

NEGOTIATING THE TRICKY BORDER BETWEEN QUANTUM AND CLASSICAL

In his article "Decoherence and the Transition from Quantum to Classical" (October 1991, page 36) Wojciech H. Zurek has outlined a description of the quantum measurement process that is contained within quantum theory itself. As such, it stands in contrast to views such as those of Roger Penrose,¹ who holds that quantum mechanics is incomplete and is unable to describe the measurement process without additional physics. In Zurek's view, decoherence, that is, the loss of coherence in an initially coherent state, or, as it is sometimes referred to, the collapse of the wavefunction, arises during the measurement process through the interaction of the system being measured, the measuring apparatus and the external environment.

Two things puzzle me about Zurek's article. For one, it makes no mention of David Bohm's analysis² of the measurement process. Bohm also developed an analysis of the measurement process that led to decoherence without additional assumptions such as John von Neumann's "process 1." But unlike in Zurek's proposal, the decoherence comes about solely through the interaction of the system being observed and the measuring apparatus. Bohm argued that for a measurement to be made, the measuring apparatus had to be able to distinguish macroscopically between the possible microscopic states of the system being measured, and then showed that after the system interacted with such an apparatus the system's initial, coherent state became effectively a decoherent or mixed state to a high degree of approximation.

Zurek argues that "unitary evolution condemns every closed quantum system to 'purity.'" Nevertheless, Bohm's analysis deals with a closed system: the system being observed plus the measuring apparatus, which together satisfy a Schrödinger equation. Although the total state vector remains coherent throughout the

measurement, it effectively decoheres to a high degree of approximation. Thus in a Stern-Gerlach measurement of the spin of an atom one can assert with almost absolute certainty that the z component of the spin of the atoms is up in the upper beam and down in the lower beam even though there is a vanishingly small but finite probability of the reverse's being true for any one atom. However, as Bohm showed, the better the measurement, the less likely is this possibility.

The other puzzling thing about Zurek's approach is the way in which the system being observed interacts with its environment. He seems to be claiming that this interaction takes place only during the measurement process. But what keeps the system from interacting and decohering at other times? Alternatively, one might ask, What turns the interaction on just during the measurement?

Aside from this latter difficulty, Zurek's analysis of the interaction of a quantum system with its environment using the Wigner distribution appears to offer a new and useful way of analyzing the mesoscopic domain lying between the classical and the quantum ones.

References

1. R. Penrose, *The Emperor's New Mind*, Oxford U.P., Oxford (1989).
2. D. Bohm, *Quantum Theory*, Prentice-Hall, Englewood Cliffs, N.J. (1951), ch. 22.

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12/91

In his article on decoherence, Wojciech H. Zurek asserts that because of the studies he describes, there is "a growing consensus" that the quantum measurement problem is being resolved. Zurek's resolution requires, for every physical situation, the identification of a microscopic system, a detector and an environment. By tracing over the environment states

he shows that the reduced density matrix describes decohering detector states, and he declares: "A preferred basis of the detector . . . has been singled out. . . . Moreover, we have obtained all this—or so it appears—without having to appeal to anything beyond the ordinary, unitary Schrödinger equation."

A consensus depends upon who is polled. Zurek's consensus certainly didn't include John Bell, who warned: "Here are some words which, however legitimate and necessary in application, have no place in a *formulation* with any pretension to physical precision: system, apparatus, environment. . . . The concepts 'system,' 'apparatus,' 'environment,' immediately imply an artificial division of the world."¹ Indeed, contrary to Zurek's assertion, an appeal *has* been made that goes beyond the ordinary Schrödinger equation, to a prior split of a physical system into microscopic system, detector and environment. But no rules have ever been given for making such a split, and certainly a physical system does not come with a subsystem containing a little sign reading, "I am the environment: Trace over me." Without such rules one cannot, in the general case, apply the environment-trace prescription to determine what is desired, namely the "preferred basis" states that one can actually observe. Thus the whole scheme appears devoid of fundamental significance.

To apply decoherence ideas in the context of a quantum theory of the universe, which has no environment to trace over, Zurek advocates the "many histories" approach, which is supposed to give us the "preferred histories" that actually can occur, together with their probabilities. But no one has ever given the rules for obtaining the set of projection operators needed to define the mutually exclusive alternative histories. Indeed, one can choose different sets of projection operators such that one is faced with different sets of alternative

histories, with no criterion for choosing the set actually relevant to our world.² Once again, we see that the interpretation and its application require *something* besides the criteria of decoherence, and that something is ill defined.

No interpretation of the quantum formalism, as it stands, has been able to respond satisfactorily to the following operational test: Given a state vector describing, say, 10^{30} particles and the Schrödinger equation describing its evolution, but no more information (that is, you are not told whether it describes a laboratory in which a single particle is undergoing a scattering experiment, a mouse in the woods, or anything else), give a prescription for determining the preferred-basis states that can actually occur. But even were this preferred-basis problem to be solved, a deeper difficulty would remain. The problem with standard quantum theory, well described by Zurek, is that it readily generates a state vector that is the sum of macroscopically different preferred-basis states, whereas in nature we actually see one or another of these macroscopic states. Therefore one must interpret the state vector of standard quantum theory as describing something other than the individual reality we see around us.

This leads us to advertise the approach we favor. We hypothesize that the state vector ought to describe the nature we see. That it does not provide such a description we regard as a clue suggesting that the Schrödinger equation ought to be modified. The modification should be such that the state vector describing the evolution of a microscopic system is scarcely affected but the state vector of a macroscopic system, except for extremely brief intervals of time (during which "reduction" dynamically takes place), always describes an observed macroscopic state. This program, now in its 25th year, has recently progressed quite rapidly. In its present form (the continuous spontaneous localization theory³) it offers a modified linear Schrödinger equation possessing a new term that depends upon a randomly fluctuating field. This term distinguishes states in a superposition that differ from one another in particle number density anywhere in space. If the differences in particle number density are large enough, the superposition rapidly evolves to one or another of these states (depending upon what fluctuation actually occurs); the dynamics thereby determines the observed macroscopic preferred-basis states in a well-defined way. If there are small differences in

particle number density, as for a microscopic system, the reduction takes place at a negligible rate.

