **I:** Bohr da o zaman "probability" den bahseden model gibi bir şey mi oluyor?

¶36: **St3:** *(Sessizlik).* "Bohr" u öyle demek istemedim.

¶37: **I:** Bohr olasılıktan bahsetmiyor zaten. Hani kuantum mekaniksel olarak Bohr' a baktığın zaman diyorum, yörünge tanımlıyordu değil mi?

¶38: **St3:** Bu yörüngede dönmesi böyle bir yarıçapından falan bahsediyor.

¶39: **I:** Yani tam olarak belirliyor mu elektronun yerini?

¶40: **St3:** Yani böyle mesela, "r" diyelim, birçok durum var mesela işte bu elektron sayısı falan şeyin nükleer hareketi falan, onları düşündüğümüz zaman mesela göz önünde bulundurduğumuz zaman şu anda da görüyoruz mesela hani herhangi bir yarıçapı var. Ama bunu mesela biz şu anki zaman ve deney ortamında biz bunu farklı bir "r" değeri okuyabiliriz. Ama Bohr un yaptığı bir "normalization" yani, şey, bir standardize etmeye çalışıyor. İşte bazı şeyleri ne bileyim "approximation" falan, ondan sonra böyle bir "r" değeri buluyor. Bu yüzde yüz şey değil diye düşündüm. İhtimal değil diye düşünüyorum *(gülme).*

¶41: **I:** Peki **6.** By considering the quantum theory of an atom, what does the "m_s" term mean? What does it describe? Explain. *Bir atom için kuantum teorisini göz önüne aldığımızda, m_s" terimi ne anlama gelir? Neyi açıklar? Açıklayınız.*

¶42: **St3:** Spinin kuantize olması *(gülme).*

¶43: **I:** Neden öyle dedin? Nasıl bir çıkarım yaptın?

¶44: **St3:** Çünkü ne varsa kuantize. Bunda mesela "principle quantum number", bunlar üzerine eklenirken mesela. Sorun şuradaki bunları nasıl şekillendirebileceğini düşünemiyorum mesela. Enerjinin bu şekilde bir şeyler söylediğini, nasıl kuantize olabileceğini, momentumun, bir de momentum vektörünün, "spin magnetic", onun nasıl olacağına ilişkin.

¶45: **I:** Spin ile ilgili bir şey söylüyordur dedin ama nasıl olduğuyla ilgili bir fikrin yok.

¶46: **St3:** Evet. *(sessizlik)* Spin de hani elektronların içinde bulundukları alan diye düşünüyorum.

¶47: **I:** Nasıl bir alan?

¶48: **St3:** Onu bir arkadaş sunum yapmıştı da geçen. Nasıl bir şey olduğunu anlayamadık. Aslında anlattığı şey bunun üzerindeydi, belirsizlikler üzerineydi mesela, spin üzerindeydi mesela. Spin nasıl bir şey olabilir ki böyle vektör gösterebilir mesela *(kendi kendine sorarak)?* Oradan birçok şeyler çıkarttı mesela, enerji "distribution" ı olsun, momentum olsun falan. Bunlardan nasıl, ne gibi bir şey olabileceğini tahminlerde bulundu biz de hani bir şeyler öğrenmeye çalıştık. Onun üzerine hani fiziksel anlamını sadece hani elektronun dönüş, yani kendi etrafında dönüşü olarak baktığımız zaman mesela böyle bir bilgileri bize vereceğini düşünüyorum mesela. Başka ne gibi bir madde, nasıl bir şey olduğunu söylersem, atomun bulunduğu yere göre, bulunduğu o şeye göre, orbitale göre, değişen şeyler.

¶49: **I:** Eklemek istediğin var mı?

¶50: **St3:** Yok. Burada bir şey yok.

¶51: **I:** Bohr'un açısal momentumun kuantize olduğunu göstermesi ile kuantum mekaniksel olarak açısal momentumun kuantize olduğunun gösterilmesine ilişkin… Bohr'un ki "nħ" demiştik.

¶52: **St3:** Ya şuradan *("l" yi açıkladığı sorudaki boşlukta, kuantum için yazdığı formülün yanına yazarak)* bu da bi şey "energy quantization" ı. "n" için "l" değerleri bulduk, çıkacak bir şey sanmıyorum da.

¶53: **I:** Tamam, "l" nin alabileceği değerler nedir?

¶54: **St3:** "n-1" e kadar alabiliyor. "l" için sıfır. Bu da "n" çıkıyor.

¶55: **I:** Çıkıyor mu? Nasıl çıkıyor?

¶56: **St3:** *(Denklemde "n-1" koyuyor)* √(n-1). (n-1+1). Bir eksiklik var. *(Farklı sonuçtan dolayı şaşırdı).* Bir eksiklik var. Hah şöyle diyebilir miyiz? Sıfır olsa. "Integer" olacağı için daha, buradan bir şey çıkacağını sanmıyorum.

¶57: **I:** "l" sıfır olsa "n" zaten 1 dir, değil mi?

¶58: **St3:** Sıfır?

¶59: **I:** "n= 2" olursa "l=1" ya da "0" dır bu durumda öyle değil mi?

¶60: **St3:** Neden? "l=0" sa?

