

Lawrence Berkeley National Laboratory

Recent Work

Title

EXPERIMENTAL DISTINCTION BETWEEN THE QUANTUM AND CLASSICAL FIELD THEORETIC PREDICTIONS FOR THE PHOTOELECTRIC EFFECT

Permalink

<https://escholarship.org/uc/item/7m81n05g>

Author

Clauser, John F.

Publication Date

1973-10-01

EXPERIMENTAL DISTINCTION BETWEEN THE
QUANTUM AND CLASSICAL FIELD THEORETIC
PREDICTIONS FOR THE PHOTOELECTRIC EFFECT

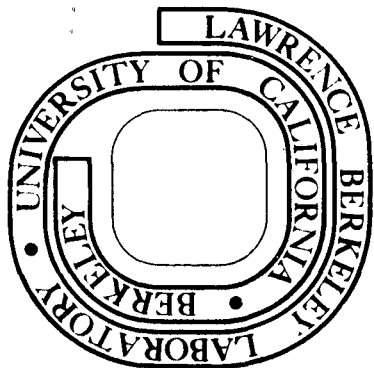
John F. Clauser

October 1973

Prepared for the U. S. Atomic Energy Commission
under Contract W-7405-ENG-48

For Reference

Not to be taken from this room



DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

U 0 0 0 0 4 0 0 1 0 1 4

LBL-2028 Rev.

EXPERIMENTAL DISTINCTION BETWEEN THE
QUANTUM AND CLASSICAL FIELD THEORETIC PREDICTIONS
FOR THE PHOTOELECTRIC EFFECT*

John F. Clauser

Department of Physics and Lawrence Berkeley Laboratory
University of California, Berkeley, California 94720

October 1973

ABSTRACT

We have measured various coincidence rates between four photomultiplier tubes viewing cascade photons on opposite sides of dielectric beam splitters. This experimental configuration, we show, is sensitive to differences between the classical and quantum field theoretic predictions for the photoelectric effect. The results, to a high degree of statistical accuracy, contradict the predictions by any classical or semiclassical theory in which the probability of photoemission is proportional to the classical intensity.

INTRODUCTION

It is commonly believed that experimental observations of the photoelectric effect establish the existence of uniquely quantum mechanical properties of the electromagnetic field. Various classic experiments, coupled with the notion of microscopic energy conservation, are usually cited to establish this claim.¹ Unfortunately the insistence upon microscopic energy conservation amounts to an auxiliary criterion, which for a classical field theory (CFT), is inherently ambiguous. The quantum mechanical energy of a photon, $h\nu$, is experimentally relevant to the photoelectric effect, determining the kinetic energy of the ejected electrons. This insistence, on the other hand, demands that the classical field energy $\int (E^2 + H^2)dV/8\pi$ be equal to this and be simultaneously conserved. The classical Maxwell's equations contain no constraint that these energies be equal, as a quantum field theory (QFT) does.² This demand is, in fact, unreasonable for a classical field theory. It is therefore also unreasonable to use this constraint as a basis for an experimental distinction between the theories. With equal justification one might say that these experiments disprove microscopic energy conservation during the photoelectric process while upholding CFT. The above belief was finally shown to be totally unfounded when it was demonstrated that the above observations can be quantitatively accounted for by a semiclassical radiation theory in which the electromagnetic field is left unquantized.³ The basic elements of this theory have since been used as a skeleton for the more recent and widely discussed neo-classical radiation theory of Jaynes, Crisp, and Stroud⁴ (NCT). In both of these theories it is hypothesized that the classical Maxwell's

equations describe the free electromagnetic field, and that this field never needs to be quantized to account for experimental observations. Previous experimental observations of the photoelectric effect, in and of themselves, are in agreement with this hypothesis, and do not appear to necessitate quantum mechanical properties for the radiation field.

In 1955, following Schrödinger's suggestion, Ádám, Jánossy, and Varga⁵ (AJV) searched for anomalous coincidences in a partially collimated beam of light. Jauch,⁶ in his discussions of the foundations of quantum mechanics, has recently emphasized the importance of this experiment and an associated one performed by Jánossy and Naray⁷ in establishing the existence of a wave-particle duality for photons. Moreover the arguments of AJV and Jauch do not rely on energy conservation (although other assumptions are needed for their specific scheme) and as such are not subject to the above criticism. Attention is naturally called to this experiment by the recent discussions of semiclassical theories, in hopes that it might provide an additional aspect of the photoelectric effect upon which the predictions of CFT and QFT differ.

In this paper we will show that the actual values of the parameters for the arrangement of AJV (and subsequent similar experiments) unfortunately were insufficient to make that experiment conclusive. We then report new experimental results which are conclusive. Our measurements involved a comparison of various twofold coincidence rates between four photomultiplier tubes viewing cascade optical photons, emitted by the same source through various beam splitters. We further

show that this configuration is sensitive to differences between the QFT and CFT predictions for this effect without additional assumptions, such as those required by AJV. The results, to high statistical accuracy, contradict the predictions by any classical or semiclassical radiation theory in which the probability of photoemission is proportional to the classical field intensity. This includes, for example, NCT. Our experiment thus resurrects the photoelectric effect as a phenomenon requiring quantization of the electromagnetic field.

