

## Review Article

# Interpretations of Quantum Mechanics: A Critical Survey

Michele Caponigro\*

### Abstract

This brief survey analyzes the epistemological implications about the role of observer in the interpretations of Quantum Mechanics. As we know, the goal of most interpretations of quantum mechanics is to avoid the apparent intrusion of the observer into the measurement process. In the same time, there are implicit and hidden assumptions about his role. In fact, most interpretations taking as ontic level one of these fundamental concepts as information, physical law and matter bring us to new problematical questions. We think, that no interpretation of the quantum theory can avoid this intrusion until we do not clarify the nature of observer.

**Key Words:** quantum mechanics, interpretation, critical survey.

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\* Michele Caponigro, Ph.D., Epistemology of Complexity, Bergamo University. E-mail: [michele.caponigro@unibg.it](mailto:michele.caponigro@unibg.it) Note: This work was completed in November 2008 (See <http://arxiv.org/abs/0811.3877> )

## I. QUANTUM THEORY: BRIEF OVERVIEW

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 satisfied 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.

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 Quantum Mechanics (QM), on the contrary, is based on a number of rather abstract axioms without a clear motivation for their existence. The problem about quantum mechanics does not lie on its effectivity, but on its interpretation. Any attempt to interpret quantum mechanics tries to provide a definite meaning to issues such as realism, completeness, local realism and determinism. 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). The standard interpretation of quantum mechanics, attempts, as much as possible, to give an ontological model of physical systems using the concept of the quantum state. However, the interpretation does not fully succeed in giving such a model, for this reason one solution to this problem is to abandon any attempt at an ontological model and to put quantum mechanics on a purely epistemological footing (the context of informational approaches). We believe that a possible ontological model arises by the application of formalism of quantum mechanics to the entire universe (including observers).

We will start next sections presenting, first, the basic formalism and postulates of QM, and then overviewing some relevant historical interpretations of QM.

## II. POSTULATES OF QUANTUM MECHANICS.

Quantum mechanics is a mathematical model of the physical world that describes the behavior of quantum systems. A physical model is characterized by how it represents *physical states, observables, measurements, and dynamics* of the system under consideration. A *quantum system* is a number of physical degrees of freedom in a physical object or set of objects which is to be described quantum mechanically. The *physical state* (standard view) of a system is a mathematical object which represents the knowledge we have about the system, and from which all measurable physical quantities relating to the system can be calculated. A special class of quantum states are called the *pure states*. The dimension of  $\mathcal{H}$  is a property of the degrees of freedom being described. For example, the state of a spin-half particle lives in a two-dimensional Hilbert space, such systems is called a quantum bit or *qubit*, and its basis vectors are labelled  $|0\rangle$  and  $|1\rangle$ . Pure states are

sometimes called *state vectors*. We will see that more general states cannot be described by a simple state vector, but will require a *density matrix*. The traditional way in which measurements on quantum systems are described is in terms of *observables*. Observables are Hermitian operators which correspond to physically measurable quantities such as energy, momentum, spin, etc. Any Hermitian operator has a complete set of real eigenvalues corresponding to orthogonal eigenspaces.

#### A. Basic formalism and postulates of quantum mechanics.

A quantum description of a physical model is based on the following concepts:

A *state* is a complete description of a physical system. Quantum mechanics associates a ray in *Hilbert space* to the physical state of a system.

- Hilbert space is a complex linear vector space. In Dirac's ket-bra notation states are denoted by *ket vectors*  $|\psi\rangle$  in Hilbert space.
- Corresponding to a ket vector  $|\psi\rangle$  there is another kind of state vector called *bra vector*, which is denoted by  $\langle\psi|$ . The *inner product* of a bra  $\langle\psi|$  and ket  $|\phi\rangle$  is defined as follows:

$$\begin{aligned}\langle\psi|\{|\phi_1\rangle+|\phi_2\rangle\}&=\langle\psi|\phi_1\rangle+\langle\psi|\phi_2\rangle \\ \langle\psi|\{c|\phi_1\rangle\}&=c\langle\psi|\phi_1\rangle\end{aligned}\tag{1}$$

for any  $c \in \mathbb{C}$ , the set of complex numbers. There is a one-to-one correspondence between the bras and the kets. Furthermore

$$\begin{aligned}\langle\psi|\phi\rangle&=\langle\phi|\psi\rangle^* \\ \langle\psi|\psi\rangle&>0\text{ for }|\psi\rangle\neq 0\end{aligned}\tag{2}$$