Although the theory may appear somewhat *ad hoc*, it is actually highly constrained by the necessity of agreement with the spectacular successes of standard quantum theory and with the idea that it should be a mathematically precise formalism allowing a unified description of all phenomena, containing a single fundamental dynamical principle that governs all processes, and having nothing else in it but the wavefunction. In particular, there is no need for additional, ill-defined concepts like environment, apparatus and system. The dynamics lets microscopic systems spread out and interfere, and it prevents macroscopic systems from doing so. It has some experimental consequences that differ from predictions of standard quantum theory, so it is a testable theory. It is a Galilean-invariant theory, but some progress has been made toward a special relativistic generalization.⁴ Unlike standard quantum theory in any of its interpretations, its preferred-basis states are well defined, it opens the door to an explanation of why we get one result rather than another when we do a quantum experiment, and it allows the state vector to describe reality as we see it.

References

1. J. S. Bell, in *Sixty-two Years of Uncertainty*, A. Miller, ed., Plenum, New York (1990), p. 19.
2. See, for example, B. d'Espagnat, *Phys. Lett. A* **124**, 204 (1987); A. Rimini, in *Classical and Quantum Systems—Foundations and Symmetries*, D. Doebner, W. Scherer, F. Shroeck Jr, eds., World Scientific, Singapore (in press).
3. See the review articles by G. Ghirardi and A. Rimini and by P. Pearle in *Sixty-two Years of Uncertainty*, A. Miller, ed., Plenum, New York (1990), pp. 167 and 193, respectively, with refs. including the important contributions of V. P. Belavkin, J. S. Bell, L. Diosi, N. Gisin and T. Weber.
4. G. C. Ghirardi, R. Grassi, P. Pearle, in *Symp. on Foundations of Modern Physics*, P. Lahti, P. Mittelstaedt, eds., World Scientific, Singapore (1990), p. 109; *Found. Phys.* **20**, 1271 (1990).

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I am surprised that physicists, and even specialists like Wojciech Zurek, present the passage from the Schrödinger equation

$$i\hbar \frac{d\psi}{dt} = H\psi \quad (1)$$

to a diagonal mixed state

$$\rho = \begin{pmatrix} a & 0 \\ 0 & b \end{pmatrix} \quad (2)$$

as the solution of the "quantum measurement problem" or, more generally, as the signature of the emergence of classical physics out of quantum physics. Actually equation 2 has already been derived from equation 1 with an infinite environment (called at that time the "reservoir") in the 1970s by Klaus Hepp,¹ Barbara Whitten-Wolfe and Gérard G. Emch,² and others.

But anyway, what does equation 2 really tell us? Zurek writes, "The coefficients [of equation 2] may be interpreted as classical probabilities." Well, one can do a lot of things! The term ρ can indeed represent a probability distribution of pure states. But it can also represent infinitely many other such distributions. Why choose one rather than the other? Is such a choice an additional quantum postulate? Moreover, in my lab I do not see pure states; I measure frequencies of events. And the very concept of events is present neither in equation 1 nor in equation 2! This is, I believe, the crucial question. The event is the basic concept of relativity, but in quantum physics it is not yet even defined. It is hopeless to try to relate a theory that does not include a representation of events to real and laboratory life in a rigorous way.

Finally, another point about the approximation necessary to go from equation 1 to equation 2: It is a first-year exercise to prove that a unitary evolution such as equation 1 describes always maps pure states into pure states, so that equation 2 can only be an approximation. Now, Zurek and others have proved that the discrepancy between equation 2 and the exact solution can never be detected in practice after the coherence time. This reminds me of the very pragmatic reasoning of my children: It is not forbidden to do silly things, but it is forbidden to get caught. Can our basic understanding of our fundamental physical theory rely on such pragmatic pseudophilosophy?

References

1. K. Hepp, *Helv. Phys. Acta* **45**, 237 (1972).

continued on page 81

continued from page 15

2. B. Whitten-Wolfe, G. G. Emch, *Helv. Phys. Acta* **49**, 45 (1976).

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Wojciech Zurek attempts to revive an old argument to the effect that a central problem at the foundations of quantum mechanics, the so-called problem of measurement, can be resolved through a careful analysis of the interactions of measuring systems with their environments. While we agree that Zurek's analysis of that interaction is a valuable and accurate one, we do not think that it answers the question raised about measurement theory—namely, how to account for the emergence, at the macroscopic level, of determinate, classical states of affairs, even though there may frequently fail to be any determinate matter of fact about whether, say, a given electron is to the left of a given proton or to the right of it.

Zurek's argument exemplifies one particular confusion about solving that problem that, no matter how often and how definitely it has gotten cleared up, has resurfaced again shortly later on, in slightly different garb and with new vigor, throughout the recent history of theoretical physics.¹ The confusion consists (very briefly) in supposing that certain features of the interactions between macroscopic physical systems and their environments allow us to regard superpositions of macroscopically different states (unlike superpositions of microscopically different ones) as situations in which either one or another of those macroscopically different states actually *obtains*.

We would like to make one further attempt at clearing up that confusion.

Let's start with the basics. Remember why the proposition that a certain physical system is in a coherent superposition of the states $|A\rangle$ and $|B\rangle$ has always been thought to be incompatible with the proposition that the system is in either state $|A\rangle$ or state $|B\rangle$ but we don't know which: It's because there are necessarily real, physical, measurable properties of the coherent superposition of states $|A\rangle$ and $|B\rangle$ (whatever those states are) that are properties of neither $|A\rangle$ nor $|B\rangle$ separately, and that consequently also cannot be properties of a situation that is *either* $|A\rangle$ or $|B\rangle$ but we don't know which. That's what taught us to say of such superpositions that they represent not situations in which we are *ignorant* of whether it is $|A\rangle$ or $|B\rangle$ that obtains, but rather situations in which there is

simply not any *fact* to the matter of whether $|A\rangle$ or $|B\rangle$ obtains.

Consider, for example, an electron in a coherent superposition of an "up" z -spin state and a "down" z -spin state with equal coefficients. That superposition has the property that, with certainty, the x spin is "up." Neither the "up" nor the "down" z -spin state, nor any situation in which either one or the other of those states (but we don't know which) obtains, has that property.

