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Experimental Investigation of a Polarization Correlation Anomaly*

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An experiment was performed to search for the anomalous two-photon polarization correlation observed earlier by Holt and Pipkin using a cascade of atomic mercury. The experiment is a sensitive test of various aspects of the foundations of quantum mechanics. Although the present experimental arrangement differed only slightly from theirs, the anomalous results were not observed.

Following the suggestion by Clauser *et al.*,[1] which in turn was inspired by Bell's theorem,[2] two experiments were performed. Their purpose was to distinguish between the predictions by the whole class of local hidden-variable theories and conventional quantum mechanics. Moreover, Clauser and Horne[3] have since shown that these experiments also test the more general (not necessarily deterministic) class of objective local theories. This class includes any theory containing objectivity *and* naive locality, and thus has a strong intuitive appeal. Unfortunately, the results of the two experiments are in conflict. The results obtained by Freedman and Clauser[4] at the University of California, Berkeley are in excellent agreement with the predictions of quantum mechanics, and appear to exclude general objective local theories.[3] On the other hand, the unpublished results obtained at Harvard University by Holt and Pipkin[5] distinctly favor objective local theories (and/or local hidden-variable theories) and, as such, are in disagreement with the quantum-mechanical predictions. This Letter describes a third experiment attempting to repeat, at least in part, the conditions of the Harvard University experiment.

The experiment consists of measuring the polarization correlation of optical photons emitted in certain atomic cascades. Atoms undergoing cascade decays are viewed by two symmetrically placed optical systems, each containing a rotatable linear polarizer and a single-photon detector (see Fig. 1). The rate of coincidence counts $R(\varphi)$ for two single-photon detections is measured as a function of the angle φ between the orientations of the inserted polarizers. It is compared with the coincidence rate R_0 measured with both polarizers removed.

Objective local theories and local hidden-variable theories require that the following constraint governs these rates[1,3,4]:

$$\delta = |R(22\tfrac{1}{2}°)/R_0 - R(67\tfrac{1}{2}°)/R_0| - \tfrac{1}{4} \leq 0. \qquad (1)$$

An appropriate choice of a cascade is required so that the photons, though spatially separated, are strongly quantum-mechanically correlated, with the individual photon polarizations retaining a mutual nonlocal interference effect.[6] With such a choice, as well as with some rather stringent minimum requirements on the polarizer efficiencies and collimator solid angles, the quantum-mechanically predicted correlation violates the above constraint.[1-3] These specifications were achieved in the experiment of Freedman and Clauser by generating the photons in a $J=0 \to J=1 \to J=0$ cascade of atomic calcium. The cas-

