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Article

Quantum Mechanics: Philosophy & Interpretations

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Abstract

We discuss and review the philosophy and interpretations of quantum mechanics.Technically, QM is a set of mathematically formulated prescriptions that serve for calculations of probabilities of different measurement outcomes. The most serious problem has been the inability to demarcate with mathematical precision just where microscopic processes leave off and where macroscopic processes begin. The fact that observers report definite outcomes of experiments has, therefore, been a mystery. Explanations of this mystery have supplemented QM with a wide variety of additional assumptions

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1 What are the problems?

QM was initially formulated in what appeared to be two fundamentally distinct ways, as Matrix mechanics, and Wave mechanics with the function ψ. The former developed by Heisenberg, Born and Jordan and the latter by Schrödinger. Dirac, Jordan, Pauli, and Schrödinger subsequently provided arguments for the equivalence of these two approaches. From a technical point of view, QM is a set of mathematically formulated prescriptions that serve for calculations of probabilities of different measurement outcomes. The calculated probabilities agree with experiments. But most serious problems that QM would have to face was its inability to demarcate with mathematical precision just where microscopic processes leave off and where macroscopic processes begin[2]. This ambiguity has played an important role in the debate since 1930 in QM. Many of the solution proposed to rescue the formalism (from Bohr to von Neumann, and Wigner to more recent attempts) **are based on the possibility of setting this line of demarcation**

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[2] Since the pioneering work of von Neumann, the observer of a quantum state $|S\rangle$ has been treated as a physical system that becomes entangled with $|S\rangle$. The fact that observers report definite outcomes of experiments has, therefore, been a mystery. Explanations of this mystery have supplemented QM with a wide variety of additional assumptions, **but have not questioned the fundamental premise of system: observer entanglement**. Fields (Fields,2011), proposed in his paper (as fundamental assumption for QM) to consider the "observer" not as a system, but as a functional requirement. Treating observation as a functional requirement naturally leads to the concept of a minimal observer, a concept fully formed by classical automata theory over 50 years ago. A minimal observer functions in a quantum environment exactly as would be expected for a system with finite observational and memory resources.

at any point one pleases. The explicit consideration of such interpretation of the quantum formalism can be historically traced back at least to Einstein's consideration at the 1927 Solvay conference of two alternative understandings of quantum theory, which he called "interpretation I" (his own proto-interpretation, in which the quantum description is an incomplete one for the specification of state for individual systems) and "interpretation II" (Bohr's interpretation, in which the quantum description is understood to be as complete a description of quantum phenomena as can be given). This distinction reflects Einstein's philosophical preoccupations and a fundamental disagreement with Bohr. Mittelstaedt has identified, in addition to the Copenhagen interpretation, three classes of interpretation that he has identified as probably the most important:

- the Minimal interpretation, which "does not assume that measuring instruments are macroscopic bodies subject to the laws of classical physics. Instead they are considered proper quantum systems with respect to measuring instruments. Replaces Bohr's position with von Neumann's approach but on the other hand "refers to observed data only merely the values of a 'pointer' of a measurement apparatus"
- the Realist interpretation, which is similar to the minimal interpretation but "is concerned not only with measurement outcomes but also with the properties of an individual system"
- the 'Many worlds' interpretation which, like the previous two, considers QM to be universal but "avoids any additional assumption that goes beyond the pure formalism, even the very few weak assumptions that are made in the minimal interpretation"

A more recent illustration of the desire to consider the quantum formalism 'self-interpreting' is the information-focused approach vigorously advocated by Fuchs and Peres (Interpretation without interpretation for QM, 2000). They affirm:

> "*The thread common to all the nonstandard 'interpretations' is the desire to create a new theory with features that correspond to some reality independent of our potential experiments. But, trying to fulfill a classical world view by encumbering QM with hidden variables, multiple worlds, consistency rules, or spontaneous 'collapse', without any improvement in its predictive power, only gives the illusion of a better understanding. Contrary to those desires, quantum theory does not describe physical reality. What it does is provide an algorithm for computing probabilities for the macroscopic events ('detector clicks') that are the consequence of our experimental interventions. This strict definition of the scope of quantum theory is the only interpretation ever needed, whether by experimenters or theorists.*"

