On using Greenberger-Horne-Zeilinger three-particle states for superluminal communication

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Abstract.

Using a three-particle entangled system (triple), it is possible in principle to transmit signals faster than the speed of light from sender to receiver in the following manner: From an emitter, for every triple, particles 1 and 2 are sent to the receiver and 3 to the sender. The sender is given the choice of whether or not to measure polarization of particle 3. Meanwhile the receiver measures particle correlation vs. relative polarization angle for the polarizers of particles 1 and 2. The particle 1 and 2 correlation statistics depend on whether or not particle 3 polarization was measured, instantaneously. This dependence is a basis for faster-than-light communication.

Introduction.

In this article, it is proposed that a three-particle entangled quantum state, or Greenberger-Horne-Zeilinger (GHZ) state, enables faster-than-light or superluminal communication (FTLC). The idea is simple: for every entangled triple of particles, 2 particles, *e.g.* photons, are sent to one of two observers, labeled the receiver. The other particle of the triple is sent to the observer labeled as the sender. These names for the observers originate from the fact that the sender will attempt to send information, and the receiver, receive information, instantaneously, using the 3-photon entangled state. The sender sends information by the ability to choose between one of two operations done on the photon sent to its end: (a) measuring the photons polarity or path information with polarimeters or beam splitters or (b) erasing path information. On the receiver end, there are two photons received, and the receiver measures polarity for both. The two beam splitters on the receiver end are held at various relative angles with respect to one another, and the receiver records the correlations, as in a normal two-photon correlation experiment as was done by Aspect and co-workers [1]. See figure 1.

Since the two receiver photons may not travel along a common axis as in the two-photon case, it is necessary to define what is meant by the *relative angle* between the two receiver beam splitters. This can be done by choosing a normal vector **N** in the plane of propagation of the two photons and defining the absolute angles of the two polarimeters as the relative angle to **N**. Again, refer to figure 1.

For the set-up shown in figure 1, we choose the GHZ state

$$\left|\psi\right\rangle = \frac{1}{\sqrt{2}}\left[\left|1-\right\rangle\left|2-\right\rangle\left|3-\right\rangle + \left|1+\right\rangle\left|2+\right\rangle\left|3+\right\rangle\right]. \tag{1}$$

For the equation or "state vector" (1), the numberings refer to the number of a given photon in the three-way state, where 1 and 2 go to the receiver and 3 to the sender. Plus + and minus – symbols refer to the polarity of each photon. Now in order to communicate between sender and receiver, many GHZ triples will need to be sent, even for the transmission of a single bit of information. For a given population of triples sent out for the transmission of a single bit, the receiver will record the correlation between the data of the two received photons, and this depends on whether or not the sender chooses to measure polarization of the sender's photons. The procedure for this will be outlined in more detail below.

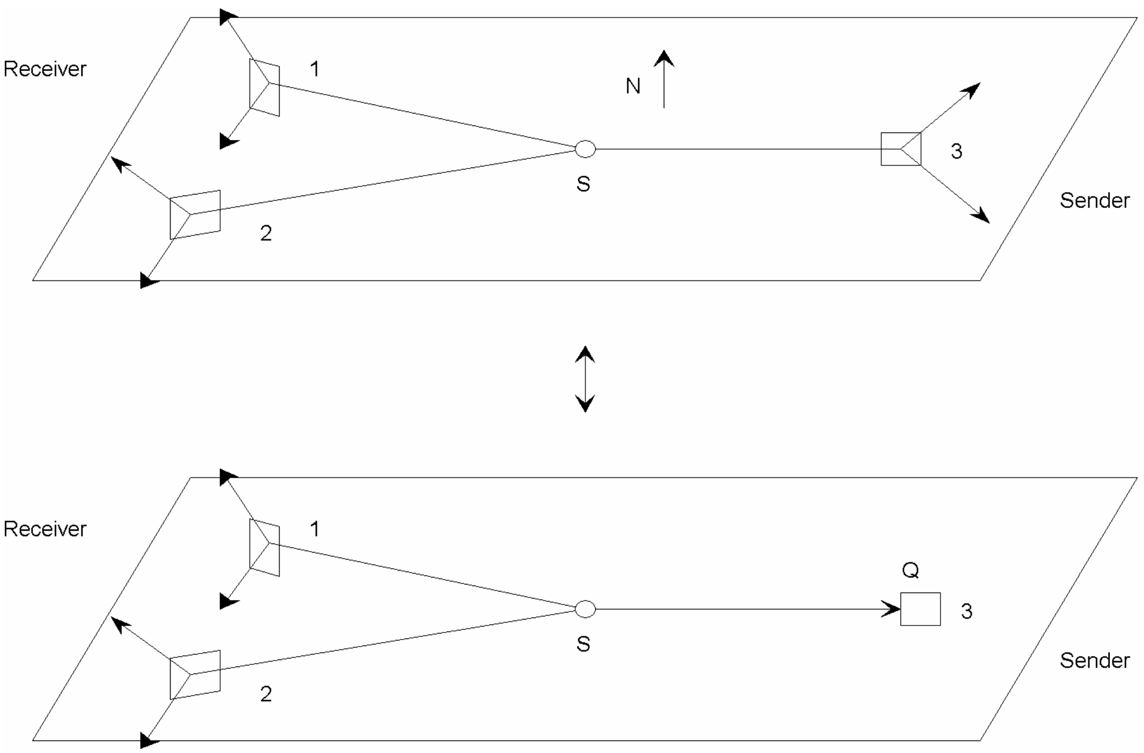

Figure 1. The FTLC device proposed in the text, shown in two configurations, top and bottom. There are triples of entangled photons emitted by the source *S*, and they propagate in the plane with normal N shown. The sender is on the right and receiver on the left. For every triple, the sender gets one photon and is given the choice of measuring the photon's polarization (top) or erasing the information (bottom). The receiver meanwhile gets two photons and performs a coincidence or "Aspect-type" experiment between the photons. The top configuration will yield coincidence data fitting equation (2), and the bottom, (3). The difference in the statistics is a basis for FTLC.

Now, we claim that when the sender chooses to measure polarization information, (top of figure 1) the correlation statistics for the receiver are

$$\begin{aligned} P_{++} = P_{--} &= \frac{1}{4}\cos^2\theta + \frac{1}{8} \\ P_{+-} = P_{-+} &= \frac{1}{4}\sin^2\theta + \frac{1}{8}. \end{aligned} \tag{2}$$

The plus and minus symbols again refer to the polarity of the receiver photons. *E.g.* ++ means that both receiver photons have + polarity, according to the polarizer measurements.

Now it is also claimed that when the sender chooses to erase path information, (bottom of figure 1), the statistics (2) change to:

$$
\begin{aligned}
P_{++} = P_{--} &= \frac{1}{2}\cos^2\theta \\
P_{+-} = P_{-+} &= \frac{1}{2}\sin^2\theta.
\end{aligned}
\tag{3}
$$

The statistics (3) are the same as those discovered by Aspect and co-workers [1] and so violate Bells inequality. On the other hand, the statistics (2) do not violate Bell's inequality; so clearly these statistics are distinguishable by the receiver.

Now Eberhard and Ross (ER) [2] claim impossibility of transmission of FTLC and in particular, for three-way systems such as that described by (1) using the set-up in figure 1. Since they do not explicitly show their calculation in their article, their argument is demonstrated in the following section. In the section following the next, it is then shown how this argument can be circumvented by considering an operation which is defined here as "erasure." In a later section, experimental evidence is reviewed, which demonstrates that the types of operations ER consider in their analysis is insufficient.

