Basics Quantum Mechanics teaching in Secondary School: One Conceptual Structure based on Paths Integrals Method

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Abstract

This paper integrates a doctoral thesis* to investigate the Basics Quantum Mechanics (MQ) teaching in high school. This work adopts as Conceptual Structure of Reference the Paths Integrals method of Feynman [4], and a Proposed Conceptual Structure for Teaching (PCST) [2, 3] is designed, analyzed and proposed. The PCST does not follow the historical route and it is complementary of the canonical formalism. The concepts: probability distribution, quantum system, *x(t)* alternative, amplitude of probability, sum of probability amplitude, action, Planck´ s constant, and classic-quantum transition were constructed with the students. The math formalism was eluded and simulation software assistance was used. Also, we are presenting results about the affective impact (PCST) in the class group.

Keywords: Quantum Mechanics Teaching, Physics Didactic, Affectivity.

Resumen

Este trabajo es parte de una tesis doctoral* que investiga la Enseñanza de Fundamentos de Mecánica Cuántica (MC) en la Enseñanza Media. En ella se establece como Estructura Conceptual de Referencia al método de Integrales de Trayectoria de Feynman [4], y se analiza, propone e implementa, una Estructura Conceptual Propuesta para Enseñar (ECPE) [2, 3] que no sigue la génesis histórica y es complementaria al formalismo canónico. Se pretende reconstruir con los estudiantes de nivel medio los conceptos: distribución de probabilidad, sistema cuántico, *x(t)* alternativas, amplitud de probabilidad, suma de amplitudes de probabilidad, acción, constante de Planck, transición clásico-cuántico, eludiendo el formalismo y con asistencia de software de simulación. En este trabajo se presentan resultados acerca del impacto afectivo de la propuesta en los estudiantes del grupo de clase que participaron de la implementación.

Palabras clave: Enseñanza de la Mecánica Cuántica, Didáctica de la Física, Afectividad.

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I. INTRODUCTION

This work comprises an investigation about the Basics Quantum Mechanics (QM) teaching in the high school. The organization of the concepts does not follow a time line. The Paths Integrals method of Feynman [1] was adopted as Referential Conceptual Structure (RCS) [2, 3] that is an alternative to the canonical formalism [4]. We have designed a Proposed Conceptual Structure for teaching the foundations of Quantum Mechanics (QM) eluding the math formalism and using simulation software.

The investigation intends to analyze the viability of a proposal to study QM in the high school. We want to understand the knowledge construction process in the classroom and in each group of discussion; the adaptation of designed materials; and the interaction between the students and the teacher. In a previous publication, we presented and discussed results obtained by the students in their evaluation tests. [5]. In the present work, we are also analyzing results on the affective dimension.

In order to know students' perceptions about the studied concepts; the results of the implemented sequence; and the students' performance using the software, we will

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present and discuss the students' answers to a test given at the end of the implementation (See it in the Appendix). We will also present the four fundamental steps of a developmental sequence to teach QM. We will describe the proposed situations to construct the concepts: probability distribution, quantum system, $x(t)$ alternative, amplitude of probability, sum of probability amplitude, action, Planck´ s constant and classic- quantum transition [6].

II. THEORETICAL FRAMEWORK

In Physics, a lot of conceptual fields [7] onto which at least one conceptual structure of reference is distinguished [2; 3] can be recognized. When a physics teacher presents to his students a specific conceptual field, he adopts in a more or less explicit way a particular Conceptual Structure of Referential (CSR). A CSR is a set of concepts, the relationships among them, the principles, the affirmations of knowledge and the explanations relative to a conceptual field, accepted by the scientific community of reference. In this investigation the Paths Integrals method of Feynman [1] was adopted as CSR. A detailed analysis of this CSR can be consulted in [4]. The full proposal of adapted conceptual organization for students of high school can be founded in Fanaro, Otero, Moreira [5] and Fanaro, Arlego, Otero [6]. The CSR adopted will be partially or fully reconstructed by a group of class, or by someone it tries to study it in the high school, in the basic courses at a university or in the advanced courses.

All attempt of reconstruction originates a different conceptual structure, as much for the components as for the relationships among them. In a more or less explicit way, each professor of a certain group will reconstruct or select -based on an existing structure- one to be taught, and, in the best one of the cases, he will invite his class to study it. We called this other structure: Proposed Conceptual Structure for Teaching (PCST) [2, 3]. It is the set of concepts, relationships among them, affirmations of knowledge, principles, and explanations related to a certain conceptual field, that must be reconstructed by professors based on a Conceptual Structure of Reference (CSR). The professor aims at transforming the scientific knowledge and reconstructing it in a given context and institution [1, 2].

