The Bohr and Einstein debate: Copenhagen Interpretation challenged

by Rochelle Forrester

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This paper is the second edition of my paper Bohr v Einstein published in 2002 and contains additional material on the EPR experiment derived from my paper Sense Perception and Reality: A theory of Perceptual Reality, Quantum Mechanics and the Observer Dependent Universe.

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Abstract

The Bohr Einstein debate on the meaning of quantum physics involved Einstein inventing a series of thought experiments to challenge the Copenhagen Interpretation of quantum physics. Einstein disliked many aspects of the Copenhagen Interpretation especially its idea of an observer dependent universe. Bohr was able to answer all Einstein's objections to the Copenhagen Interpretation and so is usually considered as winning the debate. However the debate has continued into the present time as many scientists have been unable to accept the idea of an observer dependent universe and many alternatives to the Copenhagen Interpretation have been proposed. However none of the alternatives has won general acceptance because all have problems that make them implausible or impossible.

The debate between Bohr and Einstein over the interpretation of quantum theory began in 1927 at the fifth Solvay Conference of physicists and ended at Einstein's death in 1955. The most active phase of the debate ran from 1927 to 1936 when Bohr replied to the EPR paper written by Einstein and two colleagues. The debate took the form of various thought experiments invented by Einstein in which it would be theoretically possible to measure conjugate and complementary properties such as the position and momentum of a particle, or its energy at a certain point in time, or to observe it behaving as a particle and wave at the same time. If these measurements were possible it would show that Bohr's idea of complementarity and Heisenberg's uncertainty principle were wrong and that the quantum theory proposed by Bohr, called the Copenhagen Interpretation, was wrong. Before addressing Einstein's attack on Bohr's theory, it is necessary to examine the theory to see what Einstein was objecting to.

The best way to understand quantum theory is in comparison with the classical theory of physics derived from Newtonian laws of motion, Maxwell's electromagnetic theory and statistical thermodynamics. Classical physics provides a description of the physical world that assumes a continuity of motion and fields of force. This means that we are able to use a series of observations to see the changes in a particular system. We are able to given a continuous description of the system as it undergoes particular changes. Classical physics also assumes causal interactions in space and time between bodies which are considered to be independent objects. The mathematics used to describe a physical system amounted to a theoretical model in which the terms of the theory correspond to the elements in the physical system. It was possible for example to make a series of measurements of the positions and motions of the planets and using Newton's laws to determine with certainty the past and future behaviour of the planets. As long as the system was closed and not subject to any external disturbances we could know the state of the system at any time, past or future.

Observations made of the system could confirm whether the predictions made under the theory were correct or not, but would not disturb the system itself. The system could be considered as being entirely independent of the observer and any disturbances caused by the observation or measurement could be controlled or allowed for by the observer.

Bohr's theory for the quantum world differed radically from the classical theory in a number of respects. A key factor in Bohr's theory was the discovery of Planck's constant. In 1900 Max Planck while working on a problem in physics concerning blackbody radiation suggested that radiated energy should be seen as not being continuous as is assumed by classical theory, but as being composed of discrete indivisible bundles of energy. This unit of energy, also know as a quantum or the quantum of action, was soon used to explain other problems in physics such as the photoelectric effect where electrons are ejected from metals and the orbits of electrons in atoms.

A further important factor in Bohr's theory was wave-particle duality. Electromagnetic energy had been assumed to consist of waves, but the discovery of Planck's constant, the photoelectric effect and eventually in the 1920's the Compton effect, where x-rays were found to knock electrons out of a gas, it was concluded that electromagnetic energy could also behave as particles. Quantum entities such as electrons were normally regarded as particles but were also found to behave as waves in certain experiments. This meant that both energy and matter were capable of behaving as both waves and particles. This was considered to be a problem as waves and particles had contradictory qualities such as waves are inherently in motion, spread out in space and may merge together to reinforce or cancel each other out, while particles may be stationary and occupy a single point in space and rebound of each other like billiard balls when they collide.

