About the wave's concept in quantum mechanics and how university student understand its aspects. Algerian students' case

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ABSTRACT

The most important basic aspect of Quantum Mechanics description is the wave, but there are many different interpretations between different schools and scientists about the reality of this wave. Till now there are more than thirteen important schools of interpretation for the basic concepts of quantum mechanics. In the case of the wave, some interpretations consider it as a real wave, while others consider it as only a mathematics toll. Through our experience in teaching quantum theory, we conclude that teaching quantum mechanics is not only just deriving beautiful and maybe logical equations and relations related to the subject. We believe that each step of deriving those equations or relations should be followed by deep discussions of concepts and meanings. Because of the students difficulty for understand the wave concept as an example of general basic concepts of quantum mechanics. For this purpose and in order to clarify and focus on the problematic, a questionnaire sheet was presented to homogenous sample of Algerian third year physics students related to the subject. But we concluded from the results of students' survey, that the basic concepts of quantum mechanics should have a profound educational revision.

KEYWORDS

Classical Mechanics principles, Quantum Mechanics basic principles, wave in Quantum Mechanics. Copenhagen interpretation, Everett III interpretation

RÉSUMÉ

Le concept fondamental le plus important de la Mécanique Quantique est le concept d'onde. Cependant, sur la réalité de cette onde, il y a de nombreuses et différentes interprétations selon les écoles d'interprétation. Jusqu'à présent, on dénombre plus de treize écoles d'interprétation pour les concepts de base de la mécanique quantique. Dans le cas de l'onde, certaines interprétations considèrent l'onde comme une onde réelle, tandis que d'autres la considèrent seulement comme un outil mathématique. Suite à notre expérience dans l'enseignement de la théorie quantique, nous concluons que l'enseignement de la mécanique quantique ne se limite pas à juste dériver des équations et manipuler des relations. Mais nous croyons que chaque étape de dérivation de ces équations ou relations devrait être suivie par des discussions profondes des concepts et de significations physiques. En raison de la difficulté des étudiants à comprendre le concept d'onde comme exemple de concept de base de la mécanique quantique, nous avons envisagé l'étude de cette problématique. À cet effet, et afin de clarifier la problématique, un questionnaire lié au sujet du concept d'onde a été présenté à un échantillon homogène *d'étudiants algériens de troisième année de physique. Les résultats d'investigation nous permettent de conclure, que les étudiants ont des obstacles pour assimiler les concepts de base de la mécanique quantique. Nous pensons que l'enseignement de ces concepts devrait subir une révision profonde.*

MOTS-CLÉS
Les principes de la mécanique classique, les principes de base de la Mécanique quantique, l'onde en mécanique quantique, interprétation de Copenhague, interprétation de Everett III

PART ONE: EPSTEMOLOGICAL STUDY

Introduction

First of all in order to give importance and legitimacy to our work, we quote the following sentence said by a famous physicist Feynman "Quantum mechanics is the description of the behavior of matter and light in all its details and, in particular, of the happenings on an atomic scale. Things on a very small scale behave like nothing that you have any direct experience about. They do not behave like waves, they do not behave like particles, they do not behave like clouds, or billiard balls, or weights on springs, or like anything that you have ever seen" (Aspect & Balibar, 1984, p. 7-8). From our long experiences teaching quantum mechanics, as special case, we have noticed that students face great obstacles in understanding the meaning of the basic concepts of this theory, such as: the concept of the wave in quantum mechanics. In which all the other concepts of quantum mechanics are related or based on it. We mention that the standard interpretation used for teaching Quantum mechanics is a Copenhagen team interpretation based on: Complementarity principle of Bohr, Uncertainty principle of Heisenberg and finally the Probability density function $\psi^*\psi$ of Max Born and its interpretation (Murdoch, 1987). We believe that these obstacles rise due to the influence of basic concepts in classical mechanics, which students have studied for many years before studying quantum mechanics. For example, in classical mechanics the concept of wave and the concept of corpuscle refer to different things, while in quantum mechanics both concepts refer to the same thing, namely a "quantum particle". Besides, another thing that must add to these difficulties is its abstract mathematics tools.