The design of a SCPT requires multiple actions: in this case, to analyze and select the key concepts of the conceptual field that would be reconstructed in the class group (CG) and to create appropriate situations to use the software that simulates the double split experience. Also, the suitable parameters were chosen to avoid actions that could disorient the study. For example, for certain configurations of approach (zoom lens), software shows the effects of diffraction, making it difficult to distinguish between small balls and electrons. The energy of electrons, width and separation of the splits were properly chosen. Thus, when covering each one of them sequentially, the curves are similar -except for the scale- to the ones obtained with small balls. Two simulations were created for the didactic sequence using *Modellus* (versión 2.5 Created by Victor Duarte Teodoro, Joao Paulo Duque Viera; Filipe Costa Clérigo, Faculty of Sciences and Technology Nova University, Lisbon, Portugal.). The possible results for each execution of the simulation were analyzed beforehand and the actions of the students were anticipated.

SCR and SCPT are partly related to the idea of cognitive structure as it has been proposed by Ausubel and Novak **[**8**]** and with Vergnaud´s ideas about the conceptual field and the concepts [9, 10, 11]. The structures are systems (components + organization) that include key concepts, like the relationships, fundamental principles, explanations and explanatory mechanisms that tie them together. When we adopted Vergnaud´s idea about the concept, we included the language, the significant ones and the operating invariants that suppose the conservation of the forms of action organization. This idea of concepts related to the action in all their variants, allows tending a bridge to the underlying emotions and the feelings, also including in the conceptual structure. The conceptual structures are undissociable of the set of problems and situations that give sense to them.

The teacher and his class group will indeed reconstruct the CSPT in a given and specific institution, generating the Conceptual Structure Indeed Reconstructed (CSER). A CSER is the set of concepts, relationships among them; principles, affirmations of knowledge and explanations relative to a certain conceptual field that are reconstructed by a class group, from the actions and conversations in which the professor and the students interact, in an adapted emotional dynamic.

Each class group member will construct to a personal conceptual structure and a unique network of meanings - personal and private. Simultaneously, the class group conversations drive the meaning network construction, which is shared and public. This meaning network is a consensual product; it has been called "process of meaning negotiation" [13, 14]. This negotiation process can be more or less explicit and more or less conscientious, depending on the professionalism of the teacher, and the distance between the CSR, the CSPT and the CSER.

III. THE CONCEPTUAL STRUCTURE PROPOSED TO TEACHING (CSPT)

The CSPT was designed for a Physics course of the third Polimodal year in Sciences orientation. The group has thirty (30) students who are 17-18 years old. It is a well performing group. The curriculum establishes two one-hour periods of Physics per week. The students had the required physics and mathematical knowledge: Classical mechanics, vectors and trigonometrical functions. The habitual work style of these students -who work in groups- was respected.

The didactic sequence had thirteen lessons. The material was given period by period, regulating appropriately the new features and problem introduction.

The classes were recorded in audio and the conversations in each work group, were saved too.

The key situation in the didactic sequence is to explain the "unexpected" distribution of electrons in the Double Split experience. Using the *Sum All the Alternatives* (SAA) method, the expression for the probability curve of electrons arrival to a certain point of the screen was obtained. This allows an approach to the basic Quantum Mechanics Principles. Before applying the SAA method to explain the results of the double split experience, it studies the behavior of electrons and the free particle. This helps to understand the special characteristics of the microscopic world of electrons, and its difference with particles of greater mass.

When the students recognize the phenomenon of interference for electrons, and analyze the relationship between the interference pattern detection and the mass, an associated wavelength is assigned to the electron and to all the matter. The sequence consists of the following stages:

1- Double Split Experience (DSE) with small balls and electrons

The students imagined and predicted the results of this experience when small balls were used. Afterwards, the DSE with small balls was simulated using the "Doppelspalt". This Software allowed appreciating the impacts in the screen to generate the histogram of frequencies and to visualize the theoretical curve of frequencies distribution, named *P(x)* or probability curve. The students compared their predictions about the results of the experiment with the simulation results. They solved a set of tasks to analyze the effect in the form of the curve when the distance between the splits and the splits width were changed. This lead the group to accept and to establish the principle:

When both splits are open, the resulting curve is the sum of the individual curves

Soon the students resolved the situation consisting of simulating the Double Split Experience (DSE) where they chose electrons instead of small balls. The simulation allowed appreciating the interference pattern that is inexplicable from the classical theory and from the naive idea that the electrons would be like small balls. A perturbation takes place; therefore, it generates the need to look for an explanation for the unexpected behavior of electrons. The group formulated and accepted another key principle in the sequence:

When both splits are open and although the electrons arrive in discreet units, the resulting curve is similar to an interference pattern.

