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Instructional Designs in Quantum Physics: A Critical Review of Research

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ABSTRACT

Recent researches in instructional strategies on Quantum Physics (QP) revealed that it is not an easy task but certainly some important approaches can be applied to enhance students' conceptual knowledge of quantum concept. This study presents a critical review of research related to conceptual understandings of concepts in quantum physics. The findings reviewed address, instructional argumentation on Physics Education Research (PER), relationship between conceptual knowledge of high school and college students, the influence of technological innovations and class materials in the classroom, the development of diagnostic tools on understanding of concepts in quantum physics. This synthesis of the current state of research regarding instructional strategies and useful tools provides a comprehensive framework from which future research can be stimulated and ideas about the design and implementations are discussed.

Key words: Quantum physics, physics, physics education, teachers, science education

INTRODUCTION

Physicists involved in quantum physics almost certainly know the memorable famous proverb God never plays dice (Jupiter Books, 1999) quoted by Einstein in the early days of Modern Physics that is now called Quantum Mechanics (QM) and Quantum Physics (QP). He said those words because he was completely against the development of Quantum Mechanics, because he never believed in the concept of the probability of finding a particle in the space was the most you could know about a particle. Of course, it seems this was not probably main reason but it is a very popular fact about the conflict between supporters of quantum physics and opposed physicists. Whatever actual motive was, at present, Einstein's actions on quantum physics is not considered as important as before because today's researchers primarily focus on it's educational sides seek to discover better instructional techniques for the students to understand quantum physics concepts (Akarsu, 2004, 2007).

According to science educators (Gardner, 2002, Akarsu, 2009), science should be taught by using various teaching strategies such as discovery learning, cooperative learning, or hands-on activities and most of today's physics faculty doesn't use any of these instructional techniques. However, at the some point, we can't blame them because the topics and ideas behind it make quantum physics very difficult to teach, unlike classical (Newtonian) physics. For example, Feynman (1985), one of the famous and Nobel physics winner, said in his speech in an international conference:

What am I going to tell you about is what we teach our physics students in the third or fourth year of graduate school-and you think I'm going to explain it to you so you can understand it? No, you're not going to be able to understand it. Why, then, am I going to bother you with all this? Why

Table 1: Summary information for the experimental research papers reviewed

Sample study	Country age/grade level	N	Methods
Fischler and Lichtfeldt (1992)	Germany 17-18 years	85	The Bohr atomic model and students' conceptions, semi-classical models and teaching unit
Johnson *et al*. (1998)	Australia Junior College	33	Phenomenographic approach, computer module short response quizzes, men tal models, part-wave dual
Petri and Niedderer (1998)	Germany 18 years	1	Students' cognitive sys-tem for atomic physics as hypothetical pragmatic model. Hermeneutic interp.
Mashhadi and Woolnough (1999)	UK High school	83	Visual rep of photon and electron, ontological and epistemological status of qp., Heisenberg uncertainty, semi-structured questionnaire
Ireson (1999)	UK College	338	40 items test, SPSS, wave-particle duality, mis-understanding
Ireson (2000)	UK 17-18 years	342	40 item questionnaire answered by students for the knowledge of concepts in qp
Vokos *et al*. (2000)	USA 17-21 years	450	Particle-wave duality, Calculus, algebra, MP and QP
Zollman *et al*. (2002)	Worldwide HS and College	175	Teachers, instructional materials, no science background, visual tools
Cataloglu and Robinett (2002)	USA 17-21 years	160	Web-based instructional modules development, qp visualization Instrument, 25 item test
Singh (2001)	USA Upper undergrad	98	Misconception, intervi-ews, eigenstates, time dep., Schrodinger, concept learning
Bao and Redish (2002)	USA 17-18 years	35	Engineering students, probability difficulties, model, instructional app, quizzes
Wittmann *et al*. (2002)	USA 17-21 years	420	Non-physics students, Modern physics, open-ended, visual effects, curriculum
Muller and Wiesner (2002)	Germany High School	523	Mixed method approach College used, misconceptions avoided (18-20 years)
Budde *et al*. (2002)	Germany 16-18 years	2	Bremen teaching approach, electronium model
Olsen (2002)	Norway Upper secondary	236	Quant. Method, miscon-ceptions, TIMMS, cognitive process
Kalkanis *et al*. (2002)	Greece 17-21 years	200	Misconceptions, teacher prep program, interviews, atom model, meta-cognition, ins-tructional tools suggested
Taber (2002)	UK 16-18 years	15	Qual. Method, ontological learning impediments, Bohr atomic model, inst tools
Singh (2001)	USA Graduate level	202	Seven universities, 50 min survey, 15 inteviews, Schrodinger, Hamiltonian
Akarsu (2010a)	USA 17-21 years	93	Students' difficulties, conceptual learning, intructi-onal approaches, course mat-erials, mixed approach
Akarsu (2010b)	Turkey NA	NA	Comparison between SER and PER in methodological and conceptual aspects

are you going to sit here all this time when you won't be able to understand what I am going to say? It is my task to convince you not to turn away because you don't understand it. You see, my physics students don't understand it either. That is because I don't understand it. Nobody does.

