New Limits on Exotic Two-Body Decay of Orthopositronium

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Motivated by the recently reported discrepancy between measured and theoretical values for the orthopositronium lifetime, we have searched for an exotic decay of orthopositronium into γ plus a long-lived neutral particle X, in the hitherto unexplored mass region of m_x below 100 keV. Our negative result provides new upper limits of 6.4×10^{-5} to 7.6×10^{-6} on the branching ratio of such a decay. Consequently, we exclude the hypothesis of Samuel, i.e., that a new pseudoscalar particle with mass less than 5.7 keV is responsible for the discrepancy of the orthopositronium lifetime.

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Recently, precision measurements[1] of the orthopositronium lifetime were reported. The measured lifetimes are consistently shorter than the theoretical predictions[2] by many standard deviations. The discrepancy might be due to the higher-order QED diagrams not yet included in the theoretical calculation. Another possibility is the existence of exotic decays of orthopositronium. Glashow[3] has speculated on the decay into invisible mirror particles. Samuel[4] argues that the decay into γ plus a neutral particle can explain the discrepancy of the lifetime without conflicting with the electron $g-2$ constraint nor the various beam-dump experiments, provided that the mass of the pseudoscalar particle is below 5.7 keV and its electron coupling α_{xee} is about 2×10^{-8}. Such low-mass particles are expected to be very long lived. The orthopositronium decay into γ plus such a particle would then appear as a single monochromatic γ, which has been searched for in previous experiments.[5] These experiments, however, were unable to provide useful limits for any m_x below 100 keV due to the large background of the "pickoff" process,[6] in which the orthopositronium collide with the atomic electrons of the target material or of the gas, causing annihilation into 2γ. Samuel's hypothesis is therefore not excluded by direct experiments. We report in this paper a new search for γx decay of orthopositronium in this low-m_x region.

The layout of the experiment is shown in Fig. 1. A ^{22}Na positron source of intensity 0.5 μCi is deposited (spot diameter 2 mm) on one side of a plastic scintillator (NE102) of dimensions 7×7 mm^2 and thickness 100 μm. Positrons emitted opposite to the scintillator are stopped in an acrylic plate of 2 mm thickness. Most of the positrons emitted toward the scintillator pass through the scintillator, giving light pulses to two photomultipliers (Hamamatsu H-3165-04) which peer into the target with the help of two thin parabolic mirrors. The positrons then stop in a target of silica aerogel of dimensions 13×13 mm^2 and thickness 6 mm to form positronium. In order to minimize the pickoff probability, the silica aerogel (air glass, $\rho=0.1$ g cm^{-3}) is placed in a highly evacuated (10^{-4} Torr) aluminum container of window thickness 100 μm. The energy of γ rays from the positronium decays is measured by a high-purity coaxial germanium detector of volume 56.3 cm^3 (Ortec GEM 10195). The energy calibrations, as well as the measurements of the absolute peak efficiencies of the germanium detector, are performed by using line γ peaks from seven sources, i.e., ^{57}Co, ^{133}Ba, ^{85}Sr, ^{22}Na, ^{60}Co, and ^{152}Eu of known strength placed at the target position. The energy resolution obtained is 1.0, 1.3, and 1.8 keV FWHM at 100, 511, and 1274 keV, respectively.

Opposite to the germanium detector, a matrix of nine CsI counters of dimensions $55\times55\times300$ mm^3 each are placed to surround the target in order to provide veto signals against the second γ from the pickoff annihilations. The CsI counters are calibrated by utilizing the 22 and 88 keV γ rays from a ^{109}Cd source. The energy resolution of the CsI counters is about 5.5 keV rms at 22 keV. The material to be traversed by the second γ ray in front of the CsI counter is kept to a minimum in order to minimize the probability of Compton scattering. The material thickness (the aerogel plus the aluminum window) amounts to 0.027 to 0.087 g cm^{-2} depending on the position of the positronium formation. This thickness is small enough for most of the electrons which are Compton scattered out by the second γ rays to reach the CsI