Bohr's theory also concerned the problem of how can we objectively describe the things we can not directly experience. Bohr considered we have no choice but to use the language of classical physics and our everyday macro-world experience when describing the quantum world. This is because there is no other language we could use. If we tried to use a purely theoretical language not related to our experiences in the macro-world, we would not be able to objectively communicate to each other what we thought was happening in the quantum world. Such a language not being related to our common experiences in the macro-world would be ambiguous and would be unable to be used objectively to describe the quantum world. It is a necessary condition for the unambiguous communication of our ideas of the quantum world that they be in a language that relates to the everyday world we are all familiar with. The principle that we must use the familiar classical concepts to describe the quantum world is known as the correspondence principle. Bohr actually used the term correspondence principle to refer to two separate ideas. The other use of the correspondence principle is the situation where the macro-world and the quantum world merge and where for the higher quantum numbers the classical and quantum theories produce the same calculations.

A further factor in Bohr's thought was that if one wished to provide an objective description of the world, it is necessary to have external points of reference available. Such external points of reference available in the macro-world are the concepts of space and time and of causality, yet these points of reference are not available in the quantum world. The only external points of reference available when investigating the quantum world are re-identifiable macroscopic particulars and measuring apparatus. It is the existence of such apparatus that allows quantum theory to be objective. (Horner, 1987, 149). The example is given of two identical pens which in the macro-world one can distinguish by virtue of their different spatial locations. If they were both put in a box which is then closed and shaken about, it will then no longer be possible to re-identify which pen is which. Observations of the quantum world are like opening the box; in both situations we have lost the continuity which exists in the macro-world. This leaves the macroscopic measuring apparatus as the only frame of reference available for creating objective descriptions of the quantum world. (Horner, 1987, 204-205). This situation is forced on us by the quantum of action (or Planck's constant) which causes the discontinuity which exists in the quantum world. A later measurement will render information gained by an earlier measurement to be of dubious value due to the interaction between the quantum entity being observed and the measuring apparatus. With no continuity in space and time available as a frame of reference and given the effect that observations have on the quantum entities being observed, the interaction between the quantum entity and measuring apparatus is the only frame of reference available. (Horner, 1987, 67). Due to this Bohr considered the quantum theory could not describe the unobserved state of quantum entities, but only the interaction between the entity and the measuring apparatus. The quantum world is observer dependent.

A further important element in Bohr's thought is the concept of complementarity. Complementarity provides a general framework to put together various aspects of nature which cannot be understood within a more restricted framework. It allows phenomena which might otherwise be considered contradictory, like wave-particle duality, to be put together. The contradiction is avoided as matter and energy do not behave as wave and particle at the same time in the same experiment. Complementarity allows the complete description of quantum phenomena; without it descriptions would be incomplete. Bohr considered complementarity replaced but also embraced the classical concept of causality, when dealing with the quantum world. It is not possible to consider observations as being in a series, as one does in classical physics, in the quantum world. In the quantum world you have to go back and forth between sets of observations which may be put together under the framework of complementarity.

The uncertainty principle established by Heisenberg was also part of the Copenhagen Interpretation championed by Bohr. The uncertainty principle states that it is not possible to obtain completely accurate measurements of certain pairs of properties of quantum systems, such as position and momentum or time and energy, at the same time. The more accurately one property such as position was measured, the less accurately momentum could be simultaneously measured. This is caused by the quantum of action which is of sufficient size to disturb quantum systems when we observe them and because the quantum of action is indivisible we cannot reduce the disturbance by reducing the amount of energy used to observe the quantum system. The other problem is that the disturbance is uncontrollable and unpredictable and so cannot be allowed for when observing quantum systems. The uncertainty principle meant that determinism, the ability to assess both the past and future behaviour of a physical system was no longer possible. The initial information required, for example both the position and momentum of a body is impossible to establish with certainty and any changes are unpredictable.

