Defense Intelligence Reference Document

Acquisition Threat Support

30 March 2010

ICOD: 1 December 2009

DIA-08-1003-016

The Space-Communication Implications of Quantum Entanglement and Nonlocality

The Space-Communication Implications of Quantum Entanglement and Nonlocality

Prepared by:

(b)(3):10 USC 424

Defense Intelligence Agency

Author:

(b)(6)

Administrative Note

i

Contents

Figures

The Space-Communication Implications of Quantum Entanglement and Nonlocality

Foreword and Introduction

This paper reviews quantum entanglement and nonlocality and considers the possibility that this phenomenon could be used for sending observer-to-observer signals. Such a demonstration would break several quantum "no-signal theorems" in the physics literature. Nonlocal quantum signaling would have far-reaching implications as an enabling technology for superluminal and retrocausal signaling. Scenarios that might lead to nonlocal quantum communication are described, and applications to retrocausal signaling and real-time space communication are considered. Also considered briefly is the nonlocal communication implications of nonlinear quantum mechanics.

Communication in space at the scale of the solar system is severely limited by the space-time scale set by the speed of light. Light signals, whether in the form of radio waves, microwaves, visible light, X-rays, or gamma rays, require about 3.3 microseconds to travel a distance of 1 kilometer. A light signal sent from Earth requires about 1.3 seconds to reach the Moon, between 4.4 and 20 minutes to reach Mars, and between 4 and 4.3 hours to reach Neptune, depending on their orbital positions. This time delay makes real-time control of remote space-based devices impossible and leads to the need for pre-programmed robotic devices with enough "intelligence" to perform limited operations with a minimum of remote control.

The burden of these limitations raises the question of whether there is some way to speed up the space communications link. The conventional answer is "No!," because the well-established special theory of relativity is viewed as limiting signal transmission speed to the speed of light, with superluminal communications strictly forbidden. However, as will be discussed in Section III, relativity prohibits only certain forms of superluminal communication, while other forms are not in conflict with relativity. One phenomenon that appears, at least superficially, to exhibit superluminal aspects while preserving compatibility with special relativity is quantum nonlocality, the ability of quantum phenomena to enforce correlations between quantum states over large separations in space-time.

When two photons emerge from a single quantum event, the state of one photon may be subtly connected to that of the other. The classical view is that, once separated, such photon states must be fixed according to mechanics and conservation relations that act at the point of their origin, so that modifying one later will not affect the other. In quantum physics, however, as borne out by experiment (Reference 1, 2), the outcome of a measurement of the state of one of the photons, even well after their point of joint creation, can affect the state of the other photon. This connection is referred to as quantum entanglement, a phrase first coined by Erwin Schrödinger (Reference 3). Questions raised by the phenomenon of quantum entanglement are: (1) what is the causal connection between entangled states, and (2) can the phenomenon possibly be used for sending observer-to-observer signals? This

paper attempts to address these questions by taking a close look at quantum entanglement, quantum nonlocality, the experiments that have explored them, and proposed experiments to test the causal and faster-than-light communication issues evoked by such physics.

Quantum entanglement describes the condition of separated parts of the same quantum system in which each of the parts can be described only by referencing the state of other parts. This is one of the most counterintuitive aspects of quantum mechanics, because classically one would expect system parts out of "local" contact to be completely independent. Thus, entanglement represents a kind of quantum "connectedness" in which measurements on one isolated part of an entangled quantum system have nonclassical consequences for the outcome of measurements performed on the other (possibly very distant) part of the same system. This quantum connectedness acting in entangled quantum systems is called quantum nonlocality.

Nonlocality was first highlighted by Albert <u>E</u>instein and his coworkers Boris <u>P</u>odolsky and Nathan <u>R</u>osen in their famous EPR paper (Reference 4). They argued that the nonlocal connectedness of quantum systems was unphysical in that it implied a faster-than-light connection in apparent conflict with special relativity. Despite their objection, quantum nonlocality has now been demonstrated (see Section I) in many quantum systems (Reference 1, 2). In the physics community, it is now generally acknowledged to be implicit in the quantum formalism as applied to entangled systems, although there remain a few Copenhagen "holdouts" who would require an explicit demonstration of nonlocal signaling before admitting that nonlocality can be considered a real quantum phenomenon.

The question investigated in this paper is whether quantum nonlocality is the private domain of nature or whether it can be used in experimental situations to send signals from one observer to another. As we will see, there is at present no compelling answer to this question. However, it is clear that if such nonlocal observer-to-observer communication were possible, it would have far-reaching implications. In particular, it would represent an enabling technology for superluminal (and retrocausal) signaling and communications, and perhaps make possible the real-time exploration of the universe.

I. Quantum Entanglement, Nonlocality, and EPR Experiments

In the quantum mechanical description of elementary entities like photons, there is a duality between the description as a particle and as a wave. Photons can be thought of as traveling through space as waves but delivering energy (and other conserved quantities) at detection as particles. By choosing the kinds of measurements made on such objects, one can force wave-like or particle-like behavior to be exhibited in the measurements results. Between the entangled parts of a quantum system (for example, the emission of a pair of entangled photons), this wave-like or particle-like behavior in a measurement on one part of the system may force similar behavior in the other part. This is considered further in Section IV below.

The quantum entanglement condition is usually a consequence of some conservation law acting within the system, so that the subsystems are connected by the conserved quantities. For example, if two photons are emitted back to back in a joint state that has zero angular momentum and positive parity, then whatever linear or circular polarization state one photon is measured to have, the other photon must have an identical polarization if measured in the same basis (linear or circular). This condition must exist to ensure that the net angular momentum of the two photon states is zero. In this situation, if the photons are measured for circular polarization, they must both be in states of right circular polarization or in states of left circular polarization. Because linear polarization is a coherent superposition of circular polarization states, if measured in the vertical/horizontal linear polarization basis, they must be in the same vertical or horizontal polarization state, and in the 45° left or right linear polarization basis, they must be in the same 45° left/right polarization state.

Classically, such a polarization correlation condition could in principle exist in some particular polarization basis but not in all of the many possible polarization bases simultaneously. This is the underlying physics of the Bell Inequalities (Reference 8), which deal with the falloff rate of the correlations as the polarization basis of one of the measurements is rotated in angle. The Bell Inequalities demonstrate mathematically that the predictions of semi-classical local hidden-variable theories are inconsistent with those of standard quantum mechanics. Tests of such polarization correlations have been the basis for a number of Bell-Inequality tests (or so-called EPR experiments), in which the validity of the predictions of quantum mechanics and the inadequacies of semi-classical local hidden-variable theories have been demonstrated to high statistical precision (Reference 1, 2).

It was later demonstrated (Reference 5, 6) that the issues surrounding a violation of the Bell Inequalities could be separated into violations of either *parameter independence* (the outcome probability of a measurement on one of a pair of entangled particles is independent of the choice of *parameters* of a measurement performed on the other member of the entangled pair) and violations of *outcome independence* (the outcome probability of a measurement on one of a pair of entangled particles is independent of the *outcome* of a measurement performed on the other member of the entangled pair). The observation of a violation of the Bell Inequalities indicates a violation of either *parameter independence* or *outcome independence* (or both). Outcome independence is fairly evident in the quantum formalism, while parameter independence is more elusive and depends on specific assumptions. Below, the

implications of this dichotomy are considered in the context of the "no-signal" theorems.

It is noted that there is some misinformation in the literature concerning the chronology of successful EPR polarization correlation experiments, and here we wish to set the record at least somewhat straighter. The experimental measurement that first demonstrated a polarization correlation related to EPR nonlocality was performed by C. S. Wu and I. Shanknov in 1949 (Reference 7), well before Bell's work and the subsequent interest in testing Bell's Inequality. Wu and Shanknov showed that the linear polarizations of back-to-back entangled gamma rays from electron-positron annihilation (an L=0 *negative* parity state) were anticorrelated, for example, if one photon was polarized vertically, then the other was polarized horizontally. They did not, however, investigate the falloff of the correlation with polarimeter angle, which is the basis of Bell Inequality tests, nor did they depict their results as a consequence of quantum nonlocality.

Almost two decades passed before the publication of John Bell's pivotal work (Reference 8) in 1964 and 1966. In 1972, Freedman and Clauser (Reference 1) performed the first definitive Bell inequality test by measuring the polarization correlation of entangled photons from a positive parity L=0 atomic cascade in calcium. Their results were in agreement with the predictions of quantum mechanics and were inconsistent with local hidden-variable theories by 6.7 standard deviations. A decade later, in 1982, EPR measurements of the Aspect group (Reference 2) eliminated several "loophole" scenarios that might constitute unlikely ways of preserving classical locality and again demonstrated agreement with quantum mechanics and inconsistency with local hidden-variable theories, this time by 46 standard deviations. In a more recent example of an EPR experiment, the Gisin group (Reference 9) used the fiber-optic cables owned by the Swiss Telephone System to demonstrate the nonlocal connection between EPR measurements made at locations in Geneva and Bern, Swiss cities with a line-of-sight separation of 156 km—a direct demonstration, if one was required, that quantum nonlocality can operate over quite large distances.
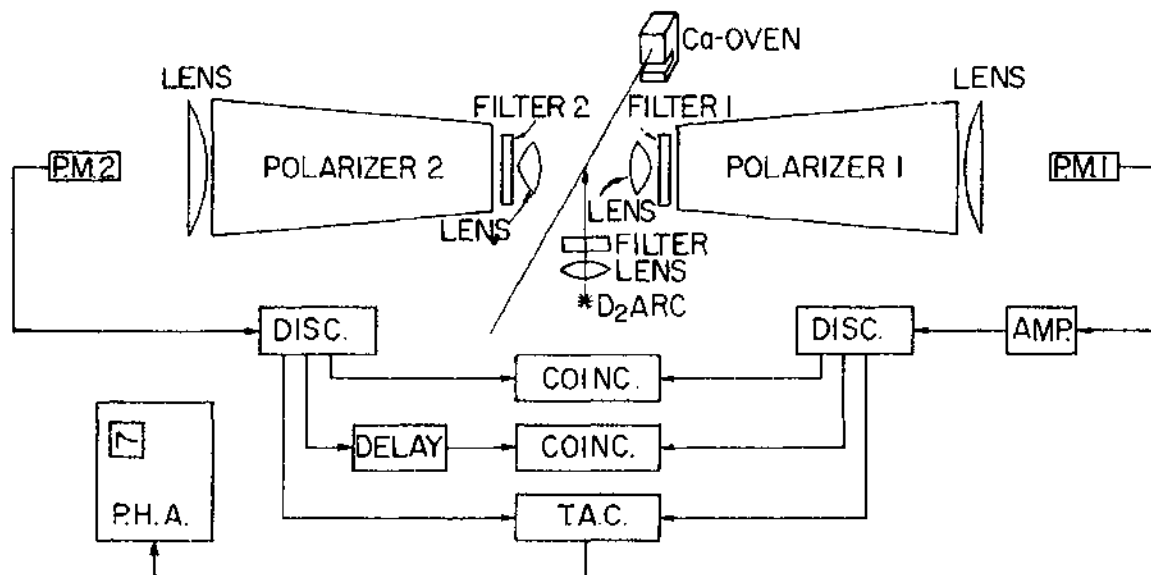

Figure 1. Schematic of the 1972 Freedman-Clauser Experiment (Reference 1)

Do these EPR experiments constitute a demonstration of the existence of quantum nonlocality? There is more than one way of interpreting the implications of the experimental results (Reference 1, 2), and one can find much discussion in the literature as to whether it is locality or "realism" (the objective observer-independent reality of external events) that has been refuted by these EPR measurements.