¶61: **I:** O "n" in 1 olduğunu göstermez mi?

¶62: **St3:** Buradan çıkmaz öyle bir şey o zaman *(denkleme göre karar veriyor).*

¶63: **I:** "n" ye 1 ver, "l" ne alır? Sıfır. Tek alabileceği değer sıfır.

¶64: **St3:** Tamam oradan da *(düşünüyor)*…

¶65: **I:** "n" ye 2 dersen "l" 1 ve sıfır alır. Yine sıfır alır. Kafanda bir soru işareti oluştu herhalde neden böyle diye?

¶66: **St3:** Oluştu.

¶67: **I:** Ama evet, açısal momentumun kuantum mekaniksel ve Bohr'un tanımlaması, kuantize olduğunu söylemelerde değer olarak farklı, çünkü kullandıkları şeyler farklı. Ekleyeceğin şey var mı bunlara?

¶68: **St3:** *(Kağıdını kontrol ediyor).* Bu sefer bayağı bi üzerinde düşündüm. Şu *(açısal momentumun kuantize durumuna tekrar bakarak).*

¶69: **I:** Hala söyleyecek bir şeyler var herhalde. Konuşalım.

¶70: **St3:** Yok ya… O spin için. "Information theory" mi öyle bir şey vardı galiba, spinin nerede olduğunu yerini belirlemek için onlardan bahseden. Ama spinin ne olduğunu çok fazla anlayamadım.

PART 2: SAMPLE EXCERPTS FROM THE INTERVIEWS

Directions for Part 2: Part 2 requests you to code the excerpts from the interviews of different students by using the same coding booklet.

2. Bölüm Yönergesi: 2. Bölüm, aynı kodlama kitapçığını kullanarak farklı öğrencilerin görüşmelerine ait alıntıları kodlamanızı istemektedir.

SAMPLE EXCERPT 1

... text continues before the excerpt...

St2: Enerjinin devamlı olmadığını. Yani böyle "continuous" bir şekilde ilerlemediğini artışın ya da azalışın.

I: Yani "continuous" derken neyi kastediyorsun? Enerjinin "continuous" olmadığını dedin.

St2: Orda şimdi, Planck'ın formülünde bir tane Planck sabiti var hocam, bu bir sayı. Dolayısıyla bu sayının katları şeklinde enerji yayılıyor gözüküyor.

I: Hangi enerjiden bahsediyorsun?

St2: Herhangi bir fotonun ya da herhangi bir maddenin sahip olduğu enerji. Sonuçta hepsinde var. DeBroglie'ye de bağlantı kurarsak normal elektron için de aynı şeye formüle koyabiliriz o "h" yi. Dolayısıyla "h" nin olduğu her yerde enerji hep böyle zıplayarak devam ediyor. Buna "continuous" değil dedim. Planck' ı ben onu buldu diye düşünmüştüm.

... text continues after the excerpt...

SAMPLE EXCERPT 2

... text continues before the excerpt...

I: Bu aslında bize neyi açıklar diye soracaktım, sen isminden önce hemen "enerji" dedin. Nasıl açıklar enerjiyi. Ne söylemek istersin bu konuda?

St7: Enerjiyi şöyle açıklar. Belli enerji düzeylerine sahip olabilir elektron. Bu sahip olabileceği, bulunabileceği belli "energy state"lerini, değerlerini gösteriyor. Seviyelerini gösterir.

... text continues after the excerpt...

SAMPLE EXCERPT 3

... text continues before the excerpt...

I: Peki bu sadece teorik bir kutu mu yoksa fiziksel bir anlamı var mı, ne düşünüyorsun?

St21: Bence teorik. Böyle bi şey olması imkansız.

I: Peki, eğer bu teorik bi kutunun içindeki parçacıkla ilgili ne söylemek istersin? Nedir bu parçacık?

St21: Büyük ihtimalle elektron… Ya da foton olabilir.

I: Peki, bu parçacığın enerjisi hakkında ne düşünüyorsun? Çünkü bu parçacık "Elektron ya da foton olabilir" dedin. Bu parçacığın enerjisi kuantize mi?

St21: Bence değil. Enerji burada kuantize değil!

I: Neden kuantize değil?

St21: Çünkü enerji sabit, değişmiyor. Parçacık kutunun içinde sadece ileri geri gidiyor, o yüzden kuantize değil.

... text continues after the excerpt...

J.2 Inter-coding Document for the Textbooks

An external coder coded the selected pages of two textbooks. The information of inter-coder reliability examination for the textbooks is presented below:

First try:

Textbook code	Chapter no	Coded pages in the chapter	Case	Context
Textbook 1	4	pp. 133- 138	Quantization of Energy	Context 3: Energy Levels and Atomic Spectra
Textbook 2	7	pp. 214- 218	Quantization of Angular Momentum	Context 62.b: Quantum Atom

Second try:

Textbook code	Chapter no	Coded pages in the chapter	Case	Context
Textbook 1	6	pp. 208- 212	Quantization of Angular Momentum	Context 62.b: Quantum Atom
Textbook 2	6	pp. 185-189	Quantization of Energy	Context 3: Energy Levels and Atomic Spectra