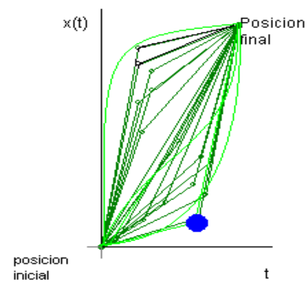
The probability curve cannot be obtained adding the individual curves produced when the splits are opened once at a time. Then it would be inadequate to consider electrons as particles. This newness in the way to consider electrons was driving us to introduce the concept of "quantum system". Also it showed that a probabilistic formulation was necessary to explain the diagram of interference obtained in the double split experiment with electrons (according to the experimental fact that these arrive at the screen as measurable and discreet units).

2- Analysis and application of SAA method for free electrons

The sequence emphasizes the probabilistic character of the predictions as the central aspect of the quantum theory. To help the students to use the "Method of multiple ways of Feynman for the Quantum mechanics" we have replaced the complex numbers representation by a vectorial one. The method can be used with any physical system, like the free particle. A key didactic decision has been to start off in the free particle case, getting up the properties of quantum systems. This example joins the most general properties of these systems [4].

The method to calculate the probability was seen by to students as the "Sum all the Alternatives" (SAA) and it has been done in the following steps:

*1- There is not a unique form, but multiple forms to connect initial state I with the final state F - using a lot of x (t) - all equally possible (*In order to simplify some functions were only drawn to connect the initial state with the end - straight sections-. These are the only functions that the software used by the students allows modeling).



Then, each possible x(t) has an associated numerical value called action, represented by "S". The action is related to the kinetic average energy (of movement) and potential average energy (of the position with respect to other bodies with which it interacts).

$$S = (E_{cin} - E_{pot})\, T$$

If the particle is "free", thus it is not in the presence of forces and it has null potential energy. Then, in this case the action is directly:

$$S = E_{cin}\, T$$

$$S = \tfrac{1}{2} m v^2\, T$$

2- Using the action S, a vector on the plane is constructed, it has module one and angle of measurement $S/\hbar$ (respect to positive x-axis). This vector is called "Probability amplitude". The denominator of this quotient is $\hbar = h/2\pi$, where $h = 6.625x10^{-34}$ Js is the Planck ´s constant and it ´s one of basic constant in Physics.

That is to say:

Every x(t) has a value of S

using these S, a vector is constructed:

⇩

Amplitude Vector associated to each x(t)

$$\left(\cos\frac{S}{\hbar};sen\frac{S}{\hbar}\right)$$

3-All the amplitude associated vectors at the different functions that connect both states initial and final are added. We'll call to the Sum vector(head to tail method):

"Total Probability Amplitude"

Total Probability Amplitude = Sum of all associated vectors

4- The MODULE of total probability amplitude is calculated (that is the resultant vector of the sum) and it rises to the square. This account gives the probability of arriving at final state F, having started off of initial state I.

In the double split experience the electrons could be considered free between the instant they leave the source until they arrive at the screen. We could suppose they are sent at time intervals as long as there is not interaction with each other. The analysis of the free electron allows: a) to validate the technique, b) to generate later, an explanation of the position of maxima and minima that were obtained in the first simulation.

To help the students apply the technique SAA to the free electron, a simulation using *Modellus* was developed.

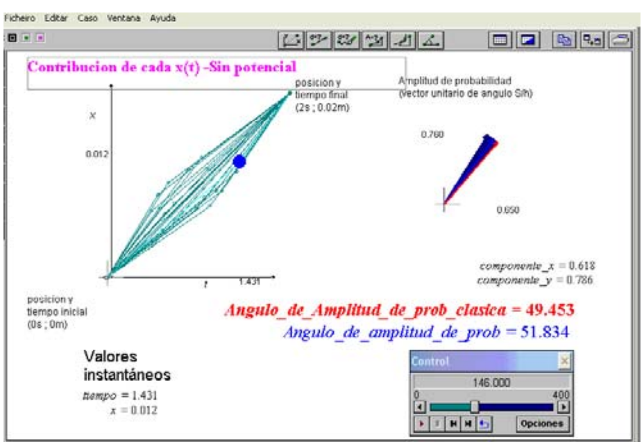


FIGURE 1. Screen about the first simulation. Selecting different functions x (t) that connect the initial and final states, the simulation shows the angles on the Cartesian plane and the angle value of this vector in sexagesimal degrees. The probability amplitude vectors are drawn simultaneously for each function $x(t)$ selected.

