Symmetry Sorting in a Delayed Choice Quantum Eraser

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Abstract:

We propose that the delayed "choice" quantum eraser experiment described by Kim *et al.* actually demonstrates a symmetry sorter in which predetermined information about the radiation symmetry of a parametric double source of correlated photons is either sorted or not after some delay. This interpretation eliminates the need for nonlocal, time-reversed explanations involving notions of delayed choice, which-path determination, and quantum entanglement.

PACS numbers: 03.65.Ta, 42.50.Xa, 42.25.Kb, 42.65.Lm

Text:

The principle behind “delayed choice,” as first described by Wheeler [1], asserts that the properties of a photon depend on how it is measured, irrespective of its history. In a delayed-choice experiment the decision to measure the quantum is delayed until after it has presumably committed itself to one property or another, such as particle or wave. According to Wheeler, this creates “an unavoidable effect on what we have a right to say about the already past history of that photon.” [2]

Kim *et al.* have reported on an experiment with entangled photons [3] that combines delayed choice with “quantum erasure,” a term that subscribes to the notion that information about which path a photon takes can be either preserved or erased, and in so doing reveals its wave- or particlelike nature through the presence or absence of interference effects. In their experiment, each photon of an entangled pair is directed into a separate interferometer, but the registration of one photon (via coincidence detection) is intentionally delayed relative to its twin. The delayed photon encounters a set of beam splitters and detectors that the experimenters claim randomly determines the particle- or wavelike properties of *both* entangled photons based on which path the delayed photon chooses to take at each beam splitter. Even though these complementary properties are purportedly decided after the registration of the undelayed photon at another location, the wave/particle behavior of both photons still correlates.

The entangled photons are created inside a single nonlinear crystal of β-barium borate (BBO) using spontaneous parametric down conversion (SPDC) with non-collinear type-II phase matching (Fig. 1). A slit mask in front of the BBO crystal divides the wavefront of a single Argon-ion laser beam into two closely spaced beams that pump two regions (1 and 2) of the BBO.

With non-collinear type-II phase matching, the parametrically pumped regions within the crystal create divergent pairs of signal/idler photons, denoted here as γ and φ, respectively. A Glan-Thompson prism (not shown in Fig. 1) is used to separate the orthogonally polarized γ-φ photons into two different interferometers. Both crystal regions contribute to each γ and each φ created, and form a double source imitating Young's classic double-slit source.

The γ photons propagate through a lens where a single scanning detector D_0 in the focal plane records their spatial distribution along a horizontal axis. The φ photons propagate into four exit channels defined by three 50-50 beam splitters (BSA, BSB, and BS) and four detectors D_α ($\alpha = 1, 2, 3, 4$). The optical path lengths from the BBO to D_α are all equal, but the path length from the BBO to D_0 is intentionally made shorter.

D_0 is linked to D_α through coincidence circuitry, which enables the collection and collation of joint detection events (γ detections at D_0 paired with φ detections at D_α). Since γ-φ photon pairs are created simultaneously in the BBO, a γ detection at D_0 is followed a known time later by a φ detection at one of the D_α detectors, the delay time depending on the optical path-length difference between the BBO and detectors D_0 and D_α.

The experiment is conducted by recording joint detections between D_0 and D_α as D_0 is scanned across the focal plane of the lens. The patterns recorded by D_0 are sorted and displayed separately according to which D_α coincidence is involved. The joint detection data of D_0-D_1 reveal a classic double-slit interference pattern, while D_0-D_2 shows the same pattern phase-shifted π radians, in other words with maxima and minima interchanged. Such interference would indicate wavelike behavior. However, the joint-detection data for D_0-D_3 and D_0-D_4 yield single-slit diffraction patterns with a sinc^2 distribution and no apparent interference modulation, which has been construed as particlelike behavior implying that each photon followed a path originating at one or the other of the two “slits.”

These results have led many physicists to conclude that events happening in the future (signified in the experiment as the random path “choices” made by each φ photon at the beam splitters) can control events of the past (represented here as which spatial distribution the corresponding γ photon has previously fallen into). One observer has called the experiment “a magnificent affront to our conventional notions of space and time.” [4] Others have declared that it “dramatically underscores the difference between our classical conceptions of time and how quantum processes can unfold in time.” [5]

We offer an alternative interpretation that obviates the need for time-reversed speculations involving quantum entanglement, which-path information, and delayed choice. It considers the radiation symmetry of the parametrically driven double source, the nature of photon propagation, and wavefunction collapse.

