OPINION

Quantum Theory Needs No "Interpretation"

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Recently there has been a spate of articles, reviews, and letters in PHYSICS TODAY promoting various "interpretations" of quantum theory (see March 1998, page 42; April 1998, page 38; February 1999, page 11; July 1999, page 51; and August 1999, page 26). Their running theme is that from the time of quantum theory's emergence until the discovery of a particular interpretation, the theory was in a crisis because its foundations were unsatisfactory or even inconsistent. We are seriously concerned that the airing of these opinions may lead some readers to a distorted view of the validity of standard quantum mechanics. If quantum theory had been in a crisis, experimenters would have informed us long ago!

Our purpose here is to explain the internal consistency of an "interpretation without interpretation" for quantum mechanics. Nothing more is needed for using the theory and understanding its nature. To begin, let us examine the role of experiment in science. An experiment is an active intervention into the course of Nature: We set up this or that experiment to see how Nature reacts. We have learned something new when we can distill from the accumulated data a compact description of all that was seen and an indication of which further experiments will corroborate that description. This is what science is about. If, from such a description, we can *further* distill a model of a free-standing "reality" independent of our interventions, then so much the better. Classical physics is the ultimate example of such a model. However, there is no logical necessity for a realistic worldview to always be obtainable. If the world is such that we can never identify a reality independent of our experimental activity, then we must be prepared for that, too.

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

Quantum probabilities, like all probabilities, are computed by using any available information. This can include, but is not limited to information about a system's preparation. The mathematical instrument for turning the information into statistical predictions is the probability rule postulated by Max Born.[1] The conclusiveness of Born's rule is known today to follow from a theorem due to Andrew Gleason.[2] It is enough to assume that yes-no tests on a physical system are represented by projection operators P, and that probabilities are additive over orthogonal projectors. Then there exists a density matrix ρ describing the system such that the probability of a "yes" answer is $\mathrm{tr}(\rho P)$. The compendium of probabilities represented by the "quantum state" ρ captures everything that can meaningfully be said about a physical system.

Here, it is essential to understand that the validity of the statistical nature of quantum theory is not restricted to situations where there are a large number of similar systems. Statistical predictions do apply to single events. When we are told that the probability of precipitation tomorrow is 35%, there is only one tomorrow. This tells us that it is advisable to carry an umbrella. Probability theory is simply the quantitative formulation of how to make rational decisions in the face of uncertainty.

We do not deny the possible existence of an objective reality independent of what observers perceive. In particular, there is an "effective" reality in the limiting case of macroscopic phenomena like detector clicks or planetary motion: Any observer who happens to be present would acknowledge the objective occurrence of these events. However, such a macroscopic description ignores most degrees of freedom of the system and is necessarily incomplete. Can there also be a "microscopic reality" where every detail is

completely described? No description of that kind can be given by quantum theory, nor by any other reasonable theory. John Bell formally showed[3] that any objective theory giving experimental predictions identical to those of quantum theory would necessarily be nonlocal. It would eventually have to encompass everything in the universe, including ourselves, and lead to bizarre self-referential logical paradoxes. The latter are not in the realm of physics; experimental physicists never need bother with them.

We have experimental evidence that quantum theory is successful in the range from 10^{-10} to 10^{15} atomic radii; we have no evidence that it is universally valid. Yet, it is legitimate to attempt to extrapolate the theory beyond its present range, for instance, when we probe particle interactions at superhigh energies, or in astrophysical systems, including the entire universe. Indeed, a common question is whether the universe has a wavefunction. There are two ways to understand this. If this "wavefunction of the universe" has to give a complete description of everything, including ourselves, we again get the same meaningless paradoxes. On the other hand, if we consider just a few collective degrees of freedom, such as the radius of the universe, its mean density, total baryon number, and so on, we can apply quantum theory only to these degrees of freedom, which do not include ourselves and other insignificant details. This is not essentially different from quantizing the magnetic flux and the electric current in a SQUID while ignoring the atomic details. For sure, we can manipulate a SQUID more easily than we can manipulate the radius of the universe, but there is no difference in principle.

