The Spooks Of Quantum Mechanics

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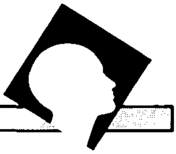
> *I cannot seriously believe in [the quantum theory] because it cannot be reconciled with the idea that physics should represent a reality in time and space, free from spooky actions at a distance.*
>
> —Albert Einstein

The "spooky actions at a distance" that so disturbed Einstein about quantum mechanics have provided comfort to those who seek a scientific basis for spooky things like telepathy and faster-than-light communication. For some, they have also confirmed the holistic notion that everything that happens in the universe is simultaneously connected to everything else.



Quantum effects are indeed weird and spooky, but do they provide any mechanism for simultaneous connection between events or for extrasensory channels of communication?

Do paranormalists and holists have a right to be comforted, or are they just whistling in the graveyard? I'm afraid that they would have been better off if things had turned out not quite so spooky. As we will see, the conventional interpretation of quantum mechanics, disputed by Einstein but triumphantly confirmed by experiment, provides no mechanism for psychic phenomena or simultaneous connections between events. On the contrary, paranormal phenomena violate the foundational principles of twentieth-century physics—relativity and quantum mechanics. These principles are confirmed by countless empirical tests, having withstood every challenge scientists and pseudoscientists have been able to mount.

Einstein's unhappiness with quantum mechanics is legendary, though his photon theory of light contributed mightily to the quantum revolution. In the seventeenth century, Isaac Newton proposed that light was material, or "corporeal," in nature. By the nineteenth century, however, the wavelike behavior of light led scientists to largely dismiss Newton's corpuscular theory in favor of the wave theory first proposed by his contemporary Christian Huygens (1629-1695).

In 1905 Einstein built on Max Planck's five-year-old idea that light occurs in discrete bundles, or "quanta," and resurrected the corpuscular theory in an updated form. He proposed that light was composed of localizable particles he called "photons." Today it is unquestioned that light consists of discrete quanta—a fact daily confirmed in thousands of laboratories.

Empirically, light exhibits the discrete and local properties associated with particles. But the wave characteristics of light, such as its apparent ability to pass simultaneously through several openings separated in space, are also confirmed.

This type of schizophrenic behavior is not confined to photons alone. Electrons, neutrons, and other entities that normally appear as localized particles also can't seem to decide whether they are really particles or waves. It all depends on what you try to measure. If you look for localized electrons, neutrons, or photons, you find them. If, on the other hand, you set up an experiment designed to measure wave properties, you find these too. This wave-particle duality, exhibited by normal matter as well as light, is precisely what gives quantum mechanics its spooky nature.

In his 1905 special theory of relativity, Einstein emphasized a feature of scientific method that was to become a key to the development of quantum mechanics: physical quantities are defined by the way they are measured. This reliance on measurement was consistent with the "logical positivism," school that had been developing in philosophy at about the same time. Positivism held that the only reality was empirical observation. Metaphysical notions were nonsense, since they dealt with concepts that had no empirical content and so could not be tested observationally.

Today logical positivism is out of fashion, but any new philosophical system must still confront the question of how to make meaningful statements about the universe that are not directly related to empirical facts.

Although Einstein had provided the greatest impetus to the positivist view of nature, he later backed off considerably, insisting that physical properties must have an intrinsic reality beyond their mere measurement. This change of heart was the result of his development of the general theory of relativity, first appearing in 1916, in which space and time seem to have intrinsic holistic reality.

The Copenhagen Interpretation

Positivism in physics was instead championed by Niels Bohr, Max Born, and others of the Copenhagen School. The Copenhagen Interpretation of quantum mechanics, which is widely accepted by most physicists today, holds that an object does not even possess certain properties until those properties are measured.

When we observe anything in the universe, we must interact with the object being observed, disturbing it in some way. This presents no problem for large objects, like the moon and most bodies in our everyday experience, which hardly recoil under the action of the photons we bounce off them from the sun or artificial lights. However, at the atomic and subatomic level, photons can wreak havoc with the system being observed. For example, since the position of the electron inside an atom cannot be measured without destroying the atom, the Copenhagen Interpretation holds that an electron has no definite position in an atom.