- The state vectors in Hilbert space are normalized which means that the inner product of a state vector with itself gives unity, i.e.,

$$\langle\psi|\psi\rangle=1\tag{3}$$

- Operations can be performed on a ket  $|\psi\rangle$  and transform it to another ket  $|\chi\rangle$ . There are operations on kets which are called *linear operators*, which have the following properties. For a linear operator  $\hat{a}$  we have

$$\begin{aligned}\hat{\alpha} \{ |\psi\rangle + |\chi\rangle \} &= \hat{\alpha} |\psi\rangle + \hat{\alpha} |\chi\rangle \\ \hat{\alpha} \{ c |\psi\rangle \} &= c \hat{\alpha} |\psi\rangle\end{aligned}\tag{4}$$

for any  $c \in \mathbb{C}$ .

- The sum and product of two linear operators  $\hat{\alpha}$  and  $\hat{\beta}$  are defined as:

$$\begin{aligned}\{ \hat{\alpha} + \hat{\beta} \} |\psi\rangle &= \hat{\alpha} |\psi\rangle + \hat{\beta} |\psi\rangle \\ \{ \hat{\alpha} \hat{\beta} \} |\psi\rangle &= \hat{\alpha} \{ \hat{\beta} |\psi\rangle \}\end{aligned}\tag{5}$$

Generally speaking  $\hat{\alpha} \hat{\beta}$  is not necessarily equal to  $\hat{\beta} \hat{\alpha}$ , i.e.  $[\hat{\alpha}, \hat{\beta}] \neq 0$

- The *adjoint*  $\hat{\alpha}^\dagger$  of an operator  $\hat{\alpha}$  is defined by the requirement:

$$\langle \psi | \hat{\alpha} \chi \rangle = \langle \hat{\alpha}^\dagger \psi | \chi \rangle\tag{6}$$

for all kets  $|\psi\rangle, |\chi\rangle$  in the Hilbert space.

- An operator  $\hat{\alpha}$  is said to be *self-adjoint* or *Hermitian* if:

$$\hat{\alpha}^\dagger = \hat{\alpha}\tag{7}$$

Hermitian operators are the counterparts of real numbers in operators. In quantum mechanics, the dynamical variables of physical systems are represented by Hermitian operators. These operators are usually called *observables*.

**Postulates of quantum mechanics:**

Quantum theory is based on the following postulates:

**Postulate 1:** To any physical isolated system is associated a complex vector space, where is define an inner product (Hilbert space) which is called state space of the system. The system is completely described by a state vector.

*This postulate give us the universal mathematical model of any physical system: a vector Hilbert space on the complex numbers[1].*

**Postulate 2:** The evolution of a closed quantum system is described by an unitary transformation. That is, the state,  $|\psi(t)\rangle$  of the system at time  $t$  is related to the state  $|\psi(t_0)\rangle$  a time  $t_0$  by a unitary operator  $U$  which depends only on the time  $t$  and  $t_0$  :  $|\psi(t)\rangle = U |\psi(t_0)\rangle$ .

*The second postulate describes the temporal evolution of a closed physical system.*

**Postulate 3:** *This postulate is about the "quantum measurement:*

- Mutually exclusive measurement outcomes correspond to orthogonal *projection operators*  $\{ \hat{P}_0, \hat{P}_1, \dots \}$  and the probability of a particular outcome  $i$  is  $\langle \psi | \hat{P}_i | \psi \rangle$ . If the outcome  $i$  is attained the (normalized) quantum state after the measurement becomes:

$$\frac{\hat{P}_i |\psi\rangle}{\sqrt{\langle \psi | \hat{P}_i | \psi \rangle}} \tag{8}$$

Measurement made with orthogonal projection operators  $\{\hat{P}_0, \hat{P}_1, \dots\}$  is called *projective measurement*.

**Postulate 4:** The state space of a composite physical system is the tensor product of the state spaces of the component physical systems. Moreover, if we have a quantum system  $H_i, i = 1, \dots, n$  and system  $H_i$  is prepared in the state  $|\psi_i\rangle$ , then the joint state of the total system is:  $|\psi_1\rangle \otimes |\psi_2\rangle \otimes \dots \otimes |\psi_n\rangle = H_1 \otimes \dots \otimes H_n$ .

