A New Look at the Quantum Mechanical Problem of Measurement

NICHOLAS MAXWELL
Department of History and Philosophy of Science
University College at London
London WC1, England
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According to orthodox quantum mechanics, state vectors change in two incompatible ways: "deterministically" in accordance with Schrodinger's time-dependent equation, and probabilistically if and only if a measurement is made. It is argued here that the problem of measurement arises because the precise, mutually exclusive conditions for these two types of transitions to occur are not specified within orthodox quantum mechanics. Fundamentally, this is due to an inevitable ambiguity in the notion of "measurement" itself. Hence, if the problem of measurement is to be resolved, a new, fully objective version of quantum mechanics needs to be developed which does not incorporate the notion of measurement in its basic postulates at all.

I. INTRODUCTION

In this paper my concern is to propose that a new approach be adopted to the quantum mechanical problem of measurement. This approach involves developing a new version of elementary quantum mechanics (QM). In essence my suggestion is this: In order to resolve the problem of measurement we need to eliminate the notion of "measurement" from the basic postulates of QM altogether.

II. THE MEASUREMENT PROBLEM

The problem of measurement arises in the following way.[1] Let us suppose we have an ensemble of systems, S, in a state ψ_S, and we measure some observable A, with eigenvalues a_i $(i=1, \cdots, n)$, by means of an ensemble of measuring instruments M. In this case, after each system of S has interacted with each M, the measuring instruments are each left in one of n possible states, m_i say $(i=1, \cdots, n)$, each state m_i corresponding to a value a_i of observable A.

Suppose now we apply QM to the joint ensemble $S+M$; that is, we prepare each member of M so that it is in some specific quantum mechanical state ψ_M. Just before S and M interact, each joint system $S+M$ is in a pure state $\psi_S \cdot \psi_M$. Now QM predicts that as long as no further measurement is made on each member of $S+M$, the systems remain in a pure state. This means that each apparatus does not have a definite state m_i, rather, each apparatus is in a superposition of such states. It is only when a further measurement is made on each member of $S+M$ that QM predicts that each apparatus is in one or another of the possible states m_i.

Here then is a contradiction. If we designate the systems M as measuring instruments, QM predicts that after each S interacts with each M, the measuring instruments have some definite state m_i. If, on the other hand, we regard the systems M as physical systems with associated state vectors, QM predicts that each M remains in a superposition of states m_i, unless further measurements are made on $S+M$. According to the first prediction of QM, the state of $S+M$ is a *mixture* after the interaction; according to the second prediction of QM, the state of $S+M$ remains a *pure state* unless *further* measurements are made.

III. ANALYSIS OF THE PROBLEM

A number of attempts have been made to solve this problem without altering the basic postulates of QM.[2] None of these attempted solutions has won general acceptance.[3] Recently it has been argued that the problem of measurement is insoluble and requires that the basic postulates of QM be modified.[4] It is this viewpoint that is adopted here.

I suggest that the problem of measurement arises because precise conditions for a measuring-type interaction to occur are not specified within orthodox QM. The issue here can be put like this. Two kinds of transformations occur within QM: (a) "deterministic" transformations, which occur in accordance with Schrödinger's time-dependent equation, as long as no measurement is made; (b) probabilistic transformations, associated with a "reduction of the wave packet," and a transition from pure state to mixed state (according to orthodox QM, these probabilistic transitions occur if and only if a measurement is made).

Now the point that I would like to make is this. Transformations of type (b) are incompatible with transformations of type (a). If a type (b) transformation occurs, then this cannot occur in accordance with the Schrödinger time-dependent equation. We need then to specify precise limitations on the domain of applicability of Schrödinger's time-dependent equation. The equation applies in all circumstances except those in which transformations of type (b) occur.

However, orthodox QM does not place any such precise restrictions on the domain of applicability of Schrödinger's time-dependent equation. It is precisely for this reason that the measurement problem arises. The problem arises precisely when Schrödinger's time-dependent equation is applied to a system $S+M$ which involves a *measuring-type interaction,* i.e., an interaction of type (b).

