Teaching Uncertainty Principle by Hybrid Approach: Single Slit Diffraction Experiment

Erdoğan Özdemir[1] and Mustafa Erol[2]
[1]*Departmen of Physics Education, Graduate School of Natural and Applied Sciences, Balıkesir University, 10100, Balıkesir, Turkey.*
[2]*Department of Physics Education, Education Faculty of Buca, Dokuz Eylül University, 35100, Buca, İzmir, Turkey.*

E-mail: erdoganozdemir_1979@hotmail.com

(Received 9 June 2010, accepted 2 September 2010)

Abstract

A hybrid teaching model, which contains 44% peer tutoring, 26% group and class discussion, 26% problem solving within group, 4% demonstration and finally some homework activities that contain problem construction and problem solving activities, is developed and administered to teach the uncertainty principle. Pre-test and post-test control grouped experimental model is employed in the research with a sampling of 35 undergraduate students. Data of the research was collected by means of a "Single Slit Diffraction Experiment Classical Exam" which is made up of 8 separate questions and a "Semi Structured Interview Form". The content is formed through the single Slit Diffraction Experiment in order to investigate the Uncertainty Principle especially the limits of classical and quantum mechanical regions. The data were analyzed by means of Mann Whitney U Test and Wilcoxon Signed Rank Test and additionally qualitative analyses techniques are employed. The overall results clearly indicate that the hybrid approach is more effective than the conventional technique on academic achievement, retention and on building true student conceptions.

Keywords: Physics Education, Instructing Quantum Physics, Uncertainty Principle, Hybrid Teaching Approach, Single Slit Diffraction.

Resumen

Se muestra un modelo de enseñanza híbrido, que contiene 44% tutorías entre pares, el 26% discusión en grupo y clase, el 26% de resolución de problemas dentro del grupo, el 4% de demostración y, finalmente, algunas que actividades de tareas que contienen construcción de problemas y actividades de resolución de problemas, está desarrollado y administrado para enseñar los Principio de Incertidumbre. El modelo experimental de pre-test y post-test de control agrupados se emplea en la investigación con una muestra de 35 estudiantes de pregrado. Los datos de la investigación fueron obtenidos a través de un "Examen del experimento clásico de una rejilla de Difracción", que se compone de 8 preguntas por separado y de un "Formato de Entrevista Semi Estructurada". El contenido está formado por el experimento de una rejilla de difracción con el fin de investigar el principio de incertidumbre, especialmente los límites de las regiones de la mecánica clásica y cuántica. Los datos se analizaron por medio del Test U de Mann Whitney y del Test de Rango Firmado de Wilcoxon, además, se emplean las técnicas de análisis cualitativos. Los resultados globales indican claramente que el enfoque híbrido es más eficaz que la técnica convencional en los logros académicos, la retención y en la creación de concepciones verdaderas del estudiante.

Palabras claves: Educación en Física, Instrucción de Física Cuántica, Principio de Incertidumbre, método de enseñanza híbrida, Difracción de una rendija.

PACS: 01.40-d, 01.40.Fk, 01.40.Ha **ISSN 1870-9095**

I. INTRODUCTION

In spite of being a very well-built theory, due to being based on probabilities and uncertainties, quantum theory is criticized by many scientists [1]. The principles of quantum theory, which contain clear controversies with daily experiences and human observant, are very demanding and difficult to internalize and understand [2, 3, 4, 5, 6, 7, 8, 9, 10]. Majority of the students have convinced problems to understand quantum physical concepts due to mainly following points: 1) Students being thought classical physics, based on the causality and determinism, experience great difficulties to understand quantum physical principles based mainly on the uncertainty and probability [9]. 2) Quantum physics are considered to be mysteries and absurd hence students believe that it is not fully understood. 3) Quantum physics is full of very complicated mathematical equations. 4) Students are insensible towards quantum physical laws

In recent years, studies on the teaching of quantum physics are greatly increased. These studies can be categorized under two sub-titles. Firstly, "*misconceptions and teaching difficulties*" and secondly "*experimental studies on more effective learning of quantum physics*".

