Single-photon interference over large distances

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The interference pattern from a light source containing a single excited atom was observed with an interferometer 45 m in length. The visibility of the single-photon interference pattern was the same as that obtained with a high-intensity light source to within the experimental uncertainty of ±5%.

I. INTRODUCTION

Low-intensity optical interference effects have been investigated in a number of earlier experiments[1–7] which were intended to demonstrate the wavelike properties of single photons. The photon anticorrelations in the recent experiment[8] by Grangier, Roger, and Aspect clearly demonstrate that single photons can produce an interference pattern. In the experiment described here interference effects from a light source containing a single excited atom were observed using an interferometer 45 m in length. Single-photon interference effects in the limit of large spatial separations are of interest with regard to the issues of local realism and the nonlocal nature of the quantum-mechanical measurement process.

II. MOTIVATION

In the quantum-theory description of single-photon interference the wave function associated with a photon propagates simultaneously down both paths through an interferometer. If the photon should happen to be detected in one of the paths, then the wave function must collapse or reduce to zero in the other path, regardless of the distance between the two paths. This nonlocal change in the wave function is analogous to that which occurs in experiments based upon Bell's theorem,[9] where the measurement of the spin or polarization of one of two emitted particles reduces the wave function of the second, distant particle. Local, realistic[10] theories do not allow such instantaneous, nonlocal changes in a field and are inconsistent with the quantum-theory description of interference effects.[11]

The large spatial separations in this experiment were motivated by a desire to ensure that the absorption or detection of the photon in one path and the collapse of the wave function in the other path must be spacelike separated events. If that is not the case, then one cannot rule out the possibility that information may have been exchanged between the various parts of the experiment at velocities less than the speed of light, in accordance with some local, realistic theory.[12]

In the quantum theory, photons can be emitted or detected in an arbitrarily small time interval and such events would be spacelike separated, regardless of the dimensions of the interferometer. But one would like to include the possibility of some alternative theory in which a photon is emitted or absorbed over a time interval comparable to the lifetime τ of the excited atomic state, for example.[12] In that case, the dimensions of the interferometer would have to be much larger than τ multiplied by the speed of light c in order to ensure spacelike separated events.

An apparent alternative to using a large interferometer would have been to use a pulsed laser whose output had been attenuated with filters. Then it would have sufficed to require only that the dimensions of the interferometer be larger than the length of the laser pulses, as in the recent delayed-choice experiments.[13–14] However, the initial laser pulses would have contained a large number of photons, each of which would have had some small probability of being detected in either path through the interferometer. As a result, the detection of a photon in one path would not have precluded the absorption of a second photon in the other path and thus would not have reduced the wave function to zero. Since it was the nonlocal collapse or reduction of the wave function which was of primary interest in this experiment, a high-intensity light source whose output had been attenuated was not considered to be an adequate "single-photon" source.[15]

For these reasons, the present experiment was performed using a light source which, to a good approximation, contained only a single atom in the appropriate excited state and therefore emitted single photons. The two paths through the interferometer were each 45 m in length, which was much larger than $c\tau$. In the context of a local, realistic[10] theory, one could then say that a single photon which had been emitted must have been contained entirely in one path or the other.[11] In addition, no information or interaction could have propagated along the optical paths at the speed of light in such a way as to provide a local alternative to the reduction of the wave function. In order to achieve the necessary stability, however, a Jamin interferometer[16] with a relatively small (5 cm) average separation between the two paths was utilized, as described in Sec. III. As a result, the experiment does not rule out the possibility of some local interaction or flow of information which is not confined to the optical paths.

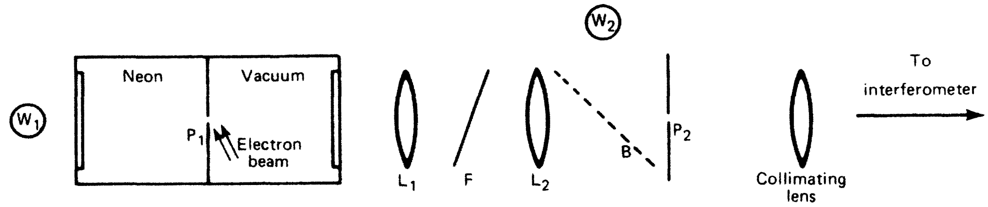

FIG. 1. Atomic-beam light source and collimating optics.

