Entangled “Frankenstein” Photons

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Abstract: The H> and V> outputs of a Polarizing Beam Splitter can be combined to restore the original input superposition state, as long as no knowledge is obtained regarding the path taken through the PBS. Using this principle, it should be possible to create entangled photons from the identical H> and V> components of different polarization entangled photons. These “Frankenstein” photons will also be polarization entangled and should violate a Bell Inequality.

I. Introduction

Recent experiments with entangled photons have demonstrated a variety of interesting and somewhat counterintuitive situations beyond standard Bell tests [1]. These include:

a) Entanglement of particles that have never interacted [2]
b) Entanglement of particles after they were detected (delayed choice) [2]
c) Entanglement of more than 2 photons [3]
d) Hyper-entanglement (multiple degrees of freedom) [4]
e) Entanglement of particles from fully independent sources [5]

An important element of these fascinating experiments is that they are fully consistent with the predictions of Quantum Mechanics. This is also true of the current proposal. Here, we will proceed in 3 steps towards the main result:

i) A photon with an unknown polarization may be decomposed into H> and V> components, which can then be recombined to restore the unknown state (Section II);
ii) Entangled photons may likewise be decomposed into H> and V> components, which can then be recombined to restore their entangled state (Section III);
iii) Entangled photons may be decomposed into H> and V> components, which (being identical) can then be re-arranged and combined to create photons which are in an entangled state (demonstrating that each are in fact a hybrid of both Alice and Bob) (Section IV).

These hybrid photons are here nicknamed “Frankenstein” photons to acknowledge they are made from parts of individual photons. Specifically, Chris and Dale are composed of component wave states originating from entangled twins Alice and Bob. The component wave states are here treated as real parts which can be manipulated as such.

II. Decomposition and recombination of photon polarization components: Analyzer Loops

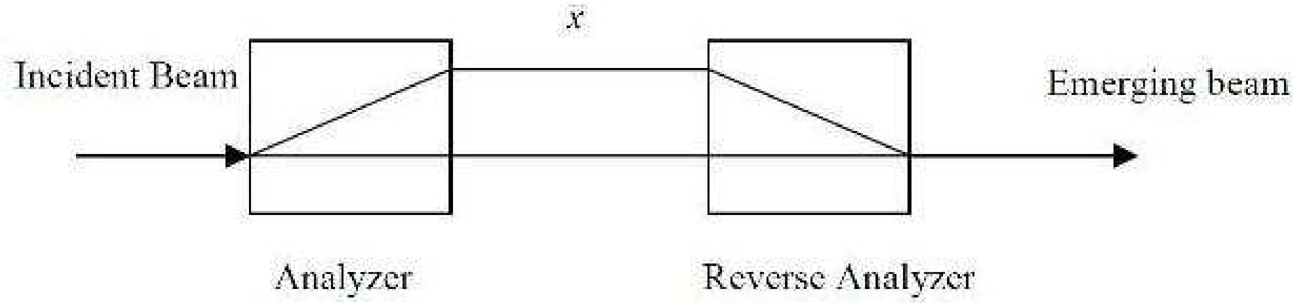

Fig. 1: An Analyzer Loop splits a beam and then recombines to restore its initial state in all respects.

According to French and Taylor [6]: An Analyzer Loop is a two-part device of which the first part is a beam splitter; and "the second part of the analyzer loop is a 'reversed' analyzer of the same type, which recombines the beams separated by the first analyzer in such a way as to reconstruct the original beam in every detail…". Presumably, the wave state of the reconstructed beam is identical to that of the initial beam. This applies on a photon by photon basis as well.

Thus: a photon which passes through such an analyzer loop – if initially in some superposition of polarizations – would return to that same superposition in the ideal case. Of course, a requirement would be that it must not be possible, in principle, to gain any knowledge of which path the photon traverses. That knowledge must be completely erased.

