Quantum Physics and Understanding God

MEASUREMENT AND INDETERMINACY IN THE QUANTUM MECHANICS OF DIRAC

by Carl S. Helrich

Abstract. The quantum-measurement problem and the Heisenberg indeterminacy principle are presented in the language of the Dirac formulation of the quantum theory. Particularly the relationship between quantum state prior to measurement and the result of the measurement are discussed. The relation between the indeterminacy principle and the analog between quantum and classical systems is presented, showing that this principle may be discussed independently of the wave-particle duality. The importance of statistics in the treatment of many body systems is outlined and the approach to investigating God's interaction with human beings is discussed in this context. The treatment is nonmathematical.

Keywords: God's action; indeterminacy principle; measurement; operator; quantum statistics; quantum theory; state vector.

That we would encounter problems of understanding and interpretation in the emerging quantum theory was clear from the first steps down the twisted path toward that theory. We have only human language on which to base our communication and only human experience on which to base our images of the world described by the quantum theory. Both are inadequate to the task because there is no human experience of the world of the quantum theory. The closest we may ever come to an experience of this quantum world is through our measurements, and so the understanding of our measurements is key to a comprehension of that world. In this brief

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paper I outline what Paul Dirac has to say about quantum measurement in his classic monograph, *The Principles of Quantum Mechanics* (Dirac 1958).

I choose this task for three reasons: (1) Dirac's monograph remains a classic reference today occupying a place on the bookshelf of many, if not most, theoretical physicists; (2) Dirac's approach to the measurement problem is blunt and clear; and (3) I have found Dirac's monograph a useful basis for my own teaching of quantum mechanics. Students appreciate the elegance and clarity.

In this paper I avoid the use of mathematics, attempting instead to provide verbal explanations. Mathematics does provide a clarity that cannot in general be attained by the verbal argument; for the limited goals of this discussion, however, it may be adequate to convey the essential ideas with words alone. Nevertheless, certain points should be made regarding Dirac's mathematical approach, which has become the standard of the physics community and is rapidly making its way into chemistry and biophysics. The approach is more fundamental than that of either Erwin Schrödinger (1926a; 1926b) or Werner Heisenberg (1925). Schrödinger's wave mechanics and the matrix mechanics of Max Born, Heisenberg, and Pascual Jordan both emerged in the early days of the quantum theory. Schrödinger was able to show their equivalence as being two representations of the same structure (Schrödinger 1926c). The approach of Dirac places that structure in an abstract form from which either can be extracted.

I first describe what is meant by the state of a quantum system in comparison to that of a classical system. Next I undertake a discussion of the measurement of the state of a single photon. (This is an outline of the discussion given by Dirac to introduce the measurement concept.) I then introduce the basic concept of the state vector, central in the Dirac development, and with it the idea of superposition of states in the quantum theory. This is followed by an exploration of Dirac's identification of the fundamental relationship tying the quantum and classical theories together: the quantum analog of the Poisson bracket in terms of the commutator. This leads immediately to the indeterminacy principle of Heisenberg and consideration of the relationship of the wave function to this theory. Finally I discuss the role of statistics in the quantum theory.

Quantum statistics must be used in any discussion of God's interaction with us, since that interaction will involve the human brain as the physical system. The human brain, or even a single neuron, is a large composite quantum system. In the final section of the paper I consider this in some detail. There I discuss the very difficult problem of determining the action of God through any measurement, which must be conducted by the individual brain on itself. This problem differs fundamentally from those encountered in any normal investigation of complex systems. I presently believe that this is the level at which we must approach any investigation of God's action.

The State of the Quantum System

A quantum system may be anything we choose to study, including a single electron or photon. To claim to know the state of the system is to claim to know all we can know about that system. In classical physics it is rather easy to define the state of any particle, such as an electron. If we agree that all electrons have the same charge and the same rest mass, then all we need in order to specify the state of the electron is the position in terms of three Cartesian coordinates, say $\{x,y,z\}$, and the momentum along the three Cartesian directions, say $\{p_x,p_y,p_z\}$. Classical mechanics has no knowledge of the spin. We can, however, measure the magnetic moment, which the quantum theory teaches us is related to the spin; so classically we could also specify the three Cartesian components of the magnetic moment of the electron, say $\{\mu_x,\mu_y,\mu_z\}$. The classical state of the electron is known once we specify these nine numbers. As the electron sails along, these numbers may change in value because of interactions. And classical mechanics provides us with a method of calculating these changes.