III. EXPERIMENTAL APPARATUS

The light beam had to be well collimated in order to be focused onto the detector at a distance of 45 m. In order to achieve a reasonably high detection efficiency, this required a light source sufficiently small to be imaged onto the interior of a collimating pinhole with a diameter of 50 μm. A single-photon light source with an effective diameter of approximately 25 μm was obtained using the effusive atomic beam apparatus shown schematically in Fig. 1.

Neon gas was maintained at a pressure of 10 Torr behind a platinum pinhole P_1 with a diameter of 20 μm. An electron beam accelerated to an energy of 180 eV was incident upon the neon atoms as they emerged into an evacuated chamber. Light emitted by the excited neon atoms was collected by lens L_1 and focused onto collimating pinhole P_2 (50-μm diameter) by lens L_2, after passing through an interference filter F with a bandwidth of 1.0 nm. The focal lengths of L_1 and L_2 were both 120 mm. Filter F could be rotated to measure the spectrum of the emitted light and was centered on the 585.2-nm neon spectral line during the data collection intervals. Lens L_1 was mounted on a three-axis micropositioner controlled by a small computer, which allowed automatic focusing of P_1 onto P_2. Based on numerical calculations, the average detection efficiency for this geometry was 90% of that of a point source located at P_1.

White light W_1 could be focused onto the rear of pinhole P_1, which simplified the initial focusing of P_1 onto P_2. W_1 was also used periodically during the data collection intervals as a means of determining the phase of the interferometer, as will be discussed in more detail shortly. A second white light source W_2 could be reflected onto pinhole P_2 by means of a pellicle beam splitter B, which reflected approximately 10% of the incident light. The light from W_2 did not pass through the spectral filter and thus could be used to align the interferometer to the white-light fringes. Additional lenses, not shown in Fig. 1, were used to focus the light from W_1 and W_2 onto the corresponding pinholes.

Photon counting rates as low as 0.1 $\sec^{-1}$ required the interferometer to be as stable as possible over long periods of time. This stability was achieved using the Jamin interferometer shown schematically in Fig. 2. The collimated beam of light was reflected off both the front and back surfaces of fused-silica plate S_1, producing two parallel beams which then traveled a distance of 45 m to plate S_2, where their amplitudes were recombined to produce an interference pattern. The front surfaces of S_1 and S_2 were half silvered on the appropriate areas to provide equal intensities of the two beams. The beams were 2.5 cm in diameter and the distance between their centers was 5.1 cm.

This arrangement was insensitive to translational motion of one end of the interferometer with respect to the other, which changed the lengths of both paths by an equal amount. The sensitivity to rotational vibration was greatly reduced by placing S_1 and S_2 on massive aluminum plates suspended on vibration isolation mounts. The entire interferometer was contained inside a light-tight enclosure evacuated to a pressure of 50 mtorr.

Fused-silica plates S_1 and S_2 were 63.5 mm thick and were polished[17] to give a wave-front distortion of less than $\frac{1}{20}$ wavelength. Motorized micrometers equipped with optical encoders allowed the computer to control the orientation of the two plates with a resolution of 0.2 arcsec. Mirrors M_1, M_2, M_3, and M_4 allowed the computer to aim the light beam onto the detector while keeping them centered on S_1 and S_2. The interferometer plates could be automatically aligned using the light from W_1 and W_2, and the lengths of the two paths were equal to better than one part in 10^9 after alignment to the white-light fringes. Under these conditions the interferometer produced a condition of constructive interference over the entire area of the recombined beams. The relative phase of the two beams could then be varied by