First, we note that coherent parametric pumping of the BBO creates symmetric or antisymmetric emission from the two regions. This is because the phase-matching condition requires that the sum of the phases of γ and φ waves equals that of the pump wave in both regions 1 and 2. This condition is unchanged if π radians are added to γ and φ phases in just one of the two regions. Therefore both symmetric (in-phase) and antisymmetric (anti-phase) radiation states satisfy the parametric conditions. These even or odd symmetry excitations can be expected to arise spontaneously with equal probability from the traveling wave of nonlinear susceptibility created by the pump beam. *The γ and φ waves exit the crystal with the same symmetry because both waves are created simultaneously by a double source that is either in-phase or anti-phase.* [6] The future of these photons is all but established at this point except for the presence of beam splitters BSA and BSB, which, as we shall show, add nothing of consequence to the experiment.

Next, we maintain that light radiated from a source propagates through space in a manner independent of its intensity, the principles of physical optics applying irrespective of photon flux, even for single photons. A single quantum of light can fill the same space as a multi-photon beam from the same source. This picture is implicit in Fermi's classic review paper on the quantum theory of radiation [7,8]. In short, the photon propagates as a wave and reveals its quantum nature upon absorption.

A critical example of this single-photon propagation occurs at beam splitter BS, where the φ_2 branch of the φ wave undergoes the same π-radian phase shift upon reflection as a continuous wave would. Moreover, the phase difference along the φ_1 and φ_2 branches is either zero or π radians (depending on the source symmetry) for equal path lengths from the source. The resulting interference pattern causes D_2 to be dark for the symmetric state, and D_0-D_2 consequently registers no coincidence counts; while for the antisymmetric state, D_1 is dark and D_0-D_1 registers no coincidence counts (Fig. 2). *It is* *interference and not random "choice" that determines the outcome of the encounter of the multi-path quantum with BS.*

The φ interferometer defined by BS, D_1, and D_2 therefore functions as a symmetry sorter. D_0-D_1 coincidences flag the symmetric state (Fig. 2a), while D_0-D_2 coincidences flag the antisymmetric state (Fig. 2b). On the γ side of the experiment, the scanning D_0 detector encounters two complementary intensity patterns: $\mathrm{sinc}^2\cos^2$ for the symmetric state, and $\mathrm{sinc}^2\sin^2$ for the antisymmetric state. *In this way φ registrations at D_1 and D_2 provide a symmetry-sorting key for segregating γ registrations into two subsets.*

The intended role of D_3 and D_4 is to provide which-path information for identifying either slit 2 or 1, respectively, as the source of γ photons via φ registrations and the "entanglement" property, thereby demonstrating that such information prohibits interference from the double-slit setup. However, we maintain that D_0-D_3 and D_0-D_4 coincidence data cannot display interference fringes for simpler reasons.

To better explain the D_0-D_3 and D_0-D_4 coincidence data, we simply remove all of the beam splitters (BS, BSA, and BSB) from the apparatus depicted in Fig. 1. With the beam splitters removed, D_1 and D_2 function as D_3 and D_4, respectively (Fig. 3). This arrangement creates two separate exit channels for a single, double-slit parametric light source. This is a prototypical condition for applying the concept of wavefunction collapse—one source, two available paths, two detectors, and one photon. At single-photon flux levels, only one detector can respond. When a photon is detected at D_4, for example, there is no energy left to support that part of the wavefunction approaching D_3, which goes to zero [9]. The same is true for a detection event at D_3, in which case the wavefunction approaching D_4 collapses.

Because of this wavefunction collapse, a registration at one detector does not necessarily prove that the photon was created in only one region of the BBO, since each detector can only respond to one part of the wavefunction created by both regions. D_3 and D_4 also cannot distinguish between symmetric and antisymmetric photons because they react equally to both; and this is consistent with what one expects with propagation of multi-photon beams through the apparatus. The removal of BS eliminates the sorting capacity because which-symmetry information is rendered inaccessible to D_3 and D_4. Consequently, D_0-D_3 and D_0-D_4 coincidences can assign both $\mathrm{sinc}^2\cos^2$ and $\mathrm{sinc}^2\sin^2$ distributions from the γ side of the apparatus. The accumulation of the two distributions would be a sinc^2 pattern indistinguishable from the single-slit diffraction pattern observed in the experiments. *Thus the role of which-path information as a criterion for non-interference is unsupported.*

