Hidden Variable Theories in Quantum Physics

by

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Nearly seven years ago I read a paper to this group on Bell's Theorem and the crisis .in our understanding of reality precipitated by the outcome of experiments designed to test the implications of Bell's Theorem.

In discussing the history of developments leading up to Bell's work, I had occasion to touch briefly on the topic of Hidden Variable Theories. At that time my attitude toward this class of theories was more or less the conventional one: namely, that these represented attempts to maintain traditional concepts of reality against the overwhelming evidence, theoretical as well as experimental, that has been marshaled in favor of the "Copenhagen" interpretation advanced by Niels Bohr, Max Born and Werner Heisenberg, and accepted as dogma by nearly everyone in the physics community.

Recently, as a result of reading papers by John Bell, David Bohm and others, it has become clear that this dismissive attitude regarding so-called hidden variable theories is not justified.

My purpose in this talk is to clarify the nature of these theories, avoiding technical details as much as possible, and to show how they establish the fact that naive realism is not incompatible with the results of quantum theory.

There probably is, or should be if there isn't, a myth regarding a man who saves his fellows from a disaster the possibility of which they had never even imagined.

Thus although I bring you good news regarding the acceptability of thinking of quantum phenomena in the traditional realistic manner, it is not unlikely that some of you may not appreciate that this attitude of realism was, until quite recently, considered to be grossly primitive.

In its weakest form, realism demands that there is something out there that exists independently of our observing it or even thinking about it. A much stronger version of realism might demand that the real world may be considered to comprise vast numbers of particles of various types together with some small number of fields which move and interact according to certain unchanging descriptions not yet completely explicated. Each particle is to be characterized by a finite set of parameters, which include, amongst perhaps others, its position and momentum. These are required to be continuous functions of time, so that each particle moves along a definite trajectory through space as time proceeds.

The standard interpretation of quantum mechanics developed by Niels Bohr, Max Born and Werner Heisenberg in the late twenties seemingly demolished utterly not only the strong but even the weak form of naive realism.

Here is a quotation from Heisenberg that should give you the flavor of the Copenhagen thinking:

> "Some physicists would prefer to come back to the idea of an objective real world whose smallest parts exist objectively in the same sense as stones or trees exist independently of whether observe them. This however is impossible"

Our first task is to review the circumstances that led to this dramatic rejection of classical realism.

The whole difficulty stems from the notorious wave/particle duality exhibited by the fundamental entities such as photons, electrons, protons, neutrons, neutrinos and other more exotic members of what used to be called the family of elementary particles, now numbering over one hundred.

All of these entities behave like particles when they are emitted or absorbed, but in between, in free flight so to speak, they exhibit definite wavelike characteristics.

The intuitive idea of a particle includes the property of wholeness or indivisibility and a high degree of localization. Electrons, protons and neutrons all qualify in that they always carry definite values of rest mass, electric charge, and intrinsic angular momentum – spin, as it is usually called. Photons and neutrinos, while possessing neither rest mass nor charge, nevertheless always carry off or deliver a definite amount of angular momentum and, depending upon their wavelength, a definite amount of energy. And in every instance the processes of emission and absorption are highly localized.

The wave nature of these fundamental entities is well illustrated by the classic double-slit experiment in which an emitter and a detector array are separated by a screen that is impenetrable except for two narrow parallel slits. If the fundamental entity under investigation behaves at all times like a particle, then each one that is eventually detected must have passed through one slit or the other. And because of its presumed localization, it cannot be affected by the presence or absence of the other slit. If this is so, then the pattern observed with both slits open should reproducible by simply superposing the two patterns produced when only one slit is open. But this is not what happens: The results when both slits are open can be understood only in terms of wave interference phenomena.