This position is today called: Radical Bayesian interpretation. The fact that Radical Bayesianism has appeared in the era of quantum information science is not accidental. It explicitly interprets quantum theory almost entirely as a theory of information rather than of physical objects.The revolutionary nature of quantum theory, we think is not linked to the interpretation of theory but at the observation of violations of Bell-type inequalities. This leads physicists to seek new ways of interpreting QM. Independently from philosophical position, we agree with Maudlin's words (Maudlin, 2002):

> ”*Realism in philosophy of science is generally contrasted with instrumentalism or empiricism, which views assert that one can have no grounds to believe that the unobservable ontology of a theory is accurate. In this sense, theories are neither realistic nor non-realistic, only interpretations of (or better: attitudes toward) theories.[....] The beauty of Bell's theorem, of course, is that it is insensitive to the details of the theory suggested: any theory which can save the phenomena (if the phenomena include claims about the behavior of macroscopic devices located in space and time) must be non-local. Even a classical instrumentalist would be forced to accept non-locality.*”

The problem, as we have seen, is that the standard interpretation of QM, tells us nothing about the underlying reality. It provides just the essential mathematical formalism in order to make extremely accurate predictions, to compute the probabilities of different outcomes. The state vector represents our knowledge of the system, not its physics.
The basic support of the standard interpretation is that ”measurement process” is an interaction between system and apparatus. This interpretation divides the world in apparatus and system but do not tell us nothing about these two ”abstracts” concepts. More in details, the position regarding the measurement theory can be summarizing as following:

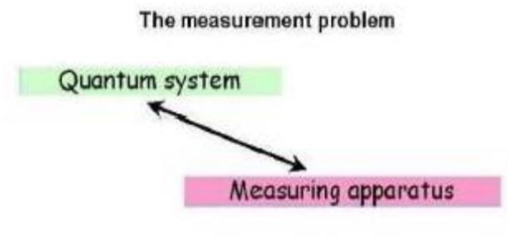

Figure 1: What is a measurement apparatus?

- Measurement is an interaction between system and apparatus.
- Measurements do not uncover some preexisting. physical property of a system. There is no objective property being measured.
- The record or result of a measurement is the only objective property.
- Quantum mechanics is nothing more than a set of rules to compute the outcome of physical tests to which a system may be subjected.

This interpretation solve most pragmatic problems but does not solve the measurement problem, how and why occurs the collapse of the wave function during the measurement process. The famous Schrödinger's cat paradox is exactly this. Why the measurement apparatus behave classically? After all it is constituted of particles that are governed by QM rules. Where is the limit between quantum and classical world? Next considerations put in evidence the problem. Consider a two-state microsystem whose eigenfunctions are labelled by ψ_+ and ψ_-. Furthermore, there is a macrosystem apparatus with eigenfunctions ϕ_+ and ϕ_- corresponding to an output for the microsystem having been in the ψ_+ and ψ_- states, respectively. Since prior to a measurement we do not know the state of the microsystem, it is a superposition state given by

$$\psi_0 = \alpha\psi_+ + \beta\psi_-, \qquad |\alpha|^2 + |\beta|^2 = 1. \tag{1.1}$$