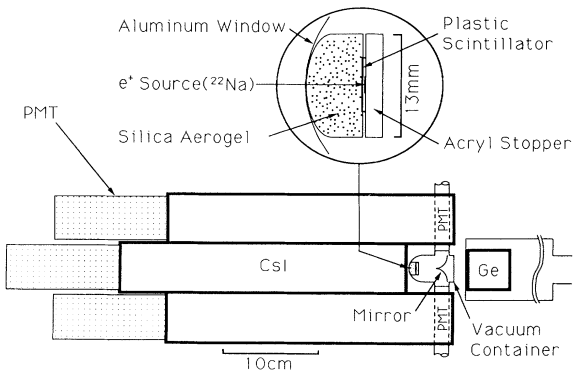

FIG. 1. Setup of the experiment.

counter.

The trigger and the data-acquisition system is as follows. The scintillator pulses from the two photomultipliers are linearly added and discriminated. One of the discriminator outputs gives the start signal to the time amplitude converter (Ortec TAC-457), and the other is used for the delayed coincidence to the signal from the germanium detector. One output from the preamplifier of the germanium detector is fed through a fast filter amplifier (Ortec-579) into a constant-fraction discriminator (Ortec-583), whose outputs are used as the stop signal into the TAC and also for the delayed coincidence to the scintillator pulse. The differential and integral time of the fast filter amplifier are optimized together with the threshold and the external delay of the constant-fraction discriminator in order to obtain a good time resolution of 5 nsec rms while keeping the lowest possible threshold of 40 keV. Signals from the nine CsI counters are linearly added, amplified by a spectroscopy amplifier, and then discriminated with an energy threshold of 36 keV. The discriminator output is used as the veto signal to the delayed coincidence. 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 (PHA), one gated by the delayed coincidence with veto from the CsI counter, the other gated by the corresponding accidental coincidence.

A typical time spectrum between the scintillator and the germanium pulses is shown in Fig. 2 for the germanium energy window of 398 to 492 keV. A sharp peak of the prompt annihilation is followed by the exponential decay curve of the orthopositronium and subsequently by the constant accidentals. The time scale is thoroughly calibrated to ± 0.1 nsec absolute accuracy by using a time calibrator (Ortec-462) as well as by delay cables. By fitting the time spectrum with an exponential plus a constant term, a decay time of 134 ± 0.5 nsec is consistently obtained for various time spans provided that the span starts no earlier than 70 nsec after the prompt peak. The decay times are also measured with the germanium energy window set on top of the 511-keV peak where the prompt and the pickoff annihilations dominate, and also with a wide window of 110 to 520 keV. Consistent decay times of 132 ± 2 and 133 ± 1 nsec, respectively, are also obtained with these energy windows.

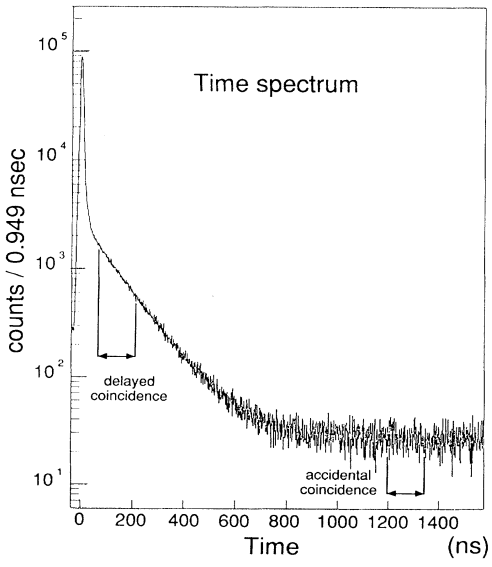

FIG. 2. Time-difference distribution between the scintillator and the germanium pulses.

