SCHRÖDINGER'S CAT AND DIVINE ACTION: SOME COMMENTS ON THE USE OF QUANTUM UNCERTAINTY TO ALLOW FOR GOD'S ACTION IN THE WORLD

by Robert J. Brecha

Abstract. I present results of recent work in the field of quantum optics and relate this work to discussions about the theory of quantum mechanics and God's divine action in the world. Experiments involving atomic decay, relevant to event uncertainty in quantum mechanics, as well as experiments aimed at elucidating the so-called Schrödinger's-cat paradox, help clarify apparent ambiguities or paradoxes that I believe are at the heart of renewed attempts to locate God within our constructed physical theories and tend to narrow the gaps proposed as an opening for divine action. Some problems arise because of imprecise use of nonmathematical language to force quantum mechanics into an intuitive "classical" framework.

Keywords: determinism; divine action; measurement; quantum chaos; quantum mechanics; realism; Schrödinger's cat.

In discussions about the possible modes of interaction between religion and science, reference is often made to physical theories of the twentieth century and ways in which these theories may open new avenues for achieving a closer integration between the two disciplines. Theologians, as well as some physicists, have begun to explore in greater detail, and in the spirit of serious dialogue, the extent to which the "battle" between science and religion may have been the result of misunderstanding on both sides. It is probably the case that this discussion has been reawakened only fairly recently because of what would appear to be the final death of the two great demons of classical physics, those of Pierre Simon Laplace and James Clerk

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Maxwell. In the spirit of Enlightenment rationalism, physicist and mathematician Laplace made the somewhat presumptuous conjecture that it would be possible in principle for a hypothetical being to apply mathematical and physical principles to any system in such a way that one would be able to predict future developments with arbitrary accuracy for arbitrarily long periods of time. That Laplace himself apparently felt that his omniscient demon could be none other than God did not prevent his idea from being used thereafter by both scientists and theologians as a starting point for claiming a complete separation of their respective fields.

My purpose in this article is to examine one specific aspect of the revived dialogue between religion and science. Many scholars have used concepts from the theory of quantum mechanics to provide an example of how God's divine action in the world might be formulated so as to be consistent with physical theory. According to this bottom-up model, the inherent ontological indeterminacy seemingly required by our best present-day understanding of quantum mechanics can be seen as equivalent to saying that "God is the hidden variable" (Murphy 1997, 342). Thus, God can make choices about the detailed behavior of quantum systems, as long as the outcome is consistent with probabilities as calculated using the mathematical tools of quantum mechanics, and still not be seen as interventionist. I present what I hope is a concrete contribution to this discussion by emphasizing results of some relevant recent experiments in the field of quantum optics.[1] These do not prove any one view of quantum mechanics but rather show that the approach taken by physicists to the open questions of a physical theory is to do experiments and refine the mathematical theory. The outcome, as has almost always been the case in the past, is to close down further the gaps proposed as an opening for divine action. Expressed in a slightly different way, the general result of the experiments described here is to clarify what sometimes seem to be ambiguities, or paradoxes. These perceived ambiguities are what I believe to be at the heart of renewed attempts to locate God within a constructed physical theory such as quantum mechanics. I present as well a short discussion of some recent experiments aimed at understanding quantum chaos, which in some ill-defined way sits on the boundary between the quantum and nonlinear worlds and therefore has in the past been taken to be relevant to the divine-action arguments.

A few preliminary comments are in order. Most authors writing about divine action and quantum mechanics start from a realist metaphysical perspective. In a recent article in *Zygon*, Gregory Peterson raises the important point that the ontological status of physical laws is a too-often-neglected subject for consideration in discussions between scientists and theologians (Peterson 2000, 884). It seems to me that there are at least two possible directions in which we could go if we were to take a step away from believing in the strict realism of quantum mechanics. Peterson believes that we can approach the question of divine action very differently if we consider the laws of physics to be only approximations or to represent only statistical regularities, since there would be no sense in which God must be contravening inviolable laws of physics. A second possibility is to give up realism, critical or otherwise, as a criterion for physical law, because then we could ask more fundamentally about the necessity of even worrying about divine action in connection with a specific mathematical construct that we happen to be using at this point in history to try to understand our physical world. Peterson mentions the point about realism as an aside in his article, but I believe that he has touched on an extremely important topic that must be given further consideration. I find some of the ideas on this topic expressed by William Stoeger (1993) very stimulating.