Eberhard and Ross' argument for no FTLC.

It has been claimed by ER [2] that for a given quantum system, it is impossible for an observer (*i.e.* the sender), spacelike separated from another (*i.e.* the receiver), to influence eigenvalue correlations between two or more measurements done by the latter. Since their proof is not carried out explicitly in their article, we construct it here. In the section following, it is then shown that ER do not consider a particular action which may be done by the sender; namely erasure of path information of the sender's particle. Then it is shown that the ER argument does not hold for when the sender is allowed to perform erasure. Meaning, erasure changes the receiver's eigenvalue correlations as compared to when the sender performs an eigenvalue measurement or takes no action. And again, lastly, we argue on the basis of experimental evidence for erasure.

To begin, we consider a general quantum system Q represented by the time-dependent state equation or wavefunction $|\Psi(t)\rangle \in \mathcal{V}(\mathbf{A})\otimes\mathcal{V}(\mathbf{B})\otimes\mathcal{V}(\mathbf{C})$ where $\mathcal{V}(\mathbf{A})$, $\mathcal{V}(\mathbf{B})$, and $\mathcal{V}(\mathbf{C})$ are Hilbert spaces; the eigenspaces of three respective operators **A**, **B**, and **C**. **A** is an operator which corresponds to an operation which *may* be done by the sender, whereas the latter two correspond to operations which are *always* done by the receiver. Let the sets of eigenvalues of operators **A**, **B**, and **C** be $\{a_1, a_2, \ldots\}$, $\{b_1, b_2, \ldots\}$, and $\{c_1, c_2, \ldots\}$ respectively. Consider the case where the receiver measures eigenvalues b_i and c_j. We wish to first calculate the joint probability of this occurrence when the sender "takes no action;" *i.e.* makes no measurement. By definition the operator associated to this (in)action is the identity operator **I**.

Sender takes no action

Suppose then at time t_1, b_i is measured, at time t_2, c_j is measured by the receiver upon applying its operations **B** and **C** respectively, and without loss of generality, $t_1 < t_2$ in the frame of reference of the receiver. Up to t_1, the wavefunction of Q is given by

$$\left|\Psi(t)\right\rangle = U_0(t)\left|\Psi(0)\right\rangle \tag{4}$$

where $U_0(t)$ is the evolution operator between times 0 and t_1, with the "0" subscript signifying that the sender does not change the Hamiltonian operator for Q in between measurements. We write the Hermitian conjugate of the evolution operator as $U_0^\dagger(t)$. At time t_1, "collapse" of $\left|\Psi(t)\right\rangle$ occurs; and after a short time ε where $t_1 + \varepsilon < t_2$ the wavefunction becomes, by the fifth postulate [3]

$$\left|\Psi(t_1+\varepsilon)\right\rangle = \frac{1}{\sqrt{P(b_i)}} U_0(t_1)\tilde{\Pi}_{b_i}(t_1)\left|\Psi(0)\right\rangle \tag{5}$$

where $P(b_i)$ is the probability of b_i occurring, given by the fourth postulate [3]

$$P(b_i) = \left\langle\Psi(0)\right|\tilde{\Pi}_{b_i}(t_1)\left|\Psi(0)\right\rangle \tag{6}$$

and $\tilde{\Pi}_{b_i}(t_1)$ is the projection operator associated to obtaining eigenvalue b_i at t_1:

$$\tilde{\Pi}_{b_i}(t_1) = U_0^\dagger(t_1)\Pi_{b_i}(t_1)U_0(t_1) \tag{7}$$

where

$$\Pi_{b_i}(t_1) = \sum_{k=1}^{N_i} \left| B_{ik}\right\rangle\left\langle B_{ik}\right| . \tag{8}$$

In (8) the $\left|B_{ik}\right\rangle$ are the N_i-fold degenerate eigenvectors associated to eigenvalue b_i, and these $\left|B_{ik}\right\rangle$ form the standard basis for $\mathcal{V}(\mathbf{B})$ {*cf.* (5) with (25) in ER [2]}. At time t_2, the receiver measures c_j, and so the conditional probability $P_0(c_j \mid b_i)$ of this occurring given that b_i was measured is

$$\begin{aligned} P_0(c_j \mid b_i) &= \left\langle\Psi(t_1+\varepsilon)\right|U_0(t_1)U_0^\dagger(t_2)\Pi_{c_j}(t_2)U_0(t_2)U_0^\dagger(t_1)\left|\Psi(t_1+\varepsilon)\right\rangle \\ &= \left\langle\Psi(t_1+\varepsilon)\right|U_0(t_1)\tilde{\Pi}_{c_j}(t_2)U_0^\dagger(t_1)\left|\Psi(t_1+\varepsilon)\right\rangle; \end{aligned} \tag{9}$$

where

$$\begin{aligned}\tilde{\Pi}_{c_j}(t_2) &= U_0^\dagger(t_2)\Pi_{c_j}(t_2)U_0(t_2)\\ &= U_0^\dagger(t_2)\left[\sum_{l=1}^{N_j}\left|C_{jl}\right\rangle\left\langle C_{jl}\right|\right]U_0(t_2)\ ;\end{aligned} \tag{10}$$

cf. (26) in ER [2]. The $\left|C_{jl}\right\rangle$ in (10) are the N_j-fold degenerate eigenvectors associated to eigenvalue c_j which give a standard basis for $\mathcal{V}(\mathbf{C})$. In (9), we note that the combined operators $U_0(t_2)U_0^\dagger(t_1)$ function as the evolution operator of Ψ between times t_1 and t_2. Combining (5) and (9), we get

$$P_0(c_j \mid b_i) = \frac{1}{P(b_i)}\left\langle\Psi(0)\right|\tilde{\Pi}_{b_i}(t_1)\tilde{\Pi}_{c_j}(t_2)\tilde{\Pi}_{b_i}(t_1)\left|\Psi(0)\right\rangle; \tag{11}$$

thus the joint probability (“correlation probability”) of the receiver obtaining eigenvalues b_i and c_j is, using the definition of conditional probability,

$$P_0(c_j \,\&\, b_i) = \left\langle\Psi(0)\right|\tilde{\Pi}_{b_i}(t_1)\tilde{\Pi}_{c_j}(t_2)\tilde{\Pi}_{b_i}(t_1)\left|\Psi(0)\right\rangle. \tag{12}$$

Sender performs a measurement

Next, suppose the sender performs an eigenvalue measurement and measures eigenvalue a_m, at time $t_s > 0$. We wish to again calculate the joint probability that the receiver obtains eigenvalues b_i and c_j however, given the condition that a_m is measured by the sender; that is, $P(c_j \,\&\, b_i \mid a_m)$. Using the reasoning given in the previous subsection, it is not difficult to see that this conditional probability is, given $t_s < t_1 < t_2$,

$$\begin{aligned}P(c_j \,\&\, b_i \mid a_m) &= \frac{P(c_j \,\&\, b_i \,\&\, a_m)}{P(a_m)}\\ &= \frac{1}{P(a_m)}\left\langle\Psi(0)\right|\tilde{\Pi}_{a_m}(t_s)\tilde{\Pi}_{b_i}(t_1)\tilde{\Pi}_{c_j}(t_2)\tilde{\Pi}_{b_i}(t_1)\tilde{\Pi}_{a_m}(t_s)\left|\Psi(0)\right\rangle\end{aligned}\ . \tag{13}$$

