Superluminal Signalling by Path Entanglement

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Abstract

Entanglement studies dwell on multi-particle systems by definition – one particle, via a global symmetry/conservation law is correlated to another. It has often been wondered via EPR/Bell/Aspect/Dopfer-Zeilinger/Zbinden whether: first, a communication scheme is possible by entangled quantum state collapse and secondly, whether such a scheme would work over spacelike separations. This study follows on from the author's earlier scheme of sending classical data over a Bell Channel, to now, using an unentangled source. The rationale for this is that single particles are entangled with the vacuum state in path entanglement by the principle of conservation of probability: measurement of a photon in one path causes a collapse of the wavefunction in all the others. The new communication scheme represents an improvement over using expensive and complicated entangled sources of poor purity, for common-or-garden coherent sources.

1. Whence entanglement in single particle systems?

The phenomenon of Quantum Entanglement is the fascinating and logical interplay of global conservation laws and indeterminacy in measurement. For instance Bell's analysis[1, 2] and Aspect's experiment[3] focused on spin, which corresponds to angular momentum and its conservation. Franson[4] utilised entanglement resulting from a two level system and this is a manifestation of the conservation of energy.

In non-Relativistic Quantum Theory there is "Conservation of Probability". Recounting the author's earlier paper[5]:

"The probability density of a normalised wavefunction in QM is given by the square of the wavefunction:

$$\rho(\mathbf{r},t) = |\psi(\mathbf{r},t)|^2 \quad and \quad \int \rho(\mathbf{r},t) d^3r = 1 \qquad \text{eqn. 1}$$

If there is any sense in the concept, probability is conserved and would obey the continuity equation:

$$\frac{\partial \rho(\mathbf{r},t)}{\partial t} + \nabla \cdot \mathbf{j}(\mathbf{r},t) = 0 \qquad \text{eqn. 2}$$

Where the probability current density $\mathbf{j}$ is derived on application of the Schrödinger equation to the above relations as:

$$\frac{\hbar}{2mi}\left(\psi^* \nabla \psi - \psi \nabla \psi^*\right) \qquad \text{eqn. 3}$$

Take a spherical source of particles (figure 1) emitted slowly enough to be counted one at a time. Arranged on a sphere one light-year in diameter (say) is a surface of detectors. Only one particle will be counted per detection event as the light-year diameter wavefunction collapses (becomes localised) randomly so that probability is conserved. The wavefunction, mistakenly in current thought, is not perceived as something that is 'real' but is then discarded and a classical path is ascribed from the source to the detector that registered the event to say the particle, *retrospectively* went along that path."

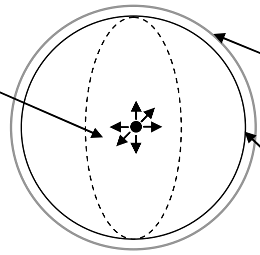

Figure 1 – Conservation of probability

The appendix analyses a beamsplitter from the Stokes relations[6, 7] to arrive at the quantum mechanical treatment. Numbering the input ports 1 and 2 and then the output ports 3 and 4, a photon through port 1 (created from the vacuum eqn. 10, appendix) of a 50:50 beamsplitter evolves thus:

$$|1\rangle_1 |0\rangle_2 \rightarrow \psi_{out} = \frac{1}{\sqrt{2}}|1\rangle_3 |0\rangle_4 + \frac{i}{\sqrt{2}}|0\rangle_3 |1\rangle_4 \qquad \text{eqn. 4}$$

This shows path entanglement and a coherent superposition of the Fock states on both ports. The expectation measurement of the photon count at port 3 or 4 is:

$$\left\langle \hat{N}_3 \right\rangle = \psi^\dagger_{out} \hat{a}^\dagger_3 \hat{a}_3 \psi_{out} \qquad \left\langle \hat{N}_4 \right\rangle = \psi^\dagger_{out} \hat{a}^\dagger_4 \hat{a}_4 \psi_{out} \qquad \text{eqn. 5}$$

This computes to ½. The joint expectation measurement $\psi_{out}^{\dagger}\hat{a}_3^{\dagger}\hat{a}_3\hat{a}_4^{\dagger}\hat{a}_4\psi_{out}$ is zero and shows that the photon cannot be at both ports.