Precisely the same sort of thing is true of, say, the z spin of an electron in an atom of hydrogen in its ground state, in which the spins of the electron and the proton are quantum mechanically *entangled*. That state (which is a coherent superposition of one state in which the z spin of the electron is "up" and another in which it is "down") is associated not with a definite value of any spin-observable of the electron by itself nor with any spin-observable of the *proton* by itself, but rather with a definite value (namely 0) of the total spin angular momentum of the *two*-particle system. And it happens that there is no state of that two-particle system in which the z spin of the electron is "up" and the total spin angular momentum is 0, nor is there a state of that system in which the electron's z spin is "down" and the total spin angular momentum is 0. Thus the total spin angular momentum's being 0 is simply *incompatible* with the hypothesis that there is any fact of the matter about the value of the electron's z spin.

And so it goes for superpositions in general.

Now, what Zurek and his predecessors have accurately pointed out is that the observable properties of the world that have determinate values for coherent superpositions of *macroscopically* different quantum states (that is, the properties analogous to the x spin and the total spin angular momentum in the two *microscopic* examples above) turn out to be extraordinarily difficult to measure in practice. To put it another way, they have pointed out that the values of those properties tend to be radically unstable—that the states of macroscopic systems tend to become very quickly and very intricately entangled with the states of their environments.

And we agree with all that.

But it certainly does not entail what Zurek and his predecessors seem to think it does. That is, it does not entail that superpositions of macroscopically different states can be regarded as situations in which either

one or another of those states, but we don't know which, actually *obtains*. The situation is, alas, precisely the same on the macroscopic level as on the microscopic one. According to quantum theory the world has certain definite physical properties when such superpositions obtain that it would not have in the event that one or another of the superposed states obtained. The *practical measurability* of those properties is completely beside the point; all that's relevant to the question at issue here is their *reality*. And since Zurek and his predecessors accept that the linear quantum mechanical equations of motion can be taken as the true and complete equations of motion of the entire physical world, the reality of those properties is not in dispute.

That's why the interactions of measuring devices with their environments cannot be regarded as a solution to the quantum mechanical measurement problem.

Reference

1. Some examples of that confusion (of which there are many others) can be found in A. Daneri, A. Loinger, G. M. Prosperi, *Nucl. Phys.* **33**, 297 (1962), and in A. Peres, *Phys. Rev. D* **22**, 879 (1980). One attempt to clear that confusion up can be found in J. S. Bell, *Helv. Phys. Acta* **48**, 93 (1975).

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[*Editor's note:* The above letter was edited and shortened after Gerald Feinberg's death. (See the obituary in *PHYSICS TODAY*, January, page 84.)]

A striking feature of Wojciech H. Zurek's discussion of the connection between classical and quantum mechanics is the absence of any reference to the interpretation of quantum mechanics in which this relation is most transparent, the de Broglie-Bohm theory of motion.¹ Attempts to account for the classical behavior of quantum systems purely in terms of wavefunctions and density matrices miss the point: The classical concept of state, that is, the position of a corpuscle at each instant of time, is logically distinct from and not contained as a special case in the quantum concept of state—not even as an approximation. This point is overlooked in the books. It means that a treatment based on wavefunctions alone can never arrive at a consistent conceptual or mathematical derivation of classical mechanics from quantum

mechanics. At some stage the particle trajectory is slipped in by hand.

The de Broglie-Bohm theory shows how one may consistently attribute precise position and momentum variables simultaneously to a quantum system in arbitrary quantum states. The connection with the classical regime is thus established at the outset, and the approach provides quite novel twists to the study of the quantum-classical interface. (For example, it shows that the generic classical multivalued trajectory fields can never emerge from the single-valued wavefunction.) Within the de Broglie-Bohm framework the problem of attributing definite outcomes to measurement operations is almost trivially solved. The apparatus and observed systems *always* have well-defined locations, and these simply evolve in a correlated fashion under the influence of the global wavefunction in such a way that looking at the apparatus allows us to infer the state of the object. This is an entirely objective process.

In contrast, the pure wavefunction analysis does not solve the measurement problem. To begin with, arranging for the density matrix to "decohere" results only in an improper mixed state (in which the component pure states coexist), not in the proper mixture required for a unique outcome. But more seriously, even if the proper mixture were obtained, the objective classical system described by well-defined spatial coordinates would not have been deduced. Arranging for the wavefunction (or some function derived from it) to be peaked about a classical orbit does not address this issue. In its conventional interpretation the wavefunction determines the probability distribution in the outcomes if measurements are performed. Tacitly shifting the interpretation so that it refers to the likely *actual* location of a substantive object, which is ultimately what one must do, is precisely the de Broglie-Bohm theory!

Quantum physicists often implicitly invoke the assumptions of Louis de Broglie and David Bohm, and it is truly remarkable that a theory that is so perfectly suited to settling a wide range of quantum puzzles should continue to be so systematically ignored.

Reference

1. For a comprehensive presentation see P. R. Holland, *The Quantum Theory of Motion*, Cambridge U.P., New York (1992).

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As a practicing quantum mechanic who, whenever he thinks deep thoughts about the foundations of quantum mechanics, has the sneaking suspicion that he is thinking shallow thoughts about the foundations of quantum mechanics, I am of course familiar with the point of view expressed by Wojciech Zurek, because his is the standard way in which quantum mechanics operate:

▷ When in doubt, enlarge a system to include its immediate environment.

▷ Calculate using instructions written in Göttingen and printed in Copenhagen.

▷ Average over unobserved variables to produce nonunitary, dissipative time evolution in the system of direct interest.

This procedure has always worked in my experience in condensed matter physics, where there in fact is an environment ready to smother the coherence in the quantum development of a subsystem. I have to confess that I would be disappointed if this were all there is to interpreting quantum mechanics at the cosmic level but, alas, have nothing to contribute to that question.