In the original experiment (Fig. 1), the sorting and non-sorting conditions are combined through the use of beam splitters BS, BSA, BSB, and the four detectors D_α. The presence of beam splitter BS enables segregation of which-symmetry information, whereas this same information is simply unavailable and effectively unsegregated in the exit channels defined by BSA-D_4 and BSB-D_3. *We know of no physical mechanism that can exploit coincidences involving D_3 or D_4 in order to display γ fringes.* The failure of D_0-D_3 and D_0-D_4 coincidences to display γ fringes therefore provides no logical proof that γ photons have been committed to one path or the other by subsequent φ registrations at D_3 and D_4. The result is unsurprising and seems unrelated to considerations of delayed choice, quantum erasure, or entanglement.

The entire set of D_0-D_α coincidence data therefore amounts to a symmetry ledger containing two categories of four equal subsets: symmetry known (D_0-D_1 and D_0-D_2 data) and symmetry unknown (D_0-D_3 and D_0-D_4 data). Any delay in receiving the φ portion of the data caused by a longer path length from the source to D_α merely postpones receipt of the symmetry information. The fact that γ photons are assigned to one symmetry or another after their registration at D_0 is thoroughly unremarkable and expected because the symmetry of each γ-φ pair is determined at the source, not at the beam splitter BS as others contend [10].

Our explanation avoids the counterintuitive, time-reversed argument that necessarily emerges from Wheeler's delayed-choice assumption that a quantum's properties can be established after the fact and irrespective of its history [11]. The past history of the photons used in the delayed-choice experiment of Kim *et al.* is very relevant to the outcome, because it is the symmetry imprinted on every photon pair at its creation that determines how it is sorted and how it interferes.

In conclusion, we interpret the delayed choice quantum eraser experiment to be a symmetry sorter in which pre-existing information about the symmetry of a parametric photon source is either sorted or not after some period of delay. We reach this conclusion by recognizing that the photon, as the unit excitation of a propagating field, carries a signature of the source symmetry. No nonlocal, time-reversed explanations or quantum entanglement are required to understand the experimental results.

References and Notes

[redacted]

1. J. A. Wheeler, in *Mathematical Foundations of Quantum Theory*, A. R. Marlow, Ed. (Academic Press, New York, 1978), pp. 9-48.
2. J. A. Wheeler, in *Quantum Theory and Measurement*, J. A. Wheeler, W. H. Zurek Eds. (Princeton Univ. Press, Princeton, NJ, 1983), pp. 182-213.
3. Y.-H. Kim, R. Yu, S. P. Kulik, Y. Shih, and M. O. Scully, *Phys. Rev. Lett.* **84**, 1 (2000).
4. B. Greene, *The Fabric of the Cosmos* (Alfred A. Knopf, New York, 2004), p. 199.
5. Y. Aharonov and M.S. Zubairy, *Science* **307**, 875 (2005).
6. An analogous situation is the radiation from a pair of oscillating dipoles or radio-frequency antennas driven in phase (even symmetry) or push-pull (odd symmetry). Even at arbitrarily low excitation, the radiation pattern will be that of the coupled system.
7. E. Fermi, *Rev. of Mod. Phys.*, **4**, 87 (1932).
8. Fermi represented the light from an atom classically as an expansion of plane waves of the vector potential, examining the time dependence of the appropriate coefficients and calculating the probability of absorption by another atom.

9. Physics presents no detailed picture of wavefunction collapse, but it is a fundamental tenet of quantum mechanics.

10. See, for example, Note 9 of Y. Aharonov and M.S. Zubairy, *Science* **307**, 875 (2005), in which γ-φ symmetry is described as a superposition of odd and even states that collapses to one or the other "after" φ encounters beam splitter BS.

11. Wavefunction collapse resolves Wheeler's "delayed choice" paradox, which he introduced through a thought experiment involving the paths taken by single photons through a Mach-Zehnder interferometer. If he removed the final beam splitter (BS), a photon could be registered in either of two detectors that looked back along the two possible paths, and the path that the photon had actually taken was thereby established by noting which detector clicked. However, he imagined that if he could quickly reinsert BS after each photon had taken one or the other path but before it reached BS, interference between the two components of the wavefunction would occur as with a continuous beam and the photon would be registered by the detector that was set in the bright fringe position. Thus one could choose the path history of the photon after the fact—both paths simultaneously, or either path randomly. The quick insertion of the BS purportedly erased which-path knowledge and thus permitted interference. We prefer to believe that the wavefunction of a single photon always approaches along both paths as it would for a continuous beam, and that the random click of one of the two detectors with BS absent is simply a manifestation of wavefunction collapse. The concept of

wavefunction collapse eliminates retroactive chance from the description of a photon’s history.