Now, according to the linearity of Scrödinger's equation, the final state obtained after the interaction of the two systems is

$$\Psi_0 = (\alpha\psi_+ + \beta\psi_-)\phi_0 \longrightarrow \Psi_{out} = \alpha\psi_+\phi_+ + \beta\psi_-\phi_- \tag{1.2}$$

where it is assumed that initially the two systems are far apart and do not interact. It is obvious that, the state on the far right side of the last equation does not correspond to a definite state for a macrosystem apparatus. In fact, this result would say that the macroscopic apparatus is itself in a superposition of both plus and minus states. Nobody has observed such macroscopic superpositions. This is the so-called measurement problem, since the theory predicts results that are in clear conflict with all observations. It is **at this point** that the standard program to resolve this problem invokes the reduction of wave packet upon observation, that is,

$$\alpha\psi_+\phi_+ + \beta\psi_-\phi_- \longrightarrow \begin{cases} \psi_+\phi_+, & P_+ = |\alpha|^2; \\ \psi_-\phi_-, & P_- = |\beta|^2. \end{cases} \tag{1.3}$$

Various attempts (interpretations) to find reasonable explanation for this reduction are at the heart of the measurement problem.

In relation to the standard interpretation, de Muynck (de Muynck, 2002) fix some fundamental points (see next table and figure): According to de Muynck (de Muynck, 2002) scheme, in the first realist case (a)QM is thought to describe microscopic reality most in the same way classical mechanics is generally thought to describe macroscopic reality.

Positive features	**Negative features**
+1. pragmatism	-1. pragmatism
+2. crucial role of measurement	-2. confusion of preparation and measurement
	-3. classical account of measurement
	-4. completeness claims
	-5. ambiguous notion of correspondence
	-6. confused notion of complementarity

In the empiricist case b) state vector and density operator are thought to correspond to preparation procedures, and quantum mechanical observables correspond to measurement procedures and the phenomena induced by a microscopic object in the macroscopically observable pointer of a measuring instrument. We mention, here, another interpretation of QM called Many worlds (MWI) or relative state (see chap.3.7), this interpretation has no collapse. All possible outcomes co-exist in different branches of the 'universe'.These different branches cannot interfere or communicate in order to protect the theory itself from producing illogical situations. This theory 'resolves' the cat paradox assuming that the cat is alive in one branch and dead in the other. Also all the observers in these branches are in the states that agree with their observation of the

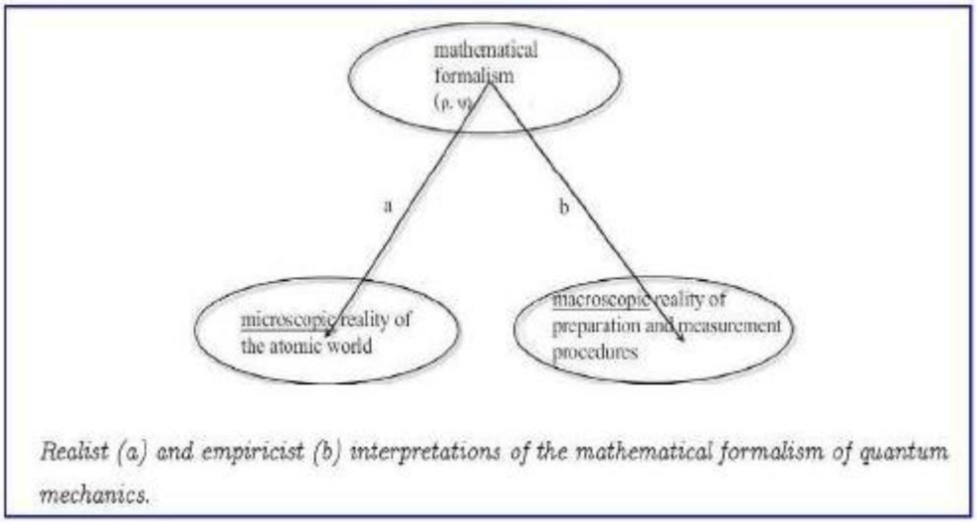

Figure 2: Realist (a) and empiricist (b) interpretations of the mathematical formalism of quantum mechanics.