The concept of the quantum state of an electron is similar. The quantum state is all we know about the system. We shall not be as explicit here as requiring nine numbers to specify the state. Rather, we shall content ourselves with a somewhat abstract reference to the state of the electron as something that has meaning because the electron exists.

All we can know about a quantum system is contained in what is called the quantum-state vector. By itself the state vector has no direct physical meaning, as do the nine parameters that specify the classical state of the electron. The physical information contained in the state vector must be extracted. This is done by using mathematical operators, which act on the state vector. These mathematical operators bear a relationship to the act of measurement, because they extract information from the state vector in a fashion that must parallel the actual measurements. This results in what appears as a peculiarity in quantum measurements.

The Measurement

Dirac makes a very important statement in the first chapter of his monograph. This statement is buried at the end of a paragraph that deals with polarization of photons and may easily be missed on a first reading. But it should be highlighted, because it clarifies his position throughout the book. Dirac writes, "Only questions about the results of experiments have a real significance and it is only such questions that theoretical physics has to consider" (Dirac 1958, 5). The importance of this becomes clear in the first example Dirac considers regarding measurement. He chooses to study photon polarization.

Some background is necessary. The origin of the concept of the photon is Albert Einstein's paper, "On a Heuristic Point of View about the Creation and Conversion of Light" (Einstein 1905). Subsequently Robert Millikan showed that the so-called photoelectric effect, in which electrons are ejected from a surface upon exposure to light, can only be understood using Einstein's radical idea of the light corpuscle (Millikan 1916). The experiments are now a part of the standard undergraduate laboratory. Light is, of course, an electromagnetic wave, and has electric and magnetic field components. The orientation of the electric field defines the polarization of the wave. A plane polarized light beam with the electric field oriented in a single direction can be prepared by passing the light beam through a polarizer. It is easily shown that there is a preferred direction for the photoelectron emission if the light is polarized (Dirac 1958, 4). Because the photoelectric effect requires a photon description, we may say that polarization therefore has a meaning at the photon level of description.

The photon is a quantum of the electromagnetic field. It is not a particle in the sense in which we picture a particle, or even a fuzzy sphere moving at the speed of light. But we can register single photons and do so in, for example, x-ray diffraction studies of surfaces (Helrich et al. 1989). In some measurements we may register only a few photons per minute at a detector. The presence of a quantum of the electromagnetic field is registered by the emission of an electron from the first photo-surface of a photomultiplier tube, which is multiplied on subsequent surfaces producing a pulse in our circuitry. In this way we count single photons. With Dirac let us now consider that we have a very low-intensity beam of light. In other words, we register single photons at our detector. Suppose we place a polarizer between the source of the beam and the detector. This produces a very low-intensity beam of polarized photons, which we are able to count. We now take a second polarizer and place it between the detector and the first polarizer. If the axis of the second polarizer is perpendicular to that of the first, we register no photons at the detector. If the axis of the second polarizer is parallel to that of the first, we register as many photons per second as we did before we inserted the second polarizer. That is, as expected, the photons stay polarized in the direction defined by the first polarizer as they move through space.

The interesting experiment is to align the second polarizer with its axis at an angle, say α, to the first. In this case we sometimes detect a photon and sometimes do not. We never observe part of a photon. The photons we observe are those with polarization along the axis of the second polarizer. This is a simple experiment that is easily understood in classical terms considering light to be a wave, but is incomprehensible if we try to think classically, using photons. Classically we believe that we know all the photons leaving the first polarizer to be polarized along the axis of the first polarizer. Therefore, classically none of these is polarized at an angle α. Our measurement, however, shows us that a certain fraction of these photons is, indeed, polarized at the angle α. Because the polarizer absorbs photons polarized perpendicularly to the axis, we also know that some of these photons are polarized at an angle (α + 90°). If we make the measurement over a long period of time and record the result for a large number of photons, we do obtain an average that corresponds to the classical result. It is only the individual measurements that are incomprehensible classically.

