How Does Nature Accomplish Spooky Action at a Distance?

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The enigmatic nonlocal quantum correlation that was famously derided by Einstein as "spooky action at a distance" has now been experimentally demonstrated to be authentic. The quantum entanglement and nonlocal correlations emerged as inevitable consequences of John Bell's epochal paper on Bell's inequality. However, in spite of some extraordinary applications as well as attempts to explain the reason for quantum nonlocality, a satisfactory account of how Nature accomplishes this astounding phenomenon is yet to emerge. A cogent mechanism for the occurrence of this incredible event is presented in terms of a plausible quantum mechanical Einstein–Rosen bridge.

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1 Introduction

In 1975 a young French doctoral candidate Alain Aspect went to John Bell's office at CERN seeking his advice about the suitability of carrying out experiments on Bell's inequality for a thesis. After listening to the proposal, the first question from Bell was,

> "Have you a permanent position?" [1, p. 119]

Obviously, little did Bell know at the time that the consequences of his rather modest paper [2] in an obscure, short lived journal would explode in bringing about one of the most profound discoveries of Nature.

For more than a decade, John Bell has earned his living working almost exclusively on theoretical particle physics and accelerator design at CERN. But his prodigious curiosity drove him to devote much of his thinking to a rigorously honest exploration of how Nature really works, a pursuit which Einstein had considered being the heart of science. From his own experience as a student, he felt that generations of undergraduates in quantum physics had been steered away from thinking too deeply about the reality of quantum physics and thus effectively brainwashed. This conviction drew Bell to the foundational aspects of quantum physics.

In 1964, after a year's leave from CERN, spent at various universities in the United States, he published his seminal paper what is now known as the famous Bell's theorem in the now defunct journal, Physics. With his exceptional keen insight, Bell devised for the first time an experimental procedure [2] to decipher the long standing Einstein–Podolsky–Rosen (EPR) paradox [3], which had been sadly ignored for three decades as merely a philosophical quandary. Bell, a devotee of Einstein and an admirer of Bohm, had set out initially to prove Einstein right in his dismissal of "spooky action," and in search of the Bohm–de Broglie hidden variables. But science does not always take us where we expect to be taken, and he wound up with a very different conclusion.

For the proposed experiments, he devised a formulation known as Bell's inequality. Experimental results violating Bell's inequality will prove the predictions of quantum mechanics known as entanglement and nonlo-

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cality to be true. What Bell found was that there was no theory of local hidden variables that could account for these predictions. For a decade, this remarkable discovery was essentially ignored. No one envisioned that Bell's theorem will bring about an inconceivable transformation in physics. Further details on quantum entanglement have been presented in a previous article by Bhaumik [4, §5].

The very first indication of the violation of Bell's inequality was presented in 1972 by Stuart J. Freedman and John F. Clauser [5]. The first convincing experiment was carried out by Alan Aspect and his colleagues [6]. Countless papers followed, closing nearly all the possible loopholes in the theory as well as experiment. But for a minority of hold-outs, quantum entanglement and nonlocality are now generally accepted as genuine phenomena of Nature despite their strikingly counter intuitive characteristics. These are discussed in an abundant number of articles. A representative samples may be found in the works of Ryszard Horodecki and colleagues [7] and Dominik Rauch and colleagues [8].

Successful experiments validate theories, but it is the application of the findings that leads to widespread acceptance of a new truth. For many years, entanglement and nonlocality were treated largely as mere philosophical matters by much of the physics community. However, since the first usage [9] in secure, quantum cryptography and the possibility of devising a quantum computer that could be a trillion times faster than the fastest digital super computer, the field has literally exploded. Countless research articles published in the most prestigious scientific journals are effectively erasing any trace of skepticism.

Applications of quantum entanglement and nonlocality span a wide and varied range: from quantum cryptography [10, 11] to secure communication systems, and even a global quantum internet. All are now deemed possible. Quantum teleportation has also been demonstrated. But perhaps the most promising application could be in the development of quantum computers, which is the object of feverish research worldwide.

Entanglement is now finding applications in very diverse fields. In defense application, development of a radar system that uses quantum entanglement to beat the stealth technology of modern military aircraft is being considered [12]. Presumably the most promising resolution of the quantum measurement problem at the moment appears to be the theory of decoherence, which is intimately connected with entanglement. Some eminent scientists even consider spacetime itself to be stitched together with quantum entanglement.

Heaps of praise is now being bestowed on the erstwhile unheeded Bell's theorem to be one of the most ingenious discoveries of science.

