Conceptual and Epistemological discussions on Quantum Mechanics in a Virtual Laboratory

F. Ostermann and S. D. Prado

Instituto de Física, Universidade Federal do Rio Grande do Sul, 91501-970 Porto Alegre, RS, Brazil

(Dated: October 17, 2018)

We argue here for a more conceptual or qualitative approach in the introductory teaching of Quantum Physics which is built on the basis of epistemological and ontological discussions and as such is a valuable tool mainly in the initial and continued formation of school teachers. We illustrate our point with the analysis of undulatory and corpuscular phenomena of a single photon in a virtual Mach-Zehnder Interferometer - an experimental setup similar to double slits device but simpler - using key ideas of the most known interpretations of quantum formalism, including the many worlds interpretation.

I. INTRODUCTION

There are several factors prompting new strategies in the teaching of physics. First, the upsurge in interest in questions concerning fundamental aspects of Quantum Physics which has been stimulated by the experimental progress of the last two decades. It is now becoming possible to apply Quantum Mechanics (QM) particularly in the fields of Computater Science and Cryptography. There is then a need for introducing the teaching of Quantum Mechanics for people with little or no background in Physics. For this technological motivation some authors suggest teaching students just enough operational quantum mechanics to understand and develop algorithms in quantum computation and quantum information theory. Second, there are initiatives of introducing quantum mechanics in the upper secondary school based on the fact students should have some understanding of how fundamentally this part of physics differs from classical physics. Finally, some authors point towards a greater focus on conceptual understanding and the cognitive skills required to understand and apply physics concepts and the use of technology as a teaching tool to revert the decline in the number of students choosing physics as a major field of study.

Our claim here is that special attention has to be given to problems of conceptual understanding and interpretation of Quantum Physics since students from other careers or Physics teachers have not enough time in their standard courses to devote a great deal of effort to trying to understand the formal structure of quantum theory. The long training in the quantum formalism is a requisite for any theoretical physicist, but the formalism can not be alone a tool in teaching introductory quantum mechanics in more general situations. Also, a conceptual approach as an introduction to the formalism should be used as a motivation even in regular physics courses. By formalism or formal structure we mean the theory’s mathematical structures that is well supported by experimental evidence, while an interpretation of quantum mechanics is an attempt to answer what exactly quantum mechanics is talking about.

For our purposes we have to be more precise about the kind of picture an interpretation provides. Like other theories, Quantum Physics can be formalized in terms of several axiomatic formulations. Accordingly to Jammer, we can distinguish at least two components in a physical theory T: (1) an abstract formalism F and (2) a set of correspondence rules R. The formalism F, the logical backbone of the theory, is an axiomatized deductive calculus in general devoid of any empirical sense. Although the formalism might contain words like particles and state that may suggest physical reality, these terms do not have any other meaning besides the place they occupy in the context of F. For F to be physically meaningful, some formula need to be correlated with observable phenomena and empirical operations. These correlations are expressed through correspondence rules R. F without R is a game without physical context. We denote FR the formalism F when entwined by the correspondence relations R. It is the interpretation of FR which gives rise to the philosophical problems like the ontological problem of physical reality. As an example of FR in QM, there is the statistical interpretation introduced by Max Born in 1926. This interpretation relates the wavefunction modulus squared to probability densities of finding an electron, for example, in a particular region of space. It relates the abstract elements of the theory, such as the wavefunction, to operationally definable values, such as probabilities. This interpretation is a consensus among physicists, since predictions obtained via this rule are in agreement with experiments to an excellent degree of accuracy. Actually, it is not the teaching of this kind of interpretation which is embodied in the theory we will explore in this paper.

There is another class of interpretation in QM which is not an FR. These are lines of philosophical thoughts or school of thoughts that coexist. Each one has elements that escape from a complete and detailed description of an experiment and that are not, by any means, verifiable in laboratory, at least immediately, since they all predict the same result for a given experiment. These interpretations deal with the ontology of QM, that is, with the nature attributed to a quantum object: corpuscular, undulatory or dualist (wave and particle) and with epistemological attitudes: realist (there is a world independent of an observer who perceives it) or positivist (all our knowledge...
derives from our senses). The difficulties about interpretations in QM are twofold, to say the least: first, it is about the way the theory is related to the physical phenomena and second, it is still missing an appropriate ontology.