2. The apparatus to transmit classical data over a quantum channel

The state at the output ports in eqn. 4 is coherent and the outputs can be made to interfere constructively or destructively by path length adjustment. However, if a measurement, that is, a non-unitary operation is performed on one (or both) of the output ports[8], the state will collapse into the mixed state:

$$\rho_{mixed} = \frac{1}{2}|1\rangle_3|0\rangle_4\,{}_4\langle 0|\,{}_3\langle 1| + \frac{1}{2}|0\rangle_3|1\rangle_4\,{}_4\langle 1|\,{}_3\langle 0| \quad \text{eqn. 6}$$

This is well known from simple "which path" experiments with interferometers, where in figure 2, an obstruction is suggested at the output of one of the beamsplitter ports:

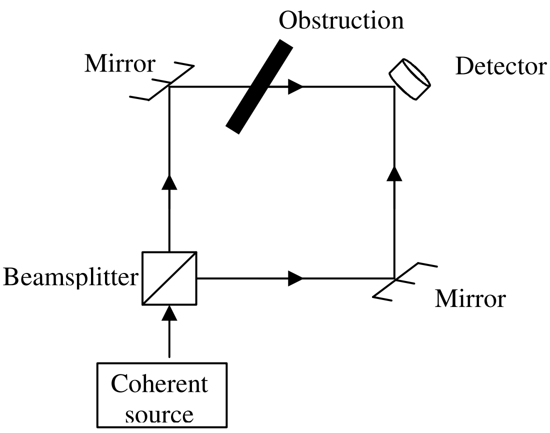

Figure 2

A re-arrangement of the interferometer can then effect the communication of classical digital data over a quantum channel[5] by interfering one output port of the interferometer with another coherent source.

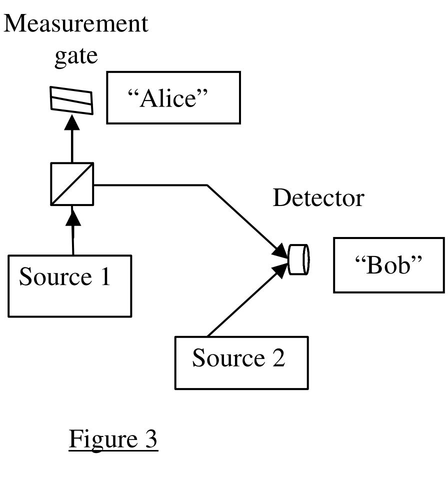

Figure 3

Obviously the two coherent sources would need good relative coherence, we shall discuss a way to use just one source later.

If we can imagine that the output ports of the beamsplitter and source are made to separate in opposite directions, the spatial arrangement of entangled and mixed states after measurement is some what akin to a ticker tape, as the wavefunction propagates through space:

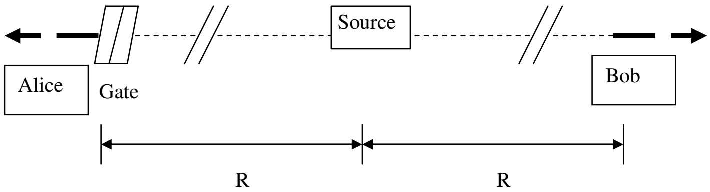

Figure 4

That is, before measurement, the wavefunction exists in space in a pure entangled state. "Bob's" interferometer will only correctly perceive the mixed state of "Alice's" measuring gate and modulations when he is equidistant or greater from the source. We note too that the coherence length/time of the sources must be greater than the "bit" time of the classical digital protocol over the quantum channel:

Alice	Bob
0: No measurement	No signal, destructive interference from pure state
1: Measurement	Signal from mixed state

Table 1 – Classical digital data over a quantum channel. Bob uses destructive interference

3. Apparatus using just one coherent source

Figure 3 required two coherent sources and it is unlikely that two sources would keep good relative coherence for long. We shall show several means to use just one coherent source.

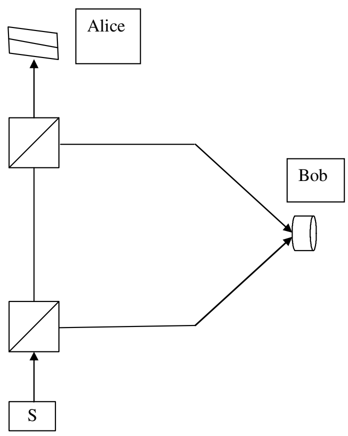

Figure 5

Figure 5 shows an arrangement with two beamsplitters that can have their reflectivities and transmissivities tailored to ensure good destructive interference at Bob's detector.

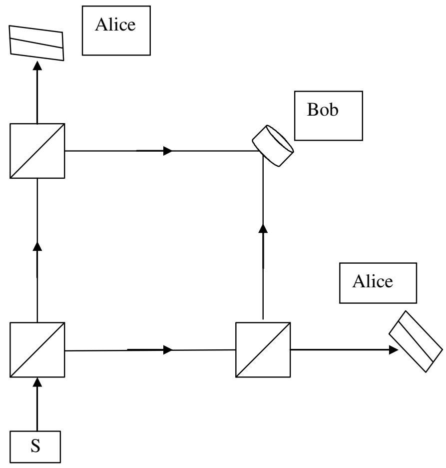

Figure 6

Figure 6 shows an arrangement with three beamsplitters and two measuring gates (though only one gate need be used). It is not to difficult to imagine ways that the paths of Alice and Bob can be brought out from the closed arrangement and sent in opposite directions by mirrors.