There are, at present, more than thirteen important interpretations schools of Quantum Mechanics, and many more will certainly be suggested in the future. All these schools have different ways and different points of view concerning the interpretation of the basic concepts of Quantum Mechanics. The major differences between these interpretations are: the meaning of: the collapse waves, the complementarity principle, and the interpretation of superposition principle. If we consider the following Table 1 (Bub & Clifton, 1996), we notice that they mostly do not agree whether the quantum mechanics is deterministic or not? For example of the concept of wave (Table 1), gives two variants: the first regards the waveform as being a tool for calculating probabilities only, and the second regards the wave as an element of reality. We notice that when we say wave, we mean its physics meaning or whether is it objective or not? We don't mean the wave function which represents its mathematical form. We would like to notice that the goal of our brief study of these different interpretations is to show the conceptual difficulties of Quantum Mechanics which face even great physicists. This explains why Quantum Mechanics is very difficult and hard to teach and not easily assimilated by students. We think that the problem of students' understanding of the basic principles of quantum mechanics is due to the influence of the easy domestic concepts of Classical Mechanics' basic principles. Let us give our brief original comparisons between the basic epistemological principles of Classical Mechanics, and its corresponding principles in Quantum Mechanics, according to Copenhagen interpretations.

TABLE 1

Different important school's interpretations of the wave in quantum mechanics

Interpretation	Author(s)	Deterministic?	Wave function real?	Collapsing
Many-worlds interpretation	Hugh Everett, 1957	Yes	Yes	No
Copenhagen interpretation	Niels Bohr, Werner Heisenberg, 1927	No	No	Yes
de Broglie–Bohm theory	Louis de Broglie, 1927, David Bohm, 1952	Yes	Yes	No
Von Neumann interpretation	von Neumann, 1932, Wheeler, Wigner	No	Yes	Yes
Ensemble interpretation	Max Born, 1926	Agnostic	No	No
Popper's interpretation	Karl Popper, 1957	No	Yes	No
Many-minds interpretation	H. Dieter Zeh, 1970	Yes	Yes	No
Objective collapse theories	Ghirardi–Rimini–Weber, 1986, Penrose interpretation, 1989	No	Yes	Yes

Final causality principle

Due to this principle, whenever we know the initial state or initial conditions consisting of the system's position and momentum, and know all external forces acting on it, we also know what will be its later states. The knowledge of the initial state is usually acquired by observing the state properties of the system at the time selected as the initial moment 'final causality' (Moyal, 1949). This important domestic and objective basic principle in classical mechanics does not exist in quantum mechanics. Everyone knows that the uncertainty principle in Quantum Mechanics violates this mainstay principle in classical mechanics.

Determinism principle

In classical physics, we can always draw a sharp distinction between the state of the measuring instrument being used on a system and the state of the physical system itself, because the definition of any later state is not dependent on measuring conditions or other observational conditions. This means that the physical description of the system is objective (determination principle). We note that it is not the case in quantum mechanics, where measurement depends on the measuring instrument being used (Katsumori, 2011; Plotnitsky, 2013). According to Bohr interpretation, for example, $[\psi(x)]^2$ (where $\psi(x)$ is the wave function), denotes the probability density of the position of the particle. The probability density of finding the particle at *x* occurs once a suitable measurement takes place. Before the measurement, it is neither here nor there, (Katsumori, 2011; Plotnitsky, 2013). So we note that Quantum Mechanics is well known by the problem of non-determinism.

Space and time principle.
In classical mechanics the space is composed of three dimensions, and physical processes (the evolution of systems) take place in space and time, and physical objects (systems) exist separately in space and time in such a way that they are localizable and countable (Held, 1994). Students are familiar with such space, where they can easily imagine or see how the physical processes takes place in it. In Quantum Mechanics, objects (systems) take place in a totally different space than the one of Classical Mechanics, which is called 'Hilbert space', which is a vector space, provided with inner product. This Hilbert space is composed of infinite complex functions (infinite sets).

Continuity principle
In this principle, all processes exhibiting a difference between the initial and the final state have to go through every intervening state; that means there is no discontinuity during the progress of physics quantities, such as energy and momentum, and so on (Held, 1994). As the above principles, this principle of continuity in classical mechanics does not exist in Quantum Mechanics which is known by the Principe of quantification.

Principle of the conservation of energy
The energy of a closed system can be transformed into various forms but is never gained, lost or destroyed (Simpson, 2014). We note that only this important principle 'energy conservation' in Classical Mechanics exists also in Quantum Mechanics. We may note that in Classical Mechanics there are states which are called rest states (energy nil).While in Quantum Mechanics, rest states (energy nil) doesn't exist. Besides, the energy in quantum mechanics is quantified, while in classical mechanics it is not.