Searching fundamental misconceptions on teaching quantum physics highlights the following studies. Bilal and Erol [2] expressed that students do not comprehend the relation between wave functions and the concepts of probability. Steinberg *et al.* [7] searched the possible impact of classical physics upon student learning of quantum physical concepts and found out that students do not have scientifically acceptable models concerning wave concepts. Mashhadi and Woolnough [8] investigated how students visualize electron and photon in their mind. They suggest that the students have a wide range of non-scientific representations in their minds. Olsen [4] propounded that students do not understand the structure of electron and photon. It is also expressed that underlying cause of these concepts is classical physical concepts. Difficulties on teaching quantum physical concepts require identification of factors that complicate quantum physics. Ambrose *et al.* [11] resolute some models structured by the students on the structure of light and they also found out that students are unable to develop scientifically logical models about structure of light. Müller and Wiesner [6] searched how to learn the concept of atom, spatial confinement, and uncertainty principle and emphasized some learning difficulties of quantum mechanics. Bethge and Niedderer [12] expressed that students accepted physical structure of particles and the relation with uncertainty principle; however they insistently carry some thoughts from classical physics. Aylward [13] articulated that the principle of uncertainty caused by the technological deficiency, it means of absolute error and it is about single particle measurement. The effort of explaining quantum physical concepts by means of the classical concepts causes certain misconceptions especially on understanding the uncertainty principle [14]. The misconceptions can principally be summarized as follows: 1) Uncertainty principle means that the position and momentum of a single particle can not possibly be measured by any means [13]. 2) Uncertainty principle originates from the measurement faults. 3) Uncertainty principle also means that performed measurement varies the actual measured value. 4) The uncertainty of the position is actually equal to the width of the confinement. 5) Position uncertainty means the spatial interval of the position. 6) Uncertainty is caused by the technological inefficiency. 7) Uncertainty caused by the measurement mistakes. 8) Uncertainty is caused by the very fast motion of the microscopic particles. 9) Δx and ΔP_x are the differences between the two measured values of the position and momentum, respectively. 10) Δx is the mean value of the displacement at the direction of x. 11) Δx and ΔP_x are the mistakes of the measurements on the position and momentum [15].

Steingberg *et al.* [7] investigated the effects of classical concepts on learning quantum mechanics and concluded that lack of classical physics knowledge causes misunderstanding of quantum physical concepts. Ireson [5] suggested that quantum physics ought to be thought independently from classical physics. Abhang [9] emphasized learning difficulties of quantum mechanical concepts based on uncertainty and probability with convincing concepts from classical physics. Additionally, it is more beneficial to focus on the logical link between the concepts. Quantum physics, it is ought to be to express limit of classical physics, to apply thought experiment and instead of separately to explain the concept, to specify logical relationship between concepts.

In the literature a number of studies deal with the determination of misconceptions and getting rid of learning difficulties. Müller and Wiesner [16] developed a curriculum enriched with some experiments and found out that the students learned quantum physical concepts correctly. Niedderer *et al.* [17] developed some materials on teaching quantum physics focusing on physical dimension of the concepts rather than mathematical and also containing some specific simulations. Bergström *et al.* [18] explain wave structure of electron by electron diffraction experiments and the structure of quantum physical system by using classical wave experiments. Johanson and Milstead [19] put forward that an effective teaching of uncertainty principle can be achieved by performing the single slit diffraction experiment. Robblee *et al.* [20] explored that using computer technology on teaching quantum physics. Rebello and Zollman [21] administered their visual computerized materials to undergraduate students and find out those student misconceptions is substantially reduced.

Evaluation of the overall literature indicates that the fundamental gap on teaching quantum physics is more less to perform specific experimental research on effective and consistent conceptual learning. This study specifically concentrates on bridging the gap. The present work specifically focuses on the uncertainty principle which is one of the most fundamental concepts of quantum physics and also considered as one of the most confusing concepts. We designed a basic single slit experiment and performed the experiment by varying the slit width and demonstrated clear shift from classical limits to quantum mechanical limits. This shift allowed us understanding correspondence principle and limitations of classical physics. So, it can be helpful to clearly understanding of Heisenberg Uncertainty Principle [19]. And also to support students' attention, cooperation, sharing ideas, problem solving skills and individual working, we performed hybrid approach consists of 44% peer tutoring, 26% group and class discussion, 26% problem solving within group, 4% demonstration and finally homework containing problem construction and solving.

II. RESEARCH QUESTIONS

Are there any significant differences on academic achievement, retention level and misconceptions concerning instruction of uncertainty principle between the experimental group students trained by hybrid teaching approach and the control group students trained by conventional methods?

