2013 APS April meeting, Denver, Colorado
Abstract K2.00009
Session K2, Sunday, April 14

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# A Practical, Straightforward Experiment to Obtain Distinct Overall Which Way and Non-Which Way Distributions at a Distance Using Delayed Choice

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### The Sequel to Scully's 1991 Article in Nature and Its Relevance to The Proposed Experiment

Losing a photon that could provide which-way information to another particle with which the photon is initially entangled before a detection of either of the entangled particles was done was proposed by Scully, Englert, and Walther (1991. *Nature*, 351: 111-116 ). In the sequel to their article, an atom emitted a photon in one of two micromaser cavities filled with classical microwave radiation through which the atom initially passed. As the authors wrote: "the cavities contain classical microwave radiation…and therefore do not store which-way information…" Since the cavities were filled with microwave radiation, there was no entanglement between the emitting atom and the emitted photon. If the microwave radiation had not been present, the emitting atom and the emitted photon would have been entangled in a manner similar to Eqn. 1 in my paper where Eqns. 6 and 7 below apply. Instead, the emitting atom in the sequel is described by an equation similar to Eqn. 2 in my paper which does not show entanglement after the emitting atom loses its own which-way information. In the sequel, Scully and his colleagues are not proposing a quantum eraser. What the authors want to do there is show that one can develop an overall non which-way distribution (interference) where there would have been an overall which-way distribution where which-way information carried by the atom itself is lost. In the experiment proposed here one can either lose or not lose the idler photon which has which-way information with effects on the distant paired signal photon which does not have its own which-way information. In the sequel, on the other hand, the authors simply want to lose the emitted photon in classical microwave radiation so that it does not affect the subsequent distribution of the emitting atom.