Noble Laureate Anthony Leggett of the University of Illinois recently pushed this issue somewhat further (Reference 10). He demonstrated that by focusing on the falloff of correlations with *elliptical* polarization rather than the linear polarization used in the Bell Inequality EPR experiments, one can compare the predictions of quantum mechanics with a class of nonlocal realistic theories that he constructed. The resulting Leggett Inequalities can be used in the same way as the Bell Inequalities, but to test theories incorporating *nonlocal* realism instead of *local* realism. Anton Zeilinger's group at the Institute for Quantum Optics and Quantum Information (IQOQI) in Vienna performed a definitive test of the Leggett Inequalities (Reference 11). The results show that using elliptically polarized entangled photons, the Leggett Inequalities in two observables are violated by 3.6 and by 9 standard deviations. This is interpreted as a statistically significant falsification of the whole class of nonlocal realistic theories constructed by Leggett. The IQOQI group summarizes its results with the statement "We believe that our results lend strong support to the view that any future extension of quantum theory that is in agreement with experiments must abandon certain features of realistic descriptions."

It is our view, however, that this is mainly an exercise in demolishing a "strawman." Leggett's nonlocal realistic theories assume that when entangled photons emerge from their emission source, they are in a definite state of polarization. It is well known that when that assumption (and no others) is made, one does not observe the quantum mechanical prediction of Malus's Law for the correlations of the photon pair.

However, Leggett solves that problem by assuming an unspecified nonlocal connection mechanism between the detection systems that fixes the discrepancy. In effect, the two measurements talk to each other nonlocally in such a way that the detected linearly polarized photons obey Malus's Law and produce the same linear polarization correlations predicted by quantum mechanics calculations. Leggett then shows that this nonlocal "fix" cannot be extended into the realm of elliptical polarization, and that quantum mechanics and this type of nonlocal realistic theories give differing predictions for the elliptic polarization correlations. In other words, the "reality" that is being tested is whether the photon source is initially emitting the entangled photons in a definite state of polarization. It is this version of "reality" that has been falsified by the IQOQI measurements.

It is our view that this assumption, clearly inconsistent with the formalism of quantum mechanics, is invalid, and that nature is both nonlocal and unrealistic, if by realism one means that when entangled photons emerge from their emission source, they are in a definite state of polarization. This very restricted definition of realism is not required, and it is assumed that the intrinsic nonlocality of standard quantum mechanics is a physical fact.

It is noted that the several polarization bases used in these kinds of polarization EPR experiments make demonstrating the quantum nonlocal connections straightforward but also make it effectively impossible to use those connections for observer-to-

observer signaling (Reference 12), because one would need to deduce from the arriving photons the polarization basis that was being used in the distant measurements. This is an aspect of the parameter independence mentioned above. While each observer is free to choose a parameter that specifies the polarization basis (for example, circular right/left, linear at any angle) for the measurement, he is not free to force the photon into a particular state of that basis, as would be required for nonlocal communication. However, measuring *polarization correlations* in a system with angular momentum constraints is not the only way to demonstrate the nonlocal connection between the entangled separated parts of a quantum system. Below, EPR experiments that use *momentum entanglement* are discussed, and the question of whether such quantum systems might provide a better vehicle for observer-to-observer nonlocal communication is explored, because by using momentum entanglement, an observer is able to force the photon into particle-like or wave-like behavior.

II. The Quantum No-Signal Theorems

As Einstein implied with his well-known "spooky actions at a distance" comment, enforcement of quantum correlations across spacelike and negative timelike intervals by nonlocality is very counterintuitive. It appears to imply the twin possibilities of superluminal communication and of reverse causation through back-in-time communication between observers. However, a number of authors (Reference 13) have presented "proofs" that such nonlocal observer-to-observer communication is impossible within the formalism of standard quantum mechanics. These theorems assert that in separated measurements involving entangled quantum systems, the quantum correlations will be preserved, but there will be no effect apparent to an observer in one sub-system if the character of the measurement is changed in the other sub-system. Thus, it is asserted, nonlocal signaling is impossible.

As mentioned above, EPR experiments can be viewed (Reference 5, 6) as demonstrating violations of outcome independence or parameter independence or both. Outcome independence cannot be used for nonlocal signaling, while parameter independence can. Thus, any test of nonlocal signaling is, in effect, a test of the parameter independence of quantum phenomena, and the no-signal theorems are "proofs" of parameter independence.

Do these no-signal "proofs" really have the status of mathematical theorems? Perhaps not. Recently it has been pointed out (Reference 14) that at least some of these "proofs" ruling out nonlocal signaling are tautological, assuming that the measurement process and its associated Hamiltonian are local, thereby building the final conclusion of no signaling into their starting assumptions. Standard quantum mechanical Bose-Einstein symmetrization in systems of bosons has been raised as a counter-example, shown to be inconsistent with the initial assumptions of some of these "proofs." Therefore, at least from some perspectives, the possibility of nonlocal communication in the context of standard quantum mechanics remains open and appropriate for experimental testing.

III. Nonlocality Versus Special Relativity?

If nonlocal communication is possible, would it be in conflict with special relativity, with its well-known prohibition against faster-than-light signals? The answer is **no**.

The prohibition of signals with superluminal speeds by Einstein's theory of special relativity is related to the fact that the definite simultaneity of two separated space-time points is not Lorentz invariant. Since some hypothetical superluminal signal could be used to establish a fixed simultaneity relation between two such points—for example, by clock synchronization—this would imply a preferred inertial frame and would be inconsistent with Lorentz invariance and special relativity. In other words, it would be inconsistent with the even-handed treatment of all inertial reference frames in special relativity.

However, if a nonlocal signal could be transmitted through measurements at separated locations performed on two entangled photons, the signal would be "sent" at the time of the arrival of the photon in one location and "received" at the time of arrival of the other photon. By varying path lengths to the two locations, these events could be made to occur in any order and time separation in any reference frame. Therefore, nonlocal signals (even superluminal and retrocausal ones) could *not* be used to establish a fixed simultaneity relation between two separated space-time points, because the sending and receiving of such signals do not have fixed time relations. The transmission and arrival instants of a nonlocal signal cannot be used for synchronization because the transmission and reception instants are path- and delay-dependent variables.

To put it another way, the nonlocal connections of entangled photons lie along segmented lightlike world lines that transform properly under Lorentz transformations. Therefore, there is no conflict between nonlocal signaling and the Lorentz invariance of special relativity. On the other hand, the principle of causality (cause must precede effect in all reference frames) appears very likely to be violated (or at least violate-able) if nonlocal signaling is possible.

Is it possible that the universe does have some preferred reference frame, perhaps that laid down by the cosmic microwave background or implied by Mach's Principle? Perhaps, but if such a preferred frame existed, its existence could not be established by nonlocal communication.

IV. Momentum Domain Entanglement and EPR Experiments

Einstein's original objection (Reference 4) that quantum mechanics appeared to be nonlocal was made with arguments based on a *gedankenexperiment* in the momentum domain. However, almost all of the modern EPR experiments testing the Bell Inequality and demonstrating quantum nonlocality have been performed in the polarization (that is, angular momentum) domain, usually with linearly polarized photons. Interestingly, it appears that if nonlocal quantum communication is possible at all, it may be more easily achieved in the momentum domain of Einstein's original focus.

The optical process of spontaneous parametric down-conversion (Reference 15) turns out to be a very useful way of generating photon pairs entangled in either the polarization or the momentum domains. In this process, a photon from a "pump laser"

5

interacts with a nonlinear crystal and is transformed into two photons with energies and vector momenta that add up to those of the original pump photon. Depending on the type of down-conversion process, there are well-defined polarization correlations between the entangled photons. The down-converted photons may also be easily prepared in momentum-entangled states, because within the nonlinear medium, the vector momenta of the down-converted pair of photons must add to give that of the pump photon.

The first measurement using momentum-entangled down-conversion photons that might be related to nonlocal communication is the Ghost Interference experiment reported in 1995 by the Shih group (Reference 16), shown schematically in Figure 2. The experimenters used degenerate collinear Type-II down-conversion of 351-nm UV pump radiation from an argon-ion laser passed through a 3-mm-long BBO (β-BaB$_2$O$_4$) crystal that had been cut with the optic axis at a phase-matching angle of 42.2° to the pump beam to produce a pair of collinear momentum-entangled 702-nm photons with opposite polarizations. The entangled photons emerge from the crystal very nearly parallel with the pump beam. The pump beam is then split off from the pair using refraction in a quartz prism (**UV Prism**), and the entangled photons are separated with a polarization-selecting beam splitter (**BS**) that reflects the "extraordinary" vertically polarized photon (**e**) and transmits the "ordinary" horizontally polarized photon (**o**). Both photons are passed through 702 ± 10-nm wavelength–selective filters (**f**$_{1,2}$) and then detected (**D**$_{1,2}$).
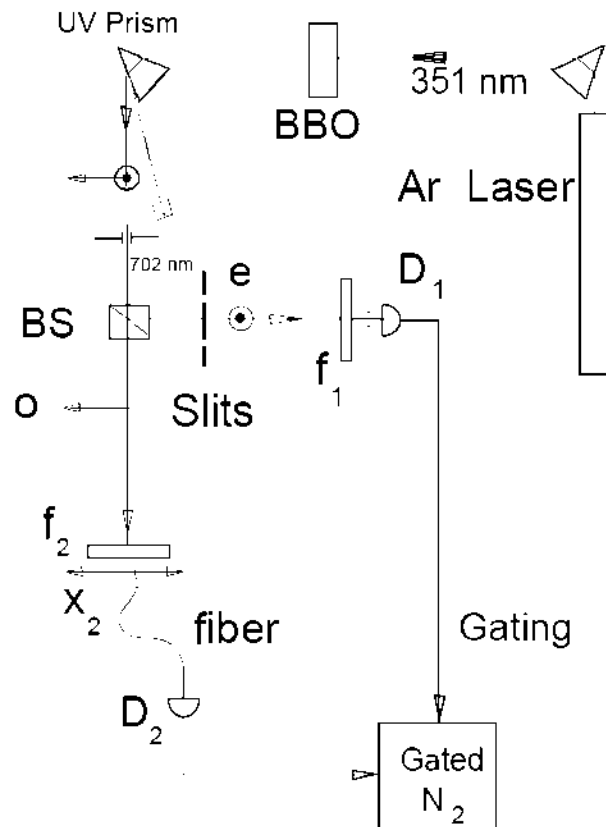

Figure 2. Schematic of the 1995 Ghost Interference Experiment (Reference 16) of the Shih group

The experimenters demonstrated that passing the vertically polarized photon (**e**) through a double- or single-slit system before detection at **D₁** produced a "comb" interference distribution or a "bump" diffraction distribution, respectively, in the position **X₂** of the horizontally polarized photon (**o**) detected at **D₂** when the pair of photons is examined in coincidence. In other words, the position distribution of the straight-through photon shows patterns characteristic of the single- or double-slit system through which its twin entangled photon passed. Figure 3 shows the observed position distributions for the two cases.

