Review Article
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Multiple ontologies in learning quantum mechanics

Abstract

In this study, consistent with the interpretivist paradigm, focus group discussions (FGDs) were used together data about tertiary physics students' multiple ontologies / realities on wave – particle duality. Findings of the study show the need to afford tertiary physics students opportunities to critically think so that they develop ontologies which may contribute to debates aiming to solve pertinent wave – particle issues. Therefore physics educators should expose tertiary physics students to teaching and learning contexts which develop flexible ontologies about wave – particle duality. Such exposure encourages tertiary physics students to engage in exploring alternatives which may be scientifically significant.

Keywords: interpretivist paradigm, wave – particle duality, tertiary physics, Quantum Mechanics

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Introduction

Quantum physics is a subatomic world which deals with modelling, aiming to understand the invisible subatomic particles and their interactions like ordinary particles. Understanding interactions of ordinary / macroscopic objects like golf balls, cars, trees and stars in the macroscopic world is based on the English scientist Isaac Newton.[1-14] Before Newton it was believed that one set of rules governed motion on earth and another set governed motion in the heavens. In the heavens stars seemed to move forever, while on earth objects seemed to move for a while and then come to rest. Today all varied information is organised based on Newton's concept that all motion is governed by one set of laws called Newton's three laws of motion, along with Law of Universal Gravitation. This explains the fall of an apple from a tree to the ground, and the orbit of the moon around earth. Success of Newton's laws in explaining motion resulted in the philosophy of determinism. Determinism says action including human, is caused entirely by preceding events.[8,14]

Transmission of energy has been observed for many years to be through either waves or particles. For instance water waves carry energy, while a particle like a stone carry energy from a top of a mountain to the bottom. In classical physics electrons have been considered for many centuries to be particles. However, the idea by de Broglie that electrons had a wave property was independently confirmed by Clinton Davisson an American physicist and the British physicist George Paget Thomson [4]. Davisson diffracted electrons through nickel and Thomson similarly diffracted electrons through gold. In 1906 George Paget Thomson's father J. J Thomson won the Nobel Price for proving experimentally that electrons are particles.[4]

In modern physics, quantum mechanics is applied in diverse fields, but being cognisant that quantum physics can be intellectually challenging,[15,18] due to conceptual changes the quantum theory has brought.[1] Experience with things that act like particles or waves, but not both as wave – particle duality suggests, causes confusion in understanding quantum theory.[1] This is because ontologically, the concept of wave – particle duality has accrued many meanings over time, therefore it remains a vague concept neither well explained nor used with consistency.[6] However, it should be noted that scientific concepts with multiple meanings are not new. Some examples are fundamental concepts like mass and space. A concept with multiple meanings is not problematic because the intended meaning becomes evident in the specific context of use. Consequently, there are many science textbooks which variedly exhibit wave – particle duality,[4] hinged on multiple interpretations of quantum mechanics that have been considered as proposals of wave – particle duality. The primary ground for multiple interpretations in line with the interpretivist paradigm for the wave – particle duality is an outcome of multiple physicists like Einstein, de Broglie, Born, Bohr and Heisenberg.[4]

Multiple interpretations of wave – particle duality ontology

Research in physics education shows resistance to conceptual change in quantum mechanics stemming from prior knowledge acquisition. It is crucial to note that there is diversity in whether it is the beliefs, epistemological framings or ontologies that are supposed to change in the minds of learners so that there is no resistance to learn quantum concepts.[2] Ontological flexibility is necessary in order to comprehend wave – particle duality. For instance when performing the double – slit experiment with low – intensity beam, individual electrons will register at the detector individually, but eventually an interference pattern will develop.[13,19] While interference is a property associated with waves, localised detections signify the presence of particles. Interpretation of these phenomena by physicists varies, depending on their ontological and epistemological orientations.[2] Copenhagen interpretation of quantum mechanics[11] would say these experimental results reveal an abstract whole where an electron is neither a particle nor a wave. The dual use of distinct classical ontologies (particle and wave) is an attempt to understand behaviour of electrons in familiar terms of macroscopic concepts.[2] Pursuant to the objective of understanding the dual behaviour of electrons, the wave function is used to describe electrons as they propagate through space, and the wave collapse postulate is invoked to explain localised detection (particle nature). The switch between particle and wave is made in the sense of how the electron is represented at a particular point. The wave function is viewed as nothing more than a mathematical construct for the purpose of predicting measurement outcomes with no reference to any underlying reality.[2]