*Last postulate formalizes the interaction of many physical systems with the combination of different Hilbert spaces coming to a unique Hilbert space.*

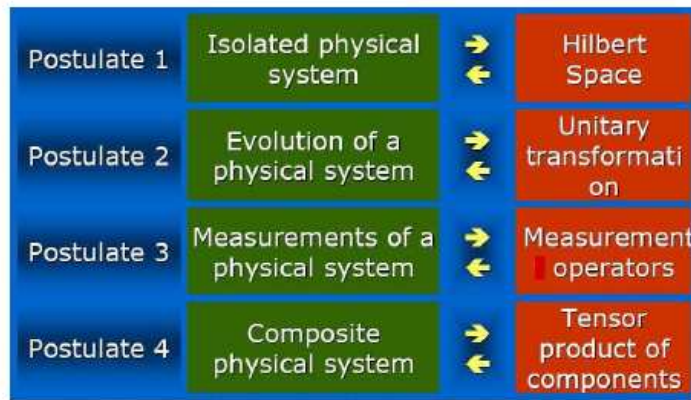


FIG. 1: Summary of Postulates.

## B. Quantum Entanglement, Bell Inequality

The phenomenon of quantum entanglement is widely considered to be central to the field of quantum computation and information. This phenomenon can be traced back to Einstein, Podolsky and Rosen (EPR)'s famous paper [2] of 1935. EPR argued that quantum mechanical description of *physical reality* can not be considered *complete* because of its rather strange predictions about two particles that once have interacted but now are separate from one another and do not interact. Quantum mechanics predicts that the particles can be *entangled* even after separation. Entangled particles have correlated properties and these correlations are at the heart of the EPR paradox. Mathematically, the entanglement is described as follows. For a system that can be divided into two subsystems quantum mechanics associates two Hilbert spaces  $\mathcal{H}_A$  and  $\mathcal{H}_B$  to the subsystems. Assume that  $|i\rangle_A$  and  $|j\rangle_B$  (where  $i, j = 1, 2, \dots$ ) are two complete orthonormal basis sets for the Hilbert spaces  $\mathcal{H}_A$  and  $\mathcal{H}_B$ , respectively. The tensor product  $\mathcal{H}_A \otimes \mathcal{H}_B$  is another Hilbert space that quantum mechanics associates with the system consisting of the two subsystems. The tensor product states  $|i\rangle_A \otimes |j\rangle_B$  (often written as  $|i\rangle_A |j\rangle_B$ ) span the space  $\mathcal{H}_A \otimes \mathcal{H}_B$ .

Any state  $|\psi\rangle_{AB}$  of the composite system made of the two subsystems is a linear combination of the product basis states  $|i\rangle_A |j\rangle_B$  i.e.:

$$|\psi\rangle_{AB} = \sum_{i,j} c_{ij} |i\rangle_A |j\rangle_B \quad (9)$$

where  $c_{ij} \in \mathbb{C}$ . The normalization condition of the state  $|\psi\rangle_{AB}$  is  $\sum_{i,j} |c_{ij}|^2 = 1$ . The state  $|\psi\rangle_{AB}$  is called *direct product (or separable) state* if it is possible to factor it into two normalized states from the Hilbert spaces  $\mathcal{H}_A$  and  $\mathcal{H}_B$ . Assume that  $|\psi^{(A)}\rangle_A = \sum_i c_i^{(A)} |i\rangle_A$  and  $|\psi^{(B)}\rangle_B = \sum_j c_j^{(B)} |j\rangle_B$  are the two normalized states from  $\mathcal{H}_A$  and  $\mathcal{H}_B$ , respectively. The state  $|\psi\rangle_{AB}$  is a direct product state when:

$$|\psi\rangle_{AB} = |\psi^{(A)}\rangle_A |\psi^{(B)}\rangle_B = \left( \sum_i c_i^{(A)} |i\rangle_A \right) \left( \sum_j c_j^{(B)} |j\rangle_B \right) \quad (10)$$