J.3 Inter-coding Document for the Video-recorded Classes

An external coder coded the selected video records. The information of inter-coder reliability examination for the videos is presented below:

<u>First try:</u>

Week	Lecture no	Date of record	Record period	Coded period	Case	Context
Week 6	Lecture 11	26.03.2009	~120 min.	< 60 min	Quantization of Energy	Context 4: Particle in a Box

<u>Second try:</u>

Week	Lecture no	Date of record	Record period	Coded period	Case	Context
Week 8	Lecture 15	09.04.2009	~120 min.	< 30 min	Quantization of Angular Momentum	Context 61.b: Bohr Atom

APPENDIX K

ETHICAL ISSUES

K.1 Permission 1

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Orta Doğu Teknik Üniversitesi
Middle East Technical University

Öğrenci İşleri Dairesi
Başkanlığı
Registrar's Office

06531 Ankara, Türkiye
Phone: +90 (312) 2103417
Fax: +90 (312) 2107960
www.oidb.metu.edu.tr

B.30.2.ODT.0.70.00.00 906-177

13.2.2009

FEN BİLİMLERİ ENSTİTÜSÜ MÜDÜRLÜĞÜ'NE

İLGİ: 10.2.2009 tarih ve B.30.2.ODT.0.40.05.02/126/305-2258 sayılı yazınız.

İlgi yazınız ile Ortaöğretim Fen ve Matematik Alanları Eğitimi Doktora Programı öğrencilerinden Nilüfer DİDİŞ'in 16 Şubat-31 Aralık 2009 tarihleri arasında, "Öğrencilerin Kuantum Mekaniği Anlamakta Kullandıkları Modeller İçin Bir Tasarı" başlıklı tez çalışmasına ilişkin olarak Üniversitemiz Fen Edebiyat Fakültesi Fizik Bölümü öğrencileri ile uygulama yapma isteği Rektörlük Makamınca uygun görülmüştür.

Gereğini bilgilerinize arz ederim.

Saygılarımla.

Nesrin ÜNSAL
Öğrenci İşleri Dairesi Başkanı

ODTÜ
Fen Bil. Enst. Müdürlüğü
340

K.2 Permission 2

O.D.T.Ü.
FEN BİLİMLERİ ENSTİTÜSÜ
YÖNETİM KURULU KARARI

Tarih: 10.02.2009
Sayı: FBE: 2009/ 9

GÖREVLENDİRME VE İZİN

Ortaöğretim Fen ve Matematik Alanları Eğitimi EABD doktora programı öğrencisi Nilüfer Didiş'in 16 Şubat -31 Aralık 2009 tarihleri arasında "*Öğrencilerin Kuantum Mekaniği Anlamakta Kullandıkları Modeller için Bir Tasarı*" başlıklı araştırmaya ilişkin ODTÜ Fen Edebiyat Fakültesi Fizik Bölümü öğrencileri ile uygulama yapmak için görevlendirme başvurusu incelenmiş; ilgili danışman görüşüne dayanarak adı geçen öğrencinin isteği doğrultusunda görevlendirilmesine oybirliği ile karar verilmiştir.

Prof. Dr. Canan Özgen *FBE Müdürü*	**Prof. Dr. R.Sezer Aygün** *FBE Müd. Yard.*	**Prof.Dr.Ali Kalkanlı** *FBE Müd. Yard.*
KATILAMADI **Prof. Dr. Cahit Eralp** *Üye*	**Prof. Dr. Vedat Toprak** *Üye*	**Doç.Dr.Cem Topkaya** *Üye*

K.3 Consent Form

Consent Form for Participants

Dear Students;

I am a Ph.D student at the Department of Secondary Science and Mathematics Education at Middle East Technical University. I study on physics education, and my research area is students' understanding of quantum mechanical concepts.

For my doctoral dissertation, I investigate university physics and physics education students' understanding of some quantum mechanical concepts. For this aim, I will follow the Modern Physics course (2300202) with you in this semester (2008-2). In Modern Physics classes, I would like to do some observations, and implement tests. And, before and after the classes, I would like to conduct some interviews with you, and record them by the video camera. If you would like to participate, the time schedule of the interviews will be at your convenience. The participation will not be graded in course, and you will not be penalized if you choose not to participate.

During the data collection process, there will be no element that creates physical, psychological and mental harms for you. All the data will be kept private, and they will be used only for the scientific publications, and they will not be used for any other aims. We hope that, in the future, other people might benefit from this study through improved understanding of students cognition.

Please fill the form below and give it to the researcher after signed it. If you do not want to continue to the study, you can stop participating at any time. If you have any other questions about the study, please do not hesitate to communicate with me.

Yours sincerely.

Res. Assist. Nilüfer Didiş
Physics Education Major, Department of Secondary
Science and Mathematics Education,
Faculty of Education,
Middle East Technical University
Office: EF A 37, Phone: 210 7509
E -mail: dnilufer@metu.edu.tr

I understand the information given to me, and agree to conditions of this study. I would like to participate to this study, which is scientific investigation of students'undestanding of quantum mechanical concepts.

