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On the Problem of Measurement in Quantum Mechanics

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Abstract

In this paper the "measurement problem" posed by quantum mechanics is examined. The discussion of the problem is based on the analysis of the concepts of an "isolated physical system", a "possible state of a physical system" and "interaction between physical systems". The solution proposed is suggested by W. Heisenberg's philosophical position on the theory, which he expressed in terms of the metaphysical binomial power-act. Many of the abstractions characterizing modern theoretical physics have been discussed in the philosophy of past centuries. In those times these abstractions could be ignored as mere mental exercises by scientists whose only concern was reality, but today we are compelled by the progress of experimental results to take them into serious consideration.

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Introduction

W. Heisenberg was the first to exhibit a coherent formulation of quantum mechanics (QM) (Heisenberg, 1925). In the debate on the conceptual foundations of the theory, on various occasions the German physicist used the metaphysical concepts of "potentiality" and "actuality," albeit intended in senses different from those with which Aristotle introduced them. Consider, as an example, the following remark [10].

In experiments on atomic events, we deal with things and facts, with phenomena that are just as real as everyday life phenomena. But atoms and even elementary particles are not equally real; they form a world of possibilities and potencies rather than a world of things or facts.

According to A. Shimony "Heisenberg drew from quantum mechanics a deep and radical metaphysical thesis: that the state of a physical object is a collection of potentialities. But his discovery is incomplete, as the transition from potentiality to actuality remains mysterious." The aim of this paper is to examine this transition and to propose an explanation [13].

That a body can act on another at a distance through vacuum, without mediation of anything else, is for me such an absurdity that I believe no man, with a competent faculty of thinking in philosophical matters, could ever fall into it - Isaac Newton.

Isolated Systems and Interactions

In this paper, a "isolated system" means a system that does not interact with other systems One might think that isolated systems are a mere abstraction, i.e., boundary cases ideally extrapolated from real systems. This rests on the assumption that interactions between physical systems are continuous over time. For example, if the interaction between the electron of the hydrogen atom and the proton that constitutes its nucleus were continuous over time, the electron and the proton would never be isolated from each other, unless the atom is ionized and the electron carried to an infinite distance from the proton.

However, according to R. Feynman (Feynman, 1985) "the electron is kept within a certain distance from the nucleus of the atom by the exchange of photons with the proton." If the interactions between physical systems are not continuous in time as occurs when they are mediated by the exchange of interaction mediators itself then, in the time interval more or less short that elapses between one interaction and another, the systems physically are effectively isolated.

If the word "state" is considered as a description of potentiality rather than of a reality, then the concept of coexisting potentialities is quite plausible, since a potentiality can involve overlapping with other potentialities - W. HEISENBERG (Heisenberg, 1958).

Possible States and Superposition

In this work, by "possible state" of a physical system we mean any of its states that respect the constraints to which the system is subject. An isolated system is subject only to its internal constraints, that is, those constraints that define the system itself, and thus exist independently of the physical context in which the system is placed. In other words, an isolated system is not subject to constraints that interaction with other systems would require it to respect, and which will hereafter be called external Therefore, an constraints. isolated system cannot discriminate among its possible states, that is, it cannot assume one (or some) of its possible states and exclude the others, which also satisfy the same internal constraints.

Suppose, for the sake of argument, that an isolated system S is in only one of its possible states. This would mean that, in addition to the internal constraints that determine its possible states, it is subject to an additional constraint that selects the state it is in, that is, that excludes the others. Such a constraint cannot be internal, because that would contradict the premise that the other states of the system are also possible. Therefore, it must be an external constraint, that is, it must be imposed by a system S' different from S, which requires the two systems to interact. But this requirement is incompatible with the premise that system S is isolated. It thus seems necessary to conclude that an isolated system superposes all its possible states. In fact, as Heisenberg observed (Heisenberg, 1955), "a system cut off from the external world is of potential but not actual character." We will therefore say that the state of an isolated system is a potential state, meaning by this that it is a plural state, given by the superposition of all its possible states, those that satisfy its internal constraints.

