Search for Spatial Anisotropy in Orthopositronium Annihilation

A. P. Mills, Jr., and D. M. Zuckerman
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

(Received 29 December 1989)

Conservation of angular momentum and the isotropy of space prohibit orthopositronium (*o*-Ps) from annihilating into two photons. Nevertheless, the observed *o*-Ps decay rate in excess of theory tempts one to speculate on the existence of a ubiquitous field that would couple to Ps, allowing a small partial rate for *o*-Ps to annihilate into two photons. We apply a 3.4-kG magnetic field to a sample of Ps to quench the $m=0$ states in the laboratory frame of reference, and search for a 12-h periodicity in the 3γ yield. The observed effect is consistent with the assumption that space is isotropic and, at the 80% confidence level, is too small to explain the observed *o*-Ps decay-rate discrepancy with theory.

PACS numbers: 36.10.Dr, 11.30.−j, 78.70.Bj

A remarkable series of precision experiments conducted at the University of Michigan over the last 15 years[1] has shown that the vacuum decay rate of orthopositronium (*o*-Ps) is about one part in 500 more rapid than predicted so far by a QED calculation[2] that includes corrections of order α. The coefficient of the order α^2 correction term would have to be unusually large to bring theory and experiment into agreement. While a large coefficient is not prohibited, the disagreement might conceivably indicate the presence of a new physical process. In particular, recent experiments have searched for and ruled out significant contributions to the *o*-Ps decay rate due to annihilation into one photon plus an undetected low-mass particle such as an axion.[3]

In the present paper we explore the possibility that unperturbed *o*-Ps, besides decaying into three photons (3γ), has a small partial rate for decaying into 2γ. While such a decay is not possible if we assume space is isotropic and angular momentum is conserved,[4] the close analogy between the $m=0$ states of Ps and the neutral K-meson system prompts us to explore the 2γ decay possibility further: The long-lived K_L state decays principally into 3π but has a probability of 0.002 for 2π decay due to a CP-violating interaction.[5]

A spatial anisotropy that would permit $o\text{-Ps}\rightarrow 2\gamma$ could be caused by a vector field Ω_μ originally considered by Phillips[6] that acquires a nonzero vacuum expectation value by a spontaneous symmetry-breaking mechanism. Since there will be a preferred frame in which $\Omega_0=0$, the vacuum state would thus be neither Lorentz nor rotationally invariant. A possible interaction permitting $o\text{-Ps}\rightarrow 2\gamma$ would be a point interaction of the electron-positron current with both the ordinary vector potential (photon field) A_μ and the anisotropic vector field. A possible candidate for an effective nonrenormalizable Lagrangian density describing the interaction would be[7]

$$L=g\bar{\psi}O_{\alpha\beta}\psi A^\alpha\Omega^\beta . \qquad (1)$$

The coupling constant $g\approx 10^{-4}m_e^{-2}$ is chosen to give a partial rate for $o\text{-Ps}\rightarrow 2\gamma$ about 10^{-6} of the 2γ decay rate for singlet Ps. The smallness of g and the relatively high momentum transfer in 2γ annihilation might imply that second-order processes involving the anisotropic field would only produce feeble effects in low-energy experiments using ordinary matter. Because of the nonrenormalizability of the interaction, the only unambiguous calculations we are presently able to make would involve radiative transitions analogous to the decay of Ps. As an example, the metastable $2S$ state of H decays by the emission of two optical photons to the $1S$ state at a rate $\Gamma(2S\rightarrow 1S+2\gamma)=7\ \text{s}^{-1}$. The anisotropic interaction of Eq. (1) would allow single-photon decay of the $2S$ state to occur at a rate $\Gamma(2S\rightarrow 1S+1\gamma)\approx\alpha^3m_e^4g^2\times\Gamma(2P\rightarrow 1S)\approx 10^{-6}\ \text{s}^{-1}$, negligible compared to the allowed two-photon decay rate.