Name- Surname	**Date**	**Signature**
--------------------	----/----/-----	

APPENDIX L

TIME SCHEDULE OF THE DISSERTATION

Years	Months	Conceptual Context	Preparation for Data Collection	Data Collection	Organization of the Data-Transcriptions	Analysis of the Data	Presenting Results & Conclusion	Writing Dissertation & Revision due to feedback
2007	**1-12**	X						
2008	**1-9**	X						
	9	X	X					X
	10	X	X					X
	11	X	X					X
	12	X	X					X
2009	1	X	X					X
	2	X	X					X
	3	X	X	X				X
	4	X		X	X	X		X
	5	X		X	X	X		X
	6	X		X	X	X		X
	7	X		X	X	X		X
	8	X			X	X		X
	9	X			X	X		X
	10	X			X	X		X
	11	X			X	X		X
	12	X			X	X		X
2010	**1-8**	X			X	X		X
	9	X				X		X
	10	X				X		X
	11	X				X		X
	12	X				X		X
2011	**1-8**	X				X	X	X
	9	X					X	X
	10	X					X	X
	11	X					X	X
	12	X					X	X
2012	**1-4**	X					X	X

APPENDIX M

FREQUENCY OF THE CODES

M.1 Frequency and Percentage of Each Code Identified in Students' Explanations about Quantization

CODES	f	(%)
MENTAL MODELS OF QUANTIZATION		
1 ONLY BOUND PARTICLE OBP	125	6.16
2 DISCRETENESS or-and DISCRETENESS CHARACTERISTIC D-DC	1191	58.69
3 NATURAL CHARACTERISTIC NC	275	13.55
4 ANY VALUES AV	53	2.61
5 ARTIFICIAL CHARACTERISTIC AC	61	3.00
6 EINSTEIN'S RELATIVITY ER	26	1.28
7 CHANGE C	112	5.52
8 INTEGRATION I	53	2.61
9 EVERY PARTICLE EP	133	6.55

M.2 Frequency of the Codes for Mental Structures of Each Student Over the Contexts

STUDENTS	CONTEXT 1	CONTEXT 2	CONTEXT 3	CONTEXT 4	CONTEXT 5	CONTEXT 6.a1	CONTEXT 6.a2	CONTEXT 6.b1	CONTEXT 6.b2	CONTEXT INDEPENDENT FRAGMENTS*	TOTAL
St1	**NM** D/DC:3 ER:1 EP:1	**ShM** **D/DC:3, EP:1** **AV:2** **AC:2**	**NM** D/DC:10, C:5 OBP:2 AV:3	**AM** D/DC:1, **C:6** **NC:1, EP:8** **AV:1**	**NM** AV:1 C:2	**NM** OBP:2 AC:1 D/DC:4 C:1	**NM** OBP:2 C:2 D/DC:3	**NE**	**NM** D/DC:2 AV:1 C:4	D/DC:7 AC:3	*D/DC:33, AV:8* *OBP:6, EP:10* *NC:1, AC:6* *I:0, ER:1, C:20*
St2	**PSM** **D/DC:6** **NC:1** **EP:2**	**NM** D/DC:14 EP:1	**PSM** **D/DC:17** **NC:2** **EP:3**	**SM** **D/DC:5** **OBP:3** **NC:2**	**NM** D/DC:2 EP:1	**NM** D/DC:8 NC:2	**SM** **D/DC:11** **OBP:3** **NC:4**	**NM** OBP:1 D/DC:4	**SM** **D/DC:13** **OBP:2** **NC:7**	D/DC:5, EP:1 NC:9 I:2	*D/DC:85, AV:0* *OBP:9 , EP:8* *NC:27, AC:0* *I:2 , ER:0 , C:0*
St3	**PSM** **D/DC:1** **NC:1** **EP:1**	**PSM** **D/DC:10** **NC:4** **EP:1**	**NM** D/DC:17, C:1 NC:3 OBP:2	**SM** **D/DC:7** **OBP:4** **NC:4**	**NM** D/DC:1	**SM** **D/DC:10**, C:1 **OBP:1** **NC:2**	**SM** **D/DC:5** **OBP:1** **NC:1**	**NM** D/DC:8 NC:1	**NM** D/DC:7 C:1	D/DC: 6 NC:1	*D/DC:72 , AV:0* *OBP:8 , EP:2* *NC:17 , AC:0* *I: 0, ER:0 , C:3*
St4	**IM** **I:3, AC:2** **EP:3** D/DC:2	**NM** D/DC:7 EP:8 AC:1	**NM** D/DC:20, C:1 NC:3, AC:4 OBP:2, I:1	**NM** D/DC:12, C:3 EP:3 AV:1	**NE**	**NM** D/DC:1	**SM** **D/DC:9** **OBP:1** **NC:1**	**NE**	**IM** **I:3, AC:4** **EP:2,** NC:3 D/DC:11	EP:4, AC:6 D/DC:2 I:4	*D/DC:64 , AV:1* *OBP: 3, EP:20* *NC: 7, AC:17* *I:11, ER: 0, C:4*
St5	**NM** D/DC:7 AC:1 AV:1	**NM** D/DC:2	**NM** D/DC:18, C:2 NC:3, AV:1 OBP:1, I:1	**NM** D/DC:1, C:2 EP:2, NC:1 AV:1, ER:3	**NE**	**IM** **I:4** **EP:1** **AC:1**	**SM** **D/DC:8** **OBP:1** **NC:2**	**NE**	**NM** D/DC:18 NC:1 AC:1	I:11 AC:1	*D/DC:54 , AV:3* *OBP:2 , EP3:* *NC:7 , AC: 4* *I:16 , ER:3 , C:4*
St6	**NM** D/DC:27 EP:1 OBP:1	**NM** D/DC:5	**SM** **D/DC:30**, EP:1 **OBP:10** **NC:4**	**SM** **D/DC:5** **OBP:7** **NC:2**	**NM** D/DC:6 OBP:1	**NM** D/DC:10 OBP:2	**NM** D/DC:6	**NM** D/DC:3 OBP:1	**NM** D/DC:4	EP:2 D/DC:6 NC:2	*D/DC: 102, AV:0* *OBP:22, EP:4* *NC:8, AC: 0* *I:0 , ER:0, C:0*
St7	**PSM** **D/DC:9**, AV:1 **NC:6** **EP:1**	**NM** D/DC:11, OBP:1 NC:11 EP:1	**PSM** **D/DC:17**, OBP:1 **NC:6** **EP:1**	**SM** **D/DC:23** **OBP:19** **NC:18**	**NM** D/DC:1	**SM** **D/DC:11** **OBP:2** **NC:4**	**NM** D/DC:5 OBP:1 NC:3	**SM** **D/DC:4** **OBP:2** **NC:1**	**NM** D/DC:2 EP:1	D/DC:11 NC:6	*D/DC: 94, AV:1* *OBP:26 , EP:4* *NC:55, AC:0* *I:0 , ER:0 , C:0*
St8	**NM** D/DC:2 C:1	**NE**	**NM** D/DC:22 OBP:3	**NE**	**NM** D/DC:2 AV:1	**SM** **D/DC:8** **OBP:2** **NC:4**	**NM** C:3	**NM** D/DC:4 NC:2	**NM** D/DC:1	D/DC:6 NC:1	*D/DC: 45, AV:1* *OBP: 5, EP:0* *NC:7 , AC:0* *I:0 , ER:0 , C:4*