The single-energy spectrum of the germanium detector is shown as the top curve (*a*) of Fig. 3. The dominant peak at 511 keV is mostly due to the prompt annihilations. In order to obtain a pure sample of orthopositronium decay, a delayed coincidence is required between the scintillator and the germanium pulses. As indicated in Fig. 2, a delayed coincidence is issued if the germanium signal arrives between 72 to 217 nsec later than the prompt annihilation. To measure the accidental contributions, the accidental coincidence is defined by the timing indicated in Fig. 2, i.e., 1200 to 1345 nsec from the prompt peak. The "accidental" energy spectrum is then stored simultaneously into the second PHA which is gated by the accidental coincidence. The middle curve (*b*) of Fig. 3 shows the germanium energy spectrum taken with the delayed coincidence (the accidental contribution

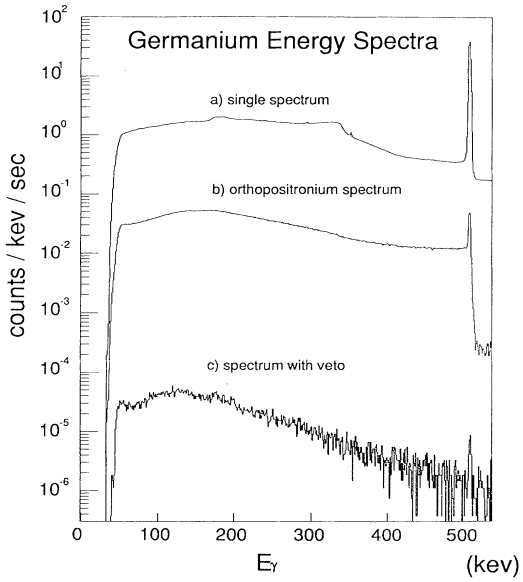

FIG. 3. γ-ray energy spectra detected by the germanium detector. The vertical scale is the absolute counting rate per keV per sec. Curve (*a*), the single (all time) spectrum. Curve (*b*), orthopositronium spectrum taken with the delayed coincidence. The accidental contribution is subtracted. Curve (*c*), the spectrum taken with the veto from the CsI counters imposed on the delayed coincidence. The accidentals are subtracted.

subtracted). A large reduction of the 511-keV peak is visible. It is consistent for the energy spectrum (denoted as "orthopositronium spectrum") to be due to the pickoff annihilation and the 3γ decay of the orthopositronium. Finally, data are collected in fourteen runs for a total of 2.72×10^6 sec with the veto from the CsI counters imposed on the delayed coincidence as well as on the accidental coincidence. The stability check and the energy calibrations are performed by utilizing the 511- and 1274-keV peaks in the single spectrum taken between the runs. The narrow width (1.8 keV FWHM) of the accidental 1274-keV line observed in the actual data assures excellent energy resolution and stability throughout the data-taking period. The resulting germanium energy spectrum, the accidental contributions subtracted, is shown as the bottom curve (c) of Fig. 3 and also in Fig. 4(a) (hereafter denoted as "spectrum with veto").