III. METHOD

A. Research Model

Pre-test and post-test control grouped experimental model is employed in the research. Independent variables of the research consist of hybrid model and conventional teaching method. Dependent variables of the study are academic achievement, level of retention and finally students' misconceptions and learning difficulties.

B. Sampling of the Study

The sampling of the research comprised of overall 35 undergraduate students who all attend third grade of physics education department at a state university in İzmir. The students were randomly divided into two groups. The first group is called experimental group and comprised of 14 female and 3 male students. The second group is called control group comprised of 13 female and 5 male students. In order to determine the pre knowledge and the equivalence of the groups, the classical exam test is initially administered two the both groups and the result is presented in the table I.

TABLE I. Comparison of the pre measurements of the experimental and control groups.

Group	N	Tier Mean	Tier Sum	z	p
Experimental	17	17,50	297,50	144,5	0,782*
Control	18	18,47	332,50		

The table I clearly confirms that there is no significant difference concerning pre measurement points of the experimental and control group students. It is also clear that mean of the control group students is slightly higher than mean of the experimental group students.

C. Data Collection Tools

In order to explore potential answers of the research problem, two separate data collection tools are employed. These are “Single Slit Diffraction Experiment Classical Exam ” and “Semi-Structured Interview Form”.

I- Single Slit Diffraction Experiment Classical Exam

To investigate the relation between the independent variable that is teaching method and dependent variables which are academic achievement and retention levels, a Classical Exam is prepared. The exam consists of eight questions on the topic of single slit diffraction. The draft copy of the classical exam was criticized by two experts of the field and the final form is reached by considering suggestions of the experts. The students were given 20 minutes to answer and the evaluation of the outcomes was carried out by means of a pre developed Classical Exam Rubric. During the development session, the scale was administered to 26 undergraduate students who all attended quantum physics course and the scale was evaluated twice within two mouths. The scale has a Pearson correlation coefficient of 0, 86.

II- Semi Structured Interview form

Semi structured interview form was developed by considering the answers of the students to the classical exam questions. The interview focused on the physical meaning of the uncertainty principle.

IV. TEACHING SEQUENCE

A. Content and Order

The wave property of the particles ought to be understood very deeply in order to understand the uncertainty principle of the quantum physics [3, 7, 15]. One of the main factors that effect the instruction of the wave property of the particles is the presence of the wave particle duality [4]. This concept blocks the learning channels of the students rather than to easy the instruction mechanism. Its is clear that the students have learning difficulties because they try to understand the quantum physical concepts by simply considering the classical concepts [5, 13, 22]. In order to prevent that sort of misconceptions, statistical interpretation of the quantum physics is placed within the program. Additionally, the thought experiment designed by Heisenberg is widely employed throughout the applications. The experiment explains the uncertainty of a single electron, however it would cause that the uncertainty is actually about only single electron. The content is therefore structured on especially single slit diffraction experiment rather than the thought experiment of the Heisenberg such that the students can compare the classical and quantum limits of the uncertainty principle. The content order is therefore structured as follows: Uncertainty concerning single slit diffraction experiment: a) single slit diffraction experiment at classical limits b) single slit diffraction experiment of the quantum mechanical particles.

B. Applied Techniques and Instructional Studies

Following the content, a hybrid approach model is developed by consideration the structure and misconceptions on the subject. The stages, techniques, durations and percentages of the model is given by the table II.

TABLE II. Hybrid teaching model.

Hybrid teaching model			
Stages	Instruction Technique	Duration(min.)	Percentage(%)
Preparation	Demonstration	5	4
Instruction	Peer instruction	60	44
In-classroom activity	Discussion	35	26
	Problem solving within group	35	26
Out-classroom activity	Individual problem solving and problem development	-	-

The stages of the developed hybrid approach can briefly be summarized as follows:

Preparation: It's crucial to use visual methods to succeed the teaching approach [23]. Visual techniques and methods ease the learning and also motivate the students in a better way [24]. Demonstration technique is therefore used at the preparation stage.

Instruction: It is proposed to improve the students' social interaction abilities and also by entering each others "approximate progress field" it is aimed to determine the needs of the students and to help and support them in accordance [36]. In order to realize peer instruction, one of the active learning techniques, is employed [26, 27]. The students are divided into groups and the group students were made to study the content within the group. The feedbacks and corrections are given simultaneously [28].

