Two-photon interferometry over large distances

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Two correlated photons incident upon two distant interferometers can produce a coincidence rate that depends nonlocally on the sum of the phases of the interferometers. This effect has been observed for the case in which the optical path length between the two interferometers was 102 m. The results of the experiment are in good agreement with the quantum theory predictions and violate a recently derived inequality for semiclassical field theories.

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It has been shown theoretically [1] and experimentally [2-4] that two correlated photons incident upon two distant interferometers can produce a coincidence rate with a nonlocal dependence on the sum of the phases of the interferometers. Bell's inequality [5] will be violated [1,4] if the visibility of the interference pattern is sufficiently high, while experiments with a lower visibility may still violate a newly derived inequality [6] for semiclassical field theories.

This paper describes a recent two-photon interferometer experiment in which the optical path length between the two interferometers was 102 m. The results of the experiment are in good agreement with the predictions of the quantum theory and are inconsistent with any semiclassical field theory.

Nonlocal effects of this kind are often viewed as a result of the instantaneous collapse of the quantum-mechanical wave function at the time of a measurement, although such an interpretation is not essential. It has been suggested [7] that the collapse of the wave function could conceivably be degraded if sufficiently large distances were involved, leading to a gradual departure from the quantum theory at large separations. The results of this experiment suggest that the collapse of the wave function is unaffected even when very large optical path lengths are involved. The experiment demonstrates that the quantum theory, originally developed for systems of atomic dimensions, remains valid when extrapolated to distances many orders of magnitude larger.

The interferometer experiments of interest are sketched in Fig. 1. A light source (typically a nonlinear crystal) emits a pair of photons γ_1 and γ_2 that are very nearly coincident, although the time at which they were emitted remains uncertain in the quantum-mechanical sense. After traveling a large distance D, the photons encounter two identical interferometers that have a shorter path of length S and a longer path of length L. The path-length difference $\Delta l = L - S$ is chosen to be much larger than the first-order coherence length. Phase shifts ϕ_1 and ϕ_2 are introduced in the two longer paths. Two mirrors (not shown) were used in the present experiment to reflect the photons back towards the source, so that the optical path lengths were much larger than the actual separation between the two detectors, as will be discussed shortly.

Consider the case in which coincident photons are observed in detectors D_1 and D_2 with a time resolution much better than the difference in travel times $\Delta T = \Delta l / c$, where c is the speed of light. Then both photons must have traveled over the shorter paths or both photons must have traveled over the longer paths. Interference between the quantum-mechanical probability amplitudes for those two possibilities results in a coincidence rate given [1] by

$$R_c = \tfrac{1}{4} R_{c0} \left[\cos^2 \left[\frac{\phi_T + \omega_0 \Delta T}{2} \right] \right] , \tag{1}$$

where ω_0 is the frequency of the pump laser, $\phi_T = \phi_1 + \phi_2$, and R_{c0} is the coincidence rate with the beam splitters removed.

Although Eq. (1) violates Bell's inequality, the time resolution of the coincidence circuits is often much worse than ΔT, in which case there is also an incoherent contribution to the coincidence rate corresponding to situations in which one of the photons traveled along the longer path while the other photon traveled along the shorter path. The coincidence rate is then given [1,6] by

$$R_c = \tfrac{1}{4} R_{c0} \left[\cos^2 \left[\frac{\phi_T + \omega_0 \Delta T}{2} \right] + \frac{1}{2} \right] . \tag{2}$$

The resolution of the coincidence circuit used in the present experiment was 3 ns while ΔT was 132 ps, which corresponds to the conditions of Eq. (2) rather than Eq. (1). The visibility of the corresponding interference pattern was therefore insufficient to violate Bell's inequality but will be seen to violate the classical inequality of Ref. [6].

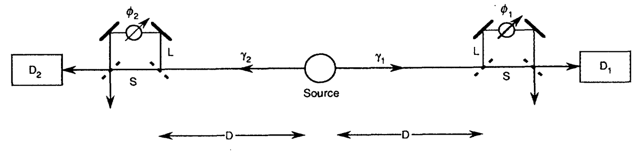

FIG. 1. Typical two-photon interferometer experiment.