Now by assumption the receiver has no way of knowing which particular eigenvalue is measured by the sender; thus we sum over all a_m using Bayes’ formula, to get the joint probability $P(c_j \,\&\, b_i)$ given that the sender has performed a measurement:

$$\begin{aligned}P(c_j \,\&\, b_i) &= \sum_{a_m} P(c_j \,\&\, b_i \mid a_m)P(a_m)\\ &= \sum_{a_m}\left\langle\Psi(0)\right|\tilde{\Pi}_{a_m}(t_s)\tilde{\Pi}_{b_i}(t_1)\tilde{\Pi}_{c_j}(t_2)\tilde{\Pi}_{b_i}(t_1)\tilde{\Pi}_{a_m}(t_s)\left|\Psi(0)\right\rangle\\ &\left\langle\Psi(0)\right|\sum_{a_m}\tilde{\Pi}_{a_m}(t_s)\tilde{\Pi}_{b_i}(t_1)\tilde{\Pi}_{c_j}(t_2)\tilde{\Pi}_{b_i}(t_1)\tilde{\Pi}_{a_m}(t_s)\left|\Psi(0)\right\rangle.\end{aligned} \tag{14}$$

The goal here is to show that equations (12) and (14) are the same. To do this, it is sufficient to invoke the following axiom, as is done in ER [2]:

(I) *Suppose* $\Pi_{\mathbf{a}}$ *and* $\Pi_{\mathbf{b}}$ *are two projection operators corresponding to measurements done on a quantum system Q at respective points* **a** *and* **b** *in space-time which are spacelike separated. Then* $\Pi_{\mathbf{a}}$ *and* $\Pi_{\mathbf{b}}$ *commute.*

This is a reasonable axiom, in particular when the theory of relativity is taken into account; since it is a matter of ones own reference frame as to the order of operations, and further, all observers should agree on the outcomes of the operations. This would not be so if the operators did not commute!

Now by assumption, the sender and receiver are spacelike separated between the times they perform measurements. That is, given that the sender performs a measurement at a point **s** [= (s, t_s)] in spacetime and the receiver performs the two measurements at points $\mathbf{r}_1$ [= (r_1, t_1)] and $\mathbf{r}_2$ [= (r_2, t_2)], then **s** and $\mathbf{r}_1$ are spacelike separated, and so are **s** and $\mathbf{r}_2$. From (I) then, the operators in (14) which correspond to spacelike-separated points commute, and so

$$\begin{aligned} P(c_j \,\&\, b_i) &= \left\langle \Psi(0) \middle| \tilde{\Pi}_{b_i}(t_1)\tilde{\Pi}_{c_j}(t_2)\tilde{\Pi}_{b_i}(t_1)\sum_{a_m}\tilde{\Pi}^2_{a_m}(t_s) \middle| \Psi(0) \right\rangle \\ &= \left\langle \Psi(0) \middle| \tilde{\Pi}_{b_i}(t_1)\tilde{\Pi}_{c_j}(t_2)\tilde{\Pi}_{b_i}(t_1)\sum_{a_m}\tilde{\Pi}_{a_m}(t_s) \middle| \Psi(0) \right\rangle \end{aligned} \tag{15}$$

where we used the idempotent property of projection operators in the second step. Now, by the fourth postulate [3],

$$P(a_m) = \left\langle \Psi(0) \middle| \tilde{\Pi}_{a_m}(t_s) \middle| \Psi(0) \right\rangle . \tag{16}$$

Summing equation (16) over all a_m and using the property of conservation of probability, we have

$$\begin{aligned} \sum_{a_m} P(a_m) &= 1 \\ &= \left\langle \Psi(0) \middle| \sum_{a_m}\tilde{\Pi}_{a_m}(t_s) \middle| \Psi(0) \right\rangle \\ &= \left\langle \Psi(0) \middle| \Psi(0) \right\rangle . \end{aligned} \tag{17}$$

Thus $\sum_{a_m}\tilde{\Pi}_{a_m}(t_s)$ is the identity, so from (17), (14) becomes

$$\begin{aligned} P(c_j \,\&\, b_i) &= \left\langle \Psi(0) \middle| \tilde{\Pi}_{b_i}(t_1)\tilde{\Pi}_{c_j}(t_2)\tilde{\Pi}_{b_i}(t_1) \middle| \Psi(0) \right\rangle \\ &= P_0(c_j \,\&\, b_i). \end{aligned} \tag{18}$$

Thus by (18) we have equality between (12) and (14); *i.e.*, there is no difference in the correlation statistics of the receiver between the cases where the sender (i) takes no action and (ii) makes a measurement.

But are these actions considered by ER the only ones which the sender may take?

We claim that the answer is no; the sender may also perform erasure or "erase path information" of the part of Q it interacts with. After defining this action in the next section, we look at the effects on the correlation statistics for the receiver, given that the sender is allowed to perform erasure.

In a later section, experimental justification for erasure is given. Eberhard and Ross do *not* consider erasure. Hence their proof of "no signaling" is incomplete and thus invalid. This is the reason why their conclusion contradicts the conclusion of this article.

Construction of erasure.

Consider a state equation representing two entangled particles **a** and **b** with bases $\{|\mathbf{a}_1\rangle, |\mathbf{a}_2\rangle\}$ and $\{|\mathbf{b}_1\rangle, |\mathbf{b}_2\rangle\}$ respectively. Further, suppose the particles are represented by the state equation

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left[|\mathbf{a}_1\rangle|\mathbf{b}_1\rangle + |\mathbf{a}_2\rangle|\mathbf{b}_2\rangle\right]. \tag{19}$$

We wish to "erase" particle **b**; *i.e.* reduce (19) to

$$|\Psi'\rangle = \frac{1}{\sqrt{2}}\left[|\mathbf{a}_1\rangle + |\mathbf{a}_2\rangle\right]. \tag{20}$$

The projection operator which accomplishes this task is the following:

$$\begin{aligned}\Pi_{\mathrm{E}} &= |\varphi\rangle\langle\varphi| \\ &= \frac{1}{2}\left[|\mathbf{b}_1\rangle\langle\mathbf{b}_1| + |\mathbf{b}_1\rangle\langle\mathbf{b}_2| + |\mathbf{b}_2\rangle\langle\mathbf{b}_1| + |\mathbf{b}_2\rangle\langle\mathbf{b}_2|\right].\end{aligned} \tag{21}$$

That is, using (21), (19) becomes

$$\begin{aligned}\Pi_{\mathrm{E}}|\Psi\rangle &= \frac{1}{2\sqrt{2}}\left[|\mathbf{b}_1\rangle\langle\mathbf{b}_1| + |\mathbf{b}_1\rangle\langle\mathbf{b}_2| + |\mathbf{b}_2\rangle\langle\mathbf{b}_1| + |\mathbf{b}_2\rangle\langle\mathbf{b}_2|\right]\left[|\mathbf{a}_1\rangle|\mathbf{b}_1\rangle + |\mathbf{a}_2\rangle|\mathbf{b}_2\rangle\right] \\ &= \frac{1}{2\sqrt{2}}\left[|\mathbf{a}_1\rangle|\mathbf{b}_1\rangle + |\mathbf{a}_1\rangle|\mathbf{b}_2\rangle + |\mathbf{a}_2\rangle|\mathbf{b}_1\rangle + |\mathbf{a}_2\rangle|\mathbf{b}_2\rangle\right] \\ &= \frac{1}{2\sqrt{2}}\left(|\mathbf{a}_1\rangle + |\mathbf{a}_2\rangle\right)\left(|\mathbf{b}_1\rangle + |\mathbf{b}_2\rangle\right).\end{aligned} \tag{22}$$

In comparing (19) to (22) we see the two particles which were formerly entangled are no longer so. Thus the isolated particle **a** given by (20) will give the same statistics as **a** given by (22) (upon normalization); hence the particle **b** is made irrelevant or rather has been "erased." Physically, a particle's eigenvalue or path information is erased if we allow the particle to be detected without measuring its eigenvalue information. For example, if a single particle is allowed to pass through a double-slit without the observer attempting to discover which slit the particle passes through, then the path information of the particle has been erased. We simply refer to such action as *erasing* the particle.