In-classroom activity: The stage is made up of two stages, namely discussion and problem solving within the group. In the first stage, the students having efficient background prepares some problems by considering common misconception and the developed problems are discussed by the students within the group. The researcher maintains the frame of discussion by simply moving around continuously. A classroom discussion is realized finally to end the first session. By doing so questionnaire, analyze and a better learning is aimed. In the second stage it's aimed to teach the mathematical bases of the concepts in a deeper manner [29]. To do so the students are asked to solve the problems within the group and a selected student is asked to solve the problem at the board.

Out-classroom activity: At this stage the students are given some home works to maintain their personal developments [30]. The home works contain problem solving and problem development stages. The activities are evaluated within the week and feedbacks are given to the students.

VI. FINDINGS

A. Classical Exam Findings

In order to investigate the effect of hybrid approach teaching on academic achievement within the experimental group students the classical exam was administered before and after the teaching season as pre and post measurements. Due to be working on very small sampling sizes, Wilcoxon Signed Rank Test and *Mann-Whitney U Test* were employed during the evaluation of the data [24].

TABLE III. Comparison of Pre and Post Measurements of the Experimental Group Students.

Pos Test- Pre Test	N	Tier Mean	Tier Sum	z	p
Negative Tier	0	0,00	0,00		
Positive Tier	17	9,50	9,00	-3,625	0,000
Equal	-				

*significant difference if, $p < 0{,}05$.

The table III shows that there is significant and meaningful difference between pre measurements and post measurement result of classical exam for the experimental group students. It is also clearly seen from the tier sum points that the difference is in favor of the positive rank that means in favor of the post test. Analysis of the students' answers to the classical exam questions highlights a few points: firstly majority of the experimental group students (66%) affirmed that the uncertainty principle is obeyed by classical particles concerning single slit diffraction experiment. Following the hybrid approach teaching, most of the students (83%) changed their view and confirmed that the uncertainty principle is only valid for quantum mechanical particles but not for classical particles. Additionally 16% of the students consistently protects their views. Secondly, only 5% of the experimental group students expressed that the interference pattern form even the slit gap is much larger than the de Broglie wave length of the quantum mechanical particles. However, none of the students insist this view at the end of the training and 77% of the students believe that if the slit gap is much larger than the wave length of the particles, a Gaussian distribution is expected to occur just like for classical situations.

TABLE IV. Comparison of the Pre and Post Measurements of the Control Group Students.

Pos Test- Pre Test	N	Tier Mean	Tier Sum	z	p
Negative Tier	1	10,00	10,00		
Positive Tier	14	7,86	110,00	-2,849*	0,004
Equal	3				

* significant difference if, $p < 0{,}05$.

The table IV clearly shows that there is a significant and meaningful difference between pre and post test results of the classical exam of the control group students. It is also clearly seen from the tier sum points that the difference is in favor of the positive rank that means in favor of the post test. If we investigate classical exam pre and post answers of the control group students, the following points come forward.

Investigation of the student's answers to the classical exam questions highlights a few points: firstly 37% of the control group students acknowledged that the uncertainty principle is obeyed by classical particles concerning single slit diffraction experiments. Following the conventional teaching, 16% of the students consistently protects their view. Additionally, 68% of the students expressed that a Gaussian distribution occurs on the screen for the classical particles. However, 21% of the control group students expressed that classical particles obey uncertainty principle concerning post test answers. Secondly, only 37% of the control group students expressed that the interference pattern form even the slit gap is much larger than the de Broglie wave length of the quantum mechanical particles. However 47% of the students believe that if slit gap is much larger than the wave length of the particle, a Gaussian distribution is expected to occur just like classical situations. Some 42% of the students think that if the slit width and the wave length is comparable then interference pattern is expected to occur on the screen.

TABLE V. Comparison of the post measurements of the experimental and control group students.

Groups	N	Tier Mean	Tier Sum	z	p
Experimental	17	23,71	403,00	56,000	0,001
Control	18	12,61	227,00		

* significant difference if, p <0,05.

The table V indicates a meaningful difference between experimental and control group students' post test results concerning the Classical Exam in favor of the experimental. Additionally considering tier means, it is also clear that the mean of the experimental group is much higher than the mean of the control group students.