The final element making up the Copenhagen Interpretation is the wave function invented by Schrodinger, but which was interpreted by Max Born as being probability waves. It is not possible according to quantum theory to predict the behaviour of individual quantum systems; rather we can only predict the probable behaviour of the individual system. This is caused by the discontinuity in the quantum world and because each measurement involves an interaction with the system being measured. This interaction, which disturbs the system, is uncontrollable and unpredictable.

When a measurement is made the probability waves are considered to have collapsed to a specific state giving the actual position (or whatever else is being measured) of the quantum system. Prior to the measurement the quantum system is considered not to have any real position at all. It is the actual act of measurement which brings the quantum system into existence or whatever property of the system that is being measured. This is because the focus of the Copenhagen Interpretation is on what can be known. It is not possible in principle to know what a quantum system is doing prior to measurement. The determinism that enables the behavior of bodies in the macro-world to be calculated simply does not exist in the quantum world. The indivisibility of the quantum of action and the fact that measurements disturb quantum systems in an uncontrollable and unpredictable way eliminates the possibility of determinism in the quantum world.

Bohr's argument has been summarized by Max Jammer in *The Philosophy of Quantum Mechanics* as

"1. Indivisibility of the quantum of action. (quantum postulate").
2. Discontinuity (or indivisibility) of elementary processes.
3. Uncontrollability of interaction between object and instrument.

4. Impossibility of a (strict) spatio-temporal and at the same time causal description.
5. Renunciation of the classical mode of description."

(as quoted in Horner, 1987, 106)

A more detailed summary of Bohr's thought is provided by Horner. It is

"(0) All knowledge presents itself within a conceptual framework adapted to account for previous experience, and any such frame may prove to narrow to comprehend new experiences.

(i) The quantum of action is a discovery which is universal and elementary.

(ii) The quantum of action denotes a feature of indivisibility in atomic processes.

(iii) Ordinary or classical descriptions are only valid for macroscopic processes, where reference can be unambiguous.

(iv) Any attempt to define an atomic process more sharply than the quantum allows must entail the impossible, dividing the indivisible.

(v) Because of the limit of indivisibility a new and more general account of description and definition must be devised.

(vi) It is a necessary condition for the possibility of unambiguous communication, that suitably refined everyday concepts be used no matter how far the processes concerned transcend the range of ordinary experience.

(vii) Our position as observers in a domain of experience where unambiguous application of concepts depends essentially on conditions of observation demands the use of complementary descriptions if description is to exhaustive."

(Horner, 1987, 104).

Unlike Jammer's description this introduces both the Correspondence Principle as (vi) and complementarity as (vii). However both descriptions of Bohr's thought emphasize that it is the indivisibility of the quantum of action that is the cause of the need for a new non-classical theory for the quantum world. However Bohr's view of the situation was not accepted by Einstein.

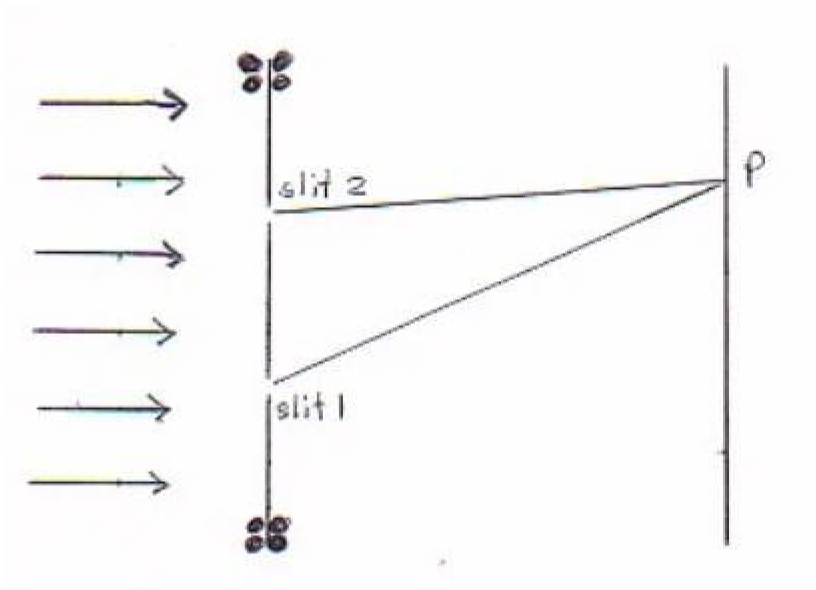
Einstein did not like Bohr's interpretation of quantum theory. He did not like the uncertainty principle and the probability inherent in Bohr's theory. He considered "God did not play dice." He also did not like the discontinuity and the loss of causality involved in the theory. Most of all he did not like the loss of a world that existed independent of our observations. Einstein wanted a more complete view of the universe than Bohr's theory provided and he wanted a single view to cover both the quantum world and the macro-world. The view he considered ought to apply to both worlds was the view of classical physics with its independent reality, causality, determinism, continuity and space-time framework. Einstein's view was essentially ontological. He wanted to know what was going on "out there".

