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THE QUANTUM WORLD

JOHN POLKINGHORNE, Trinity Hall, Cambridge

Introduction

The discovery of quantum theory produced the most profound modification of Newtonian physics that has occurred since the publication of the *Principia.* The clear and determinate character of physical processes, as Sir Isaac understood it, has dissolved at its constituent roots into the cloudy and fitful quantum world. That was a transformation much more radical than the invention of the field concept (which in some ways was just an interpolation into action-at-a-distance) or even the relativising of time (since the guiding principle of relativity is, in fact, the absolute invariance of proper-time). Einstein was the last of the ancients; his uncompromising resistance to the insights of modern quantum theory was a stubborn clinging to the old familiar ways of thought. By and large, theologians have found his company more congenial than that of Schrödinger and Heisenberg, and so they too have proved reluctant to come to terms with the peculiar novelties of what quantum theory has to say. In casting that stone I am aware of the sound of tinkling in the scientific glasshouse, since the physicists themselves have only recently begun to wrestle afresh with the problematic interpretation of quantum theory. Between this contemporary activity and the early (but not wholly satisfactory) struggles of the heroic 1920s, lies fifty years of patient and successful exploitation, in which physicists were content to draw consequences from the theory without troubling themselves to ask profound questions about its interpretation.

My purpose in this paper is not to attempt a systematic account of basic quantum physics. I have tried elsewhere to do that for the general reader.[1] Rather, I want to draw attention to a number of issues which arise from the character of the quantum world and which seem to me to be of some significance for the metaphysician and the theologian. I also wish to repudiate a number of claims which have been advanced as consequences of quantum theory, but which do not seem to me to follow from it.

Issues Which Arise from the Quantum World

First let me address the more positive part of the task. I think there are nine issues worth our attention. I discuss each in turn.

Quantum theory has lent its aid to the death of mere mechanism. The Newtonian picture of the solar system appeared so precisely mechanical that the regular rotation of an orrery seemed a fitting representation of its character. Obviously that clockwork universe could not survive the dissolution of the picturable and predictable into the cloudy and fitful, produced by the advent of quantum theory. But, in fact, that theory has only had a minor part to play in the demise of the mechanical. The seeds of its actual decay lay within Newtonian theory itself. That fact is important, since quantum theory in general only manifests its idiosyncratic character in processes of a smaller scale than normally concerns us. For example, most neurophysiologists seem to think that the synoptic activity of the brain does not occur at a level which makes it an intrinsically quantum phenomenon. (Therefore the curious hope that the Heisenberg uncertainty principle gives us a basis for free will proves to be misplaced.) It is necessary that quantum theory should recapture the impressive successes of Newtonian dynamics for these larger systems, since otherwise it would only have succeeded in explaining the microworld at the expense of our understanding of the macroworld. The correspondence principle (the requirement that quantum theory turns smoothly into Newtonian physics for "large" systems) is a well-understood consequence of quantum mechanics. The real *coup de grâce* for mechanism comes at that "large" level, with the realization that predictable systems, like the orrery and the simple pendulum, are only very exceptional cases, even in the Newtonian account of physical processes. At the beginning of this century, more or less contemporaneously with the first intimations of the quantum world, Poincaré's exploration of the instabilities of classical dynamical systems began to reveal that they possess such an exquisite degree of sensitivity to particular circumstances as makes them intrinsically unpredictable. The celebrated fact that there is no analytic solution to the gravitational three-body problem is due to this very property. Recent investigations have considerably extended our understanding of the openness of complex dynamical systems, linking these properties with the irreversibility of time and the genuine novelty of the future.[2]

Quantum theory provides a striking instance of the general fact that exploration of the physical world often yields surprises, so that, if we are to do justice to the way things are, we need a release from an undue tyranny of common sense. The counter-intuitive character of a world governed by Heisenberg's uncertainty principle (which says that if we know where an electron is we don't know what it is doing, and *vice versa*) needs no stressing. Even things which at first sight seem contradictory — for example, that entities should manifest properties of both waves and particles — can turn out actually to be the case. I would like to emphasize that the apparent paradox of wave/particle duality has, since the invention of quantum field theory by Paul Dirac in 1927, been perfectly understood. It is *not* the case that we use a wave model at one time and a particle model at another and that is all we can say about it, as theologians sometimes allege. It *is* the case that we have a theory that combines wave and particle models without taint of paradox and which is open to our rational inspection.