Now the general erasure projection operator we define as

$$\begin{aligned}\Pi_{\mathrm{E}} &= |\varphi(t_s)\rangle\langle\varphi(t_s)| \\ &= \sum_k \sum_{l=1}^{N_k} \sum_m \sum_{n=1}^{N_m} \alpha_{kl}(t_s)\alpha_{mn}^*(t_s) |A_{kl}\rangle\langle A_{mn}|\end{aligned} \tag{23}$$

where $|\varphi(t_s)\rangle = \sum_k \sum_{l=1}^{N_k} \alpha_{kl}(t_s) |A_{kl}\rangle \in \mathcal{V}(\mathbf{A})$ is normalized and gives the same eigenvalue statistics $P(a_m)$ at t_s as does $|\Psi(t)\rangle \in \mathcal{V}(\mathbf{A}) \otimes \mathcal{V}(\mathbf{B}) \otimes \mathcal{V}(\mathbf{C})$, the state equation of the quantum system Q under study. Since the eigenvalue measurements conversely do not affect the eigenvalue statistics of the sender, we see that (23) is well-defined. Now $\alpha_{kl} = r_{kl} e^{i\theta_{kl}}$ where r_{kl} is real and nonnegative and the phase factor θ_{kl} is real. But we wish to keep the "paths" a particle may take, indistinguishable. Therefore we set all phase factors equivalent to a global phase factor ϕ in (23); thus the α_{kl} can be considered to be real and nonnegative.

Erasure not equivalent to taking no action/eigenvalue measurement.

Suppose then that the sender performs erasure at time t_s. By extension of the fifth postulate we have using (23):

$$|\Psi(t_1 + \varepsilon)\rangle = N\, U_0(t_s) \widetilde{\Pi}_{\mathrm{E}}(t_s) |\Psi(0)\rangle, \tag{24}$$

where N is a real normalization constant, defined below, and

$$\widetilde{\Pi}_{\mathbf{E}}(t_s) = U_0^\dagger(t_s) \Pi_{\mathbf{E}}(t_s) U_0(t_s). \tag{25}$$

A similar extension of the fifth postulate is presented in the Cohen-Tannoudji text [3] in section III e.

By (24) and (25) the conditional probability of the receiver obtaining eigenvalues b_i and c_j is, given that the sender has performed erasure, is

$$P(c_j \,\&\, b_i \,|\, \mathrm{E}) = N^2 \langle \Psi(0) | \widetilde{\Pi}_{\mathrm{E}}(t_s) \widetilde{\Pi}_{b_i}(t_1) \widetilde{\Pi}_{c_j}(t_2) \widetilde{\Pi}_{b_i}(t_1) \widetilde{\Pi}_{\mathrm{E}}(t_s) | \Psi(0) \rangle. \tag{26}$$

[*cf.* (13)] But since the sender *only* performs erasure, we have

$$P_{\mathrm{E}}(c_j \,\&\, b_i) = N^2 \langle \Psi(0) | \widetilde{\Pi}_{\mathrm{E}}(t_s) \widetilde{\Pi}_{b_i}(t_1) \widetilde{\Pi}_{c_j}(t_2) \widetilde{\Pi}_{b_i}(t_1) \widetilde{\Pi}_{\mathrm{E}}(t_s) | \Psi(0) \rangle. \tag{27}$$

Using axiom (I), and the idempotent property of (23) we have from (27),

$$P_{\mathrm{E}}\left(c_j \,\&\, b_i\right) = N^2 \left\langle \Psi(0) \middle| \tilde{\Pi}_{b_i}(t_1) \tilde{\Pi}_{c_j}(t_2) \tilde{\Pi}_{b_i}(t_1) \tilde{\Pi}_{\mathrm{E}}(t_s) \middle| \Psi(0) \right\rangle$$
$$\neq P_0\left(c_j \,\&\, b_i\right) = P\left(c_j \,\&\, b_i\right) \tag{28}$$

in general. The exception to the inequality is where the erasure projection operator is equivalent to the identity operator (in this case, $N^2 = 1$), but this is not true in general.

Using (26), we see that

$$N^2 = 1 / \left\langle \Psi(0) \middle| \tilde{\Pi}_{\mathrm{E}}(t_s) \middle| \Psi(0) \right\rangle. \tag{29}$$

In the next section, we apply the equations derived in these last two sections toward calculations of equations (2) and (3); *i.e.* the statistics for the two configurations of the apparatus shown in figure 1.

Calculation of equations (2) and (3).

We begin the calculation of (2), the statistics for the receiver given sender eigenvalue (path) measurement, with equation (1), and in consideration of the apparatus shown in figure 1. Relative to its polarizer, suppose photon 3 has polarization angle φ. Using the rotation transformation equations

$$\begin{aligned} |3\ +\rangle &= \cos\varphi |3\ +\rangle' - \sin\varphi |3\ -\rangle' \\ |3\ -\rangle &= \sin\varphi |3\ +\rangle' + \cos\varphi |3\ -\rangle' \end{aligned} \tag{30}$$

equation (1) becomes, in the basis of polarizer 3,

$$\begin{aligned} |\psi\rangle = \frac{1}{\sqrt{2}} \Big[&\sin\varphi |1\ -\rangle |2\ -\rangle |3\ +\rangle' + \cos\varphi |1\ -\rangle |2\ -\rangle |3\ -\rangle' \\ &+ \cos\varphi |1\ +\rangle |2\ +\rangle |3\ +\rangle' - \sin\varphi |1\ +\rangle |2\ +\rangle |3\ -\rangle' \Big] \end{aligned} \tag{31}$$