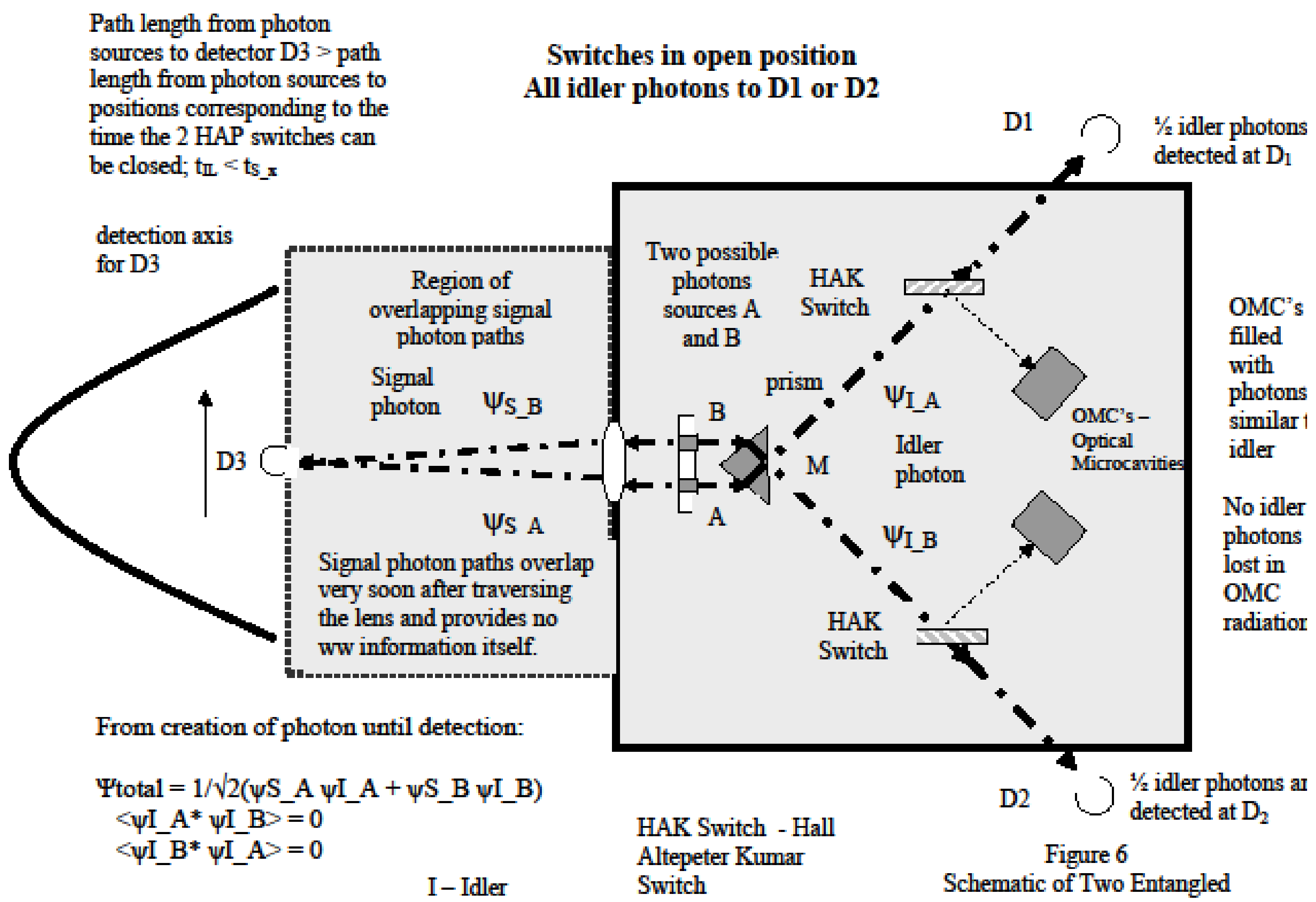


Figure 6
Schematic of Two Entangled Photons Where Switch in Open Position

P1

For a pair of entangled signal idler photons, one may "lose" the idler photon that carries which-way information and provides which-way information to the entangled signal photon before the signal photon is detected, thereby losing the entanglement. Over a number of runs, the result is an overall non-ww distribution of the signal photons. If instead the idler photon is not lost, the idler photon continues to supply ww information to the signal photon and over a number of runs the result is an overall ww distribution of the signal photons. These different overall distributions of signal photons do not depend on correlating detections of the entangled paired signal idler photons. Not needing to correlate detections allows for a delayed choice on the idler photons to determine the distribution of distant signal photons (either overall ww or overall not ww) without having to make correlations between signal and idler photon detections.

### 1. Introduction

In quantum erasure (e.g., 1,2,3), fringes and anti-fringes occur and are developed through correlating measurements on both of two entangled particles (for example, atom-photon pairs in the Scully experiment and signal-idler photon pairs in the Kim experiment). [Figures 1 and 2 near here.] In addition, the fringes and anti-fringes resulting from quantum erasure sum to an overall which-way distribution pattern. One obtains an overall which-way distribution whether or not the overall distribution results from many experimental runs where there is quantum erasure or instead from many experimental runs where there is no quantum erasure (e.g., 1,3). The fringes and anti-fringes in quantum erasure indicate that specific which path information no longer exists with erasure, but as noted *the only way to develop the fringes and anti-fringes in the quantum eraser is through correlating measurement results on the entangled paired particles*.

In contrast, the proposed experiment allows for obtaining either distinct overall which-way or non-which-way distributions at a distance *without* correlating measurements on the two paired particles and using a delayed choice (4,5,6). The underlying method essentially involves setting up a situation where one of two entangled particles (particle A) supplies which-way information to the other (particle B). One then can make a delayed choice whether or not to lose the particle that supplies the which-way information to the other. Whether or not this particle is lost determines whether or not the entanglement is lost. If particle A is not lost over many runs, then particle B shows an overall which-way distribution. If particle A is lost over many runs, then particle B shows an overall non-which-way distribution (interference).

Figure 3 presents the method to obtain distinct overall which-way and non-which-way distributions at a distance. [Figure 3 near here.] The conceptual foundation of an experiment is developed below involving photons that implements the method in a practical way. A very important consequence of the experiment is that one can use delayed choice with the idler photons to determine the distribution of distant signal photons (overall ww or overall not ww distributions) without having to take time to make correlations between signal and idler photon measurements. The experiment provides the basis for a useful digital delayed choice quantum communications device.

### 2. The Conceptual Foundation of the Experiment

This section provides an outline of the conceptual foundation of the experiment, the first conceptual formulation of the experiment, and the conceptual formulation of a practical version of the experiment.

*2.1 Conceptual Outline of Experiment*

The proposed experiment relies on a delayed choice whether or not to keep the entanglement between paired signal and idler photons where the idler photon provides which-way information to a distant signal photon. One can produce an overall distribution of the signal photons showing interference by losing the idler photons in many other similar photons over many experimental runs or instead an overall which-way distribution for the signal photons at a distance by not losing their paired idler photons over many experimental runs. The idler photon is either detected or lost before the entangled signal photon is detected. Ultrafast switches for single entangled photons can be used to change the paths for the idler photon while the idler photon is in flight. An optical microcavity filled with photons similar to the idler photon can be used to lose the idler photon. No correlations between measurements on the paired signal-idler photons are needed to develop the signal photon distributions noted above.

P2

As a first test, movable mirrors can be used instead of the ultrafast switches to either send an idler photon to one of two detectors along the two idler photon paths or instead send the idler photon into an optical microcavity filled with photons similar to the idler photon. The result is two different distributions of the paired signal photons depending on whether or not the idler photons are lost before the paired signal photons are detected.

