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A. J. Leggett

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The Quantum Measurement Problem

A. J. Leggett

Despite the spectacular success of quantum mechanics (QM) over the last 80 years in explaining phenomena observed at the atomic and subatomic level, the conceptual status of the theory is still a topic of lively controversy. Most of the discussion centers around two famous paradoxes (or, as some would have it, pseudoparadoxes) associated, respectively, with the names of Einstein, Podolsky, and Rosen (EPR) and with Schrödinger's cat. In this Viewpoint, I will concentrate on the paradox of Schrödinger's cat or, as it is often known (to my mind somewhat misleadingly), the quantum measurement paradox.

Basically, the quantum measurement paradox is that most interpretations of QM at the microscopic level do not allow definite outcomes to be realized, whereas at the level of our human consciousness it seems a matter of direct experience that such outcomes occur (indeed, it seems so difficult to imagine what it would be like for the world to be otherwise that I suspect that Immanuel Kant, had he had occasion to consider the problem, would have classified our knowledge of this state of affairs as "synthetic a priori").

It is convenient to classify reactions to this problem into three broad classes, defined by the following three different views on the status of QM: (a) QM is the complete truth about the physical world, at all levels, and describes an external reality. (b) QM is the complete truth (in the sense that it will always give reliable predictions concerning the nature of experiments) but describes no external reality. (c) QM is not the complete truth about the world; at some level between that of the atom and that of human consciousness, other non–quantum mechanical principles intervene.

I briefly discuss each of these possibilities in turn [for a more extended discussion, see (*1*)]. Let's start with option (a). Consider the following two questions:

(1) In a typical situation involving an ensemble of microscopic entities (such as a Young's slits experiment with, for example, electrons or neutrons) in which the QM description of the ensemble is by a superposition of amplitudes corresponding to alternative microscopic possibilities A and B (e.g., "went through slit 1" and "went through slit 2"), is it the case that each individual member of the ensemble either definitely realizes alternative A or definitely realizes alternative B?

(2) In a (thought) experiment of the Schrödinger's cat type involving an ensemble of macroscopic objects (e.g., cats) for which the formal QM description of the ensemble of relevant "universes" is by a superposition of amplitudes corresponding to macroscopically distinct alternative states A and B (e.g., "cat alive" and "cat dead"), is it the case that each member (cat) of the ensemble either definitely realizes alternative A or definitely realizes alternative B (in the absence of inspection by a human agent)?

I believe that a large majority of the portion of the physics community that advocates option (a) would answer "no" to the first question and "yes" to the second (*2*).

The usual argument given in favor of these answers involves the phenomenon of decoherence: As a result of the latter phenomenon, it is impossible to see any effects of interference between (for example) the living and dead states of the cat, and it is argued that "therefore" one state or the other has been definitely realized, irrespective of whether we have or have not observed the particular cat in question.

As I have argued at greater length elsewhere, I believe this argument embodies a gross logical fallacy: It confuses the question of truth with the question of evidence. At the microscopic level, the adherents of view (a) felt (mostly) obliged to reject a realistic interpretation; the evidence they would cite against it is the well-known phenomenon of interference between possibilities A and B. By the time we get to the macroscopic level, the evidence has gone away, but the QM formalism is in no way changed; thus, its interpretation cannot have changed either.

To complete my argument at this point, it would be necessary to discuss also those interpretations of QM (such as the Bohm-de Broglie "hidden-variables" interpretation) that answer "yes" to both the above questions, and those (such as the Everett-Wheeler "many-universes" interpretation) that answer "no" to both. Because space is limited, I will just state my own view that both these interpretations amount to little more than verbal window dressing of the basic paradox, and thus that no interpretation of class (a) is viable (*3*).

I next turn more briefly to option (b). According to the adherents of this view, the whole formalism of QM amounts to nothing but a calculational recipe, designed in the last resort to predict the probabilities of various directly observed macroscopic outcomes ("this particular cat is dead/alive"), and the symbols occurring in it, such as the probability amplitudes, correspond to nothing in the "real world." The extreme operationalism implied in this view is often softened by the observation that under many conditions relevant to human existence, the experimental predictions of QM are "as if" the world had behaved classically; this argument is made most explicit in the "consistent-histories" (or "decoherent-histories") interpretation. However, that observation does not get around the fact that these conditions are not invariably fulfilled; in particular, it does not exclude a priori the possibility that we may some day be able not merely to generate quantum superpositions like that of Schrödinger's cat, but to observe the corresponding interference effects. Personally, if I could be sure that we will forever regard QM as the whole truth about the physical world, I think I should grit my teeth and plump for option (b).

Finally, what of option (c)? Indeed, there have been a number of concrete proposals to modify standard QM at some level intermediate between that of the atom and that of human consciousness, the currently best-developed one being probably that associated with the names of Ghirardi, Rimini, Weber, and Pearle. All of these proposals have in common the feature that at a sufficiently "macroscopic" level (the precise threshold depends on the specific proposal), the superpositions predicted by the formal extrapolation of the QM formalism do not occur; rather, some non-QM mechanism intervenes and guarantees the realization of a definite macroscopic outcome for each particular member of the ensemble in question. In principle, once the threshold for such realization is specified, it would be possible to test such theories unambiguously by comparing their predictions with those of standard QM; however, for the test to be definitive it is obviously necessary that QM continues to predict interference effects, i.e., that decoherence (which of course is a concept only meaningful within the QM formalism) has not washed them out. If one can indeed detect the characteristic QM interference effects at a given level of "macroscopicness," then it is a reason-

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able inference [though not in itself a logically watertight one (1)] that no such mechanism of "realization" has come into play by that level.