Bohr's view on the other hand was more epistemological. He was interested in what we can know and the conditions for the unambiguous communication of our observations of the quantum world. Bohr accepts the existence of an indivisible quantum of action and the discontinuity of quantum processes that follow from the indivisible quantum of action. Einstein on the other hand regarded the quantum of action as merely provisional or as a heuristic device rather than as the fundamental fact of nature Bohr considered it to be.

Einstein's criticism of Bohr's view of quantum theory began at the fifth Solvay Conference in Brussels in 1927. Einstein would invent thought experiments to show that the uncertainty principle or complementarity did not always apply. One such experiment involved the double slit experiment which Einstein modified so it would be possible to tell which slit a particle passed through while still allowing the interference pattern to exist. If this was possible it would show a quantum entity acting as a particle (i.e. when you can tell which slit it passed through) and a wave (due to the evidence of the interference pattern) at the same time. This would contradict Bohr's idea of complementarity.

Einstein's idea is shown on the diagram below:

Particles First Screen on Rollers Second Screen



Einstein's modification of the double slit experiment is that the screen containing the two slits should rest on rollers and be able to move. A particle arriving at point P on the detecting screen would receive an upward kick as it went through the slit. This would mean the screen would receive a downward kick and the size of the kick would be greater if the particle had passed through slit 1 than if it had passed through slit 2. By measuring the motion of the screen it would be possible to tell which slit the quantum entity had passed through which involves the entity acting as a particle while at the same time retaining the interference pattern.

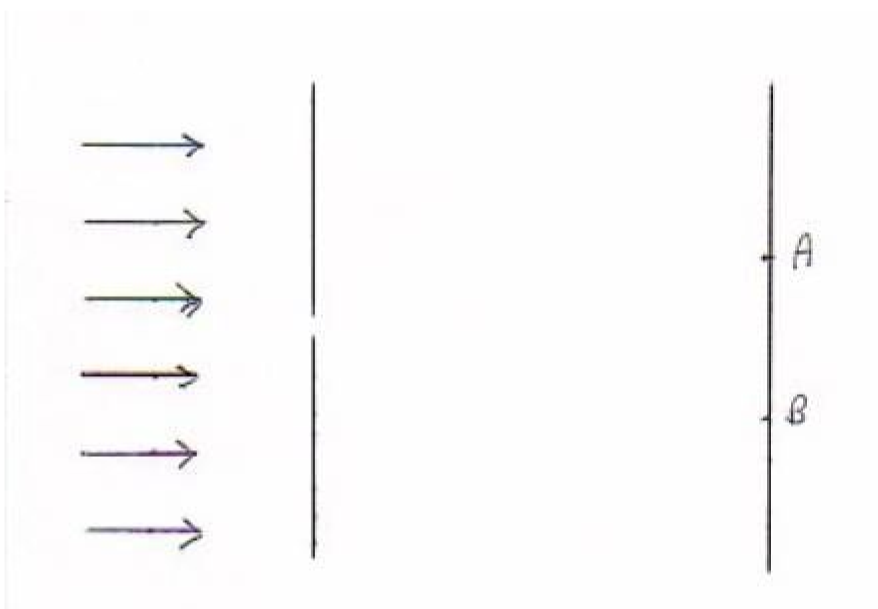
Bohr soon came up with a problem for Einstein's experiment. Bohr considered that in order to see which slit the quantum entity had passed through it was necessary to measure the movement of the screen to a particular accuracy. Any lesser degree of accuracy in the measurement will not provide us with the information required to tell us through which slit the entity went through. However due to the uncertainty principle there will be a degree of uncertainty as to the position of the slits. The uncertainty as to the position of the slits is sufficient to eliminate the interference pattern. This is because interference requires a certain relationship between the wavelength of the entity and the distance the two slits are apart and the distance between the two screens being