Figure Captions

FIG. 1. Signal and idler photon pairs γ-φ are simultaneously created by SPDC in two regions (1 and 2) of a BBO crystal. Each photon is depicted as two rays (γ_1-γ_2 for the signal and φ_1-φ_2 for the idler), and each is directed into a different interferometer. Path lengths within the φ interferometer are equal, but φ photons travel farther than γ photons. Coincidence circuitry correlates γ and φ detections. (Schematic elements are not drawn to scale. BBO is enlarged for clarity. Layout based on the original paper by Kim *et al.*)

FIG. 2. Beam splitter BS introduces a π-radian phase shift only to the φ_2 wave reflected toward D_2. No such phase shift occurs for the other reflected and transmitted waves at BS. (BS substrate thickness is exaggerated to emphasize the key difference between high- and low-index reflected waves.) The resulting interference between φ_2 and φ_1 renders D_2 dark for symmetric BBO radiation (a) and D_1 dark for antisymmetric radiation (b). This enables sorting of γ-φ coincidence detections, yielding a $\mathrm{sinc}^2(\alpha)\cos^2(\beta)$ pattern for symmetric γ radiation (a) and a $\mathrm{sinc}^2(\alpha)\sin^2(\beta)$ pattern for antisymmetric γ radiation (b). Experimental factors such as wavelength and slit width/separation determine the values of α and β. (Parallel and antiparallel arrows symbolize the symmetric and antisymmetric BBO states, respectively.)

FIG. 3. Separately directing φ_2 and φ_1 into D_3 and D_4, respectively, prevents sorting of γ-φ coincidence detections. D_0-D_3 and D_0-D_4 coincidences therefore contain both symmetric and antisymmetric γ patterns. The resultant is $\mathrm{sinc}^2(\alpha)\cos^2(\beta) + \mathrm{sinc}^2(\alpha)\sin^2(\beta) = \mathrm{sinc}^2(\alpha)$.

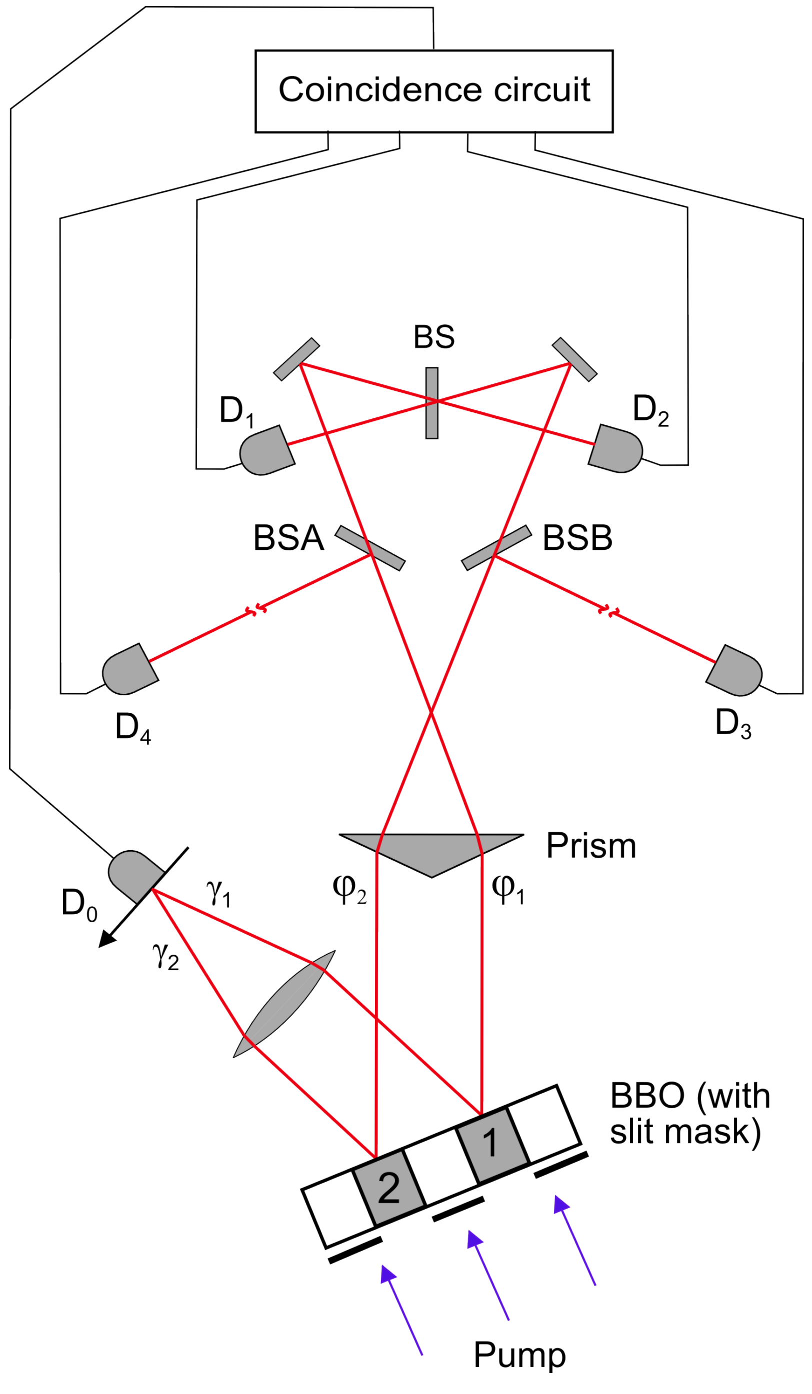
Coincidence circuit
BS
D_1
D_2
BSA
BSB
D_4
D_3
Prism
D_0
γ_1
γ_2
φ_2
φ_1
BBO (with slit mask)
2
1
Pump

