Saving Dr. Schrödinger's Cat

By Danny J. Krebs

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Quantum theory began in the early 1900s as physicists looked at how atoms interact with light. It is called quantum theory because light energy was found to only be adsorbed or emitted in discrete amounts, called quanta, the plural of the Latin *quantum*, from *quantus*, "how much". It seemed natural to think that there was a light particle called the photon that carries a fixed amount of energy, the amount of which depends on the color of light involved (Gribbin 82-85). By invoking a particle model, Einstein, Planck, and others were able to explain much about the interactions of light with matter. On the other hand, it was known that light also exhibits wave behavior, similar to the behavior of waves on the surface of a lake. Light appears to exist as point-like particles when interacting with matter, but to exist as waves when it travels from place to place. This is called the wave-particle duality. The conversion of the wave to particle is sometimes called a "wave function collapse." I will use the terms "wave function collapse" and "wave-particle duality" interchangeably, although they imply somewhat different mental pictures. Electrons, which were once thought to exist only as particles, were also found to have wavelike properties. Wave-particle duality appears to be a characteristic of all forms of matter and radiation. The application of wave equations to matter, especially electrons, accounts for much of the success of 20th century physics, giving us useful devices like transistors, computers, and lasers (Ghirardi 12-15).

In the early decades of the twentieth century, the physics community was divided regarding the proper view of the wave-particle duality and the statistical nature of quantum theory. Lively debates occurred in the 1930s, pitting Albert Einstein against the Danish physicist Niels Bohr. Einstein could not accept quantum theory as being complete (Kaiser 3-13; Herbert 200). He is famous for saying that "God does not play with dice" (Hermanns 58), but that quotation does not do justice to the depth and complexity of his misgivings. Bohr believed that quantum theory was complete as it stood and that no tinkering with its basic framework was needed.[1]

The Twin Slit Experiment

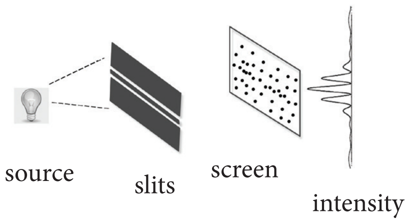

Figure 1.

The crux of the disagreement between Einstein and Bohr can be understood by looking at what happens as light passes through a pair of narrow, closely spaced slits (see Figure 1). Provided that the light is a single color, a wavy intensity pattern is seen on a screen placed at some distance from the slits. There is a central peak exactly equidistant from the two slits; there are valleys on each side; and somewhat smaller peaks repeating at fixed intervals. The peaks in the pattern are points at which the waves from each slit arrive with their positive crests overlapping. The valleys correspond to the wave crests from one slit arriving overlapping negative troughs from the other slit. If either slit is blocked, the wave pattern disappears immediately.

Here is the problem. We can reduce the light intensity so that we see point-like flashes on the screen indicating the arrival of individual photons, shown as dots in Figure 1. If we add up the arrival of photons over a long time, we still see the same peak/valley intensity pattern. How did a single light particle, which presumably travelled through only one of the two slits "know" that it was not supposed the land in a valley? How did it "know" that the other slit was open and not blocked? Did the photon somehow go through both slits? Bohr's answer was that it makes no sense to talk about a point-like particle having a life in the setup before it is detected on the screen. Between the source and the screen, light is a wave. The presence of the screen causes the particle to materialize at specific points and the distribution of those points is governed by a "wave function" easily calculated from the width and separation of the two slits. Furthermore, Bohr asserted that the interference pattern is due to the experimenter's ignorance of the photon path. Any attempt to detect which path the photon takes would instantly cause the wavy pattern to disappear. In other words, the very act of observation affects the distribution of detection events. Einstein did not buy it. To him, light particles are real, point-like entities that must take certain trajectories through the system.