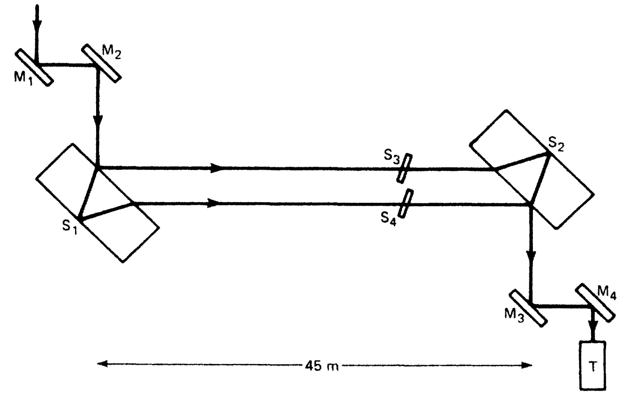

FIG. 2. Jamin interferometer and mirrors used to aim the light beams (not drawn to scale).

rotating one of the matched pair of fused-silica plates S_3 and S_4.

The photons passing through the interferometer were detected using an ITT FW 130 photomultiplier tube T which was selected for its low dark count of 0.5 sec^{-1}, resulting primarily from the small area (5.1 mm^2) of its photocathode. The light beam was focused onto the detector using a lens (not shown in Fig. 2) with a focal length of 250 mm. The single-photon detection efficiency η was measured using a calibrated photometer and a 20-μm pinhole illuminated by diffuse light. A value of $\eta = 3.8 \times 10^{-6}$ was obtained, in good agreement with the result to be expected[18] from the nominal properties of the optical components and photomultiplier tube.

Using a high-intensity light source such as W_1, the photon-counting rate would vary sinusoidally with the rotation of plate S_3. The visibility V of an interference pattern is defined[16] as

$$V = \frac{R_{max} - R_{min}}{R_{max} + R_{min}} , \tag{1}$$

where R_{max} and R_{min} are the maximum and minimum counting rates, respectively. A perfect interference pattern thus has a visibility of 1.0. The intrinsic visibility of the interferometer used in this experiment was typically 0.65, with some (~5%) variation from one run to the next. The thicknesses of plates S_1 and S_2 each corresponded to an optical path length of approximately 4.5×10^5 wavelengths, so that a differential thermal expansion or a nonuniformity of the index of refraction of less than one part in 10^6 would thus produce a significant distortion in the interference pattern.[19] Small deformations due to stress from the mounts for S_1 and S_2 may also have contributed to the distortion of the interference pattern. The small variations in the visibility from one run to the next were strongly correlated with changes in the ambient temperature; in addition, changes in temperature caused the intrinsic phase of the interferometer to drift at a rate of approximately two fringes per hour.

In order to compensate for these effects, white light W_1 was turned on briefly every 2.5 min during the data collection process. A comparison of the high-intensity counting rate thus obtained with its maximum value allowed an accurate determination of the phase of the interferometer at that particular time. The data were subsequently analyzed to estimate the phase difference as a continuous function of time. White light W_2 was used to align the interferometer to the white-light fringes every 30 min so that all the data were collected with the lengths of the two paths equal to within a few wavelengths.

The single-photon counting rate from the atomic beam light source was measured during the 2.5-min intervals between the use of white light W_1. The dark count from the photomultiplier tube was significant at the lower counting rates and was therefore measured by turning off the electron gun accelerating voltage during every other 2.5-min interval. The observed dark count was then subtracted from the atomic beam counting rate.

The data obtained in this way was put into 10° bins based upon the phase of the interferometer as determined

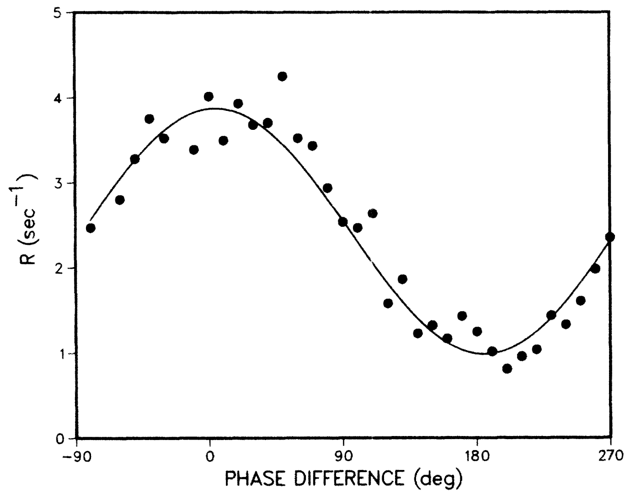

FIG. 3. Single-photon interference pattern at an average counting rate of 2.4 sec^{-1}. The photon-counting rate R is plotted as a function of the phase difference between the two optical paths.

