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EXPERIMENTAL INVESTIGATION OF A POLARIZATION CORRELATION ANOMALY*

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ABSTRACT

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 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the predictions of quantum mechanics, and appear to exclude general objective local theories.[3] On the other hand, the unpublished results obtained at Harvard by Holt and Pipkin[5] distinctly favor objective local theories (and/or local hidden-variable theories) and, as such, are in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 note describes a third experiment attempting to repeat, at least in part, the conditions of the Harvard 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 $R(\phi)$ 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_o measured with both polarizers removed.

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

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

An appropriate choice of a cascade is required so that the photons, though spatially separated, be 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 $J = 0 \rightarrow J = 1 \rightarrow J = 0$ cascade of atomic calcium. The cascade was excited by optical fluorescence, and polarizations were analyzed with pile-of-plate 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.

EXPERIMENTAL ARRANGEMENT

Our 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 $8^1P_1 \rightarrow 7^3S_1 \rightarrow 6^3P_0$ 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 $\pm 1\%$. Magnetic fields were kept to less than 50mG 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 Å 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 imageing 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 nearly uniform Brewster's-angle 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 mechanims 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 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 discriminators, which in turn drove the associated coincidence circuitry. To prevent cross-talk, 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 scalers fed by the coincidence circuits. In contrast with 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.

RESULTS

Figure 2 shows the data integrated over a running time of 412 hours. The solid curve for comparison is the quantum-mechanical prediction using the measured average polarizer efficiencies ($\varepsilon^1_{M,m} \approx$ 96.5%, 1.1%)($\varepsilon^2_{M,m} \approx$ 97.2%, 0.84%), collimator solid angles (half angle $\approx$ 18.6°), and depolarization due to residual ^{199}Hg and ^{201}Hg isotopes.[9] A comparison of the restriction (1) imposed by objective local theories with these results shows that $\delta_{exp} = 0.0385 \pm 0.0093$ is in distinct violation of the prediction by inequality (1), $\delta_{olt} \leq 0$, but is in good agreement with the quantum-mechanical prediction $\delta_{qm} = 0.0341$. For further comparison, the quantum-mechanical prediction for the apparatus of Holt and Pipkin was $\delta_{qm} = 0.016$, whereas they measured $\delta_{exp} = -0.034 \pm 0.013$.

CONCLUSION

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.[10] 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. We 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 version used ^{198}Hg.

FOOTNOTES AND REFERENCES

*Work supported by the Energy Research and Development Administration.

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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. Amer. Phys. Soc. 14, 578 (1969); A. Shimony, Foundations of Quantum Mechanics, International School of Physics, Enrico Fermi, course 49, edited by B. d'Espagnat (Academic Press, New York, 1971), p. 182; M.A. Horne, Ph.D. thesis (Boston University, 1970) (unpublished).
   Note: These texts are subject to weak additional assumption, necessary for experimental reasons. Improved experiments would not be subject to this limitation.

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), Lawrence Berkeley Laboratory Report LBL-391 (unpublished).

5. R.A. Holt and F.M. Pipkin, preprint. 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 E.S. Fry (See Ref. 6).

FIGURE CAPTIONS

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_o measurement by folding them flat at their hinge points out of the optical path. Last plate on right is shown in the removed position. Solid lines on plates depict glass plates; broken lines depict metal frames.

Fig. 2 $R(\phi)R_o$ 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.

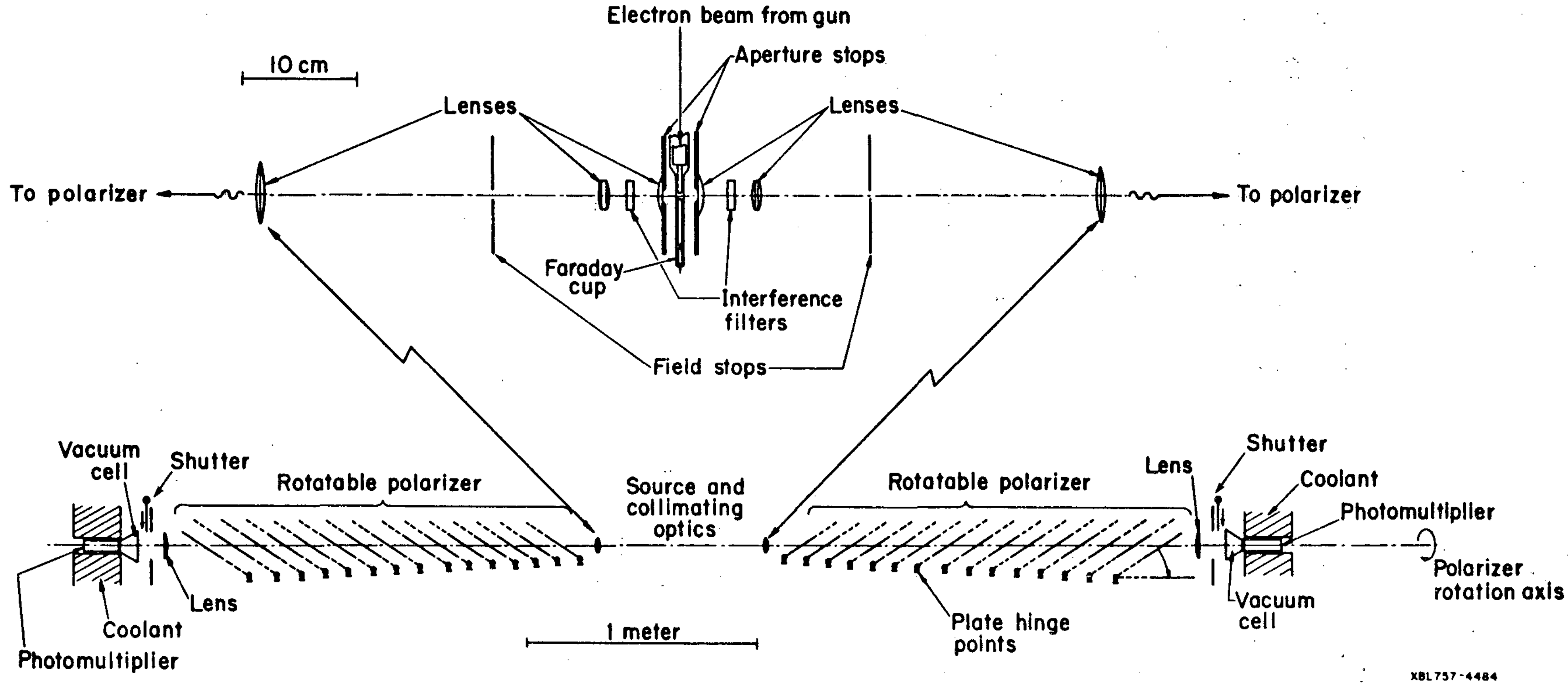
Electron beam from gun
Aperture stops
10 cm
Lenses
Lenses
To polarizer
To polarizer
Faraday cup
Interference filters
Field stops
Vacuum cell
Shutter
Rotatable polarizer
Source and collimating optics
Rotatable polarizer
Lens
Shutter
Coolant
Photomultiplier
Lens
Coolant
Photomultiplier
1 meter
Plate hinge points
Vacuum cell
Polarizer rotation axis
XBL757-4484