The Copenhagen interpretation still appears to be the most popular one among scientists\textsuperscript{11}, but it is also true that most physicists consider non-instrumental questions (in particular ontological questions) to be irrelevant to physics or even that an interpretation is nothing more than a formal equivalence between sets of rules for operating on experimental data, thus suggesting that the whole exercise of interpretation is unnecessary\textsuperscript{12}. As evidenced by Jammer\textsuperscript{9}, the success of QM has lead the majority of physicists to be more interested in practical problems or applications in such a way that it is not an exaggeration to say that most of the textbooks deal almost exclusively with one or two different formalisms used to solve specific problems, leaving no room to epistemological questioning. They fall back to the famous view of Paul Dirac: “Shut up and calculate” attributed to Richard Feynman\textsuperscript{13}.

If teaching were to be based only on the formal aspects of QM, we would never have to face the problems with interpretation. These difficulties seem to appear justly where concepts like understanding and meaning are required\textsuperscript{14}. A more conceptual and qualitative approach of QM is a really valuable tool for the initial and continued formation of school teachers. Also, possible didactic transpositions to the introduction of QM on a pre-university level depend on a solid conceptual background that can only be built on the basis of epistemological and ontological discussions. The conceptual and the epistemological are intertwined when it is asked what QM could represent for our worldview. The conception of quantum objects - which can be illustrated by a simple question about the nature of a photon - can only be made in the light of philosophical posture which, if not explicit, can drive to ingenuous or uncritical views or to the idea that only a single interpretation is possible. Moreover, students’ own epistemological views should not be neglected, since some of the difficulties they face in understanding QM concepts are of philosophical nature\textsuperscript{15}. In conclusion, any attempt of conceptual discussion on QM brings forth elements of its epistemology, which if not present, makes the understanding devoid of any meaning.

This paper is organized as follows: in section II one finds introductory notes of four lines of interpretations of QM. It is not our primary objective in this paper to discuss the interpretations of QM in full detail, but to illustrate their use as a way of enriching the teaching of QM; in section III interpretations of interference phenomena in a virtual Mach-Zehnder Interferometer available on the worldweb\textsuperscript{16} are discussed and finally, in section IV one finds some concluding remarks.

II. INTERPRETATIONS OF QM

One of the main difficulties one finds in teaching introductory QM is to bring together, in terms of understanding, antagonist ideas like the concept of wave - a non-localized phenomena - and the concept of particle - an entity. Although the undulatory theory of light describes the interference pattern in the famous Young experiment with coherent superposition, Einstein’s explanation for the Photoelectric Effect requires light to be composed of indivisible corpuscles of light called photons. Moreover, analogous double slit experiment for electrons, neutrons and more recently molecules like the C60-Fullerene\textsuperscript{17} also exhibit interference fringes. Then, to explain these results it is necessary to recall de Broglie’s Postulate that states that microscopic particles can also behave like waves sometimes. This double character is widely known as wave-particle duality and it is mostly associated with light\textsuperscript{18}.

There are no classical counterparts to this phenomenon and the result of a detection or measurement can present different epistemological views although they are internally consistent. To give a highlight to these differences in a virtual experiment (section III), we employ a few key points of four interpretations: i) Undulatory Interpretation or Schrödinger wavefunction, ii) Complementarity Principle or School of Copenhagen, iii) Hidden-variables or Dualist-realist Interpretation and iv) Many Worlds Interpretation. To partly justify our choices, we have taken into consideration the fact that the Many-worlds interpretation is currently in the media and that throughout much of the twentieth century Copenhagen Interpretation has had obvious majority acceptance among physicists\textsuperscript{19}.

i) Undulatory Interpretation (a realist interpretation proposed by E. Schrödinger in 1926) - When Schrödinger postulated the equation known as Schrödinger Equation and its boundary conditions in 1926, he established a formalism in terms of wavefunctions (or states) $\Psi$ that have identical or similar situations in Classical Mechanics\textsuperscript{20}. For didactic reasons this formalism has been widely adopted in textbooks since then. In this interpretation, physical reality is attributed to the state independently of any measurement and without any additional hypothesis that there is anything else besides the quantum formalism. However, the state is not a directly accessible reality, but under Born’s guidance, it establishes probabilities that evolve over time just like wavefunctions. $\Psi$ is the central object in this interpretation that presents no difficulties in explaining undulatory phenomena. In short, the photon is taken as a wavepacket.