Predictions about other effects might make use of a naive attempt to split Eq. (1) into two renormalizable parts using an intermediate particle analogous to the weak vector bosons. Depending on the mass m_x of the particle, one obtains either a huge effective magnetic field extending throughout space, $B_{\text{eff}}\approx 10^{-4}m_x^2$, or large contributions to the electron g-factor anomaly, $\Delta a\approx 10^{-6}m_e/m_x$. For $m_x=m_e$, $B_{\text{eff}}\approx 10^8$ G. Needless to say, such effects have been thoroughly ruled out by many sensitive anisotropy experiments including those of Michelson and Morley,[8] Turner and Hill,[9] Hughes, Robinson, and Beltran-Lopez,[10] Drever,[10] and Phillips and Woolum,[11] and by precision measurements and calculations of the lepton g factors.[12] Nevertheless, given the possibility of an anomaly in the *o*-Ps decay rate, we believe it is worthwhile to take an empirical approach by searching directly for an anisotropy effect in the decaying Ps system, rather than relying on indirect tests.

Given an anisotropic interaction as in Eq. (1), there would be a preferred choice for the axis of quantization (z axis) for which the $m=\pm 1$ triplet states could decay into 2γ final states of total angular momentum 2 or 0, whereas the $m=0$ state could not. To explain the discrepancy of theory versus experiment for the o-Ps decay rate, the $m=\pm 1$ states would need to have a partial rate ϵ for decay into 2γ of $\epsilon=3\times10^{-3}\lambda_0$, where $\lambda_0=7.05\ldots\ \mu s^{-1}$ is the 3γ decay rate of o-Ps. Experiments to date performed over long periods of time would presumably not have noticed such an effect. On the other hand, we have performed an experiment that would make an anisotropy visible by searching for a daily periodicity in the decay rate of the $m=\pm 1$ states in a laboratory frame of reference.

Our source of positronium is 40 μCi of ^{22}Na deposited on a 18-μm Al foil in the center of a 38-mm-diam, 0.5-mm-wall cylindrical 304-stainless-steel chamber filled with unbaked low-density SiO_2 powder made of 35-Å-radius grains. Positron annihilations are detected with a 3×3-in.^{2} NaI(Tl) scintillator and photomultiplier located 150 mm to the west of the radioactive source. A 3.4-kG magnetic field perpendicular to the local east-west direction and to the axis of the Earth's rotation is provided by a pair of permanent magnet disks 101.6 mm in diameter and 25.4 mm thick separated by a 40-mm Al spacer. The source, magnet, and detector are surrounded by Pb shielding and kept at a constant temperature ±0.1 K by a flow of regulated air at 299 K.

The 3γ decay probability is measured by counting the number of events per unit time in the 511-keV 2γ photopeak (P) and the number of events of lower energy due to Compton scattering of 511-keV photons and nuclear γ's and to the continuum spectrum of 3γ annihilations (C). The system gain is kept constant by a feedback loop that equalizes the counting rates in the upper and lower halves of the 511-keV photopeak. A four-input multiscaler records the total number of C and P counts accumulated every 1000 s. The rates are approximately $\dot{C}=20650\ s^{-1}$ and $\dot{P}=11200\ s^{-1}$ and are scaled by factors of 100 and 10, respectively. The ratio C/P is roughly proportional to the 3γ yield,[13] and is calibrated by quenching the triplet states using O_2 gas. With 1.1 amagats of O_2, $C/P=1.463\pm0.005$, whereas in vacuum (SiO_2 powder only), $C/P=1.843\pm0.001$. Assuming that the o-Ps lifetime in the powder is only a few percent shorter than the vacuum lifetime[14] and including the angular distribution of the 3γ's computed by Drisko,[15] we compute that a C/P change corresponding to 100% of the 3γ yield would be about 0.53.

The density-matrix formalism for Ps magnetic quenching[16] may be used to calculate the 3γ yield in a magnetic field which is at an angle θ relative to the preferred z axis. We find that the angular variation of the 3γ yield recorded by single counterdetecting photons emitted perpendicular to a 3.4-kG magnetic field is $-0.13\epsilon\sin(2\theta)$ times the 3γ yield in zero field. If the z axis is at an angle ϕ relative to the Earth's axis, the Earth's rotation at a sidereal angular frequency ω will cause a 3γ effect $-0.13\epsilon\sin^2\phi\sin(2\omega t)$, resulting in a C/P effect $-0.069\epsilon\sin^2\phi\sin(2\omega t)$. Our experiment sets an upper limit on ϵ by measuring the amplitude of the twice-per-sidereal-day component of the 3γ yield.

