Quantum Mechanics and the Nature of Physical Reality

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A discussion of wave–particle duality can be found in all modern textbooks dealing with theories of chemical structure and bonding (*1*). Almost all of these contain some summary of the experimental evidence in favor of such duality, which comes from studies of the physics of electromagnetic radiation (photons vs. waves) and "elementary" particles such as electrons, protons, neutrons, etc. Undergraduate chemists tend to accept that this kind of behavior, although at first sight pretty weird, is a true reflection of the real nature of matter at the atomic and molecular level. Acceptance of this duality leads us directly to the wave functions and operators of the Schrödinger form of quantum mechanics.

Wave–particle duality is manifested in the physics of elementary particles through Heisenberg's famous "uncertainty" principle. In essence, the principle states that it is impossible for us to measure simultaneously pairs of "conjugate" properties of particles (such as their position and momentum) without inherent uncertainties in both properties that are related by the magnitude of Planck's constant. The uncertainty principle is embodied in the Schrödinger equation in which quantum particles (like electrons) are described in terms of wave functions.

Unlike classical mechanics, the Schrödinger form of quantum mechanics deals not with the observable properties (position, momentum, energy, etc.) but with the operators required to obtain the observables from the wave function that describes the system under study. Performing an experiment (asking the "particle" what it is doing) becomes equivalent to operating on the wave function with the quantum mechanical measurement operator appropriate to the property we are trying to observe.

However, most students of chemistry have great difficulty with the concept of the wave function. What is it? Is it "real"? What kind of physical interpretation should it be given? Students in need of straight answers to such questions are rarely provided with them. I hope to demonstrate in this article that straight answers to these questions are not available.

The Quantum Measurement Problem

If we can describe a quantum system by a wave function Ψ and we wish to determine what will happen to Ψ when it is subjected to a particular measuring device, it is necessary to expand Ψ as a linear combination of the wave functions corresponding to all possible outcomes of the experiment. If the measurement has only two possible outcomes (results R_+ and R_-, as will be the case for the measurement of the spin orientation of an individual electron) then Ψ can be written

$$\Psi = c_+\psi_+ + c_-\psi_- \quad (1)$$

where ψ_+ and ψ_- are the wave functions corresponding to the two possible results and the expansion coefficients c_+ and c_- must be found by consideration of the quantum system under study. The wave functions ψ_+ and ψ_- are actually *eigenfunctions* of the measurement operator $\hat{M}$, i.e.,

$$\hat{M}\psi_+ = R_+\psi_+, \quad \hat{M}\psi_- = R_-\psi_- \quad (2)$$

In the case where the spin orientation of an individual electron is measured, the wave functions ψ_+ and ψ_- represent the final quantum states of the electron and apparatus used for the measurement, and we usually refer to these final states as spin "up" or "down" with reference to some arbitrary laboratory frame. The corresponding eigenvalues will be $+\frac{1}{2}\hbar$ and $-\frac{1}{2}\hbar$, respectively.

According to quantum theory, the probability that the result R_+ will be obtained is given by the quantity $|\int\psi_+^*\Psi d\tau|^2$, equivalent to the probability that the wave function Ψ will be "projected" into the state described by ψ_+. If we multiply both sides of eq 1 by ψ_+^* and integrate, we have

$$\int\psi_+^*\Psi d\tau = c_+\int\psi_+^*\psi_+ d\tau + c_-\int\psi_+^*\psi_- d\tau \quad (3)$$

The wave functions ψ_+ and ψ_- form an orthonormal set (they are both eigenfunctions of $\hat{M}$), and so $\int\psi_+^*\psi_+ d\tau = 1$ and $\int\psi_+^*\psi_- d\tau = 0$. Hence

$$\int\psi_+^*\Psi d\tau = c_+ \quad (4)$$

and the probability of obtaining the result R_+ is simply $|c_+|^2$, the square of the modulus of the corresponding expansion coefficient. Similarly, the probability of obtaining the result R_- is $|c_-|^2$. The expansion coefficients for the case of the measurement of the spin orientation of a single electron are $c_+ = c_- = 1/\sqrt{2}$ with the result that $|c_+|^2 = \frac{1}{2}$ and $|c_-|^2 = \frac{1}{2}$, i.e., the spin up and spin down orientations are measured with equal probability.