III. Bell Analyzer Loops and Entangled Particle Pairs

Eberly [7] has applied the above to polarization entangled photon pairs. A diagram from the reference:

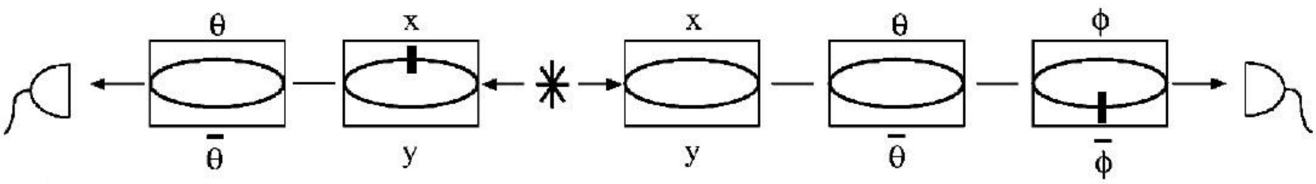

Fig. 2: A series of Bell Analyzer Loops lead to violation of Bell Inequalities, per Eberly. An entangled source [*] above has Alice going through Analyzer loops x/y and Theta/~Theta oriented at some angles. Bob goes through loops x/y, Θ/~Θ, and Φ/~Φ. Each loop for Alice and Bob splits them into components which are then recombined into their initial states. Even after such a series of loops, Eberly imagines that the resulting beams remain polarization entangled. This can be tested by checking for a violation of a suitable Bell Inequality. Eberly uses 5 loops in his example, and obtains a Bell inequality by comparing fractions of detections when one channel is blocked in each of several configurations (only one of which is shown here). The detected photons are no longer polarization entangled in this example, because the blocking of a channel reveals the path taken. Here Alice is y-polarized and Bob is Φ-polarized.

Entangled photons may go through one or more Bell Analyzer Loops on their way to being detected. Counterfactual reasoning has them taking one path or another through each loop. Eberly states: Classical analysts would say “that a state of intermediate polarization was there to be measured [in each Bell Analyzer Loop]. This assertion is the same as saying that because the photons must have gone through one or the other of the two channels, there must exist fractions representing the photon currents in the two channels. Another familiar expression of the same sentiment says that a falling tree makes noise, even if no one is available to hear it. … Quantum theory … insists that an apparatus, as it is set up and used, provides all the information that there is in an experiment. … Quantum theory says, therefore, there is no physical sense to an intermediate polarization.”

Let us assume that there is a real and definite path that the photons Alice and Bob take through the various loops. By suitable arrangement of the various permutations, Eberly obtains:

$$f(x, \Phi) + f(y,\Theta) >= f(\Theta,\Phi) \qquad (1)$$

By direct application of Malus, we obtain the following predictions (where x is set to 0 degrees):

$$f(x, \Phi) = \cos^2(0-\Phi) = \cos^2(\Phi) \qquad (2)$$
$$f(y,\Theta) = \cos^2(90-\Theta) = \sin^2(\Theta)$$
$$f(\Theta,\Phi) = \cos^2(\Phi-\Theta)$$

And after substitution into Eq. (1) we get:

$$\cos^2(\Phi) + \sin^2(\Theta) >= \cos^2(\Phi-\Theta) \qquad (3)$$

Since there are no restrictions on our choice of angles, we select the specific case where $\Phi=2\Theta$ and then end up from Eq. (3) with:

$$\cos^2(2\Theta) + \sin^2(\Theta) >= \cos^2(2\Theta-\Theta)$$

$$\cos^2(2\Theta) >= \cos^2(\Theta) - \sin^2(\Theta)$$

$$\cos^2(2\Theta) >= \cos(2\Theta) \qquad (4)$$

Whereas this inequality is false for values of Θ between 0 and 45 degrees (i.e. where $\cos(2\Theta)$ is between 0 and 1). As far as we know, this experiment (Fig. 2) has not been performed (it would be difficult to achieve in practice). However, it is clear that Quantum Mechanics would predict that the above Inequality per Eq. (4) would be violated because the realistic (counterfactual) cases do not exist, and our initial assumption was incorrect. This result relies on the idea that the each Bell Analyzer Loop “erases” the polarization result and restores the input state.