from the use of white light W_1. The visibility of the single-photon interference pattern was then obtained by fitting the data to the empirical form

$$R(\Delta\phi) = a + b \cos^2\left[\frac{\Delta\phi}{2}\right] . \tag{2}$$

Here $\Delta\phi$ is the known phase difference between the two paths, a and b are constants, and R is the observed photon-counting rate adjusted for the dark count.

IV. EXPERIMENTAL RESULTS

The visibility of the single-photon interference pattern was measured over a range of light source intensities, which was controlled by regulating the electron beam current. A typical result, corresponding to an average photon-counting rate of 2.4 sec^{-1}, is shown in Fig. 3. The observed counting rate R is plotted as a function of the phase difference in 10° bins from −90° to 270°. The solid line shows a least-squares fit of the data to Eq. (2) and corresponds to a visibility of 0.60.

The high-intensity counting rates from white light W_1 collected during the same time period are shown in Fig. 4 along with their least-squares fit, which corresponds to a visibility of 0.70. Both Figs. 3 and 4 clearly show an interference pattern, although the visibility of the high-intensity data of Fig. 4 was somewhat higher than that of the single-photon data of Fig. 3. This difference in visibilities was primarily due to the fact that the light from W_1 subtended a relatively small solid angle[20] after passing through P_1 and thus produced a collimated beam of relatively small diameter compared to that from the atomic-beam light source. The degradation in the interference pattern due to the distortion of the interferometer plates was expected to be larger for beams of larger diameters. This was confirmed by measuring the interference pattern from a high-intensity neon discharge tube

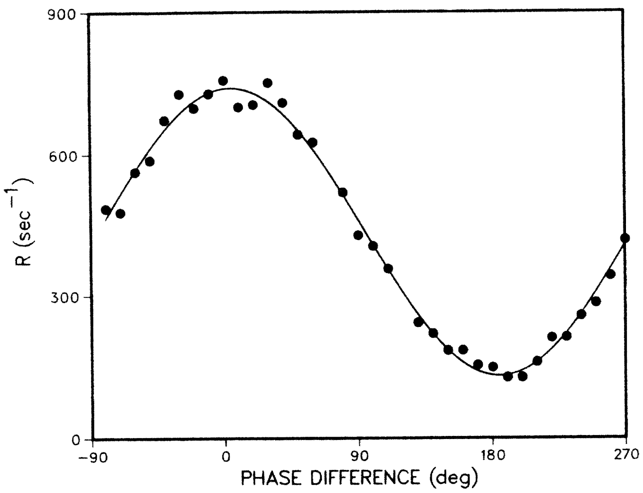

FIG. 4. Interference pattern from a high-intensity white light attenuated with a neutral-density filter.

which subtended the same solid angle as did the atomic beam light source; these two light sources were found to give the same visibility to within the experimental uncertainty.

Measurements of the single-photon interference pattern were made at counting rates as low as 1.0 sec^{-1}, as summarized in Table I. The visibilities V_W obtained using white light W_1 have also been included for comparison purposes. The last column on the right gives the ratio of the single-photon visibility to that obtained using a high-intensity neon discharge. It was estimated that this ratio was accurate to $\pm 5\%$. No significant difference[21] was observed between the single-photon interference pattern and that obtained at high intensities, and an average ratio of 1.00 $\pm$0.05 was obtained.

The number of excited atoms in the light source can be estimated from the detection efficiency and the average counting rates. The 585.2-nm photons were emitted by a $2p^5 3p$ state of neon with $J=0$ and a lifetime[22] of 14.5 nsec. The transition to the corresponding 3s state occurred with a branching ratio[22] b of 0.987. The average number $\bar{N}$ of excited atoms in the necessary state to emit a photon at 585.2 nm and contained in the light source at any given time was taken to be approximately given by

$$\bar{N} = \frac{\bar{R}\tau}{\eta b} , \tag{3}$$

where $\bar{R}$ is the average photon counting rate. The data of Fig. 3, for example, correspond to a value of $\bar{N} = 9.4 \times 10^{-3}$, and the probability of there having been two such excited atoms in the light source at any given time was approximately 8.8×10^{-5}.