ii) Complementarity Principle or School of Copenhagen (a dualist-positivist interpretation formulated by N. Bohr and W. Heisenberg in 1927) - Despite an extensive literature which refers to the Copenhagen interpretation\textsuperscript{21}, the original formulation has led to several variants, making it difficult to establish how exactly this interpretation is stated. For our purposes, we can say that the Principle of Complementarity formulated by Bohr in 1927 establishes that it is
not possible, in a single experiment, a corpuscular and an undulatory description simultaneously. This interpretation is considered dualist-positivist since it admits the wave-particle duality, but it also emphasizes that the theory can only explain the results of experiments that should be predicted, and therefore additional questions are not scientific but rather philosophical. In contrast to Schrödinger undulatory interpretation, the state here is a mere mathematical instrument that permits predictions of measurement, but it is not provided with any physical reality.

iii) Hidden-variables (a dualist-realist interpretation proposed by L. de Broglie in 1925 and reformulated by D. Bohm in 1952) - This is an interpretation of realistic content in which a quantal system is described not only by its state $\Psi$, but also with the help of additional hidden variables labelled by a parameter $\Lambda$ that contain information on the particle: energy, position and velocity. The state $\Psi$ is a guide-wave or a field of quasi-probabilities that drives the particle. $\Psi$ and $\Lambda$ together establish where a photon will be detected, for instance. Briefly, the photon is a particle to which is associated a guide-wave.

iv) Many Worlds Interpretation (a realist interpretation proposed by H. Everett III in 1957) - This is essentially an interpretation classified as undulatory-realist. Its origin is historically related to the development of Relativistic Quantum Theory where the idea of a wavefunction for the whole universe (an isolated system) has posed some difficulties to the dualist prevailing interpretations. It was Hugh Everett III who proposed an idea that in a measurement all possible outcomes of the observable are obtained simultaneously, but in parallel worlds - these worlds are complex subsystems causally connected that can be forced to interfere with one another. In this interpretation one does not recur to the postulate of wavefunction collapses, differently from all the undulatory interpretations we have previously mentioned. As a realist undulatory interpretation, the photon is again considered a wavepacket.

III. INTERPRETATIONS OF A VIRTUAL EXPERIMENT

The Mach-Zhender Interferometer (MZI) sketched in figure 1 is an experimental device totally analogous to the double slit experiment where it is possible to observe wave interference. It has been mentioned quite often in the introductory QM literature, given its usefulness as a pedagogical tool. It is composed of two half-silvered mirrors or beam splitters that transmit 50% of incident light (upper arm) and reflect the other half (lower arm), plus two usual mirrors and a screen. When a laser source is active a pattern of rings can be seen. It is relevant to recall two different regimes here: the classical regime described by the undulatory theory of light that one would obtain in any conventional teaching laboratory with a He-Ne laser, and the quantal regime, in which the beam intensity is diminished at the level of emission of a single photon at a time - a monophotonic regime. This is the regime our discussions are centered on. It is worth to say this simulator offers a much wider number of experiments with light and photons that can be discussed in a classroom. We have selected two of the most simple cases to show how interpretations allied to virtual simulations can be a powerful tool in teaching effectiveness.

Undulatory pattern

As the number of photons that have left the single photon source one at a time increases, a pattern of rings is gradually built on the screen (figure 1 on the left).

The interesting results from the QM view emerge in the limit of one photon at a time. In this case, detection is punctual and restricted to certain places over the screen. QM formalism establishes that the half-silvered mirror nearest to the source places the photon in a superposition of states - the state describing a photon running along the upper arm and the state for running along the lower arm. As the chances of being reflected or transmitted are the same, the two states are equally probable in terms of Born Postulate.

In the classic experiment (laser source), when light passes through MZI onto a screen, alternate bands of bright and dark regions are produced. These can be explained as areas in which the light waves reinforce or cancel. With a single photon source only one photon enters the interferometer each time. In performing the experiment, a photon hits the screen one at a time. However, when one totals up where the photons have hit, one will see interference patterns that appear to be the result of interfering waves even though the experiment dealt with one particle at a time.

i) Undulatory Interpretation - The photon is a wavepacket that is divided in transmitted and reflected parts in the first half-silvered mirror (mirror nearest to the single photon source). These two waves travel along upper and lower arms accumulating phases to recombine again in the second half-silvered mirror in a constructive or a destructive superposition that determines where the photon hits the screen. The detection over the screen is still punctual, as if the photon were a corpuscle, but this detection does not represent any difficult for this interpretation, since a wavefunction collapse is assumed in the process of measurement (interaction with the screen). So, the detection on the screen happens only in regions where waves satisfy the condition of constructive interference. Within this interpretation questioning the way a photon is travelling is nonsense.