It was generally assumed that Bohr had won all the arguments and that Einstein was just being difficult by not embracing Bohr's point of view, which is called the Copenhagen Interpretation. Quantum theory was too successful to worry about the best way to view the wave-particle duality. Quantum calculations explain everything from the structure of atoms to the properties of semiconductors to the numerical values of certain constants of nature. From the 1940's into the 1970's, the vast majority of physicists believed that Bohr's view of the wave-particle duality must be the correct one. Questioning the Copenhagen interpretation was considered to indicate a deficit in one's education, intellect, or both. Additionally, in the 1940's one of the greatest mathematicians of the twentieth century, John Von Neumann, developed a "proof" that sentient (i.e. human) observation was necessary to collapse the wave function. Von Neumann's proof had a logical error, but due to the prestige of its author, the error was not discovered for several years (Ghirardi 197-202). In recent years, mainstream scientific thought has evolved from a knee-jerk acceptance of the Copenhagen Interpretation to a more balanced view. This evolution is in no small part due to the work of a few courageous researchers persevering against the orthodox view formed in the 1930s.

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Other Models and Bell's Theorem

In the 1950s, David Bohm, a well-respected physicist, produced a model that duplicates the results of quantum theory but allows particles to have real trajectories. Just as in orthodox quantum theory, Bohm's model assumes a quantum wave function, but rather than dictating probabilities for photon arrival at the screen, the wave function creates a force that pushes real particles through the setup. In Bohm's model, the apparent uncertainty of quantum mechanics comes from uncertainty in the initial position of the particle. Bohm's model generated a certain amount of interest, but it was untestable because its predictions exactly match those of the Copenhagen model. Bohm was involved in the Manhattan Project, but his earlier membership in Communist organizations became an issue during the McCarthy era. Bohm was tried and acquitted for his refusal to answer questions before Congress. He later emigrated to Brazil, then to Israel, then to Great Britain.

In 1964 an Irish physicist, John Stewart Bell, discovered a tool for testing one of Einstein's objections to the Copenhagen interpretation. Certain processes result in pairs of particles that are guaranteed to have correlated attributes ("attribute" is a term physicists use for properties associated with a particle, such as velocity, position in space, energy, and spin); for instance, certain radioactive materials simultaneously emit pairs of electrons that travel in opposite directions with identical speed and opposite spins. In a 1935 paper, Einstein had speculated that measurements on pairs of such particles could overcome measurement limitations fundamental to quantum mechanics, but performing such measurements on the attributes envisioned by Einstein would be very difficult. Bell had the idea of using electron spin as the attribute that could be used to put quantum theory to the test. Because of the complexities of performing spin measurements on correlated pairs of electrons, the first tests of Bell's theory were performed on light particles, using polarization as the tested attribute. Pairs of photons from certain sources are guaranteed be emitted at exactly the same time, travel in exactly opposite directions, and have identical polarizations.[2] These pairs are called phase-entangled photons.

At this point, the reader needs to know a few things about polarized light. Polarization indicates the direction perpendicular to the direction of travel that is associated with the optical disturbance. An analogy would be to think of the light particles as Frisbees and polarizing filters as picket fences that can be oriented with the pickets tilted horizontally, vertically or at any angle in between. Only vertically spinning Frisbees would make it through a picket fence with vertical pickets. Only horizontally spinning Frisbees would make it through a picket fence laid on its side. The analogy is not perfect. Unpolarized light always appears to be composed of particles with half its photons polarized one direction and half in the perpendicular direction, regardless of which two orthogonal directions are chosen. It is as if half of all the Frisbees in the world were spinning one way and half the other way, regardless of how we tilt the fence.[3]

Bell's work showed that quantum theory predicts that if polarization measurements are performed on both of two phase-entangled photons, the results of measurements made on the polarization of one photon depend on the type of polarization measurement being performed on its phase entangled partner, regardless of where or when that other measurement is performed. The measurements could be performed on opposite sides of the earth and the effect of the polarizer settings on correlations would still be there. There is, however, no "agreement" between the two particles at the time of their separation that would permit the correlation of the subsequent polarization measurements to follow the predictions of quantum theory. Somehow information about the type of polarization measurement being performed on the first photon must be transmitted to affect the results of measurements performed on the partner photon. This is what Einstein called "spooky action at a distance." This "spooky action at a distance" violates one of the treasured ideas of physics: local causality. According to local causality, no physical effect can propagate faster than the speed of light. It was thought that relativity theory forbids violations of local causality, so there appeared to be a direct conflict between quantum theory and relativity theory. Bell's theory is considered to be one of the great achievements of twentieth century physics, but Bell died young, just as his work was gaining recognition. The Nobel committee was considering him for an award just prior to his death, but Nobel prizes are never awarded posthumously.