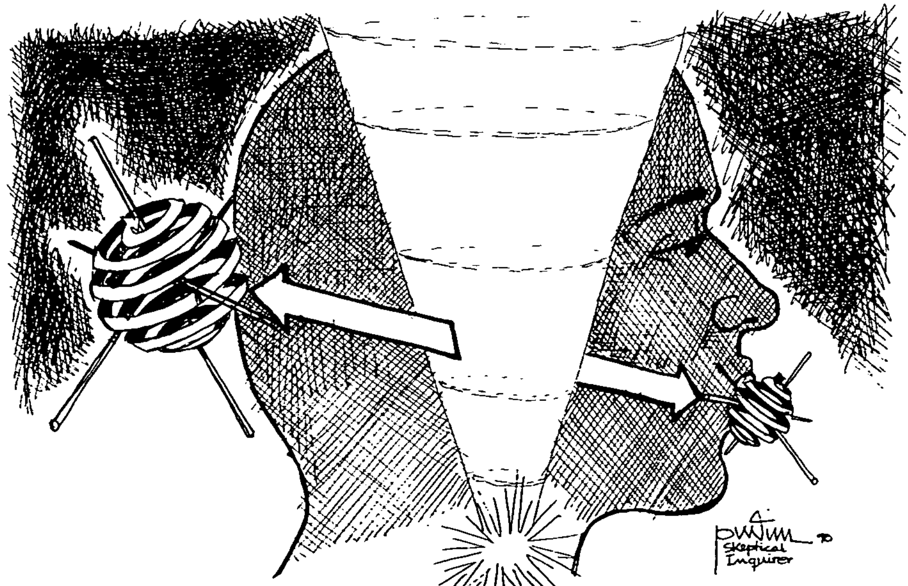
Extending this idea to all other physical quantities, we conclude that they become real only upon their being measured. Now this may sound like ancient Hindu idealism, with everything in our heads, or the New Age: "Reality is whatever you want it to be." The fact that reality rarely is what you want it to be is the best evidence that a world beyond our heads does indeed exist!

However, the reality that concerns me here is specifically that of *physical quantities:* variables used in describing observations, such as space, time, mass, and temperature. According to the Copenhagen Interpretation, these are simply human inventions—defined according to the way they are measured.

Another important element of the Copenhagen Interpretation of quantum mechanics is that the equations of physics do not allow you to predict the movement of an object from one place to another with complete certainty—only the *probability* of this movement. This probability is expressed in terms of a purely mathematical quantity called the "wave-function."

The idea that the motion of individual bodies is at least partially undetermined by what happened before contradicted the assertion of Newtonian mechanics that all motion is in principle completely predictable, provided you have sufficient information to make the calculation. By contrast, the equations of quantum mechanics only allow you to predict the *average* behavior of *similarly prepared* systems, not the exact behavior of the individual systems themselves.

Shortly after the development of quantum mechanics, the discoverer of the wave-particle duality, Louis de Broglie, proposed that particles were guided by pilot waves and that these



were responsible for the observed wavelike behavior of electrons and other particles (de Broglie 1930). He associated the quantum mechanical wavefunctions with his pilot waves.

In his 1951 book *Quantum Theory*, David Bohm developed the de Broglie idea further, proposing that some form of hidden variables may exist that provide for a more complete description of nature than conventional quantum mechanics—more complete in the sense that the statistical nature of quantum mechanics is replaced by underlying deterministic principles. The hidden variables would be analogous to the forces and potentials of classical physics that are responsible for the motion of bodies (Bohm 1951; Bohm, Hiley, and Kaloyerou 1987).

The EPR Paradox

Back in 1935, Einstein and two junior colleagues, Boris Podolsky and Nathan Rosen, had written a paper arguing that quantum mechanics must be "incomplete" in its description of reality. They argued that certain quantum systems, such as those composed of two particles, can be prepared in such a way that the result of a measurement of one particle fixes the result of a measurement of the second—before the second measurement is performed. This can happen after the particles are so separated in space that communication between them would require a signal traveling faster than light.

Einstein and his colleagues concluded that either particles intrinsically possessed certain properties before they were measured—in contrast to the quantum idea that the act of measurement brings that property into existence—or a nonlocal "spooky action at a distance" force was in effect. This has become known as the "EPR Paradox" (Einstein, Podolsky, and Rosen 1935).

Two basic concepts must be understood before we can come to grips with the EPR Paradox: (1) *reality* and (2) *locality*. Here's how Einstein and his colleagues defined reality for the purposes of their discussion: "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."

Clearly, the concrete objects of our everyday experience contain this property of reality—predictability. If we look away from a tree, we can predict with great certainty that it will still be there when we look in that direction a few moments later. Dreams and fantasies do not exhibit predictability.

