Disentangling the Einstein-Podolsky-Rosen Paradox

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Entanglement is widely believed to introduce a new inexplicable element into quantum physics that appears to require faster-than-light information transfer between particles. We show that the faster-than-light "collapse" of the two-particle wave function is fundamentally the same "mystery" that Albert Einstein raised in 1927 at the Solvay conference for a single-particle wave function - the mystery of *nonlocality.* Richard Feynman called this the "only mystery" in quantum mechanics, namely the instantaneous collapse of probabilities when a superposition of states is projected into one of the basis states. But by introducing a second indistinguishable particle, Einstein's EPR paper of 1935 added what we can call the "enigma" of *nonseparability.* Besides nonlocality and nonseparability, we show that the EPR paper also added a third layer to the problem, one that we identify as the essential source of the "EPR paradox." We argue that it is the introduction by Einstein of a time asymmetry into what is a symmetric situation from the point of view of the particles. We consider a special frame in which the source of the entangled particles (their state preparation) is at rest. In this special frame (not a "preferred" frame in the relativistic sense), the "second" particle acquires determinate properties *simultaneously* with the "first" measurement. For example, the "second" measurement will show the spin needed to conserve total electron or photon spin. A "second" measurement can be made at any "later" time and the "second" particle measurement will correlate perfectly with those of the "first" particle. The scare quotes are to remind us that in some moving frames, the "second" measurement can occur before the "first." But in our special frame, the two measurements are synchronous for symmetrically placed observers, resolving the paradox. We disentangle the three layers of EPR as a mystery (nonlocality) wrapped in an enigma (nonseparability) wrapped in a paradox (a false asymmetry).

I. INTRODUCTION

When Einstein first proposed his light quantum hypothesis in 1905 ([1], trans.[2]), his lifelong fear that the energy quantum might be in conflict with his new principle of relativity was perhaps already apparent to him. If, according to the wave theory, the energy from a light source is "continuously spread out over an increasing volume" at light speed, Einstein wondered how can it be instantly "absorbed as a complete unit?" How can it deliver "its entire energy to a single electron" in the photoelectric effect?, he asked. Reflecting these concerns, Einstein hypothesized that the "energy of a light ray spreading out from a point source is not continuously distributed over an increasing space but consists of a finite number of energy quanta which are localized at points in space, which move without dividing, and which can only be produced and absorbed as complete units."

But something *is* spreading out continuously in space. Today we interpret it as the probability amplitude ψ that a photon might appear somewhere. This wave function is needed to produce visible interference effects when there are large numbers of photons. Einstein viewed the wave as some sort of continuous field, perhaps of energy (later Schrödinger saw it as continuously distributed charge). A disturbance at one point in a field should propagate to other places at subliminal speeds, but Einstein in 1905 already saw that his "energy spread out in space" collapses faster than light. This is the core mystery of *nonlocality.* Richard Feynman famously called this the "only mystery" in quantum mechanics ([3]), although other authors have cited additional mysteries ([4]). For reasons that are unclear, Einstein waited twenty-two years to explicitly say (at the fifth Solvay conference) that the behavior of this wave field appears to contradict relativity.

Just four years after his "miraculous year," at a conference in Salzburg in 1909, Einstein first argued that his light quantum carries momentum and transfers mass from the emitter to the absorber. ([5], trans.[6]) He also illustrated the complete and instantaneous collapse (of energy, if there were any energy in the spherical wave field). He described an electron colliding with a metal plate P1, ejecting a high-energy x-ray going off in all directions. But then, with a photoelectric effect, the x-ray ejects an electron of the same energy from a second metal plate P2. See FIG. 1. Johannes Stark told the conference that x-rays leaving the x-ray tube to surrounding space could still achieve concentrated action on a single electron at a distance of 10 meters ([6], p.397). The spherical wave associated with the x-radiation thus fills a volume over a thousand cubic meters, but it is instantly absorbed by an atom with a radius of order one-ten billionth of a meter.