It is noteworthy that an analysis by Aharonov et al.⁸ presented a scheme similar to that of AJV as a Gedankenexperiment, while noting a paucity of actual experimental distinctions between CFT and QFT. The CFT prediction for our experiment follows reasoning similar to that by Titulaer and Glauber,⁹ who discussed constraints applicable to CFT which demarcate a boundary between CFT and the more general QFT descriptions of the electromagnetic field.

In what follows we first contrast the CFT and QFT predictions for a single photon falling on a half-silvered mirror. We next discuss previous relevant experiments, contrast these with our own experimental scheme, and show that of these only ours provides the desired distinction. Finally we describe the apparatus and present the results.

PREDICTIONS FOR A SINGLE PHOTON FALLING ON A HALF-SILVERED MIRROR

In this section we review the arguments by AJV and Jauch. Consider the light emitted by a single atomic decay falling on a half-silvered mirror. During the decay a wave train (packet) of electromagnetic radiation is emitted. Suppose that it impinges upon a beam-

splitting mirror, and that the two resultant wave trains are directed to two independent photomultipliers labeled γ_A and γ_B . We desire the QFT prediction for the γ_A - γ_B coincidence rate. A simpler problem to consider first involves only the source atom and a second atom in one photocathode. We need the probability amplitude that, following de-excitation of the source atom, the second atom will become excited (or ionized). This has been obtained by Fermi¹⁰ and Fano,¹¹ using the Wigner-Weisskopf approximation. The inclusion of a third atom in a second photocathode is then straightforward. Denote by S, A, and B, respectively, the ground states of the source atom and the two detector atoms, and by S^* , A^* , and B^* the corresponding excited or ionized states of these atoms. Initially the source atom is excited, and the two detector atoms are in their ground states, hence

$|i\rangle = |S^*, A, B, 0_1, \dots, 0_j, \dots\rangle$. The remaining indices of the ket designate the state of the radiation field modes. The final state then has the form

$$\begin{aligned}
 |f\rangle = & U_A |S, A^*, B, 0_1, \dots, 0_j, \dots\rangle \\
 & + U_B |S, A, B^*, 0_1, \dots, 0_j, \dots\rangle \\
 & + U_S |S^*, A, B, 0_1, \dots, 0_j, \dots\rangle \\
 & + \sum_j U_j |S, A, B, 0_1, \dots, 1_j, \dots\rangle .
 \end{aligned} \tag{1}$$

The various U_i can be evaluated from formulae found in Refs. 10 and 11. Thus QFT predicts that an observation will find at most one of the detector atoms ionized; i. e., coincident responses will occur only at the random accidental rate, induced by emissions from two different excited source atoms.¹²

Next we consider the same system from the CFT viewpoint. Our basic assumptions for this are twofold: (1) the electromagnetic field is described by the classical (unquantized) Maxwell's equations, and (2) the probability of photoionization at a detector is proportional to the classical intensity of the incident radiation. These two assumptions alone are sufficient for our purposes, and they are in evident agreement with experiment.¹³ Since ionizations at the γ_A and γ_B phototubes are independent, but are induced by nearly identical classical pulses of light, for a given split wave train both tubes will have roughly the same probability for registering a count. This independence implies that the probability that both will respond to the split wave train is simply the product of the probabilities that each will respond. The nonzero value of this product implies the existence of an anomalous coincidence rate above the accidental background. The CFT prediction is thus in marked contrast with QFT prediction, the latter requiring no coincidences above the background level.¹²

The above argument may be summarized very simply. Consider a radiation field quantum mechanically with only one photon present. If we bring this into interaction with two separated atoms we will never get more than one photoelectron. If on the other hand we represent this field classically, we find that there is a nonvanishing probability for finding two photoelectrons. The classical Maxwell field has within it the possibility of providing with some probability any number of photons. Hence experiments of the above variety can distinguish between the two theories.

Such then is the argument of AJV and Jauch. Here we have also the basis for the usual particle interpretation of photons. A particle must be either transmitted or reflected. Both may be done simultaneously only by a wave. We then see how these macroscopic features of "particle-like" objects arise from the QFT formalism.

PREVIOUS EXPERIMENTAL RESULTS

That a photon is not split in two by a beam splitter is certainly "old hat" and it may seem surprising that we have gone to the effort to test this prediction experimentally. What is in fact much more surprising is that evidently no such experimental test has heretofore been performed, and such tests are clearly of great importance. Here we briefly review previous relevant experimental results and show that none provides the desired distinction.

Since the original work of AJV many two-photon coincidence experiments have been done, some involving light beams split by a half-silvered mirror. These all fall into two basic categories—atomic-cascade observations and Brown-Twiss effect observations. Excellent reviews of these topics have been presented by Camhy-Val and Dumont,¹⁴ and by Mandel and Wolf¹⁵ respectively. Cascade-photon observations in their usual configuration are not suitable for the above test, since in these, two different unsplit photons are observed.