Quantum mechanics was developed in order to understand or at least be able to predict the intricate pattern of spectral lines produced by atoms. The abstract matrix formulation developed by Werner Heisenberg was shown by Max Born and Erwin Schrödinger to be (almost) equivalent to the much more direct and appealing "wave equation" formulation developed by Schrödinger. In this formulation, the momentum of an entity is inversely proportional to the wavelength of the wave function that represents the entity. But it is a plain mathematical fact that only in the case of an infinitely extended wave train is this wavelength well defined: according to Fourier analysis, it is necessary to include a continuous spectrum over a finite band of wavelengths in order to form a "wave packet" of finite spatial extension.

In fact, from the Schrodinger equation it can be shown that the product of the uncertainties in momentum and position can never be smaller that a very small but irreducible quantity, Planck's famous constant, h. This uncertainty principle was discovered by Heisenberg immediately following his discovery of matrix mechanics and now bears his name. He also developed an elegant proof, which showed that, even assuming that both the momentum and position were perfectly well-defined, the disturbance to the system that necessarily accompanies the process of measuring one of these quantities would produce an uncertainty in the other sufficiently large so that the uncertainty principle holds.

When Heisenberg presented this work to Niels Bohr, he was rebuked: not because there was some error, but because he had violated Bohr's strongly-held philosophical commitment to the principles of logical positivism. Bohr insisted that it is impermissible to accept the reality of anything that cannot be measured. If the position and momentum of an entity cannot both be measured with arbitrary precision, then it cannot be imagined to possess well-defined values for both position and momentum.

Regarding the meaning of the wave function, Schrodinger, its inventor, at first attempted to interpret it as actually representing in a direct manner the fundamental entity which it describes. This was possible in the case of the first problem to which the theory was applied: that of describing the behavior of the single electron in the hydrogen atom. But in every other case, it proved to be impossible.

Thus even for a single, freely-moving electron, the wave function could not be identified with the electron itself. Recall that in order to represent a localized particle, it was necessary to form a wave-packet by combining waves over a whole spectrum of wave numbers. It turns out that the phase velocities of these component waves are not equal, and as a consequence, the wave packet expands rapidly to astronomical dimensions.

Even more fundamentally, for problems involving more than one particle, it is not possible to achieve a satisfactory solution by assigning a single wave function to each of the particles. If there are N particles, one must set up a single wave function that has 6N arguments - the number required to specify the location and momentum of all of the particles in physical space. Thus the wave function for the helium atom exists in an abstract 12-dimensional space, while that for uranium wiggles about in the freedom of a space of 552 dimensions.

The modern interpretation of the wave function in terms of probabilities was introduced by Bohr, Kramers and Slater in a 1924 paper. Thus for a two-particle wave function, the square of its absolute value is proportional to the probability of finding the two particles at the two locations indicated by the pair of three vectors that are specified as arguments of the wave function. This probability interpretation remains unchallenged to this day: it is accepted, in fact, even by the hidden variable theories that we are about to consider. But when this interpretation is combined with Bohr's positivistic interpretation of the Heisenberg uncertainty principle, a difficulty arises.

If it is asserted that no description can go deeper that quantum mechanics, then the probabilistic uncertainty of the wave function must be a characteristic of the system itself. When a measurement is made, this ambiguity is resolved, but because of Bohr's proscription it is impermissible to say that we have only just discovered what was true of the system just before the measurement was made. On the contrary, we are forced to believe that the measurement process itself actually forces the system to change its state so as to be consistent with the measurement made.

Let me quote Pasqual Jordan, a colleague of Max Born, on this matter.
Jordan says regarding the measurement of an electron's position:

> "… the electron is forced to a decision. We compel it to assume a definite position: previously it was, in general, neither here nor there: it had not yet

made its decision for a definite position ... We ourselves produce the results of measurement."

Thus the observer is assigned an active role in determining, albeit in a probabilistic way, the reality that emerges. It is a striking irony that logical positivism, involving it would seem a basically humble attitude, should in this case lead to the conclusion that all of reality depends for its existence upon our willingness to observe.