*2.2 The First Conceptual Formulation of the Experiment*

The first conceptual formulation of the experiment (6) employs the same setup as the quantum eraser experiment of Kim's quantum eraser setup (2) (Fig. 2) with certain changes.

2.2.1 The Kim Quantum Eraser - The Kim quantum eraser uses a device that can act as an interferometer with two separate locations at the entrance where each of the locations has the possibility of generating an entangled signal idler photon pair but where only one location generates an entangled signal idler photon pair at a time. The two locations where the entangled signal idler photon pair can be generated are analogous to the two slits in a two slit screen. The idler photons initially travel through the interferometer along one of two possible paths, each path associated with one of the two possible locations for generating an entangled signal idler photon pair. The signal photons travel away from the entrance of the interferometer and also from the paired idler photons in what for the signal photons are essentially a two slit device. The signal idler photon pair's entanglement incorporates the idler photon's providing which-way information to the signal photon that eventually manifests itself in the form of the overall distribution of the signal photons at their detection axis (one wide hump) in the quantum erasure condition in the Kim experiment.

Besides functioning as an interferometer that allowed for quantum erasure, Kim and his colleagues structured their device so that one-half of the idler photons passing through the first part of the device, specifically that part of the device from M to Y or Z, could instead provide definitive which-way information regarding the specific paths of paired signal photons when correlations between detection events for paired signal and idler photons are made. They accomplished this through the use of beam splitters instead of full-silvered mirrors at Y and Z. In their experiment, ½ of the generated idler photons traveled through the beam splitters at Y and Z instead of being reflected at Y and Z toward beam splitter BS at N.

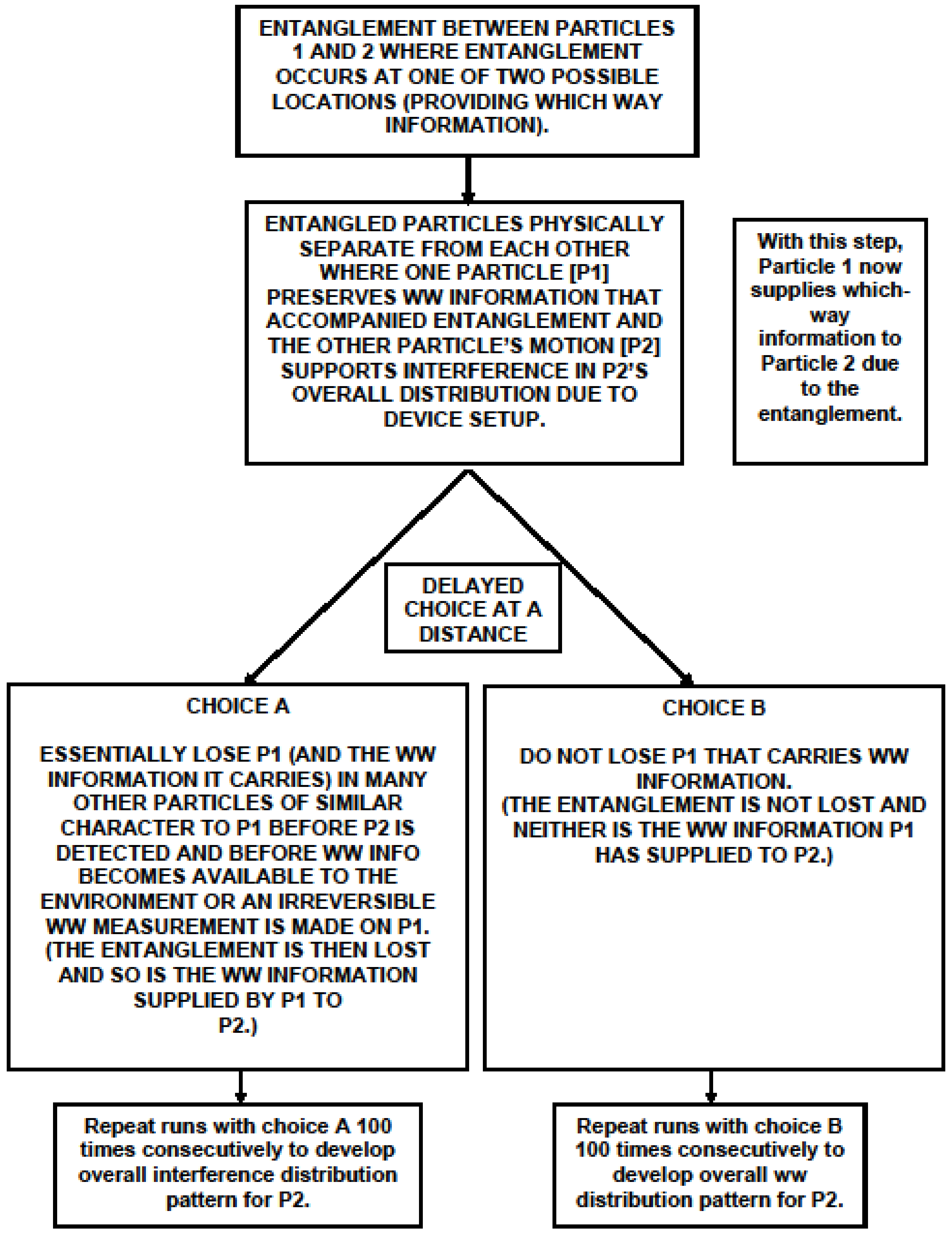
Our concern here, though, is with the ½ of the idler photons that are reflected off the beam splitters at Y or Z. For the ½ of the generated idler photons that are instead reflected at the beam splitters at Y or Z toward BS at N and that are subsequently detected at either detector D1 or detector D2, the distributions of the signal photons detected at D5 along a spatial axis x correlated with the detections of their paired idler photons are two multiple narrow hump sub-distributions that indicate the presence of interference (i.e., fringes and anti-fringes).