From the viewpoint of nonlocal communication, we note that modifying the slit system before **D₁** through which the reflected photon passes, which can be thought of as the action of a "sending" observer, nonlocally causes an observable change in the **X₂**-position distribution of the undeflected photon, as detected by a "receiving" observer at

Figure 3. Ghost Interference Position Distributions at X₂

D₂. This is a nonclassical effect that demonstrates the nonlocal connection between the entangled pair and that might form the basis for transmission of a nonlocal signal between the two observers. However, the Ghost Interference experiment does *not*, in the form reported, demonstrate nonlocal communication, because of its use of a classical communication link in imposing the coincidence requirement between the detected photons.

In their paper, the authors comment that with the two-slit system in place, in the absence of coincidences there is no observable two-slit interference pattern distributions at either **D₁** or **D₂**. They attribute this lack of an interference "signal" to the horizontal variation in the creation position of the down-converted photons. The variation is enough to cause the "**e**" photons to arrive at the two slits with relative path lengths that may differ by more than a wavelength, thereby randomly shifting and washing out any interference pattern. Furthermore, their source of entangled photons was very inefficient and noisy. Only about 1 in 10^{10} pump photons produced an entangled pair, while many unentangled "noise" photons of the same wavelength were created by fluorescence in the crystal. Therefore, even if the coincidence requirement had been in principle removable (see below), it is not surprising that coincidences were required to observe the reported effects.
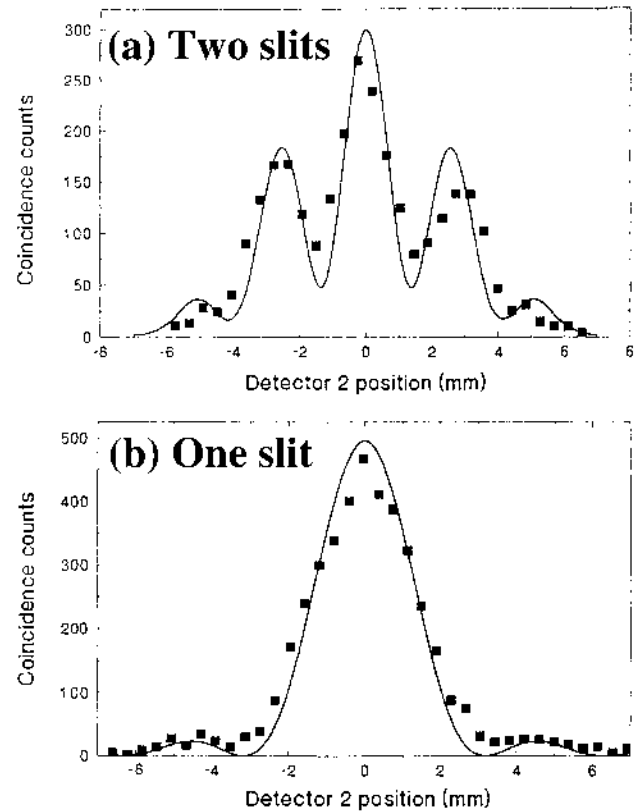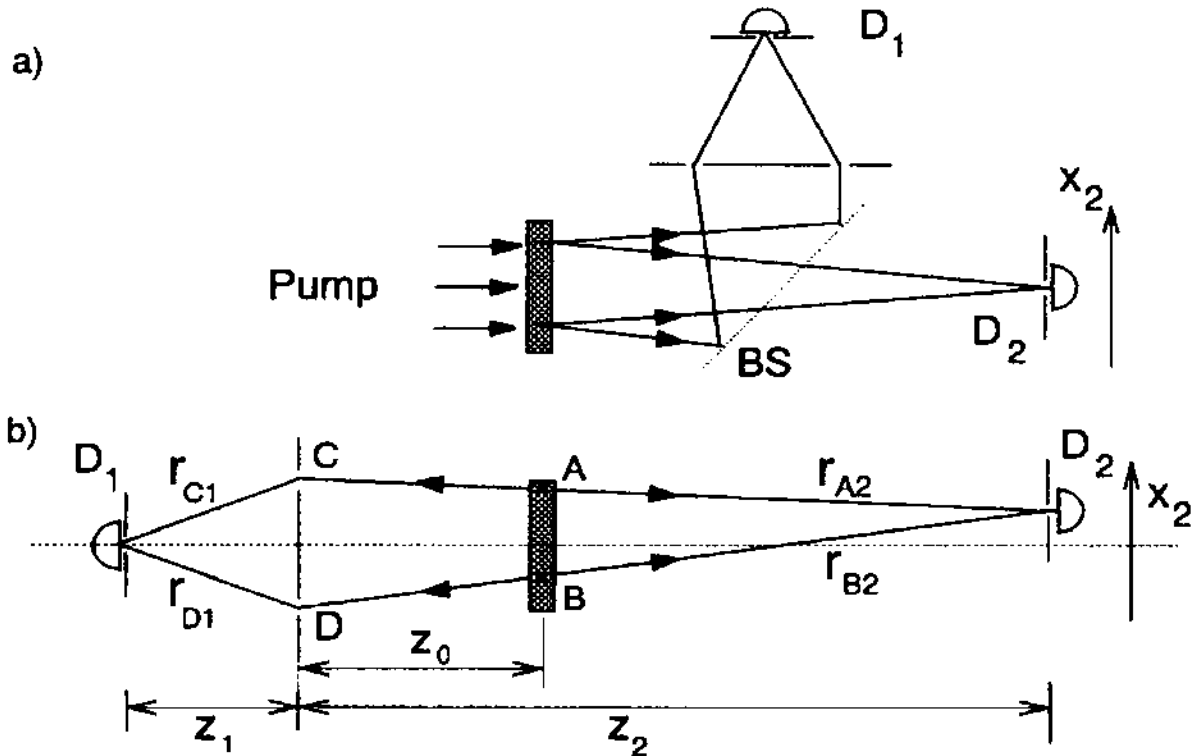
Figure 4. "Unfolding" the Ghost Interference Experiment

The authors point out that there is a simple way of thinking about momentum-entanglement measurements involving entangled photons. It can be shown from Snell's Law and conservation of momentum in the crystal that if one photon has a small momentum that causes it to be slightly deflected to the right of the pump beam by an angle θ, then the twin entangled photon will be deflected to the left by the same angle θ, a situation reminiscent of reflection from a mirror. This allows the experiment to be "unfolded" by replacing the effective reflection by a straight-through path, as shown in Figure 4. The point of the unfolding is that the entangled photons behave exactly as would be the case if the direction of the deflected photon was reversed, so that it originated at the detection point D_1, passed through one or two slits at **C** and **D**, and produced a one or two slit interference pattern at X_2 detected by D_2.

Why is the coincidence needed? First, it should be clear from Figure 2 that detector D_2 detects not only the entangled twins of the photons that pass through the slit openings, but also the entangled twins of the much larger number of photons that are stopped by the opaque parts of the slits. Therefore, without coincidences, no interference pattern could possibly be observed at X_2. Moreover, one can see from Figure 4b that detector D_1 behind the slits receives light in a very localized region, and if it were moved vertically in the diagram, the interference pattern at D_2 would be shifted, with maxima becoming minima and vice versa. Without coincidences requiring a particular location for the detection at D_1, the D_2 distribution would have to average over all possible D_1 positions, washing out the two-slit interference pattern. Therefore, because of the geometry used, the Ghost Interference experiment required a coincidence to observe a two-slit interference pattern like the one shown in Figure 3a.

Another momentum-entangled EPR experiment was the 1998 Ph.D. thesis of Birgit Dopfer (Reference 17) performed at the University of Innsbruck and shown schematically in Figure 5. In the Dopfer experiment, moving a detector in one arm nonlocally changes the observed interference pattern in the other arm. Dopfer used 351-nm UV pump radiation from an argon-ion laser with Type I down-conversion in a nonlinear $LiIO_3$ crystal cut with the optic axis at 90° to the pump beam to produce a pair of 702-nm momentum-entangled photons that emerged from the crystal at angles of 28.2° to the right and left of the pump axis, as shown in Figure 5.
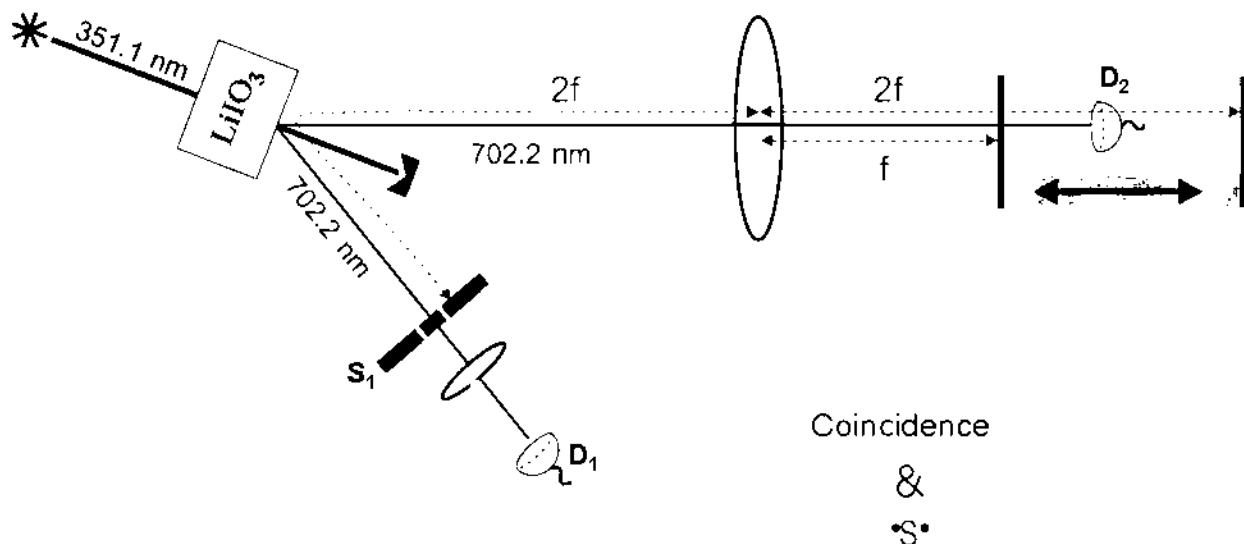

Figure 5. Schematic of the 1998 Dopfer Experiment (Reference 17)

The lower entangled photon passed through a pair of slits and into a detector, while the upper photon passed through a lens that could image the two slits to perform a "which-way" measurement if detector D_2 was placed two focal lengths behind the lens (2f). However, if detector D_2 was placed in a position one focal length behind the lens (f), the slits were not imaged, and light on the reflected line passing through either slit could reach the detector at the same points, producing a result similar to that of the Ghost Interference experiment. A structured two-slit interference pattern could be switched on and off by moving a detector in the other arm of the experiment between the **f** and **2f** positions.