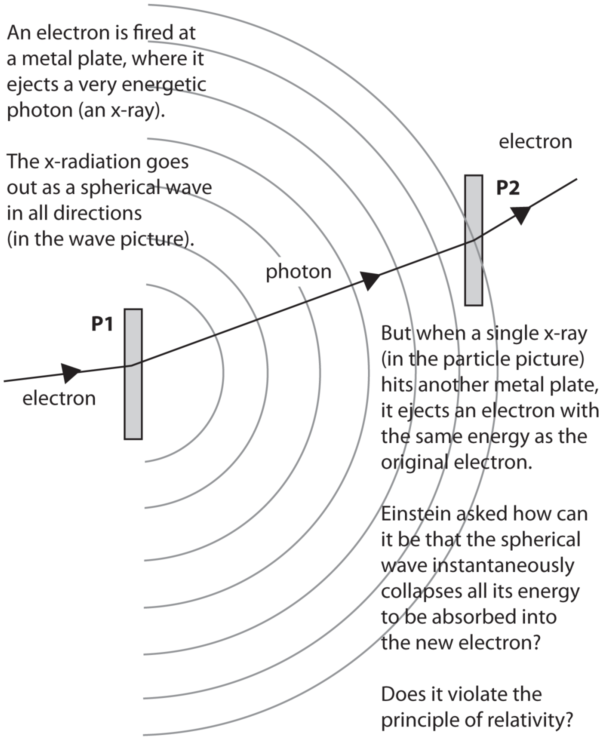

Figure 1. Einstein's 1909 Salzburg presentation.

After finishing his work on general relativity in 1916, Einstein back to quantum theory. He realized that where the electrons and photons in the above diagram are tightly coupled and conserve energy, he could not predict the direction of either the photon or the electron. His analysis of emission and absorption processes led him to connect spontaneous emission with the radioactive decay of nuclei studied by Rutherford. In neither case can we predict the time or the direction of emission. Einstin said it is "a weakness in the theory..., that it leaves the time and direction of elementary processes to chance" (*Zufall*) ([7], trans.[8], p.232). Quantum theory contains an irreducible statistical nature.

At the Solvay conference in 1927, Einstein went to the blackboard to draw electrons passing through a small opening O in a screen S and being dispersed uniformly in all directions toward a hemispherical photographic film P of large radius. See FIG. 2. Einstein then accepted that it was Erwin Schrödinger's wave function spreading out and he used Max Born's 1926 interpretation of the wave function as a probability amplitude (which Schrödinger emphatically denied). The electron has a finite probability of being found at some point on P, Einstein said, and the Born-Schrödinger picture assumes a peculiar mechanism of *action at* *a distance*, which prevents the wave continuously distributed in space from producing an action in two places on the screen ([9], p.440).

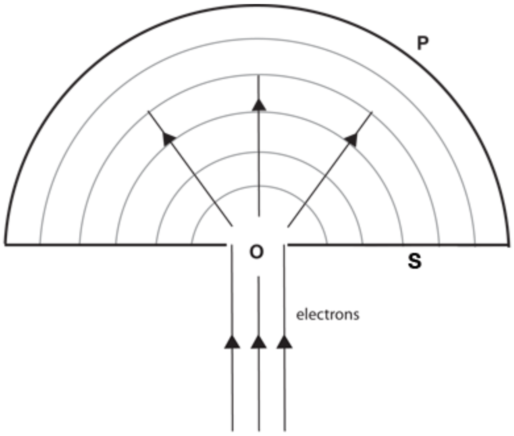

Figure 2. Einstein's 1927 presentation.

For example, if a measurement finds the photon at point A on the screen, the probability wave instantly collapses to zero at another point B. The finite probability at B appears to travel faster than the speed of light to the spot A where the photon is actually found. This violates special relativity, Einstein argued. Note that this is the same problem as energy spread out in a large volume being instantly absorbed that Einstein discussed in 1905 and 1909. Twenty years after Solvay, Bohr recalled "The apparent difficulty...which Einstein felt so acutely, is the fact that, if in the experiment the electron is recorded at one point A of the plate, then it is out of the question of ever observing an effect of this electron at another point (B), although the laws of ordinary wave propagation offer no room for a correlation between two such events" ([10], p.212) See FIG. 3. But neither Bohr nor others at Solvay seriously confronted Einstein's problem of *nonlocality*, focusing instead on Einstein's abortive attempts to invalidate Heisenberg's uncertainty principle. Most accounts of the Bohr-Einstein debates center on Einstein's lifelong preference for a deterministic field theory, but by that time Einstein had accepted the indeterminism in quantum mechanics and was concerned about violations of his relativity principle. ([12])

