LBL-2028
Preprint c.1

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

John F. Clauser

July 1973

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

LBL 2028

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

July 1973

ABSTRACT

We have measured the coincidence rates between photomultiplier tubes viewing light on opposite sides of dielectric beam-splitters. This experimental configuration 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.

In 1955, at Schrödinger's suggestion, Ádám, Jánossy and Varga[1] (AJV), searched for anomalous coincidences in a partially collimated beam of light. Jauch[2] recently emphasized the importance of this experiment and an associated one performed by Jánossy and Náray[3] in establishing the existence of a wave-particle duality for photons. The experiment is frequently overlooked since it is commonly believed that the photoelectric effect, itself, had already established a particle character for light.[4] This belief was shown by Mandel, Sudarshan, and Wolf, and more recently by Lamb and Scully[5] to be false for previously observed aspects of this effect. These earlier discussions insisted that microscopic energy be conserved. This insistence amounts to an auxiliary criterion,[6] 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. Earlier arguments, on the other hand, demanded 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. 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.

The arguments of AJV and Jauch do not rely on energy conservation. Similar experiments were also suggested by Titulaer and Glauber.[7]

In principle these can directly distinguish between the QFT and CFT predictions for this effect. Unfortunately the actual parameters of AJV were insufficient to make that experiment conclusive.[4] We report here a comparison of various twofold coincidence rates between four photomultiplier tubes viewing light produced by the same source. We show that this configuration is sensitive to differences between the QFT and CFT predictions for this effect. The results, to high statistical accuracy, contradict the predictions of any classical or semiclassical radiation theory in which the probability of photoemission is proportional to the classical field intensity. This includes, for example, the neoclassical radiation theory (NCT) of Jaynes, Crisp and Stroud.[8] The experiment thus resurects the photoelectric effect as a phenomenon requiring a particle description for photons.

Let us first discuss the QFT and CFT predictions for 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 an atom in one photocathode. We need the probability amplitude that, following de-excitation of the source atom, the second atom will become excited. It has been obtained using the Wigner-Weisskopf approximation.[9] The inclusion of a third atom in a second photocathode is 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 $|i\rangle = |S^*, A, B, 0_1, \ldots, 0_j, \ldots\rangle$. The remaining indices of the ket designate the state of the radiation field modes. The final state then has the form

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

The various U_i can be evaluated from formulae found in Ref. 9. An observation will find at most one of the detector atoms ionized. Thus QFT predicts that the only coincident responses will occur at the random accidental rate; i.e., they will be induced by two different excited source atoms.[10] Here we have the basis for a particle interpretation of photons. A particle must be either transmitted <u>or</u> reflected. Both may be done simultaneously only by a wave.

Next we consider the same system from the CFT viewpoint. <u>Our basic assumption is that the probability of photoionization is proportional to the classical intensity of the incident radiation.</u>

This is consistent with semiclassical calculations and in evident agreement with experiment.[11] 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. This anomalous rate will scale linearly with the excitation rate, and will occur for a time interval comparable with the wave-train length. The time-delay coincidence spectrum will of course depend upon the shape of the wave train, and thus upon the particular model assumed for emission of the light. The background accidental rate is clearly distinguishable from this, since it scales quadratically with the excitation rate, and has a uniform delayed coincidence spectrum. The CFT prediction is thus in marked contrast with the QFT prediction, the latter requiring no coincidences above the background level.[10]

Such is the argument of AJV and Jauch. Let us next consider the actual magnitude of the expected anomalous rate. 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 average coincidence rate as a function of event separation

τ, averaged over the response time T of the detectors, is given by

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

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

To obtain a model-independent prediction for the coincidence rate from only data on the singles rates does not appear possible. Since no universally acceptable model is at hand, one must obtain additional data. We do so by performing the above experiment simultaneously for 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 γ_{1A}-γ_{1B}, γ_{2A}-γ_{2B}, γ_{1A}-γ_{2B} and γ_{2A}-γ_{1B}. A diagram of the arrangement is shown in Fig.1.

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

$$\left[\int_{-T/2}^{T/2}\int_{-T/2}^{T/2}\langle I_1(t+t'+\tau_1)I_1(t+t''+\tau_1)\rangle\, dt'dt''\right]\left[\int_{-T/2}^{T/2}\int_{-T/2}^{T/2}\langle I_2(t+t'+\tau_2)\, I_2(t+t''+\tau_2)\rangle\, dt'dt''\right] \geq \left[\int_{-T/2}^{T/2}\int_{-T/2}^{T/2}\langle I_1(t+t'+\tau_1)\, I_2(t+t''+\tau_2)\rangle\, dt'dt''\right]^2 \qquad (3)$$

Using (2), we can write this as

$$C_{1A-1B}(0)\; C_{2A-2B}(0) \geq C_{1A-2B}(\tau)\; C_{1B-2A}(\tau). \qquad (4)$$

In our derivation 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 (4) 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 inequality (4). The prediction by QFT significantly violates this inequality, requiring no coincidences except those due to two-atom excitations.