Another problem that emerges is the epiphenomenon of "wave function collapse". Consider the light that reaches us from the photosphere of a distant star. The appropriate wave function for a photon emitted from such a source is non-zero only within a spherical shell a few inches thick that expands at the speed of light. When the photon is detected this hugely extended wave function must suddenly collapse to atomic dimensions.

While Bohr himself would never speak of such a collapse, his insistence that the quantum system cannot be imagined to possess any reality beyond that given by the wave function, really demands that such a collapse be considered, and indeed most of the members of the Copenhagen school do so. Einstein and Schrodinger found it impossible to accept these ideas.

In 1935 Schrodinger facetiously proposed his now famous cat paradox. One constructs some sort of quantum switch - say a Geiger counter observed over a short period of time so that the probability of at least one click, corresponding to the switch closing, is one-half. The switch is now set to trigger the release of cyanide gas in a covered cage containing Schrodinger’s cat. Before the cage is uncovered the wave function would consist of a fifty-fifty mixture of two states: one describing a live cat, the other a dead cat. The Copenhagen interpretation requires that this is the best description of what is "really" in the cage before the cover is lifted. What is actually observed then 'is either live cat or a dead one. According to the Copenhagen school, it is our looking that forces the outcome. Schrodinger and Einstein would insist that as soon as the switch had time to operate, there was but one single reality under the cover: either a live cat or a dead one. For them the act of observation forces nothing, but only lets us discover which reality was there all along.

Einstein spent a great deal of effort trying to convince Bohr and his colleagues to give up the idea that quantum mechanics is complete as is, and that no reality can exist that fails to satisfy the restrictions of the uncertainty principle. Finally in 1935, working with Boris Podolsky and Nathan Rosen, Einstein developed an argument that he felt would surely convince Bohr and the rest of the world. The key idea was that hypothetically one can produce a pair of particles, say electrons, that are perfectly correlated and move with exactly opposite velocities away from their initial position at rest. If we measure the momentum of one electron, we may infer, without measurement, the momentum of the other. The same is true regarding position. Furthermore, these measurements may be made to any desired accuracy. And in neither case is the second electron disturbed in any way at the time that the measurement is made on the first electron, since any such disturbance would require an interaction that propagates faster than the speed of light, in violation of the restrictions of relativity. Finally, Einstein argued, since we are free to pick either type of measurement, momentum or position, it is clear that the undisturbed electron must possess both of these properties as elements of reality.

Bohr's response must have dismayed Einstein, even though he accepted the whole argument, he rejected the conclusion because he had, a priori, rejected the possibility that electrons may possess real properties. As he had said "There is no quantum world, there is only an abstract quantum description."

It was in connection with this now famous EPR gedanken experiment, as it is usually referred to, that the idea of "hidden variables" first occurred. It was suggested, since quantum mechanics seemed to provide an incomplete description of the total reality, that perhaps some modification of the theory, involving additional variables, presently unknown, and thus "hidden" in a sense, might be developed. Surprisingly, the first such had been proposed long before, in 1925 in fact, by Louis de Broglie, the man who had started the whole business by suggesting that particles might behave like waves. In this "guiding wave" theory, the hidden variable was not something arcane: it was simply the position of the particle itself! In fact this is the case with all so-called hidden variable theories. De Broglie had discovered a way to write a differential equation for the position of the particle in which a function derived from the wave function served as a potential function. Regrettably, he gave up this approach because of objections regarding many-particle systems made by the ever-critical Wolfgang Pauli.

What appeared to be the final blow to hidden-variable theories was delivered in 1932 when John von Neumann published his *Grundlagen der Quantenmechanik* which includes a proof, now recognized to be flawed, that no such theory can produce results that agree with those of Quantum mechanics.