Again, from the viewpoint of nonlocal communication, it is noted that moving detector D_2, which can be thought of as the action of a "sending" observer, nonlocally causes an observable change in the position distribution of the second photon, as detected at "receiver" position D_1. However, the Dopfer experiment does not demonstrate nonlocal communication because, like the Ghost Interference experiment, it requires a classical communication link to impose the coincidence requirement between the detected photons because of the geometry of the experiment.

Examination of these two experiments raises a very interesting question: Can the coincidence requirement be removed? The answer is not clear. In principle, the two entangled photons are connected by nonlocality whether they are detected in coincidence or not. The coincidence should therefore be removable. However, in both experiments the authors report that *no* two-slit interference distribution is observed

9

when the coincidence requirement is relaxed. This may be explained by the action of coherence-entanglement complementarity, as discussed in the next section.

V. Coherence-Entanglement Complementarity

As discussed above, the finite extent of the source is expected to limit the possibility of observing a two-slit interference pattern, which would be the "signal" if nonlocal communication were possible. Figure 6 shows schematically (not to scale) this "thick source" effect. The source volume on the left is the region of the nonlinear crystal that is illuminated by the UV pump-laser beam directed along the **u** axis. The source volume is a cylinder a few mm thick and a mm or so in radius with a center point **C**. The source cylinder is assumed to be tilted at an angle θ with respect to the horizontal **z** axis on which the slit system and detector plane are symmetrically centered. We note that $\theta = 0°$ in the Ghost Interference experiment and $\theta = 28.2°$ in the Dopfer experiment. A horizontal distance L_{xs} away from the source is a two-slit system, a pair of apertures **a** with center-to-center separation **d**. Light passing through the slit system travels a horizontal distance L_{sd} and is detected at detector plane at position x_1.
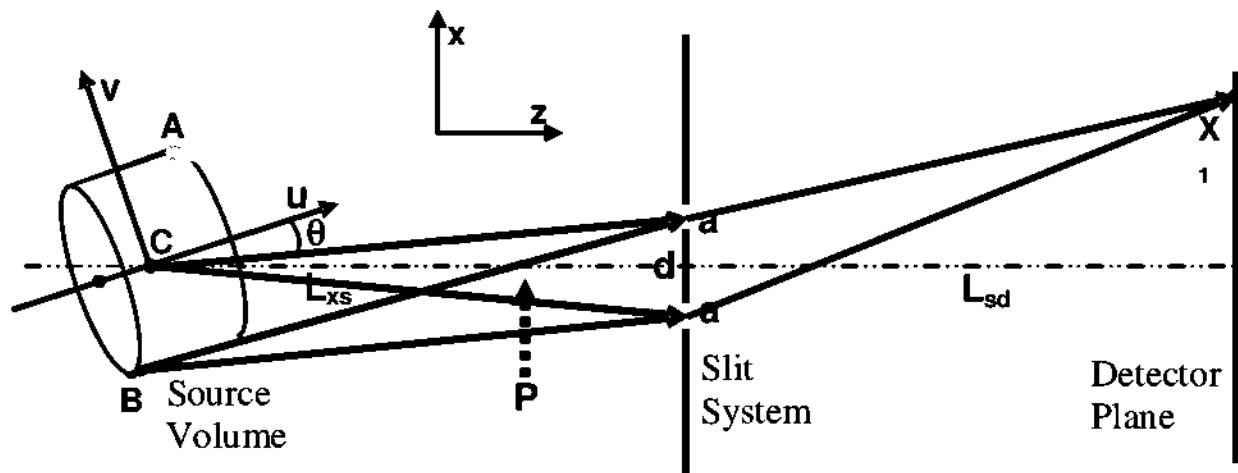

Figure 6. Thick-Source Effect (not to scale): Waves arriving at the two slits from points **A** and **B** at the extrema of the source volume may have significant path length and phase differences, while waves from the central point **C** are in phase at the slits.

If the point of photon production is off the **z** axis, there will be a path length difference between waves relative to **C** as they arrive at the two slits. In Figure 6, waves from points **A** and **B** could have path length differences greater that half a wavelength and phase differences greater than 180°. Roughly speaking, this shifts the interference pattern relative to waves created at central point **C** so that maxima become minima and vice versa. The net effect of averaging over all points in the source volume would therefore be to wash out the two-slit interference pattern. That two-slit interference pattern must be observed unambiguously, because it is the "signal" that would be used in any nonlocal communication. This operability is quantified by an observable called "visibility," which is related to the peak-to-valley ratio of the interference pattern.

The constancy of the relative phase at the two slits for photons arriving from various parts of the source is called "coherence" and ensures a high visibility. It should be clear that a point-like source has perfect coherence, while a source with a large solid angle as

10

viewed from the slits will have reduced coherence. The path length difference at the slits is, to a good approximation, inversely proportional to L_{xs}. Therefore, making L_{xs} large—that is, placing the slits some distance from the source volume—can reduce the path length differences to a value that increases coherence and allows observation of a sharp two-slit interference pattern signal at detector D_1. Alternatively, placing a thin, double-concave diverging lens at point **P** of Figure 6 can have the same effect by causing the shorter path lengths to pass through a greater thickness of lens glass. Such a lens would also demagnify the source, producing the equivalent of a longer path length and smaller source solid angle.

However, increasing source coherence has another consequence. The momentum entanglement of photons from the source arises from momentum conservation. Restricting the solid angle of the source, as viewed from the slits, means fewer photon pairs can be entangled and still satisfy the geometrical constraints of the experimental configuration. The Saleh group at Boston University has shown that there is a complementary relation between source coherence and two-photon entanglement (Reference 18). As the source-slit distance L_{xs} is increased, there are smooth transitions from one-slit to two-slit interference patterns and from a highly entangled source to a highly coherent source. We note, as mentioned above, that the parametric down-conversion technology used in the Ghost Interference and Dopfer experiments was fairly inefficient and noisy, with fairly improbable production of entangled pairs competing with much more probable production of unentangled "noise" photons of the same wavelength from pumped fluorescence in the crystal. This would tend to limit the entanglement of the source.

Nonlocal communication using momentum entanglement requires source coherence. Source coherence is needed in order to observe the "signal" of a two-slit interference pattern and two-photon entanglement so that a measurement of one of the photons "connects" with the interference pattern produced by the other photon. Where there is coherence without entanglement or entanglement without coherence, nonlocal communication with momentum-entangled photons is not possible. An unresolved issue that requires further theoretical consideration and experimental testing is whether there is a "sweet spot" in the experimental design that embraces both partial coherence and partial entanglement and that permits the transmission of nonlocal signals.

VI. Nonlocal Communication Versus Signaling

The possibility of nonlocal communication is an unresolved issue. It is perhaps likely that the coherence-versus-entanglement tradeoff is nature's way of preventing nonlocal signaling, but that has not been demonstrated. In this section, we assume that nonlocal signaling is possible and will examine its implications. As will be seen, they are so far reaching that they could be taken as a strong indication that nature would not allow such things and therefore nonlocal signaling must be impossible.

Figure 7 shows a variation of the Ghost Interference experiment (Reference 16) in which the slit-imaging technique of the Dopfer experiment (Reference 17) is used to ensure that entangled photon pairs passing through slits reach both detectors, and that those intercepted by the opaque regions of the slits reach neither detector. In particular, a lens of focal length **f** is placed in the path after the BBO crystal and before the polarization splitter so that both entangled photons pass through this lens. A pair of slits S_1 is placed at a path distance **f** beyond the lens in the path of the "o" photons,

11

which are linearly polarized horizontally (HLP) and are transmitted by the splitter. As Dopfer has shown, because of momentum entanglement, an image of slit system S_1 will be formed by the "e" photons linearly polarized vertically (VLP) at a path length **f** beyond the lens on the deflected path at position S_2, where a pair of "cleanup" slits are located that pass only those photons whose entangled twins passed through S_1. We note that because of the optical geometry, this imaging occurs even for waves that pass through both of the image points and ultimately interfere.
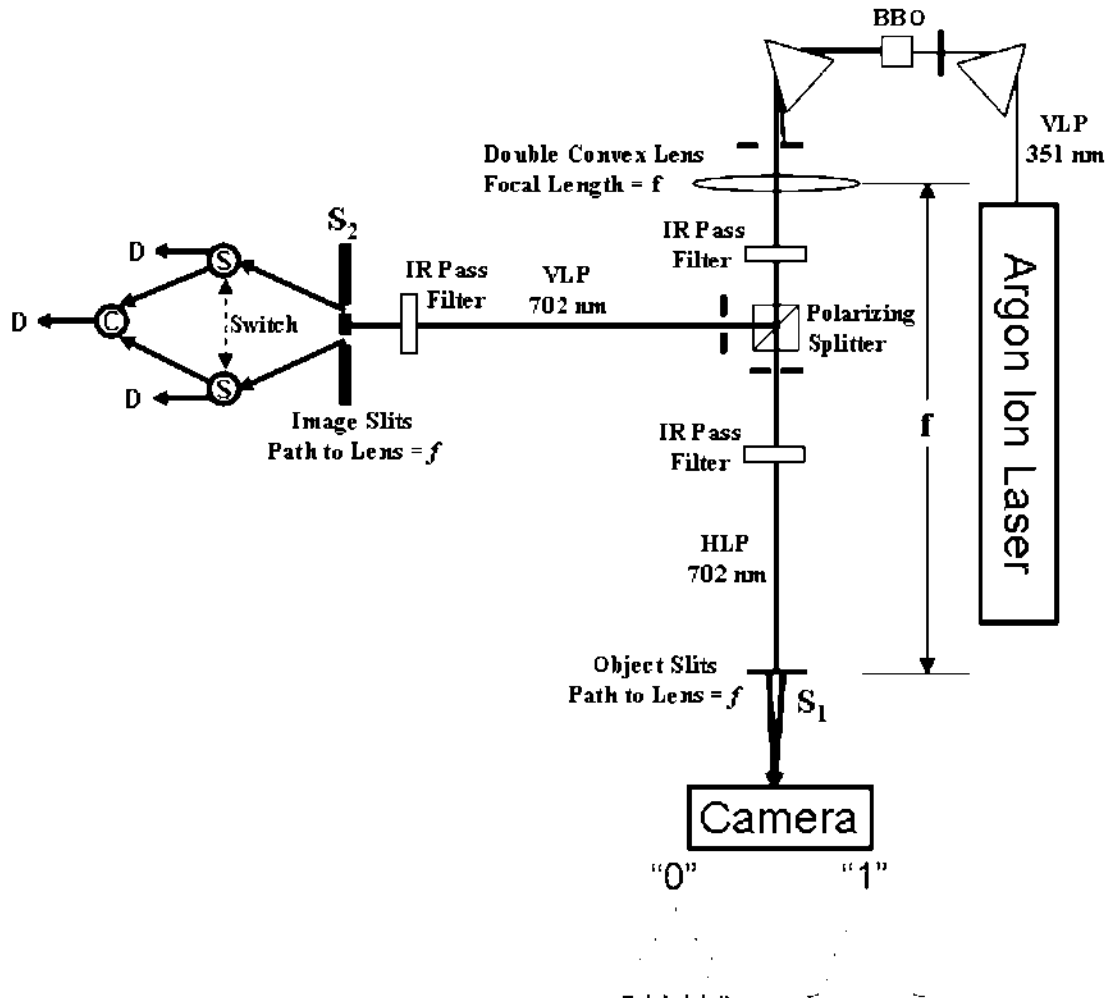

Figure 7. Slit-Imaging Coincidence-Free Version of the Ghost Interference Experiment to Demonstrate Nonlocal Communication

At the image position of each slit at S_2, we place an optical fiber, as shown. The fibers conduct the light to an optical switch, at which the light either is sent directly to two avalanche photodiode detectors **D** (providing which-way information about which of the S_1 slits the photon entered) or alternatively is routed to an optical combiner **C**, with the in-phase output of the combiner then detected, so that waves passing through both slits can contribute constructively to the detection event. We note that this fiber switching system is the fiber-optic equivalent of a Mach-Zehnder interferometer (Reference 20), in which one can activate and deactivate the last half-silvered mirror by switching, so that which-way information can be switched on and off. (We also note that similar fiber-combiner-detector technology could be employed after the S_1 slits to

determine the presence or absence of coherent interference, but this will not be considered further here.)