The wave in quantum mechanics
We believe that one of the great obstacles to the good understanding of quantum theory, in addition to the interpretations difficulties, is the mathematical structure of this theory, which is based on fairly abstract mathematics, such as the Hilbert space and the operators on it (Von Newmann, 1932). This space is composed of infinite complex functions (infinite sets) and the physical quantities related to the particle are calculated from the operations of operators (having no physical meaning) on complex functions belonging to the states' space, where the latter is a subspace of the Hilbert Space. In Classical Mechanics and Electromagnetism, on the other hand, the properties of a point mass or the properties of a field are described by real numbers or functions defined on two or three dimensional sets. These have direct spatial meaning, and in these theories there seems to be less need to provide a special interpretation for those numbers or functions (Hewson, 1970). Another property of the wave in classical mechanics is that it can't bring or be followed by a matter in its propagation, which means there is a distinction between the wave and matter. We note that it is not the case in quantum mechanics, where the wave can be a corpuscle and wave in the same time (Ladj, Oldache, Khiari & Belarbi, 2010). Also, we have always noticed that the problem of collapsing wave function is not easily understood by students. How is the phenomenon in which a wave function initially in a superposition of several different possible Eigen states appears to reduce to a single one of those states after interaction with an observer? Von Newmann (1932). Always students ask how an abstract mathematical tall (according to Copenhagen team interpretations) like wave packet will collapse into single wave in measurement? And often ask how real physics quantities (energies, momentums and so on),

can be calculated from an abstract mathematical tool. It is clear and very known that Copenhagen Interpretations of Quantum Mechanics is not the final description of quantum mechanics. As it is known, an interpretation of quantum mechanics is a set of statements which attempt to explain how quantum mechanics informs our understanding of nature. Although quantum mechanics has received thorough experimental testing, many of these experiments are open to different interpretations (see Table 1). There exist a number of contending schools of thought, differing over whether quantum mechanics can be understood to be deterministic, which elements of quantum mechanics can be considered "real" or else (Goldstein & Lebowitz, 1995). This question is of special interest to philosophers of physics, as physicists continue to show a strong interest in the subject. The two major interpretations of quantum theory's implications for the nature of reality are the Copenhagen interpretation and the many-worlds theory. For Niels Bohr proposed the Copenhagen interpretation, which asserts that a particle is whatever it is measured is to be a wave or a particle but that it cannot be assumed to have specific properties, or even to exist, until it is measured. The second interpretation of quantum theory is the many-worlds (or multiversity theory). It holds that as soon as a potential exists for any object to be in any state, the universe of that object transmutes into a series of parallel universes equal to the number of possible states in which that the object can exist, with each universe containing a unique single possible state of that object. Stephen Hawking and Richard Feynman are among the scientists who have expressed a preference for the many-worlds theory (Everett, 1957). We would like to present our modest comments to Bohr point of view, with regard relationship of the existence and measurement.

First; If we consider this point of view, so, any measurement's toll (represents also a quantum system), needs to be measured and so on…, in This case, we will not finish with real suitable tool. Then we will never finish with any reality.

Second; it is well known in case of Schrödinger cat, Bohr saw that the cat in the box, before the measurement is either die or live so we can represent the cat state by $\psi = a\varphi_{die} + b\varphi_{live}$. But when the measurement is done, the wave function ψ collapse into only one wave function either $a\varphi_{die}$, or, $b\varphi_{live}$., the wave function ψ will collapse to only one wave function either: die or live wave function. This interpretation half die and half alive does not reflect the reality at all.

Again my modest comment for Everett who proposed; as soon as a potential exists for any object to be in any state, the universe of that object transmutes into a series of parallel universes. According to him, how the linearity of Schrödinger equation can be preserved. And how can the interference experiment of electrons be explained?

PART TWO: EDUCATIONAL STUDY

Introduction

Today, many physicists are interested in the epistemological and the didactical aspects of Quantum Mechanics. We can classify them into the following categories:

- Some of them are working in pure epistemological Quantum Mechanics researches. These scientists are interested in the interpretations of the basic concepts of quantum theory. The interpretations have started since the rise of quantum theory and many different schools of quantum theory have appeared.
- Some others are working on Visual Quantum Mechanics **(**VQM**)** where they present some basic ideas of quantum mechanics by integrating hands-on activities and computer

visualization**.** They use (QSAD**)** “Quantum Science across Disciplines” which is a software application producing graphical representations of atoms and molecules without requiring students to perform high-level computations. Students can create visual models of different atoms and molecules, predict their behavior and test those predictions. To exemplify this kind of work; we suggest the work of Table 1.