Fig. 1

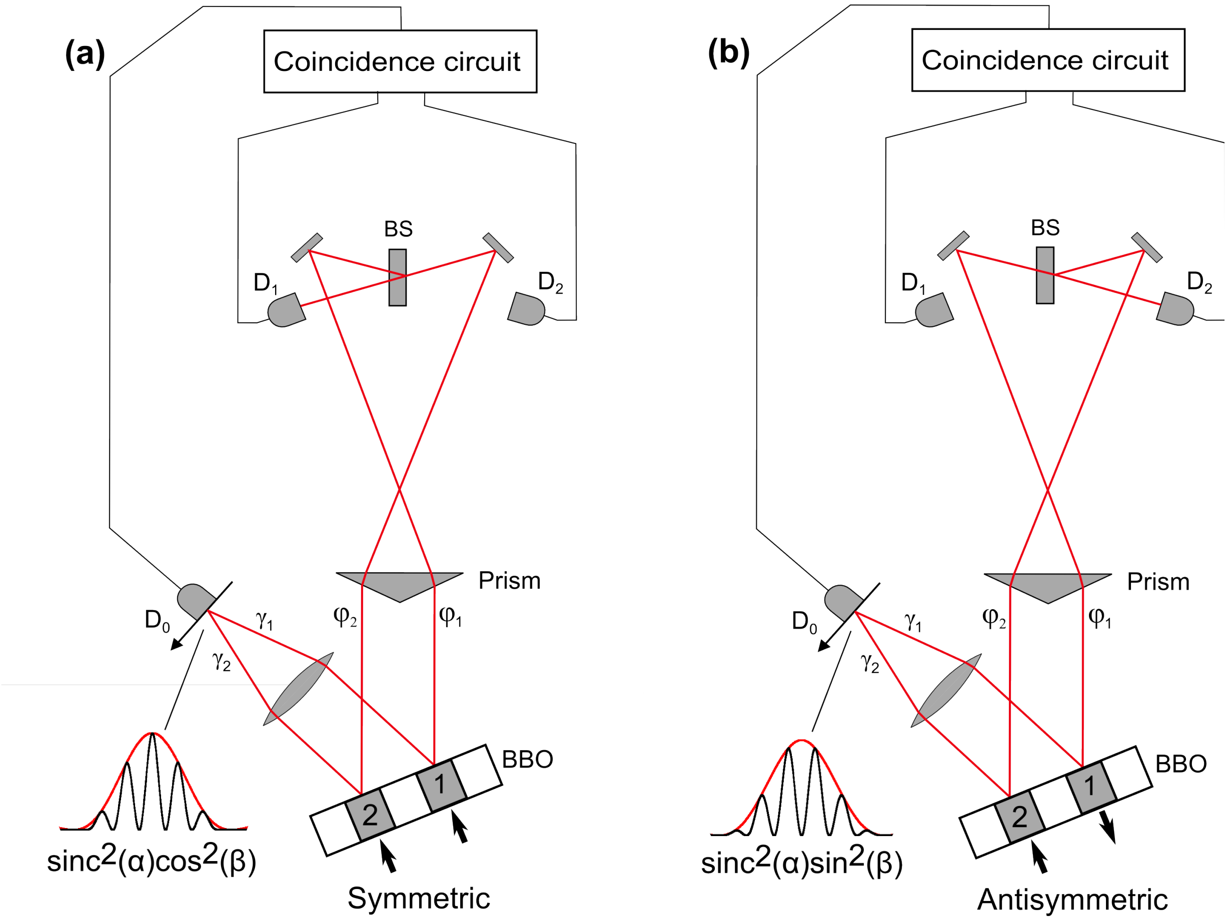
(a)
Coincidence circuit
BS
D_1
D_2
Prism
D_0
γ_1
γ_2
φ_2
φ_1
BBO
2
1
$\mathrm{sinc}^2(\alpha)\cos^2(\beta)$
Symmetric
(b)
Coincidence circuit
BS
D_1
D_2
Prism
D_0
γ_1
γ_2
φ_2
φ_1
BBO
2
1
$\mathrm{sinc}^2(\alpha)\sin^2(\beta)$
Antisymmetric