Comparison of the experimental and control group students' post measurements concerning the classical exam, highlights the following points: 83% of the experimental group students after the actual training expressed that the classical particles experiencing the single slit diffraction form a Gaussian distribution and only 47% of the experimental group students assumed that the uncertainty principle is meaningless for the classical particles. Some 68% of the control group students believe that the classical particles obey the Gaussian distribution however 21% of the control group students expressed that the uncertainty principle gives meaningful results for the classical particles. Some 77% of the experimental group students affirmed that if the slit width is much larger than the de Broglie wave length of the quantum physical particles than the results would be very close to the classical case and a Gaussian distribution occurs on the screen. These students the think that if the slit width is comparable with the de Broglie wave length of the particles then the uncertainty principle gradually becomes important and as the width gets narrower the uncertainty of the momentum becomes larger. Some 47% of the control group students state that if the slit width is much larger than the wave length a Gaussian distribution occurs, however 42% of the control group students state that in the case of comparable width and de Broglie wave length an interference pattern is expected to occur.

The table VI indicates a insignificant difference between post and delayed measurements of the experimental group students concerning the Classical Exam. Considering additionally the difference, the difference is in favor of the negative tier which means in favor of the post test.

TABLE VI. Comparison of the post and delayed measurements of the experimental group students.

Post-Delayed Tests	N	Tier Mean	Tier Sum	z	p
Negative tier	10	7,00	70,00	-1,717	0,086
Positive tier	3	7,00	21,00		
Equal	4				

*insignificant difference , if p >0,05.

TABLE VII. Comparison of the post and delayed measurements of the control group students.

Post-Delayed Tests	N	Tier Mean	Tier Sum	z	p
Negative Tier	9	6,56	59,00	-0,945	0,345
Positive Tier	4	8,00	32,00		
Equal	5				

*insignificant difference, if p >0,05.

The table VII indicates a insignificant difference between post and delayed measurements of the control group students' regarding the Classical Exam. Considering additionally the difference, the difference is in favor of the negative tier which means in favor of the post test results.

TABLE VIII. Comparison of the control and experimental groups' delayed measurements.

Groups	N	Tier Mean	Tier Sum	z	p
Experimental	17	22,18	377,00	82,00	0,017
Control	18	14,06	253,00		

*insignificant difference (if p >0,05)

The table VIII indicates a significant difference between the control and experimental group students delayed measurements relating to the Classical Exam. Considering additionally the tier means, the mean of the experimental group students is considerably larger then the control group students.

B. Interview

The classical exam findings are also supported by some student interviews. The interviews of the research were carried out just before and after the actual experimental sequence. The data of is evaluated by means of the content analysis. The content analysis was realized in order to reach the specific concepts and relations that could explain the actual data. The genuine activity of the content analysis was to group similar concepts and themes and present them in a most understandable manner. The interview focused on the physical meaning of the uncertainty principle and the fundamental results are presented below.

TABLE IX. The answers and percentages of the experimental group and control group students before and after the actual schooling session.

Experimental group students' views before the application		Sharing views	
Answer Type	Student View	frequency	%
Uncertainty principle deals with position and momentum uncertainty of a single electron.	Student 3: "yes, we use the multi measurements of position and momentum of a single electron."	4	66
Experimental group student' views after the application			
Uncertainty principle deals with position and momentum uncertainty of many identical electrons.	Student 3: "we use the statistical values of the many measurements performed for different identical electrons."	5	83
Control group students' views before the application		Sharing views	
Answer Type	Student View	frequency	%
Uncertainty principle deals with position and momentum uncertainty of a single electron measured many times.	Student 10: "Uncertainty is the average of the many simultaneous measurements of position and momentum of a single electron."	2	50
Control group students' views after the application			
Uncertainty is obtained from the values of many measurements performed on a single electron.	Student 8: "we obtain the uncertainty by measuring the position and momentum of a single electron at different times."	3	75

VI. DISCUSSION AND IMPLICATIONS

The present work designed to explore the effect of a hybrid teaching design on academic achievement regarding the single slit diffraction experiment, specifically designed to investigate the quantum mechanical and classical limits. It is finally detected that the hybrid teaching method influenced the academic achievement and also the retention level substantially in comparison with the conventional techniques. The overall results are in a good agreement with the previous findings; similarly employ a hybrid teaching approach with some active teaching techniques [31, 32]. The success is possibly due to the content of the hybrid teaching method in the sense that a single slit diffraction experiment realized in the classroom by varying the slit width in order to show the classical and quantum limits [33].