$$\frac{\text{distance between the two screens x wavelength}}{\text{distance between the two slits}}$$

Uncertainty in the position of the two slits in the experiment will eliminate the interference pattern. Placing the first screen on rollers in order to observe the movement of the slits so it is possible to tell which slit the entity went through causes uncertainty in the position of the slits of a sufficient amount to eliminate the interference pattern. (Greenstein & Zajonc, 1997, 86-88).

A further thought experiment invented by Einstein at the fifth Solvay Conference involved a stream of electrons hitting a screen with a single slit in it. The electrons that pass through the slit would form a diffraction pattern on the second screen. A diagram is below:

Electrons First Screen Second Screen

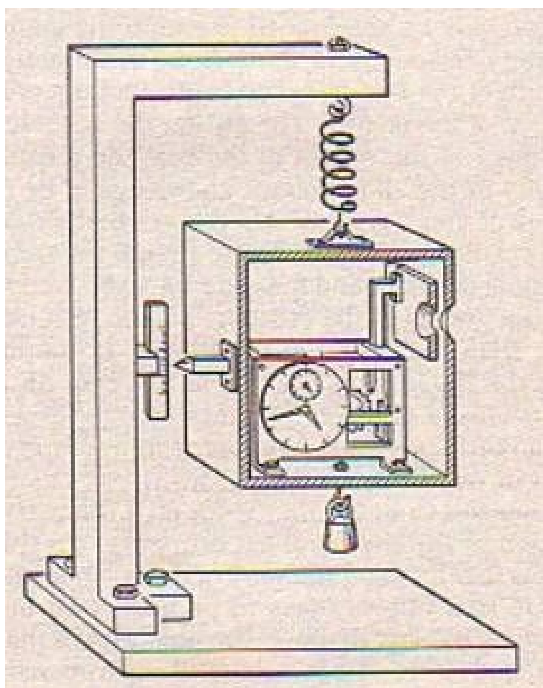


Einstein considered the experiment showed Bohr's theory could not describe the behaviour of individual electrons. If an electron arrived at A on the diagram above then we immediately know it has not arrived at B. However quantum theory does not explain why the electron arrived at A rather than B. It only predicted the probability that a particular electron would hit a particular point on the second screen. Einstein suggested we should be looking for a better theory.

Bohr's reply was that there was a change in momentum of the electron as it passed through the slit due to interaction between the electron and the screen. The width of the slit which effects the position of the electron and the wave cone brings a degree of uncertainty into the position of the electron as its momentum changes. This uncertainty was consistent with

Heisenberg's uncertainty principle and the only way to predict with certainty where an individual electron would land would be to have a slit of zero width (e.g. no slit at all) or an infinite number of diffraction rings which is no diffraction at all. (Horner, 1987, 119-121).

Einstein also attempted to disprove quantum theory at the sixth Solvay Conference in 1930 with the "Clock in the Box Experiment". This involved a box with a hole in one wall covered by a shutter which could be opened and closed by a clock mechanism inside the box. The box also contained radiation which would add to the weight of the box. The box would be weighed and then at a given moment the clock would open the shutter allowing a single photon of radiation to escape. The box could then be re-weighed, the difference between the two weights telling us the amount of energy that escaped using the formula $e=mc^2$. Under the uncertainty principle it is not possible to obtain an exact measurement of the energy of the released photon and the time at which it was released. Einstein's experiment was designed to show such exact measurements were possible, the clock measuring the time of release of the energy and the weighing of the box disclosing the amount of energy involved. A diagram showing Einstein's idea is below.



