Polarization Correlation of the Two Photons Emitted by Metastable Atomic Deuterium: A Test of Bell's Inequality

W. Perrie, A. J. Duncan, H. J. Beyer, and H. Kleinpoppen
Atomic Physics Laboratory, University of Stirling, Stirling FK9 4LA, Scotland
(Received 28 January 1985)

The polarization correlation of the two photons emitted simultaneously by metastable atomic deuterium in a true second-order decay process has been measured for the first time. The results are in agreement with quantum mechanics and violate Bell's inequality by nearly 2 standard deviations in an experiment where the process of absorption and reemission is not important.

PACS numbers: 32.80.Wr, 03.65.Bz

Over many years theoretical and experimental work in atomic hydrogen has served to elucidate our understanding and extend our knowledge of the fundamental properties and behavior of atoms. For decades such work was dominated by measurements of the fine-structure constant and the Lamb shift. However, other effects in atomic physics were also considered first with reference to atomic hydrogen. For example, in 1931, Göppert-Mayer,[1] in a paper which pioneered the field of multiphoton transitions, predicted the possibility of spontaneous two-photon decay processes and, in 1940, Breit and Teller[2] applied this theory to the $2S$-$1S$ transition in atomic hydrogen. Although the two-photon decay of singly ionized helium was observed in 1965,[3] it was not until 1975 that such a process was observed in a laboratory in atomic hydrogen itself.[4,5] It is unusually fortunate that, among all one-electron atoms and ions, hydrogen itself is unique in that the wavelengths of the emitted photons fall mostly in a region of the spectrum where polarization can be measured in air by use of conventional pile-of-plates polarizers.

In this paper, we report the measurement of the polarization correlation of the photons emitted in the two-photon decay of metastable atomic deuterium and apply the results to test Bell's inequality,[6] which allows a quantitative distinction to be made between the predictions of quantum mechanics and local realistic (hidden-variable) theories. Several tests[7-13] of Bell's inequality, culminating in the meticulous experiments of Aspect and co-workers, have been carried out recently with use of the photons emitted in atomic cascades in which an excited atomic level decays to a state of lower energy via an intermediate state with a finite lifetime. These experiments have the advantage of good signal intensities compared to the present experiment but most of them have been criticized recently[14-15] on the grounds that there may be significant absorption and reemission of photons in the source. Such criticism is not applicable to the present experiment. In addition, since the two photons from the decay of $D(2S)$ are emitted simultaneously, this experiment is conceptually closer to the version of the Einstein-Podolsky-Rosen[17] thought experiment proposed by Bohm.[18] The fact that the emission is simultaneous also ensures that, in an experiment such as the one to be described here, the detection events for the two photons are spacelike separated in the relativistic sense.

A schematic diagram of the apparatus is shown in Fig. 1. A 1-keV metastable atomic deuterium $[D(2S)]$ beam of density about 10^4 cm^{-3} is produced by charge exchange, in cesium vapor, of deuterons extracted from a radio-frequency ion source. It is possible to produce higher beam densities at higher energies but it was found empirically that the best statistical accuracy in a given time can be obtained at 1 keV.

Deuterium is used rather than hydrogen since, for a given metastable density and hence two-photon signal, the noise generated by interaction of the beam with

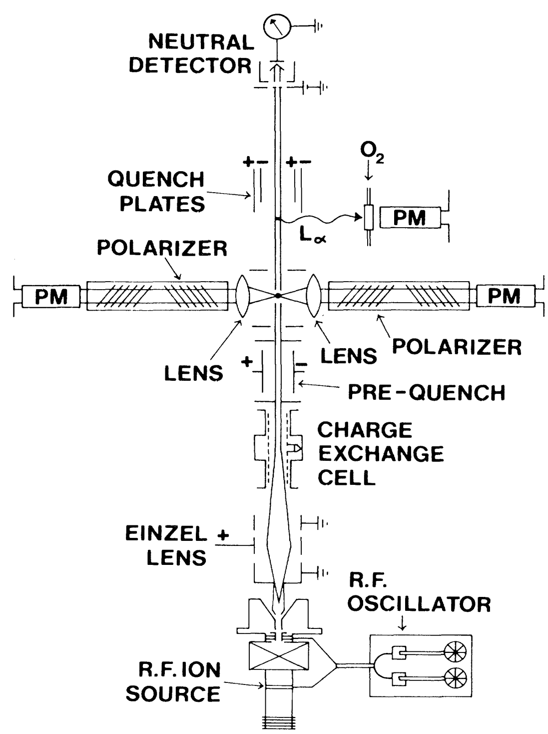

FIG. 1. Schematic diagram of the apparatus (not to scale).

the background gas in the vacuum is less in the former case.