The evaluation of the classical exam papers indicate that the experimental group students heavily think with respect to the control group students that the classical particles obey Gaussian distribution during the single slit diffraction experiment however the quantum mechanical particles do not obey diffraction pattern at any case. The other aim of the present work was to determine the student misconceptions and learning difficulties regarding the uncertainty principle and explore possible ways to eliminate them. The most pronouncing detected misconception before the actual training for both experimental and control group students was that they mostly believe that the uncertainty relates to the movement of only a single electron. A very similar result was determined by [13]. The students interpret the uncertainty just like for the classical measurements, in other words, the position and momentum of a single electron is measured many times and then the standard deviation is calculated.

To our view, the detected misconceptions and learning difficulties originates from the student trend of interconnecting the novel quantum physical concepts with the previous classical concepts [7]. The majority of the students think that the quantum physical particles have definite position and momentum beforehand the measurement just like the classical cases [8, 7, 15]. The fundamental problem here is that the students interrelate the quantum physical concepts with the previous ones mistakenly and their daily experiences and intuitive views mislead them eventually creating the problem.

Supporting the instruction session by means of some visualized materials and tools, thought experiments and actual physical experiments certainly helps the student understanding and internalizing the difficult quantum physical concepts [34, 35] intuitive and controversial structure of the quantum physical concepts increase the actual need to designing an effective and understandable instruction materials

The other point is that the trend of linking quantum physical concepts with the classical concepts seems to be creating challenging misconceptions and learning difficulties. It is therefore important to especially eliminate this trend by designing the courses in a revolutionary manner.

The overall conclusion of the research is that the hybrid teaching method meaningfully increases the student understanding and internalizing of the quantum physical concepts. Hence, the research can be extended to explore the influence of different techniques and proportions to eventually reach the perfect hybrid teaching approach.

REFERENCES

[1] Hooft, G., *In Search of the ultimate building blocks* (Cambridge University Press, Cambridge, 1997).

[2] Erol, M., *Philosophy and instruction of quantum physics (QP)*, Balkan Physics Letters, Special Issue, 16-24 (2008).

[3] Bilal, E. and Erol, M., *Student understanding of some quantum physical concepts: Wave function, Schrödinger's wave equation and wave-particle duality,* American Institute of Physics **899**, 499 (2007).

[4] Olsen, R. V., <http://folk.uio.no/rolfvo/Publications/Tessaloniki_paper.pdf.>, visited in June-3-2007.

[5] Ireson, G., *A multivariate analysis of undergraduate physics students' conceptions of quantum phenomena,* European Journal of Physics **20**, 193-199 (1999).

[6] Müller, R. and Wiesner, H., *Students' conceptions of quantum physics,* The annual meeting of National Association for Research in Science Teaching. Boston, Massachusetts, (1999).

[7] Steinberg, R., Wittmann, M. C., Bao, L. and Redish, E. F., *The influence of student understanding of classical physics when learning quantum mechanics*, The annual meeting of National Association for Research in Science Teaching. Boston, Massachusetts, (1999).

[8] Mashhadi, A. and Woolnough, B., *Insights into students' understanding of quantum physics: Visualizing quantum entities*, European Journal of Physics **20**, 511-516 (1999).

[9] Abhang, R. Y., *Making introductory quantum physics understandable and interesting*, Resonance **10**, 63-73 (2005).

[10] Pospiech, G., *Uncertainty and complementarily: The heart of quantum physics,* Physics Education **35**, 393–399 (2000).

[11] Ambrose, B. S., Heron, P., Vokos, S. and McDermott, L. C., *Student understanding of light as an EM wave: Relating the formalism to physical phenomena*, American Journal of Physics **67**, 891- 898 (1999).

[12] Bethge, T. and Niedderer, H., <http://www.idn.uni-bremen.de/pubs/Niedderer/1995-AJP-TBHN.pdf.>, visited in 10-May-2006.

[13] Aylward, K., <http://www.kevinaylward.co.uk/qm/index.html.> , visited in 10-May-2006.