A quantum sensitive cooled CCD camera is substituted for detector D_1 of the Ghost Interference experiment (Reference 11) and is set to measure distributions like those shown in Figure 3. In the arrangement in Figure 7, switching the optical fiber routing can be considered an act of transmitting a binary 0 or 1 signal. If the switch is in the position leading to the outer detectors, then which-way information is available, and the pattern detected by the camera should be a single-slit diffraction pattern labeled "1" in Figure 7. If the switch is in the position leading to the combiner and middle detector, waves from both slits contribute to the detection, no which-way information is available, and the pattern detected by the camera should be the two-slit interference pattern labeled "0" in Figure 7.

If the pattern observed by the camera can indeed be changed by switching the optical fiber routing, then this would constitute a direct demonstration on nonlocal communication. Such an observation would falsify the no-signal theorems mentioned above, which require that in a noncoincidence scenario, no action on one entangled photon can produce a "signal-capable" observable result at the detection of the other entangled photon of the pair.

It should be emphasized that demonstrating nonlocal communication with momentum-entangled photons, as described above, is not the same as actually sending a signal. It should be clear that no real signal can be communicated with a single photon pair. Only when multiple photons are detected can the underlying distribution function become apparent. One can estimate that if the distribution functions to be distinguished are a "pure" two-slit interference pattern modulated by a diffraction envelope and a "pure" two-slit diffraction pattern, then about 10 photon detections would be required for a 3σ decision between these two possibilities.

However, as mentioned in the previous section, it is likely that if nonlocal communication is possible at all, it would have to be accomplished in a situation where some compromise between entanglement and coherence has been achieved, and such a compromise would inevitably cause the two patterns to be distinguished to be more similar and more difficult to separate. Therefore, the 10 photon detections cited above must be taken as a rather optimistic lower limit, and it is likely that a significantly larger number of detections (perhaps ~100 or more) would be required. The time required to send a single bit of information would then be the product of the photon detection rate in the two arms of the experiment times the number of photons that must be detected to receive the signal. In principle, such a transmission rate might be improved (and fluorescence noise suppressed) by pulsing the pump laser, so that "clusters" of entangled photons would be received with each such pulse.

VII. A Transactional Analysis of the Nonlocal Communication Test

Now the transactional interpretation of quantum mechanics (Reference 19) to analyze the system described above is used. The transactional interpretation describes the formation of a quantum event as a three-stage process: (1) sending retarded "offer" waves (ψ) from emission location(s), (2) back-in-time responses from the reception location(s) of advanced "confirmation" waves ($\psi*$), and (3) the formation of a space-

time standing wave ($\psi\psi*$) between the locations (for example, a photon source and a photon detector). After an initial exchange of offer and confirmation waves, a particular transaction is selected probabilistically from all that are possible, based on the $\psi\psi*$ values of the alternatives. The offer/confirmation exchange continues until all the conserved quantities (energy, momentum, angular momentum, and so forth) have been transferred.

For the nonlocal communication test system described above, we will consider two cases:

- **Case 1:** The switch is positioned so that each fiber from the slits is routed to one detector, producing a "which-way" measurement of the slit through which the VLP photon passed. In this case, the HLP photon as detected by the camera should have a recorded position that falls on a broad single-slit-diffraction-pattern distribution, (*not* a two-slit interference pattern).

- **Case 2:** The switch is positioned so that light from the two fibers is combined before detection. Therefore, the detection produces no information on the path of VLP photon, which could have passed through either slit. In this case, the HLP photon detected by the camera should be in a position that falls on a two-slit interference pattern distribution.

Figure 8 shows the transaction that forms for the nonlocal communication test system in the Case 1 configuration. Here, as in the Ghost Interference experiment, we have treated the nonlinear crystal source of entangled pairs as an effective "reflector" and have represented the rays with straight-through paths to "unfold" the system, duplicating the lens for each photon and representing the system as two-lens optical imaging, with nearly parallel rays between the two lenses. Slit systems S_1 and S_2 are located one focal length **f** away from the lenses. The left-going photon is assumed to arrive at the upper slit of S_2 and to be detected by the upper detector (circled). The momentum-entangled right-going photon must then go to S_1, which is the optical image of S_2, and be diffracted by the slit and detected by the camera. If Figure 8 were vertically inverted, it would provide a similar diagram for the equally probable arrival of the left-going photon at the lower slit of S_2 and detection by the lower detector. The three stages of transaction formation are shown.
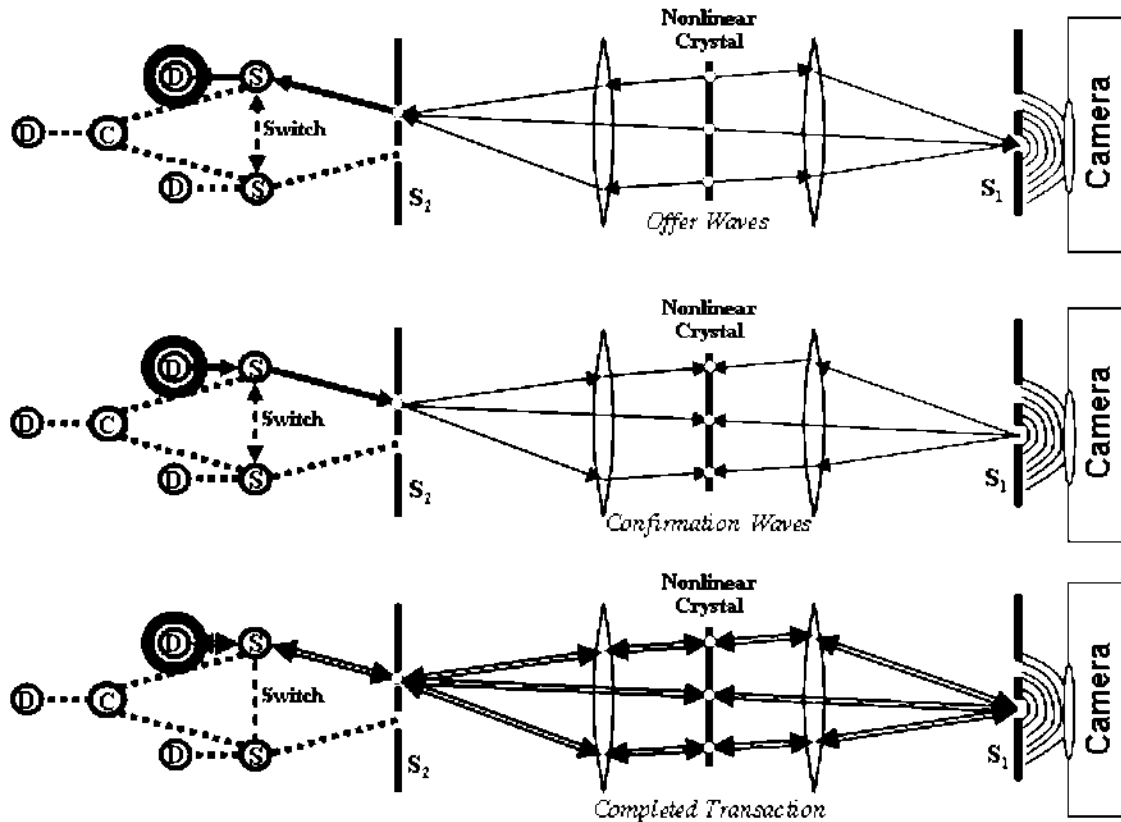
Figure 8. Transactional Interpretation Diagrams for Case 1. The left-going offer waves pass through the upper slit of S_2 and reach the upper detector (circled). The momentum-entangled right-going offer waves pass only through the lower slit of S_1, which is the optical image of upper S_2, and are diffracted to the camera. Confirmation waves return, and the one-slit transaction forms.

