How could the detection of an interference pattern be affected by photons which do not enter the interferometer?

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A three-photon interference experiment is proposed. In this experiment the contrast would be controlled by varying the conditions for the detection of photons which do not undergo an interference phase delay. In this experiment one can clearly demonstrate Feynman's uncertainty principle for explaining the Einstein–Podolsky–Rosen paradox involving energy–time observables.

So-called two-photon states are being invoked progressively more frequently in efforts to solve several fundamental and applied problems of modern physics, such as the violation of Bell's inequalities and the Einstein–Podolsky–Rosen paradox. These states are also being discussed in efforts to raise the sensitivity of various systems by depressing quantum noise. These two-photon states are characterized by a nonlocal mutual correlation between photons generated in the course of (for example) a parametric scattering of electromagnetic radiation in a medium with a quadratic nonlinearity (see Refs. 1–7 and the bibliographies there). No less interesting are three-photon states, which open up some new opportunities for observing nonclassical properties of light, as we will see below.

Figure 1 is a schematic diagram of this proposed experiment. Photons created parametrically in nonlinear crystal NC2 (we recall that a pump photon decays into a signal photon and an idler photon, whose frequencies are related by $\omega_p = \omega_s + \omega_i$) enter a two-arm Michelson interferometer, formed by mirrors M and beam splitter BS. After passing through filters F2 and F3, these photons are detected by detectors D2 and D3; only those cases in which these photons arrive simultaneously are recorded. If NC2 is pumped by monochromatic electromagnetic radiation, the diagram described above is the same as that for the experiment of Ref. 3, which can be explained as follows. We assume that one arm of the interferometer is longer than the other. Then the photon arrival times could be the same in only two cases: Both photons went through the long arm, or both went through the short one. Since we cannot distinguish between these possibilities in this detection layout, we are obliged to add the probability amplitudes for the two cases, according to Feynman's uncertainty principle.[6] We should observe an interference between the two possibilities. Indeed, by introducing phase delays by moving the lower mirror, Kwait *et al.*[3] obtained different binary-coincidence rates R in the course of the photon counting. The theory predicts

$$R \propto 1 + \cos \varphi, \qquad \varphi = \omega_p \tau, \tag{1}$$

where ω_{p2} is the angular frequency of the electromagnetic radiation pumping the

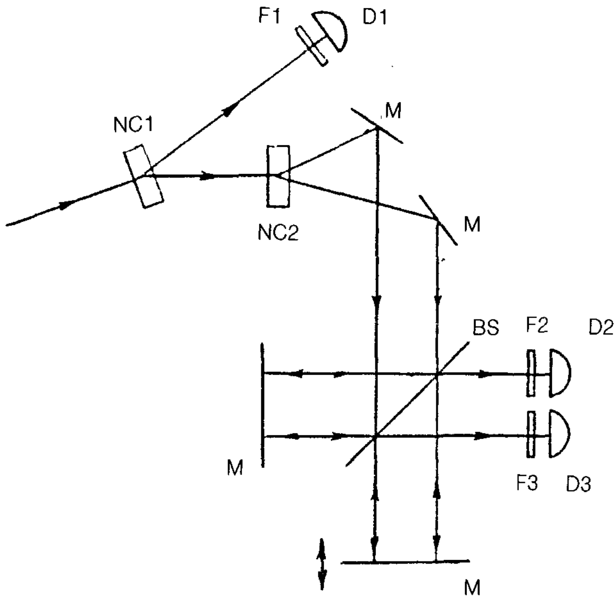

FIG. 1.

second crystal, and τ is the relative time delay in the propagation of light through the different arms of the interferometer. Actually, the finite time which the detectors took to operate lowered the contrast of the interference pattern to 50% in the experiment of Ref. 3. The reason is that the time resolution τ_r was greater than τ. Another important point to note is that in Ref. 3 the coherence time of the signal and idler components in Ref. 3 was substantially shorter than τ, so there was no possibility of an ordinary one-photon interference in either channel.

What happens if we attempt to determine the particular arm (the long one or the short one) through which the photon pair passed? Without involving interferometer, one could identify the particular arm with the help of a three-photon state prepared through multistage parametric scattering. For this purpose we use crystal NC1, which is pumped by an external source of coherent light. The light generated in it serves in turn as the pump for NC2. By detecting the arrival times of the photons at detector D1 and those of the photon pairs at D2 and D3, and by working from the time delay between these events, one could in principle identify the path taken by the signal and idler photons in the interferometer. In other words, for approximately equal optical path lengths in all the arms, we would be interested in cases of triple coincidences in a time interval τ, but with a resolution less than τ. The efficiency of the multistage generation would of course be lower than that of single-stage generation, but this "loss" could be countered by raising the sampling time.

According to Feynman's uncertainty principle, the interference should disappear in such an experiment. But how could the interference be disrupted by the detection of photons which are independent and not involved in the interference?

The explanation is that a reliable detection of a time delay with a resolution τ requires that the spectral width of filter F1, i.e., $\Delta\omega_1$, be greater than $2\pi/\tau$. According to the interpretation of the Einstein–Podolsky–Rosen paradox offered by Klyshko,[7] however, during the detection of the triple coincidences the quantum uncertainty in the width of the pump band of the second crystal, $\Delta\omega_{p2}$, is approximately equal to $\Delta\omega_1$. As a result, the uncertainty in the phase delay between the interferometer arms, $\Delta\varphi$, is greater than 2π, according to (1). Taking an average of $\cos\varphi$ in this case gives us zero, and the interference pattern does indeed disappear!

The interference can be recovered by shrinking the passband of F1 and by detecting cases of triple coincidence exclusively. By using filter F1, we can thus control the contrast of the interference pattern without acting directly on the interferometer. The latter would in turn be a "measurer" of the quantum state formed by NC1, F1, and D1, which "sense" a nonlocal coupling of photon pairs.

These arguments can serve as further support for Klyshko's explanation[7] of the Einstein–Podolsky–Rosen paradox involving energy–time observables, since that explanation thus also agrees with Feynman's uncertainty principle.

We also note that it would be possible to prepare three-photon states in media with a cubic nonlinearity,[9] without using a multistage parametric process.

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