Once the D(2S) beam is formed it passes through electric field prequench plates, which, by Stark mixing of the 2S and 2P states, allow the metastable component of the beam to be switched on and off. Collimating apertures reduce the beam diameter to approximately 10 mm. At the end of the apparatus the beam is quenched in an electric field and the resulting Lyman-α signal is used to normalize the two-photon coincidence signal. The Lyman-α signal is detected by means of a solar-blind uv photomultiplier (EMR 542G-08-18) in conjunction with an oxygen filter cell with lithium-fluoride windows through which dry oxygen flows at a constant rate. In a series of experiments it was verified that the two-photon coincidence signal is proportional to the Lyman-α signal as conditions in the radio-frequency ion source and focusing conditions in the einzel lens are varied in the neighborhood of the normal operating point.

As shown in Fig. 1, the two-photon radiation is collected and collimated by two 50-mm-diam lenses, each with a focal length of 43 mm at a wavelength of 243 nm. Each lens is placed about 50 mm from the beam, and subtends a half-angle $\theta \simeq 23°$ at the beam. The lenses are positioned such that, for a wavelength of 243 nm, the center of the beam is imaged on the 46-mm-diam cathodes of the photomultipliers 53 cm from the center of the beam. For the polarization measurements, two high-transmission ultraviolet polarizers, each consisting of twelve plates optically polished flat to 2λ at 243 nm and set at Brewster's angle, are placed as shown on either side of the source. The lenses and plates are made from high-quality fused silica (Suprasil) with a short-wavelength cutoff at 160 nm. However, because of absorption in oxygen, the short-wavelength cutoff occurs at 185 nm which in turn implies a long-wavelength cutoff at the complementary wavelength of 355 nm. Hence, given that the quantum efficiency of the photomultipliers is relatively constant at about 20% over this range, photons with wavelengths from 185 to 355 nm may contribute to the two-photon coincidence signal. The optical arrangement also determines the portion of the atomic beam which acts as a source for the two-photon coincidence signal. It is estimated that only a 4-mm-diam section of the beam is important in this respect.

The transmission efficiency ϵ_M (ϵ_m) for light polarized parallel (perpendicular) to the transmission axis of the polarizers used was measured in a subsidiary experiment by means of the mercury line at 254 nm. In this experiment the photomultiplier was removed from one detection arm of the apparatus and an almost parallel beam of polarized light was passed through the pile-of-plates polarizer (aligned with its transmission axis parallel to the plane of polarization of the light beam) to come to a focus at the position normally occupied by the center of the atomic source. The light emerging from this focus was then analyzed by the pile-of-plates polarizer and photomultiplier in the other detection arm. After application of a small correction to take into account the slight absorption in Suprasil between 185 and 200 nm it was found that $\epsilon_M = 0.908 \pm 0.013$ and $\epsilon_m = 0.0299 \pm 0.0020$.

On either side of the source the signal is detected by fast-rise-time photomultipliers (EMI 9883 QA) with bialkali cathodes and fused-silica windows. These photomultipliers are specially selected for high gain, good single-photoelectron resolution, and good timing characteristics, and have dark count rates of the order of 10^2 s^{-1}. The photomultiplier pulses are fed to a standard coincidence circuit[4] consisting of a constant fraction discriminator, a time-to-amplitude convertor, and a multichannel analyzer operated in the pulse-height analysis mode. The time-correlation spectra obtained with the metastable atoms present and quenched are stored in separate segments of the multichannel analyzer memory and then subtracted at the end of a run. This procedure ensures the elimination of any spurious true coincidence events due, for example, to cosmic rays or residual radioactivity in the apparatus. In this experiment, with the photomultiplier photocathodes 1.06 m apart, these events occur at a rate of about 10^{-2} s^{-1} which decreases as the separation of the photomultipliers is increased. A typical spectrum obtained in this way is shown in Fig. 2. The coincidence peak is symmetrical, as we should expect