In one area Zurek's presentation may be misleading. Below his equation 10 for the decoherence time scale τ_D , he writes that in certain cases " τ_D can be more than τ_R ," the relaxation time γ^{-1} . He thus leaves open the possibility that his "master equation" for the evolution of the density matrix $\rho(x, x')$ of the particle in the position representation, equation 9, can be used for microscopic objects localized on the scale of the thermal de Broglie wavelength $\Lambda_T = \hbar/\sqrt{2mk_B T}$. Actually, equation 9 does not hold on such length scales, as can be seen in the following way:¹ Since ρ is a density matrix, it must obey $\langle \psi | \rho | \psi \rangle \geq 0$ for any state. Suppose that at $t = 0$, ρ describes a pure state, so that $\rho(0) = |\phi\rangle\langle\phi|$. Let the wavefunction $\phi(x)$ be even in x , and choose $\psi(x) = d\phi/dx$. Evidently, $\langle \psi | \rho(0) | \psi \rangle = 0$. From equation 9 it follows that

$$\begin{aligned} \left\langle \psi \left| \frac{d\rho}{dt} \right| \psi \right\rangle_{t=0} &= 2\gamma \left(\int dx \psi(x) x \phi(x) \right) \\ &\quad \times \left(\int dx \psi(x) \frac{d}{dx} \phi(x) \right) \\ &\quad + \frac{4mk_B T \gamma}{\hbar^2} \left(\int \psi x \phi \right)^2 \end{aligned}$$

Now, the first term in parentheses above is negative and can be made as negative as one wishes by choosing $\phi(x)$ to be more and more peaked around $x = 0$. This means that the

right-hand side can be made negative, with the consequence that ρ violates the positivity requirement at small positive times. By choosing $\phi(x)$ to be a Gaussian centered at the origin one sees that the thermal de Broglie wavelength Λ_T is the scale below which this disease manifests itself.

I have published² the resolution of this puzzle in the proceedings of a conference celebrating the 50th anniversary of the publication of Hendrik A. Kramers's famous paper on Brownian motion.³ The point, if I am correct, is that all previous derivations of equation 9 fail to notice terms that on time scales corresponding to the duration of several collisions correlate the environment and the system. On such short time scales the time evolution does not operate on the reduced density matrix, that is, the ρ of equation 9, alone. The new terms, which describe stochastic transfers of energy, can be ignored only when one averages over these short times: Equation 9 is recovered, but the uncertainty principle then forbids lengths on the scale of Λ_T . All this is not surprising, since the derivation of the classical Fokker-Planck equation,^{3,4} to which equation 9 reduces, requires coarse-graining over several collisions.

The most explicit and down-to-earth treatment of loss of quantum coherence by way of interaction with an environment is perhaps to be found in the literature on nuclear magnetic resonance—a subject developed by physicists who could do their own theory quite well, thank you. Loss of phase coherence is described by the T_2 relaxation time in Felix Bloch's phenomenological equations, derived from a density matrix formulation by Alfred G. Redfield.⁵

I am happy to acknowledge helpful discussions with Dana Browne, currently at Louisiana State University, and Mark Oxborrow, a graduate student at Cornell now working—à *chacun son goût*—on quasicrystals.

References

1. P. Pechukas, in *Large-Scale Molecular Systems*, Proc. NATO Adv. Study Inst., Manatee, Italy, Spring 1990, W. Gans *et al.*, eds., Plenum, New York (1991), p. 123.
2. V. Ambegaokar, Ber. Bunsenges. Phys. Chem. **95**, 400 (1991). The first sentence of the second paragraph on p. 401, "It is worth nothing already . . .," is not translated from the Yiddish: "nothing" should be, and was when the proofs left my hand, "noting."
3. H. A. Kramers, Physica **8**, 284 (1940).
4. S. Chandrasekhar, Rev. Mod. Phys. **15**, 1 (1943).

5. A. G. Redfield, IBM J. Res. Dev. 1, 19 (1957). C. P. Slichter, *Principles of Magnetic Resonance*, Springer-Verlag, New York (1980), sec. 5.6.

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Wojciech H. Zurek's article is very lucid and incisive. It implies that the *pointer basis* determines the arrow of time and that the phase changes¹ that occur in the evolution of the universe are essentially changes in the pointer basis.

To a casual observer who perceives only those states that are most readily observable, the universe appears to evolve deterministically, because the most readily observed states are the simultaneous eigenstates of a complete set of commuting observables whose eigenfunctions form the preferred basis. A physicist with a Superconducting Super Collider, on the other hand, can observe other states (including some that are very difficult to observe in the present era), and in so doing verifies the essential probabilism of the quantum theory.

According to particle astrophysics, researchers who observe high-energy resonances are like archaeologists digging up fossils—not at all the sort of thing that the pedestrian observer is likely to come across—and the more ancient the fossil, the deeper it is buried (the more energy it takes to dig it up). These fossil states, however, were the most readily observed states of past eras. (The proton-shattering X particle—indicated in figure 3 of the article by Savas Dimopoulos, Stuart A. Raby and Frank Wilczek in *PHYSICS TODAY*, October 1991, page 25—was the *Tyrannosaurus rex* of its time, so to speak.)

Decoherence occurs spontaneously in the natural course of events, whereas "recoherence" (that is, regeneration of lost states) is extremely unlikely outside of high-energy physics laboratories. Recoherence verifies the quantum theory, while decoherence explains the apparent determinism of classical theory.

It turns out that the Moon is there even when no one looks at it (to use Einstein's analogy²). We hear it through the friction grapevine, which lets nothing go unnoticed. It also informs us that Schrödinger's cat is in a classical state, even though we do not know which one until the box is opened.

The only remaining uncertainty is in how people are going to act. The living organism is probably the most coherent system in the universe and, consistent with this, retains an

autonomy that is in sharp contrast to the predictability that results from decoherence. Yet, as Roger Penrose³ and others⁴ have pointed out, it is impossible to be at all certain what the source of this autonomy is. This may be the most striking example of the Heisenberg uncertainty principle, and the surest proof that mental functioning is a macroscopic quantum phenomenon.