To explain the EPR Paradox, we also have to define precisely what we mean when we say that two events are local. This can occur even when the events are separated in space. If we can find another reference frame, any reference frame, in which the two events occur at the same place, we are forced to conclude that the events are *local* since our descriptions cannot depend on any one point of view. In this case, no "action at a distance" between events has taken place.

Before Einstein and relativity, scientists believed that no limit existed on the speed of bodies. Thus, whatever the separation of two events in space and time, it was always possible to find a reference frame in which the events were local.

However, if Einstein is correct, then there must exist certain events that cannot be made local in any reference frame—because any signal passing between them must exceed

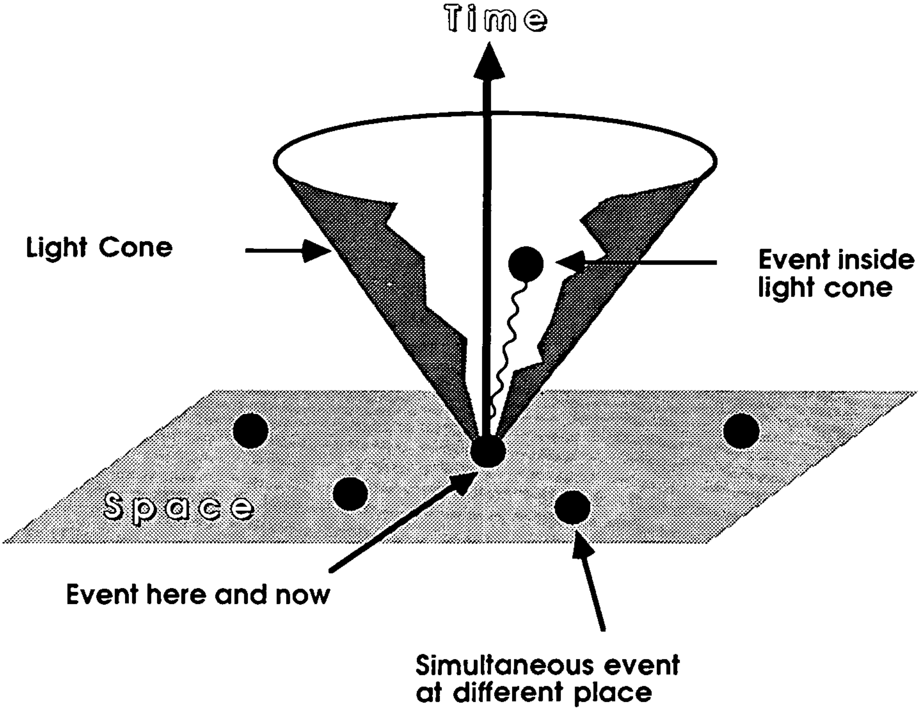


FIGURE 1. Representation of events in space and time. For illustration, space is indicated as a two-dimensional plane, with the time axis vertical. An event occurring "here" and "now" is indicated at the base of the time axis. It can only be causally connected to events inside the light cone. To reach an event outside the light cone, a signal must travel faster than the speed of light. Simultaneous events at different places cannot be connected, since they lie outside the light cone.

the speed of light. In relativity jargon, such events are said to be "outside the light cone." (See Figure 1.)

The "spooky actions at a distance" that concerned Einstein were apparent causal connections between events that lay outside the light cone. According to relativity, there must exist phenomena in the universe that are independent of one another—namely, those events that are outside the light cone. No interaction between these events can take place. An important special set of events outside the light cone are those occurring simultaneously at different places. Simultaneous events that are separated in space cannot affect one another in any way. (See Figure 1.)

This is a point that hardly anyone, and not many scientists, recognize: *Holism violates Einstein's relativity.* If simultaneous holistic connections between separated events exist, then either the whole foundation of twentieth-century physics must be destroyed or these connections must be supernatural—they must be *miracles.*

In his 1951 book, David Bohm speculated that "no theory of mechanically determined hidden variables can lead to *all* of the results of quantum theory." He proposed an EPR-type experiment involving electron spins that would much later provide the conclusive test (Bohm 1951).

Bohm's proposal exploited the

remarkable properties of the elementary quantity called *spin:* the intrinsic angular momentum of a particle. Spin is a vector with components along each of the three axes of space: x, y, and z. According to quantum rules, however, only one of its three components can be measured at a given time.