Since only one or other of the two possible results can be observed in an experiment on a single quantum particle, the act of measurement "collapses" the wave function Ψ into *either* ψ_+ or ψ_-. As we have shown above, we can deduce the *probabilities* of obtaining the results R_+ and R_-, but we cannot predict in advance *which* of the possible results will be obtained. How are we meant to interpret such probabilities? Are they statistical probabilities applicable to experiments performed on a large number of quantum particles that individually exist in defined quantum states prior to measurement? Or do they describe the probabilities for each individual particle? If the latter definition is the most appropriate, it would appear not to be meaningful to describe a quantum particle as existing in *any* defined quantum state prior to measurement, since we would further assume that the particle can have no prior "knowledge" of how the apparatus is set up and therefore no prior knowledge of the measurement quantum states into which it may be projected.

If Ψ represents all that can be known about an individual quantum particle, conceptual difficulties arise because we are free to choose the nature of the experiments. Thus, if we change the nature of the measuring device (perhaps simply by changing the orientation of a magnetic field or a polarizer), it becomes necessary to express Ψ as a linear combination of the eigenfunctions of the measurement operator of the new experimental configuration in order to determine the probabilities of obtaining the corresponding results.

The Copenhagen Interpretation

In quantum theory, the nature of the measuring device becomes as important as the system on which we are trying to perform measurements. In response to the conceptual difficulties of the quantum measurement problem, Neils Bohr and his colleagues in Copenhagen formulated an interpretation of quantum mechanics in which the measuring device is given a primary role (*2*). In fact, it was Bohr who suggested that it is meaningless even to consider a quantum particle as existing in any specific state until it is projected into a state by the measuring device.

There is a subtle point to be made here, since Bohr's argument is *not that we are merely ignorant of the identity* of the quantum state in which a particle exists prior to measurement, and which is changed irreversibly at the moment of measurement, but that it is meaningless to ascribe *an identity (reality) to such a state.*

If true, such considerations are obviously quite alarming, since they seem to suggest that no quantum particle has any physical reality (it does not exist in a definite quantum state) unless there is something there to detect it! Unlike all other previous theories of the physical world, quantum theory abdicates its responsiblity for providing a description of objective reality, a reality independent of something (or someone) to observe it. Taken to its logical conclusion, the theory implies that quantum particles (and hence the entire universe) has no existence independent of observation.

The EPR Argument

The Copenhagen interpretation of quantum mechanics would appear to take the study of the properties of the fundamental constituents of matter and radiation out of the realm of physical science and into the realm of philosophy. The theory surrenders the physical world to indeterminism, i.e., it is no longer possible to say that a given measurement will yield a given result, only that a given measurement will *probably* yield a given result, for each individual quantum particle. Some scientists, of which Albert Einstein was most notable among them, completely rejected this idea.

In a long-running and scholarly debate, Einstein and Bohr fought over the interpretation of the new quantum theory (*2*). At one stage Bohr appeared as the clear winner of the debate, but in 1935 Einstein published a paper coauthored with Boris Podolsky and Nathan Rosen (*3*) in which he seemed at last to have the upper hand. The argument set out in that paper has become known as the Einstein–Podolsky–Rosen (EPR) argument or the EPR paradox.

EPR first allowed themselves what they considered to be a "reasonable" definition of physical reality (*3*):

> If, without in any way disturbing a system, we can predict with certainty (i.e. with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.

According to the Heisenberg uncertainty principle, the measurement of the magnitude of one conjugate variable (e.g., momentum) with certainty means that the magnitude of the other (e.g., position) has an infinite uncertainty and therefore no physical reality. EPR then went on to propose the following thought experiment. Suppose two particles, A and B, interact and move apart. Using our knowledge of the physics of the interaction, we know that if we can measure one property of particle A (its position, say) we can infer the corresponding property of particle B. Now let us measure, with certainty, the value of the position of particle A; this measurement thus enables us to predict, with a probability equal to unity, the position of particle B. We conclude that *the position of particle B must have physical reality,* even though it has not been measured. However, we are quite free to choose exactly what kind of measurement we would like to make on either particle. If we had chosen, instead, to measure the momentum of particle A with certainty, we could have inferred the momentum of particle B with a probability equal to unity.