This conclusion is decidedly counter-intuitive, because physical systems always appear to observation in only one of their possible states. But observed systems are not isolated systems, precisely because the observation of a system requires an interaction with it. Therefore, the counter-intuitive nature of the above conclusion rests on the prejudice that even isolated systems, like those observed, would be in only one of their possible states (with the only difference that, in the case of isolated systems, it would not be possible to know their state).

Based on what has been considered, the superposition of states that characterizes isolated systems takes on an ontological value, even before an epistemic one. However, it is interesting to consider this superposition also from an epistemic point of view.

A physical theory must provide a description of known physical systems that is consistent with the available experimental evidence. In the best case, this description is also complete, in the sense that it fully describes each of the known physical systems. Such a description can be considered complete if it includes and composes all the possible states of the system, that is, all the states of the system compatible with the constraints to which it is subject. Therefore, if the theory describes a system through a state function, this must formally express the superposition of the system's states.

Precisely because the maximal description of the system requires that its state function formalizes the superposition of all its possible states, and precisely because these are possible states, not actual, the state function necessarily has a statistical value in the sense that, as will be argued below, it must express the relative frequency with which the system S, otherwise isolated, assumes each of its possible states when it interacts with another system S'. In other words, if the description of the system given by its state function is complete, the values it takes on the space of possible states can only express the relative frequencies with which the system assumes them actually by virtue of the interaction with another system.

From this point of view, the intrinsically statistical character of the wave function does not represent a limitation of quantum mechanics. On the contrary, as just considered, if a physical theory offers a complete description of physical systems, it does not seem reasonable to require that it predict the outcomes of measurements.

The formal relations contained in this theory – that is, its entire mathematical formalism – will probably have to be included, in the form of logical deductions, in every non-useless theory of the future - A. EINSTEIN (Einstein, 1949).

Equation of State

According to the first law of thermodynamics, an isolated physical system conserves its own energy.
Based on Noether's symmetry theorem, every symmetry of the Lagrangian of a physical system corresponds to a conserved quantity of that system. If it is required that the state function also contains maximal information about the system, it must formally express the same symmetries as the Lagrangian. Since a symmetry operation is defined as a transformation that leaves its object unchanged, the state function must be invariant under the action of the operator corresponding to the conserved quantity of the system. On the basis of these premises, it seems necessary to require that the state function of an isolated system be an eigenfunction of the operator corresponding to the energy of the system, with the eigenvalue E expressing the related conserved quantity.

1 In this ψ perspective, the equation of state of an isolated system is as follows.

$$\hat{H}\psi=E\psi \tag{1}$$

The constraint that this equation imposes on the system to which it refers, that is, the isolated system, is to conserve the energy E. Therefore, the state function that solves it must superpose all the degenerate states of the system, which represent all its possible states, assigning each its own statistical weight.

As long as the reduction of the wave packet remains an essential component, and as long as we do not know exactly when and how it replaces the Schroedinger equation, we will not have an exact and unambiguous formulation of our most fundamental physical theory - J. BELL (Bell, 1987).

Interaction and reduction

Consider a system S that interacts with another system S'. By virtue of the interaction, the two systems become parts of the composite system SS'. From the point of view of a third system S'' isolated with respect to the system SS', it superposes all its possible states. Each of these states, in addition to respecting the internal constraints to which the composite system SS' is subject, must associate a possible state of component system S with a possible state of the other component system S'. It follows that the interaction between two otherwise isolated systems S and S' must reduce their respective superpositions of possible states to a pair of actual states. This reduction process, which in this perspective is logically necessary, does not admit a mathematical formalization since it involves the discontinuous transition between two state functions irreducible to each other: that of the isolated system S (before and after measurement) and that of the isolated system SS' (during measurement).

The present work aims to explain this reduction process starting from the philosophical position of W. Heisenberg (Heisenberg, 1955), according to whom the equations of quantum mechanics "govern the possible and not the actual." In fact, equation (1) governs isolated systems which, as noted above, are systems of potential, not actual, nature. In this regard, it is worth reiterating, as Heisenberg himself observed (Heisenberg, 1955), "a system cut off from the external world is of potential character but not actual." But what does it mean, from a physical point of view, that an isolated system "is of potential character but not actual"? The proposal put forward by this work is to assume that the terms "potential" and "actual," rather than expressing a merely nominal distinction, identify two distinctlevelsof physical reality. More precisely, since the existence of the "actual" level of physical reality is not in question, the proposal is to hypothesize the existence of a second level of physical reality, the "potential" level, which according to Heisenberg is governed by quantum mechanics.