In the final analysis, the human mind is at the crossroads of the infinite and the infinitesimal, and holds the key to both.⁵

References

1. Ø. Grøn, Am. J. Phys. 54, 46 (1986).
2. A. Pais, Rev. Mod. Phys. 51, 863 (1979).
3. R. Penrose, *The Emperor's New Mind: Concerning Computers, Minds, and the Laws of Physics*, Oxford U.P., Oxford (1989).
4. C. Lamont, T. W. Clark, *The Humanist*, May 1990, p. 18.
5. K. J. Epstein, Int. J. Psycho-Analysis 72, 167 (1991).

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1/92

ZUREK REPLIES: Quantum theory allows many more states for the objects it describes than we seem to encounter. Moreover, quantum dynamics (especially the dynamics required to model measurements) takes simple, localized initial states of individual systems into entangled nonlocal superpositions. We do not perceive such superpositions. Macroscopic objects always appear to us in a small classical subset of states chosen from a much larger quantum menu that is in principle available in the Hilbert space. No one has made this point more clearly than Albert Einstein, who, in a 1954 letter to Max Born, wrote: "Let Ψ_1 and Ψ_2 be solutions of the same Schrödinger equation... When the system is macroscopic and Ψ_1 and Ψ_2 are 'narrow' with respect to the macrocoordinates, then... [typically] this is no longer the case for $\Psi = \Psi_1 + \Psi_2$. Narrowness with respect to macrocoordinates is not only *independent* of the principles of quantum mechanics, but, moreover, *incompatible* with them."¹ Hence predictions of quantum theory seem to be in conflict with our perceptions.

The goal of my article was to show that this conflict is only apparent: The classical behavior of systems we encounter can be accounted for by the "openness" of the macroscopic objects, including the memory devices that we, the observers, employ to keep records. Here, in addition to addressing specific comments made by the authors of the letters above,

I will focus on the correspondence between our perception of the "familiar reality" and quantum formalism. Near the end of this note I will describe an *existential interpretation* of quantum theory. It builds on the relative-state interpretation of Hugh Everett,² but goes beyond it (and in the direction pointed out by Niels Bohr) by taking advantage of the *environment-induced superselection*—a consequence of the decoherence process—to delineate the border between the quantum and classical domains, a concept so crucial to the Copenhagen point of view.

The central lesson of decoherence is simple: There is a basic difference between the predictions of quantum theory for systems that are closed (isolated) and open (interacting with their environments). In the case of a closed system, the Schrödinger equation and the superposition principle apply literally. By contrast, for an open quantum system the superposition principle is not valid: Decoherence results in a negative selection process that dynamically eliminates nonclassical states. This consequence of openness is critical in the interpretation of quantum theory but seems to have gone unnoticed for a long time.

The distinguishing feature of classical systems is persistence of their properties—the ability to exist in predictably evolving states. The course of such evolution can in principle be computed and confirmed by observations, providing the initial state is known with sufficient accuracy. This suggests relative stability—or, more generally, predictability—as a criterion that decides which states will be used as the ingredients of the "classical reality."³ (This connection between "reality" and "predictability" is not new: Einstein, Boris Podolsky and Nathan Rosen wrote, "A sufficient condition for the reality of a physical quantity is the possibility of predicting it."⁴)

A useful analogy is with a collection of stable and unstable nuclei that can be transformed into one another by decays, but that have very different lifetimes. The composition of this sample will—after a time longer than the lifetimes of the short-lived nuclei—be dominated by the stable species (usually the end result of the decay of the unstable ones), nearly independently of its initial composition. Thus in our world we usually encounter only stable nuclei. By the same token, quantum mechanics allows one to consider and, at least in principle, to prepare a great variety of different initial states: Every state in the Hilbert space is a possibility.

However, on a time scale associated with the process of decoherence, the composition of such an arbitrarily selected sample will be dramatically altered. Only certain stable states (which—as in the nuclear analogy—turn out to be, in a sense, decay products of the unstable superpositions) will be left on the scene. In the context of the transition from quantum to classical one must keep in mind that the states of our records also must be treated as a part of the sample. And only stable records—states of neurons or other memory devices that can survive decoherence and maintain *correlations* with the measured system—can be used as a physical basis for perception.

Quantum measurement is a classic example of a situation in which a coupling of a macroscopic (but nevertheless ultimately quantum) apparatus $\mathcal{A}$ and a microscopic system $\mathcal{S}$ forces the composite object $\mathcal{A}-\mathcal{S}$ into a correlated but usually exceedingly unstable state. In a notation where $|A_0\rangle$ is the initial state of the apparatus and $|\psi\rangle$ the initial state of the system, unitary evolution establishing an $\mathcal{A}-\mathcal{S}$ correlation is described by

$$|\psi\rangle |A_0\rangle = \sum_k a_k |\sigma_k\rangle |A_0\rangle \\ \rightarrow \sum_k a_k |\sigma_k\rangle |A_k\rangle = |\Phi\rangle \quad (1)$$

This single premeasurement quantum correlation—even when it involves the macroscopic but isolated apparatus considered by David Bohm in his textbook,⁵ as related above by James L. Anderson—does not provide enough of a foundation on which to build a correspondence between quantum formalism and the familiar classical reality. It allows only for Everett-like pairing of an *arbitrary state*—including nonclassical superpositions of localized states of the apparatus (observer)—with the corresponding *relative state* of the other system. This is a prescription for a Schrödinger cat, not a resolution of the measurement problem. Bohm has realized this, and in a chapter on the relationship between quantum and classical concepts he states (with an air of resignation, and after noting the role of friction in assuring the irreversibility of measurements): “We conclude that quantum theory presupposes the classical level... it does not deduce classical concepts as a limiting case of quantum concepts.”¹⁵