Even a decade ago, considerable skepticism existed about the prospect of ever observing quantum superpositions involving more than a few "elementary" particles. However, in the last 5 years progress in this direction has been spectacular, ranging from traditional Young's slits experiments conducted with C_{70} molecules (~1300 "elementary" particles) to SQUID experiments in which the two superposed states involved ~10^{10} electrons behaving differently (1). Thus, the experiments are beginning to impose nontrivial constraints on hypotheses of class (c). If in the future these constraints grow tighter and tighter, we may find that at the end of the day we have no alternative but to live with option (b).

References and Notes

1. A. J. Leggett, *J. Phys. Cond. Mat.* **14**, R415 (2002).
2. This belief is based on extensive canvassing of representative physics-colloquium audiences.
3. It is fair to warn any readers new to this topic that this conclusion is controversial in the extreme.

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VIEWPOINT

From Pedigree Cats to Fluffy-Bunnies

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We consider two distinct classes of quantum mechanical entanglement. The first "pedigree" class consists of delicate highly entangled states, which hold great potential for use in future quantum technologies. By focusing on Schrödinger cat states, we demonstrate not only the possibilities these states hold but also the difficulties they present. The second "fluffy-bunny" class is made up of robust states that arise naturally as a result of measurements and interactions between particles. This class of entanglement may be responsible for the classical-like world we see around us.

The nature of quantum superposition states and how we can "see" them in our classical world continues to fascinate scientists. In recent years, this fascination has led to a new awareness of the potential uses of these states in science and technology. Their nature opens the door to a whole range of new types of precision measurements. They also have important implications for what the classical world around us can look like. In this Viewpoint, we illustrate the nature of entanglement by focusing on two types of quantum states that we call "pedigree cats" and "fluffy-bunnies" (1). We want to explain why these states are so fascinating and why the pedigree cats are so difficult to breed and keep alive. They can be thought of as highly entangled, highly vulnerable, and easily killed off. The type of quantum entanglement that is breeding all around us and is responsible for the way we see the world is the wild fluffy-bunny kind.

The idea of a cat state first came about as a consequence of a famous thought experiment of Schrödinger in 1935 (2). In it, he imagined that a cat was placed in a box along with a radioactive sample arranged so that if a decay occurred, a toxic gas would be released and the cat killed. Quantum mechanics tells us that at any time the nucleus involved is in a superposition of the decayed and original state. Because the fate of the cat is perfectly correlated with the state of the nucleus undergoing decay, we are forced to conclude that the cat must also be in a superposition state, this time of being alive and dead. This result does not sit comfortably with our experience of the world around us—we would expect the cat to be either alive or dead but not both—and continues to fascinate and provoke discussion. Cat states have now come to refer to any quantum superposition of macroscopically distinct states. Here we call them pedigree cats to emphasize their prized but delicate nature.

Cat states are interesting not only for the questions they raise about quantum mechanics but also for their potential use in new quantum technologies. An important example of this is their use in pushing the limits of precision measurements. Because measurement is a physical process, we would expect the accuracy we can achieve in any measurement to be governed by the laws of physics. For quantum states, the very act of measuring changes the state and so affects subsequent results. This process is known as back-action. We will focus our discussion on interferometry, which is the basis for a wide range of precision measurements. Ultimately the precision that can be achieved in any measurement is subject to Heisenberg's uncertainty principle, which states that the uncertainty in any pair of conjugate variables obeys an inverse relation. The more accurately one variable is measured, the less accurately the other can be known. This leads to a fundamental limit to how accurately quantum phases can be measured that scales as $\Delta\phi \sim 1/N$, where N is the total number of particles involved. In practice, however, measurements are limited by more practical effects. Interferometry schemes, for example, usually use a stream of photons or atoms and are, therefore, normally limited by shot noise, where the measurement accuracy scales as $N^{-1/2}$. This conventional bound to measurement accuracy is a consequence both of the discrete nature of particles and of independent-particle statistics. The fundamental quantum limit (3, 4) can be reached, however, by taking advantage of "cooperation" between the particles in entangled states. There are a number of proposals for how this might be achieved, and an excellent review of them is given by Giovannetti *et al.* (5). We will focus here on how entangled states, i.e., pedigree cats, open the door to this possibility.

If we were to split a single particle along the two paths of an interferometer, the state of the particle would be $|\Psi\rangle = (|1\rangle|0\rangle + e^{i\phi}|0\rangle|1\rangle)/\sqrt{2}$, where the first ket in each term represents the number of particles on one path and the second ket represents the number of particles on the other path. A particle on the second path acquires a phase shift ϕ relative to one on the first. Interferometry schemes generally use a stream of such single-particle states to make a measurement of ϕ. If instead we had a cat state of the form

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|N\rangle|0\rangle + |0\rangle|N\rangle) \qquad (1)$$

things would be quite different. The particles in this state are entangled because we cannot write the total state as a tensor product of the state of each of the particles. Another way of saying this is that if we know which way one of the particles goes, we know which way all of them go. This property makes these states very fragile—knowledge of the whereabouts of one particle blows the cover for all the others and destroys the superposition. However, this same property also makes the state very sensitive to phase shifts. In the case considered here, the phase shifts acquired

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