While it is known that wave – particle duality has been extensively studied, its multiple definitions make it a debatable issue for which there is no consensus. Many prominent scientific pedagogic texts draw from these trends, hence they depict wave – particle duality differently. Some researchers,[2, 3] argue that quantum particles are indeed particles, but whose behaviour differs with our preconceived conceptions stemming from prior experiences with classical physics. Various epistemological perspectives are employed ontologically in categorising electrons as particles based on localised detections.[2,17] Localised detections imply continuously localised existence of massive charged particles in space. Particles are by definition localised. However, there is no consensus among practicing physicists regarding the correct ontological nature of electrons.[2]

Multiple views subsumed under wave – particle duality, engender multiple interpretations which give rise to multiple realities consistent with the interpretist paradigm ontology.[4] Bohr proposed a contextualised view of the principle of complementarity in 1927, and Heisenberg in 1929 expressed wave and particle views as merely two different aspects of one and the same physical reality. For Heisenberg duality is a situation in which two equivalent mathematical formulations exist for describing the same quantum phenomenon. Dirac held a similar view.[4] While the first views about wave – particle duality are old, but they are not obsolete as evidenced by their endorsement by many interpretations found in current scientific literature The present plurality about wave – particle duality interpretation is largely due to the inadequate way in which this concept is dealt in the pedagogy of quantum mechanics.[10] Premised on this, the current study sought to find out tertiary physics students' ontologies of wave – particle duality and suggest how understanding of wave – particle duality can be enhanced during physics learning.

Methodology

The interpretivist paradigm guided this study. Various views and interpretations by focus group discussions (FGDs) participants on wave – particle duality generated data based on multiple ontologies / realities consistent with the interpretivist paradigm. Ontology is the nature of existence or reality about things or knowledge.[16] A total of twelve students majoring in physics education volunteered to participate in the study. FGDs were done in the third week of the final year of the three Diploma in Education in which Physics and Chemistry were subjects majored in. Each FGD involved three female and three male participants, hence achieving gender balance in the sample. To establish understanding of participants, each FGD began by asking participants to describe their understanding of the atomic structure. Participants described a basic atom as comprising a nucleus (protons plus neutrons) at the centre, with electrons arranged around the nucleus in energy levels or orbitals, this the Bohr model. After establishing the context of understandings of FGD participants in each case (FGD) procedures in the FGD guide were used to collect data.

Findinings

Presentation of findings in this section is done under four themes which are Particle based ontologies, Development of New Ontologies through self – Interrogation, Outcome and Measurement Process, and Pilot – Wave ontologies.

Particle based ontologies

In classical physics a particle is a small object with mass and negligible spatial extent. Therefore there is a tendency for introductory quantum physics students to persist thinking of electrons this way, especially if educators continue to refer to them particles.[1] Responses by FGD participants R and U suggest that their ontological views of electrons had been influenced by particle nature of matter as considered in classical physics. For instance R said:

An electron is a small particle, which is part of an atom. In atom electrons are located in energy levels called orbitals. Electrons are identical particles with the same mass.

FGD participant U said:

If something is very small solid mass and can be located at a fixed position implying it has volume, then it can be considered a particle. Electrons are particles because they fit this description. However, for electrons it sometimes confuses because they are described as small discrete clouds of negative charges.

Similar sentiments were expressed by other FGD participants, as demonstrated by participant T saying:

Electrons are particles of an atom which move around the nucleus in energy levels. The nucleus comprises protons which are positively charged and neutrons which have no charge.

These responses show how ontologies students apply may influence their reasoning and understanding. Another important issue revealed by participants as illustrated by responses of R and U is how prior knowledge influence or interfere with construction of knowledge or understanding of quantum physics concepts.

The dual use of distinct classical ontologies (particle and wave) is an attempt to understand the behaviour of electrons in familiar terms of macroscopic concepts [2]. A noteworthy point about these responses are challenges the students faced in explaining electrons in terms of mass or charge also linking them with fixed or localised position. This could be probably due to the fact that in classical physics electrons have three attributes, which are mass, charge and position, but in quantum mechanics electrons sometimes possess mass and charge, but position being uncertain based Heisenberg principle [4]. In this case it appears epistemologically prior learning experiences influence subsequent ontologies students apply in their learning.

Development of new ontologies through self – interrogation

Six of the FGD participants queried their conceptual understanding of the behaviour an electron short as a particle, and subsequently undergoing diffraction and interference after passing through double slits. Summarising the view of the six FGD participants student M noted.

