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AN EXPERIMENTAL TEST OF THE QUANTUM THEORY

A single-photon interferometer experiment to test the validity of the quantum theory is in progress. The preliminary results are in apparent agreement with Einstein's assertion that the laws of nature must be local.

INTRODUCTION

The quantum theory is one of the most basic principles of physics. Nevertheless, Einstein refused to accept much of it. Schrödinger and de Broglie, who played important roles in the development of the theory, eventually became two of its strongest critics. Most of the criticism of the quantum theory is based on the fact that it is nonlocal; roughly speaking, a nonlocal theory is one that allows instantaneous action at a distance. Several experiments currently in progress, including one at APL, are intended to investigate whether this aspect of the quantum theory is correct or if, instead, the laws of nature are local as Einstein insisted.

The nonlocal nature of the quantum theory can perhaps be most easily understood by considering the two-photon correlation experiments based on Bell's theorem.[1] In these experiments, an atom emits two photons that travel in opposite directions. The polarizations of the two photons cannot be predicted in advance, but they are known to be the same. In the quantum theory, this uncertainty is reflected in the field or wave function describing the two photons. The wave function is the same for all such pairs of photons and gives the probability of their having any particular polarization. Uncertainties in the description of the state of physical systems are a fundamental feature of the quantum theory, as expressed by the Heisenberg uncertainty principle. These uncertainties result because the process of measuring one quantity unavoidably perturbs the value of other unmeasured quantities by an amount that is significant at the atomic level.

If the polarization of one of the photons in the preceding example is subsequently measured, however, the quantum theory requires that the measurement immediately determine the polarization of the other photon as well, since they are known to be the same. Thus, such a measurement process produces an instantaneous change in the field (wave function) describing the second photon, regardless of its distance from the first, which is an example of the nonlocal nature of the quantum theory. Einstein argued[2] instead that the polarizations of both photons must have been determined all along, even if they were unknown. In a local theory, different pairs of photons would have to be described by different fields or sets of parameters, depending on the polarizations that they had at the time of their emission. A more detailed discussion of these issues can be found in an article by B. d'Espagnat.[3]

Bell was later able to show[1] that the quantum theory predicts larger correlations between the measured polarizations of two such photons than are allowed by any local theory in which information cannot propagate faster than the speed of light. Consider two distant polarizers aligned with an angle θ between their axes, and let $P(\theta)$ be the probability that both photons will pass through the corresponding polarizers. According to Bell's theorem, the quantum theory and any local theory predict different values for $P(\theta)$, so that measurements of $P(\theta)$ as a function of θ can be used to assess the validity of either of the two classes of theories. In general, the quantum theory prediction for $P(\theta)$ corresponds to a larger correlation between the measured polarizations of the two photons than can be accounted for by any local theory. Most early experiments[3,4] of this type agreed with the quantum theory but are considered inconclusive because they could not rule out a possible interaction or exchange of information between the source and detectors at velocities less than or equal to the speed of light.

A recent experiment[5] avoided this difficulty by placing high-speed optical switches in front of each of the polarizers. As a result, the measurements of the photon polarizations must have been completed in a time interval small enough to ensure that no information could have been transferred beween the measurement devices. The results of this experiment also agreed with the quantum theory predictions and have been widely accepted[6] as providing conclusive evidence against all local theories. However, as part of an ongoing research and development program at APL, it has been shown[7] that the interpretation of this experiment contains a hidden assumption and that the results of the experiment are actually consistent with a plausible local theory. Experiments of this type cannot measure $P(\theta)$ directly but, instead, measure the rate, $R(\theta)$, of coincident photon counts in the detectors following the polarizers. Part of $R(\theta)$ is due to accidental coincidences from photons emitted by two different atoms; this accidental counting rate must be evaluated in some way and must be subtracted from the total counting rate to obtain $P(\theta)$. In order to do this, it was tacitly assumed that two photons emitted by different atoms have uncorrelated polarizations. A theoretical analysis of the high-intensity light source used in the experiment indicates that substantial correlations of this type should be expected to occur and that they may have significantly affected the values of $P(\theta)$ that were deduced from the experiment. Excellent agreement with the experimental results was obtained from a local theory containing no adjustable parameters.