Even logic finds a modification in the quantum world. The distributive law of Aristotelian logic does not hold for subatomic particles, and a new quantum logic is required to mirror their idiosyncratic character.

All these strange aspects of the quantum world (uncertainty, wave/particle duality, quantum logic) arise from what Dirac correctly identified, as the basic feature which distinguishes quantum from Newtonian physics, the superposition principle.[3] This states that in the quantum world we can mix together possibilities which in the Newtonian world are for ever separate and distinct. For Newton a particle is either here or there. In that clear, determinate world there can be no ambiguity about its position. Quantum theory, however, allows states in which a particle is a mixture (a superposition) of "here" and "there". Such states are not to be interpreted as corresponding to a particle's being in the middle, spatially between "here" and "there"; rather, they are to be interpreted probabilistically, as states in which the particle will sometimes be found "here" and sometimes be found "there". Thus the superposition principle underlies the unpicturability and statistical character of the quantum world.

Quantum theory helps us to distinguish reality from naive objectivity. The unpicturable quantum world certainly does not enjoy the objective character of the world of everyday experience. Ironically, when Dr. Johnson kicked the stone in his "refutation" of Bishop Berkeley, from the quantum mechanical point of view he was in contact with something which was mostly empty space, and for the rest a weaving of wave mechanical patterns. The entities of the quantum world are curiously elusive. Does that mean in fact quantum theory is just a peculiar manner of speaking about events in the everyday world of laboratory apparatus? Are there not really electrons? Some have been tempted to espouse the positivistic answer. The subject's grandfather, Niels Bohr, succumbed; he once said, "There is no quantum world. There is only abstract quantum physical description." I am sure he was wrong to say that. The beautiful patterns of the structure of the physical world, revealed by elementary particle physics, demand to be taken more seriously than that.

It was because he wanted to maintain a realistic view that Albert Einstein fought so strongly against the mature version of quantum theory which developed in the late 1920s. His basic instinct was right, but his error was to suppose that picturable objectivity — a clear and determinate world — was the only form that physical reality could take. In fact, the first duty of a realist is to respect the nature of that with which one has to deal. Quantum entities do not have the properties of simultaneously possessing exact position and momentum, of being visualisable. Following Werner Heisenberg,[4] I want to say that they possess the potentiality of position and momentum, one of which can be actualized in the act of observation, but not both simultaneously. (This potentiality for a variety of possible outcomes corresponds precisely to the superposition of those classically immiscible outcomes, which quantum theory permits.) On this view,[5] it is ontology which controls epistemology. (I suppose that is a definition of realism.) The uncertainty principle arises from the nature of the entities with which we have to deal, not from our lack of dexterity in investigating them. Those who are familiar with analyses of attempts to get round the uncertainty principle in thought-experiment schemes of measurements — a battle which Einstein lost to Bohr — will recall that these efforts only fail if quantum theory is applied consistently to all participating systems.[6] That remark precisely exemplifies the control of epistemology by ontology. It is a similar realist stance which leads me to interpret the intrinsic umpredictability of complex Nextonian systems as indicating an ontological openness to the future in the nature of such systems.

Heisenberg seems to have thought that his picture of quantum entities as the carriers of potentiality in some way made them less real than the picturable objects of everyday. I think he was wrong, as I shall argue next.

It seems to me that the view of quantum theory I am espousing encourages the position that it is intelligibility which is the ultimate guarantor of reality. My endorsement of the reality of the quantum world, and my rejection of Bohr's positivism, arose from the conviction that the rationally beautiful and transparent patterns of that world must be taken with the utmost seriousness. They cannot be downgraded into mere ways of speaking. As a quantum physicist I find myself in sympathy with Bernard Lonergan when he says: "since we define being by its relation to intelligence, necessarily our ultimate is not being but intelligence."[7] Lonergan was talking about God conceived as the unrestricted act of understanding. The unpicturable and Unpicturable have something in common.

I should be misleading you if I were to suggest that our understanding of quantum theory is complete. One of its lessons is that science can live with unresolved questions. The mystery yet to be clarified is the exact nature of the act of measurement. Here it is that the potential becomes actual; the electron which has been a superposition of "here" and "there", on being addressed with the experimental question "where are you?" has to settle for one or the other. How does that cloudy, fitful quantum world produce clear answers registered by the everyday measuring apparatus of the laboratory? It is perhaps the most striking of all the quantum paradoxes that, after sixty years of enormously successful cultivation of the subject, there is no agreed answer to that fundamental question. Broadly speaking, four lines of attack have been pursued.