Figure 7 shows another method where the beam is expanded such that the widened beam is partially incident on the beamsplitter. The transmitted beamsplitter output and the part of the widened beam that skirted past the splitter are brought into interference at Bob's detector by path length adjustment (there are several means, such as a dielectric medium). The convergence of the beams can be achieved by lens or skewing the paths, as shown.

Conclusion

The focus of Cornwall's researches has been on utilising (or trying to obtain) expensive entangled sources. Apart from their obvious technical limitations, it has been proven in this paper that two particle entangled sources are not needed to affect Cornwall's[5] protocol (table 1). In due course, results of the experimentation will be presented.

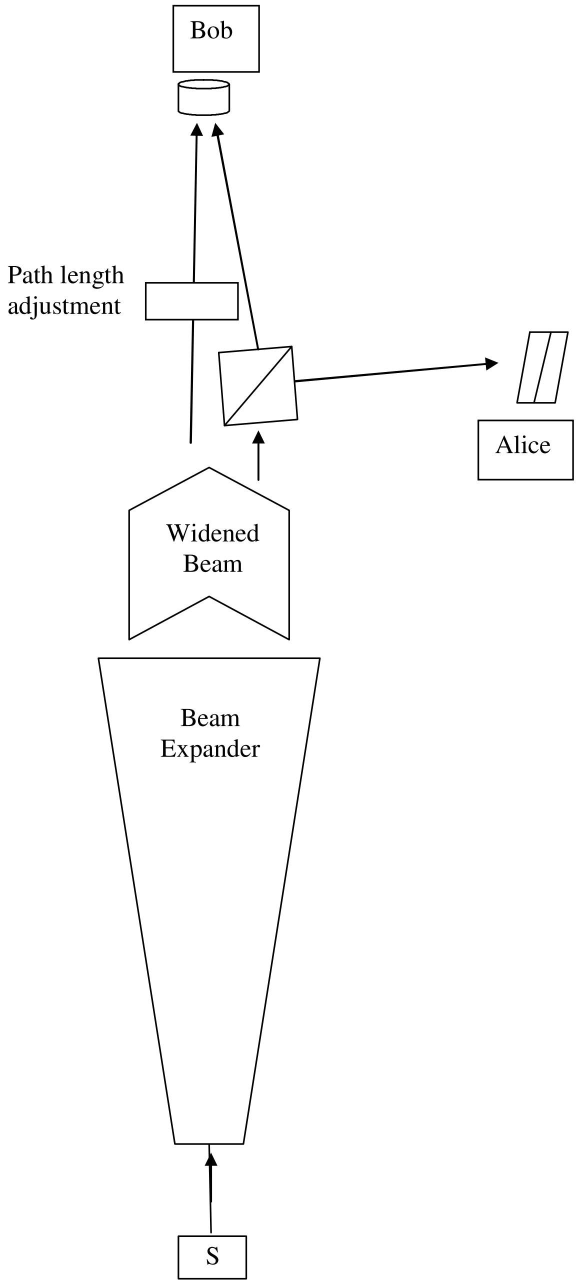

Figure 7

Appendix: Analysis of the beamsplitter

A beamsplitter[9] can be considered a four port device. We consider the source only entering one port but the beam could enter via the other. Let us call the input ports 1 and 2 and the output ports 3 and 4. To a good approximation, a beamsplitter is lossless and hence unitary, we write the evolution of electric fields (or magnetic as) :

$$\begin{pmatrix} E_1 \\ E_2 \end{pmatrix} \rightarrow \begin{pmatrix} T & R \\ R & T \end{pmatrix} \begin{pmatrix} E_3 \\ E_4 \end{pmatrix} \qquad \text{eqn. 7}$$

Where the beamsplitter 2x2 matrix coefficients are complex numbers subject to the constraints:

$$\begin{aligned} |T|^2 + |R|^2 &= 1 \\ R^* T + R T^* &= 0 \end{aligned} \qquad \text{eqn. 8}$$

The reflected and transmitted intensities are given by $|R|^2$ and $|T|^2$ respectively. If we let T = 1 and R = $|R|e^{i\theta}$, then a 50:50 beamsplitter can be represented by the matrix:

$$\frac{1}{\sqrt{2}} \begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix} \qquad \text{eqn. 9}$$

Thus a reflected photon suffers a phase shift. Photon input at a port is represented by the creation operator associated with the port acting on the vacuum state. Thus we can write, respectively, for a photon at port 1 and then port 2 as:

$$\begin{aligned} \hat{a}_1^\dagger |0\rangle &= |1\rangle_1 |0\rangle_2 \\ \hat{a}_2^\dagger |0\rangle &= |0\rangle_1 |1\rangle_2 \end{aligned} \qquad \text{eqn. 10}$$

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