This simple experiment teaches us three lessons that are at the heart of quantum mechanics and the measurement problem. The first lesson we learn is that if we measure a system state (the first polarizer), obtain a value for a variable characterizing that state (polarization direction), and repeat the same measurement immediately thereafter (the second polarizer parallel to the first), we will obtain the same result. The second lesson we learn is that each photon leaving the first polarizer is polarized along the axis of that polarizer, but that same photon is polarized either perpendicularly or parallel to the second polarizer if the second polarizer is oriented at an angle with respect to the first. The third lesson we learn is that we have no way of deciding what this polarization is until we allow the photon to pass through the second polarizer. The only thing we are measuring is polarization, so this is the only thing we have that defines the state of the photon.

Each of these is very important. The first lesson is what we would expect classically, but it is important to understand that the measured state is that with which the photon leaves the polarizer and not the state the photon had before it entered the polarizer. From the second lesson we conclude that the general state of a quantum system must be considered a sum of all possible states that the system can occupy. From the third lesson we conclude that the measurement returns only a single value and not an average.

Our conclusion from the second lesson is what is termed the superposition principle in quantum mechanics. This principle does not appear in classical mechanics. In classical mechanics it is absurd to say that an electron has, for example, two separate orientations of its magnetic moment at the same time. Before a measurement is made on a quantum system, however, we cannot specify the state of the system. As regards the measurement we propose to make on the system, we must accept that our state of knowledge about the system is expressed as a sum over all possible states. This linear sum of system states is necessary to preserve the identity of the quantum system. Our measurement does not partition the photon. Nor would it partition an electron.

The conclusion from the third lesson makes clear that our sum of states is always with respect to the measurement we are proposing. From the first lesson we realize that if we propose to make the measurement we have just made, there is only a single state. We then have no sum.

In our example the measurement process returns a single value for the polarization. If we were measuring the orientation of an electron spin along a single axis, for example, the measurement would return a single value, $+1/2\hbar$ or $-1/2\hbar$. where $\hbar = h/2\pi$ and h = Planck's constant. If we could measure the energy of the state of an electron in an atom, we would obtain a single value.

INTERPRETATION

Compared to classical mechanics, quantum mechanics is a very honest theory. Classical mechanics has at its basis the contention that all states of all systems considered can always be measured exactly. The limitations are only on our instruments. Quantum mechanics makes no such a priori claim. Rather, we must accept that we do not know the value of a parameter without first measuring it. Quantum mechanics also makes no hypothesis about what that measurement will mean and places no limits on the measurement. These are consequences to which we are led by the experiments themselves.

But we do have an interpretation of our superposition. Dirac tells us what it is (Dirac 1958, 73). The most we can say about the system before the measurement is to provide a probability for the outcome. The probability that the measurement will produce a value of the measured parameter corresponding to a certain state is proportional to the modulus squared of the coefficient of that state in the sum. If all coefficients are equal, all states are equally probable. Dirac makes this explicit in stating, in reference to a quantum system, that "We can . . . speak of the probability of its having any specified value for the state, meaning the probability of this specified value being obtained when one makes a measurement of the observable" (Dirac 1958, 47). Probabilities are measures of the state of our knowledge before the measurement, not the result of statistical inference from the measurement.

HEISENBERG'S INDETERMINACY PRINCIPLE

The Heisenberg indeterminacy principle (Heisenberg 1927) is an integral part of the Dirac development. But this principle is not obtained by considering the wave-particle duality or limits on measurements. Dirac introduces the basic concept that will lead him to the Heisenberg principle in chapter 4 of the monograph. Obviously considerable mathematical development has taken place in three chapters, but we really need consider only two items. The first of these is almost self-evident. The second was a surprise to all of the early workers in quantum theory.

As mentioned at the outset, in quantum mechanics we extract information from the state vector through the operation on the state vector by an operator. If the system is in a state for which it is possible to know a particular property, the operator for that property will produce a particular value, called an *eigenvalue* ("characteristic" or "singular" value, from the

German) for that variable (Dirac 1958, 35). This was not unexpected. What was unexpected, however, is the fact that certain operators do not commute. That is, the mathematical results arising from applying operators Q and P in the order QP are different from those that result from applying them in the order PQ (Dirac 1958, 24).

