Quantum Nonlocality and the Possibility of Superluminal Effects

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ABSTRACT:

EPR experiments demonstrate that standard quantum mechanics exhibits the property of *nonlocality*, the enforcement of correlations between separated parts of an entangled quantum systems across spacelike separations. Nonlocality will be clarified using the transactional interpretation of quantum mechanics and the possibility of superluminal effects (e.g., faster-than-light communication) from nonlocality and non-linear quantum mechanics will be examined.

1. BELL'S THEOREM AND QUANTUM NONLOCALITY

Albert Einstein disliked quantum mechanics, as developed by Heisenberg, Schrödinger, Dirac, and others, because it had many strange features that ran head-on into Einstein's finely honed intuition and understanding of how a proper universe ought to operate. Over the years he developed a list of objections to the various peculiarities of quantum mechanics. At the top of Einstein's list of complaints was what he called "spooky actions at a distance". Einstein's "spookiness" is now called *nonlocality*, the mysterious ability of Nature to enforce correlations between separated but entangled parts of a quantum system that are out of speed-of-light contact, to reach faster-than-light across vast spatial distances or even across time itself to ensure that the parts of a quantum system are made to match. To be more specific, *locality* means that isolated parts of any quantum mechanical system out of speed-of-light contact with other parts of that system are allowed to retain definite relationships or correlations only through memory of previous contact. *Nonlocality* means that in quantum systems correlations not possible through simple memory are somehow being enforced faster-than-light across space and time. Nonlocality, peculiar though it is, is a fact of quantum systems which has been repeatedly demonstrated in laboratory experiments.

In 1935 Einstein, with his collaborators Boris Podolsky and Nathan Rosen, published a list of objections to quantum mechanics which has come to be known as "the EPR paper" [1], in which they lodged three complaints against quantum mechanics, one of which was nonlocality. The EPR paper argued that "no real change" could take place in one system as a result of a measurement performed on a distant second system, as quantum mechanics requires.

A decades-long uproar in the physics literature followed the publication of the EPR paper. The founders of quantum mechanics tried to come to grips with the EPR criticisms, and a long inconclusive battle ensued. EPR supporter David Bohm introduced the notion of a "local hidden variable" theory, a partially reformulated alternative to orthodox quantum mechanics that would replace quantum mechanics with a theoretical structure omitting the paradoxical features to which the EPR paper had objected. In Bohm's hidden-variable alternative, all correlation were established locally at sub-light speed.

Working physicists, however, paid little attention to hidden variable theories. Bohm's approach was far less useful than orthodox quantum mechanics for calculating the behavior of physical systems.

Since it was apparently impossible to resolve the EPR/hidden-variable debate by performing an experiment, physicists tended to ignore the whole controversy. The EPR objections were considered problems for philosophers and mystics, not Real Physicists.

In 1964 this perception changed. John S. Bell, a theoretical physicist working at the CERN laboratory in Geneva, proved an amazing theorem which demonstrated that certain experimental tests could distinguish the predictions of quantum mechanics from those of any local hidden-variable theory [2,3]. Bell, following the lead of Bohm, had based his calculations not on measurements of position and momentum, the focus of Einstein's arguments, but on measurements of the states of polarization of photons of light.

Excited atoms often produce two photons in a process called a "cascade" involving two successive quantum jumps. Because of angular momentum conservation, if the atom begins and ends with no net angular momentum, the two photons must have correlated polarizations. When such photons travel in opposite directions, angular momentum conservation requires that if one of the photons is measured to have some definite polarization state, the other photon is required by quantum mechanics to have *exactly* the same polarization state, no matter what measurement is made. Such correlated photon pairs are said to be in an "entangled" quantum states. Experimental tests of Bell's theorem, often called "EPR experiments", usually use entangled photons from such an atomic cascade.

EPR experiments measure the coincident arrival of two such photons at opposite ends of the apparatus, as detected by quantum-sensitive photomultiplier tubes after each photon has passed through a polarizing filter or splitter. The photomultipliers at opposite ends of the apparatus produce electrical pulses which, when they occur at the same time, are recorded as a "coincidence" or two photon event. The rate $R(\theta)$ of such coincident events is measured when the two polarization axes are oriented so as to make a relative angle of θ. Then θ is changed and the rate measurement is repeated until a complete map of $R(\theta)$ vs. θ is developed.