Fig. 2

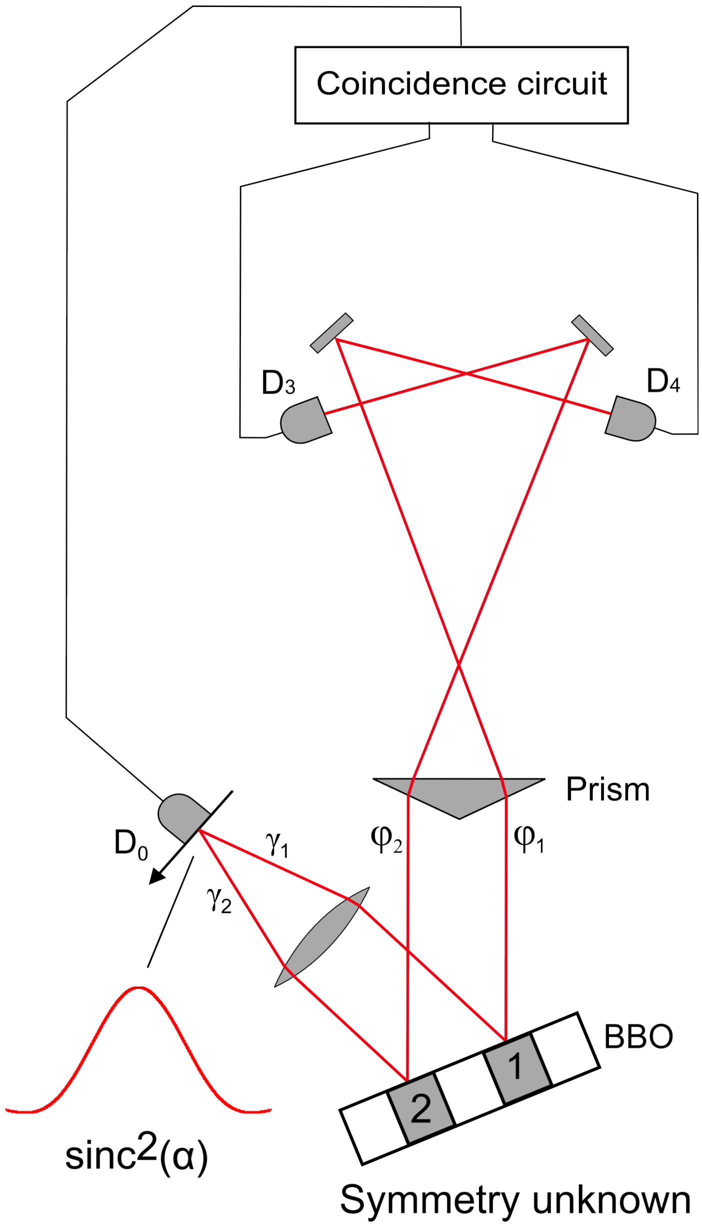
Coincidence circuit
D3
D4
Prism
D0
γ1
γ2
φ2
φ1
BBO
2
1
sinc2(α)
Symmetry unknown

Fig. 3