The proposed situations to use the software and the representation in a same cartesian plane of several vectors associated to functions $x(t)$ near and distant to the classical one, allow the GC to formulate the following conclusions:

- The action S is minimum for the classical functional relation $x(t)$ -a straight line- if it is compared with other arbitrary functional relations $x(t)$.
- The angles of the amplitude vectors associated with those paths $x(t)$ near the classical path $x_{clas}(t)$ are similar. However, the angles of the vectors associated to the $x(t)$ placed far to the classical path are different from each other. This means that only a set of paths "around" the classical path contributes to the sum. The paths that are too far of the classical one, have associated vectors in different directions that will be annulled in the sum.
- If the mass of the particle is increased, there are less vectors to add in the sum, because up to the near paths, they are annulled. For a macroscopic particle, in the limit case, it is only the classical path $x_{clas}(t)$ contributing to the sum.

3- Applying the SAA method to reconstruct the interference diagram with electrons

The previous stage allows to institutionalize in the CG the STA method and to justify an exact expression to calculate the amplitude in the case of the free particle. In this case, the conventional action plays a central role; this expression can calculate using so much the method of Feynman as [4] the canonical formalism.

Soon we can do the key question again: Which is the probability that an electron started off of the source arrives at a distance x of the screen center? The answer arises when the method SAA is applied to the DSE with electrons for certain experimental dispositions: the separation of the splits, the distance between the source and the screen and the speed of electrons. Then, adopting a geometric-vectorial frame, some trigonometrical properties and sum of vectors the next expression of $P(x)$ [4] is obtained:

$$P(x) \sim \cos^2\left(\frac{md}{4\hbar T}x\right).$$

The students discussed and analyzed with their group the applied processes and the functional form of the expression $P(x)$. Using this expression and certain experimental characteristics (separation distance, time, etc.) given by the teacher, they made an approximate graphical representation of *P(x)*. The students used the values of the independent variable suggested by the professor to see the maxima and minima. Without this help, the graph construction would have turned the students aside to the first: to recognize that the graph adopts a similar form to the graph of *P(x)* obtained in the first simulation. This result returns to the generatrix question of the sequence: how to explain the maxima and minima of interference?

4- Classic-quantum transition in the double slip experience

In order to show how the relationship between the mass and the Planck's constant establish the interference diagram, one more simulation with *Modellus* was generated. Fixing the rest of the parameters, it was observed how every time larger values of the mass have affected the curve *P*(*x*).

The simulation also represents the associated vector to each alternative -started through one split or the other, the extreme vector and the curve-. The following figures show that the interference diagram disappears when the mass increases, making evident the transition between the quantum mechanics and the classical mechanics.