The question we now wish to address: Can the outputs of a polarizing beam splitter (PBS) be recombined to restore the initial wave state, including that of an entangled photon? I.e. can entangled Alice be split and then be merged back together so that she remains polarization entangled with Bob?

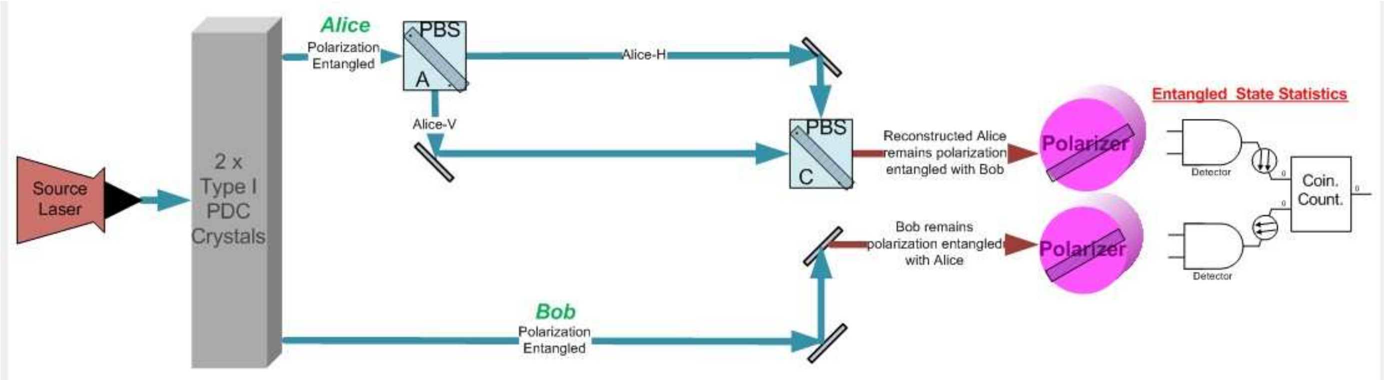

Fig. 3. Polarization entangled Alice is split into H> and V> components, then recombined to her original state. Alice is still entangled with Bob after recombination (in the ideal case).

We have reformulated the essential Eberly hypothesis as shown above. Together, PBS A and PBS C function as Bell Analyzer Loop. This is functionally equivalent to the Analyzer Loop shown in Fig. 1. In Fig. 3, Alice is decomposed by PBS A into H> and V> components. These components are recombined in some ideal reverse beam splitter PBS C in which path lengths and phase are such that the output is the original Alice. This recombined Alice is still polarization entangled with Bob.

Specifically: The output of the Type I PDC crystals, when suitably prepared, will be Alice and Bob in the polarization entangled Bell state:

$$\psi(\text{Bell}) = H_{\text{Alice}}\, H_{\text{Bob}}> + V_{\text{Alice}}\, V_{\text{Bob}}> \qquad (5)$$

So Alice, being in a superposition of H> and V> is decomposed, in some arbitrary basis Φ, into H> and V> components. These are then recombined to restore the original superposition. As before, the caveat is that we cannot obtain any knowledge of which path Alice takes through the apparatus. The PBS and the reverse PBS function as a Bell Analyzer Loop (a la Eberly) and the final state resembles the initial. Since the initial state was entangled, Alice is still entangled. It is meaningless to think of which path Alice took, as in some sense both paths were taken. Therefore we still have Eq. (5) holding. If we measure Alice and Bob at any identical polarizer setting we would expect to get the usual "perfect" correlations which are the signature of entangled particles.