Figure 9 shows the transaction that forms for the nonlocal communication test system in the Case 2 configuration. The left-going photon passes through both the upper and lower slits of S_2. The two paths connect to a combiner and are detected by the central detector (circled). The momentum-entangled right-going photon must then also pass through both slits of S_1, which are the optical images of S_2, to form a two-slit interference pattern detected by the camera. The three stages of transaction formation are shown.
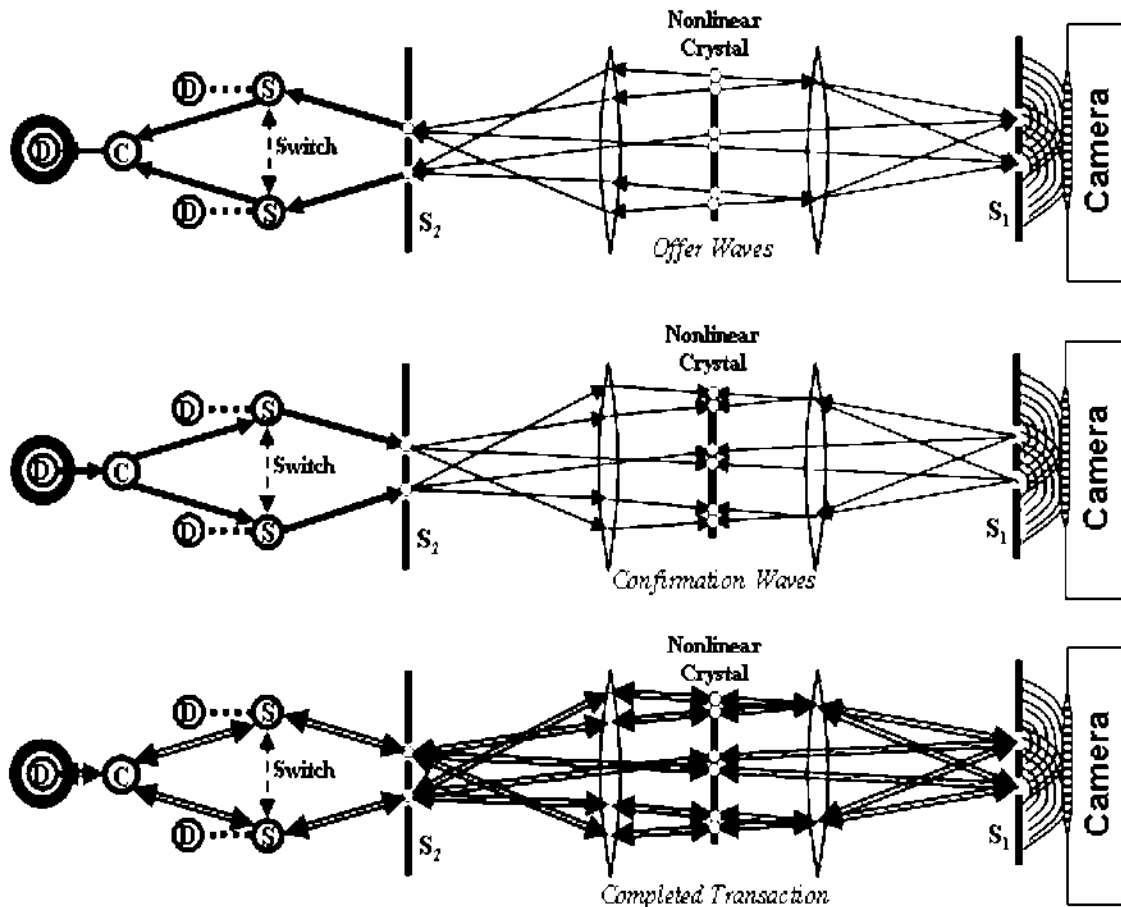
Figure 9. Transactional Interpretation Diagrams for Case 2. The left-going offer waves pass through both slits of S_2, where the waves are combined and detected by the center detector (circled). The momentum-entangled right-going offer waves pass through the both slits of S_1, which are the optical images of S_2, and interfere at the camera. Confirmation waves return, and the two-slit transaction forms.

Therefore, from the point of view of the transactional interpretation of quantum mechanics (Reference 19), the nonlocal connection between detection events at the two ends of the experiment arises because the detection transactions for the two entangled photons must share a "two-way handshake" at the nonlinear crystal, a condition that can be realized only when the summed vector momenta of the two photons equals that of the pump-laser photon that created them. This view explains Dopfer's observations (Reference 19) and indicates that, in the absence of overwhelming noise or restrictions imposed by coherence/entanglement complementarity, no coincidence should be required between the two detectors in the experiment to observe that change in the pattern observed at D_1 when detector D_2 is moved. This remains true in the configurations discussed below, when slit S_2 is lengthened with many kilometers of fiber-optic light transmission cable to enable superluminal and retrocausal signal transmission. In other words, analysis of the nonlocal communication test system with the transactional interpretation reveals no "show-stopper" aspects that would prevent superluminal and retro-causal signal transmission. The transactional interpretation is neutral on whether such signals are possible.

VIII. Superluminal and Retrocausal Nonlocal Communication

As mentioned in the previous section, we will assume for the sake of discussion that nonlocal signaling is possible and will consider its implications for the speed of transmission of signals. For definiteness, schemes for doing this are based on the slit-imaging coincidence-free version of the Ghost Interference experiment described above and shown in Figure 7. In that system, the instant at which a nonlocal signal is sent is the arrival of the VLP photon at the fiber-optic system on the left, and the instant at which the signal is received is the arrival of the HLP photon at the camera at the bottom of the diagram. Assuming the workability of this scheme, both the instants of sending and of receiving can be delayed, in principle, by the introduction of delay paths—for example, runs of fiber-optic cables—in the system.

In particular, the "send" instant could be made to occur well *after* the "receive" instant in the system, constituting a direct demonstration of retrocausal signaling. This is shown in Figure 10. Here the cleanup two-slit system S_2 becomes the entrance for two 10-km-long runs of fiber-optics that are carefully matched to have identical exit phases at S_3, the end of the fiber runs where the light enters the optical switching arrangement described above. If the index of refraction of the fiber is 1.5, light transiting the 10-km path requires about 50 μs. In the presence of detection noise or the degradation of pattern visibility because of compromises between entanglement and coherence, considerably more photon detection events—say 100—might be required.
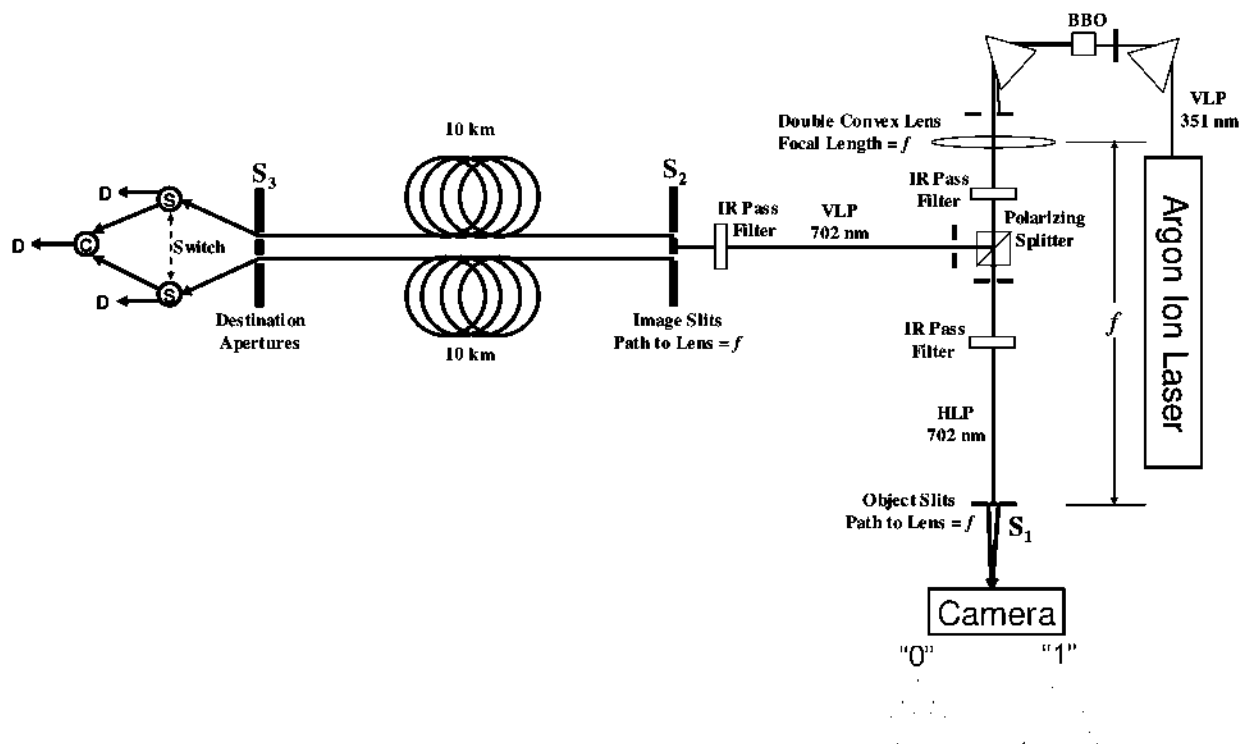

Figure 10. Slit-Imaging Coincidence-Free Version of the Ghost Interference Experiment Demonstrating Superluminal and Retrocausal Signaling

Assume then that the fiber coils of Figure 10 remain rolled up and stored in a corner of the laboratory and that the source can be made strong enough so that the average rate at which the entangled photon pairs are detected is 10 MHz (which would correspond to the efficient detection of about 3 nW of 702-nm photons). This would require a source of entangled photons considerably stronger than is achievable with the "bulk" BBO or $LiIO_3$ crystals used in the Ghost Interference and Dopfer experiments, which produce a usable entangled photon pair from only about 1 in 10^{10} pump photons.

Fortunately, a recently emerging technology makes the production of entangled photon pairs much more efficient through the use of "periodically poled" nonlinear crystals. In "bulk" nonlinear crystal there is a "walk-out" phenomenon that limits the distance within the crystal over which phase matching holds, permitting entangled pairs to be produced efficiently by down-conversion. However, nonlinear crystals like potassium titanyl phosphate ($KTiOPO_4$ or KTP) have very large nonlinear coefficients and are also ferroelectric, with a large electric dipole moment. By using a large pulsed electric field during crystal production, one can "write" on KTP crystals to change the orientation of their local dipole moment over small distances (a few tens of wavelengths) periodically along the pump direction through the crystal, so that the phase drift regularly reverses and cancels out as the pump radiation progresses through the crystal. This is called "periodic poling." With this kind of crystal, the walk-out is suppressed, and one can use very long crystals that efficiently produce entangled pairs of photons over their entire length. The IQOQI group of Anton Zeilinger in Vienna, using a periodically polled KTP crystal 25-mm long, has measured the entangled pair production rate at 2.73×10^5 pairs per second per mW of pump radiation per nm of wavelength[20]. Such a source should be easily able to produce the 10-MHz detection rate assumed above.

Now consider that the "sending" detector system and the "receiving" camera are in the same room and separated by a distance of 1 meter or less. If the switch is set on the 0 or 1 position, the "message" that it is in that position begins to arrive at the camera 50 μs *before* the switch position is moved. If 100 photon counts constitute a signal, then, even allowing for the latency in signal reception, the message could be received 40 μs *before* it was sent. This would be a direct demonstration of retrocausal signaling using nonlocal communication and would constitute a direct violation of the principle of causality.

IX. Paradoxes and Nonlocal Communication

The setup described above, with its retrocausal communication link, raises some time-communication paradoxes. First, let us consider the issue of "bilking." Suppose we construct a million linked systems of the type shown in Figure 10 (or use 10^7 km of nonattenuating fiber). Then the transmitted message would be received 40 seconds before it was sent. Now suppose a tricky observer receives a message from himself 40 seconds in the future and then decides not to send it. This produces an inconsistent timelike loop, which has come to be known as a "bilking paradox." Could this happen? If not, what would prevent it?

There are discussions of such bilking paradoxes in the physics literature by Wheeler and Feynman (Reference 22), who were considering the retrocausal aspects of the advanced waves of absorber theory, and by Kip Thorne and colleagues (Reference 23), who were considering the paradoxes that might arise from timelike wormholes. The general consensus of both groups is that nature will forbid it and will require a consistent set of

conditions. Thorne and coworkers showed that "nearby" to any inconsistent paradoxical situation involving timelike wormholes there is always a self-consistent situation that does not involve a paradox. As Sherlock Holmes said, "When the impossible is eliminated, whatever remains, however improbable, must be the truth." These speculations assert that equipment failure producing a consistent sequence of events is more likely than producing an inconsistency between the send and receive events. The implications of this are that bilking itself is impossible, but very improbable events could perhaps be produced in avoiding it.