The design of the light source was as shown in Fig. 2. The light from a helium-cadmium laser operating at a wavelength of 325 nm was incident upon a half-wave plate used to rotate the polarization of the light from the vertical plane to the horizontal plane. Filter F_1 passed the ultraviolet light from the laser but attenuated any visible light produced in the gas discharge tube. A nonlinear crystal of lithium iodate converted a small fraction of the pump photons into coincident pairs of photons γ_1 and γ_2 via parametric down conversion [8]. The pump power was 5 mW and the crystal was 1 cm thick. The orientation of the crystal was automatically adjusted by a personal computer to satisfy the phase-matching conditions necessary to produce down-converted photons traveling in very nearly the same direction as the incident pump beam (degenerate type-I process). Filter F_2 then absorbed the ultraviolet pump photons with very little fluorescence and passed the visible down-converted photons, both of which had a wavelength centered around 650 nm. The singles counting rate was equal to the detector dark count whenever the crystal was rotated away from the phase-matching angle, which demonstrated that the ultraviolet pump photons were completely eliminated by filter F_2 and that any fluorescence was negligible.

Lens L_1, a microscope objective, was mounted on a three-axis translator whose position could be controlled with a resolution of 0.1 μm by the computer. Proper positioning of the lens allowed both photons to be focused through pinhole P with a 25 μm diameter. Achromatic lens L_2 then produced a collimated ($<10^{-4}$ rad) beam with a diameter of approximately 2.5 cm. Filter F_3 was an interference filter with a bandwidth of 10 nm centered on 650 nm. Beam splitter BS_2 separated the two photons onto different paths toward the detectors; those events in which both photons traveled along the same path produced no coincidence counts and could be neglected.

The light from a helium-neon laser was attenuated by neutral density filter F_4 before being imaged onto pinhole P by means of mirror M_1 and beam splitter BS_1. This was used in the alignment of the apparatus and in stabilizing the interferometers against thermal drift, as will be described below. When not in use, the HeNe beam could be blocked off by a shutter under the control of the computer.

The large distances between the source and the interferometers required that both light beams be very well collimated. That, in turn, resulted in a relatively low coincidence rate typically on the order of one event every 3 min. Because of the low counting rates, the interferometers had to be extremely stable over long periods of time. In addition, it was desirable that the interferometers be constructed in such a way that their alignment could not change when they were moved from one location to another.

Each interferometer was therefore constructed from a solid plate of fused silica, as illustrated in Fig. 3. One of the collimated light beams from the source was incident upon the fused silica plate at very nearly a normal angle of incidence. Reflections from the front and back surfaces of the plate, both of which were coated with a dielectric giving 17% reflectance, produced a uniform interference pattern. The phase of the interference pattern could be controlled by the computer by rotating the plate through a small angle θ. Most of the incident light was transmitted and absorbed by a black surface behind the plate. Beam splitter BS_3 was necessary to extract the reflected beam from the incident beam, although it did not form part of the interferometer itself. All the data were collected within one fringe of $\theta=0$.

The front and back surfaces of the fused silica plates were flat to within $\frac{1}{20}$ wavelength, giving a total wave front distortion of less than $\frac{1}{10}$ wavelength upon reflection or transmission. The visibility of the usual (first-order) interference pattern observed using the HeNe laser and a single detector was typically 90% and was limited primarily by the reflective coatings. The fused silica plates used in the two interferometers had equal thicknesses (13.6 mm) to within one wavelength, having been cut from a single polished plate.

The main advantage of this kind of interferometer was its long-term stability. The phase shifts of both interferometers were periodically monitored by the computer using the HeNe laser and adjusted as needed by changing the angle θ. The observed phase shifts at $\theta=0$ varied by roughly one fringe throughout the course of the entire experiment as a result of temperature changes in the laboratory. The wavelength of the down-converted photons (650 nm) was sufficiently close to that of the HeNe laser (632.8 nm) that the corresponding phase shifts differed by

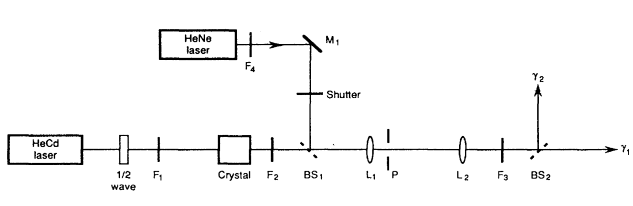

FIG. 2. Parametric down-conversion light source.