state of the cat. Many worlds interpretation is suitable to those who try to describe the whole Universe with a wavefunction, assuming no **external observers**,and there have been serious efforts about this program.
As we have seen above, recently, with the development of quantum information theory, several scientists have given to the information a fundamental role in the description of the Nature. All these approaches (quantum theoretic description of physical systems) start in general from the assumption that we live in a world in which there are certain constraints on the acquisition, representation, and communication of information. They play on the ambiguous ontology of quantum states. They affirm that quantum states are merely states of knowledge (or of belief); this idea has led to the claim that quantum theory "needs no interpretation" (Fuchs, 2002). More in details, the field of quantum information theory opened up and expanded rapidly, QE[3]began to be seen not only as a puzzle, but also as a resource which can yield new physical effects and techniques. New insight into the foundations of quantum physics, suggesting that information should play an essential role in the foundations of any scientific description of Nature. The primitive role of the information seem to explain, according to some authors, the deep nature of physical reality. In this context, the description of a state of a QS (in this case, the measurement is **not** a physical process). The quantum state is a construct of the observer and not an objective property of the physical system. Some radical positions (Fuchs, 2002) claims that the nature of reality can be explained as subjective knowledge. On the other hand, others authors have argued that quantum theory is fundamentally just a theory of relations or of correlations**?**. For instance, the relational approach to probability suggest that probability should be thought of as a relation between a present and a possible future.

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[3] Entanglement recently come to play an essential role for physicists in their development of quantum information theory, moreover the entanglement of two or more states seem to be a basis for the discussion of the possible holism in quantum physics.

2 Interpretations of QM

The problem linked to the collapse postulate (chap.2) is given in this term: we have to consider on the one hand the temporal evolution of the wave function **U**, provided by the rigorously causal, deterministic and time-reversal Schrödinger equation, and on the other the reduction processes of the state vector, that we call **R**. Different standpoints are possible about the role of the processes **R** in QM. We will analyze most important positions. We can individuate three main standpoints about **R**:

1. The wave function contains the available information on the physical world in probabilistic form; the wave function is not referred to an "objective reality", but due to the intrinsically relational features of the theory, only to what we can say about reality. Consequently, the "collapse postulate" is simply an expression of our peculiar knowledge of the world of quantum objects; (**this is the group of Copenhagen and neo-Copenhagen (de Muynck, 2002) interpretations**[4])

2. The wave function describes what actually[5]happens in the physical world and its probabilistic nature derives from our perspective of observers.[**the group of Everett, (Everett, 1959), Deutsch (Deutsch, 1985), Bohm (Bohm, 1951) theories**]

3. The wave function partially describes what happens in the physical processes; in order to comprehend its probabilistic nature and the postulate R in particular, we need a theory connecting **U** and **R**. (This view includes all those theories which tend to reconcile U with R by introducing new physical process: [(Penrose,2005);(GRW, 2005)theories]

3. The wave function describes and represents an individual agent's subjective degrees of belief. In few words, the physical reality is a subjective information. (**Informational approaches group(Fuchs, 2002)**)

The figure 3 put in evidence the measurement problem through Schrödinger's cat again. The leftmost panel gives the standard Schrödinger cat story. There is a single observer, to be called Ob1, outside the box. Before Ob1 opens the window to look, the cat is in a superposition of being both alive and dead. By opening the window and looking, Ob1 "collapses the wave-packet" so that the cat is now in a unique state of being alive or dead. The story gets more interesting if we place O1 in a second box as shown in the second panel. If we, the second observer, are not looking, then O1 is in a superposition of states seeing an alive cat and seeing a dead cat. Once we make an observation, Ob1 collapses to one state or the other. The third panel removes the split even further, placing it in our brain.

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[4] One of the most imposed points of view in the physicist community is to conclude that QM is merely an algorithm that provides the right answers to our questions; i.e. QM should be taken solely as an instrumentalistic theory about our observations.

[5] Realism is the assumption that there exists an objective external world independent of our perception of it. In a realistic physical theory, one thus requires a clear ontology of the basic "objects" used for example fields which are really fields, particles which are really particles, etc. Locality means that these objects are defined locally with no instantaneous action at a distance. Local realism may thus be defined by the combination of the principle of locality with the assumption that all objects must objectively have their properties already before they are observed. The paradigmatic example is that of local hidden variables.