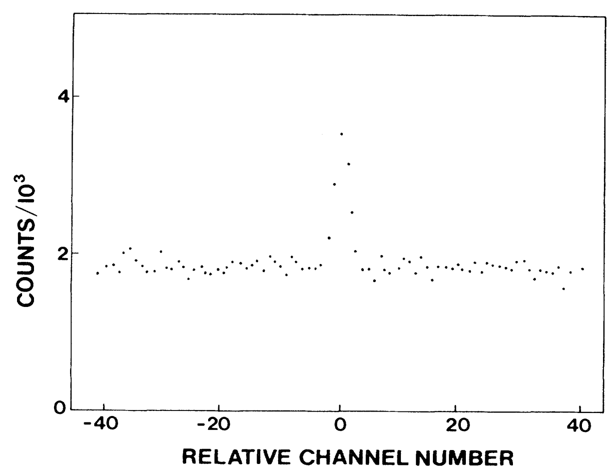

FIG. 2. A typical time-correlation spectrum after subtraction of the spectrum obtained with the metastable component of the beam quenched. Polarizer plates are removed. Time delay per channel is 0.8 ns. Total collection time is 21.5 h. Singles rate with metastables present (quenched) is about 1.55×10^4 s^{-1} (0.85×10^4 s^{-1}). True two-photon coincidence rate is 490 h^{-1}.

for a simultaneous-emission process. Note that the background signal resulting from the typical singles count rates of order $10^4\ \mathrm{s}^{-1}$ is due mainly to radiation produced by interaction of the atomic beam with background gas at a typical pressure of 2×10^{-2} Torr, and only slightly (about 0.01%) to uncorrelated photons from the two-photon decay process itself. The photomultipliers are linked to their corresponding polarizers and rotate with them so that any sensitivity to polarization that might exist in the photomultiplier windows or photocathodes can be ignored. The rotational invariance of the detection system was checked by verifying that the background singles rate is constant as the angle of the polarizer transmission axis is varied in each detection arm independently.

The measured coincidence signals were all normalized to a typical Lyman-α count rate and hence metastable beam density. This normalized coincidence signal $R(\phi)$ for various angles ϕ between the transmission axes of the polarizers is shown in Fig. 3 relative to R_0, the normalized coincidence signal with all the polarizer plates removed. The error bars denote 1 standard deviation and vary from point to point because of the different total counting times allocated to different angles. The points at 22.5° and 67.5° result from measurements extending over a total counting time of 240 h each.

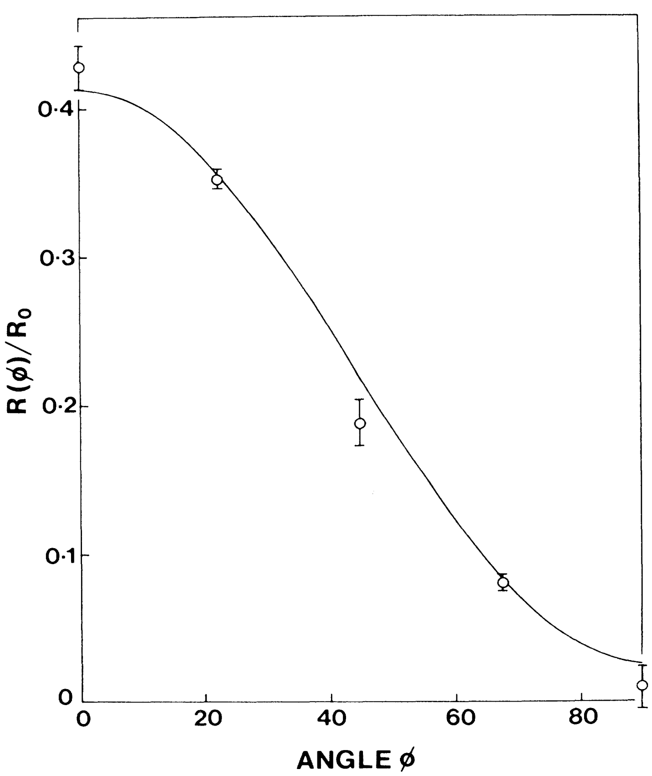

FIG. 3. Coincidence signal as a function of the angle ϕ between the transmission axes of the polarizers, relative to R_0, the coincidence signal with the polarizer plates removed. The solid curve represents the QM prediction using the median values for ϵ_M and ϵ_m.