ii) Complementarity Principle - The result of the virtual experiment shows a pattern of interference so the photon behaved as a wave. It does not even make sense to ask what a photon is before it hits the screen. Physics is the science of outcomes of measurement processes and speculation beyond that is not justified. The act of measuring
causes an “instantaneous” collapse of the wavefunction. This means that the measurement process randomly picks out exactly one of the two possibilities allowed for by the wavefunction.

iii) Hidden-variables - In this interpretation there is not any difficult about the fact that detection on the screen is punctual. The undulatory behavior and corpuscular characteristics are all together in the description of the experiment. In the MZI, the wavepacket is partially transmitted and partially reflected in the first half-silvered mirror. Just like in the undulatory interpretation, these waves will recombine again after they reach the second half-silvered mirror in a way that constructive or destructive interference will determine the probabilities that the photon will be detected on a particular region of the screen. However, the particle photon will follow one of the two arms according to hidden variables - this information is not accessible in the experiment. The detection will happens at those places where waves interfere constructively.

iv) Many worlds Interpretation - When a photon reaches the first half-silvered mirror the world splits into two identical new ones - one with the photon travelling in the upper arm while in the other, the photon goes along the lower arm. Observer in one world ignores the simultaneous existence of the other which is unaccessible unless there are interference of one with another. For that to happen, all atoms, subatomic particles, photons and other degrees of freedom have to be in the same state, meaning that they have to be in the same place or to have a significant superposition. This superposition condition is made through the second half-silvered mirror. So, after a passage through the second mirror, a photon will be detected only in regions of constructive interference on the screen.

Corpuscular behavior
With a detector at the upper arm, there is a click in the detector or a photon hitting the screen. After many photons have gone through the interferometer the pattern built up on the screen is corpuscular (figure 4 on the right).

i) Undulatory Interpretation - The photon that enters the MZI splits into a transmitted wave that follows the upper arm and a reflected wave that follows the lower arm, so that its behavior is described by a non-localized wave function which is travelling through both arms at the same time. However, a measurement forces the wavepacket to collapse and the detection happens in the detector where a collapse of the wavefunction is likely.

ii) Complementarity Principle - In the virtual experiment, a photon is detected in the counter or it hits the screen. Then, as the result of the experiment shows, the photon behaved like a particle that had been transmitted or reflected in the first mirror with equal probabilities.

iii) Hidden-variables - In this interpretation the wave-guide or associated wave that travels with the photon divides itself into a transmitted and a reflected part in the first half-silvered mirror but the photon follows one of the two trajectories. The wave-guide dictates where the photon will be detected. Again, there are some difficulties in explaining a corpuscular pattern without taking into account the peculiarities of the measurement process or wavefunction non-local collapses.

iv) Many worlds Interpretation - In this interpretation, the world is split into two when a photon reaches the first mirror. In this way, if the photon is detected in one of the arms in one world, it hits the screen in a second world, but this result in unaccessible to the former observer, just as the photon hitting the detector is a result unaccessible to the second observer. The photon is still a wavepacket, but no interference fringes are observed. The addition of a detector in one of the arms destroys the perfect match of all degrees of freedom that should be in superposition to show interference fringes.

IV. FINAL REMARKS

The strangeness of QM instigates questions that varies from a lack of a proper language - words that have yet to be invented - to describe microscopical scale behavior to the need of a non-classical logic - a quantum logic. Exclusively undulatory interpretations show some difficulties in explaining corpuscular phenomena just like a exclusively corpuscular interpretation should face difficulties in explaining an interference pattern. The complementarity interpretation combines both characteristics - undulatory and corpuscular - but in a way that one excludes the other. Although the many worlds interpretation gets rid of wavefunction collapses, it implies the existence of parallel universes that are connected only weakly through interference phenomena.