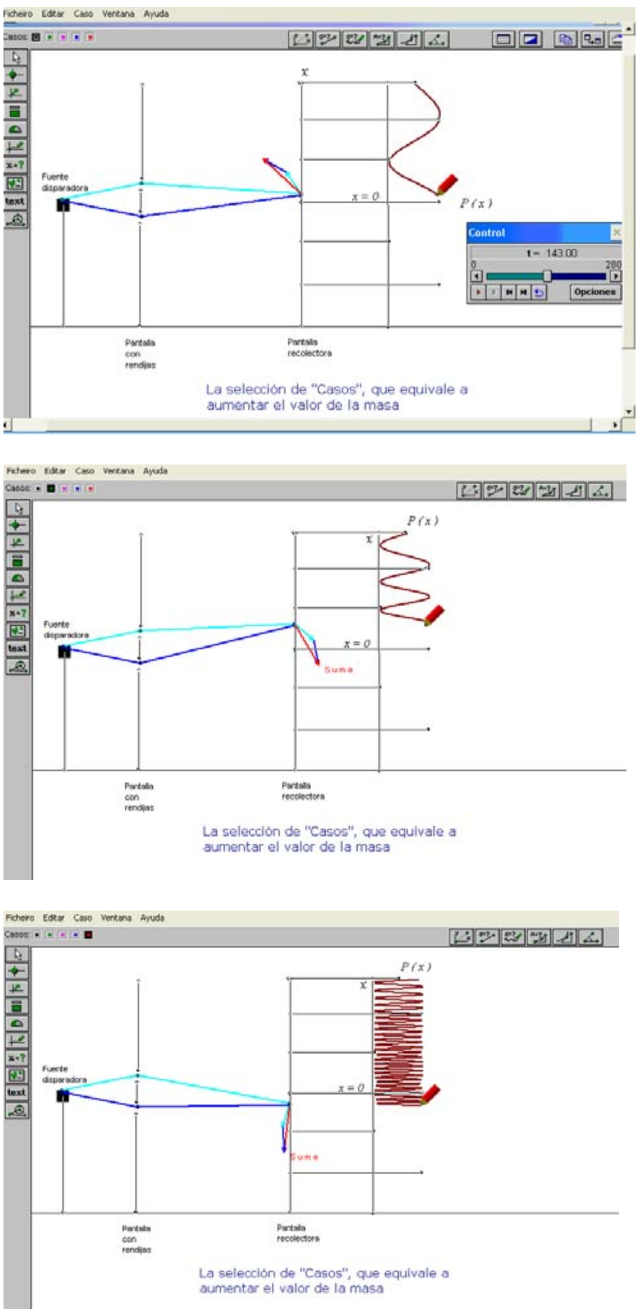


FIGURE 2. Screens about the simulation of the DSE.

Comming back to the DSE phenomenon and in agreement that the electrons arrive at the screen one at a time, the students were invited to analyze results of the DSE obtained in Tonomura in 1974. They looked at a series of photographs of successive collector screens in the time. Against this background, the concept of wavelength associated to electrons: $\lambda \propto h/(mv)$ was defined, discussed and justified. After we generalized the concept to all the particles: the matter behavior is not the one of classical particles, and is not the one of classical waves. The matter behavior is actually well described by the quantum theory.

Soon the question was discussed, why is quantum interference not detected when the experience is realised with small balls? The students were invited to analyze the relationship between the associated wavelength and the interference diagram. Why doesn't it happen to the small balls while it is possible to detect it with electrons? In this last case, the quotient between the Planck 's constant and the mass is extremely small, due to the value of h; therefore, the associated wavelength is too small, and the maxima and minima of the curve *P(x)* are indistinguishable, obtaining an average curve like the classical curve. The sequence finished analyzing the role of the Planck's constant as a fundamental constant in the nature, to establish if the quantum behavior was or not evident.

IV. THE TEST ABOUT AFFECTIVE ASPECTS AND THEIR ANALYSIS

In order to obtain data about the affective aspects, the students who participated in the implementation individually responded a questionnaire of 30 closed questions and one open (see Annex) in a subsequent evaluation class. The closed questions offered a scale of five options with ends between: nothing in agreement and total agreement. The coefficient alpha of Cronbach was α*=0.7*. The questions were related to the following aspects:

1- Students perceptions about the studied quantum concepts (SQM) (eleven questions)

That is to say, if they felt displeasure when they studied the quantum concepts or if they were very difficult for them. In previous exploratory studies, we find that the uncertainty of the quantum world usually produces misfortune feelings, even certain malaise; perhaps because traditionally the scholastic physics favors ingenuous deterministic realistic positions. Also, we supposed that the abstraction of the quantum concepts, the impossibility to imagine them and their epistemological implications, would affect the students.

Mathematical aspects: refers to the students' perceived difficulty of the mathematical model of the STA, the work with vectors and with the trigonometric functions. If they were an obstacle for the understanding of quantum concepts.

Disagreement, inconvenience: The probabilistic character of the QM is difficult to accept. In our daily life the illusion of certainty gives us feelings of safety and trust and the uncertainty the opposite things. On the other hand, our students are adolescents and they have difficulties to relativize their thoughts, because they still have characteristics of the concrete operational period, where the possible thing is subordinated to the reality; possibility hardly ever includes reality as a subgroup. The necessity to leave the determinism – accepted in macrocospic level; changing exact predictions of the physical phenomenons, by the probable predictions, generates resistance and demands big changes in our thinking. Essentially the sequence proposes to leave aside the electron idea as "punctual portions of matter" and to assign them a new meaning: quantum systems. The description of the quantum phenomena that appear on microscopic scale, that needs new laws and new explanations.

Interest in understanding: These questions are related to the following subjects: if the students have interest in or curiosity for the present physical knowledge, if they feel satisfaction or not, to have been successful understanding the concepts with the effort that this required.

Relationship with the previous knowledge: Did the students feel that the new concepts were fully related to their previous knowledge? When they analyzed the quantum transition from the classical transition as much as in the case of the free particle like in the experience of the double split, did the students establish relationships between the quantum results and the familiar macroscopic descriptions about the movement?