APPENDIX M.2 (continued)

STUDENTS	CONTEXT 1	CONTEXT 2	CONTEXT 3	CONTEXT 4	CONTEXT 5	CONTEXT 6.a1	CONTEXT 6.a2	CONTEXT 6.b1	CONTEXT 6.b2	CONTEXT INDEPENDENT FRAGMENTS*	TOTAL
St9	**AM** **NC:1, AV:1** **C:2** **EP:1**	**NE**	**AM** **NC:1, AV:1** **C:6**, D/DC:5 **EP:1**	**AM** **NC:1, AV:1** **C:3**, D/DC:1 **EP:5**	**NE**	**AM** **NC:1, AV:1** **C:3**, D/DC:2 **EP:1**	**AM** **NC:1, AV:1** **C:5**, D/DC:1 **EP:1**	**NM** D/DC:1	**AM** **NC:2, AV:1** **C:4**, D/DC:3 **EP:1**	C:9, ER:2 NC:4, AV:4 EP:3	*D/DC:13 , AV:10* *OBP:0 , EP:13* *NC:11 , AC:0* *I:0 , ER:2 , C:32*
St10	**NM** D/DC:1 AV:1	**NE**	**PSM** **D/DC:25**, AV:1 **NC:7** **EP:6**	**SM** **D/DC:9**, AC:1 **OBP:3** **NC:6**	**NA**	**SM** **D/DC:6** **OBP:2** **NC:1**	**SM** **D/DC:5**, C:1 **OBP:1** **NC:1**	**NM** D/DC:10 NC:2	**NM** D/DC:14, OBP:1 NC:1 AC:1	D/DC:8	*D/DC:78 , AV:2* *OBP:7 , EP:6* *NC:18 , AC:2* *I:0 , ER:0 , C:1*
St11	**EM** **AC:1**, **EP:1** **ER:1, C:2** D/DC:9, AV:1	**NE**	**NM** D/DC:17, EP:1 AV:1	**NM** D/DC:3 AV:1	**NA**	**NM** D/DC:8	**NM** D/DC:1 AV:3	**NM** D/DC:7 OBP:2 AV:1	**PSM** **D/DC:16, EP:1** **NC:3**, AV:3 C:1	EP:1 C:1	*D/DC:61 , AV:10* *OBP:2 , EP:4* *NC:3 , AC:1* *I:0 , ER:1 , C:4*
St12	**NM** D/DC:1	**NE**	**PSM** **D/DC:9** **NC:5** **EP:1**	**NE**	**NA**	**NM** D/DC:1 EP:1	**NA**	**NM** D/DC:3	**NM** D/DC:5	D/DC:2 EP:1	*D/DC:21 , AV:0* *OBP:0 , EP:3* *NC:5 , AC:0* *I: 0, ER:0 , C:0*
St13	**NM** D/DC:3 EP:1	**NE**	**NM** D/DC:19 EP:1	**NE**	**NE**	**NM** D/DC:2	**NE**	**NE**	**NM** D/DC:11		*D/DC:35 , AV:0* *OBP:0 , EP:2* *NC:0 , AC:0* *I:0 , ER:0 , C:0*
St14	**NM** D/DC:1 OBP:1 I:1	**NE**	**NM** D/DC:9 OBP:1	**NE**	**NE**	**NE**	**NE**	**NE**	**NE**	ER:3, D/DC:3 EP:2, NC:3 C:1	*D/DC:13 , AV:0* *OBP:2 , EP:2* *NC:3 , AC:0* *I:1 , ER:3 , C:1*
St15	**NM** D/DC:5	**NM** D/DC:1	**SM** **D/DC:21** **OBP:4** **NC:5**	**SM** **D/DC:5** **OBP:1** **NC:1**	**NM** D/DC:1	**SM** **D/DC:6** **OBP:1** **NC:3**	**NM** D/DC:4	**NE**	**NM** D/DC:9 NC:1	D/DC:5 NC:1	*D/DC:57 , AV:0* *OBP:6 , EP:0* *NC:11 , AC:0* *I:0 , ER:0 , C:0*
St16	**NM** D/DC:4 NC:1	**NE**	**NM** D/DC:23 NC:5	**NM** EP:2 D/DC:2	**NE**	**NM** D/DC:5 NC:2	**NM** D/DC:1	**NE**	**NE**	D/DC:3 EP:1	*D/DC:38 , AV:0* *OBP:0 , EP:3* *NC:8, AC:0* *I:0 , ER:0 , C:0*
St17	**PSM** **D/DC:9** **NC:2** **EP:3**	**NM** D/DC:2	**NM** D/DC:9 NC:2	**NM** D/DC:2	**NE**	**NM** D/DC:3	**NE**	**NE**	**PSM** **D/DC:7** **NC:3** **EP:2**	D/DC:9 NC:5	*D/DC:41 , AV:0* *OBP: 0, EP:5* *NC:12 , AC:0* *I: 0, ER:0 , C:0*

