Direct Search for Orthopositronium Decay into Two Photons

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We have performed the first direct search for orthopositronium decay into two photons in order to determine if this decay, forbidden by space-rotational invariance, is the cause of the reported discrepancy in the orthopositronium decay rate. A high-resolution measurement of the photon-energy spectrum by a germanium detector was used to discriminate the expected sharp peak of the two-photon decay from the broader peak of the pickoff annihilations. No evidence of such decay is observed, resulting in an upper limit on the branching ratio of 3.5×10^{-4}, a factor of 6 below the level that could explain the decay-rate discrepancy.

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Positronium (Ps) has been a very successful laboratory of quantum electrodynamics. However, recent measurements of orthopositronium (o-Ps) decay rates in low-pressure gases[1] and in vacuum cavities[2] have resulted in vacuum decay rates which are respectively 0.19% and 0.14% more rapid than predicted by a QED calculation.[3] Since the QED calculation includes only corrections up to order α, higher-order corrections may in principle account for the discrepancy. Otherwise, the discrepancy might indicate the presence of a new decay channel. In this respect, the o-Ps is in fact a promising hunting field because the slow decay rate of o-Ps (a factor of 1100 slower than parapositronium) might eventually give an exotic process a detectable branching ratio.

Various exotic decay modes have been investigated without any evidence so far. Axion-search experiments[4] rule out at the 30-ppm level the decay into a single photon plus a long-lived and weakly interacting particle X in a limited X-mass region above 150 keV. The remaining low-mass region is excluded by a recent experiment[5] at the 60-ppm level. The decay into a photon plus a short-lived particle was searched for by another experiment[6] which hunted for a peak in the inclusive photon-energy spectrum, and is excluded at a level of 200 ppm for M_X above 200 keV. Decay into noninteracting particles is also ruled out[7] down to the 580-ppm level. It looks, therefore, as if the remaining candidates of exotic o-Ps decay are those (a) into γX, where X is light (below 200 keV) and abnormally short lived, and (b) into 2γ. In this paper we investigate the latter decay mode, which is forbidden if space-rotational invariance strictly holds. Recently, Mills and Zuckerman[8] searched for spatial anisotropy in the 3γ decay rate of o-Ps placed in a magnetic field which is perpendicular to the Earth's rotational axis. Based on the nonobservation of the 12-h periodicity and by assuming the existence of a model-Lagrangian term which is not invariant under space rotation, they have concluded that either this term is too weak to explain the o-Ps decay-rate discrepancy or the preferred direction in the noninvariant term lies within 35° of the Earth's axis.

We report here the first direct and model-independent search of o-Ps decay into 2γ in order to determine if this decay mode is the cause of the reported discrepancy in the o-Ps decay rate. The detection of the 2γ decay is generally believed to be difficult due to the background of the "pickoff" processes in which o-Ps collides with the atomic electrons of the target material or of the gas, causing annihilations into 2γ. We have reduced the pickoff contribution to 1.0% of the vacuum decay rate by selecting special silica powder of low density as the target and by placing it in vacuum. A high-resolution (1.3 keV FWHM) measurement of the photon-energy spectrum by a germanium detector can then be used to separate the expected sharp peak of the o-Ps decay into 2γ from the peak of the pickoff process which has a much broader (2.8 keV FWHM) shape due to the non-negligible initial momenta of the colliding atomic electrons.

The sharpness of the 2γ peak might be affected by the Doppler effect due to the nonzero velocity of the decaying o-Ps. The velocities of the Ps have been measured as a function of time in various silica aerogels[9-11] and powders[10,11] including ones similar to the powder used in this experiment. The measurements show that the Ps, after being repelled out of the silica grain into a vacuum void with a kinetic energy of 0.85 eV, is slowed down rapidly to an average kinetic energy[12] of 0.4 eV within a few nsec. Subsequently, elastic collisions with the surface silica atoms slow the Ps down gradually toward the thermal velocity. According to the measurements, this relaxation process appears to be governed simply by the number of collisions, and is the same in aerogel and in powder, probably because only a limited number of atoms are directly involved in the collisions. A model[10] based on these assumptions fits[13] all of the data rather well. This model, applied to the powder used in our experiment, predicts[13] that the average kinetic energy of o-Ps is about 0.08 eV in our time window of 120 to 270 nsec after the formation. The Doppler broadening due

to this amount of kinetic energy will add a negligible contribution to the energy resolution of the germanium detector. Therefore, we expect that the 2γ peak is sharp with a width determined by the resolution of the detector.