Of course, we have not actually measured the values of the conjugate variables for particle B, we have only inferred them from our measurements on A. However, unless we are prepared to concede that the reality of *either* the position *or* momentum of particle B is determined by the kind of experiment we *choose* to perform on A, we must accept that *both have simultaneous physical reality, in contradiction to the* Copenhagen interpretation of the uncertainty principle. Our only assumption is that of separability of the particles (sometimes called "Einstein separability") such that we are *free to make measurements* on A without in any way disturbing B. Since we can choose to allow the particles to move an arbitrarily large distance apart before making measurements, this assumption does not seem at first sight to be a particularly damaging one.

In summary, the EPR argument makes the case that a quantum particle does indeed exist in some definite quantum state *before* it is projected into a new state by the measuring device. Since there is no variable in the quantum theory that dictates which quantum states are preferred before measurement, EPR concluded simply that quantum theory is incomplete. Bohr's response to the incompleteness argument was to suggest that the key assumption, that of Einstein separability, is invalid (*4*).

Versions of quantum theory have been formulated that contain explicitly such "hidden variables" as are required to reintroduce determinism and causality into an otherwise uncomfortable description of the physical world. These hidden variable theories are necessarily more complicated than quantum theory itself, and, until relatively recently, they suffered from the disadvantage that their predictive capability vs. quantum theory could not be tested directly by experiment.

Bohm's Contribution and Bell's Theorem

In 1951, the physicist David Bohm formulated an alternative version of the EPR thought experiment that led to a renewed interest in possible experimental verification of the need for hidden variables (*5*). In Bohm's experiment, an interaction was assumed to produce two spin-½ particles (such as electrons) that were constrained by the physics of the interaction to separate with their spin orientations opposed. Thus, measurement of the component of the spin of particle A along some arbitrary axis could be used to infer the corresponding component of particle B. However, the experimenter may choose to measure any other component of the spin of either particle A or B. Assuming Einstein separability, we conclude that all components of the spin of each particle have physical reality (not just those components that are measured), in support of the need for hidden variables and in contradiction to the Copenhagen interpretation.

In 1965, the physicist John S. Bell published a theorem (*6*) with which he demonstrated that for *any* variant of the quantum theory that preserves determinism and locality (i.e., assumes hidden variables and Einstein separability) there are *fixed limits to the extent to which the properties of* pairs of quantum particles can be correlated. The equations relating the magnitudes of the correlations to their upper and/or lower limits are known as Bell's inequalities. Under *certain circumstances, these limits can be exceeded* by the predictions of quantum theory, allowing direct experimental tests to be made for a whole class of hidden variable descriptions.

The reason for this difference is clear: since the particles are described in quantum theory by a single wave function, they are always "in contact" until the moment of experimental measurement, at which point the wave function collapses into one of the measurement eigenfunctions. Measurements made on one particle *do* affect the behavior of the other (Copenhagen interpretation), and the correlation between their properties can therefore be greater than is possible if the two particles are Einstein separable.

Since 1972 a number of experimental tests of the quantum theory have been made based on the study of correlations between the spin components of pairs of quantum particles that experience some kind of interaction (*7*). Many of the practical realizations of the EPR–Bohm thought experiment have actually made use of the spin (polarization) properties of photons, and we will examine below the most recent (and most conclusive) of these.

The AGR Experiments (*8, 9*)

In 1981–1982, Alain Aspect, Phillippe Grangier, and Gérard Roger (AGR) at the Université Paris–Sud in Orsay performed a series of experiments on the correlation between the polarization orientations of pairs of photons emitted in rapid succession from the excited $4p^2\,^1S_0$ state of Ca atoms that had been prepared in an atomic beam by two-photon laser excitation (Fig. 1). The two-photon cascade