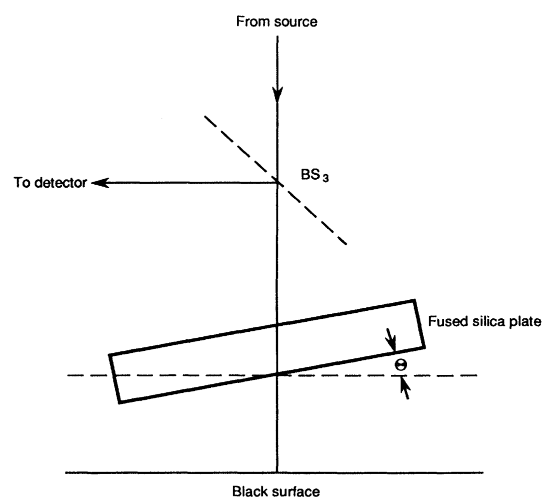

FIG. 3. Design of the interferometers.

an unknown constant that depended upon the exact thicknesses of the plates. Since the path-length difference never varied by more than one wavelength, the small difference in wavelengths was negligible over that range. Thus, the phase shifts measured with the HeNe laser provided a direct measurement of ϕ_1 and ϕ_2, aside from a fixed but unknown offset.

It would have been desirable in an experiment of this kind to have the two photons travel in opposite directions toward the two detectors. That was not possible due to the limited size of the laboratory and, instead, both beams traveled side by side down a long (~ 25 m) metal enclosure to two mirrors which reflected the beams back towards the source. The optical path length D was 51 m while the actual separation of the two beams was 20 cm.

The data were collected by setting the two interferometers to a series of phase shifts (as measured with the HeNe laser) ranging from 0° to 360° in 45° increments. These phase settings were changed roughly every 2 min for one interferometer and every 3 min for the other, so that there was no synchronization between the two settings. The number of coincidence counts obtained for each such pair of settings was recorded by the computer, along with the difference in detection times. Photon counts differing by more than 4.5 ns were rejected as accidental. The accidental rate was simultaneously determined from the events outside that range and subtracted off; the accidental rate was typically a factor of 10 less than the true coincidence rate. The coincident events were also put into bins based on the sum of the phases of the two interferometers. All data collection was performed automatically by the computer over a total time interval of 98 h and no data editing or selection was performed.

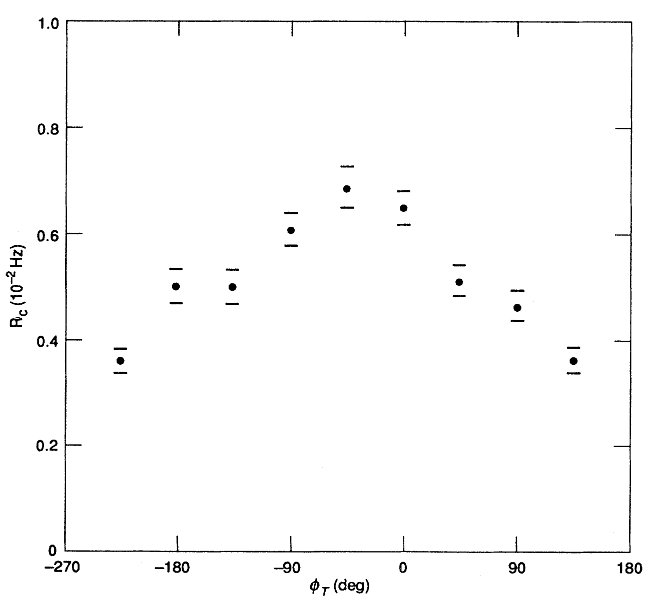

FIG. 4. Coincidence counting rate R_c as a function of the total phase ϕ_T.

The coincidence data obtained at a large optical path length ($D = 51$ m) are shown in Fig. 4. Here ϕ_T is the sum of the phases of the interferometers as measured with the HeNe laser, which differs from the corresponding phase at the wavelength of the down-converted photons by an unknown constant, as discussed above. A peak in the coincidence rate can be seen at approximately $-45°$, indicating that the thicknesses of the two plates were such that the difference between the phases at the two wavelengths happened to have that value. Measurements made at a shorter distance ($D = 0.55$ m) gave the same offset in phase.