As noted, the fringes and anti-fringes sub-distributions for the signal photons sum to the one wide hump characteristic of which-way information. These fringes and anti-fringes indicate the loss of which-way information concerning the specific path through the interferometer of the paired idler photons that are reflected from BS at N. This specific which-way information concerning the path of the idler photon through the interferometer until BS at N stemmed from the origin of the entangled idler and signal photon pairs at one specific location of two possible ones at which the signal-idler photon pair could be generated.

Even though specific which-way information is lost concerning the path of the idler photon through the interferometer when the idler photon passes through BS at N, general which-way information appears to be preserved (since the entanglement is preserved) in the overall one wide hump distribution of the signal photons of the signal-idler photon pairs. An inspection of Figure 2 shows that when the idler photon passes through BS at N, it has arrived via a single path since it originated at 1 of the two "slits". This general which-way information that the idler photon arrived at BS at N from one of two possible paths is preserved in the overall which-way distribution of the idler photons. This overall which-way distribution is the sum of the fringes and anti-fringes where these fringes and anti-fringes depend on correlations between paired signal and idler photons and where these fringes and anti-fringes show the loss of specific which-way information concerning at which "slit" of the two possible "slits" the signal-idler photon pair was created even though we know that the signal-idler pair was created at one of them.

The proposed experiment relies on a delayed choice whether or not to keep the entanglement between paired signal and idler photons where the idler photon provides which way information to a distant signal photon. One can produce an overall distribution of the signal photons showing interference by losing the idler photons in many other similar photons over many experimental runs or instead an overall which way distribution for the signal photons at a distance by not losing their paired idler photons over many experimental runs. The idler photon is either detected or lost before the entangled signal photon is detected. The overall which way or non which way distributions (the latter exhibiting interference) for the signal photons are not dependent on correlating measurement results on the paired signal and idler photons. Ultrafast switches (such as that of Hall, Altepeter, and Kumar, http://iopscience.iop.org/1367-2630/13/10/105004/fulltext/) can be used to change the paths for the idler photon while the idler photon is in flight. Optical microcavities filled with photons similar to the idler photon can be used to lose the idler photon. The method underlying the experiment is described. One reference to the delayed choice method proposed here is: http://meetings.aps.org/link/BAPS.2012.MAR.K1.303.

Fig. 3



ENTANGLEMENT BETWEEN PARTICLES 1 AND 2 WHERE ENTANGLEMENT OCCURS AT ONE OF TWO POSSIBLE LOCATIONS (PROVIDING WHICH WAY INFORMATION).

ENTANGLED PARTICLES PHYSICALLY SEPARATE FROM EACH OTHER WHERE ONE PARTICLE [P1] PRESERVES WW INFORMATION THAT ACCOMPANIED ENTANGLEMENT AND THE OTHER PARTICLE'S MOTION [P2] SUPPORTS INTERFERENCE IN P2'S OVERALL DISTRIBUTION DUE TO DEVICE SETUP.

With this step, Particle 1 now supplies which-way information to Particle 2 due to the entanglement.

DELAYED CHOICE AT A DISTANCE

CHOICE A

ESSENTIALLY LOSE P1 (AND THE WW INFORMATION IT CARRIES) IN MANY OTHER PARTICLES OF SIMILAR CHARACTER TO P1 BEFORE P2 IS DETECTED AND BEFORE WW INFO BECOMES AVAILABLE TO THE ENVIRONMENT OR AN IRREVERSIBLE WW MEASUREMENT IS MADE ON P1. (THE ENTANGLEMENT IS THEN LOST AND SO IS THE WW INFORMATION SUPPLIED BY P1 TO P2.)