What is needed is a fixed domain of states in which classical systems can safely exist, but superpositions of which are extremely unstable. What is needed is an effective superselection

rule that will outlaw superpositions of these preferred *pointer states*. Environment-induced decoherence fits this bill. The transition from a pure state $|\Phi\rangle\langle\Phi|$ to the required effectively mixed state $\rho_{\mathcal{A}\mathcal{S}} = \sum_k |a_k|^2 |\sigma_k\rangle\langle\sigma_k| |A_k\rangle\langle A_k|$ can be accomplished by coupling the apparatus $\mathcal{A}$ to the environment $\mathcal{E}$. The correlations between the record-keeping pointer states of the apparatus and the measured system will be preserved, however, in spite of an incessant measurement-like interaction between the apparatus pointer and the environment. In simple models of the apparatus one can assure this stability of correlations by postulating the existence of a record-keeping pointer observable Λ with eigenstates (or, more precisely, eigenspaces) that remain unperturbed in the course of evolution of the open system. This requirement will be exactly satisfied when the total Hamiltonian depends on and, therefore, commutes with Λ :

$$[H + H_{\text{int}}, \Lambda] = 0 \quad (2)$$

where H_{int} is the interaction Hamiltonian. For an idealized quantum apparatus this condition can be assumed, and—providing that the apparatus is in one of the eigenstates of Λ —it leads to an uneventful evolution, $|A_k\rangle |\mathcal{E}_0\rangle \rightarrow |A_k\rangle |\mathcal{E}_k(t)\rangle$. However, when the initial state is a superposition of the eigenstates of Λ , the $\mathcal{A}-\mathcal{E}$ combination will evolve into an entangled state: $(\sum_k a_k |A_k\rangle) |\mathcal{E}_0\rangle \rightarrow \sum_k a_k |A_k\rangle |\mathcal{E}_k(t)\rangle$.

Correlation with the environment makes the decay of the interference terms inevitable. This is why—as Anderson notes in his second comment—the environment causes decoherence only when the apparatus is forced into a superposition of states that are distinguished by their effect on the environment. The basic act—the establishment of a quantum correlation—happens just once in quantum measurements, but is (crudely speaking) repeated in the process of decoherence with a frequency corresponding to the decoherence time scale. The monitoring by the environment is then an unending sequence of such correlation-inducing interactions. And (as Philip Anderson is fond of emphasizing in the context of phase transitions) “more is different.” Moreover, the information lost to the environment becomes effectively inaccessible, and thus $\mathcal{E}$ must be traced out.

Effective reduction of the state vector immediately follows. When the environment becomes correlated with the apparatus, $|\Phi\rangle |\mathcal{E}_0\rangle \rightarrow \sum_k a_k |A_k\rangle |\sigma_k\rangle |\mathcal{E}_k(t)\rangle = |\Psi\rangle$, then

we will have the desired outcome:

$$\rho_{\mathcal{A}\mathcal{S}} = \text{Tr}_{\mathcal{E}} |\Psi\rangle\langle\Psi| \\ = \sum_k |a_k|^2 |A_k\rangle\langle A_k| |\sigma_k\rangle\langle\sigma_k| \quad (3)$$

Only correlations between the pointer states and the corresponding relative states of the system retain their predictive validity.

Can a similar process be responsible for the classical behavior of systems that cannot be idealized as simply as an abstract apparatus? The crucial difference arises from the fact that in general there will be no (nontrivial) observable in such a system that will commute with both parts of the total Hamiltonian $H + H_{\text{int}}$. Thus all of the pure states—and all of the correlations—will lose coherence on some time scale. The distinction among various states will now have to be quantitative rather than qualitative: The majority of states will deteriorate on the decoherence time scale. This is the time required for the reduction of the wavepacket. For nonclassical states of macroscopic objects, it is many orders of magnitude shorter than the dynamical time scale—so short that from the point of view of the observers, responding on their dynamical time scale, it can be regarded as instantaneous.

The form of the interaction Hamiltonian will continue to play a crucial role. Monitoring of the to-be-classical observable by the environment is still the process responsible for decoherence, and H_{int} determines the set of states that leave distinguishable imprints on the environment. For example, the commutation condition, equation 2, for the interaction Hamiltonian explains the approximate localization of classical states of macroscopic objects: The environment is nearly always coupled through the coordinate x (that is, interaction potentials depend on distance). Therefore states that are localized will be favored.^{6,7} This feature of the preferred states follows from the form of the interaction alone. It does not need to be put in by hand, as is the case in the *ad hoc* scenario described by GianCarlo Ghirardi, Renata Grassi and Philip Pearle.

A natural generalization of absolutely stable pointer states of the apparatus is the most predictable states of less idealized open quantum systems. An algorithm for “trying out” all of the states in the Hilbert space can be readily outlined:³ For each candidate initial state we can calculate the density matrix that obtains from its evolution in contact with the environment, compute its

LETTERS

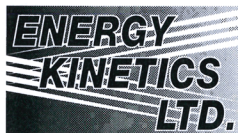
entropy as a function of time and—after an interval comfortably longer than a typical decoherence time scale—construct a list of the pure initial states, ordered according to how much entropy was generated, or how much predictability was lost, in the process. The most predictable, least entropy-producing states near the top of the list would be, in effect, the most classical. This *predictability sieve* was recently implemented for a harmonic oscillator, with the resulting evolution of the reduced density matrix generated by the appropriate master equation. For a weakly damped harmonic oscillator, the pure states selected by the predictability sieve turn out to be the familiar coherent states.⁸ And as Murray Gell-Mann and James B. Hartle have emphasized,⁹ inertia and coarseness of resolution help make the future course of events more predictable.

Vinay Ambegaokar criticizes the high-temperature master equation used in my article for generating unphysical evolutions on very short time scales. This comment is easy to deal with: A careful derivation of the master equation shows that for short times the relaxation rate γ and the diffusion coefficient D (which multiplies the third terms of equations 9 and 15 of my article) are both time dependent in precisely such a manner as to make the unphysical behavior of $\rho(x, x')$ impossible. It is therefore clear that coefficients of all of the dissipative terms grow on a short but finite time scale—a conclusion in accord with Ambegaokar's reference 2. This cures the technical problem he points out, but has little effect on the conclusions concerning decoherence time scales.⁷

The concept of systems is indeed crucial (as Ghirardi, Grassi and Pearle point out) in the discussion of decoherence. Is this "artificial division of the physical world" a reason for dismissing decoherence as a step toward a resolution of the measurement problem? Certainly not! The problem of measurement cannot even be stated without dividing the universe into a system and the apparatus.³ In the absence of such a division any closed system will evolve in a completely deterministic, unitary manner, in accord with the Schrödinger equation. Difficulties with interpretation start only when one realizes that such a deterministic evolution in the Hilbert space takes a composite object (the apparatus plus the measured system) from an initial state in which each of the components has a definite proper-

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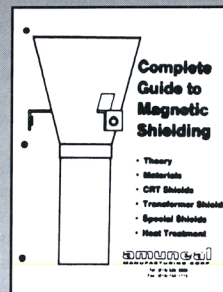
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ty to a state (such as equation 1) where neither of them appears to be entitled to "a state of its own."