Since the same requirement can be made with respect to other conserved quantities of an isolated system, the state ψ of the system must also be an eigenfunction of the corresponding operators.

ψ

The proposal might appear at least exotic. However, from a methodological point of view, it is in some ways analogous to what cosmology has long proposed by hypothesizing the existence of dark energy, in order to make certain cosmological evidence compatible such as the accelerated expansion of the universe with the theory of general relativity.

If one takes seriously the existence of a potential level of physical reality, the statistical nature of the wave function becomes a consequence of this hypothesis. In fact, due to the interaction on which measurement is based, the system to be measured ceases to be isolated, that is, it passes from the potential level to the actual one. As previously considered regarding isolated systems, at the potential level the system S overlaps all its possible states, while based on what has just been considered regarding interacting systems S and S', at the actual level the system S (and the system S') assumes only one of its possible states. It follows that the interaction introduced by the measurement forces the system S (and the system S') to assume only one of its possible states and, precisely because the measurement selects one of the possible, its outcomes can only states, its outcomes can only present an intrinsically statistical distribution.

If the state function of a system S describes the isolated system, the effect of measurement is not to cause its 'collapse', but rather to make its physical meaning disappear. In fact, at the moment of measurement, the measured system S ceases to be an isolated system, and therefore its state function ceases to describe its evolution. The interaction between the measured system S and the measuring system S' forms an isolated system SS' different from the first, which will therefore be described by a different state function.

The proposed interpretation differs from the 'many worlds' interpretation advanced by Hugh Everett III (Everett, 1957) in the sense that, as considered in this work, the 'many worlds' would configure the potential level of physical reality, while the 'world' would represent the actual physical reality.

The simplest atom, called hydrogen, is made up of an electron and a proton. Through the exchange of photons, the proton keeps the electron close to it, which dances around it - R. FEYNMAN (Feynman, 1985).

The Hydrogen Atom

According to the above hypothesis, physical reality would be structured on two levels, the potential and the actual one. This hypothesis is now used to propose a description of the hydrogen atom. In this attempt, the generic systems S and S' considered above take on the roles of the electron and the proton, respectively, while the composite system SS' represents the atom itself. The proposed description assumes that the electron and the proton interact by exchanging mediators of the interaction, and therefore that their interaction is not continuous in time. In this case, the electron and the proton alternate phases of interaction with phases of isolation, that is, they pass from the actual level to the potential level of physical reality, and vice versa.

As considered above, in the interaction phase each of them assumes one of their possible states. In particular, if the interaction is such as to select one of their possible positions, in the interaction phase the electron and the proton take position relative to each other. In fact, the position of a physical system is defined only in relation to a reference system, and since in physical terms this relationship must be considered as an interaction, the reference system cannot be understood as an abstract system of space-time coordinates, but as a real physical system with which the other system interacts. In this sense, if the interaction between S and S' selects one of their possible positions, each of the two systems becomes the reference system for the other.

Once the interaction has ceased, the electron and the proton are isolated from each other. Based on what has been considered above regarding isolated systems, in the isolation phases both the electron and the proton overlap their possible states, each with its own statistical weight. In particular, since the Schrödinger equation is formally analogous to the heat equation (with an imaginary diffusion coefficient), once the interaction ceases, the statistical weights of the positions of the electron and the proton evolve over time. Since the diffusion coefficient is inversely proportional to the mass, the diffusion of the electron is much faster than that of the proton.

Therefore, with good approximation, the proton can be considered as a persistent and stationary body, and the electron as an ephemeral body Andin motion.

