The EPR paper and its preceding and succeeding perspectives

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When Einstein's revolutionary interpretation of Planck's and other experimental results related to microscopic phenomena came out in the early years of the 20th century, the ideas he put forward were not accepted by the physics community at large due to the fact that he challenged the accepted wave theory. The wave-particle duality of light was nothing less than scientific blasphemy! However, as the subsequent development of quantum mechanics, largely by the Copenhagen camp, involved an indeterminism that to Einstein was inherently unacceptable, he decided to find his answers elsewhere—and co-authored the EPR paper. Here I try to chart the story of that attempt at wiping away the indeterminism in quantum mechanics—after all, mused Einstein, God doesn't play dice…or does he?

THE COPENHAGEN INTERPRETATION IN A NUTSHELL:

The years 1925-26 witnessed the publication of two papers providing varying perspectives on quantum mechanics—the paper on matrix mechanics by Werner Heisenberg and the wave mechanical equations of Erwin Schrodinger. These papers marked important stages in the development of quantum theory each initiating its own path of interpretation. Schrodinger's famous equation used a function psi to define the state of a particle—it was a product of the wave-particle duality concept. Max Born tried to reconcile the above two ideas by interpreting Schrodinger's wave function psi (rather its square) as the probability of existence of the particle within a given region of space. Bohr used the Heisenberg formulation as the basis for his theoretical explanations. The Copenhagen camp consisted of a lot of brilliant, young physicists like Heisenberg, Pauli, Jordan and Dirac, under the guidance of the mentors Bohr and Born. With their combined capacities, they were a force to reckon with.

The Copenhagen formalism, though ultimately discredited to a certain extent by arguments put forward by people like EPR, still continues to be the basis for one of the quantum mechanical explanations of phenomena in vogue today. These are a few of its main postulates:

1) An arrow of unit length is used to represent a Hilbert space, in which the state of the particle is represented by a vector.
2) A given property will have a definite value only in certain vector positions, which are called the eigenvectors for that property. In general, the state vector of a particle will be in a superposition of the different values of some property.
3) The state vector evolves in a continuous and deterministic way, determined by Schrodinger's wave mechanical equation, unless a measurement is made.
4) As soon as a measurement is made to determine the value of a particular property, the state vector collapses in to an eigenvector for that property.
5) There is a greater probability that for a given property measurement, the state vector will collapse into a particular eigenvector as dictated by Born's rule: The probability of finding a certain eigenvalue upon measurement of some property is given by the square of the component of the state vector in the direction of the corresponding eigenvector.

Bohr identified certain pairs of properties, whose eigenvalues could not simultaneously occur—this he derived from the Heisenberg Uncertainty Principle. The pairing of these properties was called Complementarity. This was an attempt to explain the mutual exclusiveness of certain properties (e.g., energy and time, position and momentum).

EINSTEIN'S TRYST WITH COPENHAGEN:

In Arthur Fine's "The Shaky Game", the author describes Einstein's attitude towards the two new theories of 1925-26 as ambiguous. The Heisenberg formulation didn't appeal to Einstein for several reasons (to be given below). He objected to the Schrodinger wave mechanical interpretation too and described it as "uncausal and altogether too primitive". He contended the following about the two ideas: their treatment of many electron systems involved correlations between electrons that violate the action by contact principle; they require the renunciation of the treatment of individual systems and offer a descriptive completeness only in the form of statistics.

Einstein also felt uncomfortable with Heisenberg's uncertainty principle and the indeterminism it implied. From 1927 (when Einstein received a prepublication of Heisnberg's paper) through till 1930, Einstein had numerous discussions with Bohr (largely at the Solvay Conferences), the subject of which was, in simple terms, a way to bypass the uncertainty relations. Einstein attempted to use an example of an electron passing through a slit and falling on a screen, whereby its position and momentum could possibly be measured deterministically by his thought experiment. Later, at the Sixth Solvay Conference, Einstein's "Box" made its appearance—a contraption that tried to work around the energy-time uncertainty relation. However, Bohr was able to refute all of Einstein's objections, in the latter case using Einstein's own gravitational redshift formula to do so. Ultimately, Einstein ended up accepting the uncertainty concept, yet retained all of his other arguments, including arguments regarding the violation of relativistic mechanics.