In 1952 David Bohm, unaware of de Broglie's "pilot wave" theory, and in spite of von Neumann's theorem, sought to discover whether or not, in his own words, "a deterministic extension to the quantum theory could be found." His positive results were published in two articles in the *Physical Review*. De Broglie immediately made Bohm aware of his very similar early work, and Pauli detailed his objections. This prompted Bohm to expand his treatment to - include many-particle systems, and at the same time, to develop a theory of measurement that eliminated the need for any wave function "collapse."

To give a fuller understanding of the nature of the theory it is best to let Bohm speak for himself. Regarding the single particle theory he writes:

> "The basic assumption was that the electron <u>is</u> a particle, acted on not only by the classical potential. V, but also by the quantum potential, Q. This latter is determined by a new kind of wave that satisfies Schrodinger's equation. This wave was assumed, like the particle, to be an independent actuality that existed on its own, rather than being merely a function from which the statistical properties of phenomena could be derived. However, I showed on the basis of further physically reasonable assumptions that the intensity of this wave is proportional to the probability that a particle <u>actually is</u> in the corresponding region of space (and is not merely the probability of our observing a particle there). So the wave function had a double interpretation - first as a function from which the quantum potential could be derived and, secondly, as a function from which probabilities could be derived."

Regarding the many-particle theory Bohm continues:

"A more detailed consideration of this extended theory led me to look more carefully at the meaning of the quantum potential. This had a number of interesting new features. Indeed, even in the one-particle system these features showed up to some extent, for the quantum potential did not depend on the intensity of the wave associated with this electron; it depended only on the form of the wave. And thus, its effect could be large even when the wave had spread out by propagation across large distances. For example, when the wave passes through a pair of slits, the resulting interference pattern produces a complicated quantum potential that could affect the particles far from the slits in such a way as to "bunch" them into a set of fringes equivalent to those predicted in the usual interpretation of the quantum theory. Thus, by admitting that, even in an "empty" space in which there is no classical potential; the particle can be acted on by a quantum potential that does not fall off with the distance, one is now able to explain the well-known wave particle duality of the properties of matter. And by noting that this quantum potential can generally have a major effect on the particle, an effect that indeed reflects the whole environment, one can obtain a further insight into the crucially significant feature of wholeness of the electron and its relevant experimental context, which Bohr had shown to be implicit in the quantum theory.

"When one looked at the many-particle system, this new kind of wholeness became much more evident, for the quantum potential was now a function of the positions of all the particles which (as in the one-particle case) did not necessarily fall off with the distance. Thus one could at least in principle have a strong and direct (non-local) connection between particles that are quite distant from one another. This sort of non-locality would, for example, give a simple and direct explanation of the paradox of Einstein, Podolsky and Rosen, because in measuring some property of one of a pair of particles, one will alter the (non-local) quantum potential so that the other particle responds in a corresponding way. "…(this quantum potential interpretation also) later led Bell to develop his theorem (which) demonstrates quite precisely and generally how quantum non-locality contrasts with classical notions of locality."

Bohm continues

"These proposals did not "catch on" among physicists. The reasons are quite complex and difficult to assess. Perhaps the main objection was that the theory gave exactly the same results as does the usual theory. I myself did not give much weight to these objections. Indeed, it occurred to me that if de Broglie's ideas had won the day at the Solvay Conference of 1927, they might have become the accepted interpretation; then, if someone had come along to propose the current interpretation, one could equally well have said that since, after all, it gave no new experimental results, there would be no point in considering it seriously. In other words, I felt that the adoption of the current interpretation was a somewhat fortuitous affair, since it was affected not only by the outcome of the (1927) Solvay Conference but also by the generally positivistic empiricist attitude that pervaded physics at the time."

Incidental to the present discussion, Bohm's fascination with the wholeness inherent in the quantum potential interpretation has led him in recent years to develop a radical view of the nature of reality. He uses the phrase implicate order to describe this view. He makes an analogy with holograms in which information regarding images is stored globally, rather than locally, as in an ordinary photograph.