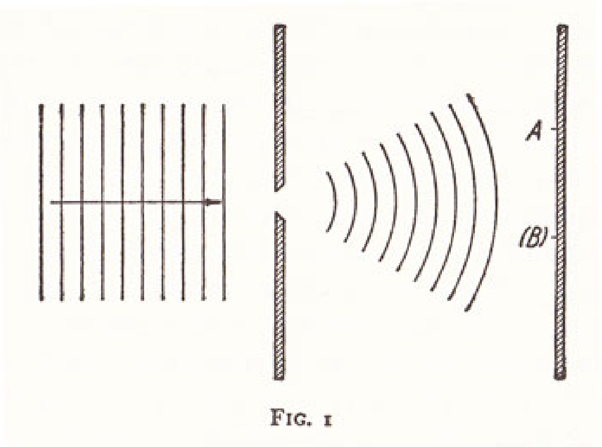

Figure 3. Bohr's memory of Einstein's Solvay presentation. Bohr adds point B, at which point Einstein 8 years later will put an identical particle that introduced *nonseparability*.

Einstein at Solvay also hinted at another puzzle he would develop fully in 1935. He said, "two configurations of a system that are distinguished only by the permutation of two particles of the same species are represented by two different points (in configuration space), which is not in accord with the new results in statistics" (Einstein's work with Bose on the quantum gas statistics of indistinguishable particles). ([9], p.442) This was the first indication of the *nonseparability* of identical particles.

With his colleagues Boris Podolsky and Nathan Rosen, Einstein in 1935 proposed the thought experiment (known by their initials as EPR or as the Einstein-Podolsky-Rosen paradox) to exhibit internal contradictions in the new quantum physics.[11] They hoped to show that quantum theory could not describe certain intuitive "elements of reality" and thus was "incomplete." Einstein was right that quantum physics is incomplete relative to classical physics, since it cannot specify non-commuting properties such as position and momentum of a particle with arbitrary accuracy. With only half the determinate variables of classical physics, quantum mechanics is in that sense "incomplete."

With none of the "founders" of the new quantum mechanics having responded to his concerns about nonlocality since 1927, Einstein in 1935 put a more physical element in place of the nebulous probability wave at point B which collapses instantaneously. He replaced the mere probability wave at point B with a second particle there. And he used his own concept of indistinguishable and identical particles, which followed from his discoveries with Bose in quantum gas statistics. Einstein thus introduced the question of the *nonseparability* of a two-particle wave function into a product of single-particle wave functions. It is this nonseparability which adds a new mystery we can call an "enigma," to distinguish it from the mystery of nonlocality. Both nonlocality and nonseparability seem to imply faster-than-light signaling, Einstein's worrisome "spooky action-at-a-distance." But they are distinct phenomena, as emphasized in recent years by Don Howard. ([12])

Schrödinger wrote immediately to Einstein endorsing EPR, but after an exchange of correspondence in which Einstein introduced his *separation principle*, Schrödinger explained that with real separation comes the loss of quantal interference. In two articles naming the nonseparability of identical particles "entanglement," Schrödinger criticized the EPR argument that the particles could instantaneously communicate once they are far enough apart to be regarded as disentangled. ([13], [14], p.451) He said that after separating, the *phase relations* between the complex coefficients would have been entirely lost. This would mean that the whole system would be in a mixture of independent states, not a pure state. The particles would be disentangled. For Schrödinger, entanglement (nonseparability) was the "defining characteristic of quantum mechanics." ([13])

We argue that understanding these two distinct "layers" of nonseparability and nonlocality is not enough to completely disentangle the EPR paradox. Our third "layer" is an unjustifiable assumption about time asymmetry between the measurements of two entangled particles. Einstein, in his 1935 formulation of the paradox, as well as David Bohm, in his 1952 search for "hidden" variables ([15]), and even John Bell, in his 1964 definitive description of Bell Theorem tests for local hidden variables ([16]), all assume that *one of the two entangled particles is measured "first."* They then puzzle over how outcomes of the "first" measurements are communicated to the second particle fast enough to produce perfect correlations for the "second" measurements. David Bohm thought "hidden" variables could transmit that information, but many experimenters have confirmed violation of the Bell "inequalities," has shown that any such hidden variables would still show nonlocal behavior (instantaneous "action at a distance").

A. Measuring one particle "first"

All descriptions of the experimental tests of Bell's Theorem introduce time asymmetry into the measurements, what we show is the mistaken idea that one particle is measured and becomes determinate "first," the other particle later. In standard quantum theory, the entangled particles are indistinguishable in a two-particle wave function. What we are calling the "enigma" of *nonseparability* means that they cannot be separated into two single-particle wave functions. We show that a measurement of either indistinguishable particle collapses the probabilities for both at the same instant. We do this by singling out a special frame of reference in which the two particles simultaneously acquire their determinate properties.