This current research reviewed 20 original studies that have looked for the solutions of common misconceptions, insufficient teaching techniques and other instructional or conceptually significant problems encountered while teaching or learning an important branch of physics, quantum physics, at the secondary school and college levels. A comprehensive review of research about problems in teaching quantum mechanics is important because this subject is very important to be completely understood by college students (Table 1).

Several physicists and science educators began to investigate physics education about 3 decades ago and Physics Education Research (PER) was born. The critical paper of this process believed by many physics education researchers was written by Hestenes *et al.* (1992). The authors were physicists and were Professors of physics. Their papers developed a first diagnostic tool in physics education which measures student knowledge of Newton's Laws of physics at secondary level. There is ongoing a controversy on defining a physics educator position and status in the field between science education and pure physics departments (Akarsu, 2010b).

Currently, although physics educator roots can come from both disciplines, ideal physics educators should come from both backgrounds. For example, a physics educator is supposed to know basic instructional tools for teaching physics and also needs to possess content knowledge of concepts in physics as well. Unfortunately, today's world this doesn't exist but as developments in PER move forward it is possible to achieve that in the future.

Researchers at pre-college settings: Teaching quantum physics at high school or college level (undergraduate and graduate) school settings attracted physics education researchers in the last decade and most of the papers published suggested instructional tools (Ireson, 2000; Budde *et al.*, 2002), scientific models, technological approaches, hypothetical models, visual representations of atomic particles (Steinberg *et al.*, 1996) such as motions of electrons, protons and neutrons. With a critical review of both concepts, it should be possible to develop an idea of how quantum mechanics should be taught and which instructional techniques should be applied to overcome obstacles. 20 studies reviewed in this article are subdivided into two groups, seven studies that were conducted at the secondary and pre-university level (Grade 9-12) and 13 studies that were conducted at the undergraduate and graduate level.

At pre-college school investigations, six studies were conducted as quantitative research methodology and only one of them was conducted as a qualitative study. Ireson (2000) conducted a study that suggested a teaching strategy for quantum physics course difficulties experienced by the pre-university student in United Kingdom as a different approach. This study was reviewed because it focuses on a different approach to overcoming obstacles, e.g., abstract side and strong mathematical tools in quantum topics, encountered by the students during learning quantum subjects. Petri and Niedderer (1998) reported the students' cognitive system for atomic physics as a 12 hypothetical pragmatic model conducted in a German high school with only one participant. In another study by Budde *et al.* (2002) suggested a similar model called Bremen teaching approach including the visual electronium model (Herrmann, 2000) and probability model to present an analysis of the learning of two students as they progressed through the teaching unit. Overall, all of the above studies claimed that students possess three types of understanding following a quantum course, which are quantum thinking, dual thinking and mechanical thinking.

Mashhadi and Woolnough (1999) investigated how students make efforts to accommodate the concepts of quantum physics into their conceptual frameworks and the ontological and epistemological status of theoretical entities and explored students' implicit or underlying dimensions of reasoning. Mashhadi and Woolnough (1997) also investigated the range of conceptions that pre-university students hold about visualizing quantum entities (i.e., electrons and photons). Taber (2002) reported the results of applying a particular perspective to data from an interview study conducted to investigate various features of high school students developing ideas about atomic and molecular structures. The researcher used a typology of learning impediments informed by research into learning and students' ideas in science.

Summary: To summarize, of seven pre-university level studies reviewed in this section, only one (Petri and Niedderer, 1998) conducted the investigation by using qualitative method. Also, four articles investigated instructional strategies which can be utilized to increase students' understanding of the concepts of the quantum physics. For example, Budde *et al.* (2002) suggested a teaching method Bremen teaching approach and it was a part a big project on the atomic model of Electronium. Muller and Wiesner (2002) conducted the only study that focused on students' misconceptions in conceptual issues of a quantum mechanics course. Additionally, the studies conducted in secondary level reported similar findings. All of the researchers concluded that learning the concepts of quantum physics is hard because it contains abstract ideas, requires strong mathematical tools and possesses complicated operations. Students are also experiencing misconceptions such as wave-particle duality and Bohr's model of atom. At the end of his study, Ireson (2000) recommended some ideas to physics instructors: avoid referencing to classical physics, do not introduce photons in the discussion of the photoelectric phenomena, ignore wave-particle duality (Kroemer, 1994) and statistical interpretation and finally, avoid introducing the Bohr model of atom when introducing the hydrogen atom.

Researchers at college and post-graduate schools: In the second part of this review study, previous research papers that focus on mainly undergraduate and graduate level school environment were analyzed. Most of them focus on developing instructional tools (Fischler and Lichtfeldt, 1992; Zollman *et al.*, 2002; Cataloglu and Robinett, 2002; Budde *et al.*, 2002), enhancing students conceptual knowledge such as identifying misconceptions and suggestions to prevailing over them (Singh, 2001; Muller and Wiesner, 2002; Kalkanis *et al.*, 2002; Olsen, 2002) and some of them only investigated students knowledge in quantitative method (Ireson, 1999, 2000; Akarsu, 2010a; Vokos *et al.*, 2000; Singh, 2001). In the following, we will analyze them in details.