Next, define the angles of the polarizers of photons 1 and 2 as α and β respectively. Then from (31) and transformation equations analogous to (30), we get, after dropping primes,

$$
\begin{aligned}
\left|\psi\right\rangle = \frac{1}{\sqrt{2}}\Big[&\left(\sin\alpha\sin\beta\sin\varphi+\cos\alpha\cos\beta\cos\varphi\right)\left|1\ +\right\rangle\left|2\ +\right\rangle\left|3\ +\right\rangle \\
&+\left(\sin\alpha\cos\beta\sin\varphi-\cos\alpha\sin\beta\cos\varphi\right)\left|1\ +\right\rangle\left|2-\right\rangle\left|3\ +\right\rangle \\
&+\left(\cos\alpha\sin\beta\sin\varphi-\sin\alpha\cos\beta\cos\varphi\right)\left|1-\right\rangle\left|2\ +\right\rangle\left|3\ +\right\rangle \\
&+\left(\cos\alpha\cos\beta\sin\varphi+\sin\alpha\sin\beta\cos\varphi\right)\left|1-\right\rangle\left|2-\right\rangle\left|3\ +\right\rangle \\
&+\left(\sin\alpha\sin\beta\cos\varphi-\cos\alpha\cos\beta\sin\varphi\right)\left|1\ +\right\rangle\left|2\ +\right\rangle\left|3\ -\right\rangle \\
&+\left(\sin\alpha\cos\beta\cos\varphi+\cos\alpha\sin\beta\sin\varphi\right)\left|1\ +\right\rangle\left|2-\right\rangle\left|3\ -\right\rangle \\
&+\left(\cos\alpha\sin\beta\cos\varphi+\sin\alpha\cos\beta\sin\varphi\right)\left|1-\right\rangle\left|2\ +\right\rangle\left|3\ -\right\rangle \\
&\left(\cos\alpha\cos\beta\cos\varphi-\sin\alpha\sin\beta\sin\varphi\right)\left|1\ -\right\rangle\left|2\ -\right\rangle\left|3\ -\right\rangle\Big]\ .
\end{aligned} \tag{32}
$$

Next, we calculate $P(+,+)$ using equation (18). Since the system given by (1) is time independent, all evolution operators vanish. Recall that photon 3 is sent to the sender and the photons 1 and 2 are sent to the receiver. The probability in this case, of the receiver obtaining result +,+ is, using (1), (18), and (32):

$$
\tilde{P}\left(+,+\right)=\tilde{P}_{++}\left(\alpha,\beta,\varphi\right) \tag{33}
$$

$$
=\left\langle\Psi\right|\Pi_{1+}\Pi_{2+}\Pi_{1+}\left|\Psi\right\rangle
$$

$$
\begin{aligned}
=\frac{1}{\sqrt{2}}\left\langle\Psi\right|\Pi_{1+}\Pi_{2+}\left|1+\right\rangle\left\langle 1+\right|\Big[&\left(\cos\alpha\cos\beta\cos\varphi+\sin\alpha\sin\beta\sin\varphi\right)\left|1+\right\rangle\left|2+\right\rangle\left|3+\right\rangle \\
&+\left(-\cos\alpha\cos\beta\sin\varphi+\sin\alpha\sin\beta\cos\varphi\right)\left|1+\right\rangle\left|2+\right\rangle\left|3-\right\rangle \\
&+\left(-\cos\alpha\sin\beta\cos\varphi+\sin\alpha\cos\beta\sin\varphi\right)\left|1+\right\rangle\left|2-\right\rangle\left|3+\right\rangle \\
&+\left(-\sin\alpha\cos\beta\cos\varphi+\cos\alpha\sin\beta\sin\varphi\right)\left|1-\right\rangle\left|2+\right\rangle\left|3+\right\rangle \\
&+\left(\cos\alpha\sin\beta\sin\varphi+\sin\alpha\cos\beta\cos\varphi\right)\left|1+\right\rangle\left|2-\right\rangle\left|3-\right\rangle \\
&+\left(\sin\alpha\cos\beta\sin\varphi+\cos\alpha\sin\beta\cos\varphi\right)\left|1-\right\rangle\left|2+\right\rangle\left|3-\right\rangle \\
&+\left(\sin\alpha\sin\beta\cos\varphi+\cos\alpha\cos\beta\sin\varphi\right)\left|1-\right\rangle\left|2-\right\rangle\left|3+\right\rangle \\
&+\left(-\sin\alpha\sin\beta\sin\varphi+\cos\alpha\cos\beta\cos\varphi\right)\left|1-\right\rangle\left|2-\right\rangle\left|3-\right\rangle\Big]
\end{aligned}
$$

$$
\begin{aligned}
&= \frac{1}{\sqrt{2}} \langle \Psi | \Pi_{1+} |2+\rangle \langle 2+| \big[(\cos\alpha\cos\beta\cos\varphi + \sin\alpha\sin\beta\sin\varphi) |1+\rangle |2+\rangle |3+\rangle \\
&+ (-\cos\alpha\cos\beta\sin\varphi + \sin\alpha\sin\beta\cos\varphi) |1+\rangle |2+\rangle |3-\rangle \\
&+ (-\cos\alpha\sin\beta\cos\varphi + \sin\alpha\cos\beta\sin\varphi) |1+\rangle |2-\rangle |3+\rangle \\
&+ (\cos\alpha\sin\beta\sin\varphi + \sin\alpha\cos\beta\cos\varphi) |1+\rangle |2-\rangle |3-\rangle \big] \\
&= \frac{1}{\sqrt{2}} \langle \Psi || 1+\rangle \langle 1+| \big[(\cos\alpha\cos\beta\cos\varphi + \sin\alpha\sin\beta\sin\varphi) |1+\rangle |2+\rangle |3+\rangle \\
&+ (-\cos\alpha\cos\beta\sin\varphi + \sin\alpha\sin\beta\cos\varphi) |1+\rangle |2+\rangle |3-\rangle \big] \\
&= \frac{1}{2} (\cos\alpha\cos\beta\cos\varphi + \sin\alpha\sin\beta\sin\varphi)^2 + \frac{1}{2} (-\cos\alpha\cos\beta\sin\varphi + \sin\alpha\sin\beta\cos\varphi)^2 \\
&= \frac{1}{4} \big[1 + \cos(2\alpha)\cos(2\beta) \big] \ . \qquad (33)
\end{aligned}
$$

The reason for the tilde (~) above P_{++} in (33) will become apparent in a moment. For now, fix the angle θ of polarizer 1 relative to polarizer 2 (again, using the normal **N** to the plane as reference). This fixed angle is equivalent to the difference between angles α and β since the two photons have the same, albeit indeterminate polarization angle. Thus we have $\theta = \alpha - \beta$. Thus (33) becomes

$$
\begin{aligned}
\tilde{P}_{++}(\beta) &= \frac{1}{4} \big[1 + \cos(2\theta + 2\beta)\cos(2\beta) \big] \\
&= \frac{1}{4}\cos^2\theta + \frac{1}{8} + \frac{1}{8}\cos(2\theta + 4\beta) \ .
\end{aligned} \qquad (34)
$$

Equation (34) is now a function of a single variable, β; the polarization angle of photon 2 which is picked up by the receiver. But the #2 photons as a population have all possible angles β from 0 to 2π, each angle with equal probability. This is the reason for the tilde that was put in earlier; (34) is not quite the probability we are looking for. To find that probability, the average probability, we treat β as a uniform random variable and integrate (34) as follows:

$$
\begin{aligned}
P_{++} &= \frac{1}{2\pi} \int_0^{2\pi} \tilde{P}_{++}(\beta)\, \mathrm{d}\beta \\
&= \frac{1}{4}\cos^2\theta + \frac{1}{8} \ .
\end{aligned} \qquad (35)
$$

Equation (35) is the same probability as that shown in (2). The remaining three probabilities in (2) are similarly calculated.