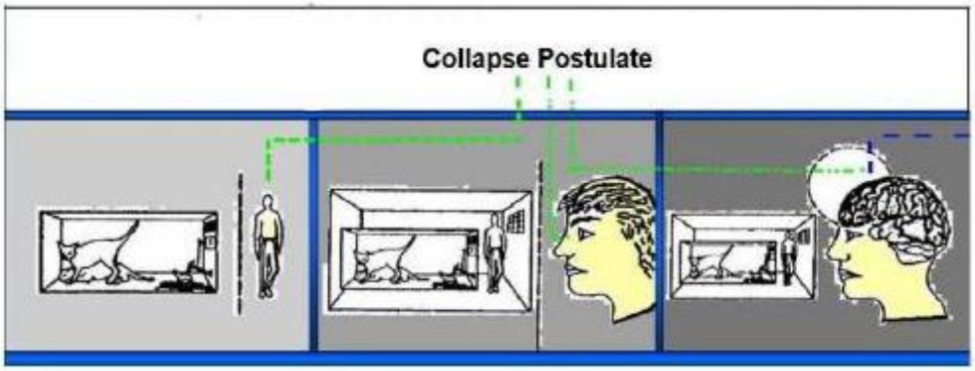

Figure 3: Measurement Problem.

2.0.1 A possible physical reality inferred from measurement process

We try to do a theoretical speculation on a possible relationship between the objectivity/subjectivity nature of measurement process and the underlying physical reality inferred. We build the following scheme:

Measurement process	Physical reality
1. ontic measurement ⟶	of ontic reality
2. ontic measurement ⟶	of epistemic reality
3. epistemic measurement ⟶	of ontic reality
4. epistemic measurement ⟶	of epistemic reality

Considerations. First case, is a realist position (without determinism), the second, a non-completely idealistic position, like the standard interpretation, last case is a pure idealistic view, third position is very intriguing, we do an epistemic measurement process but of ontic reality probably close d'Espagnat's conception of veiled reality(d'Espagnat 2003), a position supported from the discovery of nonseparability in QM. According d'Espagnat the ”veiled reality” is supported from the discovery of nonseparability in QM, he introduced the concept of the ”veiled reality” which refers to something that cannot by studied by traditional scientific methods. d'Espagnat defines his philosophical view as ”open realism”; existence precedes knowledge; something exists independently of us even if it cannot be described.PART 1: Formal Structure and Interpretations of Quantum Mechanics

We start with a basic philosophical question that involves physics and epistemology: can we explain what the world is through a fundamental physical theory? This question corresponds to the historic disagreement among scientists and epistemologists concerning how to regard physical theories to which people commonly refer as the realist/antirealist debate. The position of the antirealist is the one according to which we should not believe that physics reveals to us something about reality but rather we should be content with physics to be, for example, just empirically adequate. In contrast, the realist is strongly inclined to say not only that physics tells us about reality, but also that it is our only way to actually do metaphysics. In few words, the question is: is there an ontology? We are interested to show through a logical pathway the existence of a possible ontology in Nature, assuming two basic hypotheses which the Greek

thinkers made about Nature: 1) the existence of a real external world, 2) this external world is accessible through the existence of laws of nature(the reality is intelligible).
The abstract mathematical structure of the Lorentz transformations was deduced through simple physical principles. Thanks to the existence of these physical principles we do not have a significant debate on the interpretation of the theory of special relativity. The formulation of QM, on to the contrary, is based on a number of rather abstract axioms without a clear motivation for their existence (see the following Primas' synthesis, 2003):

1. Quantum mechanics refers to individual objects.
2. The probabilities of quantum mechanics are primary.
3. The placement of the cut between observed object and the means of observation is left to the choice of the experimenter.
4. The observational means are to be described in classical terms.
5. The act of observation is irreversible.
6. The quantum jump is a transition from the potentially possible to the actual.
7. Complementary properties cannot be revealed simultaneously.
8. Pure quantum states are objective but not 'real.'