We thus identify Einstein's introduction of time asymmetry into a fundamentally symmetric situation as the source of the *paradox* in EPR. It is ironic that the famous "twin paradox" of special relativity resulted from the introduction of a false symmetry (identical twins) into what is an asymmetric situation (one twin at home, the other rapidly moving, but most important, feeling tremendous accelerations in non-inertial frames during his journey out and back).

We adapt Winston Churchill's famous observation about Russia and say that *EPR is a mystery wrapped in an enigma wrapped in a paradox*. Disentangling the EPR paradox requires our careful peeling apart of these three layers.

II. A SPECIAL FRAME OF REFERENCE

Almost every modern presentation of the EPR paradox begins with something like "Alice observes one particle..." and concludes with the question "How does the second particle get the information needed so that Bob's measurements at a distant location correlate perfectly with Alice's?"

There is a fundamental asymmetry in this framing of the EPR experiment. It is a surprise that Einstein, who was so good at seeing deep symmetries, did not consider how to remove the asymmetry. Or did Einstein perhaps inject the time asymmetry deliberately to get the defenders of quantum mechanics to confront its deep nonintuitive departures from his local reality, particularly that something - information about probabilities - appears to move faster than light?

Consider this reframing: Alice's measurement collapses the two-particle wave function. The two indistinguishable particles simultaneously acquire determinate properties at locations in a space-like separation. To simplify visualization of the problem, assume that Alice and the second experimenter Bob are equidistant from the source of the entangled particles and not moving with respect to the source. Then the frame of reference in which the source of the two entangled particles and the two experimenters are at rest is a special frame in the following sense.

As Einstein (and Bell) knew very well, there are frames of reference moving with respect to the laboratory frame of the two observers in which the time order of their measurement events can be reversed. (Reversing the time order of events with a spacelike separation has been used by C.W.Rietdijk ([17]), Hilary Putnam ([18]), and Roger Penrose ([19]) to prove that the universe must be deterministic, the past determining the future and the future determining the past.)

In some moving frames Alice measures first, but in others Bob measures first. Valerio Scarani and Antoine Suarez proposed tests of "before-before" measurements with beam splitters moving apart in such a way that each beam splitter in its own inertial reference frame analyzes his particle before the other ([20], [21]). Nicolas Gisin, with Scarani, Suarez, and other team members have put a lower bound on the speed with which quantum correlations arise in Bell experiments. They call this the *speed of quantum information* and find a lower bound of $v = 10,000$ times the speed of light ([22], see also [23]).

There are of course, no preferred frames in relativity, but if there is a special frame for the purpose of disentangling the EPR paradox, it is the inertial frame in which the origin of the two entangled particles is at rest. See FIG. 4. In this special frame, the "speed of quantum information" is essentially infinite, in reasonable agreement with Gisin et al.

Assuming that Alice and Bob are also at rest in this special frame and equidistant from the origin, we arrive at a simple picture in which any measurement (or any decohering interaction that causes the two-particle wave function to collapse) makes both particles appear simultaneously at determinate places (just what is needed to conserve energy, momentum, angular momentum, and spin). We can now look at the symmetric collapse of the wave function in this special frame. See FIG. 5.

Note that the probability amplitude wave function is "continuously spread out over an

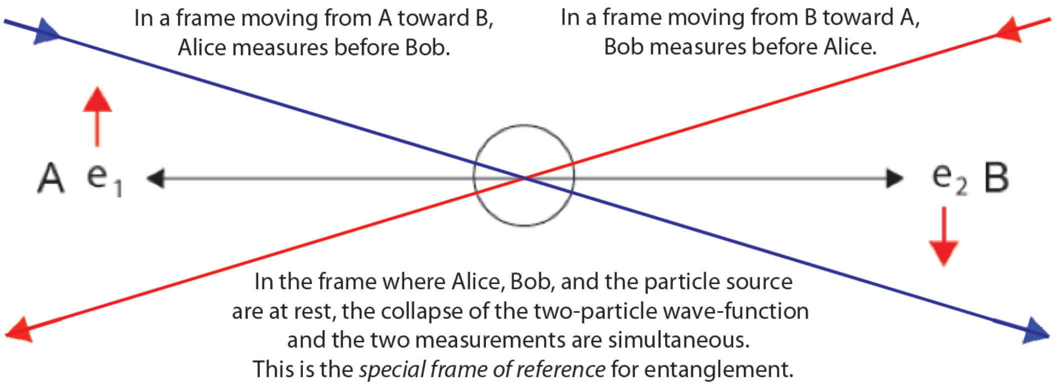

Figure 4. A special frame of reference for the EPR experiment.