The above comments are not to be taken as a sign that I endorse a naive instrumentalism with respect to quantum mechanics. One can find much of value in, for example, the works of Pierre Duhem, although he was writing before the advent of quantum mechanics. Some of the more modern adherents to variations of the ideas of Duhem include Bas van Fraassen (1980) and Nancy Cartwright (1983). These philosophers of science do not address the conversation between theologians and scientists, but their work is of at least indirect relevance as it addresses the important questions of realism and, especially in the case of Cartwright, of what physicists actually do when they use quantum mechanics as a tool. To sum up, because most of the contributions to the debate about possible room in quantum mechanics for divine action depend implicitly on some version of realism being attributed to the theory, the metaphysical foundation should be firm enough to support the whole edifice.

Although I will be looking at the arguments as a physicist and from outside the theological tradition, it is of course possible to view attempts to unify quantum mechanics and divine action from the point of view of theology as well. In recent issues of *Zygon* there are several articles that discuss the theological problems relating to these attempts. Nicholas Saunders (2000) gives a valuable overview of some of the most prominent proposals that have been circulated by scholars in this field. He points out that theologians must implicitly arrive at the orthodox interpretation of quantum mechanics, involving the collapse of the wavefunction, to retain the ontological uncertainty necessary to have divine action without interventionism. Alternative versions of quantum mechanics, such as David Bohm's pilot waves or Hugh Everett's many-worlds interpretation, are specifically designed to circumvent the perceived problem of a probabilistic theory. Given standard quantum mechanics as a starting point, the question becomes to some extent a matter of degree: Does God act in all quantum events or only in some critical events that bear macroscopic consequences? In the first case, it seems difficult to avoid a charge of occasionalism.

If one grants some sort of realism to fundamental physical theories and in the case of quantum mechanics accepts uncertainty as a key part of the theory, then a God acting in every quantum event could be accused as well of only keeping up a facade of indeterminacy to fool scientists while actually operating by very different methods. As has often been pointed out, the problem of the existence of evil looms large with this approach. Further, this seems to be a risky path to follow for at least one other reason not usually mentioned, namely, that this line of reasoning begins to sound perilously like that used by creationists who claim that God created geological structures in six days but in such a way as to simulate a 4-billion-year history of Earth.

If, on the other hand, one allows God to act only infrequently, for example during a measurement, it is difficult to avoid the charge of interventionism. The claim of divine action during the act of quantum measurement is difficult to even define, because most measurements in quantum systems are not of the type in which one opens a box to see if Schrödinger's cat is alive, dead, or a bit of each. As I discuss below, *quantum measurement* really means any interaction of a quantum system with its surroundings. Thus, because quantum mechanical processes such as collisions between atoms are taking place all the time, separating occasional measurements from continuous action seems problematic.

Another example of a theological approach is given by Steven Crain (1997), who has considered the use of "special divine action" in the work of John Polkinghorne. He concludes, in essence, that belief in a transcendent God renders highly suspicious any attempt to require that God must exploit built-in features of the world as a means for carrying out actions. Thus, the only proper solution is to separate the two domains of natural science and theology. Theology is then classed with metaphysics and is thus not part of the world open to scientific investigation. On the other hand, Crain does recognize that theology "must address the world as best we understand it" (1997, 50), that is, that developments in science must be taken into account in any practical theology. This point is, of course, implicit in nearly all *Zygon* articles.