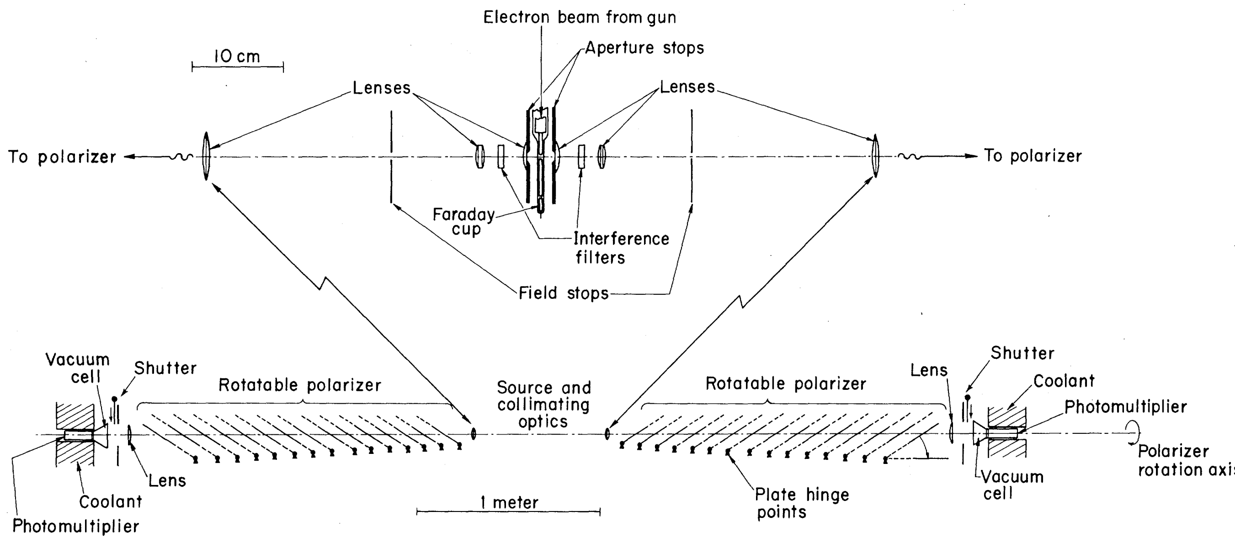

FIG. 1. Overall arrangement of apparatus, showing source and collimating optics (upper), and rotatable pile-of-plates polarizer assemblies and detectors (lower). Polarizer plates are removed for R_0 measurement by folding them flat at their hinge points out of the optical path. The last plate on the right-hand side is shown in the removed position. Solid lines on plates depict glass plates; broken lines depict metal frames.

cade was excited by optical fluorescence, and polarizations were analyzed with pile-of-plates polarizers. The experiment of Holt and Pipkin —in disagreement with quantum theory—met the above requirements by employing a $J=1\rightarrow J=1\rightarrow J=0$ cascade in atomic mercury. Excitation occurred by electron impact; calcite-prism polarization analyzers were utilized.

The present experimental arrangement employed the same cascade and excitation mechanism used by Holt and Pipkin. However, since they experienced considerable difficulty and expense in obtaining calcite polarizers with the necessary efficiencies, and since the complex mechanisms required for the pile-of-plates polarizers were available from the previous Berkeley experiment, the pile-of-plates variety was used.

A diagram of the apparatus is shown in Fig. 1. The source was enclosed in a sealed-off Pyrex bulb containing 91% ^{202}Hg at room temperature (2.1% ^{199}Hg and 2.2% ^{201}Hg).[7] Inside the bulb, a 135-eV beam of electrons was focused through 2-mm-diam collimating holes. A 2 mm length of the collimated beam was exposed and acted as the source region. Excitation of the $9^1P_1\rightarrow 7^3S_1\rightarrow 6^3P_0$ cascade occurred here, giving rise to the emission of $\lambda_1=5676$ Å and $\lambda_2=4046$ Å photons, viewed by the two optical systems. Additionally, the region was viewed by a third phototube which drove a servo loop to stabilize the 125-nA beam current to within ± 1%. Magnetic fields were kept to less than 50 mG by Helmholtz coils. The overall structure of this lamp was similar to the one used by Holt and Pipkin, and by the author in a previous experiment.[8]

Each optical system was designed to perform several functions. An aperture stop was inserted ahead of the first lens to positively limit the acceptance solid angle. The first lens focused the light approximately parallel. The light then passed through a narrow-band interference filter to select, respectively, the λ_1 or λ_2 photons emitted by the cascade. The full width at half-maximum (FWHM) transmissions of the filters were 50 and 7.5 Å, respectively. Light was then reimaged by the second lens with a field stop located in its image plane. This stop limited the object size, and thus prevented reflected light from the inside of the electron-beam collimators from entering the detectors. It also eliminated collimator shadows and prevented alteration of the imaging properties by polarizer-induced beam displacement, which would occur if stops were to follow the polarizers. Finally, before entering the polarizers, the light was refocused parallel so that it impinged with a nearly uniform Brewster's angle of incidence on the polarizer plates. Although so many optical elements reduced the net detector efficiencies and increased the required integration time, their use was felt warranted as a hedge against systematic errors.

The polarizers and their driving mechanisms were as described in Ref. 4, except that the number of plates in each polarizer was increased to 15 to improve its characteristics. A final lens focused the light exiting from the polarizers onto an appropriate photomultiplier tube (RCA 8850 at 0°C for 4046 Å, and RCA C31000E at − 80°C for 5676 Å). The two optical systems were essentially indentical except for the filters, lens antireflection coatings, and photocathode characteristics.