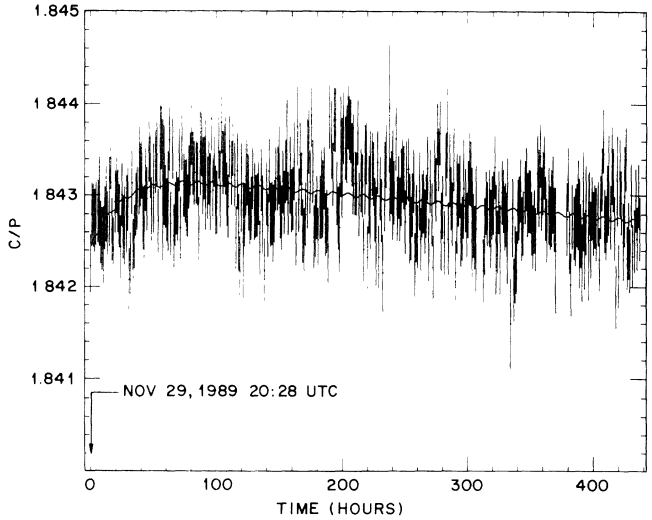

FIG. 1. The C/P ratio plotted as a function of time. A full scale change in C/P would correspond to a 1% change in the 3γ yield. The solid line is a fitted curve discussed in the text.

The C/P values obtained over a three-week period are shown in Fig. 1. Each point is an average of four consecutive 1000-s measurements of C/P. The error bars are the larger of half the actual root-mean-square deviation of the four points from their mean or the computed Poisson error. Occasional individual measurements differing from the mean by more than 4 Poisson standard deviations are excluded. The data have been fitted by a five-parameter function shown by the wavy line, $a_1+a_2\times\cos(2\omega t+a_3)+a_4t+a_5\exp(-t/\tau)$. The linear term accounts for a count-rate dependence of C/P due to decay of the radioactive source. The exponential accounts for an initial small increase of C/P due to improvement of the vacuum with $\tau=24$ h. The χ^2 per degree of freedom of the fit is $\chi^2/\nu=370.57/383$. The amplitude of the cosine term is $a_2=0.000022\pm0.000019$, from which we deduce $\epsilon\sin^2\phi=0.00032\pm0.00028$.

The data have been plotted modulo 12 sidereal hours and averaged into half-sidereal-hour bins in Fig. 2. A fit using the function $a_1+a_2\cos(2\omega t+a_3)$ yields $a_2=0.000018\pm0.000019$ and $\chi^2/\nu=23.77/21$. A 99%-confidence upper limit would be $\epsilon\sin^2\phi<0.0009$. We may conclude that either ϵ is too small to explain the o-Ps lifetime discrepancy, or that the preferred z axis is oriented within about 35° of Earth's axis. Since only about 80% of the possible directions are excluded, we may only conclude that the anisotropy effect is rejected at the 80% confidence level. At this time there is no compelling reason to speculate about a connection between the direction associated with our null effect and known effects such as the dipole asymmetry of the cosmic background radiation.[17]

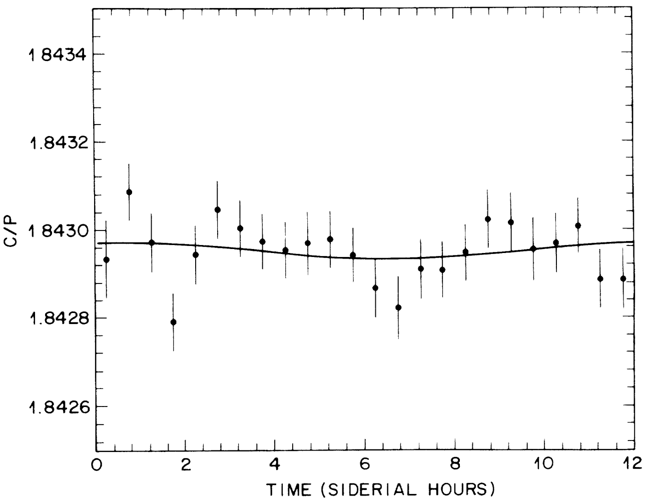

FIG. 2. The C/P ratio plotted modulo 12 sidereal hours. The full scale corresponds to a 0.2% change in the 3γ yield. The solid line is a fitted cosine function.