APPENDIX M.2 (continued)

STUDENTS	CONTEXT 1	CONTEXT 2	CONTEXT 3	CONTEXT 4	CONTEXT 5	CONTEXT 6.a1	CONTEXT 6.a2	CONTEXT 6.b1	CONTEXT 6.b2	CONTEXT INDEPENDENT FRAGMENTS*	TOTAL
St18	SM **D/DC:10** **OBP:2** **NC:4**	NM D/DC:3, NC:1 I:2 AC:1	SM **D/DC:7** **OBP:1** **NC:4**	SM **D/DC:1** **OBP:3** **NC:4**	NA	NM D/DC:2 NC:2	SM **D/DC:5** **OBP:1** **NC:2**	NM D/DC:4 NC:1	NM D/DC:1	D/DC:5 ER:1	*D/DC:38 , AV:0* *OBP:7 , EP:0* *NC: 18, AC:1* *I:2 , ER:1 , C:0*
St19	NM D/DC:4 NC:1	NE	PSM **D/DC:6** **NC:1** **EP:1**	NM D/DC:1 C:2 NC:1	NA	NM D/DC:3	NM D/DC:2	NM D/DC:2 AC:1	NE	D/DC:7, OBP:1 NC:2 I:2	*D/DC:25 , AV:0* *OBP:1 , EP:1* *NC:5 , AC:1* *I: 2, ER:0 , C:2*
St20	NE	NE	PSM **D/DC:18** **NC:1** **EP:2**	NM D/DC:1 NC:3	NA	NM D/DC:5 NC:1	NE	NM D/DC:3	NM D/DC:5	D/DC:5, AC:2 ER:1, EP:3 NC:4	*D/DC: 37, AV:0* *OBP: 0, EP:5* *NC:9 , AC:2* *I:0 , ER:1 , C:0*
St21	EM **AC:1, EP:1** **ER:1**, NC:1 **C:2**	NE	NM D/DC: 11 NC:1	AM **NC:1, EP:2** **AV:1** **C:1**	NA	NE	NE	NE	NE	D/DC:1, ER:7 NC:1, EP:2 C:5	*D/DC:12 , AV:1* *OBP:0 , EP:5* *NC:4 , AC:1* *I:0 , ER: 8, C:8*
St22	SM **D/DC:4** **OBP:1** **NC:1**	NM D/DC:8 NC:1	NM D/DC:8 C:5 OBP:2	AM **NC:3, EP:4** **AV:1** **C:5**	NA	NE	NE	NM D/DC:1	PSM **D/DC:3, NC:2** **EP:1** C:3	D/DC:8 OBP:1 NC:2	*D/DC:32 , AV:1* *OBP:4 , EP:5* *NC: 9, AC:0* *I:0 , ER:0 , C:13*
St23	NM D/DC:4	NM D/DC:4	NE	AM **NC:2, EP:1** **AV:1, C:2** D/DC:1	NA	NE	NA	NE	NE	D/DC:3	*D/DC:12 , AV:1* *OBP:0 , EP:1* *NC:2 , AC:0* *I:0 , ER:0 , C:2*
St24	NA	NM D/DC:1	AM **NC:1, EP:1** **AV:2** **C:2**	NA	NA	NE	NA	NE	NM D/DC:2 EP:1 NC:3	D/DC:1, C:1 EP:1, I:2 NC:1	*D/DC:4 , AV:2* *OBP:0 , EP:3* *NC:5 , AC:0* *I:2 , ER:0, C:3*
St25	PSM **D/DC:8** **NC:2** **EP:1**	NE	SM **D/DC:11** **OBP:5** **NC:6**	SM **D/DC:1** **OBP:4** **NC:1**	NA	NM D/DC:1 OBP:1	NM D/DC:4 OBP:1	NM D/DC:1	SM **D/DC:9** **OBP:2** **NC:4**	D/DC:8 AC:3 NC:1	*D/DC:43 , AV:0* *OBP:13 , EP:1* *NC:14 , AC:3* *I:0 , ER:0 , C:0*
St26	NE	NE	NM D/DC:5	NM EP:1 AV:1	NA	NE	NA	NE	NA	D/DC:1, C:1 NC:1 I:2	*D/DC:6 , AV:1* *OBP:0 , EP:1* *NC:1 , AC:0* *I: 2, ER:0 , C:1*