The measurement problem could then be resolved if we could specify completely general conditions for a type (b) interaction to occur. For then we could interpret QM in such a way that Schrödinger's time-dependent equation applies to systems *only in so far as the conditions for a type (b) interaction to occur are not satisfied.*

Furthermore, it seems that this approach represents the only hope of satisfactorily resolving the problem of measurement. For the problem of measurement arises essentially because, within orthodox QM, two incompatible transformations of type (a) and type (b) can both be applied to one and the same physical situation (in our example, the time evolution of the joint system $S+M$). As long as it is granted that (i) two, and only two, types of transitions are involved in QM [namely type (a) and type (b) transitions] and (ii) these two types of transitions are incompatible,[5] then the only hope of solving the measurement problem and avoiding contradictions is to ensure that *type (a) transitions apply only when type (b) transitions are inapplicable, and vice versa.* In order to ensure this we need to specify precise conditions for the applicability of type (a) and type (b) transitions which are mutually exclusive; that is, we need to develop a version of QM which specifies precisely under what circumstances type (b) transitions occur so that the range of applicability of Schrödinger's equation can be appropriately restricted.

The problem here, of course, is just to specify precise, general conditions for a type (b) transformation to occur. It is this problem that I wish now to consider.

IV. THE NEED TO ELIMINATE THE NOTION OF MEASUREMENT

The point that I wish to make now is this. In order to solve the problem of specifying precise, unambiguous conditions for a type (b) transformation to occur, we need to specify conditions which are fully objective, which make no mention whatsoever of such partly subjective notions as measurement or observation. Orthodox QM gives only an imprecise, ambiguous specification of the conditions for a type (b) transformation to occur precisely because these conditions are formulated in terms of measurement.

My claim is that the very notion of measurement contains a fatal ambiguity which ensures that any specification of the conditions for a type (b) transformation to occur, formulated in terms of "measurement," must be imprecise and ambiguous. In short the problem of measurement must remain with QM as long as "measurement" is employed as a primitive term in formulating the postulates of the theory. In order to solve the problem of measurement we need to eliminate the notion of "measurement" from QM altogether!

Here are my arguments in support of this claim.

What is a measurement? It is at least a physical interaction between a system S and an "instrument" M which is such that M is left in *one* of several possible states readily distinguishable by the trained human observer. But what precisely does "readily distinguishable by the trained human observer" mean here? We have three terms, system S, measuring instrument M, and observer O. Is the observer allowed to wear spectacles? Can we regard a microscope as being a part of O? If we can, why cannot we regard M as being a part of O? But this would mean that a system such as an electron is itself observable and exists in states "readily distinguishable by the trained observer." Clearly this is absurd. How, then, do we decide how much of the measuring instrument M can be apportioned to the observer O? Clearly, as far as quantum mechanics goes, we would say this: As long as $S+M$ includes macroscopic parts, capable of maintaining a permanent record of the interaction between S and M, it does not matter how much of the apparatus we regard as belonging to O rather than to M. But this reply in effect assumes that we already have a *fully objective* specification of the conditions for a type (b) transition to occur—a specification which does not itself employ the notion of measurement. For it is only if we have this that we will be in a position to assert that a given $S+M$ does, or does not, leave a permanent record even when it has not interacted with any observer O. Thus we cannot specify the conditions for a type (b) interaction to occur in terms of the notion of measurement; rather we need to know precise, fully objective conditions for a type (b) interaction to occur in order to know whether or not a given composite system $S+M$ qualifies as a measurement.

We might try to overcome this particular problem in a purely ad hoc way by stipulating that any composite system $S+M$ only qualifies as a measurement if M ends up on one of a number of possible states which can be distinguished by a normally sighted observer O. (Thus spectacles could be considered a part of O, but not a microscope.) But this ad hoc stipulation does not solve the underlying problem. Consider a composite system $S+M$ which passes the above test. Suppose $S+M$ remains an isolated system after S and M have interacted. *Has a measurement been completed*? Has a type (b) transformation occurred? The answer is either yes or no.

Suppose first that the answer is yes. In this case type (b) transformations are wholly *physical* interactions. They occur in composite systems $S+M$ where the possible states of M are observationally distinguishable by the normally sighted human observer. But this again does not provide a precise, unambiguous specification of the conditions for a type (b) interaction to occur. In the first place, no absolutely sharp distinction can be formulated between "observationally distinguishable" and "observationally indistinguishable." Secondly, even if a sharp distinction of this type could be formulated, it would be entirely ad hoc. There could be no reason whatsoever to suppose that the occurrence, or nonoccurrence, of a purely physical process—namely, a type (b) transformation in an isolated system $S+M$—could depend solely on whether or not the possible states of M are observationally distinguishable, where "observationally distinguishable" would be a kind of arbitrarily precise mean of what human beings can in fact distinguish. I conclude that this line of thought leads to absurdity.