Since one cannot pose the problem of measurement without recognizing that systems exist, there is no need to apologize for assuming their existence in searching for its resolution. And the environment is not an arbitrary extra ingredient, but an existing component that makes idealized models of measurements more realistic. Indeed, in all familiar situations one carries out observations by "bleeding off" a fraction of the information already imprinted on and present in the environment (for example, in the photon environment scattered by an object that we see). If the minuscule fraction of the record imprinted in just a few select kinds of environment that we are capable of deciphering suffices to satisfy our information-gathering needs, it is easy to appreciate the accuracy with which all of the environmental degrees of freedom are monitoring observables of macroscopic objects.

The next issue raised by Ghirardi, Grassi and Pearle is the applicability of the decoherence approach to the universe as a whole and its relation to the consistent-histories approach. The universe is a closed system, so it does not have an environment. However, macroscopic subsystems within it (including recording apparatus and observers) do have environments. Hence one can readily implement the decoherence program in this setting. Sequences of projection operators that define events in the consistent-histories approach would then have to satisfy not just the probability sum rules. (The resulting consistency conditions turn out to be easy to satisfy exactly by numerous sets of projection operators that demonstrably have nothing to do with the "familiar reality.") Rather, the process of decoherence singles out events and observables that become (relatively permanently) "recorded" as a result of environmental monitoring. For example, when a well-defined pointer basis exists, the histories consisting of sequences of pointer states are consistent: Approximate consistency of the familiar classical histories is a consequence of environment-induced superselection.³ Thus the additivity of probabilities of histories expressed in terms of the "usual" observables appears to be guaranteed by the efficiency with which unstable states and the corresponding off-diagonal terms of the density matrix in the preferred-pointer-basis representation are removed by a coupling with the environment.

The perception of unique events can be accounted for naturally from within the framework of decoherence. All of the arguments against decoherence—see especially the letters of Ghirardi, Grassi and Pearle; Nicolas Gisin; David Albert and Gerald Feinberg; and Peter Holland—express dissatisfaction with it because it does not force all of the wavefunction of the universe into a unique state corresponding directly to our experience. Rather, it explicitly assumes that the observers are an integral part of the universe and analyzes the measurement-like processes through which perception of the familiar classical reality comes about, thus showing why one can be aware of only one alternative. I do not believe that a fundamental collapse is called for either by the experiments or by our direct experience. Such an overly ambitious goal seems to deny the operational nature of our perceptions. Expressing disappointment with this resolution is a bit like complaining about the absence of an absolute time in special relativity and pronouncing that the theory seems to be "devoid of fundamental significance" because it fails to accommodate our preconceived notion of simultaneity.

In the quantum setting the observer must be demoted from an all-powerful external experimenter dealing *from without* with one more physical system (the universe) to a subsystem of that universe, with all of the limitations arising from such a confinement *to within* the physical entity he or she is supposed to monitor. Correlation—between the memory of the observer and the outcomes (records) of the past observations—emerges as a central concept. Thus, while we have to talk about observers when considering the interpretation of quantum theory, we need make no special appeal to their attributes. Rather, we can deduce their properties as a consequence of the processes (such as decoherence) and the ensuing limitations (such as the environment-induced superselection) considered above, which follow directly from the quantum mechanics of open systems.

It is clear from this recapitulation of the decoherence process and its consequences that an interpretation based solely on the instantaneous eigenstates of the density matrix of a single system would be, at best, naive. Such an oversimplification (which ignores the original focus on correlations,¹⁰ so essential in the discussion of information acquisition through measurements, of the existence of the preferred sets of states, and of the issue of predictability and determin-

ism, which is crucial in the definition of effective classicality) is, of course, easier to criticize than the more complete point of view presented here and is occasionally confused with it (see the letters of Gisin and of Albert and Feinberg). To establish the correspondence between the quantum realm and our direct experience, it is important to appreciate the double role of the records maintained by observers. On the one hand, a record is "just a record": It stores the acquired information. On the other hand, the record is also the state of a subsystem, defining in part the identity of the observer. (Thus, for example, if one were to "copy" an observer, it would be necessary to specify also the state of that observer's memory!) In this very direct sense, "bit is it" (as John A. Wheeler has written¹¹) and "information is physical" (as Rolf Landauer entitled his article in *PHYSICS TODAY*, May 1991, page 23). The conscious observer (as well as any other physical system) is, in part, information!

Modifications of the observer's state as a result of quantum events may be drastic (as would be the case for Schrödinger's cat) or subtle (as for Wigner's friend). Observers may or may not be conscious of them. Only states that can continue to define both the observers and the state of their knowledge for prolonged periods (at least as long as the characteristic information processing time scale of the observer's own nervous system—which, for us, is more than a millisecond, orders of magnitude longer than a macroscopic open system typically takes to decohere) will correspond to perceptions. Memory is the stable existence of records—correlations with the state of the relevant branch of the universe. The requirement of stable existence and the recognition of ultimate interdependence between the identities of the observers (determined in part by the physical states of their memories) and their perceptions define the *existential interpretation* of quantum mechanics.

The role of decoherence is to cause negative selection and thus define the stable alternatives—states of the observer's identity—that can exist in spite of immersion in the environment. The concept of "events" (which Gisin raises) and the definiteness of "matters of fact" (which concerns Albert and Feinberg) can be deduced from within this decoherence-inspired framework. Events happen because the environment helps define a set of stable options that is rather small compared with

the set of possibilities available in principle in the Hilbert space. Each time the system of interest (or the memory of an apparatus, computer or nervous system) is forced into a superposition that violates environment-induced superselection rules, it will decohere on a time scale that is nearly instantaneous when the options are macroscopically distinguishable. This onset of decoherence is the apparent "collapse of the wavepacket." Thereafter each of the alternatives becomes a "matter of fact" to the observer who has recorded it: It will evolve on its own, with negligible chances of interference with the other alternatives, but with the correlation of the records with all the relevant states of the measured observables intact.