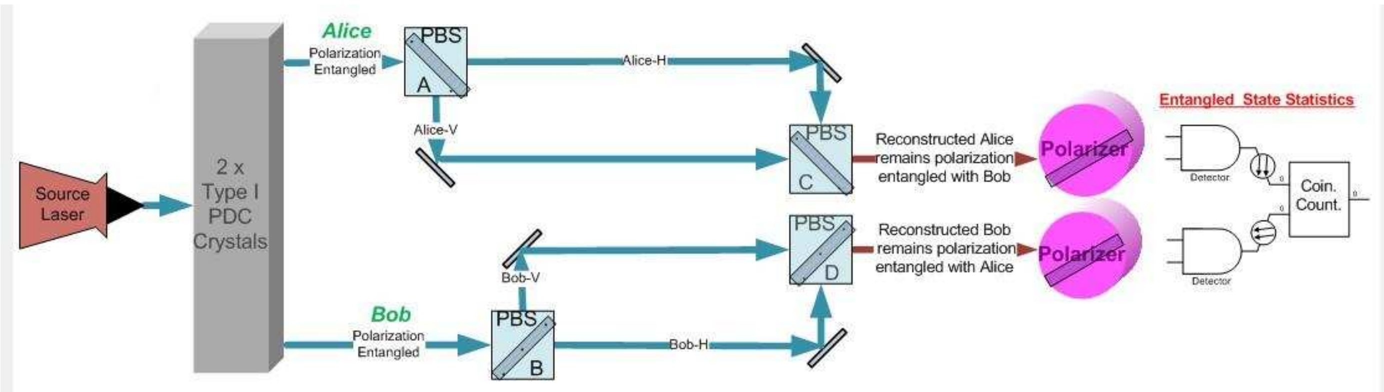

Fig. 4. Polarization entangled Alice is split into H> and V> components, then recombined to original state. Bob has the same process performed. Alice and Bob are still polarization entangled after these manipulations.

In Fig. 4 above, we extend the idea of Fig. 3 to apply to both Alice and Bob. Each are decomposed into H> and V> components in arbitrary bases Φ and Θ using PBS A and PBS B. They can then be restored to their initial entangled states using PBS C and PBS D respectively (also oriented at Φ and Θ). Alice and Bob are still entangled when they arrive at the detectors, and their Bell State can be observed. As before, we expect "perfect correlations" to indicate this state. As far as we are aware, these experiments have not been performed either. However, we believe them to be feasible. And they should be easier to realize than the Eberly setup since a single Bell Analyzer Loop is required for Alice (and optionally Bob). The Eberly setup requires a total of 5 such loops.

IV. Creating Frankenstein Photons

To create Frankenstein photons, we take the setup from Fig. 4 above and make a small change. We now require that PBS A (through which Alice passes) and PBS B (through which Bob passes) be oriented identically, let's say Φ . We need them to be separated into H> and V> components on the same basis. This makes $H_{Alice} = H_{Bob}$ as well as $V_{Alice} = V_{Bob}$. Similarly, we need PBS C and PBS D to be oriented similarly at Φ for their inputs. The paths that these components traverse must be made identical as to length, such that the actual path taken cannot be somehow distinguished by timing.