2- Students perceptions about the didactic sequence and the work in the class (nine questions).

The situations were solved in groups and implied discussion work, agreement, and writing of the agreed conclusions. Each class was an encounter with new concepts and problems and these demanded effort from the students.

	Effort/obtained results	Problems/ teacher´s explanations	Group work /individual work
Ítem	**11; 14; 1 6**	**12; 17**	**13; 18; 19**

Effort/obtained results: In order to face questions and challenges class by class, the voluntary attention and the predisposition of the students were

	Mathe matical aspects	Disagreement, inconvenience	Interest in understanding	Relationship with previous knowledge
Ítem	**1; 6**	**2; 3; 7; 8; 9**	**5; 15; 20; 29**	**4;10**

fundamental. These questions are formulated to know the students felt about the required effort to advance in the sequence development.

Problems/teacher´s explanations: a teaching model that establishes as central task of the teacher to explain is common practice in the school. The students prefer this and they are used to the teacher explanations, more than facing the challenges themselves and sharing responsibility for their learning. This didactic sequence requires a very different professor role, his actions in class are: talking and discussing with the students about the obtained results and to lead the arriving group to the partial conclusions.

The SCPT design requires a lot of tasks for the teacher that could be invisible for the students: like to consider the parameters, values, questions, and anticipations of the possible answers, to orient the student conclusions and explanations formulation that would be agreed. The questions talk on the one hand about to the affability or displeasure of the students against the challenges, and on the other, if they had preferred the professor explanations instead of asking questions and doing activities.

Individual/group work: The role of the student in the sequence requires to talk, to interact and to discuss with the group partners. In addition they must write an individual synthesis at the end. These questions are related to the student's feelings during the work with partners and when every student faced the situations.

3- Perceptions related to the use of software. From certain "pedagogical common sense" it is usually assumed that the students feel affability by the single fact of working with simulations and visual tools. In this sequence, the simulations did not have decorative aims nor looked for the students' motivation. They are tools to visualize certain calculations results, to prevent the students from doing them. This work with the software demands voluntary attention and effort.

	Confidence in software	Simulations Utility	Effort to use simulations
Ítem	**21**	**22; 26; 27; 28**	**23**

Confidence in software: Did the students take for granted the results of the simulations? When their predictions did not agree with software, did they review and modify them because they were giving credit to software? Or the opposite thing, did they question the simulations results trusting more their own ideas?

Simulations Utility: The simulations are the only scholastic alternative to visualize the results of the Double Split Experience. The simulations have been designed with *Modellus* for this case, it shows: the results of applying to SAA technique, the vectors and instantaneous values of angles, the actions corresponding to each selection, all indispensable in the conceptual construction that we looked for. These questions refer to the student evaluation about utility of simulations to construct QM concepts and to the students' satisfaction if simulations are used.

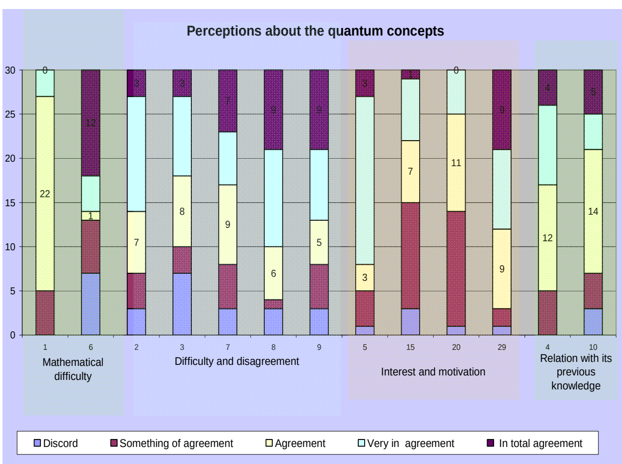
Effort to use simulations: The simulations with *Modellus*, use representations like schematic and mathematical (functions, vectors). To understand what software showed, it required as much to execute it as to answer the questions of the sequence. In the familiarization instance, the students must work with new software and the simulations demand attention during the execution. Did the students feel that they made a big effort?

V. PRESENTATION AND DISCUSSION OF RESULTS

a)Perceptions about the quantum concepts

The Graph 1 synthesizes the results in each formulated category

Mathematical difficulty: Most of the students (25) answered that the mathematical aspects were accessible to their previous knowledge. Nevertheless, a little more than half (17) did not remember some mathematical aspects so that was a difficulty for the quantum concepts understanding.



GRAPH 1. Perceptions about the quantum concepts.