Measuring a second component of spin results in a change in a subsequent measurement of the first. It's as if you measured the height of a woman and found it to be 5 feet, 4 inches, then measured her waistline, and then went back and measured her height again and found it to be 4 feet, 5 inches.

Bohm suggested the following experiment: Suppose you start out with two electrons in a certain state in which the total spin is zero, the so-called *singlet state.* Then let the electrons go off in opposite directions. (See Figure 2.) After they have separated some distance, measure the spin component of one electron along a particular axis, say the z-axis. Since total angular momentum is conserved, the total spin of the two-particle system must remain zero, even as the particles become separated.

As a result, the measurement of the z-component of the spin of electron A immediately fixes the z-component of the spin of electron B. And so, in the EPR sense, the z-component of spin corresponds to "an element of physical reality," since you can predict with absolute certainty the outcome of a measurement of electron B.

But what about the x- and y-components of the electron's spin? In classical physics, all three components are intrinsically real, as presumably are the three components of the angular momentum of the earth. The electron simply carries along these properties as it moves from the source to the detector, just as it carries its mass and electric charge. However, conventional quantum mechanics says that only one spin component can be real at any given time, specifically, the last one measured.

In the case of the Bohm experiment, the experimenter at the end of one electron beam measures the spin component along some arbitrary axis. This act determines, with 100 percent certainty, the outcome of the measurement of the spin component *along the same axis* at the end of the other beam. The two measurements could happen at a sufficiently large separation and small time interval to be outside the light cone. Somehow the information that the first electron's spin has been measured is transmitted instantaneously to the second. Thus, Bohm's experiment seems to demonstrate Einstein's "spooky action at a distance."

One point should be filed away for future reference: Note that the second measurement must be along the same axis as the first. Measurements of the spin along any other axis are not predictable with 100 percent certainty, so the second observer must know ahead of time what axis to use.

Several types of hidden variables are possible, but let me focus on the type that is consistent with our own intuitions carried over from classical physics: hidden variables that are both real and local.

Real, local hidden variables (1) connect events in space only within the light cone and (2) have intrinsic reality that we can take to be defined in the EPR sense. If the three components of spin are all real, then at least two of them must be hidden variables, since all three cannot be simultaneously measured. In conventional quantum mechanics, they are not hidden; rather, they are *not real,* because only measurement makes a variable real.

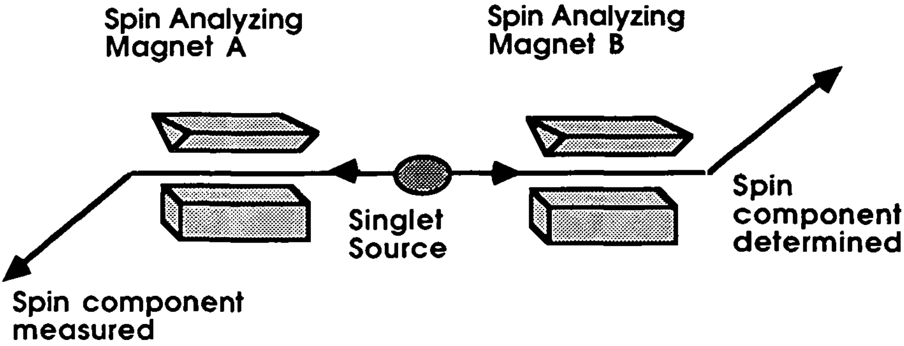


FIGURE 2. The EPR Paradox experiment proposed by David Bohm. Electrons from an initial singlet (total spin zero) state are analyzed by magnets that are oriented to deflect the particles one way when they are spinning along a particular axis, and the opposite way when they are spinning opposite. Once the spin component at one end is measured, the component at the other end is determined. In conventional quantum mechanics, spin components do not exist until they are measured.

The hidden variable interpretation implements the traditional notion that reality goes beyond measurement. Which interpretation do you prefer? The spooky one of Bohr and Born or the sensible one of Einstein, de Broglie, and Bohm? How can we decide? The same way we decide anything in science—by experiment.

Bell's Theorem

In 1964, John S. Bell analyzed Bohm's proposed experiment and was able to prove that it provided a practical means for distinguishing conventional quantum mechanics from real, local hidden variables theories. Basically, Bell showed that the quantitative correlation between measured spin components of the two electrons from a singlet source, as computed from quantum mechanics, is greater than would be possible in any theory of real, local hidden variables (Bell 1964; Clauser and Shimony 1978; d'Espagnat 1979; Redhead 1987).