Bohr's reply involved looking at the practicalities involved in making the required measurements. The box had to be weighed so it had to be suspended by a spring in a gravitational field. To weigh the box it is necessary to compare a pointer attached to the box against a scale. After the photon had left the box weights can be added to the box to restore the pointer to the same position against the scale as it had been before the photon escaped. The weight added to the box gives the weight of the escaped photon. However this involves a measurement of the box to ensure the pointer is back at its original position. This measurement is subject to the uncertainty principle concerning the position and momentum of the box which brings uncertainty into the measurement of the weight of the box. If there is uncertainty in the weight of the box, then there will be an uncertainty in the energy of the released photon. There will also be uncertainty in the time of the released energy as the speed of time depends upon the position of a clock in a gravitational field. If this position is uncertain, then the time of the release of the photon will also be uncertain. This means both the time and the amount of energy released will be uncertain so Einstein's thought experiment did not contradict the uncertainty principle. (Greenstein & Zajonc, 1997, 89-92).

Einstein's thought experiments had previously tried to show quantum theory was wrong, but in 1935 he presented a paper arguing quantum theory was incomplete. In this paper, Einstein and two colleagues, Podolsky and Rosen, proposed a thought experiment, widely known as the EPR experiment or the EPR paradox, which involved two correlated particles emitted from a source and moving away from the source in opposite directions at the speed of light.This correlation, now known as entanglement, was experimentally proven in 1980. Measuring the position of particle 1 can give an exact idea of its position, while measuring the exact momentum of particle 2 allows us to know the exact momentum of particle 1 due to the correlation of the two particles.This means we can know the exact position and momentum of particle 1 contrary to the uncertainty principle. Einstein also argued that the measurement of particle 1 could not disturb particle 2 due to the impossibility of faster than light signaling.

Bohr's reply was that if you make a measurement of the position of particle 1 then this involves the complete measuring system so that it is not possible to make an exact measurement of the momentum of particle 2. Bohr considered if both particles existed within the same frame of reference then a measurement of particle 1 will disturb particle 2 as it disturbs the whole frame of reference. If they are not considered to be in the same frame of reference, then the measurements would be considered to be successive experiments which does not establish simultaneous measurements of position and momentum.

Subsequent developments on the EPR experiment involved a theorem invented by John Bell, known as Bell's Theorem, and experiments carried out by Alain Aspect and others that have tended to support Bohr's position. They are usually interpreted as requiring the abandonment of either the idea of locality, which means faster than light signalling is possible, or the idea that quantum entities have their properties independent of the act of measurement.

The Aspect experiment was carried out on photons which have a property known as polarization. Polarization is the angle at which light waves vibrate in relation to their direction of motion. The Aspect experiment involved an atom emitting two photons in opposite directions and then measuring the polarization of each photon. The photons move apart at the speed of light so according to the theory of special relativity there is no possibility of a measurement carried out on photon 1 immediately affecting photon 2 as that would mean a signal has traveled faster than the speed of light. The polarization of the photons is co-related in that if one knew the polarization of one photon you also knew the polarization of the other. The Copenhagen Interpretation holds that the photons do not have any definite polarization until a measurement is made to detect their polarization and that the measurement brings the polarization into existence. Einstein and his colleagues when inventing the EPR experiment hoped to show that the photons had a particular polarization from the time they were emitted from the atom so that there existed a reality independent of the act of measurement. Such a theory is known as a hidden variables theory as it assumes there is something not known to us which will ensure photons and their polarization exist independently of the act of measurement.