Dirac realized that this same strange situation actually existed in classical mechanics in what are called the Poisson brackets. The Poisson brackets appear in the Lagrange-Hamilton formulation of classical mechanics. Dirac noticed that the Poisson bracket of the same components of the momentum and the position of a particle was equal to unity. With this Dirac could postulate the relationship that connects classical and quantum mechanics. The commutator of quantum mechanics, which for the operators Q and P is $(QP - PQ)$ is analogous to the product of $i\hbar$ and the Poisson bracket of the corresponding classical variables (Dirac 1958, 87). From this result Dirac coaxed the form of the momentum operator from his theory and, subsequently, the Heisenberg principle (Dirac 1958, 91, 98). After his identification of the Poisson bracket-commutator relationship, the development was strictly mathematical with no need to discuss the wave-particle duality or aspects of measurements.

Of course, this does not stand in opposition to the development of Niels Bohr's group. The principle of complementarity claims that certain measurements are incompatible in the sense that if one particular measurement is made, it is impossible to make certain other (incompatible) measurements. These consequences are identical to those for observables corresponding to noncommuting operators. For such noncommuting operators Dirac's development produces a Heisenberg indeterminacy principle identical to the original obtained by Heisenberg for a more restrictive situation. The result in terms of noncommuting operators is how the indeterminacy principle is normally presented at this time, because of its mathematical elegance and the fact that it embraces a more general case of operators than simply those for momentum and position. The wave-particle duality questions and the thought experiments of the Copenhagen school are part of our history, and physicists should be aware of them, but they are not considered fundamental in discussions of indeterminacy.

The Wave Function

In no part of the discussion thus far have I introduced the wave function. This is a construction unnecessary for obtaining the Poisson-bracket identification, which is the source of indeterminacy. This aspect of the Schrödinger picture is, however, necessary for applying the principle and obtaining physical results (Dirac 1958, 98). The use of relatively simple language and concepts has been possible so far because only the abstract formalism of the theory has been needed. At some point we must attempt actual calculations on paper or use a digital computer. In order to do that, we must first represent our theory in a basis (Dirac 1958, chapter 3). This concept, fairly simple once grasped, is one of the most important in modern physics, but as it is not a part of our everyday thinking it seems difficult at first. An abstract state vector is written as a symbol: $|S\rangle$. This symbol has no explicit dependence on space or time. We can write general equations involving this symbol, but we can obtain no numbers or predictions for experiments. To obtain these, we must project the state vector onto space and time coordinates. What results is the wave function. In other words, the wave function is the space and time representation of the general quantum-state vector for the system. This wave function contains no more information than the original-state vector, but we are now in a position to extract that information through the use of the operators referred to above. Usable forms of these operators are obtained, as well, by space and time projections of the abstract operators.

This representation, in which the projection of the state vector carries the space and time dependence of the system, is called the Schrödinger picture. This is not the only representation in which we can cast our theory, but it is the representation in which most discussions take place. Of course, no more fundamental information is obtained by this projection. The pictures obtained only become more intuitive.

As a representation of the state vector, the wave function has no physical meaning by itself. This is mathematically almost self-evident because the wave function is in general what is termed a complex-valued function with real and imaginary parts. Because the state vector is a sum over possible states, the wave function will be a sum over wave functions for possible states.

Applying what we have said about the state vector to its representation as the wave function, we have that the square of the modulus of the wave function may be interpreted as a probability density for the location of the particle in question. This does not mean that the particle is "spread out" over the region in which the probability density is non-zero. If we were to measure the position of the particle, we would receive a number. There is nothing in the quantum theory that denies our ability to measure the position of the particle. Errors in the measurement of this quantity are limited strictly by our instruments and ingenuity. There also is nothing in the quantum theory that is inherently statistical. The quantum theory states emphatically that any measurement will result in a specific value for the parameter measured. The quantum theory simply does not allow us to predict, before measuring, what the result will be. The exception is only in the event that we perform two identical measurements immediately following one another, as in the case of our photon-polarization example. The statistical aspects of the theory only enter into the interpretation of the superposition principle, and there the statement is with respect to a measurement that is going to be made and not of the results of a single measurement.

Quantum Statistics

Superposition in the quantum theory and the interpretation of that invite the claim that the quantum theory is statistical. No physical theory can be only statistical and still be regarded as a theory. The underlying equation of motion of the quantum theory, the Schrödinger equation, is as deterministic as the canonical equations of mechanics. This fact is embedded in the theory through the postulate of the Poisson bracket and commutator analogy already discussed.