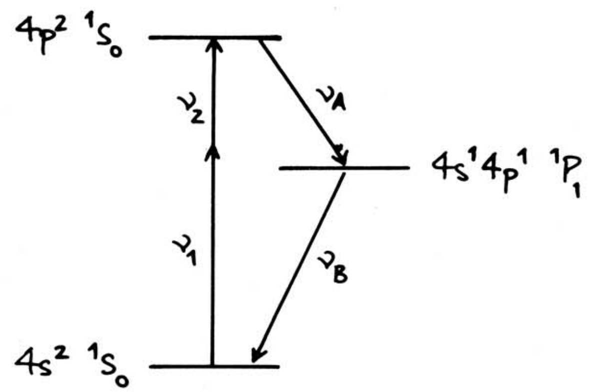

Figure 1. The two-photon absorption and cascade emission transitions of atomic calcium. In the experiments described in the text, ν_1 (496 nm) and ν_2 (581 nm) were provided by single-mode Kr^+ and dye lasers, respectively. ν_A (551.3 nm) and ν_B (422.7 nm) are emitted with correlated polarizations.

emission process proceeds via the state $4s^1 4p^1\,^1P_1$, and so the total (orbital plus spin) angular momentum quantum number J changes from $0 \rightarrow 1 \rightarrow 0$. Conservation of angular momentum demands that these changes in J are balanced by the angular momenta of the emitted photons. Thus, the two photons are emitted with opposite spin orientations ($m_s = -1$ and $m_s = +1$), corresponding to states of right and left circular polarization, respectively.

This two-photon emission process has therefore provided a pair of correlated photons, ideally suited for testing the applicability of quantum theory vs. hidden variable theories that assume Einstein separability. In the AGR experiments (*9*), pairs of photons propagating in opposite directions were analyzed using polarizers—polarizing cubes that transmit the vertical component of the polarized light and reflect the horizontal component. The individual transmitted and reflected photons were detected and arrival coincidences were counted (Fig. 2).

The polarizers decompose the circularly polarized light into vertical and horizontal components. According to quantum mechanics, the wave functions describing the states of circular polarization can be expressed as linear combinations of the wave functions corresponding to states of vertical and horizontal polarization. The probability that an individual photon will be projected into a state of vertical polarization by its interaction with the polarizer (and hence transmitted) is given by the square of the modulus of the corresponding expansion coefficient, as we described above. If the photon is projected into a state of horizontal polarization, it is reflected by the polarizer. In fact, the expansion coefficients for the vertical and horizontal components of states of circular polarization differ only in their relative *phase*, and not in their absolute magnitudes, and so the probabilities of transmission vs. reflection are equal.

In the AGR experiments (*9*), polarizer 1 was oriented so as to make vertical vs. horizontal (v, h) polarization measurements in some arbitrary laboratory frame. Polarizer 2 was oriented with its vertical and horizontal axes (v′, h′) tilted at an angle φ to that of polarizer 1 and was positioned about 13 m away from it (Fig. 2). A "+" result was recorded if a photon was found to be transmitted, a "−" result if it was reflected. We designate the number of pairs of photons that give coincident + results for both photons A and B as N_{++}. The number of pairs of photons that give a + result for photon A and a − result for photon B is designated N_{+-}. N_{-+} and N_{--} are defined similarly. The correlation between the polarization states of the pairs of photons is therefore given by

$$C(\varphi) = (N_{++} + N_{--} - N_{+-} - N_{-+})/N \quad (5)$$

where N is the total number of photon pairs observed. The experimental results are shown in Figure 3. The correlation function shows a cos 2φ dependence, so that, when $\varphi = 0°$, $C(\varphi)$ is approximately +1 and there is near perfect correlation between the measured photon polarization states. At $\varphi = 45°$ there is no correlation between the measured polariza-