Bell's theorem deals with the way in which the coincidence rate $R(\theta)$ of an EPR experiment changes as θ starts from zero and becomes progressively larger. Bell proved mathematically that for all local hidden-variable theories $R(\theta)$ must decrease linearly (or less) as θ increases, i.e., the fastest possible decrease in $R(\theta)$ is proportional to θ. On the other hand quantum mechanics predicts that the coincidence rate is $R(\theta) = R(0)\,\mathrm{Cos}^2(\theta)$, so that for small θ it will decrease roughly as θ^2. Therefore, quantum mechanics and Bell's Theorem make qualitatively different predictions about EPR measurements.

When two theories make such distinctly different predictions about the outcome of the same experiment, a measurement can be performed to test them. For quantum mechanics and Bell's theorem this crucial EPR experiment was performed first in 1972 by Freedman and Clauser[4], who demonstrated a 6σ (six standard deviation) violation of Bell's inequality. A decade later the Aspect group in France performed a series of elegant "loophole closing" experiments that demonstrated 46σ violations of Bell's inequality [5,6]. In these experiments the predictions of quantum mechanics were always confirmed, and very significant violations of the Bell Inequalities are demonstrated.

When the first experimental results from EPR experiments became available, they were widely interpreted as a demonstration that hidden variable theories must be wrong. This interpretation changed when it was realized that Bell's theorem assumed a *local* hidden variable theory, and that *nonlocal* hidden variable theories can also be constructed that violate Bell's theorem and agree with the experimental measurements. The assumption made by Bell that had been put to the test, therefore, was the assumption of *locality*, not the assumption of hidden variables. Locality, as promoted by Einstein, was found to be in conflict with experiment.

Or to put it another way, the intrinsic nonlocality of quantum mechanics has been demonstrated by the experimental tests of Bell's theorem. It has been experimentally demonstrated that nature arranges the correlations between the polarization of the two photons by some faster-than-light mechanism that violates Einstein's intuitions about the intrinsic locality of all natural processes. What Einstein called "spooky actions at a distance" are an important part of the way nature works at the quantum level. Einstein's faster-than-light spooks cannot be ignored.

A clarification about the nature of nonlocality is perhaps appropriate here. Locality in the form of memory could explain the correlation of photon polarizations for any one choice of measurements, e.g., vertical vs. horizontal polarization. It is the freedom of the observer to measure using many different polarization axes (or even circular rather than linear polarization) that leads to the need for nonlocality. To put it another way, if you were constructing a classical science-museum simulation of an EPR experiment (not using actual photons), you would need signal wires running from each measurement to the other to make the simulation operate as quantum mechanics does. Nature seems to have such wires, but we are not allowed to use them.

2. NONLOCALITY AND THE TRANSACTIONAL INTERPRETATION OF QUANTUM MECHANICS

Quantum mechanics (QM) was invented in the late 1920's when an embarrassing body of new experimental facts from the microscopic world couldn't be explained by the accepted physics of the period. Heisenberg, Schrödinger, Dirac, and others used a remarkable combination of intuition and brilliance to devise clever ways of "getting the right answer" from a set of arcane mathematical procedures. They somehow accomplished this without understanding in any basic way what their mathematics really meant. The mathematical formalism of quantum mechanics is now trusted by all physicists, its use clear and unambiguous. But even now, six decades later, its meaning remains controversial.

The part of the theory that gives meaning to the mathematical formalism is called the *interpretation*. For quantum mechanics there are several competing interpretations, with no general consensus as to which should be used. The orthodox interpretation of quantum mechanics used (sparingly) in most physics textbooks was developed primarily by Bohr and Heisenberg and is called *the Copenhagen interpretation* (CI). It takes a "don't ask -- don't tell" approach to the formalism which focuses exclusively on the outcomes of physical measurements and which forbids the practitioner from asking questions about possible underlying mechanisms that produce the observed effects.