If the state vector is known at any one time, it is determined for all times, provided the potential of the field in which the quantum system moves is specified. It is only impossible to predict the outcome of a measurement, which involves an interaction with a measuring instrument the effects of which cannot be specified beforehand.

If we are interested only in the behavior of single particle systems, the question of statistics need not concern us at all. We can still gain insight into the behavior of such systems and convince ourselves of the validity of the theory. We need only be careful in our interpretation of the information we extract from our measurements.

The more interesting applications of the quantum theory, however, involve systems of many particles. In these applications we must introduce the methods of statistical mechanics, just as we must for classical systems. In principle the actual approach is the same as that used in the classical statistical mechanics. The concept of an ensemble of identical systems is introduced using Gibbs's reasoning (Helrich 1999). The differences between classical and quantum systems arise in the requirements placed on the symmetry of the state vector for quantum systems. This is one of the deepest mysteries of nature. The state vector for a collection of identical particles with half-integer spin must be antisymmetrical, that is, it must change algebraic sign upon interchange of particles. The state vector for a collection of identical particles with integer-spin must be symmetrical, that is, it must not change at all upon interchange of particles (Dirac 1958, 210, 211). Electrons have half-integer spin, and the consequences of this for the statistics of electrons make modern solid-state electronics possible. It is important, however, to realize that the necessity of applying the methods of statistical mechanics is not inherent in the quantum theory.

Discussion

I have tried to outline portions of the development of the quantum theory by Dirac that are pertinent to an understanding of the quantum measurement problem and the Heisenberg indeterminacy principle. My intention has been to describe the issues in as simple a form as possible. To accomplish this I relied exclusively on the ideas of Dirac as expressed in his classic monograph. The monograph is at this time forty years old, but the elements of the quantum theory developed there have not changed. Because of its mathematical rigor and elegance this situation will probably remain so for many years to come.

The sole purpose of this paper has been to present the fundamental concept of measurement in the quantum theory and the relationship of the Heisenberg indeterminacy principle to that theory. What prompted my writing it was the current interest in these concepts regarding the discussion of the action of God, particularly on human beings. Many of the principles expressed in the quantum theory are inherently counterintuitive, and without a clear understanding of these principles discussions on the subject may become misleading. My opinion is that it is very important that each person entering this discussion have an understanding of these principles in as elegant a form as possible. This is provided by Dirac.

In most of my presentation I have referred only to the abstract formulation in terms of the state vector, rather than in terms of the wave function, in order to show that the principles do not depend fundamentally on the properties of the wave function. With this approach I have tried particularly to separate the basic concepts of the theory from questions of the interpretation of the wave function and the use of statistics, because the basic theory is the one with which we must deal in discussing the action of God in the context of quantum mechanics. The behavior of large quantum systems, I believe, may be important as we try to understand ourselves and our interpretation of God's action. But that exploration involves a set of questions different from those of quantum measurement and indeterminacy.

Any discussion of the action of God must be approached with care and full recognition that in doing so we are encountering mystery. Paul Tillich has pointed out that God is infinite mystery and that God is not a problem to be solved (Tillich 1951, 109). All we can expect to do, then, is to reveal the problem itself and, perhaps, to appreciate, from our perspective as human beings, what is involved when we encounter the infinite. To explore what I believe lies before us, I shall speak primarily as a physicist.

This paper has dealt so far only with fundamental questions related to measurement. It is not a simple jump to the application of quantum mechanics to large dynamical systems. The last section alluded to composite systems. The present one applies those concepts to the situation we encounter in discussing ourselves. This aspect of the application of quantum mechanics is of interest in discussions of God's interaction with us. Such questions can be deeply intriguing and stunningly difficult. The source of the difficulty is in understanding what is meant by ordinarily familiar terms such as *measurement* and *identification of boundaries*. Here we shall consider only those aspects of the situation which I believe to be essential if we are to engage this topic.

Scientifically we must recognize that what we can know is limited by what we can measure. The act of measurement and the manner in which we understand the results of measurement are relatively simple when viewed from outside of the system of interest, but these are no longer simple when we realize that we are the system. We must first consider what is meant by measurement and statistics when treating such systems.