APPENDIX M.2 (continued)

STUDENTS	CONTEXT 1	CONTEXT 2	CONTEXT 3	CONTEXT 4	CONTEXT 5	CONTEXT 6.a1	CONTEXT 6.a2	CONTEXT 6.b1	CONTEXT 6.b2	CONTEXT INDEPENDENT FRAGMENTS*	TOTAL
St27	ShM **D/DC:4, EP:1** **AV:1** **AC:1**	ShM **D/DC:5, EP:1** **AV:2** **AC:1**	NE	NM C:3 AV:1	NA	NE	NA	NE	NM D/DC:5	D/DC:5 EP:3 AC:4	*D/DC:19 , AV:4* *OBP:0 , EP:5* *NC:0 , AC:6* *I:0 , ER:0 , C:3*
St28	IM **I:2** **AC:2** **EP:1**	NE	NE	IM **I:5**, OBP:1 **AC:5**, C:2 **EP:2**	NE	NE	NE	NE	NM D/DC:4 AC:1	D/DC:2, C:3 ER:5, AC:2 EP:2, I:7	*D/DC:6 , AV:0* *OBP:1 , EP:5* *NC:0 , AC:10* *I:14 , ER:5 , C:5*
St29	ShM **D/DC:2, EP:1** **AV:1** **AC:2**	NE	ShM **D/DC:4, EP:2** **AV:1** **AC:1**	ShM **D/DC:1, EP:2** **AV:1** **AC:1**	NA	NE	NE	NE	NE	D/DC:1, I:2 EP:2, AC:1 NC:2	*D/DC:8 , AV:3* *OBP:0 , EP:7* *NC:2 , AC:5* *I:2 , ER: 0, C:0*
St30	NE	NE	NM D/DC:10 C:1	NM D/DC:3	ShM **D/DC:2, EP:1** **AV:1** **AC:1**	NM D/DC:1	NE	NM I:1	NM C:1	D/DC:1	*D/DC:17 , AV:1* *OBP:0 , EP:1* *NC:0 , AC:1* *I:1 , ER:0 , C:2*
St31	NM AV:2 ER:1	NE	SM **D/DC:8** **OBP:1** **NC:4**	NM EP:1	NM EP:2	NM D/DC:6 NC:1	NM D/DC:1	NM D/DC:1	NM D/DC:10 NC:1	EP:1 AC:1 AV:1	*D/DC:26 , AV:3* *OBP: 1, EP: 4* *NC: 6, AC:1* *I:0 , ER:1 , C:0*
TOTAL	*D/DC:126, AV:9* *OBP:5, EP:20* *NC:21, AC:10* *I:6 , ER:4, C:7*	*D/DC:76, AV:4* *OBP:1, EP:13* *NC:17, AC:5* *I:2 , ER:0, C:0*	*D/DC:376, AV:10* *OBP:35, EP:21* *NC:64, AC:5* *I:2, ER:0, C:23*	*D/DC:85, AV:11* *OBP:45, EP:33* *NC:51, AC:7* *I:5, ER:3, C:29*	*D/DC:15 , AV:3* *OBP:1 , EP:4* *NC:0 , AC:1* *I:0 , ER:0 , C:2*	*D/DC:103, AV:1* *OBP:13, EP:3* *NC:23, AC:2* *I:4, ER:0, C:5*	*D/DC:71, AV:4* *OBP:12, EP:1* *NC:15, AC:0* *I:0, ER:0, C:11*	*D/DC:56, AV:1* *OBP:6, EP:0* *NC:7, AC:1* *I:0, ER:0, C:0*	*D/DC:162, AV:5* *OBP:5 , EP:9* *NC:31, AC: 7* *I:3 , ER:0, C:14*	*D/DC:121 , AV:5* *OBP:2 , EP:29* *NC:46 , AC:23* *I:30 , ER:19 , C:21*	***D/DC:1191, AV:53*** ***OBP:125, EP:133*** ***NC: 275, AC: 61*** ***I:53 , ER:26, C:112***

NOTES:

1. The unit of analysis should be considered in the interpretation of the Table.
2. Coherently used elements were shown in **bold**.

* Students' context independent explanations about the quantization of physical observables.