Difficulty and disagreement: An important number of students (26) were surprised by the peculiar behavior of electrons; while (23) recognized that the probabilistic character is not comfortable for them. The quantum concepts were strange, difficult to imagine for a great majority (22). Nevertheless, in spite of the complexity and the difficulties that our students recognized, (22) twenty two thought that it would be possible, for other students to understand these concepts.

Interest and motivation: Half of the students (15) said were interested in understanding ideas of present physics. Although then the other half would have no interest, many students felt satisfaction studying the present knowledge of physics (25) and this generally is not taught at school. In addition almost everybody (27) valued positively the possibility of learning physics in this way.

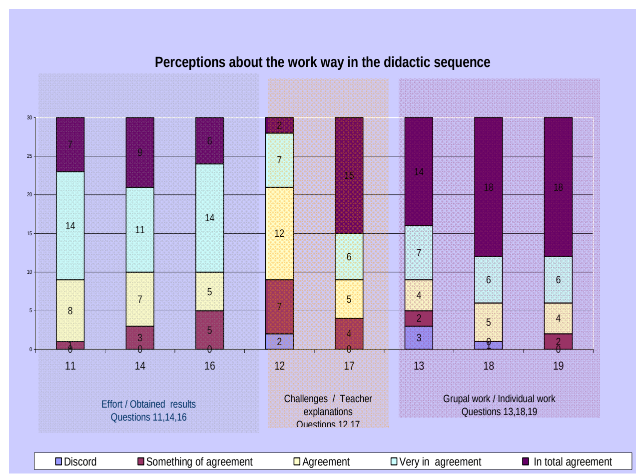
Relation with its previous knowledge: Almost all the students (25) consider that these new concepts are related to their previous physical knowledge. A great part (23) of them felt calm because although the quantum principles are novel and surprising, they also explain the classical results, that they already knew before

b) Perceptions of the didactic sequence and the work in the classes

In Graph 2 the answers related to the development of the lessons appear.

Effort/obtained results: Many students (25) recognize that they had to realize a big effort to understand. Also all (29) feel the situations were accessible and they could solve them.

Relation with its previous knowledge: Almost all the students (25) consider that these new concepts have relation to their previous physical knowledge. A great part (23) of them reported to feel calm because although the quantum principles are novel and surprising, they also explained the classical results that they already knew before.



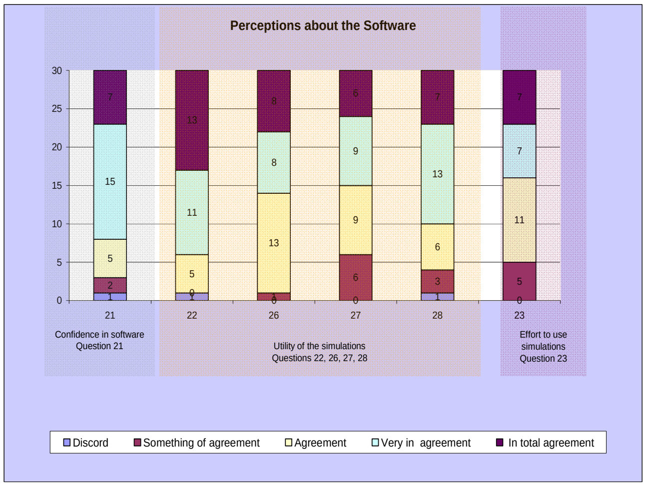
GRAPH 2. Perceptions about the didactical sequence.

Challenges/explanations of the professor: Two thirds of students (21) felt like to taste the challenges and raised questions. Almost all (26) feel that “they would have understood more” if the teacher had explained the concepts to them, instead of having to face the situations and questions.

Individual work/group work: Many students (25) recognize the relevance of group work. Also almost all (29) felt it was positive and necessary the individual written synthesis that they had to do.

a) Perceptions about the software

In the Graph 3 answers related to the software are presented:



GRAPH 3. Perceptions about the software

Confidence in software: (27) students said that they trusted software more than their ideas. That is to say that like how it happens with a book, people do not think that authors can be wrong. In this the scholar culture would have great incidence, because it is based on the request of obedience more than in the questionings.

Utility of the simulations: almost all the students consider that the simulations are useful, pleasant; although they are not visually attractive they collaborate in the understanding and reduction of abstraction.

In this aspect it is important to emphasize that the relevance, amount and quality of the simulations, were very well analyzed aspects and taken care of in this sequence. These tools were used because they avoid calculations and they maintain a geometric language, although this is abstract, it has allowed relating the mathematical aspects to the physical meaning. Nevertheless, the students have a clear perception of their effort, in all the proposed activities.