The phototube outputs were coupled to amplifiers and disciminators, which in turn drove the associated coincidence circuitry. To prevent crosstalk, the two discriminators were offset from each other by delay lines so that their triggerings for coincident counts occurred 40 nsec apart. Coincidence rates were measured using scalars fed by the coincidence circuits. In contrast to the experiment of Ref. 4, the lower effective detector efficiencies and higher source rates here made accidental coincidences contribute substantially to the total coincidence rate. These were monitored in two different ways with consistent results: (1) Accidental rates were deduced from the single-photon detection rates and the measured coincidence window (12.93 nsec). (2) A second coincidence circuit, with its window approximately 20.6 times longer than the first and displaced in time by 80 nsec, was used to directly monitor accidental rates. Dead-time corrections to all rates were small. The apparatus cycling and data reduction followed the scheme used in Ref. 4, except that shutters (shown in Fig. 1) were closed every ninth counting period to monitor the phototube dark current. This procedure permitted a continuous monitoring of the polarizer transmissions, to assure that they did not deteriorate because of an accumulation of dust on the glass surfaces.

Figure 2 shows the data integrated over a running time of 412 h. The solid curve for comparison is the quantum-mechanical prediction using the measured average polarizer efficiencies ($\epsilon_{M,m}{}^1 \approx 96.5\%, 1.1\%$ for light polarized parallel and perpendicular to the polarizer axis, respectively; $\epsilon_{M,m}{}^2 \approx 97.2\%, 0.84\%$), collimator solid angles (half-angle $\approx 18.6°$), depolarization due to residual ^{199}Hg and ^{201}Hg isotopes,[9] and alignment of the 9^1P_1 level.[10] A comparison of the restriction (1) imposed by objective local theories with these results shows that $\delta_{\rm exp} = 0.0385 \pm 0.0093$ is in distinct violation of the prediction by inequality (1), $\delta_{\rm olt} \leq 0$, but is in good agreement with the quantum-mechanical prediction $\delta_{\rm qm} = 0.0348$. For further comparison, the quantum-mechanical prediction for the apparatus of Holt and Pipkin was $\delta_{\rm qm} = 0.016$, whereas they measured $\delta_{\rm exp} = -0.034 \pm 0.013$.

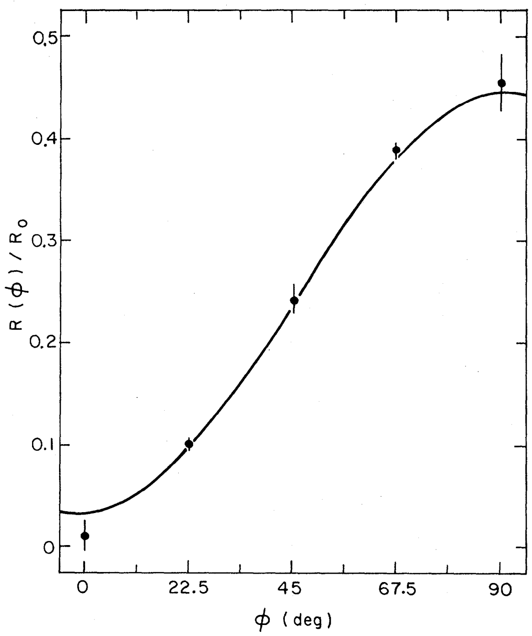

FIG. 2. $R(\varphi)/R_0$ as a function of angle φ between polarization planes. Solid curve is the quantum-mechanical prediction calculated using measured average polarizer efficiencies, solid angles, and Hg isotopic abundances.

The discrepancy with the quantum-mechanical predictions observed by Holt and Pipkin was not found in the present data. However, the cause of their discrepancy was not pinpointed either.[11] In any case, it seems clear that the cause of the differences between their results and those of Freedman and Clauser is not in the use of different cascades and excitation mechanisms. Remaining (possibly significant) differences not tested here are as follows: (1) Holt and Pipkin used calcite-prism polarizers, instead of the pile-of-plates variety used here and in Ref. 4. (2) The present arrangement, as well as that of Ref. 4, had interference filters placed ahead of the polarizers. I used the former arrangement so that the filters isolated the polarizers from each other, thus avoiding the possibility of one polarizer's position affecting the count rate at the other detector via spurious reflections. (3) The present experiment used the isotope ^{202}Hg, while the Harvard University version used ^{198}Hg.