CHOICE B

DO NOT LOSE P1 THAT CARRIES WW INFORMATION. (THE ENTANGLEMENT IS NOT LOST AND NEITHER IS THE WW INFORMATION P1 HAS SUPPLIED TO P2.)

Repeat runs with choice A 100 times consecutively to develop overall interference distribution pattern for P2.

Repeat runs with choice B 100 times consecutively to develop overall ww distribution pattern for P2.

**5. References**

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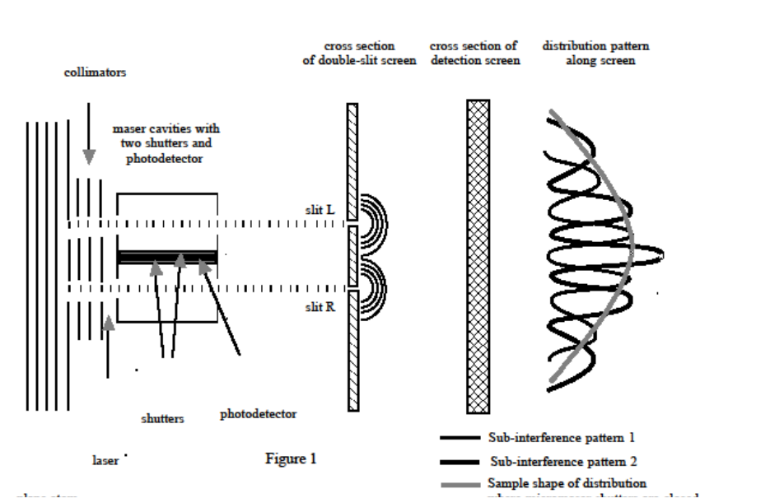