Effort to use simulations: (25) the students say that working with simulations was not easy. As we have said, this is related to the fact that the simulations were functional to the situations raised by the sequence because they presented a problematic character. Besides understanding what it showed, they involved questions which answers allows the understanding of new aspects and concepts.

VI. CONCLUSIONS

Considering the sequence was developed according to the steps predicted and the students perceived and described their intense but possible effort, we can say that the CSPT was viable in this institution. The students were not surpassed by the proposed situations and they accepted the challenges. As it was mentioned, the quantum concepts construction involved in the sequence requires the students to be able to make the necessary cognitive and affective effort. Considering the abstraction that the concepts involve and the difficulties that imply to understand them, the students overcame the temptation to leave. This is related to the type of emotional dynamics implied in the sequence design. By the way, the first stage accepts the student corpuscular ideas about electrons, before disturbing them.

In relation to software, the students also recognize the importance of its use and the effort it required. Although the chosen and designed tools try to lighten certain difficult aspects such as the calculation, they do not suppose a passive use. They are an undissociable part of the conceptualization situations; therefore they are related to the problems and questions.

Another indicator of viability is the student's satisfaction with the results of their effort and the way they worked. This way has required to pay attention and has emphasized the oral and written communication.

Finally, our investigation leads us to ask us if this way to introduce the quantum mechanics in the secondary school, apparently simple, aiming at the conceptual construction of this so important part of physics theory, could be reproduced in other groups and institutions. In that case the following questions have been opened:

What adjustments and improvements could be done in the proposed situations?

Which are the main obstacles to teach these quantum basic concepts?

What could we do in terms of physics concepts genesis in the school to collaborate with teaching planning?

What type of interaction in the class group - teacher and students- is required to hold and to resist the mental effort that the sequence demands them?

Does this development sequence impact the affective aspects the professor as much as the students'?

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APPENDIX

Questionnaire

A- Please, indicate your degree of agreement- with the following sentences about the Quantum mechanics concepts that we have studied. (1 disagree, 5 in total agreement)

1- The work with the vectors and the trigonometric functions necessary to understand the QM concepts was not finally complicated.

2- The probabilistic character of the QM made me feel me uncomfortable.

3- Studying the QM concepts has radically changed my previous ideas about the electrons.

4- I have learned a different Physics from the usual one, although it is based on that I already know

5- I feel satisfaction to have studied a very important and current part of physics knowledge; many students of the secondary school could never have studied it.

6- If I had remembered better my mathematical knowledge, it would have been easier to understand the new concepts.

7- I don't believe that I have learned so difficult things that could not be understood by other students with similar characteristics.

8- I have been surprised by the strange behavior of the electrons and the microscopic world.

9- I felt the quantum world is strange and difficult to imagine.

10- I feel confident because these new concepts that I have learned allow me to explain what I knew of before.

11- Making much effort of my part, I believe that I solved the posed questions

12- I felt affability trying to resolve the questions and the proposed challenges

13- Talking with my class group was essential to understand the quantum concepts

14- Understanding the concepts has required too much effort from me.

15- I felt very motivated by the new concepts when I found out that they were concepts of today's physics.

16- I had to make an effort to understand the QM questions proposed to answer.

17- If the teacher had explained the concepts instead of giving us activities and questions, I would have understood more.

18- Doing the personal synthesis I reflected and thought about the class work with my classmates.

19- The synthesis activities were essential to understanding and to have a global look about the studied subjects.

20- In this work I was interested in understanding the concepts proposed to be learnt.

21- I trusted the simulation results, and they made me review my calculations and my thinking if they are not in agreement with the software results showed.

22- The experience simulations were useful to understand the involved concepts.

23- Working with the simulations required much attention of my part, and was not simple.

24- If I had watched the "Dr. Quantum" video before, I would have understood everything that I understand now.

25- The "Dr. Quantum" video must be watched before; therefore it would have helped me to understand better what we studied.

26- I liked to work with the Double Split Experience simulation because it showed me the experience results that are impossible to do in the school.

27- The simulations and the video have helped me to understand the abstract quantum mechanics concepts, but without the raised questions and activities it would not have been possible.

28- The Software *Modellus* was not visually attractive, but without the simulation it would have been difficult to understand how the SAA technique can be used.

29- It seems important to me to have been able to study this physics part with the simulations and the video.

30- After we watched and we talked about “Dr. Quantum” video I thought that quantum world is strange and I have curiosity to know more about this.

B- Express freely your opinion about that you lived in these classes about QM.