The other issue raised by retrocausal signaling might be called the "immaculate conception" paradox. Suppose you are using the setup described above, and you receive from yourself in the future the manuscript of a best-selling novel with your name listed as the author. You sell it to a publisher and become rich and famous. And when the time subsequently comes for transmission, you duly send the manuscript back to yourself, thereby closing the timelike loop and producing a completely consistent set of events. But the question is, Just who wrote the novel? Clearly, you did not; you merely passed it along to yourself. Yet highly structured information (the novel) has been created out of nothing. And in this case, nature should not object, because there was no bilking, and you produced no inconsistent timelike loops.

It is not known how to resolve either of these paradoxes. Here are a few possibilities:

- If nonlocal signaling is impossible, then the paradoxes need no resolution, but better, more "air-tight" proofs of the impossibility of nonlocal signaling would be needed.

- If nonlocal signaling is possible and can be used to form timelike loops, then paradoxes become important subjects for further experimental testing, study, and theoretical treatment.

- As suggested by Stephen Hawking (Reference 24), perhaps nature "abhors" timelike loops, so that if one is about to be created, quantum vacuum fluctuations will grow without limit and destroy the apparatus that is attempting to produce the loop. Even in this case, use of nonlocal signaling might still be possible, provided timelike loops were carefully avoided in such systems. (See below.)

X. Superluminal Communication Without Paradoxes

One path to avoid the retrocausal paradoxes outlined above would be to make sure there were no timelike loops in the communication system. This can be achieved by careful arrangement of the propagation delays in the sending and receiving ends of the hypothetical nonlocal communication.

Consider the space-time interval **s**, as defined by the equation: $s^2 = x^2 - (ct)^2$, where **x** is the spatial distance separating two events (for example, send and receive), **t** is their separation in time, and **c** is the speed of light. A positive value of s^2 means the interval is spacelike and $s=0$ is a lightlike interval, and a negative value of s^2 means the interval is timelike. The interval s is a Lorentz-invariant quantity that, in particular, retains its sign independent of the choice of inertial reference frame from which the two events are viewed.

As long as the nonlocal communication system is arranged so that the space-time interval between the sender and the receiver is always separated by a spacelike or

19

lightlike interval, and in particular is never separated by a timelike interval that can go backwards down the time stream, then timelike loops are avoided, along with the paradoxes they imply.

Figure 11 shows such a system. Entangled photons in the two arms of the system are propagated through fiber-optic cables of equal length. Therefore, in the reference frame of the system, the send and receive events are simultaneous, and, aside from the latency associated with the reception of enough photons to establish the reception of a signal bit, the communication is instantaneous but does not create a timelike loop.
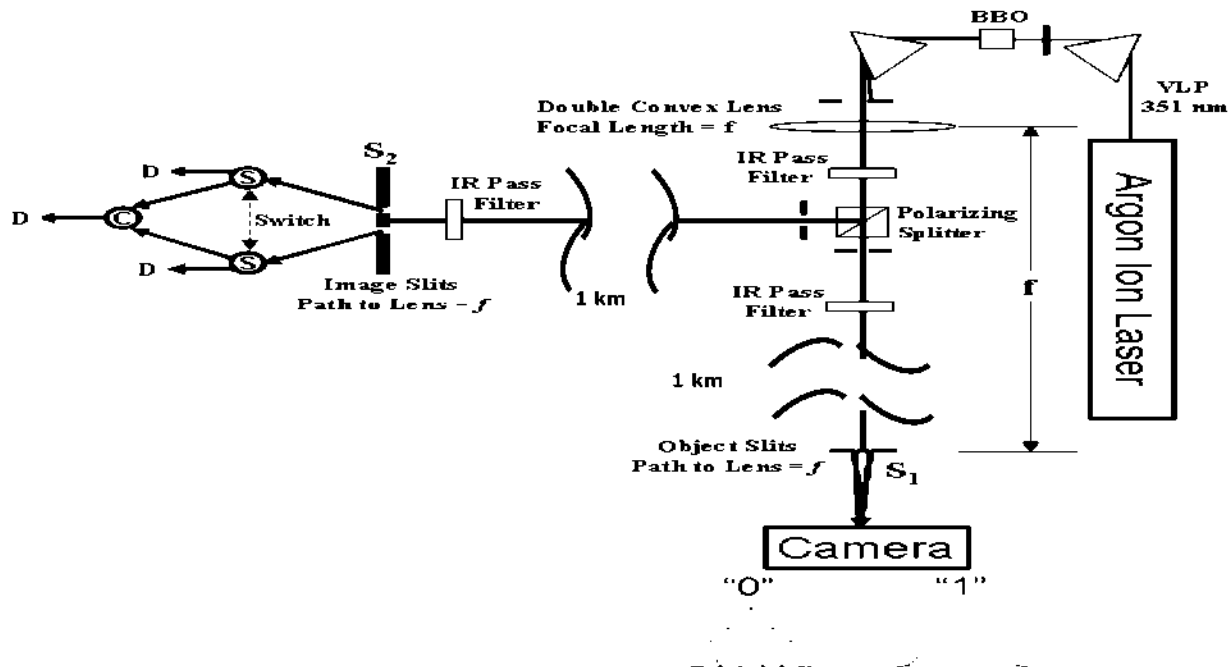

Figure 11. A Superluminal Nonlocal Communication System in Which the Communication Spans a Spacelike Interval

XI. Example: Real-Time Earth Control of Mars Rover

Now consider the application of a "rover" operated at interplanetary distances, with nonlocal communications used to provide real-time "virtual reality" control of the mobile device. Figure 12 shows a schematic of the Earth-based operation of a Mars rover. A base station on Mars would contain a high-intensity source of entangled photon pairs. One stream of photons from the entangled pairs, after passing through image slits, would be transmitted from the probe to an Earth control station, allowing a nonlocal signal to be "sent" from the control station by a time sequence of choices of whether to detect the stream of arriving photons as waves or particles. The other stream of photons from the entangled pairs, after passing through object slits, would be detected locally at the Mars base station near the source and analyzed for the presence or absence of an interference pattern, thereby "receiving" the nonlocal signal as a logical "0" or "1," respectively.
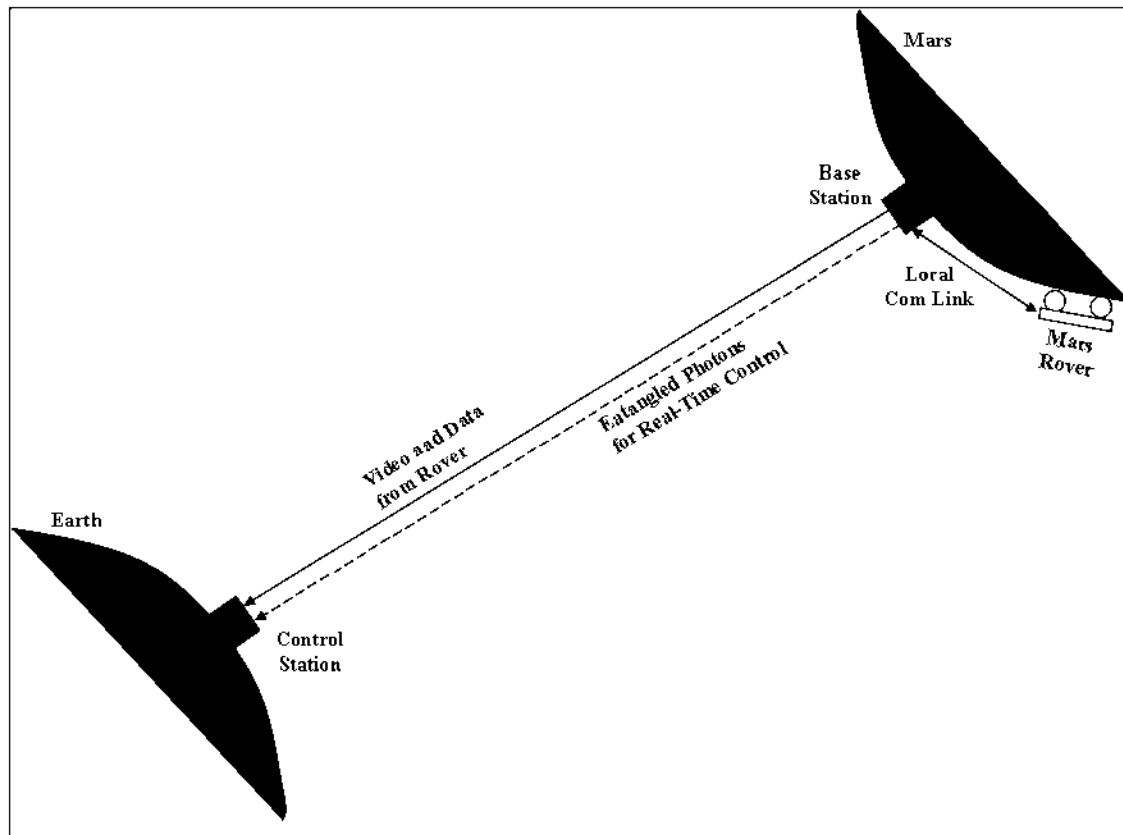
Figure 12. Schematic of Earth-to-Mars Real-Time Control of a Rover

In order to avoid having to transmit two streams of entangled photons, the equivalent of the two fiber-optic links in Figure 10, at the base station the photons from one image slit would be polarized horizontally and those the other slit would be polarized vertically before transmission. Then, at the Earth control station, detection of the polarization of photons in the stream would constitute "particle" measurements, while separating, rotating to the same polarization state, and recombining the waves so that they could interfere before detection would constitute a "wave" measurement.

In parallel with this nonlocal link, a conventional microwave or optical link would be used to communicate video images and other data to the Earth station. The video images and data would experience a propagation delay equal to the transmission distance divided by the speed of light, and would arrive at the Earth station seconds, minutes, or hours after they were transmitted. The entangled photons would experience the same delay, but the nonlocal control signal would be sent backwards up the time stream, arriving at the probe at the instant the video signals and data were being transmitted, so that the nonlocal signal could steer and control the probe in real time, and an Earth-based operator could "drive" the rover on Mars using virtual-reality techniques. One can imagine driving the Mars Rover around the planet, actively steering around obstacles, activating analysis instruments in real time as interesting objects were found, and actively controlling repair equipment to deal with problems that arise.

Such a communication loop (conventional + nonlocal) would be a light-like loop, with the two-way send and receive points located on the light cone. As such, it would not

lead to any causality problems or paradoxes but would bring the remote parts of the solar system and perhaps the universe to the here and now.

XII. Another Superluminal Possibility: Nonlinear Quantum Mechanics

Thus far, the focus has been on the possibility of nonlocal communication within the framework of standard quantum mechanics. However, even if nonlocal communication proves impossible in standard quantum mechanics, there could be another path to nonlocal communication.

The no-signal theorems described in Part III above are based on the formalism of standard quantum mechanics. Such "proofs" become invalid if quantum mechanics is allowed to be slightly "nonlinear," 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 that introduces small, nonlinear terms to standard quantum mechanics (Reference 25). The onset of nonlinear behavior is seen in other areas of physics—for example, laser light in certain media—and, he suggested, might also be present but unnoticed in quantum mechanics itself. Weinberg's nonlinear quantum mechanics subtly alters certain properties of the standard theory, producing new physical effects that can be detected through precise measurements.