However, this movement should not be understood as a continuous change of position, precisely because the electron alternates phases in which it takes position with phases in which it loses it. In other words, if the process were evaluated only from the point of view of the current level of physical reality, one would conclude that the electron 'disappears' from the position it assumed due to the interaction with the proton, and 'reappears' in a different position due to the subsequent interaction. Naturally, between the two interactions the electron does not 'disappear' in the sense of ceasing to exist, also because this would violate the principle of conservation of energy. According to the proposed conceptual scheme, when the interaction with the proton ceases, the electron becomes an isolated system, that is, it passes from the current state of physical reality to its potential level, which is governed by the Schrödinger equation. Since the operator $\hat{H}$ corresponding to the electron's energy contains both the kinetic term and the term related to the interaction potential, once the interaction ceases, the position of the electron spreads out until it restores the stationary state corresponding to its energy, or at least until the next interaction. This explains how the electron changes position without following trajectories around the nucleus, and thus without losing energy by electromagnetic radiation. In this view, an atomic orbital represents the potential position of the electron, while the position measurement gives its actual position.

Are you really convinced that the Moon exists only when you look at it? - ALBERT EINSTEIN (Einstein, 1986).

Macroscopic Systems

The two hypothesized levels of physical reality can be considered as such if they are physically different, that is, if they are governed by different physical laws. As already noted, according to Heisenberg, the laws of quantum mechanics 'govern the possible and not the actual.' The following question therefore arises: if the potential level of physical reality is governed by quantum mechanics, by which mechanics is its actual level governed? In the previous section, the proton that constitutes the nucleus of the hydrogen atom was approximated as a persistent body. This is because its diffusion is rather slow compared to that of the electron. Even more so, the hydrogen atom can be considered persistent (unless it is itself considered as an isolated system). This is not so much due to the contribution which is negligible of the electron's mass to the reduction of the diffusion coefficient, but rather because it seems reasonable to suppose that the hydrogen atom interacts even more frequently with the environment. In this view, the frequency of interaction with the environment is even greater for the carbon atom, and increases considerably for a C60 molecule (Zeilinger, 1999).

Interference effects have also been observed for molecules heavier than fullerene. However, as the size of the system increases, its frequency of interaction with the environment increases, making it increasingly difficult to keep it isolated, that is, to prevent its transition from the potential level of physical reality to the actual level. Furthermore, as already noted, a greater mass of the system corresponds to a lower diffusion coefficient, so a more massive system takes longer to pass from the pure state in which it was prepared by the interaction to the pure state it asymptotically tends to over time, that of the system isolated for an infinite time. It therefore seems reasonable to expect that the effects of environmental decoherence [2] manifest themselves more clearly for mesoscopic systems. In the case of a macroscopic system, the frequency of interaction with the environment is such that the system remains isolated for an insufficient time to appreciably diffuse. Therefore, its movement, guided by the potential to which it is subject, can be considered with good approximation as continuous. In this view, to the question formulated above, it seems possible to answer that, in the case of macroscopic bodies, the current state of physical reality is governed by classical mechanics.

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Here is a splendid theory, perhaps among the most perfect, precise and fascinating that man has ever conceived. We have external evidence but more than anything internal that its validity is limited, that it does not describe everything it claims to describe. The domain of validity of the theory is certainly enormous, but deep down it whispers to us - J. OPPENHEIMER (Oppenheimer, 1957).

Conclusions

The hypothetical potential level of physical reality, reserved for isolated systems, is by its nature inaccessible to experience, but its evolution is predictable through the Schrödinger equation, which is deterministic. The level currentof the same reality, which is instead the prerogative of interacting systems, is accessible to experience, but for microscopic systems its evolution is unpredictable due to the intrinsically statistical nature of the state function. This evolution is predictable only for macroscopic systems, in accordance with classical mechanics.

Every interpretation of quantum mechanics, and in particular every solution to the measurement problem, introduces an element of novelty compared to the classical view. The hypothesis that there exists a potential level of physical reality is rather demanding. Moreover, it does not seem possible to confirm or refute it, even in principle, which makes it somewhat problematic from a scientific point of view. However, it seems a rather natural hypothesis at least insofar as, by virtue of the linearity of the involved operators, the formalism of quantum mechanics appears to describe precisely a reality of a potential character.

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