Now a state in  $\mathcal{H}_A \otimes \mathcal{H}_B$  is called *entangled* if it is not a direct product state. In other words, entanglement describes the situation when the state of 'whole' cannot be written in terms of the states of its constituent 'parts'. Generally, it is a very hard problem to decide whether a quantum state is entangled or not. Fortunately, there are operational criteria, relying on measurements of correlations, with a possible outcome from which one can conclude that the state is entangled: the Bell inequality[3]. A Bell inequality is satisfied by all states which are not entangled. Thus, if a violation of a Bell inequality is observed the state which describes the results is entangled. Interestingly, Bell inequalities were first introduced in a context of **foundations of quantum mechanics**. Quantum mechanics gives predictions in form of probabilities. Already some of the fathers of the theory were puzzled with the question whether there can exist a deterministic structure beyond quantum mechanics which recovers quantum statistics as averages over "hidden variables". In this way, it was hoped, one could get a classical-like description which would solve the problems with the interpretations of quantum mechanics. In his famous impossibility proof Bell made precise assumptions about the form of a possible underlying hidden variable structure. Spatially separated systems and laboratories were assumed to be independent of one another [3]. He derived an inequality which must be satisfied by all such (local realistic) structures. Next, he presented example of quantum predictions which violate it. In this way the famous Einstein-Podolsky-Rosen (EPR) paradox [2] was solved. Bell proved that EPR elements of reality cannot be used to describe quantum mechanical systems. The noncommutativity of quantum theory precludes simultaneous deterministic predictions of measurement outcomes of complementary observables. For EPR this indicated that "the wave function does not provide a complete description of "physical reality". They expected the complete theory to predict outcomes of all possible measurements, prior to and independent of the measurement (realism), and not to allow "spooky action at a distance" (locality). A more general version of Bell's theorem for two qubits (two-level systems) was given by Clauser, Horne, Shimony, and Holt (CHSH), and extended by Clauser and Horne (CH) [4, 5]. The important feature of the CHSH and CH inequalities, which hold for *all* local realistic theories, is that they can not only be compared with ideal quantum predictions, but also with experimental results. The three or more qubit versions of Bell's theorem were presented by Green-

berger, Horne, and Zeilinger (GHZ)[6, 7]. Starting from the assumptions of realism and locality, in 1964 Bell [8] derived an inequality which was shown [9] later to be violated by the quantum mechanical predictions for entangled states of a composite system. As we have seen, Bell's theorem [10] is the collective name for a family of results, all showing the impossibility of local realistic interpretation of quantum mechanics. Later work [11] has produced many different types of Bell-type inequalities. The Bell inequality is expressed as follow: let  $A(a)$  and  $A(a')$  be the two observables for observer  $A$  in the an EPR experiment. Similarly, let  $B(b)$  and  $B(b')$  be the two observables for the observer  $B$ . In general, the observables  $A(a)$  and  $A(a')$  are incompatible and cannot be measured at the same time, and the same holds for  $B(b)$  and  $B(b')$ .

It is assumed that the two particles that reach observers  $A$  and  $B$  in EPR experiments possess hidden variables which fix the outcome of all possible measurements. These hidden variables are collectively represented by  $\lambda$ , assumed to belong to a set  $\Lambda$  with a probability density  $\rho(\lambda)$ . The normalization implies:

$$\int_{\Lambda} \rho(\lambda) d\lambda = 1. \quad (11)$$

Because a given  $\lambda$  makes the four dichotomic observables assume definite values, we can write:

$$A(a, \lambda) = \pm 1; \quad A(a', \lambda) = \pm 1; \quad B(b, \lambda) = \pm 1; \quad B(b', \lambda) = \pm 1 \quad (12)$$

That is, the physical reality is marked by the variable  $\lambda$ . Now introduce a *correlation function*  $C(a, b)$  between two dichotomic observables  $a$  and  $b$ , defined by:

$$C(a, b) = \int_{\Lambda} A(a, \lambda) B(b, \lambda) \rho(\lambda) d\lambda \quad (13)$$

For a linear combination of four correlation functions, define *Bell's measurable quantity*  $\Delta$  as:

$$\Delta = C(a, b) + C(a', b') + C(a', b) - C(a, b') \quad (14)$$

Only four correlation functions, out of a total of sixteen, enter into the definition of  $\Delta$ . We can write:

$$\begin{aligned} & |C(a, b) + C(a', b') + C(a', b) - C(a, b')| \\ & \leq \int_{\Lambda} \{ |A(a, \lambda)| |B(b, \lambda) - B(b', \lambda)| + |A(a', \lambda)| |B(b, \lambda) + B(b', \lambda)| \} \rho(\lambda) d\lambda. \end{aligned} \quad (15)$$

Since:

$$|A(a, \lambda)| = |A(a', \lambda)| = 1 \quad (16)$$

we have:

$$\begin{aligned} & |C(a, b) + C(a', b') + C(a', b) - C(a, b')| \\ & \leq \int_{\Lambda} \{ |B(b, \lambda) - B(b', \lambda)| + |B(b, \lambda) + B(b', \lambda)| \} \rho(\lambda) d\lambda \end{aligned} \quad (17)$$

Also  $|B(b, \lambda)| = |B(b', \lambda)| = 1$ , so that:

$$|B(b, \lambda) - B(b', \lambda)| + |B(b, \lambda) + B(b', \lambda)| = 2 \quad (18)$$

and the inequality (17) reduces to:

$$|C(a, b) + C(a', b') + C(a', b) - C(a, b')| \leq 2 \quad (19)$$

which is called CHSH form [4] of Bell's inequality.