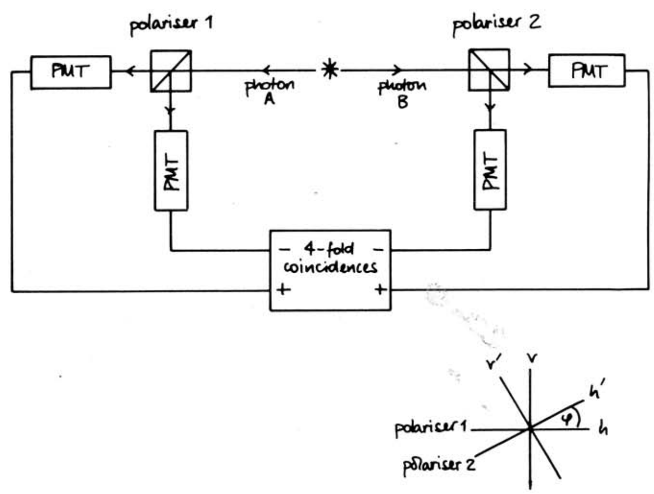

Figure 2. Emitted photons which propagated in opposite directions were analyzed by polarizing cubes. Photons that were transmitted and reflected were detected by photomultipliers (PMT), and fourfold arrival coincidences were monitored. Polarizer 1 was oriented to make vertical, horizontal (v, h) polarization measurements, while polarizer 2 was oriented with its (v′, h′) axes tilted at an angle φ to the axes of polarizer 1.

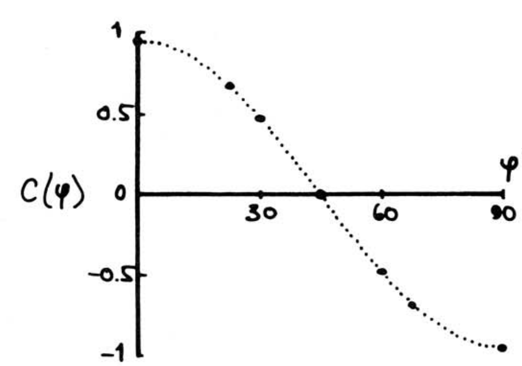

Figure 3. Experimental results for the correlation function $C(\varphi)$ as a function of φ. The error bars represent two standard deviations.

tion states (all results are equally probable). At $\varphi = 90°$ near perfect anticorrelation is observed. The correlations do not quite reach the limits +1 and −1 because of experimental errors associated with inefficiencies in the detectors, "leakage" in the polarizers and because finite solid angles for detection were used. These errors combine always to *reduce* the amount of correlation that may be observed experimentally.

We must now ask ourselves what kind of correlation we would have *predicted* on the basis of our understanding of the physics of the two-photon emission process.

Prediction 1: "The Photons Always Know What They're Doing"

For our first prediction, we *assume* that photon A propagates toward polarizer 1 in a predetermined state of circular polarization (right or left) and that photon B propagates toward polarizer 2 in a predetermined state of circular polarization in the opposite sense (i.e., we assume the operation of hidden variables). We furthermore assume that the interaction of photon A with polarizer 1 cannot influence the behavior of photon B and vice versa (Einstein separability).

We can quickly deduce that after observation of N photon pairs, where N is a statistically significant number, $N/2$ of the photons A would have been transmitted by polarizer 1 and $N/2$ would have been reflected. Similarly, $N/2$ of the photons B would have been transmitted by polarizer 2 and $N/2$ would have been reflected *irrespective of the relative orientation of polarizer 2*. Thus, of the photons transmitted through polarizer 1, half will be associated with N_{++} and half with N_{+-}. These arguments lead us to predict $N_{++} = N_{+-} = N_{-+} = N_{--} = N/4$, i.e., all combinations of observed results are equally likely, independent of the angle φ between the vertical and horizontal axes of the two polarizers, and $C(\varphi) = 0$ for all φ. This contrasts with the experimental observations where $C(\varphi) = 0$ was observed only at $\varphi = 45°$.

Prediction 2: "No They Don't!"

What is the prediction of quantum theory? According to the theory, the two photons are described by a single wave function, which we denote Ψ. We can choose to expand Ψ in any basis of orthogonal functions, but, if we wish to determine the probable outcomes of the polarization measurements described above, we are forced to expand Ψ as a linear combination of the eigenfunctions of the measurement operator.