The nonlocality of the quantum mechanics formalism is a source of some difficulty for the Copenhagen interpretation. It is accommodated in the CI through Heisenberg's "knowledge interpretation" which views the quantum mechanical state vector (ψ) as a mathematically-encoded description of the state of observer knowledge rather than as a description of the objective state of the system observed. For example, in 1960 Heisenberg wrote, *"The act of recording, on the other hand, which leads to the reduction of the state, is not a physical, but rather, so to say, a mathematical process. With the sudden change of our knowledge also the mathematical presentation of our knowledge undergoes of course a sudden change."* The knowledge interpretation's account of state vector collapse and nonlocality as changes in knowledge is internally consistent, but it is rather subjective, intellectually unappealing, and the source of much of the recent misuse of the Copenhagen interpretation (e.g., "observer-created reality").

An more objective alternative interpretation of the quantum mechanics formalism is the *transactional interpretation* (TI) proposed a decade go by the author. A reprint of the original paper[7,8] can be found on the web at *http://www.npl.washington.edu/ti.*

The transactional interpretation, a leading alternative to the Copenhagen interpretation, uses an explicitly nonlocal transaction model to account for quantum events. This model describes any quantum event as a space-time "handshake" executed through an exchange of retarded waves (ψ) and advanced waves ($\psi*$) as symbolized in the quantum formalism. It is generalized from the time symmetric Lorentz-

Dirac electrodynamics introduced by Dirac and on "absorber theory" as originated by Wheeler and Feynman[9,10]. Absorber theory leads to exactly the same predictions as conventional electrodynamics, but it differs from the latter in that it employs a two-way exchange, a "handshake" between advanced and retarded waves across space-time leading to the expected transport of energy and momentum.

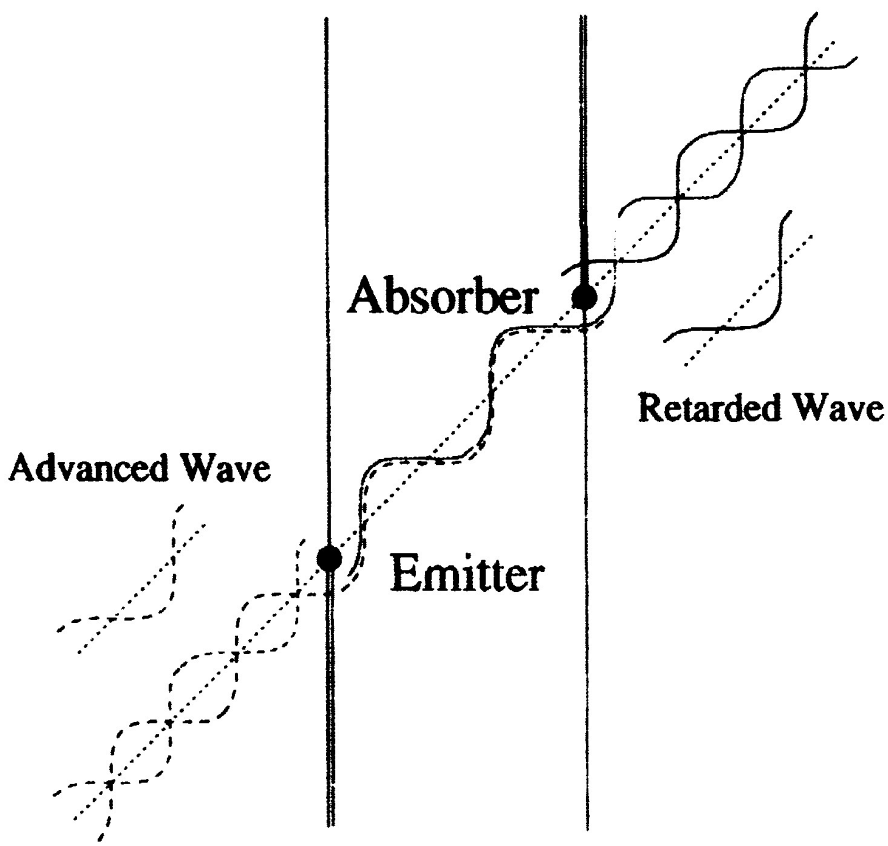

Fig. 1 Schematic of an advanced-retarded transaction

This advanced-retarded handshake, illustrated schematically in Fig. 1, is the basis for the transactional interpretation of quantum mechanics. It is a two-way contract between the future and the past for the purpose of transferring energy, momentum, etc, while observing all of the conservation laws and quantization conditions imposed at the emitter/absorber terminating "boundaries" of the transaction. The transaction is explicitly nonlocal because the future is, in a limited way, affecting the past (at the level of enforcing correlations).