The AJV experiment, although intended as a test of the above scheme, actually served as a forerunner to the Brown-Twiss effect experiments. Figure 1 reproduces a diagram of the experiment of AJV. In it they selected the light of a single spectral line with a monochromator, and focused it through a beam splitter onto two photo-

multipliers whose outputs drove a coincidence circuit.

Let us evaluate the magnitude of the expected anomalous coincidence rate. The CFT predictions for one and two photodetectors sharing the same field have been discussed earlier by Mandel¹⁶ from the above fundamental assumptions. Denote by $I(t)$ the instantaneous classical intensity incident simultaneously upon the γ_A and γ_B detectors due to their illumination by the whole source volume. The singles rates for the A and B detectors, averaged over their response time T , is given by:

$$S_A = \alpha_A T^{-1} \int_{-T/2}^{T/2} \langle I(t+t') \rangle dt', \quad (2)$$

$$S_B = \gamma_B T^{-1} \int_{-T/2}^{T/2} \langle I(t+t') \rangle dt',$$

where α_A and α_B are measures of the detector efficiencies, and the brackets denote an ensemble average over the emitted intensities.

Similarly, the average coincidence rate as a function of event separation τ is given by:

$$C_{AB}(\tau) = \alpha_A \alpha_B T^{-1} \int_{-T/2}^{T/2} \int_{-T/2}^{T/2} \langle I(t+t') I(t+t'+\tau) \rangle dt' dt''. \quad (3)$$

To obtain a model-independent prediction for the coincidence rate only from data on the singles rates does not appear possible, since (2) and (3) involve different averages of $I(t)$. AJV thus had to make various assumptions (assumptions which were unnecessary in the case of our own experiment). They tacitly assumed that

$$\left[\int_{-T/2}^{T/2} \langle I(t+t') \rangle dt' \right]^2 \approx \int_{-T/2}^{T/2} \int_{-T/2}^{T/2} \langle I(t+t') I(t+t'' + \tau) \rangle dt' dt'' \quad (4)$$

holds for each decay, when τ is the order of the decaying state lifetime. If then E pulses per second are emitted per unit time by a source, and if η is the average probability that a photomultiplier will yield a count, given an atomic decay, the count rate at that detector is

$$S = E \eta. \quad (5)$$

The expected anomalous coincidence rate predicted by the AJV assumptions is then given approximately by

$$C \approx \eta^2 E. \quad (6)$$

Assuming negligible detector dark rates, the accidental coincidence background rate from which C must be distinguished is

$$A \approx \eta^2 E^2 2\tau_c, \quad (7)$$

where τ_c is the resolving time of the coincidence system. One can now calculate the integration time required to measure to a precision of N standard deviations the difference between the excess coincidence rate given by Eq. (6) and the zero excess rate predicted by QFT. Doing this we obtain

$$T_{\text{int}} \approx (1+4E\tau_c) N^2 \eta^{-2} E^{-1}, \quad (8)$$

which in the limit of high source rates takes the form

$$T_{\text{int}} \approx 4N^2 \tau_c / \eta^2. \quad (9)$$

Thus the validity of their experiment rests directly upon the assumed or measured value of η : if it is too small, T_{int} will be too long and the

experiment will see only the random accidental background. AJV measured their detector efficiencies by assuming that it was given by the formula

$$\eta = Rh\nu/W, \quad (10)$$

where R is the count rate obtained for a given beam of photons, and W is the power in the same beam measured bolometrically. They thus found $\eta = 1/300$. With a resolving time $\tau_c = 2.3 \mu\text{sec}$ one calculates $T_{\text{int}} = 20.7 \text{ sec}$ for $N = 5$. From this reasoning AJV felt confident that they should have observed the anomalous coincidence rate, if present.

Let us re-examine from the CFT viewpoint the assumption tacitly contained in Eq. (10). Although the introductory arguments did not contain a requirement for energy conservation, AJV have unnecessarily reintroduced it with this assumption, moreover in direct conflict with our fundamental assumptions for a CFT. In our derivation above, η is the probability for a detector response, given a source atom decay. Clearly a wave-like pulse emitted by a source atom will expand, in the worst case spherically, or at best with a radiation pattern having a preferred direction.¹⁷ Much of this pulse will not enter the narrow acceptance solid angle subtended by the monochromator. Propagation will cause it to suffer an enormous decrease in intensity, commensurate with its expansion. Assuming macroscopic energy conservation on the average, the power W should then represent the total average power radiated by the source at the appropriate wavelength, not that which happens to be measured within the beam itself. The number calculated from Eq. (10) must appropriately be decreased by the fraction of the solid angle effectively subtended by the detectors. Other optical losses

will decrease this number even further.

If we conservatively estimate from their diagram the solid-angle loss to be $1/400$, their actual detector efficiency for spherically emitted wave-like pulses was undoubtedly less than 8×10^{-6} , in which case the required integration time for even $N = 1$ becomes $T_{\text{int}} \approx 1.3 \times 10^5$ sec. This is an order of magnitude longer than the duration of their experiment. Thus the experiment of Ádám, Jánossy, and Varga appears to be inconclusive when re-examined in this light.