I have one final comment before I present specific examples from current research in quantum optics. It is often claimed that the "new physics" is much less amenable to an intuitive understanding than was classical physics. For example, Polkinghorne has written that "the counterintuitive character of the quantum world . . . results in its discovery having caused the most radical revision of physical thinking since the start of modern science" (Polkinghorne 1991, 85). The belief that a physical theory is nonintuitive or even counterintuitive can lead to extreme claims about the latitude allowed in interpreting that theory. The significance of the lack of intuition about systems governed by quantum mechanics (or chaotic dynamics or special relativity) is extremely questionable. One of the most difficult tasks pedagogically in a first-semester physics course is to find ways of convincing students to accept and internalize ideas that are now three hundred years old. For example, it is still the case that one can be satisfied at the end of a semester if a significant fraction of introductory-level physics students can be considered Newtonian thinkers. That is, the ideas most of us bring into a physics course, and that many students have even *after* a course, are much closer to the physics of Aristotle (I am thinking here of the concept of inertia and the "natural" state of motion of a body, for example), which seems more intuitive. The nonintuitive nature of modern physics as compared to Newtonian mechanics is most likely irrelevant to the current discussion.

QUANTUM MECHANICS AND QUANTUM OPTICS EXPERIMENTS

Using Paul Dirac's classic quantum mechanics text as a starting point, Carl Helrich gives an excellent description of some of the basic principles of quantum mechanics in a recent issue of *Zygon* (Helrich 2000). He includes definitions of quantum mechanical versus classical states as well as discussions of the Heisenberg uncertainty principle in terms of abstract mathematical operators and of the deterministic nature of the Schrödinger equation. In what follows I repeat for emphasis a few of these points and amplify others that I feel are sometimes not appreciated enough. Helrich concludes that there is nothing in the formulation of quantum mechanics that leaves enough uncertainty for divine action within the theory. He argues further that imposing the limits of one of our current theories on God's action is in effect an impoverishment of the concept of an omnipotent deity (although this tactic has been used often in the religion-and-science dialogue).

If we begin by assuming some interaction between God and the world, mediated by physical theory, in what sense can we postulate that there is room within quantum mechanical nature for divine action? I describe a few features of the theory that seem relevant, since these have been previously linked to possible modes for understanding divine action in the world and illustrate how experimental and theoretical research continues to make more precise our understanding of these features of quantum mechanics.

Schrödinger's Cat. A first example of the alleged strangeness that comes with quantum mechanics is provided by the mystery of Schrödinger's cat. This oft-cited paradox involves one of the fundamental features of quantum mechanics, called "superposition states." In classical physics, as well as in everyday experience, we know that a particle, or a person, is either "here" or "there." If we do not have enough information about the motion of the particle (or, in the more usual case, if the system consists of many parts and is thus too complicated to describe exactly), we may have to assign probabilities to various locations. According to quantum mechanics, it is possible for a system to exist in a superposition, the state "here and there." This phenomenon is deeply ingrained in the mathematical structure of quantum mechanics and, furthermore, has in many cases observable consequences. That is, predictions that rely on the existence of superpositions can be tested.

Schrödinger's cat has been the guinea pig (to mix metaphors) in the world of quantum mechanics thought experiments for more than seventy years. The cat is assumed to be in a box with a demonic device that triggers its death with 50 percent probability in a given time. The statement of the paradox, as usually presented, is that quantum mechanics would predict that the cat is in a state of "half-alive + half-dead" (a superposition) and that the quantum mechanical "collapse" into one of the definite outcomes is produced only when an observer opens the box to make a "measurement." This example has been used so often at least in part because the proposition sounds so absurd. I have the sense that the net result of many discussions about Schrödinger's cat is to leave an impression that physicists are in a fog about what to do with their theory. The serious question to be asked before trying to interpret this thought experiment in light of arguments for divine action is the following: If quantum mechanics allows superposition states to exist, why do we never see them in the macroscopic world?

One feature of the paradox that seems to me to be irrelevant is that of amplification. Some wish to extend a metaphor for Schrödinger's cat to other systems by attaching great significance to the fact that the decay of the single radioactive atom can be amplified to result in the death of the cat or, more generally, the change in state of a macroscopic system. The triggering of a large effect by one small push can be described just as well by classical physics as by quantum mechanics. One need think only of the tiniest perturbation needed in the mountains to release an avalanche, for example. In this same spirit, some authors wish to move events of the quantum regime into the field of biology, by claiming that an individual quantum event (i.e., one X-ray photon incident on a DNA molecule) can create a mutation and thus determine the fate of an individual through altered genetic characteristics (Russell 1998b). Although I certainly do not deny that these processes occur, it does not appear to me that the events are in this case different in kind from normal classical accidents that can have large consequences. A person seriously injured or killed in an automobile accident, a very classical event from the point of view of physical theory, has a very different further development than would have otherwise been the case. From the point of view of quantum physics, a DNA molecule is already an almost hopelessly large, complicated, and classical object. Although one may speak of divine action in such a case, it must certainly be of the interventionist type and not through the framework of quantum theory.