Until John Bell produced Bell's Theorem there was no practical way to carry out the experiment. The problem was that if one looked at the polarization of the photons you could not tell whether the photons had their polarization from the time they were emitted from the atom (Einstein's view) or whether they only acquired it when we looked at the photons. Bell worked out that if we worked with three connected polarization measurements, but only measured two of them it could in principle be possible to do the experiment. The act of measuring the first photon changes the odds on obtaining a particular polarization when measuring the second photon. Many measurements are required to be made to disclose a statistical pattern which is different, if the photons acquired their polarization when emitted from the atom, from that which would apply if the photons acquired their polarization at the time of measurement of the first photon. If the photons acquired their polarization when emitted from the atom the particular pattern of measurement results that occurs would be produced more often than the pattern that results if the photons only acquired their polarization when the measurement takes place. However the Aspect experiment and a number of similar experiments show that this does not happen. This result, known as a violation of Bell's inequality, means that when the photons are emitted, they do not have any specific polarization, until a measurement is made of one of them.

The Aspect experiment is usually considered as eliminating any possible local hidden variable theories and leaving two possible alternatives for how the photon acquires its polarization. One of these is non-locality, that a faster than light signal went from photon 1, due to the measurement of photon 1, to photon 2 and this is how photon 2 acquires its polarization. This is the view supported by John Bell (Davies & Brown, 1986, 48-50). The other alternative is that in conformity with special relativity, no faster than light signal happens and photon 2 does not acquire its polarization until photon 1 is measured. This is the view suggested by Alain Aspect. (Davies & Brown, 1986, 42-43).

In order to justify the belief that photons acquire their polarization when emitted from their source it would be necessary to show the sending of the faster than light signal actually takes place and to explain how it can take place given that special relativity states nothing can travel faster than light. There is a vast amount of experimental evidence in support of special relativity which suggests faster than light signaling is impossible. No one has shown the signal actually occurs or even how it can occur. A claim that something happens when there is no evidence it happens and it is impossible for it to happen, is a very extreme claim. Normally, if there is no evidence of something, like a faster than light signal, we would say it does not exist; but in this case it is also not possible for it to exist, without rejecting a considerable amount of well supported modern physics.

The other possibility, that the photons acquire their polarization when measured, although counterintuitive, has considerable evidence in its support that can be seen in my papers *Sense Perception and Reality*, *The Philosophy of Perception* and *The Quantum Measurement Problem: Collapse of the Wave Function explained*. Counterintuitive explanations of the universe are not unusual in science. The movement of the Earth as it spins on its axis, orbits the Sun and flies through the universe is counter intuitive and so is general relativity with its curved space-time.

The idea that entities come into existence and acquire their properties when observed does not just come from 20th century quantum physics. It is also derived from 16th and 17th century idealist philosophies and has been considerably reinforced by modern science with special and general relativity with their ideas of space contraction, time dilation and curved spacetime, all of which show that different observers see the world differently. In addition, modern research into other animal senses, cognitive psychology and neurology also show that different observers perceive the world differently. If different observers perceive the world differently, then there is no single real world, that is the same for all observers, and there is no reality independent of observers, that is available to observers. Such a world may exist but it is certainly not the world we perceive and our science and scientific theories can only be about the world or worlds we perceive, whether through aided or unaided observations. Observations aided by modern science provide new views of the universe but they can always be replaced by even newer views as instruments and experiments improve. There is a wide range of support for the idea of an observer dependent universe from a wide range of modern scientific research.

Conclusion

Einstein's attacks upon the Copenhagen Interpretation are widely regarded as having failed to show the theory is either wrong or incomplete. His criticisms of the theory and especially the eventual results of the practical application of the EPR idea have greatly strengthened the theory, so that it became the orthodox interpretation of the quantum world. The debate between Einstein and Bohr was conducted with the two talking past each other, Einstein arguing how the quantum world ought to be, while Bohr argued how the quantum world can be known to us. Bohr accepted that there were some fundamental limits on our knowledge of the quantum world, (such as the quantum of action) which as a matter of principle we are unable to overcome. Einstein never accepted those limits, but was never able to show how to get around them. That does not mean that Einstein's view that the quantum world is like the macro-world is wrong, but it does mean that we are unable to know in principle any more about the quantum world than Bohr and the Copenhagen Interpretation suggest.

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