Figure 1 is a diagram of the apparatus. The source contained ^{202}Hg atoms which were excited by electron bombardment. Light produced at λ_1 = 5676Å and λ_2 = 4358Å by the cascade $9^1P_1 \rightarrow 7^3S_1 \rightarrow 6^3P_1$ was used. It was made parallel by lenses and fell on TiO_2-coated glass beam-splitters. Each resulting beam was directed through an interference filter onto a photomultiplier tube. The source lamp followed a design by Holt, Nussbaum and Pipkin.[12] 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 quandrants corresponding to the particular coincidence made. The analyzer simultaneously accumulated the four different delayed coincidence spectra, i.e., the number of event pairs as a function of event separation time.

The results, shown in Figs. 2(a)-(d), represent more than 26 hours of integration. We find no evidence for an anomalous coincidence rate in either the γ_{1A}-γ_{1B} or γ_{2A}-γ_{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 light pulses from a barium-titanate source with approximately one photon per pulse. The resultant coincidence spectra are shown in Figs. 2(e) and 2(f). Finally, Fig. 2(g) shows that our data severely violate inequality (4), for a wide range of delays τ.

The importance of experimentally demonstrating phenomena requiring a quantization of the electromagnetic field has been recently emphasized, and insufficient proof found for its necessity.[8,13] Several experiments testing the predictions by NCT and the Schrödinger interpretation have thus been performed.[14] This experiment and others[13] have tested the quantum mechanical aspects of Maxwell's equations. So far, no experiment 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.

REFERENCES

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

[1] Á. Adám, L. Jánossy, and P. Varga, Acta Phys. Hung. **4**, 301 (1955); Ann. Physik **16**, 408 (1955).

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

[3] L. Jánossy and Zs. Náray, Acta Phys. Hung. **7**, 403 (1957).

[4] See J. F. Clauser, in Coherence and Quantum Optics, edited by L. Mandel and E. Wolf (Plenum Press, N.Y. 1973) p.815.

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

[6] W. Davis and L. Mandel, in Coherence and Quantum Optics, p.113 and references therein (see Ref.4).

[7] U. M. Titulaer and R. J. Glauber, Phys. Rev. **140**, B 676 (1965).

[8] E. T. Jaynes, in Coherence and Quantum Optics, p.35 and references therein (see Ref.4).

[9] E. Fermi, Rev. Mod. Phys. **4**, 87 (1932); U. Fano, Am. J. Phys. **29**, 539 (1961).

[10] An additional coincidence rate, the Brown-Twiss effect, is also due to two-atom excitations (see Ref.9). It thus scales quadratically with the excitation rate. Its contribution here was negligible.

[11] A. T. Forester, R. A. Gudmundsen, and P. O. Johnson, Phys. Rev. **99**, 1691 (1955).

[12] R. A. Holt, private communication. See G. H. Nussbaum and F. M. Pipkin, Phys. Rev. Lett. **19**, 1089 (1967).

[13] J. F. Clauser, Phys. Rev. A **6**, 49 (1972); J. F. Clauser (to be published).

[14] J. M. Wessner, D. K. Anderson, and R. T. Robiscoe, Phys. Rev. Lett. **29**, 1126 (1972); H. M. Gibbs, Phys. Rev. Lett. **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 (Feb.1973).