There are other researchers who are only interested in the didactical aspect of Quantum Mechanics. Education research in Quantum Mechanics has given a great importance to the investigation and the deduction of the best way to teach and transmit this subject to students (see for example: Rainer & Hartmut, 1999; Özcan, 2010). All the above researchers concluded that Quantum Mechanics is difficult and abstract. Furthermore, understanding many classical concepts especially waves and optical physics are prerequisites to a meaningful understanding to quantum systems. In our work, we wanted to highlight the importance to the students of having a strong knowledge of the basic quantum concepts in general case and wave concept as special case.

Description of the Questionnaire

Because of the interpretation difficulties of the wave concepts in the quantum mechanics mentioned above, as a special case of the other Quantum Mechanics basic concepts. We wrote a questionnaire sheet related to the wave concept in quantum mechanics. The questionnaire was presented to a sample of 40 students of third year physics. Our aim was to study the problematic of the students’ misunderstanding of the wave concept. We wanted to know what the students understood about the concepts of wave in quantum mechanics according to the Copenhagen School interpretation (the standard interpretation), which is the most popular among scientists and is the used interpretation in teaching quantum theory.
Answer: (**yes**) - (or: **no**) - (or: **no idea**) for each of the following questions.

Set 1. Wave nature

- The concept wave related to objet is real, i.e., represents a real element.
- It is only an abstract mathematical tool used to describe particle motion.
- It describes the electron’s charge distribution.
- No idea.

Set 2. The relationship between the wave and the corpuscle concepts.

- Wave aspect and corpuscle aspect refer to same object (particle).
- Wave and corpuscle aspects refer to two different objects (particles).
- Wave and corpuscle aspects are intrinsic aspect of the object, that mean are not an appearance aspect of the object.
- No idea.

Questionnaire Results

The results got from the questionnaire show that nearly all students gave wrong answers to the above questions. The percentage of students who gave the right answer was only 30,5 for set 1, while, it was 30 for set 2. (See the different answers number and their correspondences right answers in fig (1, 1), fig (1, 2) and fig (2, 1) fig (2, 2)). We note that the above multiple-choice questions were given to Third year university students who studied quantum mechanics courses for at least 90 hours.