In strictly scientific terms, our language must be that of thermodynamics, and we must speak of ensembles of systems rather than single systems. This is the point at which a statistical description enters. In the quantum case the statistical treatment requires two levels. The first level introduces the *quantum mechanical average*, which results from the superposition referred to earlier. The quantum mechanical average reflects how much we could actually know about any single system if we were able to measure the quantum state of the system. This is the celebrated quantum-measurement problem. But, as Josiah Willard Gibbs pointed out, even in the classical situation detailed knowledge of the states of single systems is impossible (Helrich 1999). We can measure only a truly insignificant number of those parameters necessary to specify the system state. Therefore, we must introduce the ensemble, which is that collection of all possible systems that would produce the same measured results. The physical treatment of this situation places what is called the statistical mechanical density operator, traditionally identified as ρ, on center stage. The scientific discussion must concentrate on ρ regardless of the underlying mechanics. The only quantities of which we actually have knowledge are ensemble-averaged quantities obtained through the use of ρ.

The density operator satisfies a deterministic equation, the Liouville equation (Prigogine 1962, 15), which is derivable from the Schrödinger equation in the quantum case. The operator, ρ, produces expected values for quantities (ensemble averages) that would be determined by (possible) measurements performed on the composite system. Alternatively, ρ provides a description of the time evolution of an ensemble of such composite systems, whether or not measurements are actually made. It is important to realize that what is described is not the time evolution of a single system. A directionality in time is not a property of single systems in our present theoretical descriptions whether quantum or classical (Helrich 1999).

To address seriously in scientific terms the problems involved in understanding God's interaction with us, we must try to understand the question we are asking. For the sake of discussion, we accept the proposal that our conscious state is related to, and perhaps determined by, the state of the physiological neural network that is our brain. We do not deny here the dependence of the brain on the rest of the physical body, but we neglect that for the sake of simplicity. Of interest to us is the perception of the individual, because that is central if we are to ask concrete questions about God's action. The individual can determine the state of that neural net only by identifying certain markers, such as satisfaction or levels of concentration, which are associated consciously with the state. The ensemble is then all possible states of the neural net that could produce these conscious markers. For the individual there is then an ensemble density $\rho_{\text{individual}}$ that provides all the individual can know about this ensemble of neural net states. The scientific question of the importance of quantum mechanics in God's action on us hinges, then, on the determination of $\rho_{\text{individual}}$ and particularly its time evolution. In ordinary statistical mechanics we would write the Liouville equation for $\rho_{\text{individual}}$ in terms of what is called the Hamiltonian for the system.[1] The Hamiltonian specifies the interactions among the components of the system and is central to the discussion, whether that system is quantum or classical. In the classical case the Hamiltonian is a function, and in the quantum case it is an operator. In either case it determines the energy and behavior of the system. Basing our analysis on $\rho_{\text{individual}}$ and on the Liouville equation determining it, we would then see whether we could tie this Hamiltonian in some direct fashion to the perception of the individual. In this way we could hope to decide the importance of quantum mechanics in God's interaction with us. We could only write such a Hamiltonian, however, if we understood the connection between the neural net and the conscious state of the individual, and that we do not.

We may proceed, however, by claiming that a comprehension of the markers may allow us to inductively ascertain the dynamics of the neural net, a process not uncommon in physics. This brings us to the deeper question of how we should comprehend the self measurement by the individual of the state of the neural net. Within the context of our accepted proposal, we realize that any measurement of the markers of perception must be carried out through the same mechanism by which the markers were produced: another state of the neural net. This is a problem completely different from that encountered in the ordinary applications of physics. In any application of quantum or classical theory, we can identify the relation between our measurement and an ensemble average of some specific microscopic quantity. Here we are denied that identification because we do not understand in mechanistic terms the relation of consciousness to the state of the neural net. Nevertheless, this seems to be the point at which we should begin to discuss the problem of whether God's action on us is quantum dependent. I believe this particularly because in approaching the problem in this way, we encounter life and being (Tillich 1951, 70, 81, 189).

In this I am suggesting that to look for God's interaction with us in the quantum indeterminacy is to study the problem at the wrong level. I have considered here two levels above that, neither of which is well understood, and I have tried to point out that for scientific reasons we should consider the problem at these levels. I do believe that the final level is the important one.