Figure 1

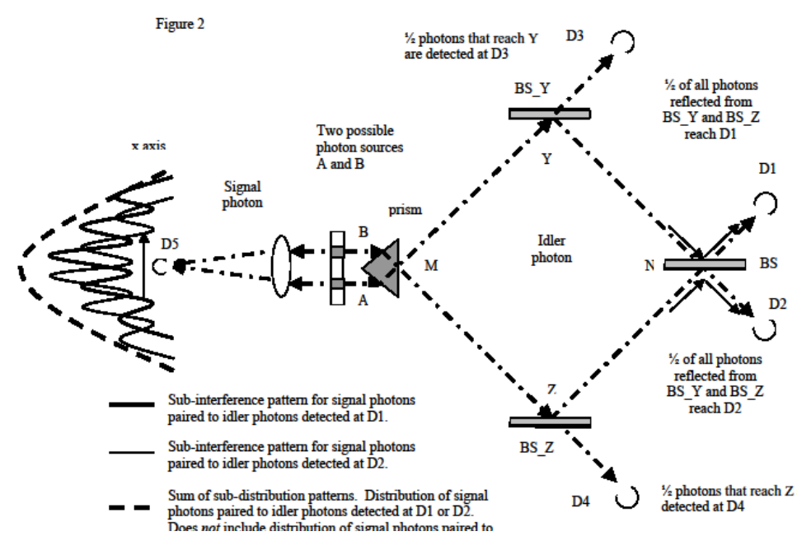
Figure 2

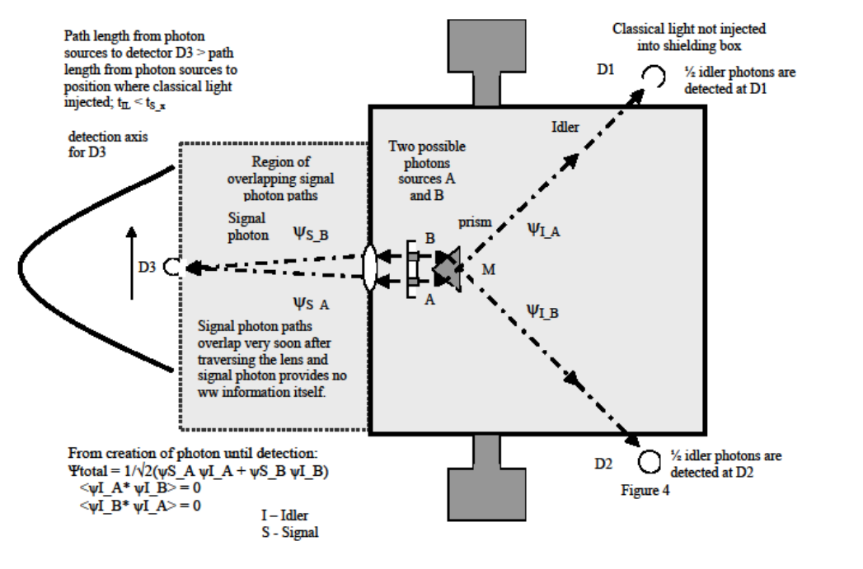

Figure 4

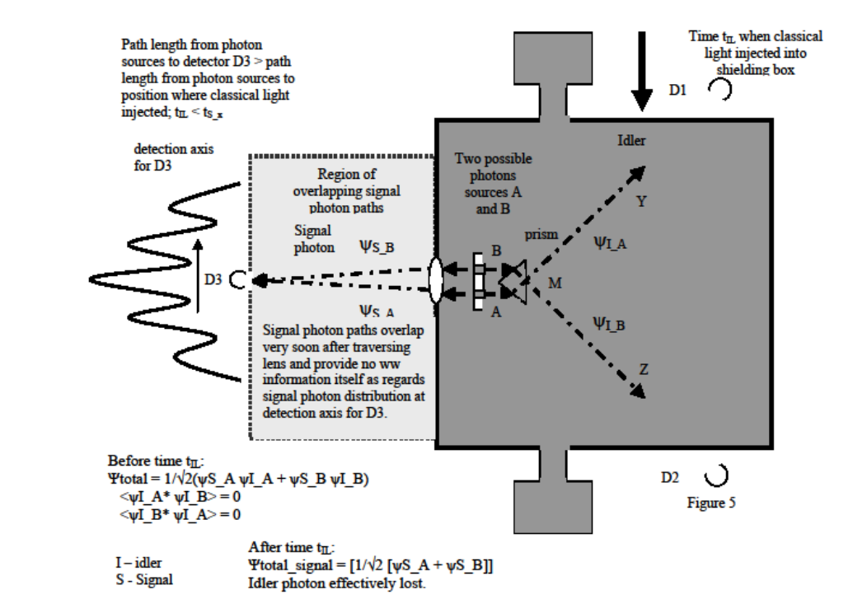

Figure 5

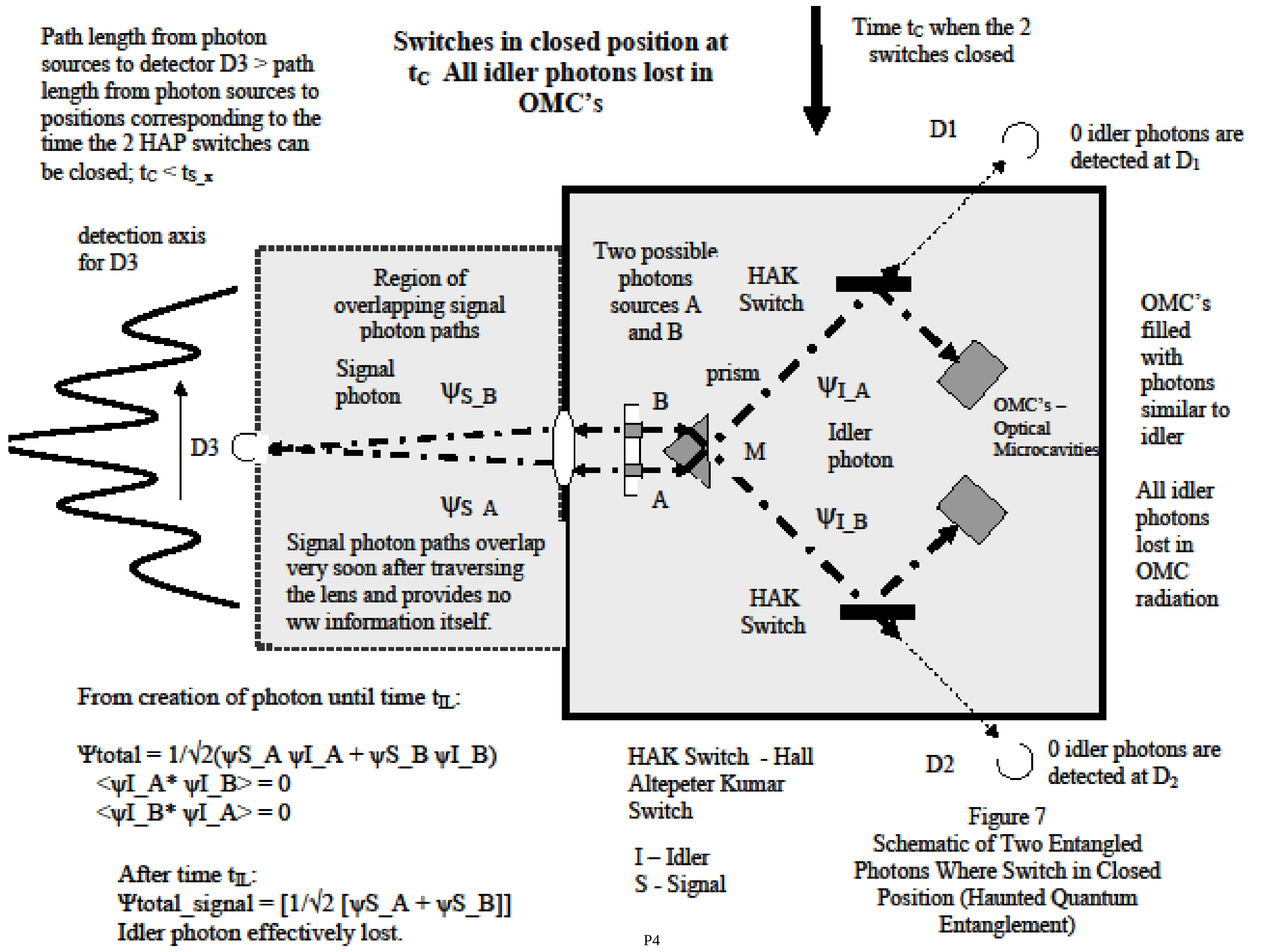

Figure 7
Schematic of Two Entangled Photons Where Switch in Closed Position (Haunted Quantum Entanglement)

P3

As noted, which-way information regarding the distribution of the signal photon at its detection axis is not provided in the Kim experiment by the signal photon itself traveling away from the interferometer and toward the spatial axis where its location is detected. Shortly after the signal-idler photon pair is generated, due to the dimensions of the "double slit," the component wave functions for the signal photon for the two possible locations where the signal-idler photon pair were created (i.e., the "double slit") overlap.

The dimensions of the double slit relative to the wavelength of the signal photons supports interference in the distribution of the signal photons at their detection axis in the absence of which-way information provided by the paired idler photons.

*2.2.2. Alterations in the Kim Quantum Eraser and Their Implications in the First Conceptual Formulation of the Experiment* - The following changes are made in the Kim quantum eraser: [Figures 4 and 5 near here.]

1. Only the first two arms of the interferometer over which the idler photons can travel, with each arm starting at one of the two possible photon sources, are used.
2. At the end of each of these arms is a photon detector instead of a beam splitter.
3. The portion of the apparatus through which the idler photon travels is isolated from the environment until just before the photon detectors. The portion of the apparatus through which the signal photon travels is also isolated until just before the signal photon is detected.
4. Attached to the container through which the idler photon travels are two reservoirs containing many photons similar in character to the idler photon. These reservoirs are closed off from the container but can be opened so that the photons in the reservoirs are injected into the container.

In the present experiment, the idler photon can be essentially lost before the signal photon is detected and before which-way information from the idler photon is available to the environment. In other words, we begin with Eqn. 1 below, *but with the essential loss of the idler photon we have Eqn. 2 that describes only the signal photon since the entanglement is lost since the idler photon is lost*.