I turn now to current attempts to understand the problem of Schrödinger's cat. The solution can on the one hand be stated almost trivially: quantum mechanics, although applicable in principle to any system, deals best with small systems; whatever "small" means exactly, a cat does not qualify. Quantum mechanics is formulated to deal with microscopic systems, and one must be careful when using quantum mechanical language to describe macroscopic systems if one wishes to avoid apparent paradoxes. Thus, before becoming too disturbed by the thought of a cat that is half dead and half alive, we must ask whether we are treating the cat rigorously according to the rules of quantum mechanics, since we are trying to talk about a mathematically modeled physical system. The clue that caution is advisable is that, once we sit down with pencil and paper, we do not have the slightest idea how to write the Schrödinger wavefunction for a cat.

A more detailed explanation of the paradox involves the concept of *decoherence*, which is essentially a description of how (microscopic) quantum systems interact with their (macroscopic) surroundings. This is an area of current active research, but not in the sense of making modifications to quantum mechanics so as to make the theory more intuitive or "classical." The idea of decoherence adds nothing new to the mathematical framework of quantum mechanics itself; rather, it is a more careful consideration of complicated combinations of systems. From this point of view, the resolution of the paradox of Schrödinger's cat is simply an example of how scientific theories are developed further with time, testing and solving their own problems.

In recent issues of *Zygon*, the concept of decoherence has been implicitly touched upon more than once. Thomas Tracy mentions the important point that decoherence essentially implies that quantum measurements are taking place continuously, and he quotes Robert John Russell to this effect (Tracy 2000, 897). The point of the reference to decoherence, as I see it, is that it tends to blur the distinction between occasional acts of divine action through measurements (which we tend to picture as a very intentional act) and the continuous divine action present in every quantum interaction. Decoherence tells us that measurements are nothing more than interactions of any sort whatsoever. I now briefly summarize the approach used in some recent experiments to investigate this more quantitatively.

Physicists do not typically work with cats in the laboratory, and a cat is in any case far too complicated to be considered useful for an experiment in quantum optics, so it is necessary to find a reasonable substitute. The requirement is that one have a quantum system (here a single atom, corresponding to the radioactive atom in the original proposal) coupled to a classical measuring device (the cat). In beautiful recent experiments on two different model systems (Brune et al. 1996; Myatt et al. 2000), the principle of creating a model Schrödinger's cat and of demonstrating decoherence has been tested, and observations have been made illuminating how the rules of quantum mechanics describe very well the coupling between systems. In the experiments of M. Brune and his colleagues, the microscopic system is a single atom of rubidium with only two pertinent energy levels. The two states of the atom correspond in the original thought experiment to the radioactive atom's having either decayed or not decayed. The measuring device ("cat") is the electromagnetic field in a nearly perfect box (superconducting cavity); the size of this field could be varied, as could the strength of the coupling to the rubidium atoms, in such a way that it was possible to move from a quantum to a classical measurement interaction.

At first sight this may not sound like the same problem that has been discussed in most contributions on the implications of quantum mechanics, but I would contend that this system, or that of C. J. Myatt and colleagues, is of exactly the type that we should be considering. These experiments are constructed such that it is possible to follow how decoherence takes place as the measuring device becomes larger (and thus more classical) and to shed light on the reason why we do not see superpositions of macroscopic systems in nature.

To summarize the results of the experiments, we do not ever see the kind of macroscopic coherences described by the dead cat/live cat example simply because there are so many quantum interactions going on that these absurd possibilities get washed out. If, as in the experiments described here, it is possible to make the classical measuring device (the "cat") small enough and to then change its size in a controllable way, one can investigate exactly how quickly the disappearance of macroscopic superpositions occurs.[2] These experiments shed light on how small quantum systems become classical ones, at least in part because of interactions with their surroundings. That is, one can explore the boundaries between classical and quantum physics in a very controllable fashion.