FIG. 1

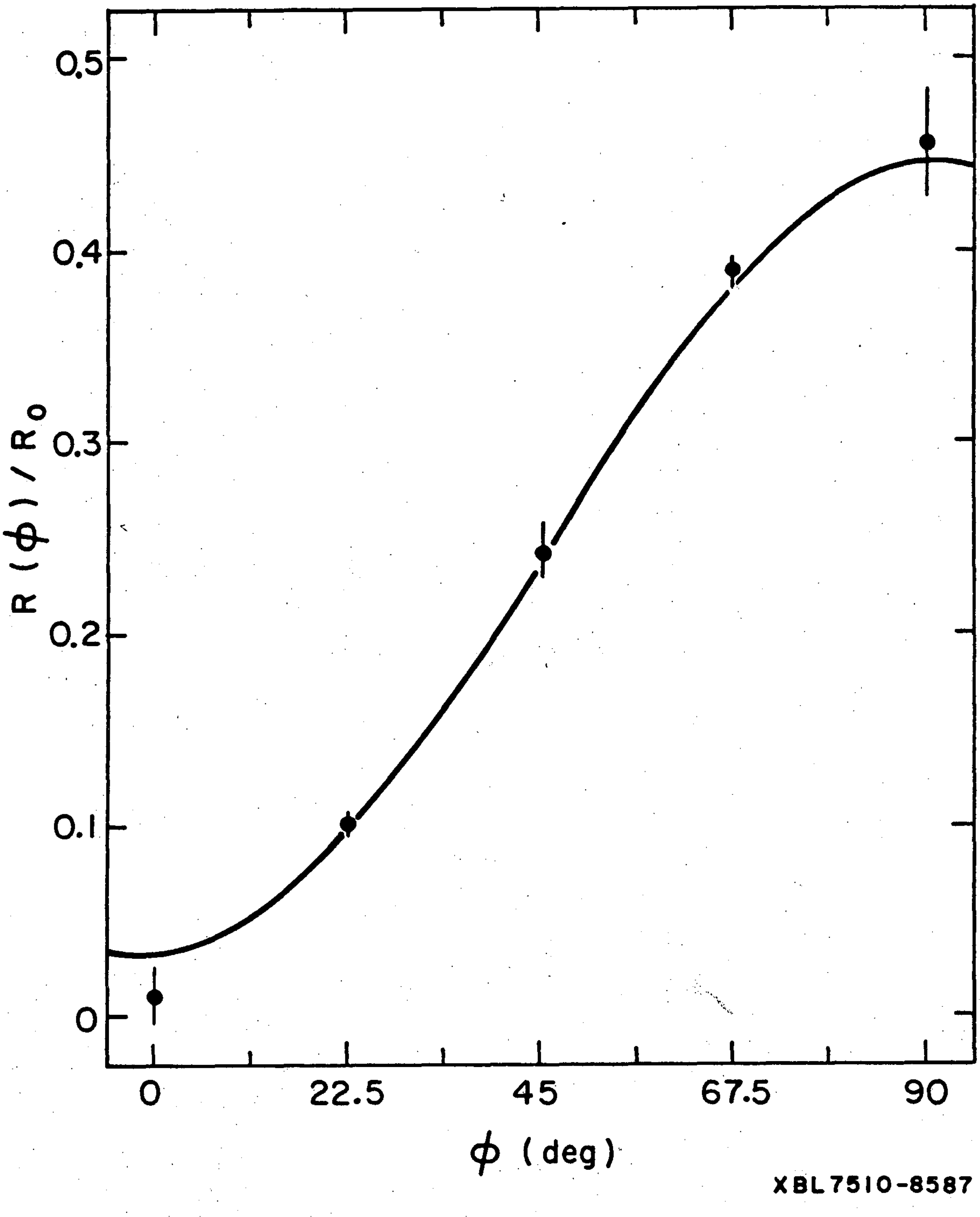

FIG. 2

U U 3 J 4 4 U J 9 3 4

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