In spite of the Everett-like framework of this discussion, the picture that emerges in the end—when described from the point of view of an observer—is very much in accord with the views of Bohr.¹² A macroscopic observer will have recording and measuring devices that will behave classically. Any quantum measurement will lead to an almost instantaneous reduction of the wavepacket, so that the resulting mixture can safely be regarded as corresponding to just one unknown measurement outcome. According to the existential interpretation, what is perceived is not a "complete wavefunction of the universe" but a few characteristics of its specific branch consistent with all of the records the state of the observer happens to include. The freedom to partition the global state vector into nearly arbitrary sets of branches (present in the original work of Everett) has been constrained by the requirement that the effectively classical states should be able to persist on dynamical time scales, that is, for much longer than the decoherence time. The global wavefunction of the universe—save for the bundle of branches consistent with the identity of the observer, including in particular his or her records—is completely inaccessible. Such an observer will remember events, perceive specific "matters of fact" and agree about them with other observers.

A more extensive presentation of the issues, stimulated in part by the correspondence I have received in the wake of my PHYSICS TODAY article, can be found elsewhere.³ Reference 13 lists some of the recent papers relevant to this subject.

I would like to thank Andreas Albrecht, Salman Habib, Jonathan Halliwell, Raymond Laflamme and

Juan Pab Paz for discussions and comments.

References

1. A. Einstein, in *The Born-Einstein Letters*, M. Born, ed., Walker and Company, New York (1969), p. 213.
2. H. Everett III, *Rev. Mod. Phys.* **29**, 454 (1957).
3. W. H. Zurek, *Prog. Theor. Phys.* **89**, 281 (1993); also to appear in *Physical Origins of Time Asymmetry*, J. J. Halliwell, J. Perez-Mercader, W. H. Zurek, eds., Cambridge U.P., New York.
4. A. Einstein, B. Podolsky, N. Rosen, *Phys. Rev.* **47**, 777 (1935).
5. D. Bohm, *Quantum Theory*, Prentice-Hall, Englewood Cliffs, N. J. (1951). K. Gottfried, *Quantum Mechanics* (Benjamin, London, 1964), goes somewhat further in the direction of decoherence.
6. W. H. Zurek, *Phys. Rev. D* **26**, 1862 (1982).
7. J. P. Paz, S. Habib, W. H. Zurek, *Phys. Rev. D* **47**, 488 (1993).
8. W. H. Zurek, S. Habib, J. P. Paz, *Phys. Rev. Lett.*, in press.
9. M. Gell-Mann, J. B. Hartle, *Phys. Rev. D*, in press.
10. W. H. Zurek, *Phys. Rev. D* **24**, 1516 (1981); also in *Experimental Gravitation and the Measurement Theory*, P. Meystre, M. O. Scully, eds., Plenum, New York (1983), p. 87.
11. J. A. Wheeler, in *Complexity, Entropy, and the Physics of Information*, W. H. Zurek, ed., Addison-Wesley, Redwood City, Calif. (1990), p. 3.
12. N. Bohr, *Nature* **121**, 580 (1928).
13. A. Albrecht, "Following a 'Collapsing' Wavefunction," preprint TP/92-93/03, Imperial College, London (1992). B. L. Hu, J. P. Paz, Y. Zhang, *Phys. Rev. D* **45**, 2843 (1992), and in press. L. A. Khalifin, B. S. Tsirelson, *Found. Phys.* **22**, 879 (1992). C. Kiefer, "Decoherence and Quantum Electrodynamics and Quantum Cosmology," preprint ZU-TH 6/92, U. Zurich (1992). R. Omnès, *Rev. Mod. Phys.* **64**, 339 (1992). H. D. Zeh, "There Are No Quantum Jumps nor Are There Particles!" U. Heidelberg preprint (1992).

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3/93

How Bubbles Blow Up (Other Things, That Is)

M. M. Chaudhri (July 1992, page 15) cited the bubble-enhanced detonation of explosive crystals as evidence of very rapid and highly efficient heat transfer. Since the 1960s, however, another possible mechanism has been known to those who study cavitation-

induced corrosion of ship propellers and the like.¹ When microbubbles in the vicinity of a surface collapse, they often "cave in" asymmetrically and form supersonic jets toward or away from the surface. The tremendous pressures induced by these jets seem a more likely mechanism of detonation than collapse heat.

Reference

1. T. B. Benjamin, A. T. Ellis, *Philos. Trans. R. Soc. London, Ser. A* **260**, 221 (1966).

CHRIS MATZNER

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8/92

CHAUDHRI REPLIES: First, I should like to correct Chris Matzner: The jet from a collapsing bubble is not always supersonic; the jet velocity very much depends on the primary shock. In one of the papers I cited in my previous letter, Frank Philip Bowden and I showed that a jet with a velocity of 120 m/sec and a localized shock of approximately 1 kilobar were associated with the collapsing bubble that caused the explosion we photographed.¹ We showed that the localized shock was too weak to initiate the explosion. Later John E. Field and I showed that the impact on an explosive single crystal of silver azide (a sensitive primary explosive) of jets of velocities of up to 450 m/sec was unable to initiate an explosion.² Having eliminated these two causes and having made further experiments with gases of different gammas (ratios of the specific heats of the gases), we concluded that the heat from the collapsing bubble was the main cause of the explosion. Furthermore, this conclusion was supported by calculations of the heat available in the bubble and of the amount transferred to the adjacent crystal surface in the time available.

References

1. M. M. Chaudhri, F. P. Bowden, *Nature* **220**, 690 (1968).
2. M. M. Chaudhri, J. E. Field, *Proc. R. Soc. London, Ser. A* **340**, 113 (1974).

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2/93

Different Angles on Errors in Textbooks

Jay M. Pasachoff suggests in his letter (July 1992, page 91) that other scientists follow his example and become involved in writing pre-college textbooks that are more correct than most present texts and urges that school