From the beginning the state I am sure of when the electron is short is that it is a particle. This suggests that when it reaches the screen then it should pass through one of the slits not both. The fact that it passes through both slits and spreads out or diffracts means it is no longer localised but delocalised. Between the point of shooting or projecting the electron and just before passing through the slits I cannot observe the behaviour of the electron but I think it will be like a particle. I suppose it is only when conditions change as the electron passes through the two slits that the electron behave different from a particle.

Expressing reservations about this conception of the behaviour of the electron student M queried:

But ummm I do not know how change occurs from particle as a solid to behave as a wave which is not solid.

Putting forward a view similar to M, student P said:

The general meaning of a particle relates to a small round solid object or piece. If electrons are particles then they should have mass and volume. If electrons behave as waves it implies they will have lost mass. How this is possible I wonder.

Students M and P responses show how new ontologies develop as through interrogation of current ontologies, based on attempt to explain phenomenon under investigation.

Outcome and measurement process

Expressing the dependence of an outcome to the measurement process eight of the twelve FGD participants indicated that they believed electrons behave in ways consistent with context or conditions at that time and point in question. Seeming to concur with student S, W said:

May be when the electron is short it will be a particle like a ball of cloud which when it encounters the two slits it spreads and then passes through them at the same time. This makes sense because from classical physics the two slits act as sources of waves which then cause diffraction and interference to occur.

Student K suggested that:

May be the slits changed the intrinsic properties of the electron so that it behaves differently as a wave.

These responses show that the students believed electrons do not behave the same in all situations. Consistent with Coenhagen interpretation the FGD participants believed that electrons can neither always be particles, nor waves, but behave as waves or particles depending on conditions they are exposed to.

Pilot – wave ontologies

Commenting on the behaviour of electrons in the double slit experiment student S said:

When an electron is short it behaves as a particle or a single entity because I know that the electron short is a single entity. However when it passes through a double slits an interference pattern is observed. Interference is characteristic of a wave so it implies the electron is now a wave. May be the double slits modified the electron so that it behaved as a wave or is it that the electron can adapt to experimental setup to behave as wave which can pass through both slits simultaneously I am not sure?

Five of the twelve FGD participants expressed the view that the electron can be a particle or a wave depending on the situation, as noted by student N:

When the electron was short it was a particle because the conditions permitted it to behave that way. However, I think when it encountered two slits it changed as it passed through the slits just like water coming out of a container through two holes punched side by side on the wall of the container. An electron behaves either as a particle or wave depending on circumstances prevailing.

One student brought in the idea of behaviour of matter being a particle or matter being influenced by the conditions under which the experiment is done. Student Q said:

I do not understand what happens when it passes through double slits for the interference pattern to occur. When the electron is projected it is a particle. Does it mean to say the electron does what a liquid does, when it takes the shape of container in which you put it in? It is true that a liquid cannot depict different shapes of containers, but it takes the shape of the container in which it is currently in. I think an electron behaves as a wave if conditions permit, and similarly as a particle when conditions allow, but not both at the same time.

Student Q is not clear about the transition state(s) under which the electron goes into between the time of projection (particle) and the time when it exhibits interference (wave). It is also clear from Student Q's classical physics analogy of water in a container taking the shape of the container it occupying, but cannot exhibit the shapes of containers it can possible occupy, that at a given time an electron can behave as either a particle or wave but not both, depending on what condition that time permit.

Discussion and implications for instructional implications for physics educators

Findings presented in the preceding section presented reveal epistemologies that form the basis of ontologies the physics Dipolma in Education students apply in identifying electrons as particles or waves. What is important about diversity of these responses is not whether they are regarded as correct or wrong, but the reflection of the factors which affect the ontologies students apply after doing quantum physics courses. Of course applying ontologies which are consistent with contemporary reasoning sound logical, but limitations should not be placed on students so that they reason within the confines of contemporary reasoning. Rather students should be afforded opportunities to critically think so that they can develop their ontologies which may contribute to the quantum physics debates to solve pertinent quantum physics problems.

Failure to offer such opportunities may interfere with attaining deeper understanding of quantum mechanics students. In the findings on conceptions of electrons, in the context of wave – particle duality, students reflected ontological flexibility[13] in varying degrees. Some viewed switching between wave and particle descriptions as context related transitions, while some linked classical distinct explanations to explain electron behaviour in quantum mechanics. In view of these diversities in ontologies, physics educators should utilise the parallel ontologies to engender instruction which promote deep learning and understanding in quantum mechanics.