> "In 1964, John Bell fundamentally changed the way that we think about quantum theory," [13]

pronounces Mathew S. Leifer. Alain Aspect adds grandly,

> "I think it is not an exaggeration to say that the realization of the importance of entanglement and the clarification of the quantum description of single objects have been at the root of a second quantum revolution, and that John Bell was its prophet." [14]

2 Quantum Entanglement

Although quantum entanglement has been demonstrated experimentally with photons [15–18], neutrinos [19], electrons [20], molecules as large as Bucky balls [21, 22] and even small diamonds [23], by far the most expedient way to produce and study entanglement is using polarized photons. In many experimental studies involving some application of entanglement, polarized photons are used as quantum particles since they are much easier to handle and preserve their coherence over a long distance, especially in passage through air, which is not dichroic.

In the exceptionally popular procedure [15], the desired polarization-entangled states are produced directly out of a single nonlinear BBO crystal. By means of such a system, one can very easily produce any of the four maximally entangled EPR-Bell states of the two photons,

$$\begin{aligned} |\Psi^{\pm}\rangle &= \frac{1}{\sqrt{2}}\left(|H\rangle_1|V\rangle_2 \pm |V\rangle_1|H\rangle_2\right), \\ |\Phi^{\pm}\rangle &= \frac{1}{\sqrt{2}}\left(|H\rangle_1|H\rangle_2 \pm |V\rangle_1|V\rangle_2\right), \end{aligned} \tag{1}$$

where $|H\rangle_1$, $|V\rangle_1$ denote the horizontal and vertical polarization state of photon 1 and $|H\rangle_2$, $|V\rangle_2$ represent the same aspects of photon 2.

The special property of nonlocality of quantum entanglement is observed when we separate the two photons by an arbitrarily large distance. Now, if we measure the polarization of one of the photons, get a result, and then measure the polarization of the other photon along the same axis, we find that the result for the second photon is correlated. The wave function of the second photon as well as the probability distribution for the outcome of a measurement of the polarization along any of its axis changes upon measurement of the first photon. This probability distribution is in general different from what it would be without measurement of the first photon.

Rather surprisingly a photon can even be entangled with another one created even at a subsequent time. E. Megidish and colleagues [24] created a photon pair (1-2). After measuring photon 1, the second photon can be stored for example in an optical delay line while a second pair (3-4) is created. Photons 2 and 3 are then projected onto the Bell basis, which swaps entanglement onto photons 1 and 4. Since photon 1 and 4 display quantum correlation even though they never coexisted, entanglement not only holds for space like separation but for time like separation as well. Incidentally, entanglement swapping plays a crucial role in quantum repeaters essential for overcoming loss of photons in long distance quantum communications.

Although so far we have discussed a bipartite state consisting of photons only, Eq. (1) holds in general for any two entangled qubits A and B each in an incoherent superposition of $|0\rangle$ and $|1\rangle$ [25, §4.17]. The four maximally entangled pure Bell states for two qubits are usually given by,

$$\begin{aligned} |\Psi^{\pm}\rangle &= \frac{1}{\sqrt{2}}\left(|0\rangle_A|1\rangle_B \pm |1\rangle_A|0\rangle_B\right), \\ |\Phi^{\pm}\rangle &= \frac{1}{\sqrt{2}}\left(|0\rangle_A|0\rangle_B \pm |1\rangle_A|1\rangle_B\right). \end{aligned} \tag{2}$$

These states form an orthonormal basis of the Hilbert space of the two qubits.

In order to illustrate nonlocal correlation, let us choose the $|\Phi^{+}\rangle$ state where there is equal probability of measuring either product state $|0\rangle_A|0\rangle_B$ or $|1\rangle_A|1\rangle_B$ as $|\frac{1}{\sqrt{2}}|^2 = \frac{1}{2}$.

Now let us separate the two entangled qubits by an arbitrarily large distance and give one qubit each to Alice and Bob. If Alice makes a measurement of her qubit, she will get either $|0\rangle_A$ or $|1\rangle_A$ with equal probability and cannot tell if her qubit had value 0 or 1 because of the qubit's entanglement. If Bob now measures his qubit, he must get exactly the same result of his measurement as Alice. For example, if Alice measures $|0\rangle_A$, Bob must measure $|0\rangle_B$ since $|0\rangle_A|0\rangle_B$ is the only state in $|\Phi^{+}\rangle$ where Alice's qubit is $|0\rangle_A$. So, for these two entangled qubits, whatever Alice measures, so would Bob, with perfect correlation, however far apart they may be and even though neither can predict in advance whether their qubit would have value of 0 or 1.