Let us suppose then that the answer to the above question is no; that is, let us suppose that a measurement is completed—a type (b) transformation occurs—only when an observer O interacts with the system $S+M$ and becomes conscious of the result of the measurement.[6]

There is now one possible defense which might be made of this extreme subjectivist viewpoint. It might be argued that a type (b) transformation—a reduction of the wave packet or a transition from pure state to mixed state—is not to be interpreted as a special kind of physical interaction at all. Rather it arises simply as a consequence of the observer acquiring new *knowledge* of the state of the system in question. It is thus entirely understandable that type (b) transitions occur only when an observer becomes conscious of the outcome of an experiment.

However, this viewpoint is indefensible. It assumes that the transition from pure state to mixture is a transition from an imprecise to a more precise specification of one and the same state. But this assumption is false. Given that an ensemble of systems is in a pure state ψ, then no more precise specification of the state of the ensemble of systems is possible within QM. No mixed state can be regarded as a more precise specification of a pure state. Thus type (b) transformations, transformations from pure states to mixed states, cannot be regarded as transitions of *knowledge*, transitions from imprecise to more precise specifications of one and the same state.

Type (b) transformations must be interpreted as genuine *physical* transformations.

Let us return, then, to a consideration of the view under discussion, namely the view that a measurement is completed, and hence a type (b) transformation occurs, only when an *observer* becomes conscious of the outcome of a measurement.

This view is open to the following objections. In the first place, it is surely bizarre in the extreme that a purely *physical* process should occur only in those systems that interact with conscious observers. Secondly, the notion of *observer* is fatally ambiguous. Do quantum observers include babies, fetuses, the extreme subnormal, chimpanzees, cats, or amoebae? It is doubtful in the extreme that a sharp distinction exists, or can be drawn, between conscious persons and nonconscious animals or organisms. In the absence of such a sharp distinction, the view under discussion fails to specify precise conditions for a type (b) transformation to occur.

To sum up, then: The notion of "measurement" involves the notion of "observational" or "observer." Thus the notion of measurement needs to be eliminated from the basic concepts of QM for two reasons. First, "measurement" introduces an undesirable subjective or anthropomorphic element into physics. Secondly, the notions of "measurement," "observational," "observer," are fatally ambiguous, so that precise conditions for a type (b) interaction to occur cannot be formulated in terms of them. In order to formulate precise conditions for a quantum mechanical measurement to occur, we need to have already a precise, fully objective specification of the conditions for a type (b) interaction to occur. Hence we cannot, without circularity, specify the conditions for a type (b) interaction to occur in terms of the notion of measurement.

There is now one other way in which we might attempt to give a precise specification of the conditions for a type (b) transformation to occur in terms of the notion of measurement. We might adopt the view of Bohr,[7] and argue that an essential condition for an interaction between S and M to constitute a *measurement* is that M is a physical system to which the laws of classical physics apply. This viewpoint allows us to hold that a type (b) transition occurs in an isolated system $S+M$ even when M is not a measuring device in the ordinary sense that the possible states of M are readily distinguishable by the trained observer. We require simply that M is a physical system to which classical physics applies. This view thus avoids the ambiguity and anthropomorphicity implicit in such concepts as "observational" and "observer."

This view runs into other difficulties however. In the first place it should be pointed out that classical physics does not apply with absolute accuracy to any phenomena whatsoever. In fact, quite prosaic macroscopic phenomena—such as the stability of matter—violently conflict with classical physics. It is at best only a suitably doctored classical physics that can be said to apply to macroscopic phenomena. However, one principle will be contained in this doctored, restricted, classical physics—namely, the principle that systems have definite states at all times and cannot exist in superpositions of states.

According to this viewpoint, then, QM is a theory which makes probabilistic predictions about micro systems interacting with approximately classical, macro systems. QM interpreted in this way is a hybrid theory, consisting of both peculiarly quantum mechanical postulates (such as the superposition principle and the Schrödinger equation) and classical theories. On this view, the classical theories are an absolutely essential part of QM.

The question before us is simply this. Can such a hybrid theory specify absolutely precise conditions for type (b) transformations to occur? (This it needs to do if the problem of measurement is to be laid to rest.) My claim is that a simple argument shows that the hybrid theory cannot specify precise conditions for type (b) transformations to occur.