Radioactive Decay and Spontaneous Emission. Another tactic for allowing divine action into quantum mechanics involves events such as the radioactive decay of a nucleus or the spontaneous emission of light from an atom or molecule.[3] In either of these cases there is a randomness built into the system: it is possible to calculate the probability that a nucleus or atom will decay within a given time (or, equivalently, to predict that of a collection of such objects a certain number will decay in a given time), but we are prohibited from knowing, even in principle, exactly when an event will occur or exactly which atom or nucleus will decay. Again, the laws of quantum mechanics give us information only about probabilities, not about specific events.

As one example, Nancey Murphy offers an argument for God's divine action based in part on the view that the microscopic quantum world operates without sufficient reason for a specific event to occur. In her typology she asks if the *when* for a quantum event taking place is (1) completely random, (2) internally determined, (3) externally determined, or (4) determined by God (Murphy 1997, 341). Option 1 she rules out primarily because she likes option 4 better, given a choice. Options 2 and 3 are ruled out because Murphy thinks that the current status of quantum mechanics, in which Bell's theorem and the Clauser-Aspect experiments (both described in the next section) have ruled out local hidden variable theories, does not allow for either internal or external sufficient causes for a quantum event.

I believe that this reading of the situation is somewhat too stringent. The following, although it does not provide a complete solution, at least opens up the question again. Consider, for example, an atom that has been excited to a quantum energy level above its lowest, or ground, state.[4] We can think of a fluorescent light in which mercury atoms are excited by impacts with electrons and then give off the visible-light photons we see when they decay again to the lowest energy level. Are these decay processes really random? That is what quantum mechanics seems to tell us. Are they without a cause? I would claim that quantum mechanics does not tell us exactly this. The cause of the decay of an excited-state atom is its interaction with the surroundings, or, to quote Murphy (1997, 341), it is "externally determined by the entity's relations to something else in the physical system." In the case described, the surroundings are the quantum vacuum, which is not at all a vacuum in the Aristotelian sense of a totally empty void. In quantum field theory the vacuum is an active place; although it has zero average energy, the fluctuations about zero are all-important.

Polkinghorne has pointed out, albeit in a different context,[5]

> Classically the vacuum is just emptiness, nothing there, nothing happening. Heisenberg does not allow a quantum vacuum to be so inert. Each possible state of matter—photons, electrons, each different sort of quark, and so on—is described by a quantum field. The state in which all of these fields have their lowest energy is the vacuum, rock bottom. There are then no photons, electrons, quarks, etc, present, but that does not mean that nothing is going on. Quite the contrary, for the vacuum in quantum theory is a humming hive of activity. . . . Heisenberg demands that the lowest energy state . . . involves a slight quivering. . . . This quivering is the zero point motion. Augmented to the complexity of a quantum field it produces the fluctuating vacuum that I have described. (Polkinghorne 1986, 67)

Polkinghorne's vivid description of the quantum vacuum reflects accurately the surroundings of every atom in a fluorescent bulb. The atom constantly "feels" these fluctuations in energy, and the resulting interaction is behind the observed fact that the atom eventually drops from the higher to a lower energy level. Thus, when Murphy (and others as well) talk about quantum events as "just happening," there is a sense of completely acausal randomness that is exaggerated.

To take this example one step further and perhaps lend a greater plausibility to the idea that the surroundings of an object, although referred to as the vacuum, can be the cause of a quantum event, I will describe briefly some experiments in which the quantum vacuum was altered in a controlled way such that the effects on a single atom could be observed. To understand the experiments, consider an atom that has energy levels such that it emits green light of wavelength 500 nm[6] when in a fluorescent tube. If we place this atom in a cubical metal box, 200 nm on a side (I skip all details about how this might be done or why it should be a metal box), we predict from quantum theory and confirm by experiment that this atom now does not emit light at all but remains in its excited state indefinitely. The rough reasoning behind this phenomenon is that our box is too small for a (half) wavelength of the light to "fit" inside, and therefore the atom is "stuck" in its excited state until we give it more room ("modes") into which it can emit. That is, the contributions of the vacuum field at those wavelengths, which would normally be present in free space, are also not allowed in the box and thus cannot cause the atom to change states. The experiments performed by various groups to test this idea (Serge Haroche and Daniel Kleppner [1989] give a good introduction) demonstrate the principle clearly, although, as usual, some idealizations are involved in translating the theoretical language into an experimental setup.