Somehow he conceives that quantum theory can be considered to incorporate two ongoing processes, inverses of one another, called enfolding and unfolding, which are analogous, it seems, to the making and projection of a hologram. The persistent forms (objects) of our experience move yet retain their general character by virtue of this process, which Bohm calls the holomovement. I have to confess that I haven't the foggiest idea of what he's talking about.

John Bell has made several important contributions, to hidden variable theory and related matters. First of all, it was Bell who pin-pointed the error in von Neumann's putative proof that hidden variable theories were incompatible with quantum theory. He did the same with later proofs offered by Gleason and by Jauch. He was able to prove that the non-locality inherent in Bohm-s theory is an inescapable feature of all hidden variable theories. His greatest achievement is perhaps his development of what is now called Bell's Theorem, which Henry Stapp, a renowned physicist himself, holds to be "the most profound discovery in science." The theorem (1964) takes the form of an inequality that limits the correlation that can be observed in certain experiments of the EPR type, especially those of the sort suggested by Bohm involving a pair of spin-correlated photons, such as that recently performed by Aspect, Dalibard, and Roger. In the theorem, the restriction on the correlations observed apply to any and all theories that are consistent with the restriction of locality, that is, local causality, in the sense that the propagation of effects are restricted to speeds less than the speed of light. The results of the experiment of Aspect and his colleagues, which are beautifully predicted by quantum theory, in fact violate Bell's Theorem. Thus quantum theory, and nature itself, violate the locality principle. It was not previously realized that quantum theory was non-local: in. fact, a common reason for dismissing Bohm's causal (hidden variable) quantum potential interpretation was that it was manifestly non-local. Now it has become clear that this is a necessary feature of any acceptable theory. Finally, John Bell has recently developed a relativistic hidden variable quantum field theory for fermions, the spin one-half family of particles which includes electrons, protons and neutrons, the basic building blocks of the material world. This theory incorporates a stochastic feature, so that causality and definite particle trajectories are lost. Nevertheless, particle location is retained as a definite element of reality, and no special status need be accorded to observers.

As Bohm has made clear, the hidden variable theories under consideration are more aptly referred to as quantum potential interpretations of quantum theory. To summarize the advantages of these interpretations over the standard Copenhagen interpretation, one may list the following points.

1) The quantum potential interpretation permits a traditional, easily imagined ontology – quantum objects are real and exist independently of observation, just like ordinary objects. In contrast, the Copenhagen interpretation holds that

> "… the elementary particles are not as real (as the phenomena of daily life); they form a world of potentialities or possibilities rather than one of things or facts."

according to Heisenberg.

2) The quantum potential interpretation preserves causality. It is non-local, but so also is the non-causal Copenhagen interpretation.

3) The Copenhagen interpretation assigns a critical role to observers, and requires that an absolute distinction be drawn between experimental apparatus and the quantum phenomenon being observed. The quantum potential interpretation treats observers and their equipment on the same basis as the phenomenon being observed.

4) The principle of complementarity, which holds that one cannot make observations regarding particle paths without destroying wave interference patterns, appears to be invalid in the modern neutron interferometry experiments of Badurek et al, in which particle paths may be identified by means of spin interactions without destroying interference effects.

In spite of these advantages, the quantum potential interpretation has not been popular. Historical accident, as Bohm points out, is no doubt a factor. Another, I think, is its ad hoc character, and its dependence upon the wave function of ordinary quantum theory. It presents, as they say, not a pretty picture. Indeed, neither de Broglie nor Bohm liked it very much. Einstein, who certainly disliked the indeterminacy of the Copenhagen interpretation, said in a letter to Max Born

> "Have you noticed that Bohm believes (as de Broglie did, by the way, 25 years ago) that he is able to interpret quantum theory in deterministic terms? That way seems too cheap to me."

I will let John Bell have the final word. Regarding the quantum potential interpretation he has said

"…but like it or lump it, it is a perfectly conclusive counter-example to the idea that vagueness, subjectivity, or indeterminism are forced upon us by the experimental facts."