Einstein thus set out to remedy the flaws in the quantum mechanical interpretation of the Bohr camp and simultaneously root out the indeterminism of the Copenhagen ideas, for though he accepted the uncertainty principle, he believed that it would be superseded by an underlying theory of much broader scope—God couldn't then be accused of playing dice…

THE MEASUREMENT OF THE PROPERTIES OF SYSTEMS:

Variants on the 1922 Stern-Gerlach experiment:

The 1922 Stern-Gerlach experiment on the properties of particles on atomic scales yielded highly erratic and theoretically confusing results regarding the simultaneous measurement of certain properties of these particles. Though the actual experiment was carried out on silver atoms and studied the angular momentum of the atoms around axes corresponding to the x- and y- axes, for convenience sake this experimental structure shall be replaced by one consisting of electrons and two arbitrary, hypothetical properties of electrons—say, their hardness and their colour.

It is an experimentally proven fact that each of these properties can have only two possible values—for colour we shall call them 'black(b)' and 'white(w)', and for hardness, the terms 'soft(s) and 'hard(h)' shall be used. Now, imagine a device called a colour box, a box with three apertures. Electrons are fed into one of the apertures, and emerge from the two other apertures separated into black and white electrons respectively. Thus, this is a process of segregation according to the two possible values that the electron can assume. A hardness box can also be constructed which works on similar principles—separation of electrons according to whether the property of hardness has a value = 'soft' or a value = 'hard'. It has been shown repeatedly that during the employment of such types of boxes the emerging electrons always distribute themselves equally between the two possible values. Nature favours a 50/50 distribution.

The predicaments involving quantum mechanical descriptions, however, arise when we look for correlations between the two properties—when we combine the two measurements in single experiments:

1) Electron made to pass through colour box and then a hardness box (or vice-versa):

   If the b electrons emerging from the colour box are made to pass into the hardness box, the emerging electrons are found to be distributed equally into h and s electrons.

2) Electron made to pass through colour box, hardness box and then another colour box (in that order):

   Black electrons emerging from the first colour box are made to pass through the aperture of the hardness box. The electrons are distributed equally into hard and soft electrons as seen before. Now on passing the electrons emerging from say, the soft aperture, through the colour box, we would assume them to emerge entirely through the black aperture (for according to the apertures they have emerged from they are now expected to be black and soft). However, it is seen that the emerging electrons are equally distributed between the white and black apertures of the third box.

This seems to imply that the intermediary hardness box has somehow randomized the colour property of the electrons and thus, equal distribution ensues. This procedure can be repeated substituting hardness boxes for colour boxes and vice-versa—the results will be analogous to the afore-mentioned experiment. Thus, the measurement of one property seems to preclude the measurement of the other. This is further emphasized by the fact that attempts to construct a colour-hardness box, which simultaneously separates the electrons according to their hardness and colour, have failed.

This result seems to fit in perfectly with the Copenhagen interpretation of Quantum mechanics. These experiments serve as clear practical demonstrations of the idea of uncertainty in simultaneous measurement, which formed a cornerstone in the Copenhagen ideas. However, they also seemed to raise questions for people like Einstein who sought to clear away the indeterminism inherent in the Copenhagen interpretation. The EPR paper used similar ideas to meet its authors' own requirements.

THE EPR PAPER:

In 1935, Albert Einstein, Boris Podolsky and Nathan Rosen (EPR) co-authored a paper titled "Can Quantum Mechanical Description of Physical Reality Be Considered Complete?". It was published in the May 15th issue of *Physical Review*. It was an attempt to rid the explanation of reality of its indeterminism. Einstein accepted the uncertainty explanations that formed an integral part of quantum mechanics, but due to his reluctance to believe that this theory in its entirety represented reality, he drafted this paper.

The paper consisted of a "paradox", according to which only one of the two conditions could be true:

1) The quantum mechanical description of reality given by the wave function is not complete; or
2) When the operators corresponding to two physical quantities do not commute, the two quantities cannot have simultaneous reality;

If the quantum mechanical description of reality were complete then all quantities that correspond to physical elements of reality would have simultaneous definite values. Also if two non-commuting physical quantities had simultaneous reality, they would fit in to the completeness condition for a theory; i.e., QM would be complete. However, as the Uncertainty principle prevents the wave function from providing simultaneous values for these two quantities, one of the two afore-mentioned conditions must be true. This was the dilemma that EPR proposed would be resolved by their work.

It is interesting to note that the authors provided their own definition of what a real physical quantity means: "If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity." They use this as a "sufficient" working definition of a physical quantity in their thought experiment.