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[1]J. F. Clauser, M. A. Horne, A. Shimony, and R. A. Holt, Phys. Rev. Lett. 23, 880 (1969); J. F. Clauser, Bull. Am. Phys. Soc. 14, 578 (1969); A. Shimony, in *Foundations of Quantum Mechanics*, *Proceedings of the International School of Physics, "Enrico Fermi," Course XLIX*, edited by B. d'Espagnat (Academic, New York, 1971), p. 182; M. A. Horne, Ph.D. thesis, Boston University, 1970 (unpublished). Note, these tests are subject to weak additional assumptions, necessary for experimental reasons. Improved experiments would not be subject to this limitation.

[2]J. S. Bell, Physics (Long Island City, N.Y.) 1, 195 (1965).

[3]J. F. Clauser and M. A. Horne, Phys. Rev. D 10, 526 (1974).

[4]S. J. Freedman and J. F. Clauser, Phys. Rev. Lett. 28, 938 (1972); S. J. Freedman, Ph.D. thesis, University of California, Berkeley, 1972 (unpublished), and Lawrence Berkeley Laboratory Report No. LBL-391 (unpublished).

[5]R. A. Holt and F. M. Pipkin, to be published. See also R. A. Holt, Ph.D. thesis, Harvard University, 1973 (unpublished).

[6]E. S. Fry [Phys. Rev. A 8, 1219 (1973)] has tabulated the possible angular momenta of the involved states which allow a violation of inequality (1) to obtain.

[7]This analysis was kindly performed by C. Otto and B. Meisenheimer of Lawrence Livermore Laboratory with a mass spectrometer.

[8]J. F. Clauser, Phys. Rev. D 9, 853 (1974).

[9]The quantum-mechanically predicted polarization correlation for cascades involving isotopes with nonzero nuclear spin has been calculated by Fry (see Ref. 6).

[10]The average polarization of the 5676-Å photons (referenced to the electron beam axis) was observed to be $\approx 1.2\%$ (although it is possible that some of this was due to phototube or final lens polarization sensitivity). The alignment of the 9^1P_1 level can then be calculated using the expressions of U. Fano and J. H. Macek [Rev. Mod. Phys. 45, 553 (1973)], averaged over the detector solid angle. The result is $\rho \pm 1/\rho_0 \approx 1.0507$. Using the formula derived in Ref. 5, one can then calculate the expected effect upon the polarization correlation magnitude—it is *increased* by $\approx 0.2\%$. It is noteworthy that essentially the same alignment can be inferred from the measurements of Ref. 5, although in that work the residual 5676-Å polarization was attributed to reflections from the inner surfaces of the electron-beam collimators. In the present work these collimators were hidden from the detectors' view by the field stops.

[11]It seems pointless to speculate here about possible systematic errors in the work of Ref. 5. None was found which in the author's opinion totally invalidates this work. Most suspicious, however, appears to be the fact that in that experiment the lamp envelope was stressed, and hence birefringent. Moreover, in order to correct for this effect, the average difference between the retardations had to be measured. In fact, it appears that it was the sum of the retardations which was measured, and the average difference inferred by assumption.

New-Particle Decays and $\mu e K$ Events*

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We consider the possible role of $Y \to Ke\nu$ new-particle decays in the $\mu^- e^+ K_s$ events in neutrino bubble-chamber experiments. We calculate transverse momentum distributions of e and K, including effects of initial Y-particle transverse motion, and invariant K-e mass distributions. We also calculate the E_e spectrum in a current-fragmentation model, and estimate expected μe event rates from dimuon event rates assuming that they have a common origin.

Neutrino bubble-chamber experiments[1,2] have recently reported $\mu^- e^+$ events, with one or more visible K_s^0 in each event, that probably signal the production and decay of some new particle that we label Y.[3] It is therefore important to study decay modes involving kaons that may be playing a role here. In this Letter we study the specific mode $Y^+ \to \bar{K}^0 e^+ \nu$ for spinless Y and calculate (i) distributions of e^+ and $\bar{K}^0$ momenta $p_\perp$ transverse to the plane defined by the incident neutrino and final μ^- momenta; (ii) distribution broadening due to transverse motion of Y; (iii) the K-e invariant