Finally let us consider experiments of the Brown-Twiss variety. These experiments have a configuration basically the same as that of AJV. Because of the nature of this effect, however, all existing data have been accumulated with detectors subtending extremely small solid angles, much smaller even than those of AJV. From Eq. (9) we see that the required integration time scales with the inverse square of the detector solid angles, hence it would be hopeless to try to search for the above anomalous coincidence rate with such arrangements. Furthermore, in these experiments, the Brown-Twiss effect itself would tend to mask the effect we seek. In summary, then, none of the above experiments can provide the desired distinction.

EXPERIMENTAL SCHEME REQUIRING NO ADDITIONAL ASSUMPTIONS

The above discussion indicates that an observation of the anomalous coincidences predicted by a CFT requires highly efficient photodetectors. However, even if AJV had had the required efficiency and integration time, their experimental arrangement necessitated assumptions concerning the various field averages, and hence assumed a basic model

for the emission mechanism. Since no universally acceptable model is at hand, we have chosen to employ a scheme which renders our results model-independent. We did this by "splitting" simultaneously both the first and second photons of an atomic cascade. We viewed the light emitted on opposite sides of an assembly of excited atoms and focused it separately into two beams. The wavelength λ_1 on one side was selected to correspond to that of the first transition of the cascade, and on the other, λ_2 , to the second. The two light beams impinged on beam splitters, thus creating a total of four beams. Four associated photomultipliers labeled γ_{1A} , γ_{1B} , γ_{2A} , and γ_{2B} detected them. We monitored the coincidence rates between the four combinations: $\gamma_{1A}-\gamma_{1B}$, $\gamma_{2A}-\gamma_{2B}$, $\gamma_{1A}-\gamma_{2B}$, and $\gamma_{2A}-\gamma_{1B}$. A diagram of the arrangement is shown in Fig. 2.

Define $I_1(t)$ and $I_2(t)$ as the instantaneous intensity at the $\gamma_{1A}-\gamma_{1B}$ beam splitter with wavelength λ_1 , and at the $\gamma_{2A}-\gamma_{2B}$ beam splitter with wavelength λ_2 , respectively. It follows directly from the Cauchy-Schwarz inequality that the following inequality holds:

$$\left[\int_{-T/2}^{T/2} \int_{-T/2}^{T/2} \langle I_1(t+t'+\tau_1) I_1(t+t''+\tau_1) \rangle dt' dt'' \right] \left[\int_{-T/2}^{T/2} \int_{-T/2}^{T/2} \langle I_2(t+t'+\tau_2) I_2(t+t''+\tau_2) \rangle dt' dt'' \right] \geq \left[\int_{-T/2}^{T/2} \int_{-T/2}^{T/2} \langle I_1(t+t'+\tau_1) I_2(t+t''+\tau_2) \rangle dt' dt'' \right]^2 \quad (11)$$

Using (3), we can write this as

$$C_{1A-1B}^{(0)} C_{2A-2B}^{(0)} \geq C_{1A-2B}^{(\tau)} C_{1B-2A}^{(\tau)}. \quad (12)$$

Here we have ignored a possible polarization dependence of the detectors, the finite photocathode areas, as well as the nonvanishing phototube dark rates. It can be shown that Ineq. (12) may be summed over these contributions without change of form. Thus it is fully general and holds for these cases as well. The coincidence rates C_{1A-2B} and C_{2A-1B} here are the nonvanishing cascade rates. The product of these sets a lower bound to the product of the anomalous rates C_{1A-1B} and C_{2A-2B} . Thus, CFT predicts a large anomalous coincidence rate satisfying Ineq. (12). The prediction by QFT significantly violates this inequality, requiring no coincidences except those due to two-atom excitations.

APPARATUS AND RESULTS

Figure 2 is a diagram of the apparatus. The source contained ^{202}Hg atoms which were excited by electron bombardment. Light produced at $\lambda_1 = 5676 \text{ \AA}$ and $\lambda_2 = 4358 \text{ \AA}$ by the cascade $9^1P_1 \rightarrow 7^3S_1 \rightarrow 6^3P_1$ was used. It was made parallel by lenses (aspheric, $f \approx 1$), and fell on TiO_2 -coated glass beam splitters (transmission $\approx 63\%$ and 35% for opposite linear polarizations, inclined at 45° to the incident beams). Each resulting beam was directed through an interference filter (transmission $\approx 50\%$ at 5676 \AA , FWHM $\approx 50 \text{ \AA}$ for γ_{1A} and γ_{1B} ; transmission $\approx 30\%$ at 4358 \AA , FWHM $\approx 100 \text{ \AA}$ for γ_{2A} and γ_{2B}) onto an appropriate photomultiplier tube (RCA 8852, QE $\approx 15\%$ at 5676 \AA , dark current $\approx 50 - 300 \text{ Hz}$, operated at -80°C for γ_{1A} and γ_{1B} ; RCA 8850, QE $\approx 30\%$ at 4358 \AA , dark current $\approx 100 \text{ Hz}$, operated at 20°C for γ_{2A} and γ_{2B}).