Since it has proven remarkably difficult to completely exclude an interaction like Eq. (1) even though we have accumulated some 5×10^{10} counts, some further experimentation would seem justified. We are presently extending our measurements using an apparatus that can take different orientations in the laboratory, rather than using the motion of the Earth alone. It might also be interesting to look directly for o-Ps$\rightarrow 2\gamma$ events by a slightly modified version of the experiment of Ref. 3.

The authors would like to thank Stephan Berko, Philip Bucksbaum, Marvin Leventhal, and Hugh Pendleton for helpful discussions.

---

[1] C. I. Westbrook, D. W. Gidley, R. S. Conti, and A. Rich, Phys. Rev. A **40**, 5849 (1989), and references therein.

[2] W. G. Caswell and G. P. Lepage, Phys. Rev. A **20**, 36 (1979); G. S. Adkins, Ann. Phys. (N.Y.) **146**, 78 (1983).

[3] S. Orito, K. Yoshimura, T. Haga, M. Minowa, and M. Tsuchiaki, Phys. Rev. Lett. **63**, 597 (1989).

[4] C. N. Yang, Phys. Rev. **77**, 242 (1950).

[5] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turley, Phys. Rev. Lett. **13**, 138 (1964); *CP Violation,* edited by C. Jarlskog (World Scientific, Singapore, 1989).

[6] P. R. Phillips, Phys. Rev. **139**, B491 (1965). See, for example, E. D. Commins and P. H. Bucksbaum, *Weak Interactions of Leptons and Quarks* (Cambridge Univ. Press, Cambridge, 1983).

[7] H. N. Pendleton, III (private communication).

[8] A. A. Michelson and E. W. Morley, Am. J. Sci. **34**, 333 (1887); A. Brillet and J. L. Hall, Phys. Rev. Lett. **42**, 549 (1979).

[9] K. C. Turner and H. A. Hill, Phys. Rev. **134**, B252 (1964).

[10] V. W. Hughes, H. G. Robinson, and V. Beltran-Lopez, Phys. Rev. Lett. **4**, 342 (1960); R. P. W. Drever, Philos. Mag. **6**, 683 (1961); J. D. Prestage, J. J. Bollinger, W. M. Itano, and D. J. Wineland, Phys. Rev. Lett. **54**, 2387 (1985); T. E. Chupp *et al.*, Phys. Rev. Lett. **63**, 1541 (1989); S. K. Lamoreaux, J. P. Jacobs, B. R. Heckel, F. J. Raab, and E. N. Fortson, Phys. Rev. A **39**, 1082 (1989).

[11] P. R. Phillips and D. Woolum, Nuovo Cimento **64B**, 28 (1969); P. R. Phillips, Phys. Rev. Lett. **59**, 1784 (1987).

[12] R. S. Van Dyck, Jr., P. B. Schwinberg, and H. G. Dehmelt, Phys. Rev. Lett. **59**, 26 (1987). See various articles in *Quantum Electrodynamics,* edited by T. Kinoshita (World Scientific, Singapore, 1990).

[13] M. Deutsch, Phys. Rev. **82**, 455 (1951).

[14] R. Paulin and G. Ambrosino, J. Phys. (Paris) **29**, 263 (1968).

[15] R. M. Drisko, Phys. Rev. **102**, 1542 (1956).

[16] A. P. Mills, Jr., J. Chem. Phys. **62**, 2646 (1975).

[17] P. M. Lubin, G. L. Epstein, and G. F. Smoot, Phys. Rev. Lett. **50**, 616 (1983); D. J. Fixsen, E. S. Cheng, and D. T. Wilkinson, Phys. Rev. Lett. **50**, 620 (1983).