Does quantum mechanics apply to the observer? Why would it not? To be quantum mechanical is simply to be amenable to a quantum description. Nothing in principle prevents us from quantizing a colleague, say. Let us examine a concrete example: The observer is Cathy (an experimental physicist) who enters her laboratory and sends a photon through a beam splitter. If one of her detectors is activated, it opens a box containing a piece of cake; the other detector opens a box with a piece of fruit. Cathy's friend Erwin (a theorist) stays outside the laboratory and computes Cathy's wavefunction. According to him, she is in a 50/50 superposition of states with some cake or some fruit in her stomach. There is nothing wrong with that; this only represents his knowledge of Cathy. She knows better. As soon as one detector was activated, her wavefunction collapsed. Of course, nothing dramatic happened to her. She just acquired the knowledge of the kind of food she could eat. Some time later, Erwin peeks into the laboratory:

Thereby he acquires new knowledge, and the wavefunction he uses to describe Cathy changes. From this example, it is clear that a wavefunction is only a mathematical expression for evaluating probabilities and depends on the knowledge of whoever is doing the computing.

Cathy's story inevitably raises the issue of reversibility; after all, quantum dynamics is time-symmetric. Can Erwin undo the process if he has *not yet* observed Cathy? In principle he can, because the only information Erwin possesses is about the consequences of his potential experiments, not about what is "really there." If Erwin has performed no observation, then there is no reason he cannot reverse Cathy's digestion and memories. Of course, for that he would need complete control of all the microscopic degrees of freedom of Cathy and her laboratory, but that is a practical problem, not a fundamental one.

The peculiar nature of a quantum state as representing information is strikingly illustrated by the quantum teleportation process.[4] In order to teleport a quantum state from one photon to another, the sender (Alice) and the receiver (Bob) need to divide between them a pair of photons in a standard entangled state. The experiment begins when Alice receives another photon whose polarization state is unknown to her but known to a third-party preparer. She performs a measurement on her two photons-one from the original, entangled pair and the other in a state unknown to her-and then sends Bob a classical message of only two bits, instructing him how to reproduce that unknown state on his photon. This economy of transmission appears remarkable, because to completely specify the state of a photon, namely one point in the Poincaré sphere, we need an infinity of bits. However, this complete specification is not what is transferred. The two bits of classical information serve only to convert the preparer's information, from a description of the original photon to a description of the one in Bob's possession. The communication resource used up for doing that is the correlated pair that was shared by Alice and Bob.

It is curious that some well-intentioned theorists are willing to abandon the objective nature of physical "observables," and yet wish to retain the abstract quantum state as a surrogate reality. There is a temptation to believe that every quantum system has a wavefunction, even if the wavefunction is not explicitly known. Apparently, the root of this temptation is that in classical mechanics *phase space* points correspond to objective data, whereas in quantum mechanics *Hilbert space* points correspond to quantum states. This analogy is misleading: Attributing reality to quantum states leads to a host of

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"quantum paradoxes." These are due solely to an incorrect interpretation of quantum theory. When correctly used, quantum theory never yields two contradictory answers to a well-posed question. In particular, no wavefunction exists either before or after we conduct an experiment. Just as classical cosmologists got used to the idea that there is no "time" before the big bang or after the big crunch, so too must we be careful about using "before" and "after" in the quantum context.

Quantum theory has been accused of incompleteness because it cannot answer some questions that appear reasonable from the classical point of view. For example, there is no way to ascertain whether a single system is in a pure state or is part of an entangled composite system. Furthermore, there is no dynamical description for the "collapse" of the wavefunction. In both cases the theory gives no answer because the wavefunction is not an objective entity. Collapse is something that happens in our description of the system, not to the system itself. Likewise, the time dependence of the wavefunction does not represent the evolution of a physical system. It only gives the evolution of our probabilities for the outcomes of potential experiments on that system. This is the only meaning of the wavefunction.