M.3 Frequency of the Codes Explaining the Quantization of Physical Observables in the Textbooks

NO	CODE ABBR.	CONTEXT 1		CONTEXT 2		CONTEXT 3		CONTEXT 4		CONTEXT 5		CONTEXT 6.a		CONTEXT 6.b		TOTAL	
		T1	T2	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2
1	OBP	12	13	4	8	14	0	24	11	1	3	2	23	29	19	86	77
2	D/DC	31	52	15	11	84	39	38	24	32	9	24	82	91	126	315	343
3	NC	8	5	6	5	18	3	15	12	2	2	3	15	21	37	73	79
4	AV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	AC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	ER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	EP	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0
TOTAL		51	70	25	24	117	42	77	47	35	14	29	120	141	182	475	499

M.4 Frequency of the Codes about the Methodology of the Textbooks while Explaining the Quantization Phenomenon

NO	CODE ABBR.	CONTEXT 1		CONTEXT 2		CONTEXT 3		CONTEXT 4		CONTEXT 5		CONTEXT 6.a		CONTEXT 6.b		TOTAL	
		T1	T2	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2
1	mthd- P	4	1	1	0	6	3	4	2	4	1	2	3	9	15	30	25
2	mthd- (T)RS	18	17	15	8	62	22	46	32	11	4	12	61	92	128	256	272
	mthd- (T)C&Q	0	11	0	0	2	0	4	3	1	0	0	9	4	6	11	29
	mthd- (T)HOS	13	15	5	13	0	1	1	0	0	0	6	0	0	0	25	29
	mthd- (T)A	0	0	0	0	3	0	0	0	0	0	0	0	0	0	3	0
	mthd- (T)N/T	1	1	0	0	8	1	2	2	4	1	0	12	2	3	17	20
	mthd- (T)R	0	0	0	0	0	0	0	0	5	0	0	0	2	0	7	0
3	mthd- (M)MR	8	10	2	3	17	2	7	2	4	3	9	18	18	10	65	48
	mthd- (M)E	7	15	2	0	19	13	13	6	6	5	0	17	14	20	61	76
TOTAL		51	70	25	24	117	42	77	47	35	14	29	120	141	182	475	499

M.5 Frequency of the Codes Explaining the Quantization of Physical Observables in the Modern Physics Classes

NO	CODE ABBR.	CONTEXT 1	CONTEXT 2	CONTEXT 3	CONTEXT 4	CONTEXT 5	CONTEXT 6.a	CONTEXT 6.b	TOTAL
1	OBP	1	4	17	17	2	15	20	76
2	D/DC	18	35	69	56	18	40	190	426
3	NC	4	16	11	9	2	12	17	71
4	AV	0	0	0	0	0	0	0	0
5	AC	0	0	0	0	0	0	0	0
6	ER	0	0	0	0	0	0	0	0
7	C	0	0	0	0	0	0	1	1
8	I	0	0	0	0	0	0	0	0
9	EP	0	0	0	0	0	0	0	0
TOTAL		23	55	97	82	22	67	228	574

M.6 Frequency of the Codes about the Methodology in Modern Physics Classes while Explaining the Quantization Phenomenon

NO	CODE ABBR.	CONTEXT 1	CONTEXT 2	CONTEXT 3	CONTEXT 4	CONTEXT 5	CONTEXT 6.a	CONTEXT 6.b	TOTAL
1	mthd-(V)RS	9	19	52	28	11	28	101	248
	mthd-(V)C&Q	0	0	0	1	1	1	0	3
	mthd-(V)HOS	3	17	0	0	0	3	1	24
	mthd-(V)S	0	1	0	0	0	0	0	1
	mthd-(V)A	0	6	0	5	0	1	4	16
	mthd-(V)N/T	0	0	5	8	0	6	26	45
	mthd-(V)R	3	3	1	3	0	0	8	18
	mthd-(V)M	2	2	8	11	2	6	17	48
2	mthd-(OB)P	1	0	10	7	1	5	13	37
	mthd-(OB)MR	2	2	5	6	2	6	29	52
	mthd-(OB)E	0	0	3	9	0	3	2	17
	mthd-(OB)RS	3	4	8	1	5	4	17	45
	mthd-(OB)N/T	0	0	1	0	0	0	1	2
	mthd-(OB)R	0	0	1	0	0	0	3	1
3	mthd-BL	0	1	3	3	0	4	6	17
TOTAL		23	55	97	82	22	67	228	574

CURRICULUM VITAE

Name- Surname : Nilüfer DİDİŞ

Birth Date- Place of Birth : 1983, Ankara - Turkey

Citizenship : Republic of Turkey

Education:

2005 *B.S.* from the Department of Physics Education, Middle East Technical University, Ankara, Turkey.

2005 *M.S.* (without thesis) from the Department of Physics Education, Middle East Technical University, Ankara, Turkey.

Experience:

2005- 2012 *Research Assistant* at the Physics Education Major of the Department of Secondary Science and Mathematics Education, Middle East Technical University, Ankara, Turkey.

2010 *Visiting Researcher* at the University of Maryland Physics Education Research Group (UMD PERG), Department of Physics, University of Maryland, MD, USA.

Research Interest:

- Models, Mental Models, Mathematical Models,
- Modern/Quantum Physics teaching and learning,
- Motivation.