This conclusion, by itself, is compatible with an interpretation in which the qubits have definite values before they are measured, with probabilities arising simply due to our ignorance of these values. However, by considering further types of measurements that project onto linear combinations of $|0\rangle$ and $|1\rangle$, Bell showed that such an interpretation cannot account for the correlations that quantum mechanics predicts, without assuming some instantaneous action at a distance.

3 No Violation of Relativity

Although the enchanting "spooky action at a distance" has been discovered to be real, which would have been a cause of great consternation to Einstein, he would have been very happy to know that it does not violate his cherished special theory of relativity. Because no useful information can be transmitted instantaneously using quantum nonlocality.

This is due to the fact that the actions of an experimentalist on a subsystem of an entangled state can be described as applying a unitary operator to that subsystem. Although this produces a change on the wave function of the complete system, such a unitary operator cannot change the density matrix describing the rest of the system. In brief, if distant particles 1 and 2 are in an entangled state, nothing an experimentalist with access only to particle 1 can do that would change the density matrix of particle 2.

The density matrix $\hat{\rho}$ of an ensemble of states $|n\rangle$ with probabilities P_n is given by

$$\hat{\rho} = \sum_n P_n |n\rangle\langle n|, \tag{3}$$

where $|n\rangle\langle n|$ are projection operators and the sum of the probabilities is $\sum_n P_n = 1$. Thus there can be various ensembles of states with each one having its own probability distribution that will give the same density matrix.

The mean value of an observable $\langle\hat{A}\rangle$ is:

$$\langle\hat{A}\rangle = \mathrm{Tr}\left(\hat{\rho}\hat{A}\right). \tag{4}$$

Furthermore, the time evolution of the density matrix $\hat{\rho}(t)$ only depends upon the commutator $[\hat{H}, \hat{\rho}(t)]$ following the von Neumann equation,

$$i\hbar\frac{\partial}{\partial t}\hat{\rho}(t) = [\hat{H}, \hat{\rho}(t)], \tag{5}$$

where $\hat{H}$ is a Hermitian operator called the Hamiltonian.

Thus as long as $\hat{\rho}$ remains the same, a change in the wave function of particle 2 does not affect any observable since all observable results can be predicted from the density matrix without needing to know the ensemble used to construct it. Consequently, no useful signal can be sent using entanglement and nonlocality between two observers separated by an arbitrary distance thereby no violation of the sanctified tenets of special theory of relativity ensues.

Still there are some very valuable applications that can be realized for example in secure quantum cryptography and communication system where the system destroys itself when an intruder eavesdrops.

4 How does Nature accomplish nonlocality

Apart from any possible practical application, it would be thrilling to uncover how such an astonishing event can take place in Nature. On this point, even Einstein would enthusiastically concur, since underlying his debates with Bohr was his contention that science should seek to explain how Nature works, not simply to tell us what we can know about how it works. A sketch of a possible exploratory process using the characteristic fluctuations of the quantum fields to form an Einstein–Rosen (ER) bridge [26] was presented by the author in a previous publication [27]. Some further elaboration of the possibility will now be presented. In order to accomplish that, it would be necessary to clearly understand the inherent, inseparable connections of the entangled particles with the underlying quantum fields and their vacuum fluctuations.

By way of many experiments over the years, the Quantum Field Theory of Standard Model has successfully explained almost all experimental observations in particle physics and correctly predicted a wide assortment of phenomena with impeccable precision and according to the experts, QFT is here to stay as an effective field theory.

Steven Weinberg asserts,

> “the Standard Model provides a remarkably unified view of all types of matter and forces (except for gravitation) that we encounter in our laboratories, in a set of equations that can fit on a single sheet of paper. We can be certain that the Standard Model will appear as at least an approximate feature of any better future theory.” [28, p. 264]

And Frank Wilczek affirms,

> “the standard model is very successful in describing reality—the reality we find ourselves inhabiting.” [29, p. 96]

Wilczek additionally enumerates the most crucial aspects of the quantum fields as the primary constituents of everything physical in this universe.

> “The primary ingredient of physical reality, from which all else is formed, fills all space and time. Every fragment, each space-time element, has the same basic properties as every other fragment. The primary ingredient of reality is alive with quantum activity. Quantum activity has special characteristics. It is spontaneous and unpredictable.” [29, p. 74].