APL EXPERIMENT

The experiment in progress at APL is not based on correlations between two photons but is, instead, based on the properties of single-photon interference over large distances. The basis for the experiment is illustrated in Fig. 1, which represents the passage of a single photon through a large interferometer. (An interferometer is a device in which a wave can travel along two separate paths to reach the same point; the contributions from the two paths can either enhance or interfere with each other, depending on their relative phase.) In the quantum theory, the field (wave function) describing a single photon can extend over arbitrarily large distances,[8] allowing single-photon interference effects to occur regardless of the separation of the two paths through the interferometer. However, the absorption or detection of the photon at one location requires that the field associated with the photon be instantaneously set to zero at all other locations in order to prevent a second absorption event. This instantaneous change in the photon field at a distance is another example of the nonlocal nature of the quantum theory and is analogous[9] to the instantaneous change in the wave function in the two-photon correlation experiments. Although the wave function has a probabilistic interpretation, it is worth noting that the photon must effectively determine the relative position of both mirrors in Fig. 1 in order to produce interference effects with the correct phase; in the quantum theory, the photon cannot be viewed simply as a particle that has a certain probability of traveling along one path or the other. The interpretation of what should occur when a single photon passes through an interferometer is discussed in more detail in textbooks on the quantum theory, where it is said that "the photon must change suddenly from being partly in one beam and partly in the other to being entirely in one of the beams."[10]

A local theory does not allow instantaneous changes in the field describing a photon, and so the situation there must be very different, as is illustrated in the upper part of Fig. 1. In a local theory, single-photon interference effects cannot occur for sufficiently large separation of the paths through an interferometer when a source of statistically independent photons is used.[9] This result is based on the experimental fact[11] that a photon can be absorbed by an atom within a relatively short time; the fact that the entire energy of a photon is always absorbed by a single atom is a quantum-mechanical effect not described by classical theories. An experimenter could thus choose to absorb any photon, at least in principle, within a limited time and volume.[11] Since the velocity of light is finite, it can be shown that the fields associated with a single photon must thus be of limited spatial extent in any local theory. In other words, a photon and its associated field cannot be distributed over an arbitrarily large volume and still be absorbed by an atom in a limited time interval. If single photons are passed through an interferometer in which the two optical paths are sufficiently far apart, as illustrated in Fig. 1, the photon would have to be confined to one path or the other, and interference effects could not occur. At optical wavelengths, the separation of the two paths through an interferometer must be much greater than 10 meters in order for this to be the case; the minimum path separation is related to the time required to absorb a photon.[9]

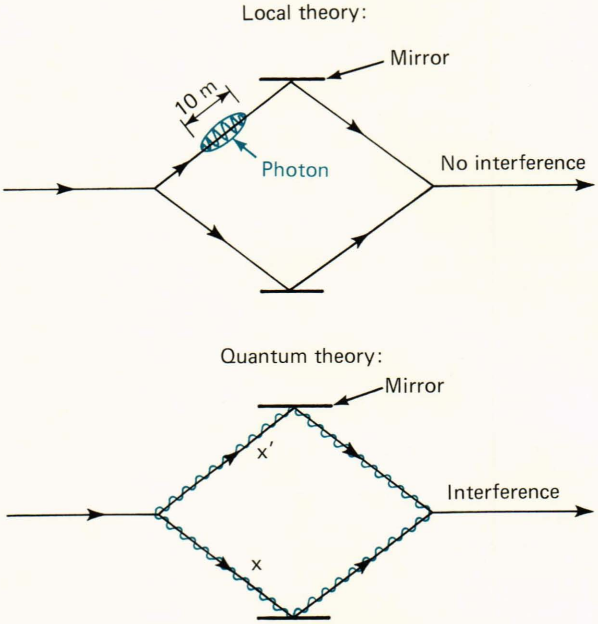
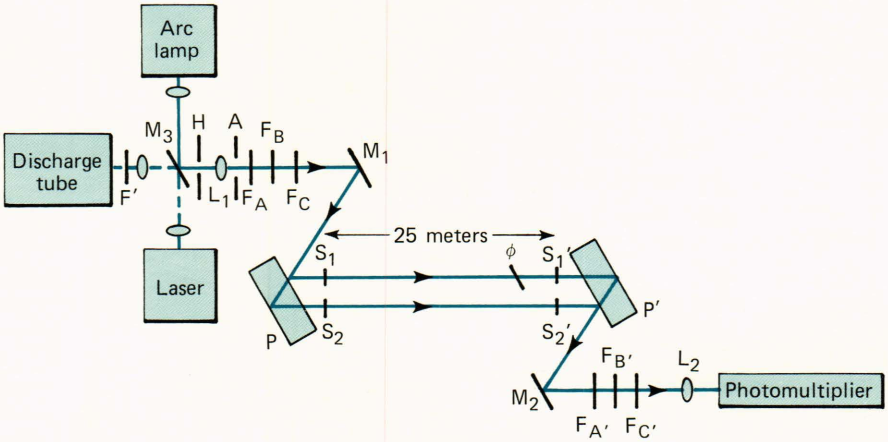


Figure 1—A single photon passing through a large interferometer. In any local theory, a single photon must be confined to one optical path or the other if the distance between the two paths is sufficiently large. In the quantum theory, the field associated with a single photon need not be so confined, and the detection of the photon at position x may require an instantaneous change in its field at a distant position x'.