One denies the validity of the question in the form in which I have put it. It supposes that quantum uncertainty arises, not from the intrinsically indeterminate character of the quantum world, as I have been alleging, but from an ignorance on our part of its detailed workings. What I have claimed to be ontological is asserted to be epistemological after all. There are undiscerned (perhaps indiscernible) causes ("hidden variables") which actually determine everything that happens. The cloudiness is in the eye of the beholder, who cannot make out what is going on. In this view quantum measurement is no different from Newtonian measurement. Both are the revealing of what has always been the case. An ingenious and instructive theory of this type has been constructed by David Bohm. I will give reasons later for rejecting it.

The other three lines of attack accept the indeterminate character of quantum theory.[8]

(a) A quantum measurement involves a chain of correlated consequences from the quantum entity (say, an electron) to the registration of the result of measurement by some macroscopic instrument (say, a Geiger-counter click). The point along the chain where the result gets "fixed" is claimed to be at the macroscopic level. It is here that a system is engaged which is sufficiently large and sufficiently complex to have an irreversible character. The celebrated Copenhagen interpretation, the orthodoxy prescribed by Bohr and his friends, espoused a relatively crude version of this idea. Bohr divided the world up into quantum entities (indeterminate) and classical measuring apparatus (the determinators). An experiment was an indissoluble combination of the two, in which the impingement of the latter on the former produced a definite result. The reason this won't do as it stands is that it is essentially a dualist description (quantum world and measuring apparatus) of a universe which is, in fact, a unity (the measuring apparatus is itself made out of quantum constituents). I think this approach looks in the right direction, but a fully satisfying answer would need to dissolve the duality by means of a much more extensive, and subtle analysis than it has so far proved possible to give.

(b) The problem for (a) is to distinguish what is large and determinating from what is small and indeterminate. All experiments of which we have knowledge involve the ultimate intervention of a conscious observer who notes the result. Some have felt it is at this final stage that things get fixed and that it is consciousness that plays the determining role. The proposal has a certain specious attraction, linking as it does the mystery of quantum measurement and the mystery of conscious thought, but it also has very strange consequences. Are we to suppose that the computer print-out of the result of a quantum experiment, stored away unread, only acquires a definite imprint months later when someone opens the cupboard and reads it?

(c) Even more bizarre is the many-worlds interpretation. This proposes that at every act of measurement the universe splits into parallel, disconnected, universes, in each of which one of the possible results of measurement is realized. There is a universe where the electron is "here" and another universe where it is "there". The world, and we with it, is being cloned at a prodigious rate. The stupendous prodigality of this proposal has meant that it has had substantially more appeal to the gee-whiz writers of popular science than to sober physicists. However, it enjoys some currency among cosmologists as a way of applying quantum theory to the whole cosmos, a project which may not be feasible or necessary.

Quantum theory affords some degree of support for an antireductionist stance. This surprising consequence of subatomic physics (which, after all, is methodologically a very reductionist subject) arises in two ways.

One is the famous EPR experiment.[9] Using quantum theory Albert Einstein, Boris Podolsky, and Nathan Rosen (EPR) pointed out that, when two quantum entities have once interacted, they retain a certain power to influence each other simultaneously, however widely they subsequently separate. EPR thought that this counterintuitive "togetherness in separation" must show an incompleteness in the theory and its need for amendment. Recent experiments, however, and particularly the beautiful work of Alain Aspect and his collaborators in Paris, have revealed that just such an effect of "nonlocality" is to be found in nature. Thus, even at the level of fundamental constituents, the world does not fall apart but, instead, exhibits a degree of mutual cohesion.

Secondly, it is conventional to say that quantum theory shows another integrationist tendency by refusing to separate observer and observed. This would be reflected, for instance, in Bohr's insistence on linking quantum entity and measuring apparatus in the description of the measurement process. That particular way of expressing it is, I think, enforced by Bohr's unacceptable dualism, which can only be salvaged by such a requirement of indivisibility. To my mind, a better way of looking at the matter is to emphasize that the determining apparatus itself arises out of an indeterminate quantum substrate. This is the emergence of a level autonomy within physics itself, quite as striking and quite as conceptually irreducible as the emergence of life from inanimate matter, or self-consciousness from animal being.[10] Here is certainly a profoundly antireductionist insight produced by quantum physics.