To accept the Copenhagen interpretation one must accept the intrinsic positivism of the approach and its interpretation of solutions of a simple second-order differential equation combining momentum, mass, and energy as a mathematical description of the knowledge of an observer. Similarly, to accept the transactional interpretation it is necessary to accept the use of advanced solutions of wave equations for retroactive confirmation of quantum event transactions, which smacks of backwards causality. No interpretation of quantum mechanics comes without conceptual baggage that some find unacceptable.

With the advanced waves employed in the transactional interpretation it is easy to account for nonlocal effects. Fig. 2 shows a transactional diagram of an EPR experiment, which *in the TI* involves twin handshakes between both measurements (D_1 and D_2) and the source (SO). The two-link transaction can only satisfy energy, momentum, and angular momentum conservation laws if the measurement outcomes at D_1 and D_2 match when the same measurement is made. Thus, the correlation between measurement outcomes is enforced, not across a spacelike interval, but across negative (ψ^*) and positive (ψ) lightlike intervals (if the EPR experiment uses photons). Therefore, the nonlocality of quantum mechanics is readily accounted for by the transactional interpretation.

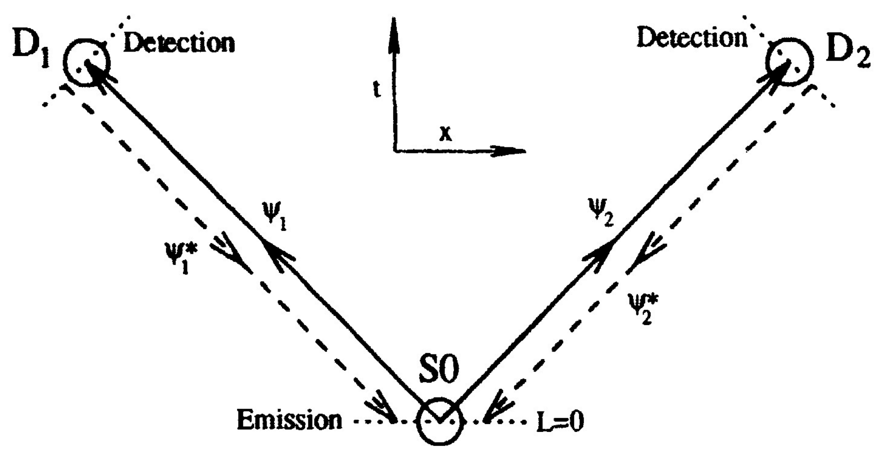

Fig. 2 Transactional diagram of an EPR experiment.

From one perspective the advanced-retarded wave combinations used in the transactional description of quantum behavior are quite apparent in the Schrödinger-Dirac formalism itself, so much so as to be almost painfully obvious. Wigner's time reversal operator is, after all, just the operation of complex conjugation, and the complex conjugate of a retarded wave is an advanced wave. What else, one might legitimately ask, could the ubiquitous ψ^* notations of the quantum wave mechanics formalism possibly denote except that the time reversed (or advanced) counterparts of normal (or retarded) ψ wave functions are playing an important role in a quantum event? What could an overlap integral combining y with ψ^* represent other than the probability of a transaction through an exchange of advanced and retarded waves? At minimum it should be clear that the transactional interpretation is not a clumsy appendage gratuitously grafted onto the formalism of quantum mechanics but rather a description which, after one learns the key to the language, is found to be graphically represented within the quantum wave mechanics formalism itself.

Can quantum nonlocality be used for faster-than-light or backward-in-time communication? Perhaps, for example, a message could be telegraphed from one measurement site of the EPR experiment to the other through a judicious choice of which measurement was performed. The simple answer to this question is "No!". Eberhard has used the standard formalism of quantum mechanics to prove a theorem demonstrating the impossibility of such nonlocal superluminal communication [11,12]. Briefly, the quantum operators characterizing the separated measurements always commute, no matter which measurement is chosen, so non-local information transfer is impossible. Nature's superluminal telegraph cannot be diverted to mundane human purposes.