He continues further to pronounce,

> “The deeper properties of quantum field theory, which will form the subject of the remainder of this paper, arise from the need to introduce *infinitely many degrees of freedom*, and the possibility that all these degrees of freedom are excited as quantum mechanical fluctuations.” [30, pp. 338–339]

Furthermore,

> “Loosely speaking, energy can be borrowed to make evanescent virtual particles. Each pair passes away soon after it comes into being, but new pairs are constantly boiling up, to establish an equilibrium distribution.” [30, p. 404]

According to QFT, a particle like an electron is a propagating ripple (quantized wave) of the underlying electron quantum field, which acts as a particle because of its well-defined energy, momentum, mass, charge, and spin, which are conserved properties of the electron [31].

Since electrons carry electric charge, their very presence disturbs the electromagnetic field around them. The disturbance in the photon or the electromagnetic field in turn can cause disturbances in other electrically charged quantum fields, like the muon and the various quark fields. Generally speaking, in this manner, every quantum particle spends some time as a mixture of other particles in all possible ways. However, the combination of the disturbances in the electron field together with those in all the other fields always maintains well-defined conserved quantities.

All these disturbances distort the shape of the ripple. However, irrespective of that shape, it can be expressed as a wave packet by Fourier analysis. Thus a wave packet is a holistic ensemble of disturbances of the primary reality of quantum fields, only the totality of which represent a particle like an electron or a photon and therefore always needs to be treated as such. It should now be abundantly clear how intimately and inseparably the quantum particles like photons are always connected to quantum fields and their inherent fluctuations.

Despite the roiling ocean of quantum fluctuations, some order can be found in the midst of all the unpredictability. A familiar example is the decay of radioactive atoms. The instance of decay for any particular atom is completely spontaneous and totally unpredictable. But for a sufficient number of these atoms, the time required for the decay of half of them is evidently calculable. Likewise, the random quantum fluctuations of the fields in any spacetime element can be embodied in a wave function (quantum state).

To a good approximation, in QFT the wave function of quantum fluctuations can be represented by a linear superposition of harmonic oscillator wave functions. The wave function $|\Psi\rangle$ of quantum fluctuations in any element of spacetime can be written as a vector in Hilbert space,

$$|\Psi\rangle = \sum_n c_n |\Psi_n\rangle \tag{6}$$

where $|\Psi\rangle$ is normalized so that $\langle|\Psi|\Psi\rangle = 1$.

As ascertained from relativistic Lorentz invariance, any quantum field is immutable at each space-time element throughout the universe. This holds in spite of the infinite degrees of freedom for creation of the vacuum fluctuations at all spacetime elements where any particular fluctuation is totally spontaneous and completely unpredictable as to exactly when that fluctuation will take place. Therefore $|\Psi\rangle$ represents an irreducible randomness that manifests itself throughout the universe without propagating from one point of space to another.

Since the expectation value of an underlying quantum field in its ground state is the same throughout the universe, reflecting this reality the state vector $|\Psi\rangle$ representing its vacuum fluctuations in any spacetime element should be the same all over the universe, resulting in a stupendous ensemble of identical quantum states. Because of the plethora of interactions between the quantum fields predicted by QFT, there will be entanglement [32] between all the $|\Psi\rangle$ throughout the universe. To give just one example, the gravitational field will interact with all the fields. Of course, the number of interactions that contribute to various degrees of entanglement on a universal scale is beyond listing. Consequently, it should be possible to construct a universal Einstein–Rosen (ER) bridge comprising the entangled $|\Psi\rangle$ states of all the space time elements.

As discussed earlier, a wave packet representing a quantum particle is a holistic ensemble of disturbances of physically real quantum fields, only the totality of which represents a particle like an electron or a photon. Thus any photon is always entangled with the vacuum and its fluctuations and consequently the ER bridge. Such a possibility seems to have been demonstrated experimentally [33].

When two photons are created simultaneously by down conversion in a nonlinear crystal, both of them will be entangled with the ER bridge. However, those photons, which are also in a maximally entangled Bell state will be concurrently entangled with the vacuum state ER bridge from their very inception thus causing the bridge to be maximally entangled as well. This is because the entanglement of the ER bridge with the maximally entangled photons is stronger compared to when the photons are not entangled. The monogamy of entanglement is not violated in this case since the two entanglements are created simultaneously and there is no cloning.

Thus a possible mechanism for a "spooky action at a distance" can be envisioned. Hrant Gharibyan and Robert F. Penna [34] have mentioned that classical ER requires monogamous EPR, stating also that quantum ER bridges have yet to be defined independently of the ER=EPR conjecture [35–38]. We believe the possibility of a quantum ER bridge presented here is worth further investigation. Extended rigorous analysis including entropy of entanglement as its measure should be carried out. The maximally entangled ER bridge can facilitate the two maximally entangled photons to maintain their nonlocal correlations even when they are separated by an arbitrary distance.

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