At least a dozen experiments have been developed to perform the tests provided by Bell's theorem. The definitive series was done by Alain Aspect and his collaborators at the Institute for Applied Optics of the University of Paris, Orsay, France (Aspect, Grangier, and Gerard 1982).

Bohm's proposed experiment involved electrons, but photons provide an equally powerful test since they too have spin. In the Orsay experiments, a singlet (spin zero) atomic source emits pairs of photons in opposite directions. Thus, when one photon is later measured to have a spin component along a particular axis, the other photon will have the opposite spin component. Conceptually, the experiment is similar to the simple one illustrated in Figure 3.

Each beam passes through polarizers of variable orientation around the beam line, and then into photomultiplier tubes capable of counting individual photons. A different polarizer orientation is randomly chosen for each pair emitted from the source. In an advanced version of the experiment, the Orsay experimenters arranged it so the choice of polarizer orientation was made after the photons left the source. This provided an unambiguous test of Einsteinian locality, since in this case no signal

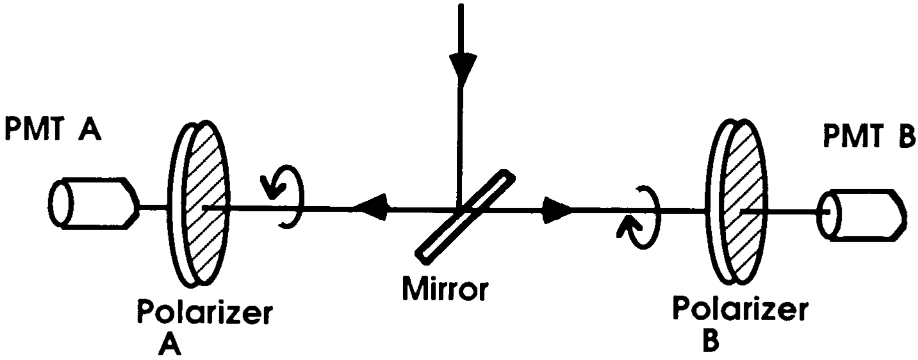


FIGURE 3. Conceptual equivalent of Aspect experiment. The mirror splits a light beam into two right circularly polarized beams. The beams pass through polarizers before being detected by photomultiplier tubes (PMT).

could pass between the ends of the beams without traveling faster than the speed of light.

Using photomultiplier tube detectors, the experiment counted the number of photons for each relative orientation of the polarizers at the ends of the two beams. From these counts, the experimenters could determine the amount of correlation between the settings at the end of one beam and the other.

The results of the Aspect experiment showed greater correlations between polarizer orientations than were possible if all three components of the spin of each photon were intrinsically real, as defined by the EPR criterion. This empirically demonstrated that the spin components of photons cannot be both local and real. Furthermore, the measured, quantitative correlation agreed precisely, within very small experimental errors, with that calculated using conventional quantum mechanics. Quantum mechanics emerged triumphant.

But this also meant that we still had spooky action at a distance. Measurements at the end of one beam seem to determine measurements at the other, within time intervals so small that any signals between the two would have had to exceed the speed of light. Is this a possible mechanism for ESP and other psychic effects? Some have claimed so (Sarfati 1977; Herbert 1985; Targ and Puthoff 1977).

Let us see if an EPR device could be built to provide a means of superluminal signaling. Suppose we have a singlet source that sends the photons of each pair in opposite directions, as in Figure 3. At the end of both beam lines we have photomultiplier tubes that can count the photons emerging with polarizations at any angle in a plane perpendicular to the beam lines, as determined by the polarizer rotation angles about the beam axes.

When the settings at both ends are the same, the spin component at one end is completely determined by the setting at the other. Thus it seems that we should be able to use this fact to signal from one end of the beam to the other, instantaneously over great distances.

But it turns out we can't! In order to communicate information from one point to another, a series of bits encoding a nonrandom message must be transmitted. Leaving both polarizers at the same angle provides for no information transfer. The photomultiplier will simply find half of the photons polarized in the selected direction, and half in the opposite direction, in random distribution.

To encode and decode messages, the polarizer angles of both sender and receiver must be changed. Now the observer at the end of the receiving beam line cannot know ahead of time what angle to use—that information must be contained in the coded message the observer would receive. So the receiver would have to randomly change the polarizer angle and then try to extract the message from the number of received hits at each angle.