### III. STANDARD INTERPRETATION: SOME PROBLEMS

Historically, the understanding of the mathematical structure of QM went through various stages. Very briefly, the Copenhagen interpretation assumes two processes influencing the wavefunction, namely, i) its unitary evolution according to the Schrödinger equation, and ii) the process of measurement.

In other words, quantum mechanics is problematic in the sense that it is incomplete and needs the notion of a classical device measuring quantum observables as an important ingredient of the theory. Due to this, one accepts that there exist two worlds: the classical one and the quantum one. In the classical world, the measurements of classical observables are produced by classical devices. In the framework of standard theory, the measurements of quantum observables are produced by classical devices, too. Due to this, the theory of quantum measurements is considered as something very specifically different from classical measurements.

As it is well known, the Copenhagen interpretation postulates that every measurement induces a discontinuous break in the unitary time evolution of the state through the collapse of the total wave function, the nature of the collapse is not at all explained, and thus the definition of measurement remains unclear. Bohr then followed the tenets of positivism, that implies that only measurable questions should be discussed by scientists. Some physicists argue that an interpretation is nothing more than a formal equivalence between a given set of rules for processing experimental data, thus suggesting that the whole exercise of interpretation is unnecessary. It seems that a general consensus has not yet been reached. Roger Penrose [12], remarks that while the theory agrees incredibly well with experiment and while it is of profound mathematical beauty, it "makes absolute no sense". The point of view of most physicist is rather pragmatic: it is a physical theory with a definite mathematical background which finds excellent agreement with experiment. So, from a technical point of view, quantum mechanics (QM) is a set of mathematically formulated prescriptions that deserves for calculations of probabilities of different measurement outcomes. The calculated probabilities agree with experiments. Pragmatic applications of the physics are interested only in these pragmatic aspects of QM, which is fine. Nevertheless, many physicists are not only interested in the pragmatic aspects, but also want to understand nature on a deeper conceptual level. Besides, a deeper understanding of nature on the conceptual level may also induce a new development of pragmatic aspects. Thus, the conceptual understanding of physical phenomena is also an important aspect of physics and cannot be viewed as simply epistemological problems. The standard interpretation of QM, tells us nothing about the underlying physics of the system. The state vector represents our knowledge of the system, not its



physics. The main 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 the theory tell us nothing about these two "abstracts" concepts. More in details, the position regarding the measurement theory can be summarizing as following:

- 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 position 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[14]. 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? The following considerations puts in evidence the problem. Consider a two-state microsystem whose eigenfunctions are labelled by  $\psi_+$  and  $\psi_-$ . Furthermore, there is a macrosystem apparatus  $\phi_0$ , with eigenfunctions  $\phi_+$  and  $\phi_-$  corresponding to an output for the microsystem having been in the  $\psi_+$  and  $\psi_-$  states, respectively. Since prior to a measurement we do not know the state of the microsystem, it is a superposition state given by

$$\psi_0 = \alpha\psi_+ + \beta\psi_-, \quad |\alpha|^2 + |\beta|^2 = 1. \quad (20)$$

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

$$\Psi_0 = (\alpha\psi_+ + \beta\psi_-)\phi_0 \longrightarrow \Psi_{out} = \alpha\psi_+\phi_+ + \beta\psi_-\phi_- \quad (21)$$

where it is assumed that initially the two systems are far apart and do not interact. 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 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,

$$\alpha\psi_+\phi_+ + \beta\psi_-\phi_- \longrightarrow \begin{cases} \psi_+\phi_+, & P_+ = |\alpha|^2; \\ \psi_-\phi_-, & P_- = |\beta|^2. \end{cases} \quad (22)$$

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

Related to this problem, Schrödinger introduced his famous cat in the very same article where entanglement was described [14]. Schrödinger devised his cat experiment in an attempt to illustrate the incompleteness of the theory of quantum mechanics when going from subatomic to macroscopic systems. Schrödinger's legendary cat was doomed to be killed by an automatic device triggered by the decay of a radioactive atom. He had had trouble with his cat. He thought that it could be both dead and alive. A strange superposition of