Although we still cannot predict when the atom will emit its photon except probabilistically, it seems to me that the cause of the decay in a general sense has been shown by the experiment described above. By performing this experimental manipulation it is possible to vary the rate at which atoms emit light. Thus, some of the mystery of the spontaneous emission of light (or, by a similar argument, of the radioactive decay of a nucleus) is removed. Certainly one of the points about quantum mechanics that sounds so strange as it is often presented in a brief synopsis is that events "just happen" for no apparent reason. That seems to me to be an oversimplified view of the quantum world.

Bell's Theorem and the Einstein-Podolsky-Rosen Paradox. It is sometimes argued that the surprisingly large (from the point of view of classical physics) correlations between quantum objects that separate after starting out as parts of a composite system means that there is a holism in nature, allowed for by quantum mechanics and denied by reductionist, Newtonian physics. Furthermore, it has been surmised that this holism could be made consistent with the possibility of divine action (Russell 1998a). An important example is given by the Einstein-Podolsky-Rosen *Gedankenexperiment*, as modified by Bohm. When two photons are emitted sequentially by the same atom, as can be arranged experimentally, and when one sets up a carefully prescribed set of measurements (Freedman and Clauser 1972; Aspect, Grangier, and Roger 1982), the correlations[7] found in measurements made on the properties of the two light particles are not what one would expect from a classical theory but do confirm the predictions of the standard quantum mechanical theory (Bell 1964). Most important, the results are in direct conflict with the so-called local-hidden-variables formulation of quantum mechanics, in which attempts have been made to derive quantum mechanical results equivalent to the successful Schrödinger equation, but without the accompanying probabilistic interpretation. Thus, in a situation for which quantum mechanics explicitly predicts an outcome at variance with our classical "intuition," the quantum mechanical result has been clearly shown to give the correct answer.

One mitigating factor to keep in mind when considering the seemingly mysterious character of the correlations predicted by quantum mechanics, and an explanation of why such effects do not seem to appear in everyday life, lies in the extreme difficulty of trying to prepare an experiment that realizes the concrete predictions of Bell and standard quantum mechanics as opposed to alternative theories. It is very challenging to create quantum mechanical systems isolated enough from their surroundings that such effects may be observed. This relates as well to the arguments I used above when discussing Schrödinger's cat; it is easy to find strange predictions if one jumps from the basic principles of quantum mechanics to systems that effectively cannot be treated rigorously within the theoretical framework. Further, one should be hesitant to jump from the fact that quantum mechanically predicted correlations are found in repeated measurements made on individual pairs of photons, separated by lengths of optical fiber in a laboratory containing hundreds of thousands of dollars' worth of equipment devoted to the task, to sweeping generalizations about the holism found in nature based on that theory. No macroscopic system would display the properties described by Bell's theorem, for reasons related to decoherence, as described earlier.

Russell (1988a) has discussed at length some of the implications of Bell's theorem for philosophical and theological appropriation of quantum mechanics. In the end, however, he relies on a metaphorical approach to relating quantum mechanics and divine action. This is certainly one possible tactic, but then I would argue that the goal for relating divine action to specific scientific theories has been changed greatly. Metaphors and models are not the basis of a theory such as quantum mechanics, but rather they serve as a tentative guide as to how one may apply a theory in a given situation. Comparing models in physics, which typically serve as guides for setting up mathematical problems, with metaphors and models in theology would seem to be a very difficult task.