One might be inclined to think that this is possible, given the fact that the measurement of a photon or electron at one end determines the outcome of a measurement of the other member of a singlet pair. But it simply does not work out that way. Remember, 100 percent certainty only occurs when the axes used at both ends are the same.

With each angle setting of one polarizer, a specific, calculable distribution of photons will be found for each setting of the other. In fact, the relative numbers of photons observed at each setting will exactly trace the intensity patterns calculated from classical optics for an experiment with circular polarized light, obeying Malus's law discovered two centuries ago! It follows that the bit sequence formed by the individual photon counts at the receiving end will have no information content. As in the case of fixed predetermined settings, the bit pattern will be purely random. No signal transmission is possible. (For a more detailed analysis of the information transferred in an EPR apparatus, see Mermin 1985.)

The experimental violation of Bell's inequality leads to a clear and unequivocal conclusion: nature cannot be described in terms of hidden variables that are both local and real. Either Einsteinian locality or certain commonsense notions of reality must be discarded. There is no third alternative.

Most popular writers prefer to discard locality rather than reality (see, for example, Herbert 1985). They cannot understand why physicists are so unwilling to give up locality. My answer is simple. We have no reason—indeed, no right—to do so. Einsteinian locality is completely consistent with everything we know about the empirical world, from the nineteenth-century experiments that failed to find the ether to the tests of Bell's inequality. We have just seen that the apparent spooky action at a distance of quantum mechanics does not provide for superluminal transfer of signals, and so does not violate Einsteinian locality. The only violation of locality occurs within the imaginary framework of our own descriptions of the observations. The wavefunction is nonlocal, but it is also nonreal.

Abiding by Occam's Razor, the more economical hypothesis is to deny the intrinsic reality of physical observables. Now, at first blush, this may not seem very economical. I appear to be making the most drastic of hypotheses. This guy is doing away with reality!

But actually I am being completely economical. I have, in fact, introduced no new hypotheses beyond those already implicit in relativity and quantum mechanics. To toss out locality and demand reality, we make two unacceptable and unnecessary, drastic hypotheses: that the two pillars of twentieth-century physics, relativity and quantum mechanics, as conventionally interpreted, are wrong. I would rather assume they are right, since they have been confirmed repeatedly, including by the experimental tests of Bell's theorem.

I am not denying the existence of

an underlying reality. I agree that the moon is there when no one is looking at it. I simply argue that the true reality of the universe is not necessarily manifested by objects possessing attributes, such as position and mass, that we assign them in the process of doing physics. These variables, after all, are human inventions with no precisely definable meaning beyond their measurements as performed with specific instruments like clocks and meter sticks.

Describing nature in terms of physical variables is like sketching or photographing an object. Isn't it rather foolish to equate images on a piece of paper with the real thing? We laugh at those ignorant and superstitious people who stick pins in dolls and think that this will harm the person represented. Yet even the most sophisticated physicists ascribe a kind of voodoo reality to their own mathematical images. Quantum mechanics is not voodoo, despite what books on the occult shelves of bookstores say.

No Support for the Paranormal

Paranormalists are dead wrong when they claim that modern physics supports their proposal of extrasensory channels in some kind of underlying ethereal reality. The opposite is true. Einstein's relativity destroyed the continuous ether and the instantaneous connection between events. Quantum mechanics destroyed the notion of continuous matter and energy. Twentieth-century science provides a picture of a universe of discrete material objects, interacting with each other within the light cone, with nothing further required by any existing data.

Quantum mechanics does not provide a mechanism for supersensory phenomena. Experiments fully support the conventional statistical interpretation of quantum mechanics, with the nonlocal and nonreal wavefunction describing ensembles rather than individual particles.

Quantum effects are certainly beyond normal experience. They are weird. But it does not follow that every weird idea is consistent with quantum mechanics.

Further Reading

An excellent lay discussion of EPR, Bell's theorem, and the experiments designed to test them can be found in the *Scientific American* article by d'Espagnat (1979). I also recommend Mermin's article in *Physics Today* (1985). A more rigorous and very complete review is given in the *Physical Review* paper by Clauser and Shimony (1978). A full philosophical discussion of these issues can be found in the book by Redhead (1987), and the opinions on the subject of many prominent people have been collected by Davies and Brown (1986). An English translation of d'Espagnat's *Reality and the Physicist* has just become available (1989). Other skeptical critiques of paranormal applications of quantum theory have been given by Shore (1984) and Gardner (1983, 1985).

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