$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|\text{excited atom, alive cat}\rangle + |\text{non - excited atom, dead cat}\rangle) \quad (23)$$

was conceived. But the wavefunction (23) showed no such commitment, superposing the probabilities. Either the wavefunction (23), as given by the Schrödinger equation, was not everything, or it was not right. The Schrödinger's cat puzzle deals with one of the most revolutionary elements of quantum mechanics, namely, the *superposition principle*, mathematically founded in the linearity of the Hilbert state space. If  $|0\rangle$  and  $|1\rangle$  are two states, quantum mechanics tells us that  $a|0\rangle + b|1\rangle$  is also a possible state. Whereas such superpositions of states have been extensively verified for microscopic systems, the application of the formalism to macroscopic systems appears to lead immediately to severe clashes with our experience of the everyday world. As we have seen, the problem is then how to reconcile the vastness of the Hilbert space of possible states with the observation of a comparably few "classical" macroscopic states. The long standing puzzle of the Schrödinger's cat problem could be resolved in terms of quantum decoherence. The central question of why and how our experience of a "classical" world emerges from quantum mechanics thus lies at the heart of the foundational problems of quantum theory. Decoherence has been claimed to provide an explanation for this quantum-to-classical transition. In classical physics, the environment is usually viewed as a kind of disturbance, or noise, that perturbs the system under consideration in such a way as to negatively influence the study of its "objective" properties. Therefore science has established the idealization of isolated systems, with experimental physics aiming at eliminating any outer sources of disturbance as much as possible in order to discover the "true" underlying nature of the system under study. The distinctly nonclassical phenomenon of quantum entanglement, however, has demonstrated that the correlations between two systems can be of fundamental importance and can lead to properties that are not present in the individual systems. The earlier view of phenomena arising from quantum entanglement as "paradoxa" has generally been replaced by the recognition of *entanglement as a fundamental* property of nature. The decoherence theory is based on the idea that such quantum correlations are ubiquitous; that nearly every physical system must interact in some way with its environment, which typically consists of a large number of degrees of freedom that are hardly ever fully controlled. Decoherence is the irreversible formation of quantum correlations of a system with its environment. These correlations lead to entirely new properties and behavior compared to that shown by isolated objects, thus the decoherence seem provides a realistic physical modelling and a generalization of the quantum measurement process.

Next figure 2 puts in evidence the measurement problem utilizing 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,

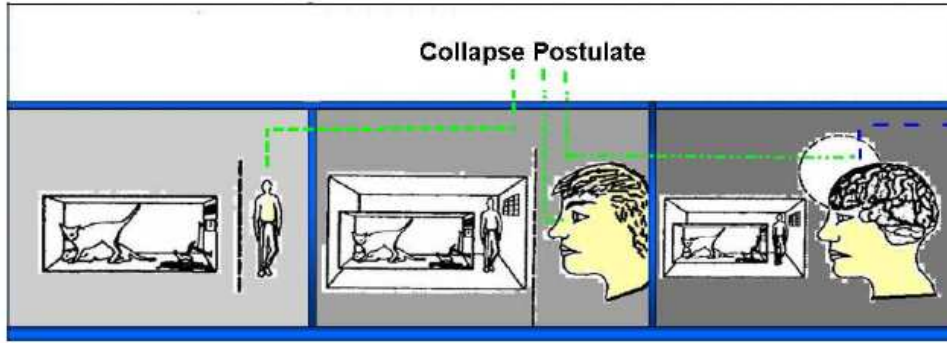


FIG. 2: Interpretations of Collapse.

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 Ob1 in a second box as shown in the second panel. If we, the second observer, are not looking, then Ob1 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.

Some objections to this interpretation (standard) has been proposed by de Muynck[13] who fixes some fundamental points (table and figure 3).

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

According to de Muynck scheme (below), in the first realist case a) quantum mechanics is thought to describe microscopic reality most in the same way of classical mechanics is generally thought to describe macroscopic reality. In the empirist 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.

Recently, with the development of quantum information theory, several scientists gives to the information a fundamental role in the description of the Nature. All these approaches 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

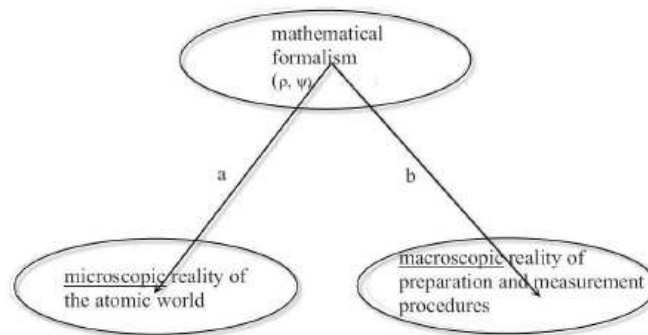


FIG. 3: Realist (a) and empiricist (b) interpretations of the mathematical formalism of quantum mechanics.