All this said, we would be the last to claim that the foundations of quantum theory are not worth further scrutiny. For instance, it is interesting to search for minimal sets of *physical* assumptions that give rise to the theory. Also, it is not yet understood how to combine quantum mechanics with gravitation, and there may well be important insight to be gleaned there. However, to make quantum mechanics a useful guide to the phenomena around us, we need nothing more than the fully consistent theory we already have. Quantum theory needs no "interpretation."

References

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FUCHS AND PERES REPLY: Like Paul Harris, we had an old friend in Alexandria. His name was Euclid. When we asked him whether his famous books *Elements* needed an interpretation, he answered categorically: "Absolutely not! Geometry is an abstract formalism and all you can demand of it is internal consistency. However, you may seek material objects whose behavior mimics the theorems of geometry, and that involves interpretation. For example, light rays might be considered analogous to straight lines." More than 2000 years later, we met a much younger friend in Göttingen and asked him eagerly, "Bernhard, have you really found a new, improved interpretation of Euclidean geometry?" His answer was no less categorical: "Riemannian geometry is not at all a new way of presenting Euclid's work. It is a broader formalism, having Euclidean geometry as a limiting case. Just reinterpreting Euclidean geometry without introducing radically new features would have been an illusion of progress. If some day people find that light rays do not behave as Euclid's straight lines, my geodesics may turn out to be a good description of them."

We do not claim that contemporary quantum theory is the final word for a description of nature; this should be clear from the last paragraph of our "Opinion" essay. There may some day be indications that our description of nature by means of vectors in a complex linear space is insufficient to represent *experimental* evidence. A more general theory may then be needed to extend the present formalism. However, as Daniel Styer correctly points out, the various "interpretations" of quantum mechanics cannot be distinguished through *experiments*. If they could, they would not be new interpretations, but proposals for new theories.

Styer compares these "interpretations" with the various formulations of classical mechanics: Lagrangian, Hamiltonian, Liouvillian, and others. The analogy is not correct. Quantum mechanics also has different formulations, such as those due to Heisenberg (close in spirit to Hamilton), Schrödinger (close to Liouville), and Feynman (which relies on a classical Lagrangian). All these formulations are mathematically equivalent and the choice of one of them for solving a particular problem is a matter of convenience. On the other hand, the so-called interpretations of quantum theory introduce new concepts, such as an infinity of parallel worlds, without any experimental support nor any benefit to the theorist who performs calculations to be compared with experiment. These gratuitous additions to quantum theory are the true analogs to Ptolemy's epicycles in Harris's story.

Stanley Sobottka apparently wishes to retain some objective status for the quantum wavefunction. He writes that interference phenomena always suggest that physical waves are interfering, and that "our understanding is greatly enhanced if we assume that the pattern is caused by actual, physical waves." However, Sobottka himself has reservations about this assumption, which is untenable for higher-order interference effects involving two or more particles. This is a problem Wendall Holladay runs into immediately when he says, "The wavefunction of the four outer electrons in the ground state of the carbon atom produces a tetrahedral structure in Euclidean three-dimensional space that undergirds the observed tetrahedral structure of the diamond crystal. This is an objective fact about the physical world ... ." The truth is that the wavefunction of the four outer electrons lives in a 12-dimensional space, while our tangible physical world has only three dimensions. This example (contrary to its intended purpose) is an excellent one for showing that the wavefunction is a mathematical tool, not a physical object.