The source itself was patterned after a design by Holt, Nussbaum, and Pipkin,¹⁸ and was made by using standard techniques. The electron gun was a standard 10 W cathode-ray tube gun obtained through the courtesy of the Raytheon Corporation. It was mounted with suitable deflecting electrodes and light masks in a quartz and pyrex envelope, evacuated, cleaned by baking and discharging, the metal parts out-gassed by induction heating, and the oxide cathode activated. A few milligrams of 93% pure ^{202}Hg were then distilled into the tube and the envelope sealed. The Hg vapor pressure was controlled by keeping a side arm immersed in ice water. A beam current of approximately $0.7 \mu\text{A}$ traversed the cylindrical excitation region (length ≈ 2 mm, diam ≈ 1 mm). The light output was stable. Photomultipliers operating in coincidence were separated from each other by more than 1.5 meters to eliminate anomalous coincidences caused by cosmic rays. Light pipes minimized the light loss during transit. The interference filters were placed at the outer ends of the light pipes to minimize anomalous coincidences due to scintillations in the beam splitter and collimator lenses. These could be excited by cosmic rays and/or residual radioactivity therein. This configuration also effectively eliminated phototube cross talk induced by light emitted at the last dynodes. High-speed electronics with ≈ 1 -nsec resolving time were used. The discriminators drove a time-to-amplitude converter whose output was fed to a pulse-height analyzer. External slow coincidence circuits gated the signals into one of the four analyzer memory quadrants, corresponding to the particular coincidence mode. The analyzer thus simultaneously accumulated the four different delayed coincidence spectra, i. e., the number of events pairs as a function of event separation time.

The results, shown in Figs. 3(a)-(d), represent more than 26 hours of integration. We find no evidence for an anomalous coincidence rate in either the $\gamma_{1A}-\gamma_{1B}$ or $\gamma_{2A}-\gamma_{2B}$ mode, but the normal cascade mode is quite apparent. For a timing and sensitivity check, both tube pairs were excited through the beam splitters by short-duration "classical" light pulses from a barium-titanate source,¹⁹ with approximately one photon per pulse. The resultant coincidence spectra are shown in Figs. 3(e) and 3(f). Finally, Fig. 3(g) shows that our data severely violate Ineq. (12), for a wide range of delays τ .

DISCUSSION

The importance of experimentally demonstrating phenomena which require a quantization of the electromagnetic field has been emphasized recently by a number of suggestions that such a quantization is unnecessary. Many standard effects have thus been challenged as not providing definitive proof for the necessity of this quantization.^{4,20} Several recent experiments testing the specific predictions by NCT and the Schrödinger interpretation have been performed²¹ in this direction. The present experiment and others²⁰ have tested the quantum mechanical aspects of Maxwell's equations. So far, none has uncovered any departure from the quantum electrodynamic predictions, but severe departures from CFT predictions have been found. The classical (unquantized) Maxwell equations thus appear to have only limited validity.

The author thanks J. A. Crawford and M. H. Prior for helpful and stimulating discussions during the performance of this experiment.

Footnote and References

*Work supported by the U. S. Atomic Energy Commission.

¹See for example W. Davis and L. Mandel in Coherence and Quantum Optics: Proceedings of the 3rd Rochester Conference on Coherence and Quantum Optics, edited by L. Mandel and E. Wolf (Plenum Press, New York, 1973), p. 113 and references therein.

²See for example W. Heitler Quantum Theory of Radiation, 3rd ed. (Oxford, London, 1954), p. 58.

³L. Mandel, E. C. G. Sudarshan, and E. Wolf, Proc. Phys. Soc. 84, 435 (1964); W. E. Lamb and M. O. Scully, in Polarization: Matiere et Rayonnement, edited by Société Francaise de Physique (Presses Universitaires de France, Paris, 1969).

⁴M. D. Crisp, and E. T. Jaynes, Phys. Rev. 179, 1253 (1969) and 185, 2046 (1969); C. R. Stroud, Jr. and E. T. Jaynes, Phys. Rev. A1, 106 (1970); E. T. Jaynes; *ibid.* 2, 260 (1970). See also the extensive review by E. T. Jaynes in Coherence and Quantum Optics, p. 35, (see Ref. 1) and references therein.

⁵A. Ádam, L. Jánosy, and P. Varga, Acta Phys. Hung. 4, 301 (1955); Ann. Physik 16, 408 (1955).

⁶J. M. Jauch, in Foundations of Quantum Mechanics, International School of Physics " Enrico Fermi," course 49, 1970, edited by B. d'Espagnat (Academic Press, New York, 1971), p. 20; J. M. Jauch, Are Quanta Real (Indiana University Press, Bloomington, Indiana, 1973).