Next, we repeat the calculation of the joint probability of obtaining +,+ by the receiver, assuming that the sender performs erasure; *i.e.* P_{++} in (3). Using (23), the erasure operator is

$$\Pi_{\mathrm{E}} = \frac{1}{2}\left[|3+\rangle\langle 3+| + |3+\rangle\langle 3-| + |3-\rangle\langle 3+| + |3-\rangle\langle 3-|\right]. \tag{36}$$

Thus the probability of the receiver obtaining +,+ if the sender performs erasure is, using (28):

$$P_E(+,+) = N^2 \langle \Psi | \Pi_{1+} \Pi_{2+} \Pi_{1+} \Pi_{\mathrm{E}} | \Psi \rangle \tag{37}$$

$$\begin{aligned}
&= \frac{2}{2\sqrt{2}} \langle \Psi | \Pi_{1+} \Pi_{2+} \Pi_{1+} \left[|3+\rangle\langle 3+| + |3+\rangle\langle 3-| + |3-\rangle\langle 3+| \right. \\
&\left. + |3-\rangle\langle 3-| \right] \left[\cos\alpha \cos\beta |1+\rangle |2+\rangle |3+\rangle \right. \\
&- \sin\alpha \cos\beta |1-\rangle |2+\rangle |3+\rangle \\
&- \cos\alpha \sin\beta |1+\rangle |2-\rangle |3+\rangle \\
&+ \sin\alpha \sin\beta |1-\rangle |2-\rangle |3+\rangle \\
&+ \sin\alpha \sin\beta |1+\rangle |2+\rangle |3-\rangle \\
&+ \sin\alpha \cos\beta |1+\rangle |2-\rangle |3-\rangle \\
&+ \cos\alpha \sin\beta |1-\rangle |2+\rangle |3-\rangle \\
&\left. + \cos\alpha \cos\beta |1-\rangle |2-\rangle |3-\rangle \right]
\end{aligned}$$

$$\begin{aligned}
&= \frac{1}{\sqrt{2}} \langle \Psi | \Pi_{1+} \Pi_{2+} |1+\rangle\langle 1+| \left[\cos\alpha \cos\beta |1+\rangle |2+\rangle \right. \\
&- \sin\alpha \cos\beta |1-\rangle |2+\rangle \\
&- \cos\alpha \sin\beta |1+\rangle |2-\rangle \\
&+ \sin\alpha \sin\beta |1-\rangle |2-\rangle \\
&+ \sin\alpha \sin\beta |1+\rangle |2+\rangle \\
&+ \sin\alpha \cos\beta |1+\rangle |2-\rangle \\
&+ \cos\alpha \sin\beta |1-\rangle |2+\rangle \\
&\left. + \cos\alpha \cos\beta |1-\rangle |2-\rangle \right] \left(|3+\rangle + |3-\rangle \right)
\end{aligned}$$

$$\begin{aligned}
&= \frac{1}{\sqrt{2}} \langle \Psi | \Pi_{1+} |2+\rangle\langle 2+| \left[\cos\alpha \cos\beta |1+\rangle |2+\rangle \right. \\
&- \cos\alpha \sin\beta |1+\rangle |2-\rangle \\
&+ \sin\alpha \sin\beta |1+\rangle |2+\rangle \\
&\left. + \sin\alpha \cos\beta |1+\rangle |2-\rangle \right] \left(|3+\rangle + |3-\rangle \right)
\end{aligned}$$

$$= \frac{1}{\sqrt{2}} \langle \Psi | 1+ \rangle \langle 1+ | [\cos\alpha\cos\beta |1+\rangle |2+\rangle$$
$$+ \sin\alpha \sin\beta |1+\rangle |2+\rangle] (|3+\rangle + |3-\rangle)$$

$$\begin{aligned}
&= \frac{1}{2} [\cos\alpha\cos\beta \langle 1+| \langle 2+| \langle 3+| \\
&- \sin\alpha\cos\beta \langle 1-| \langle 2+| \langle 3+| \\
&- \cos\alpha\sin\beta \langle 1+| \langle 2-| \langle 3+| \\
&+ \sin\alpha\sin\beta \langle 1-| \langle 2-| \langle 3+| \\
&+ \sin\alpha\sin\beta \langle 1+| \langle 2+| \langle 3-| \\
&+ \sin\alpha\cos\beta \langle 1+| \langle 2-| \langle 3-| \\
&+ \cos\alpha\sin\beta \langle 1-| \langle 2+| \langle 3-| \\
&+ \cos\alpha\cos\beta \langle 1-| \langle 2-| \langle 3-|] [\cos\alpha\cos\beta |1+\rangle |2+\rangle \\
&+ \sin\alpha\sin\beta |1+\rangle |2+\rangle] (|3+\rangle + |3-\rangle) \\
&= \frac{1}{2}\cos^2\theta
\end{aligned} \tag{37}$$

which matches the probability P_{++} given in (3). Again, the remaining probabilities in (3) maybe similarly calculated. Unlike in the previous case, where equation (33) was necessary to integrate, it is not necessary to integrate (37) since it comes out to be a constant with respect to β anyway.

Note that the Bell correlation function $f_{(3)}(\theta) = 3\cos(2\theta) - \cos(6\theta)$ calculated from equations (3) (see Ruhla's text [4] for calculating this) is *twice* $f_{(2)}(\theta)$, the correlation function calculated from equations (2); *i.e.* $f_{(3)}(\theta) = 2f_{(2)}(\theta)$. This means that $f_{(2)}(\theta)$ does not violate Bell's inequality (*i.e.* $|f_{(2)}(\theta)| \le 2$) as $f_{(3)}(\theta)$ does, which is to be expected since equations (2) ($\Rightarrow f_{(2)}(\theta)$) are obtainable from a 1:1 statistical mixture of *separable* equations $|1-\rangle|2-\rangle$ and $|1+\rangle|2+\rangle$ representing pairs of *unentangled* particles.

Note also that if ER are correct in their analysis, then the statistics (2) are the only ones obtained from the triply-entangled system (1). It does not matter whether a coincidence circuit is present or not; no experiment done on the system (1) will show the statistics (3). Since there is no experimental evidence which argues for one way or another regarding (1), we resort to a 2-particle system in the next section, for which there is experimental evidence.

Objections to the erasure projection operator (23).

Some readers may object to the use of the projection operator (23) used to define erasure. We argue in favor of its use here, with experimental data.

We will argue by contradiction: suppose that the erasure operator (23) is invalid. Suppose further, as ER claim, the sender performing a measurement or taking no action are the only two possible actions the sender may take. We will also assume that the statistics are the same for both operations, as ER have found.

Now Aspect and co-workers [5] have found using a Mach-Zehnder (MZ) interferometer and systems of entangled photon *pairs* represented by equation (19), that interference patterns are obtained from the photon which passes through MZ, when the polarization of the second photon of every pair is *not* measured. Behind MZ are two detectors, which revealed experimental data, showing a periodic intensity signal, one oppositely modulated from the other. See figure 2 for the apparatus, and figure 3 for the experimental data.