In this context I now consider a quote from Russell regarding quantum mechanics. He writes,

> Another area to which the gossamer-like quality of quantum correlations might be relevant is inter-religious unity . . . quantum correlations offer stimulating metaphors for our unity in Christ and our search for wider ecumenical unity in the global religious perspective. Moreover the insights from quantum physics can be extended as well to the constructive theological agenda. (Russell 1988, 358)

I contend that examples such as these illustrate the danger of using metaphorical language in one area of intellectual pursuit, based on the very concrete usage of language in another. If we read this passage and then think about how extremely difficult it is to maintain quantum correlations and how easily they can be destroyed, not to mention the fact that almost any experiment designed to observe quantum mechanical effects requires highly artificial conditions in elaborate laboratory surroundings, the positive metaphor can be turned around to make the quest seem like a hopeless pursuit. Theological metaphors based on the precisely defined formalism of a physical theory appear to me to be far removed from the point where the intricacies of the theory are relevant.

QUANTUM CHAOS

Some hope has been expressed in the conversation between scientists and theologians that a theory of quantum chaos might help to clear up some of the interpretational difficulties encountered in discussions of divine action as possibly allowed by nonlinear dynamics or quantum mechanics. As the name implies, quantum chaos could be considered to provide a bridge between the world of quantum mechanics and the world of chaotic behavior in nonlinear dynamical systems.[8] It should be noted, however, that it is difficult even to define precisely what we mean by quantum chaos.

I will look at one possible approach, namely, that a given classically described system sometimes has an analogous quantum mechanical system for which an experiment can be envisioned. Although there are problems with making this analogy, it seems to be the best we can attempt at this time. Unfortunately, investigations on such systems carried out thus far seem to rule out any such quantum chaos. In a recent issue of *Zygon*, Jeffrey Koperski (2000) presents an overview of the problems encountered when using the idea of chaotic quantum determinism as an avenue for allowing divine action. His conclusion is that the link between quantum mechanics and chaotic dynamics is simply too unclear, and perhaps even too contradictory, for us to appropriate these concepts theologically as the causal joint for divine action.

In the spirit of the experimental results I presented above, I show here how physicists have made progress in the past few years in performing experiments aimed at finding signs of what might be considered quantum chaos (Ammann et al. 1998; Moore et al. 1995; Klappauf et al. 1998). These results temper somewhat Koperski's statement that a retreat has been made from the search for a correspondence between the quantum and chaotic realms. The classical system being modeled is a "kicked rotor," which is essentially a swinging pendulum that is periodically given a sharp push. It can be shown experimentally and theoretically that this kicked rotor can exhibit chaotic behavior. In the recent experiments, the starting point is a "quantum" system consisting of a sample of atoms confined to a small area by laser light, which can be arranged such that the atoms slosh back and forth slightly. Interactions are arranged to be analogous to a classical system, that is, the group of atoms is periodically given a "kick" in the form of a pulse of laser light. Monitoring the experimental quantities that show the signature of chaos in the classical system, the experimenters find no sign of chaotic behavior in the quantum system. They take this experiment one step further, however, in that they use the concept of decoherence, as described above, and make the system progressively more classical by coupling it to its surroundings. As they increase the amount of classicalizing interaction, they find that the experimental signature of chaotic behavior gradually begins to appear.

The experiments described here do not demonstrate in a definitive way that there is no quantum chaos, nor that the physicists involved have disproved any particular hypothesis, either about quantum chaos or about divine action, but simply that the ideas of both quantum mechanics and nonlinear dynamics, being physical and mathematical theories, are testable. It is only through such testing, and through the usual interaction between experiment and theory that is the strength of scientific research, that we can make any sense of the sciences. On the other hand, we must say as well that the results of the experiments described above leave an important question for further investigation. If quantum mechanics is to be considered the prime theory for the description of matter, and if it is supposed to lead to classical Newtonian mechanics in some limit to be defined carefully, then where is the bridge located if not in a system such as the kicked rotor that can be approximated physically in both its quantum mechanical and classical versions?