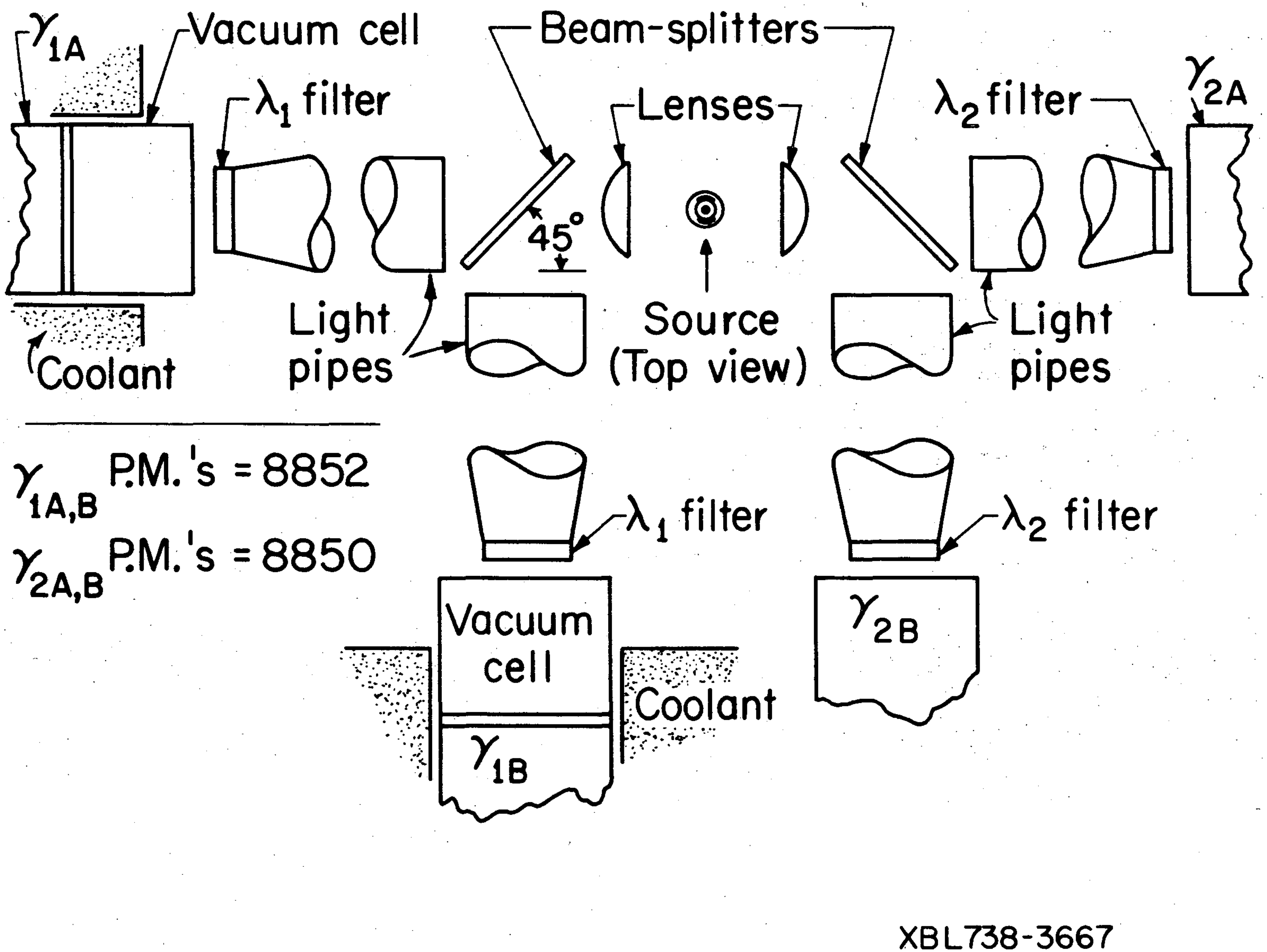
FIGURE CAPTIONS

Fig. 1.(a) Schematic diagram of the apparatus.

Fig. 2.(a)-(d) Time delay coincidence spectra of the four monitored channels: C_{1A-2B}, C_{1A-1B}, C_{2A-2B}, and C_{1B-2A}.