$$\psi = 1/\sqrt{2}\,[(S_A)|I_A\rangle + (S_B)|I_B\rangle] \qquad [1]$$

where S and I represent the signal and idler photons, respectively, and A and B represent the two possible locations where the signal-idler photon pairs are initially created. *Eqn. 1 is the equation for the quantum eraser (1), and it is known to be correct because of the empirical evidence that supports the quantum eraser (e.g., 1,2,3). As noted, we rely on the first part of the Kim quantum eraser setup in which the entangled signal idler photon pairs are generated and therefore Eqn. 1 is applicable in the proposed experiment until the idler photon is lost and the signal idler photon entanglement is lost.*

$$\psi = [1/\sqrt{2}\,[(S_A) + (S_B)]] \qquad [2]$$

and

$$|\psi|^2 = 1/2\,[|(S_A)|^2 + (S_A)^*(S_B) + (S_B)^*(S_A) + |(S_B)|^2]\,. \qquad [3]$$

*Eqn. 2 is not the quantum eraser because in the quantum eraser entanglement is maintained (e.g., 1,2,3).*

Essentially, the Kim setup is altered through introducing the possibility of "losing" the entangled idler photon in many similar photons before the paired signal photon is detected. In the first conceptual formulation, these photons similar to the idler photon are injected into a container through which the idler photon is traveling before the idler photon reaches a detector and that isolates the idler photon from the environment. At the creation of the entangled signal-idler photon pairs, both the signal and idler photons possess which-way information due to their creation at one of two "slits". After their creation, the signal photon immediately loses its which-way information since the signal photon is essentially in a two slit device setup and pathways to the signal photon detector overlap. On the other hand, the idler photon maintains the which-way information since each "slit" leads to a separate path in the first part of an interferometer. *Over a series of runs, if the idler photon is lost in many other similar photons, the signal photon, having no which-way information of its own, shows an overall distribution of non-which-way information, an interference pattern (Eqn. 3). If the idler photon is not lost, over a series of runs the signal photon shows an overall which-way distribution pattern (the absolute square of Eqn. 1 which is Eqn. 5 below).* The distribution of the signal photons is in this case given by