The articles by Jeffrey Koperski, Nicholas Saunders, and Peter Hodgson in this issue of *Zygon* make points similar to mine, but in each case the reasons are different. Koperski (2000) argues that chaos is simply not as rampant as we may think and worries about the possible connections between quantum mechanics and chaos. Saunders (2000) provides an overview of much of present and historical thought on God's action. He concludes that linking divine action to quantum processes is theologically and scientifically untenable. Hodgson (2000) concludes that quantum mechanics is not indeterminate and does not provide the means by which God can intervene.

In a certain sense Koperski and I agree: in that we must consider the macroscopic system from the outset. However, Koperski may not be aware that certain instances in biophysics counter the strength of some of his arguments. One of these is the fact that single photon-induced isomerization of a rhodopsin molecule can induce whole-cell membrane excitation, a macroscopic effect. Another instance is the ability of certain nonlinear systems to detect and transmit weak signals that can be enhanced by the presence of a certain level of noise. This effect, *stochastic resonance*, was first discussed in 1991 and has recently been identified experimentally (Russell, Wilkins, and Moss 1999). My own work has indicated the presence of dynamical chaos in biological ion channels (Helrich and Qiao 1994), and my unpublished data indicate membrane cooperative effects in an influenza channel multiplying currents by factors of more than ten thousand. I concur with Saunders's concern. Underlying his critique, it seems to me, is the objection that we have moved to a new natural theology, which subjugates God. I suggest that we should be concerned about such a move. We simply do not know enough about the physics to warrant this. There are always surprises in any science, and we must be very cautious of building elaborate theories.

Hodgson's arguments are partially sociological, based on the reputed stature and power of Niels Bohr. Because physical research takes place in a community, it is naive to suppose that human nature plays no role. But we must be careful, subsequently, in our analysis and our search for truth. Because the ideas of Louis de Broglie and David Bohm play such a large role in Hodgson's argument, it is worthwhile indicating why these seem so troublesome to physicists. Physicists are not guided by positivism. As many have pointed out (see Polkinghorne 1997), we do have a metaphysics of which certain things can be said. We do adhere to the Newtonian philosophical position that the laws of physics are only to describe experiments. This I have indicated is central to Dirac's position. We should not pretend that we have knowledge of something beyond what can be measured—but we do believe in beauty. This is known to have been the source of Dirac's dismay with the quantum-field theory he invented. What physicists generally find disturbing about the Bohm theory is what it asks us to believe beyond experimental evidence and any sense of mathematical beauty. Bohm's theory redefines the wave function—which is to be an objectively real field function, ψ—by specifying its mathematical form initially and introducing two new real functions, S and R. These determine the velocity and a new quantum potential, which is an unnecessary additive in the quantum theory and is not subject to experimental investigation. Bohm insists on random fluctuations in his objectively real ψ with the consequence that his motion of the quantum particle is similar to Brownian motion. The contention is that measurements will reveal an average of this fluctuating trajectory. It is the average of Bohm's field function, ψ, that satisfies the Schrödinger equation. Such ideas leave physicists with the very uneasy feeling that we have crossed a boundary from the real world into one in which we are asked to suppose more than can be linked to evidence. Orthodox quantum theory does not necessarily leave us settled, but we are more content to deal with the difficulties this presents than to let our imaginations wander as far as Bohm requires.

Without question, the quantum theory provides us with ideas that seem to fit more closely our concept of God's interaction with us as human beings. However, in the present paper I am arguing that attempts to search for what has been called the "causal joint" between God and us in quantum indeterminacy is misplaced for scientific reasons. To discuss realistically the large composite systems that are involved at the molecular level in biology, we must move to the ensemble description. I have suggested, however, that the actual problem is at yet a higher level, at which we become the system being studied and at the same instant are the measuring instrument. This introduces an entirely new set of problems that are not encountered in discussions of quantum indeterminacy. These are also problems that have not been previously treated in ensemble theory. Accepting this as the level for discussion acknowledges a transcendence that is otherwise sought only in the quantum indeterminacy, or denied completely. The reader has observed that I have assumed the existence of life and consciousness, both of which are fundamental aspects of the problem. I suspect that our inability to identify life ontologically may be an indication that life is evidence of the presence of God and that the scientific difficulties I have tried to point to are a reflection of that.

NOTE

1. It must be noted that to write the Hamiltonian is in no sense an easy task. For example, the problem in finding an explanation for low-temperature superconductivity was that of discovering a Hamiltonian that worked. From that Hamiltonian we understood the physics, not vice versa.

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