It has to be stressed that our point here is not to be in favor of one particular interpretation over another but to advocate that more conceptual and qualitative approaches built on the plurality of interpretations are pedagogical tools in the introductory teaching of QM. Besides the fact that for many students the formalism without some interpretation remains abstract mathematics that is very unlikely to remain in the long run, it is also a relief for many students to find out that their own epistemological views may be shared by many famous scientist. Recent polls in classrooms (motivated by) have shown that students voluntarily join themselves in groups in support of one or another interpretation. The concepts they have assimilated (or not) are evidenced when groups debate in favor of their choices. Also, in favour of a more conceptual and qualitative approach in introductory courses, is the fact that students meet in class themes like parallel universes that are often in the media or the worldweb and are not or are
FIG. 1: Virtual Mach-Zhender Interferometer using a single photon source (free code). On the left, an undulatory pattern is clearly seen after 3,419 photons were emitted. On the right, with an additional detector in the upper arm, 6,415 photons built up a corpuscular pattern. 3,184 photons were detected and 32 hit the screen.

scarcely presented in textbooks. The discussion of interpretations allied to a virtual experiment of the photon in an MZI is an important contribution to the literature devoted to initial and continued formation of Physics teachers. This is a current research project in Education of Contemporary Physics and Epistemological Foundations. It is partially supported by CNPq. We thank SR Dahmen for English improvements.

1 Zeilinger, A., “On the Interpretation and Philosophical Foundation of Quantum Mechanics”, Vastakohtien todellisuus, (1996) Helsinki University Press.
2 Mermin, N. D., “From Chits to Qbits: Teaching computer scientists quantum mechanics”, Am. J. Phys., 71 (2003) 23–30.
3 Grau, B. C., “How to Teach Basic Quantum Mechanics to Computer Scientists and Electrical Engineers”, IEEE Transactions on Education, 47 (2004) 220–226.
4 Olsen, R. V., “Introducing quantum mechanics in the upper secondary school: a study in Norway”, International Journal of Science Education, 24 (2002) 565–574.
5 Michelini, M., et al., “Proposal for quantum physics in secondary school”, Physics Education, 35 (2000) 406–410.
6 Kalkanis, G., Hadzidakate, P., Stavrou, D., "An Instructional Model for a Radical Conceptual Change Towards Quantum Mechanics Concepts", Science Education, 87 (2003) 257–280.
7 Thacker, B. A., “Recent advances in classroom physics”, Reports on Progress in Physics, 66 (2003) 1833–1864.
8 Deutsch, D., The Fabric of Reality, Penguin Books (1997).
9 Jammer, M., The Philosophy of Quantum Mechanics. A Wiley-Interscience Publication, USA, (1974).
10 Zeilinger, A., “A Foundational Principle for Quantum Mechanics”, Foundations of Physics, 29(1999) 631–643.
11 Tegmark, M., “The Interpretation of Quantum Mechanics: Many Worlds or Many Words?”, Fortschr. Phys., 46 (1998) 855–862.
12 Fuchs, C., Peres, A., “Quantum theory needs no ‘interpretation”, Physics Today, 53 (3) (2000) 70–71.
13 Mermin, N. D., “Could Feynman Have Said This?”, Physics Today, 57 (5) (2004) 10–11.
14 Bastos Filho, J.B., “Epistemological Problems of the Reality, Comprehensibility and Causality in Quantum Theory”, Revista Brasileira de Ensino de Física, 25 (2) (2003) 125–147 (in Portuguese).
15 Lising, L., Elby, A., “The impact of epistemology on learning: A case study from introductory physics”, Am. J. Phys., 73 (2004) 459–463.
16 Müller, R., Wiesner, H., “Teaching quantum mechanics on an introductory level”, Am. J. Phys., 70 (2002) 200–209. (simulator in [http://www.physik.uni-muenchen.de/didaktik/Computer/interfer/interfere.html](http://www.physik.uni-muenchen.de/didaktik/Computer/interfer/interfere.html))
17 Arndt, M. et al., “Wave-particle duality of C60”, Nature, 401 (1999) 680–682.
18 Eisberg & Resnik, Quantum Physics of Atoms, molecules, solids, nuclei and particles, (1974) John Wiley & Sons.
19 Bunge, M., “Twenty-five centuries of quantum physics: From Pythagoras to us, and from subjectivism to realism”, Science & Education, 12 (2003) 445–466.
20 Pessoa Jr., O., “Interferometry, interpretation, and intuition: a conceptual introduction to quantum physics”, Revista Brasileira de Ensino de Física, 19 (1) (1997) 27–48. (in Portuguese)
21 Pessoa Jr., O., in Conceitos de Física Quântica, Livraria da Física (2003) São Paulo (in Portuguese).
22 Tegmark, M., Wheeler, J. A., “100 Years of Quantum Mysteries”, Scientific American, 284 (2001) 68–75.