- ⁷L. Jánossy and Zs. Náray, Acta Phys. Hung. 7, 403 (1957).
- ⁸Y. Aharonov, D. Falkoff, E. Lerner, and H. Pendleton, Ann. Phys. (N. Y.) 39, 498 (1966).
- ⁹U. M. Titulaer and R. J. Glauber, Phys. Rev. 140, B 676 (1965).
- ¹⁰E. Fermi, Rev. Mod. Phys. 4, 87 (1932).
- ¹¹U. Fano, Am. J. Phys. 29, 539 (1961).
- ¹²An additional coincidence rate, the Brown-Twiss effect, is also due to two-atom excitations (see Ref. 11). Its contribution to large aperture-large solid angle systems such as those under discussion here is negligible.
- ¹³A. T. Forester, R. A. Gudmundsen, and P. O. Johnson, Phys. Rev. 99, 1691 (1955).
- ¹⁴C. Camhy-Val and A. M. Dumont, Astron. and Astrophys. 6, 27 (1970).
- ¹⁵L. Mandel and E. Wolf, Rev. Mod. Phys. 37, 231 (1965). See also Selected Papers on Coherence and Fluctuations of Light, Vols. I and II, edited by L. Mandel and E. Wolf (Dover, N. Y., 1970).
- ¹⁶L. Mandel, Proc. Phys. Soc. (London) 72, 1037 (1958). More recent discussions are summarized by J. R. Klauder and E. C. G. Sudarshan in Fundamentals of Quantum Optics (Benjamin, N. Y., 1968), Chap. 3.
- ¹⁷One might assume a model in which all decays are identical, with the emitted intensity nearly isotropic. On the other hand, recent direct observations of atomic recoil associated with spontaneous emission indicate

that in a semiclassical scheme either the radiation must be emitted with a preferred direction, or that this recoil is due to some other mechanism. [J. L. Picque and J. L. Vialle, *Opt. Commun.* 5, 402 (1972); R. Schieder, H. Walther, and L. Wöste, *Opt. Commun.* 5, 337 R. Frisch, *Z. Physik* 86, 42 (1933). These experiments were in response to an elegant proof by A. Einstein [*Phys. Z.* 18, 121 (1917)] showing that recoil is necessary if thermal equilibrium is to be maintained when a dilute gas interacts with radiation. (His arguments also relied upon microscopic energy conservation.) Various schemes to account for such beaming have been proposed. See C. W. Oseen, *Ann. Physik* 69, 202 (1932) and the more recent work by Y. Beers, *Am. J. Phys.* 40, 1139 (1972) and 41, 275 (1973).

¹⁸R. A. Holt, Ph. D. Thesis, Harvard University, 1973 (unpublished); G. H. Nussbaum and F. M. Pipkin, *Phys. Rev. Letters* 19, 1089 (1967).

¹⁹T. G. Innes and G. C. Cox, in *Lawrence Berkeley Laboratory Counting Handbook*, UCRL-3307 Rev. p. cc8-31.

²⁰J. F. Clauser, *Phys. Rev. A* 6, 49 (1972).

²¹J. M. Wessner, D. K. Anderson, and R. T. Robiscoe, *Phys. Rev. Letters* 29, 1126 (1972); H. M. Gibbs, *Phys. Rev. Letters* 29, 459 (1972) and in *Coherence and Quantum Optics*, p. 83; H. M. Gibbs, G. G. Churchill, and G. J. Salamo, *Phys. Rev. A* 7, 1766 (1973); E. Gaviola, *Nature* 12, 772 (1928). This last experiment is discussed by J. M. Wessner, D. K. Anderson, and R. T. Robiscoe in *Phys. Today* 26, 13 (1973).