Two years after Weinberg's nonlinear quantum mechanics theory was published, Joseph Polchinski published a paper demonstrating that Weinberg's nonlinear corrections upset the balance in quantum mechanics that prevents superluminal communication using EPR experiments (Reference 26). Through the new nonlinear 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 Interpretation's representation of the wave function as "observer knowledge." Polchinski has shown that a tiny nonlinear 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 Interpretation's "knowledge" interpretation.

Weinberg's experimental predictions have led to a large number of experimental tests that have searched for the predicted effects. Regrettably, all such experimental attempts to observe the nonlinear effects have failed, producing only very low upper limits. Apparently, if there are nonlinear effects that modify the quantum formalism, they are extremely small in Earth-based laboratories. 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 nonlinear properties, they would be expected to depend on mass-energy and to appear only at a very high energy scale, particularly at the highest energy densities or in very high gravitational fields. In the everyday world of weak gravity and fairly flat space, this path to nonlocal communication appears to be blocked, because the "vehicle" for sending the signal is not observable.

22

However, emerging from work on quantum gravity offers the possibility of an explicitly nonlinear form of quantum mechanics that reduces to linear quantum mechanics in the limiting case of weak or no gravity. Using the wave picture, it is possible to formulate a Laplace-Beltrami wave equation for gravitationally curved space. The Laplace-Beltrami operator on the left-hand side contains information about the space-time geometry (the metric tensor) and operates on the wave function. On the right-hand side is the same term found in the flat space Klein-Gordon wave equation. In flat space (no gravity), this "curved-space" wave equation reduces to the Klein-Gordon wave equation, but in curved space it is nonlinear in a way that could facilitate nonlocal communication. Thus, in an environment where strong space curvature is expected—for example, the vicinity of a neutron star or black hole—sufficient quantum nonlinearity may exist to facilitate nonlocal communication.

XIII. Conclusion

Ultimately, the question of whether nonlocal communication is possible is an experimental one. The issue should be resolvable by testing for nonlocal communication and observing what experimental limits appear. In particular, are the limits of coherence/entanglement complementarity so severe as to preclude signaling? Currently at least one experiment in progress aims to produce a coincidence-free version of the Ghost Interference experiment. We await the outcome of such tests.

Appendix: Glossary

Basis: In quantum mechanics, a choice of an observable quantity that may be complementary to another variable, so that both cannot be measured at the same time. An example is the choice of measuring position, which prevents the simultaneous measurement of momentum. In EPR experiments, one must choose a polarization basis (for example, linear polarization that may be either vertical or horizontal). Since both circular polarization and 45° left/right polarization are linear superpositions of vertical/horizontal polarization, they may not be measured simultaneously. In quantum mechanics, the measurement causes the wave function to collapse to a particular basis value, excluding other possible values.

Bell's Theorem: A mathematical proof by John S. Bell (Reference 8) demonstrating that in a polarization-based EPR experiment, the falloff of correlations as the basis angle of a polarization measurement is changed is qualitatively different, as predicted by local hidden-variable theories and by standard quantum mechanics. In particular, local hidden-variable theories predict a linear falloff, while quantum mechanics predicts a quadratic falloff. This difference in predictions is represented as an inequality in measurement intensity ratios that all local hidden variable theories must satisfy, while quantum mechanics does not. Tests of these predictions have been found to agree with quantum mechanics and to falsify local hidden-variable theories.

Bilking Paradox: A type of back-in-time communication paradox in which an inconsistent causal loop is created. A well-known example is the Grandmother Paradox, a time-travel scenario from science fiction in which a time traveler travels to the past and kills his grandmother before she had children. The question then arises, How could he have been born if his grandmother had no children? Several works in the physics literature (Reference 17, 18) have concluded that such trans-temporal bilking is impossible, that nature will not permit inconsistent timelike loops, and that it is more likely that some apparatus will fail than that a "bilk" of nature could be achieved.

Causality: The observation, which is regarded as a law of physics, that a cause must precede its effects as viewed in any and all reference frames. Sometimes referred to as "Cause and Effect" or "the Law of Cause and Effect."

Correlations: The mathematical connection between two variables or two measured quantities. As an example, in an EPR measurement, the basis polarization of one photon is selected, the basis polarization of the twin entangled photon is varied, and the coincidence counting rate versus varied angle is measured to establish the correlation between the two polarizations.

Coherence: Describes whether two waves (for example, those arriving at a pair of slits or at a detector) have a definite phase relation (in which case they are completely coherent), have a random phase relation (in which case they are completely incoherent), or have something in between.

Coherence-Entanglement Complementarity: The theoretical expectation and experimental observation (Reference 15) that perfect coherence and perfect entanglement cannot be achieved for an entangled pair of photons at the same time.

Coherent Superposition: The formation of a quantum mechanical state (for example, right circular polarization) by adding components of other states (for example, left and right polarization) with a definite complex phase between the added states.

Collapse: A quantum mechanical wave function is said to collapse to a particular basis value when a measurement is made in that basis. For example, if a photon is emitted isotropically (with equal probability in all directions), its wave function is distributed uniformly over a sphere with a radius that grows at the speed of light until it is detected. Upon detection, the photon's wave function is localized at the detection point and disappears everywhere else.

Entangled: The separated parts of the same quantum system are said to be entangled when each of the parts can be described only by referencing the state of other parts. This is one of the most counterintuitive aspects of quantum mechanics, because, classically, system parts out of "local" contact should be completely independent. Thus, entanglement represents a kind of quantum "connectedness" in which measurements on one isolated part of an entangled quantum system have nonclassical consequences for the outcome of measurements performed on other (possibly very distant) parts of the same system.

EPR Experiment: A class of experiments with entangled particles, usually photons, that demonstrate quantum nonlocality. A gedankenexperiment of this kind was first suggested in the famous 1936 paper by Einstein, Podolsky, and Rosen (Reference 4) in which a set of criticisms of quantum mechanics were presented.

Hidden Variable Theories: A set of alternatives to quantum mechanics intended to satisfy the objections of the EPR paper in which the uncertainty principle does not apply and a quantum system can simultaneously have definite values of complementary variables like position and momentum, provided one of these values is somehow "hidden." Hidden variable theories are usually also "local" (see below) to deal with Einstein's objection to the nonlocality of quantum mechanics.

Immaculate Conception Paradox: A type of back-in-time communication paradox in which a completely consistent causal loop produces information with no known origin. An example is the Book Paradox, in which an author receives a book in a message from the future. He publishes it, and when the time comes, he transmits the manuscript to himself in the past. The question then arises, Who wrote the book? In this case, no inconsistent timelike loops are involved, and the arguments against bilking (see above) do not apply in this case.

Locality: The assumption that the correlations between parts of a system can be established only while the subsystems are in contact (or speed-of-light communication), and that once out of such contact, no changes in such correlations are possible.

Nonlocality: The situation, apparently present in quantum mechanics, in which correlations between parts of a system can be established independent of the separation of the parts in time and space.

Retro-Causal: Situations in theory or in the real world where the effect precedes the cause, in violation of the principle of causality.

[1] S. J. Freedman and J. F. Clauser, Phys. Rev. Letters, **28,** 938-942 (1972).

[2] A. Aspect, J. Dalibard, and G. Roger, Phys. Rev. Letters, **49,** 91-95 (1982); A. Aspect, J. Dalibard, and G. Roger, Phys. Rev. Letters, **49,** 1804 (1982).

[3] Erwin Schrödinger, Proc. of Cambridge Philosophical Society, **31,** 555-563 (1935); **32,** 446-451 (1936).

[4] A. Einstein, B. Podolsky, and N. Rosen, Physical Review. **47,** 777-785 (1935).

[5] Jon P. Jarrett, Noûs, **18,** 569 (1984).

[6] Abner Shimony, **Quantum Concepts in Space and Time,** R. Penrose and C. J. Isham, eds., Chapter 12, pp. 182-203, Clarendon Press, Oxford (1986).

[7] C. S. Wu and I. Shanknov, Phys. Rev., **77,** 136 (1950).

[8] J. S. Bell, Physics, Vol. 1, 195 (1964); Rev. of Modern Physics, **38,** 447 (1966).

[9] W. Tittel, J. Brendel, H. Zbinden, and N. Gisin, Phys. Rev. Letters, **81,** 3563-3566 (1998).

[10] Anthony J. Leggett, Foundations of Physics **33,** 1469 (2003)

[11] S. Gröblacher, T. Paterek, R. Kaltenbaek, C. Brukner, M. Zukowski, M. Aspelmeyer, and A. Zeilinger, "An experimental test of non-local realism," Nature **446,** 871-875 (2007).

[12] Heinz Pagels, **The Cosmic Code,** Simon & Schuster, NY (1982).

[13] P. H. Eberhard, Nuovo Cimento B **38,** 75 (1977), ibid. B **46,** 392 (1978); G. C. Ghirardi, A. Rimini, and T. Weber, Lett. Nuovo Cimento **27,** 293-298 (1980); U. Yurtsever and G. Hockney, Classical and Quantum Gravity **22,** 295-312 (2005), gr-qc/0409112.

[14] K. A. Peacock and B. Hepburn, Proceedings of the Meeting of the Society of Exact Philosophy (1999), quant-ph/9906036.

[15] L. Mandel and E. Wolf, **Optical Coherence and Quantum Optics,** Chapter 22.4, Cambridge University Press (1995).

[16] D. V. Strekalov, A. V. Sergienko, D. N. Klyshko, and Y. H. Shih, Phys. Rev. Letters, **74,** 3600-3603 (1995).

[17] B. Dopfer, Ph.D. Thesis, Univ. Innsbruck (1998); A. Zeilinger, Rev. Modern Physics **71,** S288-S297 (1999).

[18] A. F. Abouraddy, M. B. Nasr, B. E. A. Saleh, A. V. Sergienko, and M. C. Teich. Phys. Rev. A, **63,** 063803 (2001).

[19] John G. Cramer, Reviews of Modern Physics **58,** 647 (1986); John G. Cramer, International Journal of Theoretical Physics **27,** 227 (1988); John G. Cramer, Foundations of Physics Letters **19,** 63-73, (2006).

[20] A. Fedrizzi, T. Herbst1, A. Poppe, T. Jennewein1 and A. Zeilinger, Optics Express **15,** 15377 (2007).

[21] Ludwig Zehnder, Z. Instrumentenkunde **11,** 275 (1891); Ludwig Mach, Z. Instrumentenkunde **12,** 89 (1892).

[22] J. A. Wheeler and R. P. Feynman, Rev. Mod. Physics, **21,** 425-433 (1949).

[23] F. Eschenerria, G. Klinkhammer, and K. S. Thorne, Phys. Rev. D, **44,** 1077-1099 (1991).

[24] S. W. Hawking, Phys. Rev. D **46,** 603–611 (1992).

[25] Steven Weinberg, Physical Review Letters, **62,** 485-490 (1989).

[26] Joseph Polchinski, Physical Review Letters, **66,** 397-401 (1991).