The layout of the experiment is shown in Fig. 1. A ^{22}Na positron source of 0.04 μCi with a spot diameter of 2 mm is sandwiched by two sheets of plastic scintillator (NE104) of diameter 12 mm and thickness 100 μm each. The source is held by a cone made of aluminized Mylar of 20 μm thickness, and is placed at the center of a vacuum container of diameter 50 mm made of 500-μm-thick glass. The container is filled with silica powder of density 0.05 g cm^{-3} and is evacuated to 10^{-3} Torr. Most of the emitted positrons pass through the scintillator, giving a light pulse to a photomultiplier (Hamamatsu H-3165-04), and stop in the silica powder to form positronium.

The energy of γ rays from the positronium decays is measured by a high-purity coaxial germanium crystal 60 mm in diameter and 70 mm thick (Ortec GEM 38195). The energy resolution, as well as the absolute peak efficiencies of the germanium detector, is determined as a function of the photon energy by using line γ peaks from various sources, i.e., ^{57}Co, ^{113}Sn, ^{85}Sr, ^{22}Na, ^{60}Co, and ^{152}Eu, of known strength placed at the source position. The energy resolution obtained is 1.3 and 1.8 keV FWHM at 511 and 1275 keV, respectively. During the energy-spectrum measurements, a lead sheet of 2.08 mm thickness is placed in front of the germanium detector in order to eliminate the contribution of two low-energy γ's from the 3γ decay of o-Ps simultaneously hitting the germanium detector.

The trigger and the data-acquisition system is as follows. One of the outputs of the scintillator-pulse discriminator gives the start signal to the time-to-amplitude converter (Ortec TAC-457). Another output is used for the delayed coincidence with the signal from the germanium detector. One output from the preamplifier of the germanium detector is fed through a fast-filter amplifier (Ortec 474) into a constant-fraction discriminator (Ortec 473-A), whose outputs are used as the stop signal to the TAC and also for the delayed coincidence with the scintillator pulse. The differential and integral times of the fast-filter amplifier are optimized in order to obtain a good time resolution of 6 nsec rms. The second output from the preamplifier of the germanium detector is amplified by a spectroscopy amplifier (Ortec 673), whose outputs are recorded by two pulse-height analyzers (PHAs) simultaneously, one gated by the delayed coincidence and the other gated by the corresponding accidental coincidence.

The time spectrum between the scintillator and the germanium pulses is shown in Fig. 2 for a germanium energy window of 400 to 480 keV. A sharp peak of prompt annihilation is followed by the exponential decay of o-Ps and subsequently by the constant accidentals. By fitting the time spectrum with an exponential plus a constant term, an apparent decay time of 140.6 ± 0.3 nsec is consistently obtained for various time spans. This is the measured lifetime (without corrections for pickoff, etc.), not the vacuum decay rate. 90 nsec is required after the prompt peak to reach this asymptotic value of the lifetime, as predicted by the aforementioned model of Ref. 10 for the relaxation process. In order to obtain a pure sample of o-Ps decay, the delayed coincidence is defined by the timing indicated in Fig. 2; i.e., the germanium signal should arrive between 120 and 270 nsec later than the prompt annihilation. To measure and subtract the accidental contributions, the accidental coincidence is defined by a timing of 2000 to 2600 nsec later than the prompt peak.

Data on the energy spectrum are collected in five runs

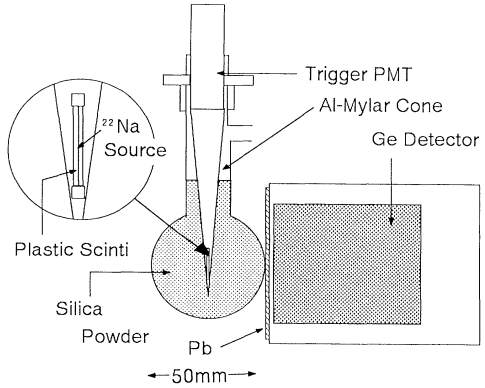

FIG. 1. Setup of the experiment. Circular inset: A magnified view of the source region.