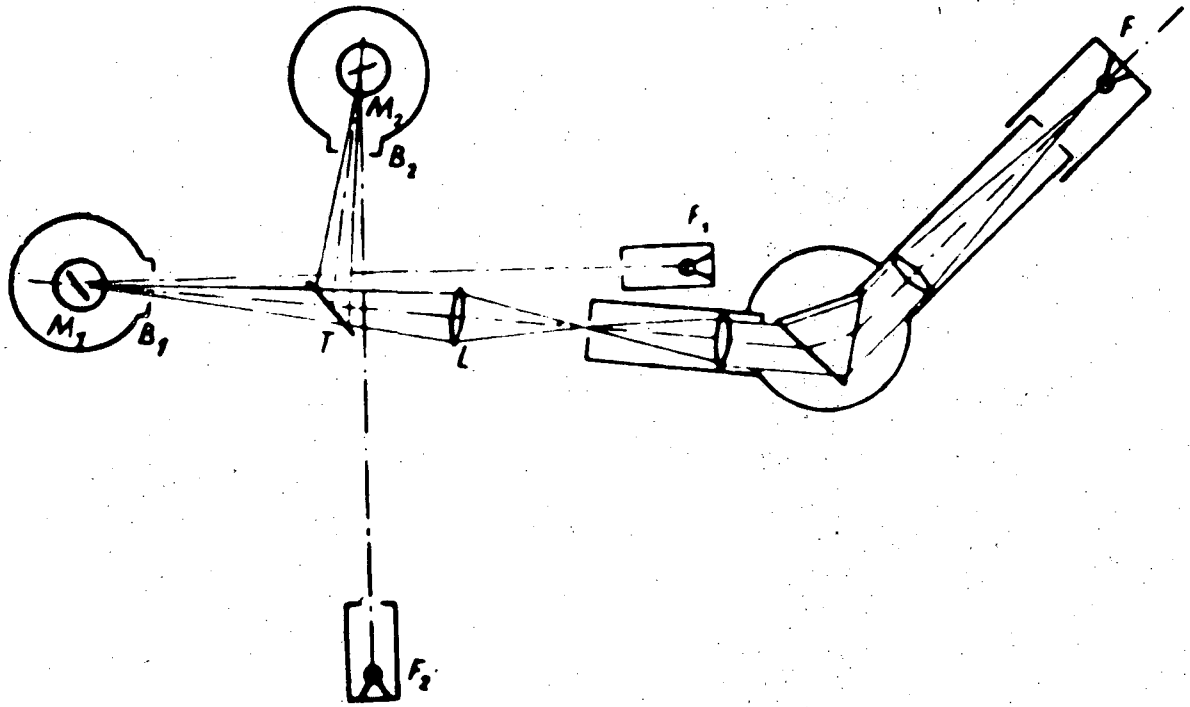
Figure Captions

Fig. 1. Experimental arrangement of Ádám, Jánossy, and Varga.

Light from source F is focused through a monochromator onto photomultipliers M_1 and M_2 via beam splitter T . (Figure after Ádám, Jánossy, and Varga).

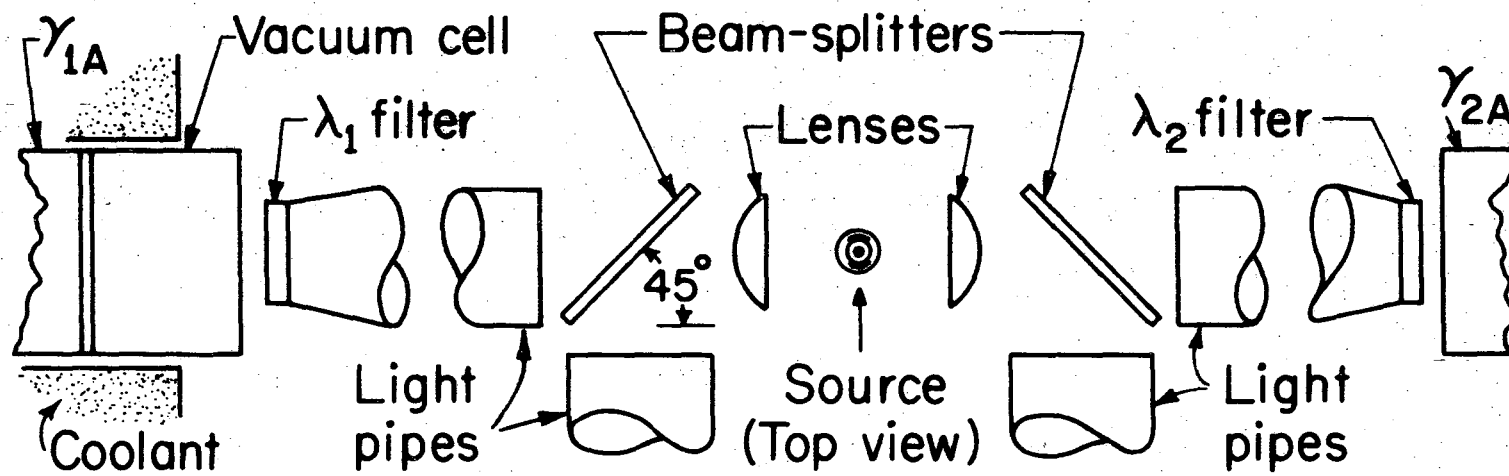
Fig. 2. Schematic diagram of our apparatus.

Fig. 3. (a)-(d) Time delay coincidence spectra of the four monitored channels: C_{1A-2B} , C_{1A-1B} , C_{2A-2B} , and C_{1B-2A} (e)-(f) C_{1A-1B} and C_{2A-2B} coincidence spectra in response to short pulses of light incident upon beam splitters produced by a barium titanate source. (g) Product of C_{1A-2B} and C_{1B-2A} versus time delay. For small times this clearly exceeds the indicated value of the product C_{2A-2B} and C_{1A-1B} evaluated at zero delay.