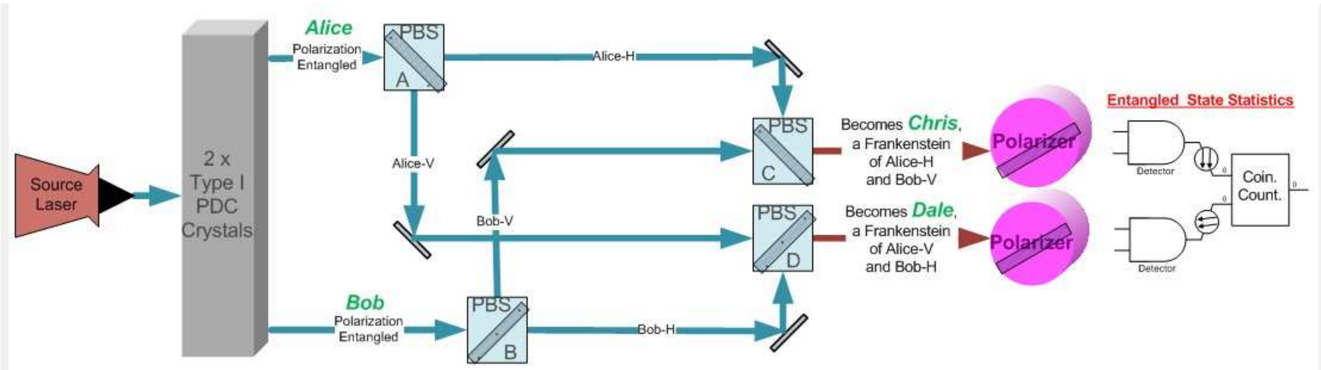

Fig 5. Polarization entangled Alice and Bob are split into H> and V> components, but recombined in a different manner than in Fig. 3. Chris and Dale are composed of one H> and one V> component each. Because the Alice and Bob H> components are identical, as are the Alice and Bob V> components, it does not matter which is combined with which. Path lengths are not shown to scale.

After emerging from PBS A and B, H_{Alice} and H_{Bob} are identical, as are V_{Alice} and V_{Bob}. PBS C and D act as reverse beam splitters, and recombine their H> and V> inputs to a single beam (when properly adjusted for path length and phase). In Fig. 4, we saw that the Alice and Bob components could be recombined in PBS C and D to "erase" the polarization measurement made when going through PBS A and B. In Fig. 5, it is shown as possible to re-arrange these H> and V> outputs of Alice and Bob in such a way as to create "Frankenstein photons" Chris and Dale. Each would be a superposition of Alice and Bob (one H> and V> component from each, as in Fig. 4). In other words, Chris is composed of half Alice and half Bob, and Dale is likewise composed of half Alice and half Bob. In a slightly modified form of Eq. (5):

$$\psi(\text{Bell}) = H_{Alice}\, H_{Bob}> + V_{Bob}\, V_{Alice}> \quad = \quad H_{Chris}\, H_{Dale}> + V_{Chris}\, V_{Dale}> \qquad (6)$$

Chris and Dale (in Fig. 5) are superpositions of H> and V> no different than the original (and recombined) Alice and Bob are in a superpositions of H> and V> (as in Fig. 4). They will be polarization entangled even though they originated as “pieces” of different photons! It must be impossible, in principle, to determine which path the photons traversed to the detectors. Then there should be no difference between Eq. (5) and Eq. (6) as to results, as they are experimentally indistinguishable and therefore both Bell State correlated.

Were we thinking in classical terms, we would say that yes, there should always be one photon presented as outputs from PBS C and PBS D. Either Alice is routed to PBS C (in which case Bob is routed to PBS D); or alternately Alice is routed to PBS D (in which case Bob is routed to PBS C). But were this a classical world, we would also say that the PBS A/B combination was an irreversible measurement of Alice and Bob and that they cannot any longer be entangled. We do not know if Chris originated from Alice or from Bob. And we do not know if Dale originated from Bob or from Alice. But we know that Chris and Dale, being in a superposition of both sources, should therefore be entangled.

Recent experiments with entanglement of photons from independent sources [5, 8] seem to support this as a proper prediction, and one which is experimentally sound. We propose that the experiment of Fig. 5 is feasible with current technology. Either Type I or Type II PDC would be suitable.

V. Conclusion

The wave function of a photon has components which can be considered “real” in the sense that they can be decomposed, manipulated and recombined in accordance with the rules of Quantum Mechanics. This includes a process in which a state component of one photon (Alice) is combined with a state component of another (Bob) to create a photon (Chris) which is, in some sense, a superposition of both Alice and Bob – but is strictly neither. Strange as this seems, it should be possible in principle to realize this experimentally.

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