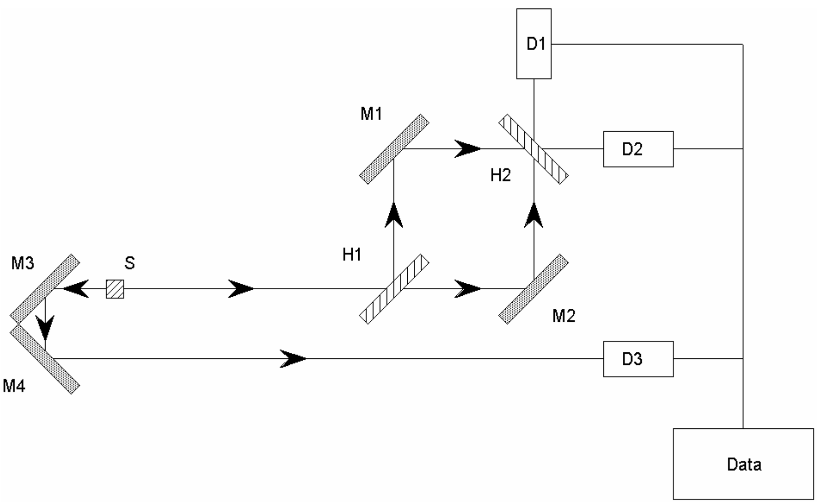

Figure 2. The experimental apparatus of Aspect and co-workers [5]. A pair of photons is emitted by *S*. Photon 1 goes through the Mach Zehnder interferometer consisting of mirrors M1, M2, and half-silvered mirrors H1, H2. Photon 1 is detected by D1 or D2. Photon 2 is reflected by mirrors M3, M4, and detected by D3. Polarization of photon 2 is not measured. It serves as a "gatekeeper," only allowing data from D1 or D2 to be admitted to the data collection device ("Data") if D3 registers a simultaneous photon.

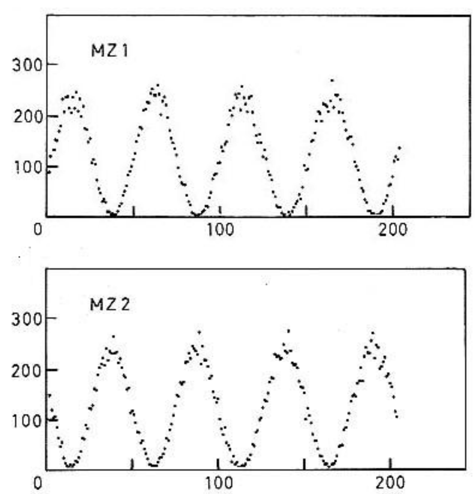

Figure 3. Experimental results (photon counts vs. L) of Aspect *et al* [5] using the instrument of figure 3. © 1986 Europhysics Letters (reprint permission pending).

Now if ER are correct, then the data of figure 3 can be calculated, assuming that the experimenter "takes no action" on photon 2, the photon which does not pass through MZ. We first the re-label (19):

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|1+\rangle|2+\rangle + |1-\rangle|2-\rangle\right) \tag{38}$$

where 1, 2 represent the numbering of the photons and +/- represent polarization. As was done with equation (32) in the previous section, we transform (38) into the basis of the plane of MZ:

$$\begin{aligned}|\Psi\rangle &= \frac{1}{\sqrt{2}}\left[\left(\cos\varphi|1+\rangle - \sin\varphi|1-\rangle\right)\left(\cos\varphi|2+\rangle - \sin\varphi|2-\rangle\right)\right.\\ &\quad\left.+\left(\sin\varphi|1+\rangle + \cos\varphi|1-\rangle\right)\left(\sin\varphi|2+\rangle + \cos\varphi|2-\rangle\right)\right]\\ &= \frac{1}{\sqrt{2}}\left(|1+\rangle|2+\rangle + |1-\rangle|2-\rangle\right)\end{aligned} \tag{39}$$

where φ is the angle between MZ, and polarization angle of either photon. Note that (39) has the same form as (38), although technically their bases are different.

Using the same transformation equations (30), we transform photon 1 into the basis of the polarizers (recall in the last step it was transformed into the basis of MZ):

$$\begin{aligned}|\Psi\rangle &= \frac{1}{\sqrt{2}}\left\{|1+\rangle\left[\cos\theta(L)|2+\rangle - \sin\theta(L)|2-\rangle\right] + |1-\rangle\left[\sin\theta(L)|2+\rangle + \cos\theta(L)|2-\rangle\right]\right\}\\ &= \frac{1}{\sqrt{2}}\left[\cos\theta(L)|1+\rangle|2+\rangle - \sin\theta(L)|1+\rangle|2-\rangle + \sin\theta(L)|1-\rangle|2+\rangle + \cos\theta(L)|1-\rangle|2-\rangle\right]\end{aligned} \tag{40}$$

Here, $\theta = \theta(L)$ is the phase difference at the half-silvered mirror H in the interferometer between photons taking one of the two paths through the interferometer. This phase difference depends linearly on the *difference* between the two path lengths, L, which is very small compared to either path's total length.

The probability of obtaining an eigenvalue α_i at time t_{r} is given by

$$P_0(\alpha_i) = \langle\Psi(0)|\tilde{\Pi}_{\alpha_i}(t_r)|\Psi(0)\rangle, \tag{41}$$

given that "no action" is taken on the respective particle. This is equation (2) in the ER paper [2].

We are now ready to calculate the polarizer statistics of photon 1, given that "no action" is taken on photon 2. We first calculate the probability $P(+1)$, the probability the MZ detector D1 registers photon 1. We get

$$
\begin{aligned}
P(+1) &= \langle \Psi | \Pi_{1,+1} | \Psi \rangle \\
&= \frac{1}{\sqrt{2}} \langle \Psi | 2+ \rangle \langle 2+ | \ \big[\cos\theta(L) |1+\rangle |2+\rangle - \sin\theta(L) |1+\rangle |2-\rangle \\
&\quad + \sin\theta(L) |1-\rangle |2+\rangle + \cos\theta(L) |1-\rangle |2-\rangle \big] \\
&= \frac{1}{2}.
\end{aligned}
\tag{42}
$$

Similarly, for D2 we get

$$
P(-1) = \frac{1}{2}. \tag{43}
$$

Thus according to (42) and (43), there should be *no* intensity variation between D1 and D2, as L is changed. This is clearly in contradiction to the data of figure 3.

Therefore the original assumption is invalid; contrary to ER's claims, taking no action or making eigenvalue measurements are *not* the only actions which may be taken. (We still agree with their assertion however that the two operations considered give the same statistics.)

On the other hand, we calculate what the statistics should be, given that erasure is a valid operation. The relevant erasure operation here is

$$
\Pi_{\mathbf{E}} = \frac{1}{2} \big(|1+\rangle \langle 1+| + |1+\rangle \langle 1-| + |1-\rangle \langle 1+| + |1-\rangle \langle 1-| \big). \tag{44}
$$

The associated probability is:

$$
P_{\mathbf{E}}(\alpha_i) = N^2 \langle \Psi(0) | \tilde{\Pi}_{\mathbf{E}}(t_s) \tilde{\Pi}_{\alpha_i}(t_r) | \Psi(0) \rangle \tag{45}
$$

where erasure is done at time t_s. Applying (44) and (45) this to (40), we get the probability D1 registers a photon (*cf*. (42))

$$
\begin{aligned}
P_{\mathbf{E}}(+1) &= N^2 \langle \Psi | \Pi_{\mathbf{E}} \Pi_{2,+1} | \Psi \rangle \\
&= \frac{2}{\sqrt{2}} \langle \Psi | \Pi_{\mathbf{E}} | 2+ \rangle \langle 2+ | \big[\cos\theta(L) |1+\rangle |2+\rangle - \sin\theta(L) |1+\rangle |2-\rangle \\
&\quad + \sin\theta(L) |1-\rangle |2+\rangle + \cos\theta(L) |1-\rangle |2-\rangle \big]
\end{aligned}
\tag{46}
$$

$$
\begin{aligned}
&= \frac{1}{\sqrt{2}} \langle \Psi | \big(|1+\rangle \langle 1+| + |1+\rangle \langle 1-| + |1-\rangle \langle 1+| + |1-\rangle \langle 1-| \big) \big[\cos\theta(L) |1+\rangle |2+\rangle \\
&\quad + \sin\theta(L) |1-\rangle |2+\rangle \big] \\
&= \frac{1}{2} \big[1 + \sin 2\theta(L) \big]
\end{aligned}
$$

Similarly, for D2 we have

$$P_{\mathrm{E}}(-1) = \frac{1}{2}\left[1 - \sin 2\theta(L)\right] \tag{47}$$

The equations (46) and (47) are plotted in figure 4. These plots match the experimental data of figure 3. Thus we claim here that the erasure operation is valid. Equations (46) and (47) were originally derived in [6], using a simpler, but more *ad hoc* argument.