I will assume a more simplistic analogue of the EPR experiment based on concepts mentioned in the earlier section on the Stern-Gerlach experiment:

Consider a particle pair in an entangled colour state (here the property of electrons I defined as colour is used; the other member of the non-commuting pair is the property of hardness). This means that the electrons will exist in a state of superposition with respect to the colour property. The entangled pair separates into its individual electrons and they travel far apart (to a relative distance of the order of a few light years apart). The colour of each electron is measured when it reaches an observer.

(1) They argued that if the colour of electron 1 were measured, then according to the Copenhagen theory the state vector of electron 2 would collapse into a given colour eigenvector. However, if the hardness were to be measured then the state vector would collapse into the eigenvector corresponding to a hardness value. Thus, by two different measurements on electron 1 we obtain two totally different state vector collapses—this implies that by changing the operation of measurement on electron 1 we change the values of electron 2. Since this happens after separation, this would represent a strange 'action-at-a-distance'. This was not acceptable to the authors.

(2) If the two measurements give different values, then the authors proved that it was possible to conceive the two quantities as being non-commuting.

(3) Now by measuring the colour of say, electron 1, we can automatically predict the colour of electron 2. This can be done because according to the Pauli exclusion principle fermions cannot occupy the same state—so in the given entangled pair, if electron 1 is found to be black, electron 2 would be white, while if electron 1 were white, electron 2 would be black.

The EPR group stated that since the value of the colour of electron 1 can be measured without in any way disturbing electron 2, and as such a measurement automatically determines the colour of electron 2 with certainty, the colour of an electron is a 'real' property. Similar arguments can be applied to the hardness property. Thus, argued EPR, as both the hardness and colour quantities represent real physical quantities.

Hence, from the above arguments, the second possibility that two non-commuting quantities do not have a simultaneous existence may be ruled out. That leaves us with the conclusion that Quantum mechanics is incomplete.

EPR postulated that the outcomes of all measurements are pre-determined by other properties, hidden variables, and the description of reality according to such a hidden variable theory would be complete. The values of the properties are thus fixed before measurement itself.

EPR and Copenhagen—head to head:

The difference between the EPR concepts and the conventional Copenhagen interpretation occurs as to when the values of the properties are determined—EPR has values fixed before measurement, while Copenhagen quantum mechanics states that the value of a property is set when the measurement is made.

According to the conventional Copenhagen interpretation, the measurement of the value of the property by one observer would cause its state vector to simultaneously collapse into any eigenvector, the highest probability being ascribed to the nearest eigenvector (decided by Born's rule). However, this runs into a lot of problems, particularly with special relativity. Firstly, when the colour of one electron is measured it should send a signal to the other electron across several light years **instantaneously** indicating which value the other electron is to assume. Thus, quantum mechanics would have to be non-local, or superluminal—signals should be able to travel faster than the speed of light. Relativity does not allow this.

Secondly, if one observer is moving with respect to another, the relativity of simultaneity comes into play—the same two events will occur at different relative times for the two observers. One observer will detect electron 1 before electron 2 while it might be the opposite case for the other observer. So the state vector collapse determination of values will not work out—which electron is detected first and sends the signal of collapse?

The EPR paper also, however, does not solve all the problems. It provides it's own tailor–made definition of reality which some people[3] consider to be tautological—recall the condition of completeness "*every element of the physical reality must have a counterpart in the physical theory*". It would be difficult to define physical reality other than through a physical theory.

The paper also adheres religiously to classical idealities (like momentum and position) that may actually have no physical significance. Bohr's complementarity principle more cleverly sidesteps this possibility.

[3]Ref- Henry Margenau 'Einstein's Conception of Reality': from Albert Einstein: Philosopher-Scientist

Bohr's reply:

One of Bohr's close associates Leon Rosenfeld recalls, "This onslaught came down on us as a bolt from the blue. Its effect on Bohr was remarkable." After they worked "day after day, week after week", they came up with a response in the form of a letter dated June 29, 1935, to the editor of *Nature,* and then a long paper published in *Physical Review*.

Though Bohr ultimately admitted that there was no question of a physical disturbance of one system brought about by measuring its correlated twin, he still had an objection, which he stated in the following now-famous words: "…but even at this stage there is essentially the question of an *influence on the very conditions which define the possible types of predictions regarding the future behaviour of the system.*" (Bohr's own italics). Bohr seems to be referring to the fact that such a measurement seems to alter the state of the particle and therefore influences the possibility of a second measurement on the particle. This refutation of Bohr's, however, has been referred to as merely a "semantic disturbance" by some of his critics[1], rather than having any real significance.