"quantum theory needs no interpretation" [15]. More in details, the field of quantum information theory opened up and expanded rapidly, for instance, quantum entanglement 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. This primitive role of the information seem to explain, according to some authors, the deep nature of physical reality. The measurement is information **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[15] claims that the nature of reality can be explained as subjective knowledge. Others authors argued that quantum theory is fundamentally just a theory of relations or of correlations[16].

#### IV. INTERPRETATIONS OF QM.

The problem linked to the collapse postulate 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[17] interpretations.
- 2. The wave function describes what actually happens in the physical world and

its probabilistic nature derives from our perspective of observers: the group of Everett[18], Deutsch[19], Bohm[20, 21] theories.

- 3. The wave function partially describes what happens in the physical processes; in order to comprehend its probabilistic nature and the postulate  $\bar{R}$  in particular, we need a theory connecting  $\bar{U}$  and  $\bar{R}$ . This view includes all those theories which tend to reconcile  $\bar{U}$  with  $\bar{R}$  by introducing new physical process: Penrose[23], GRW[22] 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[15, 25]  
The possible link between observer and interpretations of Quantum Mechanics are summarized in fig.4.

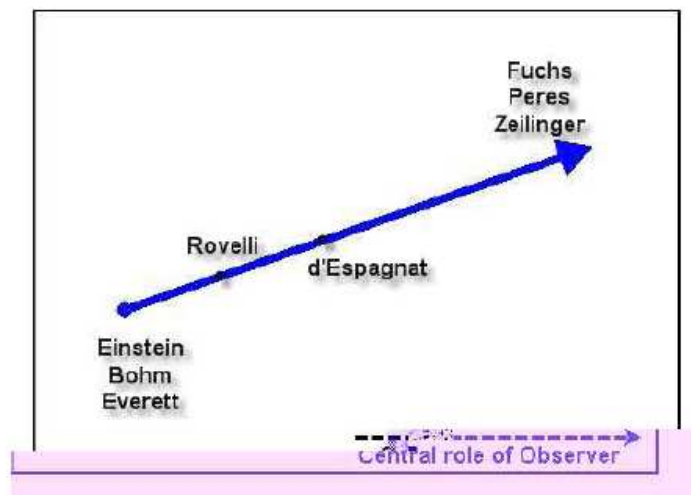


FIG. 4: Realism to Idealism, Role of Observer.

## V. 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, a position supported from the discovery of nonseparability in QM. According d’Espagnat[24] 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 be 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.

## VI. INFORMATIONAL APPROACHES TO QUANTUM MECHANICS

In this section we introduce briefly two approaches: CBH and Fuchs’ program. 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. The concept of the information, according these approaches, play a primary role. CBH[26] starting from informational constraints try to deduce the quantum mechanics principles. Fuchs’[15] program involves two strong conceptual shifts: i) quantum mechanics as a theory of information, and ii) its probabilities as subjective degrees of belief. Utilizing the Bayesian interpretation of probability, information assume a subjective role. In his program, he claims that the paradoxes of quantum mechanics, which for many interpretations provide troubling consequences, are resolved when physical objectivity is removed and in its place pure, subjective information is substituted. Last, the main thesis of these approaches are supported by the fundamentally random result of individual quantum measurements.

### A. Fuchs’ program: Bayesian Interpretation of Probability

We need to analyze, how this approach interpret the notion of probability and try to answer at fundamental questions like, what is the nature of quantum probabilities? An ontic or epistemic interpretation? Two agents in possession of the same facts can assign different or the same probabilities? According this approach we find these replies:

1. what is the nature of quantum probabilities?:⇒ **They Represent an agent’s degrees of belief.**



2. Ontic vs. Epistemic interpretation of probabilities:  $\Rightarrow$  **Epistemic interpretation.**
3. In quantum theory, two agents in possession of the same facts can assign different or the same probabilities?:  $\Rightarrow$  **Different probabilities**
4. It is indispensable for the description of physical reality to introduce the agent?  $\Rightarrow$  **Yes**

The central role played by Bayes theorem is learning from experimental data. The theorem teaches how the probability of each hypothesis has to be updated in the light of the new observation. For instance, to solve a problem via Bayes' theorem mean: to know the outcome of a series of observations of the system and to want to estimate its properties (state, parameters). The Bayesian interpretation of quantum mechanics is founded on the notion that quantum states, both pure and mixed, represent states of knowledge and that all the probabilities they predict are Bayesian probabilities.

There are many objections, for instance: how we choice the priors (subjective priors) to enter in the bayesian inference? Priors are pointed to by those critical of the Bayesian approach as the major weakness of the theory.