Surprisingly enough, no single-photon interferometer measurements had previously been made over sufficiently large distances to settle the issue. A 25-meter-long Jamin interferometer was therefore constructed in the APL Research Center and was operated at single-photon intensities using the krypton 587.1 nanometer spectral line; the apparatus used is shown schematically in Fig. 2. Photon counting rates as low as 0.1 per second were required[12] in order to ensure that the photons emitted by the light source were

Figure 2—Simplified schematic of the experimental apparatus. The light from a krypton discharge tube, arc lamp, or helium-neon laser could be focused onto a pinhole, H, by means of three lenses and an adjustable mirror, M_3. An achromatic lens, L_1, and aperture, A, produced a collimated beam. Neutral density filters mounted on filter wheels, F_A, F_B, F_C, $F_{A'}$, $F_{B'}$, and $F_{C'}$, could be inserted into the beam preceding or following the interferometer; F′ was a narrowband spectral filter. Glass plates, P and P′, formed the Jamin interferometer, while mirrors, M_1 and M_2, were used to aim the beam. Shutters, S_1, S_2, S_1', and S_2', could be inserted into the two beams. The superimposed beams were focused onto the photomultiplier tube by means of the lens, L_2. The relative phase was varied with fused silica plate, ϕ. An evacuated pipe with optical windows (not shown) occupied the space between the shutters.



statistically independent. A substantial decrease in the magnitude of the interference (visibility) was observed at low intensities,[12] consistent with the requirements of all local theories at this distance. No significant decrease in the magnitude of the interference was observed at high intensities, nor at any intensity using an interferometer length less than 1 meter. The first set of experimental data obtained from this apparatus is shown in Fig. 3. A number of possible systematic errors were considered, but none appeared to be consistent with the experimental observations. A detailed description of the results and experimental techniques has been submitted for publication.[13]

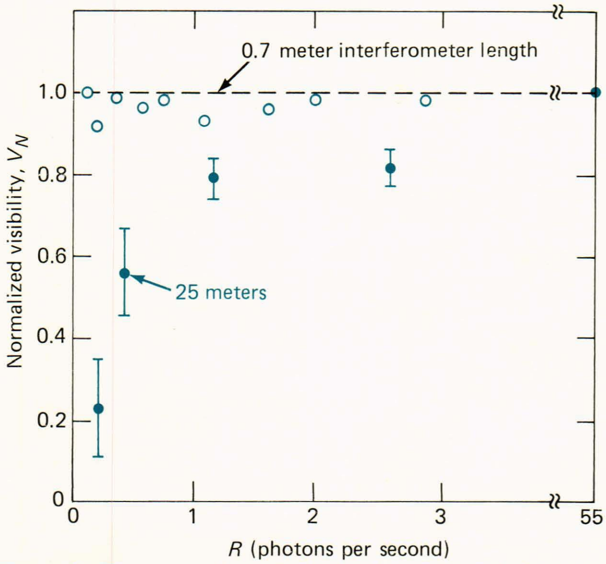


Figure 3—The normalized visibility, V_N, of the interference pattern as a function of the photon counting rate R. The solid points correspond to an interferometer length of 25 meters, while the open points correspond to an interferometer length of 0.7 meter.

IMPROVED APPARATUS

The apparatus used to make these measurements was necessarily constructed from equipment that was already available at APL. The interferometer mirrors in particular were not high quality. In addition, the data were recorded manually, and the low counting rates made it impractical to perform systematic studies such as continuously varying the length of the interferometer. For these reasons, an improved apparatus is now being constructed, part of which is shown in Fig. 4.

The new interferometer will be automatically aligned and operated by a personal computer. Although a Jamin interferometer is insensitive to translational motion because of the symmetry of the two optical paths, it is affected by rotations of one end with respect to the other. Experience with the original apparatus indicates that the walls at one end of the Research Center may rotate by a few arc seconds per hour with respect to the other end, primarily due to changes in the temperature of the building. This introduces a significant drift in the relative phase of the two paths through the interferometer. In the new apparatus, the computer will measure the phase drift periodically, using a helium-neon laser, and apply the appropriate corrections.