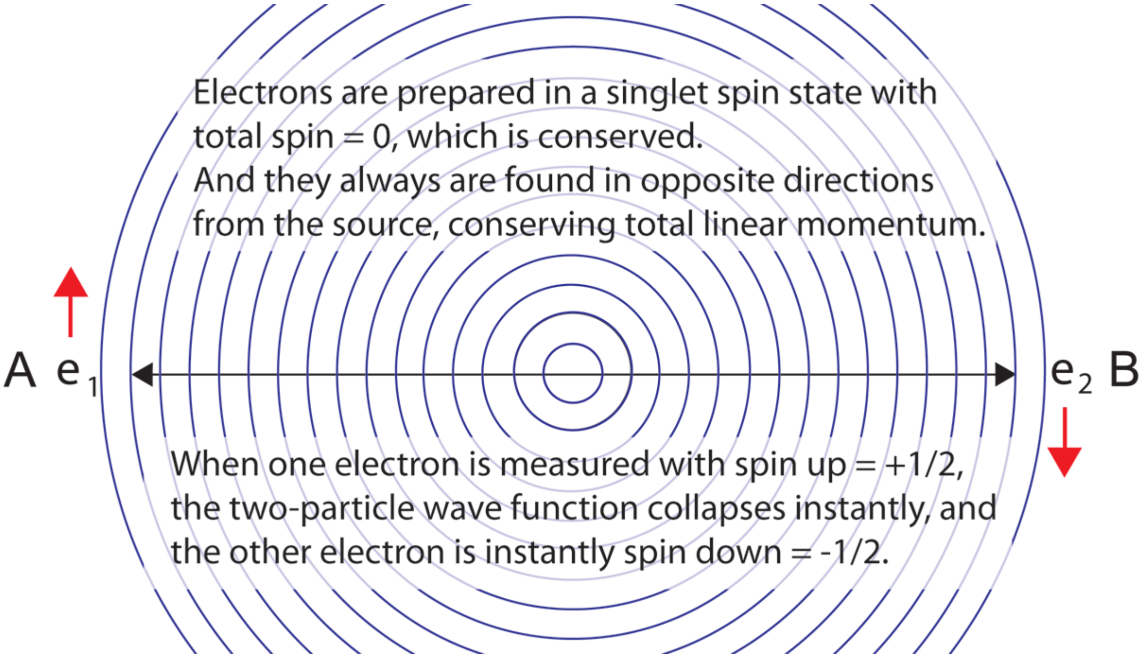

Figure 5. The symmetric collapse of the wave function in a special frame of reference.

increasing volume," as Einstein saw as early as 1905. But instead of collapsing to a single point (nonlocality), we interpret it as collapsing to two points in a space-like separation (disentanglement or the end of nonseparability).

Before the measurement and subsequent collapse, the two-particle wave function is in a superposition of states, $| \uparrow\downarrow \rangle$, where the first electron is spin up and the second spin down, and $| \downarrow\uparrow \rangle$, where the first electron is spin down and the second spin up,

$$\psi = \frac{1}{\sqrt{2}}| \uparrow\downarrow > + \frac{1}{\sqrt{2}}| \downarrow\uparrow\rangle. \qquad (1)$$

$| \uparrow\downarrow \rangle$ and $| \downarrow\uparrow \rangle$ are the basis states for an apparatus that measures particle spin.

In the two-particle case (instead of just one particle making an appearance), when either particle is measured, we know instantly those properties of the other particle that satisfy the conservation laws. This includes its location equidistant from, but on the opposite side of, the source, and its other properties such as spin. Since Bob is at the point where the second particle becomes determinate, his measurement is simultaneous with Alice's in the special frame.

We can also ask what happens if Bob is not at the same distance from the origin as Alice. This introduces a positional and time asymmetry. But there is still no time asymmetry from the point of view of the two-particle wave function collapse. And in an appropriate moving frame, Bob can still make his measurement first.

When Alice detects the particle (with spin up), at that instant the other particle also becomes determinate (with spin down) at the same distance on the other side of the origin. It now continues, in that spin-down determinate state, to Bob's measuring apparatus for a "later" measurement. See 6.