Singh (2001) sought to analyze the difficulties of advanced undergraduate students in a quantum mechanics course and to compare difficulties and misconceptions. Ireson (1999) conducted a study, which used multivariate analysis in his investigation of college physics students' conceptions of quantum phenomena. Wittmann *et al.* (2002) also investigated students' understanding of quantum physics with reporting student reasoning about models of conduction. Although, this study dealt with a very specific topic of the quantum physics area, it was well reported and well done with descriptions of the problem. Johnson *et al.* (1998), also described student difficulties in learning quantum mechanics.

Fischler and Lichtfeldt (1992) conducted another important study that focused on relationships between one of the most important modern physics subjects, the Bohr atomic model and students' conceptions. The first one was investigated by Zollman *et al.* (2002) was challenging the abstract difficulty property of quantum mechanics by creating instructional materials for quantum mechanics. Kalkanis *et al.* (2002) conducted a similar study with (Zollman *et al.*, 2002) with presenting part of a project that aims at introducing a sufficient, simple and relevant teaching approach towards quantum mechanics in pre-service teacher education. Vokos *et al.* (2000) have investigated college students' understanding of particle-wave duality in college level physics courses enrolled in quantum physics courses from introductory to advanced levels.

Bao and Redish (2001, 2002) conducted a study which focused on understanding probabilistic interpretations of physical systems by two groups of college freshmen and sophomore students. In addition, Cataloglu and Robinett (2002) wrote developed an assessment instrument designed to test conceptual and visualization understanding in quantum theory in order to probe various aspects of student understanding of some of the core ideas of quantum mechanics. Ireson (1999) recommended some useful approaches to the teaching of quantum physics. For example, he suggested the following two approaches: (a) reference to classical physics should be avoided and (b) teaching of the photoelectric effect should start with electrons, not photons.

In a study conducted by Kalkanis *et al.* (2002) claimed that physics education had to meet today's requirement for a qualitative study in Quantum Mechanics worldview. Kalkanis *et al.* (2002) focused on introducing a sufficient, simple and relevant teaching approach towards quantum mechanics into in-service and pre-service teacher education, i.e., providing teachers with scientific knowledge and an epistemological base needed for a reform of science education along an aforementioned line.

Cataloglu and Robinett (2002) investigated a study about how to test for understanding of the physics core subject quantum mechanics. The authors were proposing an assessment instrument designed to test conceptual and visualization understanding in quantum theory. Quantum mechanics is considered as maybe the hardest branch of physics because of the widely mathematical tools usage and abstract concepts in it. The test used was called Quantum Mechanics Visualization Instrument (QMVI) that focuses on conceptual and visualization understanding. After this first section, they selected the particular areas of interest in section II, where, they additionally 36 discussed the development of QMVI.

Summary: In secondary school settings, one of them dealt with teaching strategies for quantum physics course and conceptual difficulties (e.g., abstract side and heavy mathematical content in quantum physics) experienced by the pre-university student in United Kingdom as a teaching model (Ireson, 2000; Muller and Wiesner, 2002; Petri and Niedderer, 1998). Others studied how students make efforts to accommodate the concepts of quantum physics into their conceptual frameworks and the ontological and epistemological status of theoretical entities and explored students' implicit or underlying dimensions of reasoning (Mashhadi and Woolnough, 1999; Taber, 2004).

On the other hand, the second section reviewed literature in college environment. The studies mainly focused undergraduate students' understanding difficulties and misconceptions they experienced in quantum mechanics courses (Ireson, 1999; Singh, 2001; Akarsu, 2010a). The others (Cataloglu and Robinett, 2002; Zollman *et al.*, 2002) developed similar projects that aim at introducing a sufficient, simple and relevant teaching approaches toward quantum mechanics in pre-service teacher education.

CONCLUSIONS

With the achievements on several areas of researches, the articulation of the overall goals of physics education is one of the accomplishments of the science education reform documents (National Research Council, 1997). The ideas in PER are currently not revolutionary (Akarsu, 2010b) but with the increase of researches conducted by physics educators all of the researches will effect PER first and science education research focus and general educational perspectives in studies. To achieve that goal, physics educators should investigate student conceptual understandings of several physics topics in more depth research to generate more beneficial teaching tools such as technological advances in classrooms and labs. Besides, they should develop more reliable diagnostic tools than current instruments (Hestenes *et al.*, 1992; Akarsu, 2010a; Ireson, 1999) because unless we know what the reasons we cannot suggest solutions. Next, more qualitative and in-depth studies should emerge because difficulties that lie underneath the overall picture of quantitative analysis should be discovered to enhance their knowledge because today's students who study physics unfortunately do not possess enough level of knowledge of fundamental physics concepts (Ambrose *et al.*, 1999; Akarsu, 2010a; Olsen, 2002). Finally, with the accomplishments of above goals, students who are taking at pre-secondary or at undergraduate and post-graduate physics courses will achieve essential knowledge of ideas and obtain elemental theoretical perspective in the courses.

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