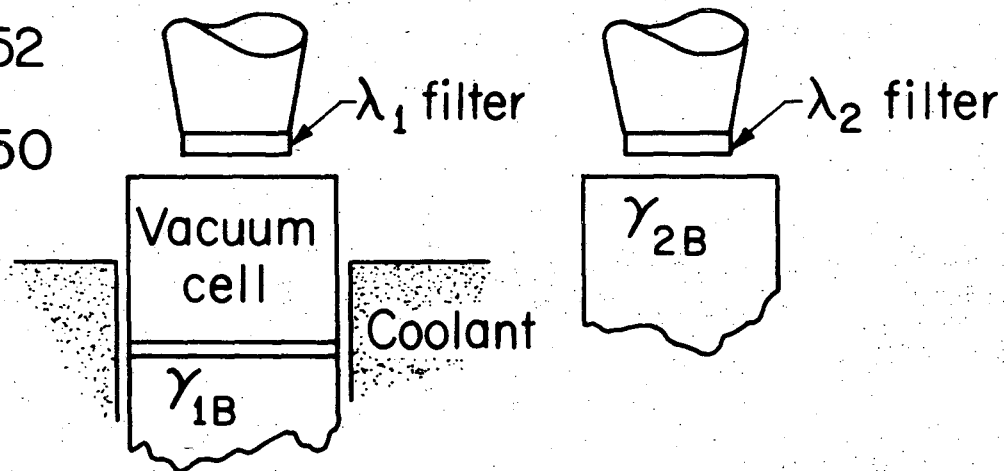


XBL 726-1061

Fig. 1

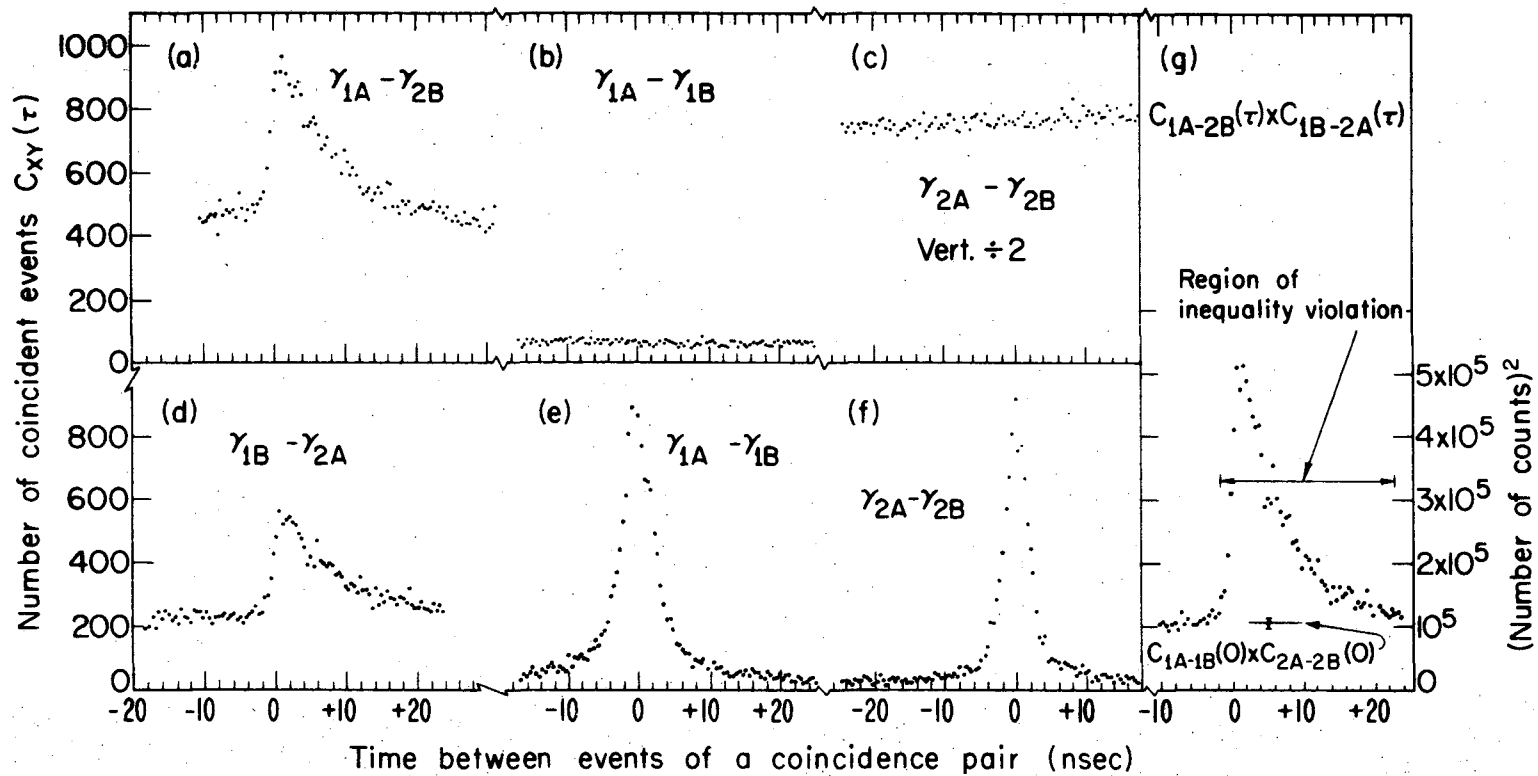


$\gamma_{1A,B}$ P.M.'s = 8852
 $\gamma_{2A,B}$ P.M.'s = 8850



XBL738-3667

Fig. 2



XBL736-3139

Fig. 3

LEGAL NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720