Consensus on correct ontological nature of electrons lacks among physicists.[2] Lack of consensus is evidenced by various approaches physics educators use when addressing interpretive themes by de – emphasising the physical interpretation of quantum theory in favour of developing of mathematical tools which demonstrate impact on student thinking.[12] Since students develop different understandings in their own contexts, so it is important that physics educators approach intuitions of students taking in account existing multiple contexts.[2] Whether an electron is described as a particle or a wave is not the most important issue, but consistently applying the particle ontology in all contexts can lead novices to paradoxical or incorrect conclusions. This implies[2] that physics educators should explicitly separate classical and quantum ontologies during teaching and learning. Such clarity will enable physics students to avoid invoking classical analogies with distort understanding of quantum mechanics. It should be pointed out that physics educators should respond to students' intuitions on classical particles and waves when teaching quantum mechanics,[2] that is students' prior knowledge. However, physics educators should assist students to develop epistemological capacity to decide when it is appropriate to apply classical or quantum particle / wave ontologies.

The ultimate goal[2] is to enable physics students to distinguish between competing views recognizing the advantages and limitations of each, applying this knowledge in novel contexts. Therefore, instead of telling students what should be believed or not in quantum physics, students should be provided with logical arguments and experimental evidence, and left to decide conclusions for themselves.[2] Quantum mechanics employs a theoretical framework which drastically differs with the classical paradigm. In this disconnect, the transition from a classical to a quantum milieu signifies a crucial revolution of understanding the physical world.[12] In order to overcome these obstacles in understanding quantum mechanics one has to be aware of conceptual changes associated with quantum mechanics. Such understanding will enable one to set aside preconceived notions that stem from experience of the macroscopic world. Experience in scientific norms of classical physics, makes it possible to easily influence concepts such as determinism and causality. Therefore physics educators should ensure that physics students are exposed to teaching and learning contexts which offer opportunities to learn concepts in quantum physics, specifically wave – particle duality, but engendering opportunities for students to develop flexible ontologies. This is particularly important if it is taken into account that quantum physics modelling attempts to understand how subatomic particles interact.

The incompleteness of modeling to explain phenomenon in quantum mechanics is articulated by[9] positing that quantum mechanics cannot be applied in all conceivable situations, because the dividing line between classical and quantum physics is like that between the past and the future. The wave function[9] constitutes a statistical prediction of future events, and it (the wave function) does not collapse after the event has occurred, but it rather becomes irrelevant. Therefore, results of past observations and facts are domain of classical physics on one hand, on the other probabilities of future events and wave functions are the domain of quantum physics. First this clearly shows that for one to understand quantum mechanics there is need to understand that interpretation is not context free. In fact interpretation is a function of the context and the experience of those interpreting. For instance, FGD participants interpreted the double slit experiment interference pattern in the context of their classical physics principles experience, which resulted in misconceptions about the wave – particle duality. However, the dependence of quantum mechanics on classical physics shows lack of clear classical – quantum physics divide which seem to suggest that quantum physics is classical physics expressed in an alternative way of reality. This argument is consistent with ontology of multiple realities in the interpretivist paradigm adopted by this study. The apparent merger of classical and quantum formalisms buttresses further the ontology of multiple realities.

In the current study findings show that students interpreted wave – particle duality based on behaviour of an electron when it passes through both slits in a double slit experiment. However, what needs to be proved is whether all particles behave like what electrons did such that we can safely generalize that all matter has potential to behave like waves. Of course de Broglie has attempted to have a universal wave – particle duality explanation for all matter, but questions still remain on how this can be applied to all matter. While such questions about the ontology of quantum mechanics exist,[7] warns that one should avoid these questions from interfering with regular physics research and learning, otherwise one's physics academic career may suffer. Continuing pursuing such a paradigm burdens one with a classical view of reality and fails to truly embrace the fundamental quantum aspects of nature.[5]

Implications from the study to learning quantum physics

When wave duality is taught according to participants in FGDs, science educators present it as absolute truth, rather as a possibility which attempts to explain scientific phenomenon. As a result rather than developing critical thinking learners' thinking is cast into a box, which creates conditions which hinder learners from exploring alternatives to existing scientific interpretations. Rather wave – particle duality should be taught as a possibility, which leaves room for learners to explore other possibilities, consistent with the interpretivst ontology of multiple realities. Such approach to teaching and learning quantum physics encourages learners to engage in exploring alternatives which may be scientifically significant.

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None.

Conflicts of Interset

None.

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