Quantum theory provides a significant testbed for claims in the philosophy of science. I have already dealt with some issues that relate to this. Let me refer to one other which relates to the underdetermination of theory by experiment. Clearly a theory which claims to cover an infinity of cases cannot be uniquely determined by a finite number of tested instances. However, an important sieve for rationally acceptable theories is provided by the requirement that one should not need continually to make *ad hoc* adjustments to keep the theory going. (If one had tried to preserve Ptolemaic ideas post-*Principia*, every new set of observations would have required a fresh batch of epicycles, whilst the Newtonian gravitational theory successfully coped for two hundred years, in a perfectly natural and unforced way, with every increase in accuracy. Still the problem of the perihelion of Mercury eventually showed that even the Newtonian theory was only verisimilitudinous.) So the question is not, "Are there ambiguities at any stage?" but, "Are there truly perplexing ambiguities, incapable of being resolved by rational criteria?" If we are to answer that in a meaningful way we shall have to look to fundamental science. It is not surprising, nor significant, that there are, say, conflicting views about chemical valency. Here, people are trying to explain a situation whose basic physics is understood, but the elucidation of its consequences is too complicated to calculate precisely. In such circumstances you have to do what you can, and competing and conflicting models result. They are all patently partial; but fundamental physics ought to be free from the ambiguity of expediency.

I can think of only one example of a significant clash in contemporary fundamental physical theory: Bohm's determinate, hidden variable, quantum theory versus conventional quantum mechanics. As I have said elsewhere, that clash seems like a "duck/rabbit" with a vengeance,[11] since both of these theories have the same experimental consequences, though they are so very different in their character. Yet almost all physicists espouse conventional quantum theory and reject Bohm's ingenious ideas. Why?

There are two answers. One lies in that fundamental requirement of fruitfulness for future development which is an important discriminator of theories. The conventional theory has been able to incorporate the requirements of special relativity in a natural and successful way which has so far eluded Bohm's approach. But even if this were not so, I think the majority verdict would still rightly fall to the conventional theory. Bohm's theory has an air of contrivance about it which does not commend it to many of us. Not only is it hard to believe that even so clever a man as he would have thought of his equations without having those of quantum theory first before him, but also, and above all, the way the statistical character is inserted into the theory has an arbitrary air about it.[12]

Though there is nothing absolutely inevitable about conventional quantum theory, its selection as the understanding of the nature of the subatomic world seems to me to be rationally motivated in the way I have described. It is an example of the fruitfulness of those skillful acts of judgment whose essential role in scientific inquiry was persuasively emphasized by Michael Polanyi.[13]

Quantum theory is also a significant testbed for claims in the history of science. The one I wish to refer to is the degree of influence exerted on scientific development by the general atmosphere of contemporary thought. I shall have to be brief, so let me say that I see no reason to suppose that the cloudy fitfulness of the quantum world was in any way related to the rootlessness of the Weimar republic, from which many of the pioneer papers originated. It is entirely and adequately understood as arising, rather, from the peculiar behavior of light and the statistical character of atomic decays. Though a fascist, authoritarian ideology emerged, physics could not abandon those necessary insights and restore a rigid predictability.

Finally, and most disturbingly, quantum theory suggests that there may be limits to rational inquiry. It is the belief of conventional quantum theories that individual quantum events are radically uncaused; only their overall statistical pattern is prescribed. No explanation is to be offered of why, on this occasion, the electron is found "here" rather than "there". What are we to make of that? It is important to recognize the surprising nature of the claim being made by the physicists. It is in no way comparable to the familiar philosophical problem of the uncertainty of the future, the indeterminate nature of the result of tomorrow's sea battle. Rather, it is the claim that there is no retrospective explanation to be offered of a particular occurrence's having happened.

Does this radical lack of physical causality represent the existence, even at the humblest levels of the universe, of a certain freedom granted to the creature? (Shades of A. N. Whitehead!) Or is God the ultimate Hidden Variable, skillfully exercising his room to maneuver at the rickety constituent roots of the world, whilst cleverly respecting the statistical regularity which his faithfulness imposes? We all know that William

Pollard[14] suggested this as a means for God's action in the world, though it seems a rather hole-and-corner sort of providence to me. Or does even physics have its apophatic element? A more profound understanding of the nature of the measuring process, irreversibly turning potentiality into actuality, is needed before we can make much progress with answering these questions.