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It was eight years before John Clauser at Berkeley carried out an experimental test of Bell's idea. The "spooky action at a distance" predicted by quantum theory was indeed present. A later experiment performed by Alain Aspect in France showed that non-local correlations occur even when the choice of polarizer angle is made *after* the photons are already in flight and no light-speed signal of polarizer settings could pass between the two polarizers. Einstein had intended that experiments on phase-entangled particles would be a challenge to the accepted precepts of quantum theory. Instead, experiment has shown that quantum theory has the power to overrule the concept of local causality.

One might think that Bell's discovery could possibly be used to send messages faster than the speed of light, but the theorists tell us that such schemes must fail. There is no information content in the data recorded on one side of the experiment. Information about the polarizer settings is only contained in the correlations of the two records, which can only be accomplished via normal communication channels. Nevertheless, somehow the choice of measurement on one photon stream affects the results of measurements on the other photon stream. Bell type experiments have been performed on electrons and even whole molecules with similar results, so the nonlocal correlations predicted by Bell's theorem are not confined to photons. There are similarities between the non-local correlations seen with phase entanglement and the questions raised by the twin slit experiment. In both cases, the quantum wave function appears to collapse to give a definite result only when forced to do so by a measurement, and the wave function collapse occurs simultaneously over all space, even when no light speed signal could connect regions of space that the wave function occupies.

The field of quantum information theory has come into being in the last thirty years partly due to insights regarding quantum entanglement. Quantum information theory has found practical application to secure communications and may someday lead to faster computers.

The experiments of Clauser and Aspect exclude so called local hidden variable theories, theories for which the particles are pre-programmed to react certain ways to certain tests. They also illustrate the absurdity of an observer-based theory of wave function collapse. Can anyone really think that Aspect's equipment did not register the correlation signals until Dr. Aspect observed the results? These experiments do not answer the question: "When does a wave become a particle?" or equivalently, "Where does the wave function collapse occur?" In order to examine these questions, we must meet Dr. Schrödinger's cat.

Schrödinger's Cat

Erwin Schrödinger was one of the true fathers of quantum mechanics. His equation for computing the quantum wave function of material particles is one of the most famous equations in science. In the Einstein/Bohr debates, he was firmly in Einstein's corner. Schrödinger conceived of a thought experiment in which his cat was confined inside a steel box with a radioactive sample that had a 50/50 chance of emitting a gamma ray in an hour's time. A radioactive sensor in the box is attached to a hammer that will break a cyanide capsule and kill the cat if the gamma ray is emitted. After an hour, the experimenter lifts the lid of the box and discovers whether the cat is alive or dead.[4]

Quantum theory maintains that it is impossible, even in principle, to know whether a radioactive nucleus will decay in a given time frame. In Bohr's view, during its hour in the box the cat is in a quantum superposition of states. It is neither alive nor dead. Only by lifting the lid of the box and looking inside do we put the cat in a definite quantum state, alive or dead.

Cat lovers will be glad to know that no actual felines have been harmed in attempts to resolve the issue. Schrödinger came up with the scenario merely as a *reductio ad absurdum* argument to highlight what he saw as a problem with Bohr's understanding of quantum theory.

There are a number of possible solutions to the Schrödinger cat paradox. One is called the "relational model". The idea in the relational model is that when the experimenter lifts the lid, his wave function interacts with the cat's wave function. There then exists a backwards-in-time chain of wave function collapses going back to the radioactive nucleus. Another alternative is the so-called many worlds interpretation. When the radioactive nucleus does, or does not, decay; the universe splits into two parallel universes, one in which the cat is dead and one in which he is alive. When the experimenter lifts the lid, he finds out which universe he is in. Science fiction writers love that interpretation, as do some theorists.

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Many scientists believe that there must be a dividing line between quantum uncertainty and macroscopic certainty (Penrose 225-99). According to this view, when the microscopic quantum event becomes observable in the larger world, the microscopic wave function collapses. Scientists have looked toward something called de-coherence theory to explain the existence of this boundary.[5] A group in France has modeled a particular type of quantum measurement with both the particle and measurement system receiving a quantum treatment. The system consisting both the particle and its measuring device briefly exists in what is called a meta-stable state (Nieuwenhuizen 1-166). Meta-stable states are states of unstable equilibrium, analogous to a pencil balanced vertically on a flat surface. The meta-stable state rapidly collapses into a definite classical result due to interactions within the system. This result shows it is possible for a strict application of quantum theory to lead to what appears to be a classical result. The evolution of a quantum measurement may be deterministic, but calculating the result may be undoable because of the very complex nature of the interactions.