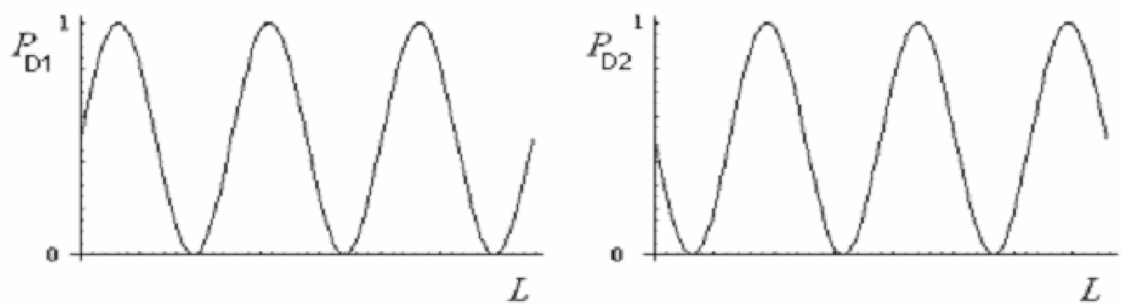

Figure 4. Equations (46) and (47) plotted on the left and right, respectively. These are the theoretical probability plots for detector D1 and D2 photon detection respectively. These plots fit the experimental data of figure 3, upon normalization.

Some basics on implementing FTLC using the device of figure 1.

In application to FTLC, the device of figure 1 will have no "coincidence circuit" between receiver and sender, in which to indicate when data are sent, and what data are noise. (Note the coincidence circuit in figure 2, where data from photon 1 are collected in coincidence with photon 2.) We argue for FTLC using photons, however similar arguments may be established for systems of other particles.

Overcoming lack of a coincidence circuit.

The first problem, lack of a coincidence circuit, can be overcome by establishing rules for sender and receiver, and standardizing times at which bits of information are to be sent. Times can be standardized by installing a beacon near the source, which emits pulses of ordinary light to either end, at given time intervals. Now for the rules:

a. The apparatus of figure 1 is placed in the top configuration by the sender if a "1" is to be sent, and that of the bottom if a "0" is to be sent.

b. Upon receiving a pulse of light from the beacon, the transmission of one bit is finished, and the transmission of the next bit is begun. Hence the apparatus can only be switched by the sender at the times at which a pulse of light from the beacon is received. Between pulses, the sender's detector is fixed either at one configuration or the other.

c. Upon receiving a pulse of light from the beacon on the receiving end, data collection for one bit is finished, and data collection for the next bit is begun.

d. The data are collected into “bins;” *i.e.* one bin for each bit. If the data from one bin is plotted and shown to fit equation (2), then the bit that was sent is interpreted as a “1.” If the data fit equation (3), then this means that a “0” was sent.

Thus, if entangled photons 1, 2,…, N are received by the sender’s detector(s) between times demarcated by two consecutive light pulses from the beacon, and hence the apparatus configuration is held fixed between those two times, then ideally those N photons’ sibling pairs will be received on the receiver’s end, and the data collected from those photons will be put into a single bin. Further, the receiver will know that all the entangled photons received between the two consecutive time stamps either give data fitting equation (2) or equation (3), if the rules are adhered to. Thus the problem of overcoming lack of coincidence circuitry is surmountable, using a set of rules which both sender and receiver have agreed upon beforehand.

Note that this technique of communication is not instantaneous; because a bit of information requires $N >> 1$ particles to construct, unless of course several apparati are used in parallel. However, if a single apparatus is used, and if the time required to construct a bit of information is Δt, and if M bits of information are to be transmitted, then so long as the distance between sender and receiver is greater than $cM\Delta t$ (c = speed of light), information transmission using this method is faster than using a conventional light pulse to send the information.

Aside, John Cramer of the University of Washington is experimenting with a device using entangled photon pairs and erasure, in order to demonstrate retrocausal, or backwards-in-time information transmission. If FTLC is possible, there is no reason to believe that retrocausal information transfer is not possible. That is, changing the location of the source so that it is closer to the receiver than the sender, does not change any of the above calculations; thus it should be possible for the receiver to receive the information before the sender has sent it! Of course this leads to a paradox, unless of course the receiver has no ability to “change the future” after the future has been presented to him.

Reducing noise.

The second problem, how to filter out noise, is a technical issue, like the first. There is *no* theory which indicates that the level of “random photons” emitted from entangled-photon sources in general is so great that effects due to entangled photons cannot be detected without the aid of a coincidence circuit. In fact, if there were such a theory, then any faster-than-light communication scheme using entangled photons would fail due to excess noise, and hence the “no-signaling” theorem of ER [2] would be superfluous.

On the other hand it has been demonstrated using parametric down conversion that coincidence counts as high as 86% [7] are obtainable, as a percentage of total photon counts. In the application here, the coincidence counts will not be so high. However, there is one advantage to FTLC when more than one particle is sent to the receiver. The receiver can weed out noise by collecting data only from photons it receives simultaneously. This eliminates noise from “singles” and in fact, by far the most noise in the receiver’s data will come from receiver-only “doubles,” which is only one of three kinds of doubles which may be emitted by the source. It is anticipated that the ratio of triples to receiver-only doubles is greater for the 3-particle system than the doubles-to-singles ratio for the 2-particle system. Thus the signal-to-noise ratio of the former should be greater than that of the latter.

A question has been raised by a reviewer as to whether or not a GHZ state is experimentally realizable. The answer to this is “yes” [8].

It is important to note however that every entangled photon propagating towards the sender must be detected, otherwise noise will increase. This is because by not detecting a given photon, the sender is in fact, “taking no action.” The arguments presented in this section are modifications of an earlier argument [9].

Conclusion.

It has been shown above that if one considers the act of erasure by the sender, then it is theoretically possible to send faster-than-light signals between sender and receiver using the device in figure 1 and a three-way Greenberger-Horne-Zeilinger entangled state described by equation (1). The sender of information alternates between eigenvalue measurements and erasure. The coincidence data collected by the receiver differs between measurement and erasure by the sender, as indicated by equations (2) and (3) respectively. This difference allows the receiver to receive information faster-than-light from the sender, by associating each with one of two different kinds of bits of information. The procedure for this is outlined above. Experimental results indicate that erasure, as defined by equation (23), is a real operation.

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