[14] Kopman, L., Kaper, W. H. and Ellermeijer, A. L., <http://www.physik.uni-mainz.de/lehramt/epec/koopman.pdf>, visited in 4-6 July 2005.

[15] Özdemir, E. and Erol, M., *Student misconceptions relating wave packet and uncertainty principle in quantum physics*, Balkan Physics Letters, Special Issue, 641-635 (2008).

[16] Müller, R. and Wiesner, H., *Teaching quantum mechanics on an introductory level,* American Journal of Physics **70**, 200-209 (2002).

[17] Niedderer, H. and Deylitz, S., *Evaluation of a new approach in quantum atomic physics in high school*, The annual meeting of National Association for Research in Science Teaching, Boston, Massachusetts, (1999).

[18] Bergström, L., Johanson, K. E. and Nilsson, C. H., The physics of Copenhagen for students and the general public, Physics Education, **Nuclear Physics**, 388-393 (2001).

[19] Johanson, K. E. and Milstead, D., *Uncertainty in the classroom-teaching quantum physics*, Physics Education **43**, 173-179 (2008).

[20] Robblee, K. M., Garik, P., Abegg, G. and Zollman, D. *Using computer visualization software to teach quantum science: the impact on pedagogical content knowledge.* The annual meeting of National Association for Research in Science Teaching, Boston, Massachusetts, (1999).

[21] Zollman, D., Rebello, N. S. and Hogg, K., *Quantum mechanics for everyone: hands-on activities integrated with technology,* American Journal of Physics **70**, 252-260 (2001).

[22] Özdemir, E., *Kuantum Fiziği Belirsizlik İlkesi: Hibrit Yaklaşımla Öğretiminin Akademik Başarıya etkisi*, Yüksek Lisans Tezi, Eğitim Bilimleri Enstitüsü, Dokuz Eylül Üniversitesi, (2008).

[23] Karamustafaoğlu, O., *Fen ve teknoloji öğretmenlerinin öğretim materyallerini kullanma düzeyleri: Amasya ili örneği,* A.Ü. Bayburt Eğitim Fakültesi Dergisi **I**, 90–101 (2006).

[24] Çepni, S., Ayas, A., Johnson, D.,ve Turgut, F., *Fizik öğretimi* (YÖK/Dünya Bankası Milli Eğitimi Geliştirme Projesi Hizmet Öncesi Öğretmen Eğitimi, Ankara, 1997).

[25] Açıkgöz, K. Ü., *Aktif Öğrenme* (Eğitim Dünyası Yayınları, İzmir, 2003).

[26] Eggen, P. and Kauchak, D., *Learning and teaching: research based methods,* (Allyn and Bacon, Boston, 1998).

[27] Shunk, D., *Learning theories: An educational perspective,* (Prentice Hall, Ohio, 2000).

[28] Sönmez, V. Program Geliştirmede Öğretmen El Kitabı, (Anı Yayıncılık, Ankara, 2004).

[29] Akarsu, B., *Students' misconceptual understanding of quantum physics in college level classroom environments*, Ph.D. dissertation, Bloomington: Indiana University, (2007).

[30] Yücel, A. S., *Ortaöğretim düzeyindeki öğrencilerin kimya derslerinde verilen ev ödevlerine karşı tutumlarının incelenmesi*, Gazi Eğitim Fakültesi Dergisi **24**, 147-159 (2004).

[31] Ramsier, R. D., *A hybrid approach to active learning,* Physics Education **36**, 124-128 (2001).

[32] Bilal, E. and Erol, M., *Influence of hybrid teaching approach on attitude and success concerning electrostatics,* Journal of Science Education **6**, 63-74 (2009).

[33] Özdemir E. and Erol M., *Single slit diffraction experiment: Investigating classical and quantum mechanical limits,* Balkan Physics Letters **15**, 1-7 (2009).

[34] Rebello, N. S. and Zollman, D. *Conceptual understanding of quantum mechanics after using hands-on*

and visualization instruction materials, (National Association for Research in Science Teaching, Boston, Massachusetts, 1999).

[35] Redish, E. F., Steinberg, R. N. and Wittmann, C., <http://www.physics.umd.edu/perg/qm/qmcourse/NewModel/index.html visited in 12-May-2008.

[36] Vygotsky, L. S., *Mind in society* (Harvard University Press, Cambridge, 1978).