Despite its success, the absence of elementary physical principles has determined a broad discussion about the interpretation of the theory. For this reason, and not only, Bell called the ordinary QM with the abbreviation FAPP (for all practical purposes). We will start presenting in this chapter, first, the basic formalism and postulates of QM, and will continue our overview by presenting main features of historical interpretations of QM. Historically QM began with two mathematical formulations, Heisenberg's Matrix Mechanics and Schrödinger's Wave Mechanics, and these were later found by Schrödinger to be mathematically equivalent. John von Neumann, in 1926, realized that a quantum system (QS) could be represented as a vector in Hilbert space, which lead to his development of an axiomatized formulation of quantum theory (von Neumann, 1932). The central feature of quantum theory is the wavefunction (ψ), which represents the state of a particle or system. Schrödinger tried a realist interpretation of ψ. Schrödinger's initial conception of the wavefunction was an extended volume charge (the "mechanical field scalar") that was centered on the atom. This interpretation had several problems, the most important of which was the continued experimental support for the notion that the electron was localized over a very small region of space, as if a point. For this and other reasons, Schrödinger later rejected his model (and its interpretations) and continued searching for a better theory.

In 1926-27, Louis de Broglie offered an interpretation he called the "double-solution" in which a particle is a singularity in a wave field (Jammer, 1974). Here, the particle retains much of its classical nature, but it is "guided" by an extended pilot wave given by Schrödinger's formalism, and thus subject to wave effects such as diffraction. This synthesis of wave and particle views would later be expanded upon by both David Bohm and John Bell. Another major class of interpretations are those that assume the formalism of quantum theory but reject that the wavefunction offers a complete description of a QS. Notably the theory of David Bohm postulates hidden variables that guide a QS according to deterministic laws (Bohm, 1951). Although Bohm's work presented a different explanation for quantum phenomena, it was criticized for offering no predictive value outside of the standard interpretation of quantum theory. However, Bohm argued that on a small enough scale, his interpretation might offer predictable discrepancies (Jammer, 1974). As we know, the most widely accepted interpretation of the formalism is Born's statistical interpretation, published in 1926. Born sought to account for the empirical results that the electron was a localized particle (corpuscle) but otherwise wanted to take advantage of Schrödinger's formalism. As a result, he interpreted the wavefunction as the probability density of finding a particle within a specific region. Standardly interpreted, particles do not possess discrete dynamical properties such as position, momentum, or energy, until the particle is measured. The probability of measuring a particular value is given by the statistical interpretation of the wavefunction, i.e. it is normalized and the probability is determined by the resulting distribution. Upon measurement, the wave function is said to collapse such as to yield a particular value of the measured dynamical property. Some problems arise within this interpretation respect a scientific realism view. The central premise of scientific realism is the existence of an external world independent of consciousness. Yet, the statistical interpretation of the wavefunction poses a problem, in that it offers no description of the state of a system before it is measured. It merely gives statistical information regarding the result of a measurement on the system. A scientific realist is prone to believing that a concrete state must exist before measurement. What actually constitutes this state is open to some discussion, but a realist will typically hold that a singular physical state exists; and that an experiment measures that state. Another serious problem for scientific realism is the phenomenon of quantum entanglement (QE). Such nonlocal interactions are not prima facie worrisome for most scientific realists. The implications are troubling when it is recognized that special relativity is the limiting velocity for any kind of causal propagation, and nonlocality violates special relativity. But the form of interaction between these particles is rather unlike other forms of causal contact, since information cannot be sent from one particle to another. The behavior of the particles is statistical, but correlated such that they are believed to interact during measurement. Thus, some hypothesize that this is an allowed form of superluminous interaction (Griffiths, 2003). In this field today, there are many works with the objective to find a causal correlation between two entangled particles. We argue in this thesis that is not possible to reintroduce the classical causality.

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