What do these eigenfunctions look like? When Ψ interacts with the measuring device, it collapses into one of four possible states. The first of these corresponds to vertical polarization (+ result) for photon A and alignment along the equivalent vertical orientation (+ result) for photon B. If we denote the vertical axis of polarizer 1 as v and that of polarizer 2 as v′ (where v′ makes an angle φ with v), the wave function corresponding to this particular collapsed state is given as the product $\psi_v^A\psi_{v'}^B$, where the superscripts *indicate the individual* photons. We denote this product state as ψ_{++}. The other three possible collapsed states are $\psi_{+-} = \psi_v^A\psi_{h'}^B$, $\psi_{-+} = \psi_h^A\psi_{v'}^B$, and $\psi_{--} = \psi_h^A\psi_{h'}^B$, where h and h′ are the corresponding *horizontal axes of the polarizers*. Hence

$$\Psi = c_{++}\psi_{++} + c_{+-}\psi_{+-} + c_{-+}\psi_{-+} + c_{--}\psi_{--} \qquad (6)$$

We will not present here a detailed discussion of how expressions for the individual expansion coefficients in eq 6 can be found. For the purposes of the present article, it is sufficient to note that Ψ is constrained only by the requirement that it represent a state of zero total angular momentum (because of the physics of the two-photon emission process) and that it obey the Pauli principle. After a little algebra, the following expression for Ψ can be deduced

$$\Psi = (1/\sqrt{2})[(\cos\varphi)\psi_{++} + (\sin\varphi)\psi_{+-} + (\sin\varphi)\psi_{-+} - (\cos\varphi)\psi_{--}] \qquad (7)$$

and comparison of this last equation with eq 6 gives us the expressions for the expansion coefficients that we require.

The square of the modulus of each of the expansion coefficients gives the probability that the corresponding experimental result will be obtained *for each photon pair*. If N photon pairs are observed, the number of pairs giving a particular result will simply be N times the corresponding probability for one photon pair, i.e.,

$$N_{++} = N\cdot|c_{++}|^2 = \frac{N}{2}\cos^2\varphi$$

$$N_{+-} = N\cdot|c_{+-}|^2 = \frac{N}{2}\sin^2\varphi$$

$$N_{-+} = N\cdot|c_{-+}|^2 = \frac{N}{2}\sin^2\varphi$$

$$N_{--} = N\cdot|c_{--}|^2 = \frac{N}{2}\cos^2\varphi$$

and so

$$C(\varphi) = \cos^2\varphi - \sin^2\varphi = \cos 2\varphi \qquad (8)$$

The function $\cos 2\varphi$, modified slightly to account for experimental factors that limit the possible accuracy of detection, is plotted through the experimental data points of Figure 3. *This line does not represent a fit to the data; it is actually the predicted variation obtained from quantum theory.*

Violation of Bell's Inequalities

Tests of Bell's theorem require that the photon pair experiments be extended to include measurement of three or more different types of correlation. In the AGR experiments (*9*), the different arrangements were (1) polarizer 2 at an angle φ to polarizer 1, (2) polarizer 2 at an angle ϑ to polarizer 1, (3) polarizer 1 at an angle χ and polarizer 2 at an angle φ, and (4) polarizer 1 at an angle χ and polarizer 2 at an angle ϑ. The correlation functions are, respectively, $C(\varphi)$, $C(\vartheta)$, $C(\varphi - \chi)$ and $C(\vartheta - \chi)$. The function S, given by

$$S = C(\varphi) - C(\vartheta) + C(\varphi - \chi) + C(\vartheta - \chi) \qquad (9)$$

is, according to Bell's theorem (*10*), constrained to lie within the limits $-2 \le S \le +2$.

We have already observed that the quantum theory prediction for $C(\varphi)$ is $\cos 2\varphi$. Similarly, $C(\vartheta) = \cos 2\vartheta$, $C(\varphi - \chi) = \cos(2\varphi - 2\chi)$ and $C(\vartheta - \chi) = \cos(2\vartheta - 2\chi)$. Thus, the quantum theory prediction for S is given by

$$S = \cos 2\varphi - \cos 2\vartheta + \cos(2\varphi - 2\chi) + \cos(2\vartheta - 2\chi) \qquad (10)$$

We will focus here on one particular experimental arrangement with $\varphi = 22.5°$, $\vartheta = 67.5°$, and $\chi = 45°$. The quantum theory prediction for S for this combination of orientations of the polarizers is $S = 2\sqrt{2} = 2.828$, in clear violation of Bell's inequalities. The experimental result? $S = 2.697 \pm 0.015$ was found for this particular arrangement. Remember that defects in the detection system *wil tend always to reduce* the amount of correlation observed experimentally (taking these factors into account led to a modified quantum theory prediction of $S = 2.70 \pm 0.05$, in excellent agreement *with experiment*). Even without these modifications, a clear violation of Bell's inequalities was obtained in the AGR experiments.