Holladay asks rhetorically, "How could a theory that does not describe physical reality give such accurate results for the magnetic moment of the electron and correctly predict the existence of antiparticles?" Similarly we could ask: How can ordinary probability theory give such reliable results in the gambling house, knowing as it does nothing whatsoever about the dynamics of the roulette wheel? The probabilistic predictions we make in gambling would work just as well whether the ultimate underlying physics were deterministic or, instead, indeterministic.[1] The point is that a theory need make no direct reference to reality in order to be successful or to be perfectly accurate in some of its predictions. Probability theory is a prime example of that because it is a theory of how to reason best in light of the information we have, regardless of the origin of that information. Quantum theory shares more of this flavor than any other physical theory. Significant pieces of its structure could just as well be called "laws of thought" as "laws of physics." However, this does not preclude quantum theory from making *some* predictions with absolute certainty. Among these predictions are the quantitative relationships between physical constants such as energy levels, cross sections, and transition rates that Holladay mentions.

The fallacy in Holladay's presumptive question is common to people not accustomed to quantum lines of thought. He makes no distinction between nature, which we try to understand, and the description of our experimental interventions into it. Accepting a distinction between these concepts requires only that we humble ourselves before nature,

something our present scientific community is often reluctant to do. On the other hand, attempting to identify the two concepts discloses nothing more than a prejudice for a method that, in the past, seemed to work well in the classical world.

When experimenters have similar information, they should make—on the rules of quantum mechanics—similar predictions and draw similar conclusions. By this account, quantum mechanics is a scientific theory without rival. We feel comfortable in saying that diamonds have tetrahedral symmetry because, on any number of occasions, various experimenters have checked this with great accuracy. They could do that because this aspect of carbon is part of the "effective reality" quantum theory produces in some regimes of our experience. Indeed, this "effective reality" forms the ground for all our other quantum predictions simply because it is the part of nature that is effectively detached from the effect of our experimental interventions. But, if one tries to push this special circumstance further and identify an overarching "reality" completely independent of our interventions, then this is where the trouble begins and one finds the *raison d'être* of the various "interpretations."

Todd Brun and Robert Griffiths point out that "physical theories have always had as much to do with providing a coherent picture of reality as they have with predicting the results of experiment." Indeed, *have always had*. This statement was true in the past, but it is untenable in the present (and likely to be untenable in the future). Some people may deplore this situation, but we were not led to reject a free-standing reality in the quantum world out of a predilection for positivism. We were led there because this is the overwhelming message quantum theory is trying to tell us.

The main point of disagreement we have with Brun and Griffiths is about the existence of a wavefunction of the universe that would include *all* its degrees of freedom, even those in our brains. We assert that this would lead to absurd self-referential paradoxes. Therefore, it is necessary to restrict the discussion to a (reasonably small) subset of the dynamical variables. Brun and Griffiths ask, "Can we only describe the Big Bang, or an exploding supernova, in terms of the light that reaches our telescopes?" We never demanded such a restriction. We did not claim that only what is directly observed exists. There is much more to say about astrophysical phenomena than just describing the light that originates from them. Yet, their description cannot be so detailed as to include every particle involved in their observation, such as those in the retina of the observer, in the

optic nerves, in the brain cells, etc. A limit must be put somewhere between the object of our description and the agent that performs that description. Quantum theory can describe *anything*, but a quantum description cannot include *everything*.[2]

We agree with Brun and Griffiths that the violation of Bell's inequality by quantum theory is not a proof of its nonlocality. Quantum theory is essentially local. Bell's discovery was that any *realistic* theory that could mimic quantum mechanics would necessarily be nonlocal. Near the end of his life, Bell was indeed inclined to seek such a theory, bearing traces of realism and nonlocality. We do not rule out that such an extension of quantum theory may some day be produced, but no one so far has achieved this goal in a useful fashion, nor is an extension required for a clear understanding of the quantum phenomena about us.

We surely agree with Brun and Griffiths that "in science, one cannot rule out alternatives by fiat; one must evaluate them on their merits." We do not find any merit in the various alternatives that were proposed to the straightforward interpretation of quantum theory: It is a set of rules for calculating probabilities for macroscopic detection events, upon taking into account any previous experimental information. Brun and Griffiths may think this a "straitjacket," but it prevents the endless conundrums that arise solely from shunning quantum theory's greatest lesson—that the notion of experiment plays an irreducible role in the world we are trying to describe.

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