3. NONLINEAR QUANTUM MECHANICS AND SUPERLUMINAL LOOPHOLES

This prohibition against superluminal communication, as stated above, is a part of standard quantum mechanics. However, this prohibition is broken if quantum mechanics is allowed to be slightly "non-linear", a technical term meaning that when quantum waves are superimposed they may generate a small cross-term not present in the standard formalism. Steven Weinberg, Nobel laureate for his theoretical work in unifying the electromagnetic and weak interactions, investigated a theory which introduces small non-linear corrections to standard quantum mechanics [13]. The onset of non-linear behavior is seen in other areas of physics, e.g., laser light in certain media, and, he suggested, might also be present but unnoticed in quantum mechanics. Weinberg's non-linear QM subtly alters certain properties of the standard theory, producing new physical effects that can be detected through precise measurements.

Two years after Weinberg's non-linear QM theory was published, Joseph Polchinski published a paper demonstrating that Weinberg's non-linear corrections upset the balance in quantum mechanics that prevents superluminal communication using EPR experiments [14]. Through the new non-linear effects, separated measurements on the same quantum system begin to "talk" to each other and faster-than-light and/or backward-in-time signaling becomes possible. Polchinski describes such an arrangement as an "EPR telephone".

The Weinberg/Polchinski work had implications that are devastating for the Copenhagen representation of the wave function as "observer knowledge". Polchinski has shown that a tiny non-linear modification transforms the "hidden" nonlocality of the standard QM formalism into a manifest property that can be used for nonlocal observer-to-observer communication. This is completely inconsistent with the Copenhagen "knowledge" interpretation.

Thus, the Copenhagen interpretation is not "robust" because it is inconsistent with a tiny modification of the standard formalism. The transactional interpretation, on the other hand, can easily accommodate this modification of the formalism and is robust enough to be tested and verified (or falsified) by the same effect. If quantum mechanics has any detectable nonlinearity, we get a faster-than-light and backwards-in-time telephone.

But *is* quantum mechanics non-linear? Atomic physics experiments have been used by several experimental groups to test Weinberg's non-linear theory. So far, these tests have all been negative, indicating that any non-linearities in the quantum formalism are extremely small, if they exist at all. These negative results are not surprising, however, because the atomic transitions used involve only a few electron-volts of energy. If quantum mechanics does have non-linear properties, they would expected to depend on energy and to appear only at a very high energy scale and particularly at the highest energy densities. Weinberg-Polchinski tests should be made, if possible, with the highest energy particle accelerators. Perhaps then we can find out what connections might be made with Polchinski's EPR telephone.

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REFERENCES:

[1] Albert Einstein, Boris Podolsky, and Nathan Rosen, (1935) Physical Review **47**, 777-780.

[2] John S. Bell, (1964) Physics **1**, 195-200.

[3] John S. Bell, (1966) Reviews of Modern Physics **38**, 447-452.

[4] Stuart J. Freedman and John F. Clauser, (1972) Physical Review Letters **28**, 938-941.

[5] A. Aspect, J. Dalibard, and G. Roger, (1982) Physical Review Letters **49**, 91.

[6] A. Aspect, J. Dalibard, and G. Roger, (1982) Physical Review Letters **49**, 1804.

[7] John G. Cramer, (1986) Reviews of Modern Physics **58**, 647-687.

[8] John G. Cramer, (1988) International Journal of Theoretical Physics **27**, 227-236.

[9] J. A. Wheeler and R. P. Feynman, (1945) Reviews of Modern Physics **17**, 157.

[10] J. A. Wheeler and R. P. Feynman, (1949) Reviews of Modern Physics **21**, 425.

[11] P. H. Eberhard, (1977) Nuovo Cimento **38B**, 75.

[12] P. H. Eberhard, (1978) Nuovo Cimento **46B**, 392.

[13] Steven Weinberg, (1989) Physical Review Letters **62**, 485.

[14] Joseph Polchinski, (1991) Physical Review Letters **66**, 397.