CONCLUSIONS

I have presented a summary of some of the most recent experimental results that to my mind have some bearing on the questions raised in the discussion of divine action in the world as it relates to interpretations based on a specific physical theory. I believe that progress in experimental testing and understanding of these theories is such that attempts on the part of theologians to appropriate these theoretical frameworks to provide an avenue for divine action run the risk of the fate of earlier God-of-the-gaps arguments. Many of the apparent paradoxes that arise in interpretations of quantum mechanics result from imprecise use of nonmathematical language to try to force quantum mechanics into an "intuitive" classical framework. This points to the danger in using classical analogies when discussing systems that can be described only with the more fundamental theory of quantum mechanics; conversely, when discussing macroscopic systems (such as cats), we must be certain that we account fully for all parts of the system if we wish to avoid paradoxical results. Some of these points have been fully realized by physicists and formulated carefully only within the last several years (Omnès 1994). Finally, it seems to me to be an even riskier strategy to use analogies and metaphors based on precise mathematical theories as justification for a theological construction of divine action.

If one wishes to relate quantum mechanics to another subject area, it is not a good strategy to do so by starting with an example (a live cat) that no physicist would ever consider trying to treat using the formalism of quantum mechanics. On the other hand, to start with a system that is well understood, such as a single rubidium atom, and to couple it in an experiment to another very simple, well-characterized system (an electromagnetic field of one single frequency, with a well-defined amplitude), and to then monitor what happens to this system and compare the results to those predicted by quantum mechanics (which in this case gives relatively simple, analytically computable answers) shows that the theory is perhaps not quite as mysterious as it might seem. In addition to the experiments I have described here, there are other recent investigations into the nature of the wave-particle duality as well as active research into the properties of quantum statistical systems consisting of bosons or fermions or mixtures of both. These latter themes have also been the subject of discussions between scientists and theologians but could have been included with the cases presented above, with similar arguments being made.

Finally, another point discussed only briefly above but one that deserves more careful attention is that the critical realist view upon which any such project must be based can also be persuasively criticized, thus undermining the goals of making a close linkage between divine action and specific physical theories.[9] It is encouraging that the dialogue between scientists and theologians has begun again, and seemingly on a different level of mutual respect. However, it does justice to neither side to overlook the limitations and strengths of the other by trying to inappropriately borrow ideas meant to serve in a bounded sphere of inquiry.

NOTES

1. Quantum optics is a specialized branch of physics that can be characterized as dealing with the interaction of light and matter on a scale at which effects predicted by quantum mechanics become important. It is probably one of the most active arenas for testing basic quantum mechanical theory.

2. Omnès provides several calculated examples (Omnès 1994, 323). For example, a particle the size of a large molecule (10 nm) interacting with the few atoms in a good laboratory vacuum (10^6 molecules/cm^3) experiences decoherence due to collisional interactions in a time on the order of 10^{-17} seconds, far too short to be measured in any conceivable experiment.

3. We are all at least vaguely familiar with the concept of radioactive decay; spontaneous emission is probably seen much more often, however. Every time we switch on a fluorescent

light, electrical current transfers energy to atoms in the fluorescent tube. After a very short time, these same atoms give off that energy in the form of light.

4. In spite of the fact that the Bohr model of the atom has been replaced by the quantum mechanical description, it is useful to think of atoms as little planetlike systems in which the radius of an electron "orbit" corresponds to the total energy (kinetic plus potential) of the electron as described here. When farther away from the nucleus, the electron has more energy; when closer, less energy. A change in total energy, corresponding to a jump between one orbit and another, occurs together with the absorption (going to a larger orbit) or emission (dropping to a smaller orbit) of a quantum of energy. Each state of the atom corresponds to one electron orbit.

5. In this case, that a quantum mechanical version of the creation of the universe resulting from a fluctuation of energy in the quantum vacuum could not be considered creation from nothing (*creatio ex nihilo*) because this quantum vacuum is a real entity.

6. The unit nm is a nanometer, or billionth of a meter. Considering light as a wave, blue light corresponds to a wavelength of 400 nm, and red light has a wavelength of about 650 nm.

7. The correlations are measurements made on one particle and compared to those made on the second light particle. We see that in a series of measurements, half the time particle 1 has a clockwise spin and half the time a counterclockwise spin, and likewise for particle 2. It is only when correlating the individual measurements according to the formula presented by Bell that we can make the comparison required to distinguish classical and quantum predictions.

8. For a nice introduction to this topic, especially as it relates to the religion-and-science dialogue, see Wildman and Russell 1997.

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