In an apparently final blow to the proponents of hidden variables, Aspect, Dalibard, and Roger (ADR) extended the experimental arrangement to include rapid switching of the photons between different optical paths (*11*). These different paths corresponded to detection of the photons using differently oriented polarization analyzers. The switching was arranged to be faster than the transit time of the photons to their respective analyzers. Thus, photon A could not "know" in advance what the orientation of polarizer 1 would be, preventing communication of this information to photon

B (unless A could "signal" to B at faster than light speed). Clear violation of Bell's inequalities was again obtained.

Conclusions? (*12–15*)

So, what are we to make of all this? The AGR and ADR experiments indicate most conclusively that quantum theory survives the test and that a whole class of hidden variable theories fail. We are forced to confront Bohr's contention that quantum particles cannot be said to exist in any defined quantum states until they interact with a measuring device. Instead, a quantum particle should be described by a rather nebulous wave function that cannot be ascribed properties that we would associate with any "reasonable" definition of physical reality: we must deal instead with the probabilities that the wave function will collapse into a set of artificially created wave functions associated with the measuring device. The reality with which we deal would not seem to be independent, but *relational.*

Where does the measurement chain stop (at what point does the wave function collapse)? When the photons in the above experiments enter the polarizers? When they are detected? When the experimental result is recorded by a human observer? The physicist Eugene Wigner favored the suggestion that the wave function collapses when the result of an experimental measurement is registered in a conscious mind (*13*). But *whose* mind?

In 1957, Hugh Everett (*13*) proposed that the collapse of the wave function results in its projection into *all* possible final states, one each of which is observed in parallel branched universes where the branching is caused by the act of measurement. Since there have been a great many quantum transitions since the Big Bang, we can only suppose that there must by now exist a large number of parallel universes. Some will look indistinguishable from the one we inhabit, and in many of them slight variants of you will be reading slight variants of this article written by slight variants of me. The branching universe theory has been describd as "schizophrenia with a vengeance". Of course, it cannot be disproved, since the branched universes are physically separated (they presumably belong in different space–times) and we are unable to move from one universe to another. However, the theory is certainly "uneconomical with universes" (*12*).

These ideas may strike you as not quite the kind of thing you expect from rational physical scientists. But we are compelled to seek some pretty strange solutions to the conceptual problems that are thrown up by the quantum theory of measurement. Of course, quantum theory is only the best interpretation of the physical world currently available and may be in need of replacement when new experimental tests are devised. However, the theory has stood up remarkably well to the experimental tests that have been devised thus far. And will a new theory necessarily disperse the philosophical mists that surround quantum theory in its present form?

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Division of Chemical Education Election of Officers for 1991

The candidates listed below have been nominated for 1991 offices in the Division of Chemical Education. With this election, the Division returns to its old method of sending mail ballots directly to members, separate from the *Newsletter*. Members of the Division will receive their ballots by late August. Ballots are due back at the office of the Secretary by September 30, 1990. All members of the Division are encouraged to participate in this election.

Chair-elect (to serve as Chair in 1992)

Donald Jones
Western Maryland College
Westminster, Maryland

Lucy Pryde
ACS DivChed Exams Institute
Stillwater, Oklahoma

Treasurer

Adrienne Kozlowski
Central Connecticut State College
New Britain, Connecticut

Mary Virgina Orna
College of New Rochelle
New Rochelle, New York

Councilor/Alternate Councilor (Nominee receiving the highest number of votes will serve as Councilor, the next highest will be Alternate Councilor.)

Jerry A. Bell
Simmons College
Boston, Massachusetts

Ralph Burns
St. Louis Community College
St. Louis, Missouri

William F. Coleman
Wellesley College
Wellesley, Massachusetts

Jerry Sarquis
Miami University
Oxford, Ohio