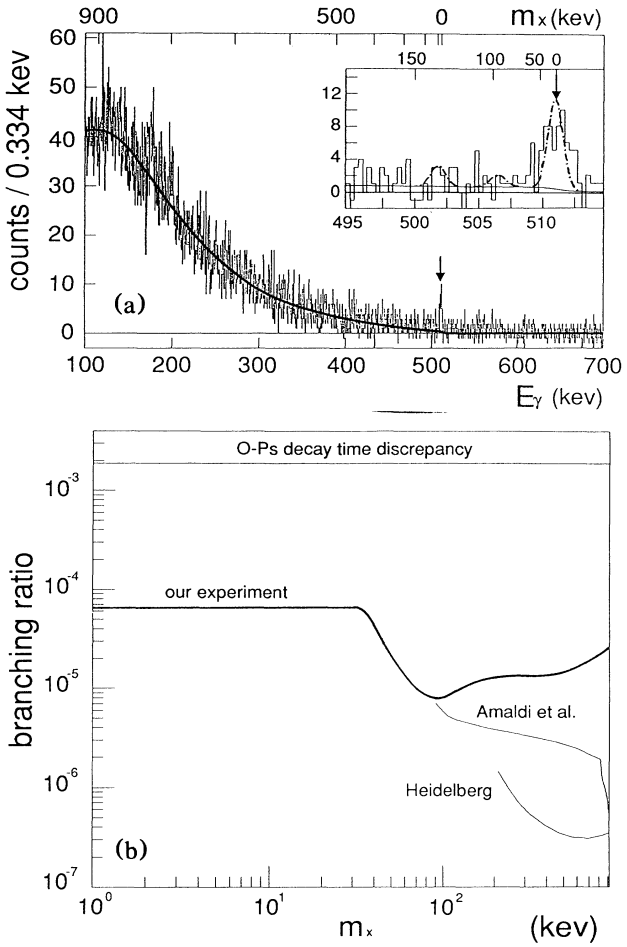

FIG. 4. (a) The same γ-ray energy spectrum as curve c of Fig. 3. The top scale is m_x, the mass of the particle in the search. The solid line is a typical smooth background curve for a specific peak position of 511 keV ($m_x=0$). Inset: A magnified view of the spectrum around 511 keV. The three peaks shown by dot-dashed lines are typical examples of the peak upper limits at 90% confidence level for $m_x=0$, 90.5, and 136 keV, respectively. (b) The resulting upper limits at 90% confidence level on the branching ratio of γx decay compared to the existing limits (Ref. 5). The top line indicates the branching ratio which corresponds to the reported discrepancy of the orthopositronium lifetime.

Narrow peaks are searched for in the whole energy region of this spectrum by checking to see if the spectrum is consistent with an overall smooth curve plus a sharp peak. The position of the peak is scanned at 0.334-keV steps from 100 to 511 keV. The smooth curve is obtained at each resonance position by fitting the spectrum with polynomials of up to seventh order while excluding the data within twice the FWHM of the assumed resonance position as well as the region from 508 to 514 keV. Since the intrinsic width of the particles in the search is expected to be extremely small, the observable width of the peak will be dominated by the energy resolution of the detector and by the thermal motion of the positronium. The thermal kinetic energies of the orthopositronium were measured[6] in an aerogel very similar to ours and are known to decrease rapidly to 0.03 eV within 60 nsec after formation. The Doppler broadening due to this amount of average kinetic energy contributes negligibly to the width of the peak. Therefore the shape of the peak is assumed to be Gaussian with the width determined by the germanium energy resolution.

No statistically significant peak is detected by this scanning except for the one at 511 keV. The peak at 511 keV is very likely not due to the γx decay but to pickoff annihilation for the following two reasons. First, the observed width of the peak (2.6 keV FWHM) is considerably wider than the 1.3 keV expected for the γx decay, and is consistent with being due to the pickoff annihilation in which the Fermi momenta of the atomic electrons cause Doppler broadening by such an amount.[6] Second, we have measured the veto inefficiency for the pickoff annihilation by the "forced pickoff" method. For this purpose the container is filled with air, which increases the pickoff probability by a factor of 14. By comparing the enhanced 511-keV peak in the delayed coincidence spectrum with and without the CsI veto, the veto inefficiency is measured to be 2.2×10^{-4}, which then predicts 63 pickoff events at the 511-keV peak in the spectrum with veto as compared to the 52 events observed. Thus there is no significant signal for the γx decay. We take a conservative attitude in this paper and assume that the observed peak at 511 keV could be all due to γx decay.