## VII. CONCLUSION

As we have seen, every interpretation, in a different ways, claims to explain the "observer" and the underlying physical reality once established as ontic level, one of three fundamentals elements: information, matter or physical law. We have presented some problems related these affirmations. We think, that no interpretation of the quantum theory can avoid this intrusion until we do not clarify the nature of observer.

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◊Michele Caponigro  
University of Bergamo  
◊ [michele.caponigro@unibg.it](mailto:michele.caponigro@unibg.it)

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- [1] P.A.M. Dirac: *The principles of Quantum Mechanics*, Oxford University Press ( 1958)
  - [2] A. Einstein, B. Podolsky, and N. Rosen, *Phys. Rev.* **47**, 777 (1935).
  - [3] J. S. Bell, *Physics* **1**, 195 (1964).
  - [4] J. F. Clauser, M. A. Horne, A. Shimony, and R. A. Holt, *Phys. Rev. Lett.* **23**, 880 (1969).
  - [5] J. F. Clauser and M. A. Horne, *Phys. Rev. D* **10**, 526 (1974).
  - [6] D. M. Greenberger, M. A. Horne, and A. Zeilinger, in *Bell's Theorem, Quantum Theory, and Conceptions of the Universe*, edited by M. Kafatos, Kluwer Academic, Dordrecht, 69 (1989).
  - [7] D. M. Greenberger, M. A. Horne, A. Shimony, and A. Zeilinger, *Am. J. Phys.* **58**, 1131 (1990).

- [8] J. S. Bell, *Physics* **1**, 195 (1964) and J. S. Bell, On the Problem of Hidden Variables in Quantum Mechanics, *Rev. Mod. Phys.* **38**, 447-452 (1966).
- [9] A. Aspect, J. Dalibard, and G. Roger, Experimental Test of Bell's Inequalities Using Time-Varying Analyzers, *Phys. Rev. Lett.* **49**, 1804 (1982).
- [10] A. Peres, *Quantum Theory: Concepts and Methods*, Kluwer Academic, Dordrecht (1993).
- [11] Asher Peres, All the Bell inequalities, *Found. Phys.* **29**, 589 (1999).
- [12] R. Penrose, *Gravity and State Vector Reduction*, in *Quantum Concepts in Space and Time*. Eds. R. Penrose and C. J. Isham (Clarendon Press, Oxford, 1986).
- [13] W. M. de Muynck: From Copenhagen to neo-Copenhagen interpretation, arXiv:0709.2613v1
- [14] E. Schrödinger, *Naturwissenschaften* **23**, 807 (1935). English translation available in *Proc. Am. Philos. Soc.* **124**, 323 (1980).
- [15] C. Fuchs: Quantum Mechanics as Quantum Information (and only a little more), arXiv:quant-ph/0205039v1
- [16] S. Saunders: Time, Quantum Mechanics and Probability. *Synthese* **114**, 373-404 (1998)
- [17] W.M. de Muynck: The Copenhagen interpretation, and pragmatism Contribution to the Conference on Pragmatism and quantum mechanics, CREA, Ecole Polytechnique, CNRS, Paris, February 22-23, (2007)
- [18] D. Wallace: Everett and Structure, *Studies in the History and Philosophy of Modern Physics* **34** (2003), pp. 87-105
- [19] D. Deutsch: The Structure of the Multiverse, arXiv:quant-ph/0104033v1 (2001)
- [20] K. Berndl, M. Daumer, D. Drr, S. Goldstein, N. Zangh: A Survey on Bohmian Mechanics *Nuovo Cim. B110* (1995) 737-750
- [21] D. Drr, S. Goldstein, N. Zanghi: Bohmian Mechanics as the Foundation of Quantum Mechanics Contribution to "Bohmian Mechanics and Quantum Theory: An Appraisal," edited by J.T. Cushing, A. Fine, S. Goldstein, Kluwer Academic Press (1995)
- [22] R. Tumulka: The Point Processes of the GRW Theory of Wave Function Collapse, arXiv:0711.0035v1 [math-ph] (2007)
- [23] R. Penrose: Road to Reality pp856-860 (2005)
- [24] B. d'Espagnat: *Veiled Reality*, Westview Press, Reprint edition (2003)
- [25] J. Bub: Quantum mechanics is about quantum information, *Foundations of Physics Festschrift issue for James Cushing* (2004)
- [26] R. Clifton, J. Bub and H. Halvorson, "Characterizing quantum theory in terms of information theoretic constraints." *Foundations of Physics* **33**, 1561-1591 (2003).