Theoretically, quantum mechanics (QM) predicts[19] that

$$\frac{R(\phi)}{R_0}=\tfrac{1}{4}(\epsilon_M+\epsilon_M)^2+\tfrac{1}{4}(\epsilon_M-\epsilon_m)^2F(\theta)\cos2\phi,$$

where $F(\theta)$ is a geometrical factor which takes into account the finite solid half-angle θ subtended by the collecting lenses at the source. In our case $\theta\simeq23°$, $F(\theta)=0.996$. The solid curve in Fig. 3, which represents the QM prediction, agrees closely with the experimental results.

The results at 22.5° and 67.5° can be used to test Bell's inequality in the form first derived by Freedman[7,20]:

$$\eta=\left|\frac{R(22.5°)-R(67.5°)}{R_0}\right|\leq0.25,$$

which applies for any local realistic theory for which the "no-enhancement" hypothesis[19,21] is made. With our values for ϵ_M, ϵ_m, and θ, QM predicts $\eta_{\mathrm{QM}}=0.272\pm0.008$, whereas from the experimental results at 22.5° and 67.5° we find $\eta_{\mathrm{expt}}=0.268\pm0.010$ in agreement with the QM prediction but in disagreement with any local realistic theory without enhancement, by just less than 2 standard deviations.

In conclusion, we have, for the first time, measured the polarization correlation of the photons emitted simultaneously in a true second-order two-photon decay process. We have shown that the results violate the Freedman form of Bell's inequality and are in agreement with the quantum mechanical prediction. Since absorption and reemission of the emitted photons is not a significant effect here, the only remaining loophole for local realistic theories lies in the denial of the "no-enhancement" hypothesis regarding the effect of the presence of the polarizers on the detection probability for photons.

The authors wish to thank Professor F. Selleri for useful discussions and acknowledge the financial support of the Science and Engineering Research Council in the construction of the ion source.

---

[1]M. Göppert-Mayer, Ann. Phys. (N.Y.) **9**, 273 (1931).
[2]G. Breit and E. Teller, Astrophys. J. **91**, 215 (1940).
[3]M. Lipeles, R. Novick, and N. Tolk, Phys. Rev. Lett. **15**, 690 (1965).
[4]D. O'Connell, K. J. Kollath, A. J. Duncan, and H. Kleinpoppen, J. Phys. B **8**, L214 (1975).
[5]H. Krüger and A. Oed, Phys. Lett. **54A**, 251 (1975).

[6]J. S. Bell, Physics (N.Y.) **1**, 195 (1964).
[7]S. J. Freedman and J. F. Clauser, Phys. Rev. Lett. **28**, 938 (1972).
[8]R. A. Holt and F. M. Pipkin, unpublished.
[9]E. S. Fry and R. C. Thompson, Phys. Rev. Lett. **37**, 465 (1976).
[10]J. F. Clauser, Phys. Rev. Lett. **36**, 1223 (1976).
[11]A. Aspect, P. Grangier, and G. Roger, Phys. Rev. Lett. **47**, 460 (1981).
[12]A. Aspect, P. Grangier, and G. Roger, Phys. Rev. Lett. **49**, 91 (1982).
[13]A. Aspect, J. Dalibard, and G. Roger, Phys. Rev. Lett. **49**, 1804 (1982).
[14]T. W. Marshall, E. Santos, and F. Selleri, Lett. Nuovo Cimento. Soc. Ital. Fis. **38**, 417 (1983).
[15]F. Selleri, Lett. Nuovo Cimento Soc. Ital. Fis. **39**, 258 (1984).
[16]S. Pascazio, to be published.
[17]A. Einstein, B. Podolosky, and N. Rosen, Phys. Rev. **47**, 777 (1935).
[18]D. Bohm, *Quantum Theory* (Prentice-Hall, Engelwood Cliffs, N.J., 1951).
[19]J. F. Clauser, M. A. Horne, A. Shimony, and R. A. Holt, Phys. Rev. Lett. **23**, 880 (1969).
[20]S. J. Freedman, Lawrence Berkeley Laboratory Report No. LBL-391, 1972 (unpublished).
[21]J. F. Clauser and M. A. Horne, Phys. Rev. D **10**, 526 (1974).