The interferometer mirrors and other optical components will be positioned using motorized micrometers equipped with optical encoders. The output of the optical encoders will allow the computer to position these micrometers with a resolution of 0.1 micrometer. Twenty-two of these micrometers will be used to position automatically the various mirrors, filters,

Figure 4—The new apparatus under construction. The photon detection equipment and a vacuum chamber containing one end of the interferometer are in the foreground. The other end of the interferometer can be seen at a distance of 45 meters. The computer, control electronics, and an optical bench containing the light sources are located in a room at the far end of the hall.

shutters, and other optical components. An additional benefit of the automated control is the ability to put the entire interferometer inside a vacuum, reducing the additional phase drifts that would otherwise result from temperature gradients in the air surrounding the mirrors.

The length of the new interferometer can be varied from 1 to 45 meters, allowing the functional dependence of the interference on the length of the interferometer to be compared with the results expected from local theories. The new apparatus also contains a monochromator, which will allow measurements to be made at a variety of wavelengths. Stable light sources are difficult to obtain at the low intensities required; the construction of a small light source consisting of an atomic beam excited by an electron beam is being considered for this purpose. Construction of the new apparatus is nearly completed, and new data should start to become available by midsummer, 1984.

SUMMARY

The experiment is intended to test the nonlocal nature of the quantum theory, which has been criticized by Einstein and others. The basic goal of the measurements is to determine whether single-photon interference continues to occur when the separation of the two optical paths through an interferometer is made sufficiently large. The preliminary results indicate a significant decrease in the visibility of the interference pattern under these conditions, which is in agreement with the requirements of all local theories and is in apparent disagreement with the predictions of the quantum theory. New data from an improved apparatus should be available soon.

Einstein once said, "Every physicist thinks that he knows what a photon is. I spent my life trying to find out what a photon is and I still don't know it." It is hoped that this experiment and others like it will help to answer some of these fundamental questions.

REFERENCES and NOTES

[1] J. S. Bell, "On the Einstein-Podolsky-Rosen Paradox," *Physics* **1**, 195 (1964).

[2] A. Einstein, B. Podolsky, and N. Rosen, "Can Quantum-Mechanical Descriptions of Physical Reality be Considered Complete?" *Phys. Rev.* **47,** 777 (1935). This particular example is from D. Bohm and Y. Aharonov, "Discussion of Experimental Proof for the Paradox of Einstein, Rosen, and Podolsky," *Phys. Rev.* **108,** 1070 (1957).

[3] B. d'Espagnat, "The Quantum Theory and Reality," *Sci. Am.* **241,** 158 (1979).

[4] For a review, see J. F. Clauser and A. Shimony, "Bell's Theorem: Experimental Tests and Explanations," *Rep. Prog. Phys.* **41,** 1881 (1978).

[5] A. Aspect, J. Dalibard, and G. Roger, "Experimental Test of Bell's Inequalities Using Time-Varying Analyzers," *Phys. Rev. Lett.* **49,** 1804 (1982).

[6] A. L. Robinson, "Loophole Closure in Quantum Mechanics Test," *Science* **219,** 40 (1983); F. Rohrlich, "Facing Quantum Mechanical Reality," *Science* **221,** 1251 (1983).

[7] J. D. Franson, "Effects of Correlated Photon Emission in Experiments Based on Bell's Theorem," submitted to *Phys. Rev. Lett.*

[8] The quantum theory does allow the formation of localized wave "packets," but a half-silvered mirror in an interferometer would then produce two separate packets, each traveling down one arm of the interferometer.

[9] J. D. Franson, "Extension of the Einstein-Podolsky-Rosen Paradox and Bell's Theorem," *Phys. Rev. D* **26,** 787 (1982).

[10] P. A. M. Dirac, *The Principles of Quantum Mechanics,* Clarendon, Oxford, p. 7 (1947).

[11] Consider a large chamber containing a single photon, and suppose that at some time, t, an experimenter decides to fill the entire chamber with some absorbing material. Based on experimentally measured cross sections for photon absorption, there will be negligible probability that the photon will not have been absorbed by an atom by time $t + \Delta t$, where Δt can be chosen to be relatively small. A rigorous discussion of these issues is given in Ref. 9.

[12] The intensity of the light source was reduced by reducing the amount of RF power used to excite the gas discharge. The discharge intensity required to ensure that the photons be statistically independent was estimated using the theoretical results of I. R. Senitzky, "Onset of Cancellation in Initially Uncorrelated Systems," *Phys. Rev.* **121,** 171 (1961). No decrease in the visibility was observed if, instead, the photon counting rate using a laser or a high-intensity gas discharge was reduced by the insertion of filters. The visibility was normalized to its value at the high-intensity limit in order to reduce any dependence on the properties of the interferometer.

[13] J. D. Franson and K. A. Potocki, "Optical Interferometer Data in Support of Local Theories," *Bull. Am. Phys. Soc.* **28,** 26 (1983); also submitted to *Phys. Rev. A.*