The Non-Consequences of Quantum Theory

Quantum theory has been prayed in aid of so many diverse points of view that it seems necessary to conclude this paper by listing a number of its non-consequences.

Quantum theory is strange and counterintuitive, but it does not license the attitude that anything goes. Flimsy analogies have often been invoked in attempts to give quantum backing to non-quantum phenomena. The togetherness-in-separation of the EPR experiment does not itself tell us anything about the possibility of telepathic communication. The idiosyncratic oddness of the quantum microworld is not a basis for believing in the paranormal in the macroworld.

Quantum theory is not of itself a sufficient basis for a universal metaphysics. In their different ways Whitehead's process philosophy and Bohm's holomovement and implicit order present grand, even baroque, metaphysical schemes claiming some anchorage in the quantum world. Whatever the merits of these detailed proposals (and I am skeptical about both), they rapidly go beyond anything that a sober assessment of contemporary physical theory could be held to sanction.

Quantum theory does not endorse the essential rightness of Eastern religious thought. Popular books, such as Fritjof Capra's *The Tao of Physics*[15] and Gary Zukav's *The Dancing Wu Li Masters*,[16] have suggested the contrary. They seek to assert that the dissolving-yet-connected quantum world corresponds to the expectations of Eastern philosophy and contrasts with the uncompromisingly structured expectations of Western thought. The arguments are half-truths, since they depend upon a lopsided account of the quantum world. Although that world has its elusive character, all does not dissolve away. There is a clarity of form that remains. This finds expression in, for example, those symmetry principles which play so important a part in contemporary fundamental physics.[17] It is instructive that Capra unwisely dismissed symmetry as an out-moded hangover from Greek thought. According to him, in Eastern thought symmetry:

> "...is thought to be a construct of the mind rather than a property of nature, and thus of no fundamental importance.... It would seem, then, that the search for fundamental symmetries in particle physics is part of our Hellenic heritage, which is, somehow, inconsistent with the general world view that begins to emerge from modern science."[18]

Those words, written in 1975, have proved a strikingly false anticipation of the path fundamental physics was to take in the subsequent years. I have argued that Western thought (particularly in its striving for a balance between God's transcendence and immanence, and between being and becoming) provides the basis for a natural theology more in accord with the pattern and structure of the physical world than that which Eastern thought provides.[19]

Quantum theory does not approve the idea of an observer-created world. To be sure, the quantum act of measurement involves a subtle, and incompletely understood, interaction between the means of observation and the system observed. The consequences are, however, strictly limited according to the potentiality available to be made actual. It is another example of the unjustified typing of quantum mechanical insight to proceed from this to extravagant claims such as John Wheeler's Participatory Anthropic Principle (PAP): Observers are necessary to bring the universe into being. The gap between saying that the act of measurement determines whether an electron is "here" or "there" and the stupendous claim of the PAP seems to me to be quite unbridgeable. I cannot see any legitimate grounds for being as friendly towards this fanciful assertion as John Barrow and Frank Tipler seem to be in their discussion of the matter.[20]

I believe that the issues that quantum theory raises for theology are best treated in ways that are modest in metaphysical intent, rather than grandiose.[21] We are presented with a picture of the physical world that is neither mechanical nor chaotic, but at once both open and orderly in its character. A simple everyday notion of objectivity is too limited an account even for physical reality. The latter displays an elusiveness which is nevertheless rationally structured, though perhaps not exhaustively so. In the twentieth century scientists have had to be exceptionally flexible in their response to the way things are, abandoning cherished conceptions of what is reasonable in the face of the way things actually seem to be. The contingent rationality of the world so explored is consonant with its being the free creation of a reasonable Creator. However strange and unexpected the discoveries of quantum physics have proved to be, it is still the case that the "unreasonable effectiveness of mathematics" (in Eugene Wigner's phrase) continues to operate as a guide to the pattern of the physical universe. Indeed, I have argued that it is this very intelligibility of the quantum world which is the guarantee of its idiosyncratic reality. Perhaps that is the most important conclusion, for it allies physics with theology in a common endeavor to understand the many-leveled structure of the universe that we inhabit.