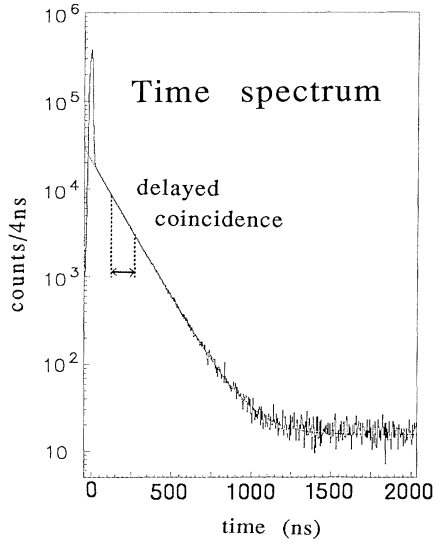

FIG. 2. A time-difference distribution between the scintillator and the germanium signals.

for a total 1.55×10^6 sec, during which time the room temperature is controlled to ±0.2 °C in order to assure the excellent stability of the amplifiers and the PHA. Stability checks are performed by utilizing the 511- and 1275-keV peaks in a single spectrum taken between runs. The peak positions are found to be stable within 0.08 keV. Furthermore, the narrow widths (1.8 keV FWHM) of the accidental 1275-keV lines observed in the actual data assure excellent energy resolution and stability throughout the data-taking period. The resulting two spectra taken with the delayed coincidence and the accidental coincidence are shown in Fig. 3(a). Figure 3(b) shows the delayed-coincidence spectrum with the accidental contribution subtracted, and thus can be regarded as the photon-energy spectrum from a pure sample of o-Ps (hereafter denoted as the "o-Ps spectrum"). This spectrum consists of a peak around 511 keV and a flatter spectrum of the 3γ decay of o-Ps.

The expected energy spectrum of the 3γ decay is calculated by a Monte Carlo simulation in which the geometries of the setup and the various materials are reproduced in detail. For every simulated event, three

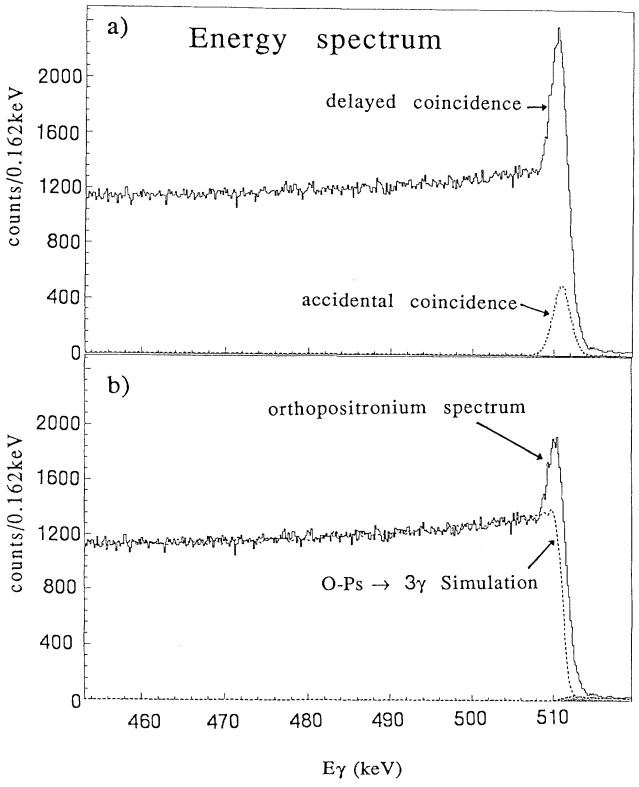

FIG. 3. (a) The photon-energy spectrum taken with the delayed and the accidental coincidences. The accidental spectrum is normalized by the widths of the time windows. (b) The delayed-coincidence spectrum (histogram) after the accidental contribution is subtracted. The dotted line, almost indistinguishable from the data below 508 keV, shows the simulated spectrum from the 3γ decay of o-Ps.

γ's are generated according to Eq. (3.26) of Ref. 14. Successive photoelectric or Compton interactions of every γ are then followed through the materials until it loses all of its energy. Events in which multiple photons hit or scatter into the detector are therefore properly included in the simulation, although the contribution of such events is small in the energy region of interest. The response function of the germanium detector as a function of the incident photon energy is deduced from the measured spectra of monochromatic γ rays from ^{137}Cs (662 keV), ^{85}Sr (514 keV), and ^{113}Sn (392 keV) and is folded in the simulation. The 3γ contribution thus simulated is stable against various systematic errors: For example, it depends only on the relative efficiency of the germanium detector, not on the absolute efficiency. The theoretical 3γ generator used in this simulation is based only on the lowest-order diagram. A higher-order correction,[14] however, does not show any change exceeding 0.3% relative on the shape of energy spectrum in this limited energy region.