In a different moving frame, it can be Alice who measures "later." If Bob had been closer to the preparation source of the entangled particles, his measurement would have been "first" and collapsed the two-particle wave function before Alice.

Einstein asked whether a particle has a determinate position just before it is measured. It does not, but we can say that before Bob's measurement, the particle spin that he will measure was determined from the moment the two-particle wave function collapsed as a result of Alice's measurement. Because the two-particle wave function describing the indistinguishable particles cannot be separated into a product of two single-particle wave functions, when either particle is measured the two-particle wave function collapses and properties of both particles simultaneously become determinate.

III. CONCLUSION

Recent commentators say that nonlocality and entanglement constitute a "second revolution" in quantum mechanics, "the greatest mystery in physics," or "science's strangest phenomenon," and that quantum physics has been "reborn." They usually quote Erwin Schrödinger as saying, "I consider [entanglement] not as one, but as *the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought." ([13], p.555) If there is something new, it is because Einstein added the enigma of nonseparability to his original concerns about nonlocality. Schrödinger endorsed nonseparability, with reservations about Einstein's *separation principle* (viz., disentanglement) in correspondence with Einstein and in print, although he never accepted the idea of quantum jumps and the collapse of the wave function. [24]

We have shown that the instantaneous collapse of probability amplitude for a wave function completely explains nonlocality and single-particle self interference. This is simply P.A.M. Dirac's "projection postulate," one of the three major assumptions in his quantum mechanics formalism, along with the axiom of measurement and the principle

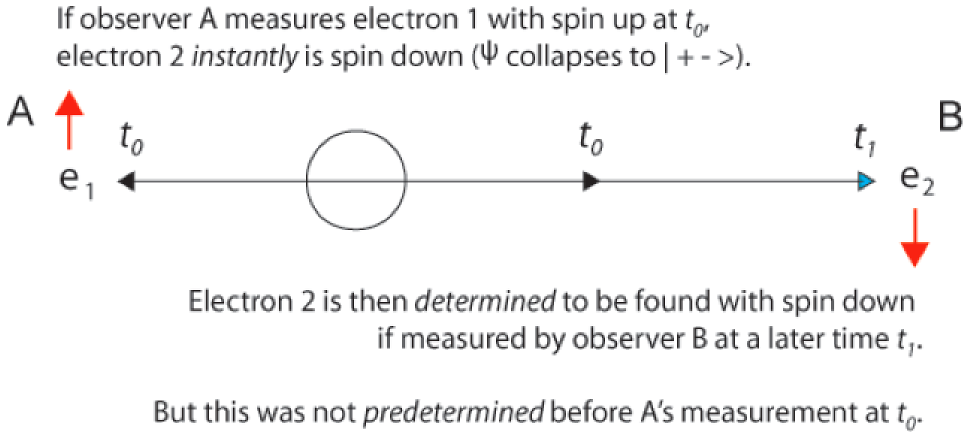

Figure 6. Bob's measurement is made at a greater distance from the source than Alice.

of superposition ([25], p.36). According to Dirac, it is the superposition of states and the collapse (projection) of states into a single state that is responsible for the departure from classical physics. Superposition is thus more fundamental than Schrödinger's entanglement. The two-particle wave function is in such a superposition of states (Eq. 1).

But EPR has definitely added another level to the EPR puzzle beyond the mystery of nonlocality. It is the enigma of nonseparability, a consequence of the indistinguishability of identical particles. In the landmark EPR article, Einstein insisted that the founders of quantum mechanics look carefully at these highly non-intuitive aspects of quantum theory, some of which we see Einstein himself discovered long before the late 1920's formulation of the standard orthodox theory of quantum mechanics.

When a measurement produces a collapse of a two-particle wave function, it affects both particles simultaneously. This is best seen in our special frame of reference. The collapse itself is the mystery of nonlocality, perhaps first discovered by Einstein in 1905. But the indistinguishability of the identical particles makes the collapse symmetric, where single-particle collapses are not symmetric. Nonseparability (the indistinguishability of identical particles) means we cannot know which of the two particles is measured first. Indeed, they are both "measured" (made determinate) at the same instant in our special frame.

We have disentangled EPR into two unique and unavoidable properties of quantum mechanics - nonlocality and nonseparability - but we argue that the outer-layer paradox can be removed by viewing the collapse of the two-particle wave function as symmetric in our special frame.

Thus we claim that EPR is a mystery (*nonlocality*) wrapped in an enigma (*nonseparability*) wrapped in a paradox (*a false asymmetry*).

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