The upper limits on the peak strength obtained from the fitting procedure have to be first corrected for the expected loss of the genuine events due to the unwanted veto caused by the 1274-keV γ ray which accompanies the β^+ decay. This is done by multiplying the limits by a factor 1/0.34, where 0.34 is the probability of the 1274-keV γ ray to escape without Compton or photoelec-

tric interactions and is calculated from the geometries of the counters by a Monte Carlo method. Since some of the Compton interaction results in an energy deposition below the veto threshold, this value corresponds to a lower limit on the escape probability and therefore to a conservative limit on the peak strength. The resulting upper limit or the number of γx events under a peak at energy k, which we denote $n_{\gamma x}(k)$, can be converted into the corresponding limit on the branching ratio, $r_{\gamma x}(k)$, using the formula

$$n_{\gamma x}(k) = N_{\mathrm{ort}} r_{\gamma x}(k) \epsilon(k) ,$$

where $\epsilon(k)$ is the absolute peak efficiency of the germanium detector in our setup for a γ ray of energy k. N_{ort}, the total number of orthopositronium decays occurring within the timing defined by the delayed coincidence, is determined by the following two ways. First, the ratio of N_{ort} to the corresponding number of pickoff annihilations, denoted N_{pick}, is

$$N_{\mathrm{ort}}/N_{\mathrm{pick}} = \frac{1}{\tau_0} \Big/ \left(\frac{1}{\tau_{\mathrm{obs}}} - \frac{1}{\tau_0} \right) ,$$

where τ_0 and τ_{obs}, respectively, are the intrinsic decay time of orthopositronium in vacuum (we take a value of 142 nsec) and the decay time measured in our experiment (134 nsec) which is shorter than τ_0 due to the pickoff annihilations. N_{pick} can in turn be determined from the number of the pickoff events (denoted n_{pick}) under the 511-keV peak in the orthopositronium spectrum by the following formula:

$$n_{\mathrm{pick}} = 2 N_{\mathrm{pick}} \epsilon(511) .$$

N_{ort} can also be determined directly from the rate of the 3γ decays. This is performed by fitting a part of the orthopositronium spectrum (420 to 490 keV where the 3γ decay dominates) with the theoretical spectrum[7] of the 3γ decay folded with the energy-dependent efficiency. The two values of N_{ort} thus obtained agree within the estimated systematic error of 7%. It should be noted that the final $r_{\gamma x}(k)$ thus determined depends only on the ratio of the efficiencies, for example, $\epsilon(k)/\epsilon(511)$, and not on their absolute values.

The resulting upper limit of the γx branching ratio at the 90% confidence level is shown in Fig. 4(b) as a function of m_x. As seen in this figure, we have obtained new upper limits on the γx branching ratio of orthopositronium in the hitherto unexplored mass region of m_x below 100 keV. The upper limits are 6.4×10^{-5} for m_x below 30 keV and about 7.6×10^{-6} for m_x around 100 keV. These limits are about 2 orders of magnitude below the branching ratio, which corresponds to the reported discrepancy of the orthopositronium lifetime. Samuel's hypothesis is excluded by this experiment. The corresponding upper limit on the coupling constant $\alpha_{xee} = g_{xee}^2/4\pi$ is 6.2×10^{-10} for m_x below 30 keV.

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[1]C. I. Westbrook, D. W. Gidley, R. S. Conti, and A. Rich, Phys. Rev. Lett. **58**, 1328 (1987), 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. L. Glashow, Phys. Lett. **167B**, 35 (1986).

[4]M. A. Samuel, Mod. Phys. Lett. **3**, 1117 (1988).

[5]G. Carboni and W. Dahme, Phys. Lett. **123B**, 349 (1983); U. Amaldi, G. Carboni, B. Jonson, and J. Thun, Phys. Lett. **153B**, 444 (1985); V. Metag *et al.*, Nucl. Phys. **A409**, 331 (1983).

[6]T. Chang, M. Xu, and Z. Zeng, Phys. Lett. **126A**, 189 (1987), and references therein.

[7]G. S. Adkins, Ann. Phys. (N.Y.) **146**, 78 (1983).