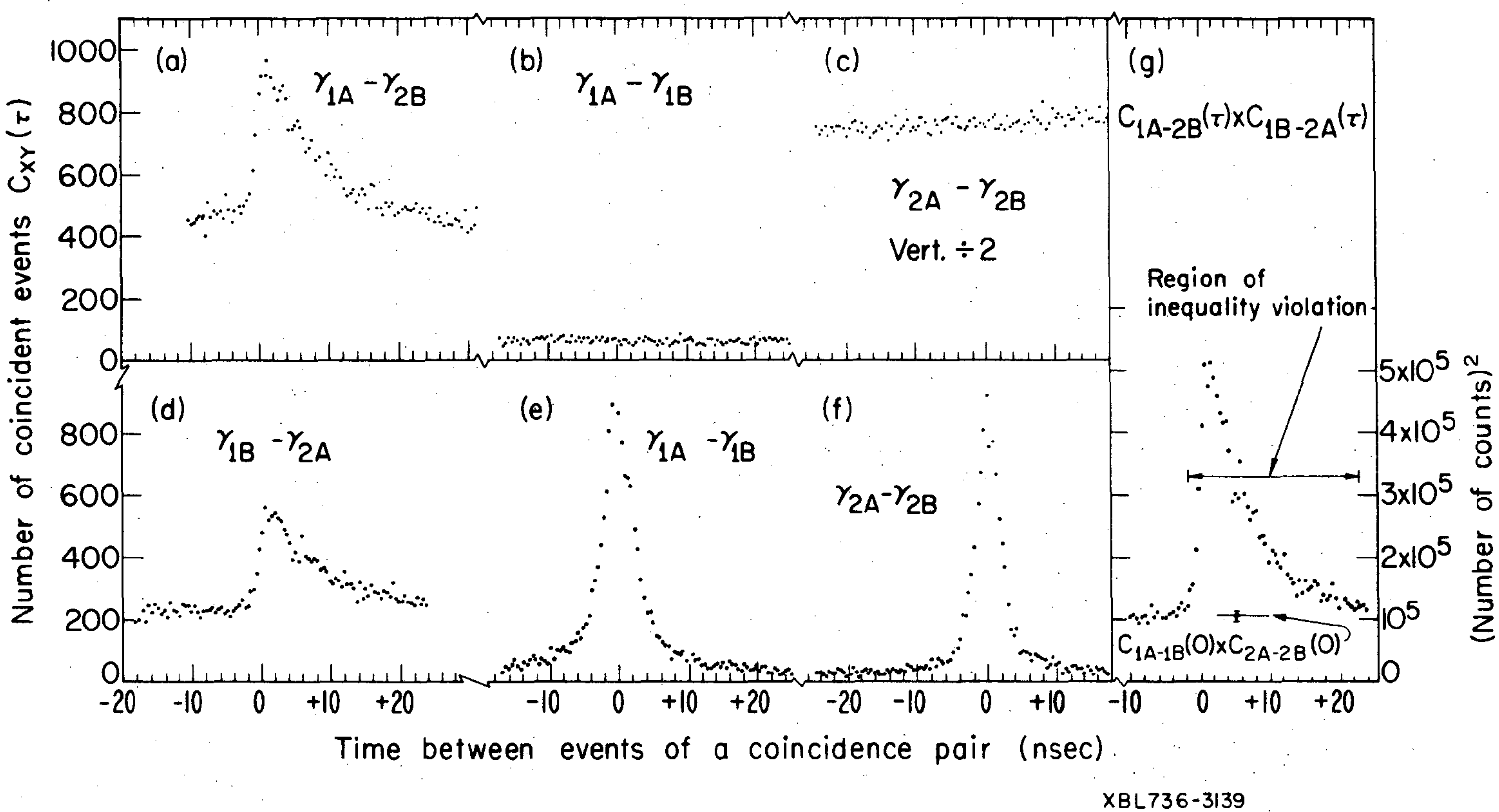
(e)-(f) C_{2A-2B} and C_{1A-1B} coincidence spectra in response to short pulses of light incident upon beam-splitters produced by a barium-titanate source.

(g) Product of C_{1A-2B} and C_{1B-2A} versus time delay. For small τ this clearly exceeds the indicated value of the product C_{2A-2B} and C_{1A-1B} evaluated at zero delay.



γ_{1A}
Vacuum cell
Beam-splitters
λ_1 filter
Lenses
λ_2 filter
γ_{2A}
45°
Light pipes
Source (Top view)
Light pipes
Coolant
$\gamma_{1A,B}$ P.M.'s = 8852
$\gamma_{2A,B}$ P.M.'s = 8850
λ_1 filter
λ_2 filter
Vacuum cell
γ_{2B}
Coolant
γ_{1B}
XBL738-3667

Fig. 1



(a)
$\gamma_{1A}-\gamma_{2B}$
(b)
$\gamma_{1A}-\gamma_{1B}$
(c)
$\gamma_{2A}-\gamma_{2B}$
Vert. ÷ 2
(g)
$C_{1A-2B}(\tau)\times C_{1B-2A}(\tau)$
Region of inequality violation
(d)
$\gamma_{1B}-\gamma_{2A}$
(e)
$\gamma_{1A}-\gamma_{1B}$
(f)
$\gamma_{2A}-\gamma_{2B}$
$C_{1A-1B}(0)\times C_{2A-2B}(0)$
Number of coincident events $C_{XY}(\tau)$
(Number of counts)^2
Time between events of a coincidence pair (nsec)
XBL736-3139

Fig. 2

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