Expert opinion varies on the significance of de-coherence theory in resolving the Schrödinger cat paradox. If we observe the spin of an electron, can we really say that the particle had that spin? Or can we only say that of the statistical possibilities passed on to the measurement apparatus by the particle, the measurement apparatus chose that spin? Did causality operate in reverse, going from the measurement apparatus back to the particle? De-coherence theory resembles the Copenhagen Interpretation with the role of the observer replaced by any large object with which the quantum particle interacts. There is a critical difference, however: the "wave function collapse" has a physical basis apart from the observer. The moon is still there even when no one is looking.

Something called Wheeler-Feynman Absorber Theory might provide clue about how to deal with the retro-causality issues. In this theory each photon absorption-emission event occurs due to a "handshake" between the emitting atom and the absorbing atom. Waves traveling forwards and backwards in time interfere with one another in such a way as to mimic the wave behavior seen in conventional models. Quantum theories built around these ideas are called Transactional Models (Gribbin 237-247), or Pilot Wave Theories (Herbert 49-50).

Outlook

Scientists continue to explore the mysteries of quantum physics. One recent experiment has detected the formation of interference patterns while the photons are still in flight approaching the detector plane (Kocsis 1170). In another of series of experiments, a group claims to have seen increases in the sharpness of the interference pattern of a twin-slit setup when "trained meditators" concentrated their attention on both slits but reductions in interference when the meditators were asked to look away (Radin 157-71). It is difficult to believe that merely looking at the slits could enhance quantum interference; identification with "New Age" concepts is one of the reasons that many professional physicists regard inquiry into the nature of wave function collapse as a useless endeavor more appropriate to metaphysics or philosophy than hard science.

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So which is it—point-like particle or wave? Probably both and neither. There is no reason for the behavior of microscopic objects to conform to our conceptions. It may turn out to be a matter of personal preference whether one regards the particle between the source and the screen as a wave or as a point-like object being pushed around by "quantum forces". My main objection to the Copenhagen concept is that it is discontinuous. Copenhagenists would have us believe that light occupies the whole interference pattern a pico-second before it hits the screen, but becomes a point-like object upon impact.

Do we live in a deterministic universe or is God really "playing with dice"? I think that the jury is still out. De-coherence theory provides a partial answer to the paradox of Schrödinger's Cat, but most experts do not see it as the whole story. Given the ability of the Copenhagen interpretation to predict any results observed by humans, one might ask, why bother with other ideas? As one theorist has observed, "The Copenhagen Interpretation of quantum mechanics is a remarkably efficient practical tool" (D'Espagnat 258). I submit that scientists should continue to search for alternatives to the Copenhagen interpretation. Valuable work such as Bell's proof of quantum non-locality and the likely role of de-coherence are examples of why Bohr's ideas should not be accepted as the last word on the subject.

Notes

1 During World War II, Bohr was smuggled out of Sweden to England in the bomb bay of a Mosquito bomber. His oxygen mask failed and Dr. Bohr lost consciousness. Fortunately the pilot saw the problem and reduced altitude, saving Dr. Bohr's life.

2 Some two-photon sources provide photons with exactly the same polarization; some provide photons with exactly opposite polarizations. The type of source used does not alter the validity of Bell's arguments.

3 Photon polarization is more complicated than suggested herein, but the additional complexities do not affect the conclusions of the next paragraph.

4 One point that should be mentioned is that quantum theory does not set a limit on how large an object can be and still be considered to have a wave function. Presumably cats can be represented by quantum wave functions, whose state depends on interactions with wave functions around them. Experiments can be constructed such that the state of a large object like a cat depends on the collapse of the wave function of a microscopic object like a radioactive nucleus.

5 Coherence is the property of a quantum particle that allows its corresponding wave to interfere with itself. De-coherence occurs when the wave loses its well-defined wave character through interactions with the environment. Quantum theory reduces to classical physics in the limit of maximum de-coherence.

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