Measurements were also made using a light-emitting diode (LED) (Hewlett-Packard HLMP-1440) driven with 22-nsec pulses. The amplitude of the pulses was such that there was less than a 10% chance of a photon being emitted during any given pulse. Measurements were made at counting rates as low as 0.08 sec^{-1}, as summarized in Table I. The visibility of the interference pattern obtained was the same as that obtained at high LED intensities to within the experimental uncertainty of $\pm 5\%$.

V. DISCUSSION AND CONCLUSIONS

The interference pattern from a light source containing a single excited atom has been observed over distances which are much larger than $c\tau$. This is in agreement with the quantum-theory prediction that optical interference effects should persist at arbitrarily low intensities and over arbitrarily large distances.

In an effort to provide a local, realistic description of single-photon interference, it had been conjectured[11] that a photon may correspond to a soliton of maximum dimensions comparable to the natural coherence length due to radiation alone. In that case, single-photon interference would have been observable over the relatively small distances characteristic of most interferometers but would have been degraded or eliminated at much larger distances. The results of this experiment rule out conjectures of that kind.

Although the results of this experiment are consistent with the quantum theory, they are also consistent with semiclassical theories in which the atomic states are quantized but the radiation is described by a classical field.[23] Since detailed energy balance is not maintained in such theories, there is no need for the field in one path

TABLE I. Summary of interferometer results obtained from various light sources.

Light Source	Counting rate (sec^{-1})	Visibility	V_W	Ratio
Neon atomic beam	0.96	0.55	0.66	0.96
	1.54	0.55	0.62	0.96
	2.43	0.60	0.70	1.05
	8.48	0.58	0.67	1.02
Light-emitting diode	0.08	0.63	0.64	0.98
	0.11	0.67	0.65	1.03
	0.21	0.64	0.62	1.02
Incandescent lamp	972[a]	0.53	0.62	0.96
Neon discharge tube	2.27[a]	0.57	0.65	1.00

[a]High-intensity source attenuated with diffusers.

through the interferometer to be reduced to zero by a detection event in the other path, which allows classical interference in a local, realistic theory. Aside from the difficulties associated with conservation of energy, such theories appear to be ruled out by the recent anticorrelation measurements of Grangier *et al.*[8] as well the earlier coincidence measurements of Clauser.[24] It may be of interest, however, to demonstrate that these effects still hold in the limit of large spatial separations. An investigation of such coincidence effects using the atomic-beam light source and the 45-m interferometer described above will be included in a follow-up experiment.

ACKNOWLEDGMENTS

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[17]Custom-made optical components were fabricated by the Muffoletto Optical Co. of Baltimore.

[18]The low value of η is due largely to the solid angle subtended by lens L_1. It should be noted that η corresponds to the total detection efficiency for a photon emitted in an unknown direction; some of the earlier experiments quoted detection efficiencies for a photon already assumed to be in the collimated beam.

[19]The phase difference in a Jamin interferometer with parallel plates is independent of the angle of incidence. As a result, any degradation due to finite source size is a "second-order" error, involving the product of the beam divergence (due to finite size) and some other error, such as a misalignment of the plates. We find such errors to be negligibly small for the dimensions (25 μm) of the light source used here.

[20]The solid angle subtended by white light W_1 was limited by the fact that the design of the atomic-beam light source required pinhole P_1 to be mounted on the end of a tube 15 cm long with an inner diameter of 6.4 mm.

[21]Preliminary results obtained using an earlier apparatus had shown an apparent decrease in the low-intensity visibility at large distances, with no decrease at high intensities or short distances [J. D. Franson and K. A. Potocki, Johns Hopkins APL Tech. Dig. **5**, 305 (1984)]. This effect is believed to have been due to changes in the shape of the rf discharge light source used at that time as a function of the intensity, which affected the diameter of the collimated beam.

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