FIGURE 1.1

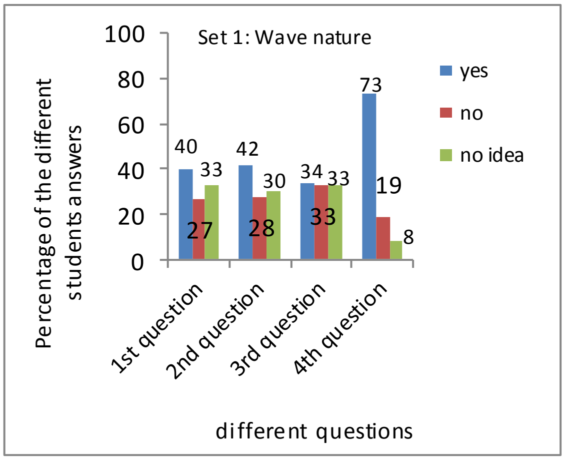


FIGURE 1.2

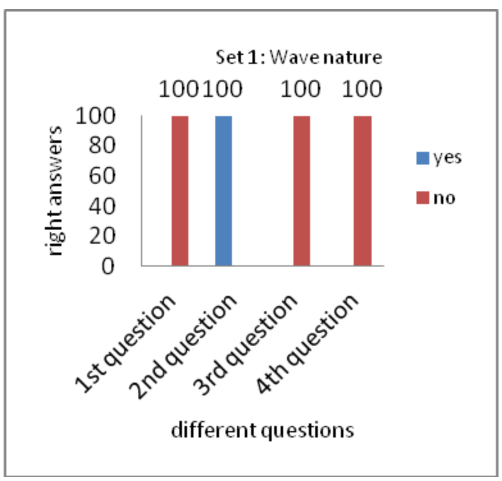


FIGURE 2.1

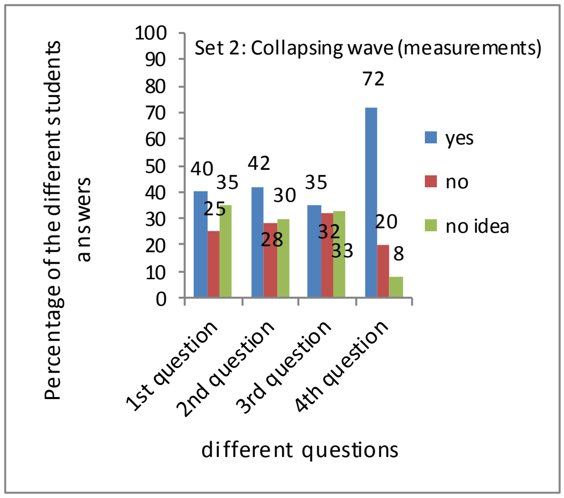
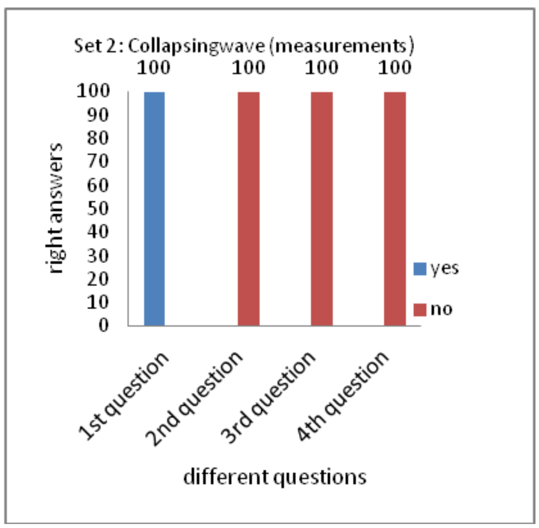


FIGURE 2.2



DISCUSSION

We can conclude from the results in different histogram graphics figures that these results are not good enough results, especially for third year physics (we should mention that these students had a Quantum Theory course for at least 90 hours in their third academic year). When we take whether set 1 or set 2 of multiple-choice questions (wave nature or collapsing waves), we conclude that students answered nearly the same percentage for the different sets, and unfortunately we conclude that students have no idea about the wave concept; most of them see it as a strange concept, or they consider it as real wave as well as waves in classical physics. We note that when we noticed the above unsatisfactory students' results, we wanted to focus deeply on the issue, and for that, we have asked ten university teachers over different universities in

Algeria the following simple question (just an oral question): Do you have an idea or knowledge about the different quantum mechanics schools interpretations? Unfortunately, we noticed that (about 40) of teachers ignore even the existence of different schools interpretations of quantum mechanics, while (about 60) have just a little knowledge about them. So we can generalize that the teaching of quantum mechanics at least in our country is just an initiation of Dirac algebra calculations and derivations of physics relations without any deep discussions and interpretations with students.

SUGGESTIONS

Before we start our suggestions, we mention that the misunderstanding problem of Quantum mechanics concepts as a general case and the concept of wave as particular concept is not only a problem of Algerian students but is a problem of major students over all the world (Rainer & Hartmut, 1999). It is important to the students to have a conceptual understanding of quantum theory, so due to our long experience in teaching the field and also according to many teachers of the field, we suggest that it is very important to discuss the basic quantum mechanics during the class very deeply, where we mention and discuss the most important different interpretations schools. We also advise to give to any quantum mechanics concept its corresponding one in classical mechanics, rather than spend all the lecture time with abstract ideas expressed in the symbolic language of mathematics see, Ladj et al. (2010). Besides, to help students to have a good understanding of quantum mechanics we suggest the following:

- Adding an extra course, distinct from all other physics courses, to the curriculum of all students of science, which should be related to the epistemological aspects of science in general (Koliopoulos & Ravanis, 1998, 2000), where the concepts and the interpretations of the different schools of thought are deeply discussed.
- For physics students, we give, in the beginning of the quantum mechanics course, a historical account of this theory, and show how it developed. We are convinced that deep discussions with students about the different schools of interpretation, especially the many words interpretation will increase their understanding faculties. When we make sure that students begin to assimilate the basic concepts of Quantum mechanics, it will be easy to move on to the mathematical tools related to the subject and its description.
- We use and generalize the computer visualization software as tall during the course to show and explain some difficult phenomena.

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