As seen in Fig. 3(b), the simulated energy spectrum of 3γ decay reproduces very well the observed energy spectrum in a wide energy region below 508 keV. The sharp falloff of the 3γ spectrum at 511 keV is due to the phase-space cutoff. The shape of the falloff is therefore determined almost entirely by the energy resolution and has no ambiguity, as long as the absolute-energy scale and the response function are properly obtained. A potential problem could have been the contribution of the events in which two low-energy γ's out of a 3γ decay simultaneously hit the germanium detector. Although such events are automatically included in the simulation, such events would result in a detected energy spectrum which increases abruptly above 511 keV, and is more vulnerable to systematic errors in the simulation. As seen in the histogram in Fig. 3(b), the simulation shows that such events are reduced to a negligible level by means of the lead plate placed in front of the germanium detector.

Figure 4 shows an enlarged view of the o-Ps spectrum after subtracting the 3γ contribution. The peak observed in this spectrum (hereafter denoted as the "peak spectrum") is symmetric around the center which is located exactly at 511 keV (511.0 ± 0.05 keV), showing that the 3γ subtraction was done properly. The peak is broad with a FWHM of 2.8 keV, with no indication of a sharp peak at the center. For a more detailed investigation, we need to know the spectrum of the pickoff annihilation. For this purpose, a total 7.2×10^5 sec of "enhanced pickoff" runs are performed, in which a slab of silica aerogel of density 0.2 g cm^{-3} with 14 mm diameter and 3 mm thickness is attached on each side of the aluminized Mylar cone supporting the positron source. Most of the positrons then stop in the silica aerogel instead of the silica powder, and the pickoff peak is enhanced by a factor of 9.5 relative to the 3γ decay. The "pickoff spectrum" is then obtained by subtracting the corresponding accidental and 3γ contributions in the same way as done

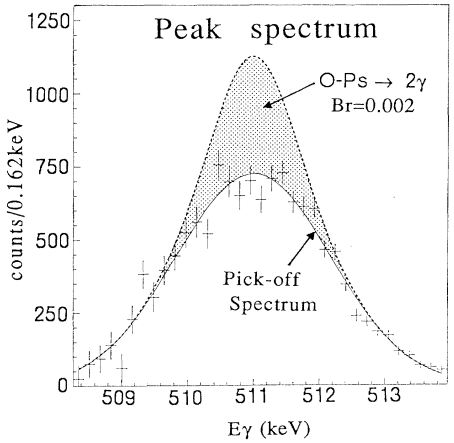

FIG. 4. The enlarged view of the peak at 511 keV after subtracting the simulated 3γ contribution. The solid curve shows the shape of measured pickoff spectrum normalized to data by total number of events under the peak. The shaded area indicates the shape and the magnitude of the peak from the o-Ps $\rightarrow 2\gamma$ decay with a branching ratio of 0.2%.

for the peak spectrum.

As can be seen in Fig. 4 the pickoff spectrum (shown by the solid curve) reproduces very well the observed peak spectrum when normalized by the total number of events under the peak. The shaded area in Fig. 4 indicates the shape and the magnitude of the peak from a 2γ decay having a branching ratio of 0.2%, which would explain the reported discrepancy in the o-Ps decay rate. No evidence is visible for a 2γ peak of such magnitude. In order to obtain an upper limit on the 2γ branching ratio in a quantitative way, we have fitted the observed peak spectrum with the function $aP(k)+bG(k)$ by freely varying both parameters a and b, where $P(k)$ and $G(k)$ represent the measured pickoff spectrum and the expected 2γ spectrum, respectively. The best-fit value and the upper limit on b obtained from this fit can then be converted directly into the corresponding values of the 2γ branching ratio by using the observed 3γ spectrum for normalization.[5] The best-fit value of the 2γ branching ratio is found to be $(1.0\pm 1.7)\times 10^{-4}$, which is consistent with zero. The upper limit on the 2γ branching ratio at the 90%-confidence level is obtained to be 3.5×10^{-4}, a factor of 6 below the level which would explain the decay-rate discrepancy. Therefore the 2γ decay of o-Ps is excluded as a major cause of the reported discrepancy in the o-Ps life time.

The 2γ decay of o-Ps, if not suppressed, would have a decay rate a factor of 1100 higher than the 3γ decay. Our upper limit thus corresponds to a lower limit on the suppression factor of 3.1×10^{6}.

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[12]We note that the Doppler broadening due to this amount of kinetic energy is already acceptably small, i.e., when added quadratically to the detector resolution of 1.3 keV FWHM, the overall peak width of 1.4 keV FWHM is expected.

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