P4

$$|\psi|^2 = 1/2\,[|(S_A)|^2 \langle I_A | I_A\rangle + |(S_B)|^2 \langle I_B | I_B\rangle + (S_A{}^* S_B)\langle I_A | I_B\rangle + (S_B{}^* S_A)\langle I_B | I_A\rangle] \qquad [4]$$

where $|I_A\rangle$ and $|I_B\rangle$ then serve as which-way markers or

$$|\psi|^2 = 1/2|(S_A)|^2 + 1/2|(S_B)|^2 \qquad [5]$$

since

$$\langle I_A | I_B\rangle = 0 \qquad [6]$$

$$\langle I_B | I_A\rangle = 0 \qquad [7]$$

*2.3 A Practical Conceptual Formulation of the Experiment*

The first conceptual formulation of the experiment appeared difficult to implement so two questions were investigated: 1) would it be possible to switch the idler photon from paths leading to detectors to paths that would lead the idler photon to a mechanism where the idler photon would be lost in many similar photons; 2) does such a mechanism exist where the idler photon could be lost in many similar photons? [Figures 6 and 7 near here.]

Regarding point 1, an ultrafast switch for a single entangled photon developed by Hall, Altepeter, and Kumar (HAK) (7,8) was found that would switch the idler photon from paths leading to detectors to paths that would lead the idler photon to a mechanism where the idler photon would be lost in many similar photons. Regarding point 2, an optical microcavity filled with many photons similar to the idler photon is a device in which the idler photon could be lost in many similar photons (9). (In the present experiment, two optical microcavities are used, one along each possible idler photon path.) (Jan Wiersig confirmed in a personal communication that a small microcavity with a high quality factor would work. Possible candidates are microdisks, micropillars, and photonic crystal defect cavities.). The optical microcavity is situated at the crossing point for the two idler photon paths that occur when the ultrafast switches located on the two possible paths for the photon after it is created are on. (Wiersig confirmed that a single optical microcavity would work in the setup I propose.) Figures 6 and 7 present the practical conceptual formulation of the experiment. With these new features, the reservoirs of photons similar to the idler photon are not needed and are removed in this practical conceptual formulation of the experiment. Other features of the first conceptual formulation of the experiment are not changed.

To begin with, one might substitute movable mirrors for the HAK switches that could be moved between one position that directs the idler photons to photon detectors over a number of experimental runs and another position that directs the idler photons to an optical microcavity filled with photons similar to the idler photon over a number of experimental runs.

### 3. A Digital Quantum Communications Device

The conceptual formulation of the experiment allows for distinct which-way and non-which-way distributions of the signal photons depending on whether paired idler photons with which the signal photons are entangled are lost. As noted, no correlations are needed between the signal photon measurements and the idler photon measurements to develop either the which-way or instead non-which-way distributions of the paired signal photons with which the idler photons are entangled. A very important consequence is that one can use delayed choice with the idler photons to determine the distribution of distant signal photons (overall ww or overall not ww distributions) without having to take time to make correlations between signal and idler photon measurements. The experiment provides the basis for a useful digital delayed choice quantum communications device. The which-way and non-which-way distributions can represent two bits 0 and 1, respectively. This possibility indicates that the conceptual formulation of the experiment could lead to the development of a useful digital delayed choice quantum communications device.

### 4. Conclusion

The conceptual foundation for a practical experiment to obtain overall distinct which-way and non-which-way distributions at a distance using a delayed choice and without needing to correlate measurements on paired particles has been presented. *The conceptual formulation of the proposed experiment differs from the quantum eraser in at least one important way, namely the fringes and anti-fringes of the quantum eraser depend on correlating measurement events on the members of entangled paired particles and the conceptual formulation of the proposed experiment does not.* The experimental setup used by Kim is changed to allow for a delayed choice of: 1) losing the idler photon in many similar particles before the paired signal photon is detected and before which-way information on the idler photon is available in the environment, or 2) not losing the idler photon which is then detected at one of two idler photon detectors. Ultrafast switches are used to route the idler photon either toward the photon detectors or toward an optical microcavity where the idler photon is lost in many similar photons. Losing the idler photon means losing the entanglement between paired signal and idler photons. The different distributions of the signal photons can be used as the basis for a useful digital delayed choice quantum communication device.