[1]Arthur Fine "The Shaky Game": Pg.35 Einstein's Critique of Quantum Theory

Einstein's dissatisfaction:

In a letter to Einstein dated June 7th, Schrodinger[2] responds to the publication of the EPR paper, and states what he thought to be possible objections. In the letter he remarks to Einstein about cases of "entanglement", in which the state function of a composite pair no longer factors out into the product of the component state functions. Thus a measurement on one of the systems now will necessarily affect the measurement of the other system. Though Schrodinger did not give a complete argument here, he gave a few ideas for Einstein's consideration.

The response to this letter is more important as far as the EPR paper is concerned, for it is here that Einstein voices his dissatisfaction with the EPR paper, which was written by Boris Podolsky. According to Einstein, Podolsky's writing obscured the clarity of some of the arguments. He says: "for reasons of language this [paper] was written by Podolsky after much discussion. Still, it did not come out as well as I had originally wanted; rather the essential thing was, so to speak, smothered by the formalism." There is some speculation that as Podolsky left Princeton for California at about the time of submission, it could be that, authorized by Einstein, he actually composed it on his own!

Einstein thus proceeded to provide his own simplistic version of the EPR argument in the letter. He gives an example of two boxes and a ball and the probability of finding the ball in one of them the argument being similar to the one constructed above with the colour and hardness measurements. He was clearly dissatisfied with the indeterministic collapse idea where only upon lifting the lids is it decided where the ball 'really' is. The statistical interpretation was not to his liking. Probabilistic explanations were **incomplete** explanations. Only if a theory could state with assurance that the ball was in one of the boxes, could it be considered complete.

[2]Arthur Fine "The Shaky Game": Ch 5 Schrodinger's Cat and Einstein's

THE AFTERMATH OF EPR:

In the 1960s, John Bell used a slight variation on the same thought experiment of EPR, and showed that the possibility of a hidden variable theory was not a viable one. His statistical arguments were experimentally substantiated by Alain Aspect during the late 70s and early 80s. Was indeterminism an inherent part of our world?

These experiments of course came after questionable attempts at the reconciliation of our ideas of definite measurements at a macroscopic level with the indeterminism of the microscopic universe. I say questionable because the ideas involve hypotheses which are experimentally unverifiable. Take, for example, the many worlds interpretation initiated by Hugh Everett III, and popularized (read: reinterpreted!) by John Wheeler and Bryce S. de Witt. The idea involves the existence of worlds corresponding to each of the possible outcomes of all the measurements carried out on systems—past, present and future. Though this was not the actual Everett interpretation, this was the version that was prevalent. My take on it: it seems to be the easiest way out! No substantiation can ever be made, no corroboration.

The more modern approach is called *decoherence* which seemingly refers to how the idea of determinism is illusory. Things never commit themselves to particular values.

<u>My own two cents:</u>

In attempting to find structure in the chaos of quantum mechanical interpretations, the impression I got was that quantum mechanics is inevitably moving towards the blurry regions of overlap between physics and metaphysics. To me theories like the many-worlds interpretation and decoherence (from the little I understand about it!) are ideas which cannot possibly be verified to the fullest extent because they are perspectives on our entire universe—a system of which we are a part. Thus, as long as we are internalized in such a system and form a part of it, an objective "theory of everything" is a philosophical abstraction, no more (a rather sad generalization of the center of mass theorem, but one I am willing to defend nonetheless!). This does not mean that we can't work towards a more practical clone of the Absolute theory, but once we get this close to the fundamentality of our universe, it's time to start taking into account other parameters—human psychology, individualistic views of reality. I know this is mere speculation, but if science reaches the end of its presently acceptable tether, it probably is time to expand the horizons of "pure science"…

Bibliography:

1) "Albert Einstein: Philosopher-Scientist" – a collection of essays edited by Paul Arthur Schilpp—referred especially to essay by Henry Margenau.
2) "The Shaky Game" by Arthur Fine.
3) "God does not play dice: He just does not make up his mind" – presentation and manifesto by Prof. Michel Janssen.
4) "Harmony and Unity: The Life of Niels Bohr" by Niels Blaedel.
5) "Quantum Physics: Illusion or reality?" by Alastair Rae.
6) Ch. 1 of David S. Albert's "Quantum mechanics and Experience" (Chapter on Superposition).