The single-photon counting rates in both detectors were recorded in a similar fashion and it should be emphasized that they showed no measurable modulation or interference, as expected. The only interference observed was in the coincidence rate and it depended only on the nonlocal sum of the two phases.

The visibility of an interference pattern is defined by

$$v = \frac{R_{\max} - R_{\min}}{R_{\max} + R_{\min}} , \tag{3}$$

where $R_{\max}$ and $R_{\min}$ are the maximum and minimum counting rates. The data of Fig. 4 give a value of $v = 0.31 \pm 0.04$. Although Eq. (2) predicts a visibility of 0.5, the expected visibility can be shown to be reduced to 0.336 by the finite coherence length (10 cm) of the pump laser, given a difference in optical path lengths of $\Delta l = 3.97$ cm as determined from the thickness of the plates and the index of refraction. The expected visibility should be further reduced by roughly 10% due to the limited perfection of the optics, giving an overall expected visibility of 0.30. Thus, the observed visibility was in good agreement with the quantum-theory prediction.

Data were also collected with the two interferometers located as close as possible to the light source, which corresponded to $D = 0.55$ m. The results obtained were similar to that shown in Fig. 4 and gave a visibility of 0.27 ± 0.04, which is consistent with the visibility measured at the larger distance to within the experimental uncertainty. Thus, there is no indication that the nonlocal correlations are reduced due to a collapse of the wave function over larger distances.

The visibility of the interference pattern of Fig. 4 is not sufficiently high to violate Bell's inequality. Nevertheless, the author recently showed [6] that the predictions of any classical or semiclassical field theory for two-photon interferometer experiments of this kind must satisfy the following inequality:

$$v \le \frac{R_{c0}(\Delta T)}{R_{c0}(0) + R_{c0}(\Delta T)} . \tag{4}$$

Here $R_{c0}(\Delta T)$ is the coincidence rate that would be obtained with the beam splitters removed and at a delay time of ΔT using coincidence electronics with unlimited time resolution. When the interferometer measurements are performed using relatively large coincidence windows, as was the case in this experiment, Eq. (4) can be generalized [6,9] to

$$v \leq \frac{\int_{\Delta T/2}^{\infty} R_{c0}(\tau)d\tau + \frac{1}{2}\int_{\Delta T/2}^{3\Delta T/2} R_{c0}(\tau)d\tau}{2\int_0^{\infty} R_{c0}(\tau)d\tau} . \tag{5}$$

It is well known that the pairs of photons emitted in parametric down conversion are highly coincident. Direct timing measurements [10] have shown that the photons are coincident to within at least 91 ps (one standard deviation), while indirect measurements [11] suggest that they are coincident to within a few fs. More recent direct measurements [12] have shown that the photon pairs from parametric down conversion are coincident to within 50 ps. Only the results of the direct timing measurements will be used here, since it is conceivable that there may be a classical model that can account for the indirect measurements without giving coincident pulses. In that case, the inequality of Eq. (5) limits the visibility in any semiclassical theory to 0.139 for the conditions of the present experiment. The experimentally observed visibility violates this limit by 4 standard deviations. Thus, there is no semiclassical theory consistent with all the experimental observations and these effects must be viewed as quantum mechanical in nature.

It has occasionally been suggested that the collapse of the wave function may be a dynamic [13,14] process, presumably nonlinear [15] in nature, in which case it would be confined to those regions of space where the wave function is nonvanishing. In that case, the collapse of the wave function would propagate only along the optical paths of the two photons and the fact that the spatial separation between them was relatively small in this experiment would be of no significance. The results of this experiment are relevant to theories of that kind but do not rule out the more general situation.

In summary, the coincidence rates in a two-photon interferometer experiment were measured with an optical path length of 102 m between the two interferometers. The coincidence rate showed an interference pattern that depended on the sum of the phases of the two interferometers, with a visibility that was in good agreement with the predictions of the quantum theory. The singles counting rates showed no modulation at all. The visibility exceeded that achievable in any semiclassical field theory, which indicated that the effects observed were quantum-mechanical in nature. No significant difference was observed between the visibilities obtained at optical path separations of 102 and 1.1 m, which provides some indication that the collapse of the wave function is not dependent upon the distance over which it occurs.

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