Consider a composite, isolated system S_1+S_2 which is such that S_1 interacts with S_2 in such a way that a type (b) transformation occurs. Now in the first place, we have no reason to suppose that such type (b) transformations occur *only if* S_2 evolves approximately in accordance with classical physics. It may well be that type (b) transitions occur even though S_2 is not even approximately a classical macro system. But if this is the case, the precise conditions for such a type (b) transformation to occur cannot be specified in terms of a micro system interacting with a classical macro system.

But secondly, even if we suppose a type (b) transformation does occur *only if* S_2 is approximately a classical macro system, the hybrid version of QM under consideration still cannot specify precise conditions for type (b) transformations to occur. For, at best, type (b) transformations would occur if and only if S_2 behaves *approximately* like a classical system. If we are to specify precise and general conditions for S_2 to behave in an approximately classical way, then we must do this in purely quantum mechanical terms (just as the precise, general conditions for Kepler's and Galileo's laws to hold approximately can only be specified in terms of a more fundamental theory—Newtonian mechanics). In other words, the precise, general conditions that S_2 needs to satisfy if a type (b) transition is to occur in S_1+S_2 needs to be specified in purely quantum mechanical terms. But clearly this violates the condition that S_2 is specified in purely classical terms. Thus, even if as a matter of fact, given any composite system S_1+S_2, type (b) transformations occur only if S_2 is approximately classical (something we have no reason to believe to be true); nevertheless, Bohr's hybrid version of QM cannot specify precisely the conditions for a type (b) transformation to occur.[8]

I hope the lesson is clear. If we are to specify *precise, necessary, and sufficient* conditions for type (b) transformations to occur (and thus resolve the measurement problem), we must do so in purely quantum mechanical terms, i.e., in terms of the state vectors of the systems involved. Any attempt to do this in terms of any kind of hybrid version of QM which incorporates nonquantum mechanical (or quasiclassical) theories and concepts that apply to measuring instruments must fail. This means that in order to resolve the measurement problem we must eliminate the notion of measurement altogether from the basic postulates of QM and develop a new, fully objective version of QM.

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[1] For recent discussions of the measurement problem and references to the literature, see B S DeWitt and R. N. Graham, Amer. J Phys **39**, 724 (1971); L E Ballentine, Rev. Mod. Phys. **42**, 358 (1970); A. Fine, Phys. Rev D, **2**, 2783 (1970); B d'Espagnat, *Conceptual Foundations of Quantum Mechanics* (Benjamin, New York, 1971).

[2] J. von Neumann, *Mathematical Foundations of Quantum Mechanics* (Princeton U. P., Princeton, New Jersey, 1955); D Bohm, *Quantum Theory* (Prentice-Hall, Englewood Cliffs, N. J., 1951); L. Landau and E. Lifshitz, *Quantum Mechanics* (Pergamon, London, 1958); A. Daneri, A. Loinger, and G. M. Prosperi, Nucl. Phys. **33**, 297 (1962); J. M. Jauch, Helv. Phys. Act. **37**, 293 (1964).

[3] For critical reviews of the main attempts to solve the measurement problem see A. Shimony, Amer J. Phys. **31**, 755 (1963); B. d'Espagnat, Ref. 1.

[4] A. Fine, Ref 1.

[5] Either of these two assumptions may, of course, be rejected. Thus Jauch and Daneri *et al.* presumably reject assumption (ii) in that they hold type (b) transitions can be reduced to type (a) transitions. Rosen, on the other hand, rejects assumption (i) in that he argues that a *third* type of change of state needs to be considered, which occurs in macro systems in accordance with a nonlinear, classical equation of motion; see N. Rosen, Amer. J. Phys. **32**, 597 (1964). I wish to maintain, however, that both assumptions are reasonable, and that once we accept these two assumptions, then the only hope of solving the measurement problem is to adopt the approach that I advocate.

[6] This view has been defended by J. von Neumann (Ref. 1), and by F London and E. Bauer, *La Theorie de l'observation en mecanique quantique* (Hermann & Cie., Paris, 1939).

[7] See, for example, N. Bohr, "Discussion with Einstein on Epistemological Problems in Atomic Physics," in *Albert Einstein: Philosopher-Scientist*, edited by P. A. Schilpp (Tudor, Evanston, Ill., 1949).

[8] Shimony (Ref. 3) criticizes the two dominant interpretations of QM discussed here but on somewhat different grounds.