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A search for massive neutral bosons in orthopositronium decay

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Abstract

We have searched for an exotic decay of orthopositronium into a single photon and a short-lived neutral boson in the hitherto unexplored mass region above 900 keV/c^2, by noting that this decay is one of few remaining candidates which could explain the discrepancy of the orthopositronium decay rate. A high-resolution measurement of the associated photon energy spectrum was carried out with a germanium detector to search for a sharp peak from this two-body decay. Our negative result provides an upper limit of 2.0×10^{-4} on the branching ratio of such a decay in the mass region from 847 to 1013 keV/c^2, and excludes the possibility of this decay mode explaining the discrepancy in the orthopositronium decay rate.

Keywords: QED; Neutral boson; Orthopositronium decay; Exotic decay; Germanium detector; Decay rate

Over the last seven years, three precision measurements of the orthopositronium (o-Ps) decay rate were performed, which report a decay rate *faster* than the QED prediction [1] by 1400, 1300 and 920 ppm, respectively, corresponding to 6.7, 6.3 and 4.3 standard deviations [2]. In an attempt to explain the origin of this discrepancy, various exotic o-Ps decay modes have been investigated without obtaining any evidence so far. The decay mode into invisible final states was ruled out at 3 ppm [3]. The decay into two and four photons, forbidden by space-rotational invariance and by the charge-conjugation invariance of QED, was excluded at 233 and 8 ppm, respectively [4,5]. The decay into two photons and a long-lived, weakly-interacting vector boson was excluded at 10 ppm [6]. The decay into a photon and a long-lived, weakly-interacting particle was also ruled out at 10 ppm for a mass less than 1010 keV/c^2 [7], while that into a photon and a short-lived neutral boson with a mass less than 900 keV/c^2 was excluded at 400 ppm [8–10]. One of the very few remaining candidates for the source of the discrepancy is the decay into a single photon and a short-lived neutral boson X^0 in the hitherto unexplored mass range above 900 keV/c^2. We report in this letter a dedicated search for such a decay.

A schematic view of the experimental setup is shown in Fig. 1. A ^{22}Na positron source of intensity 0.7 μCi (2 mm spot diameter) is sandwiched between a plastic scintillator (NE104) of thickness 100 μm and a mylar sheet of thickness 25 μm, each with a diameter of 12 mm. The source and a target of silica aerogel (dimensions $10 \times 10 \times 5\,\mathrm{mm}^3$, density $0.1\,\mathrm{g\,cm}^{-3}$) are held at the center of a pipe (18 mm diameter) made of 20μm thick aluminized mylar. The pipe is filled with N_2 gas at 1 atmosphere. Most of the positrons emitted toward the target pass through the scintillator, giving light pulses to two photomultipliers (Hamamatsu H-3165-PV). When stopped in the

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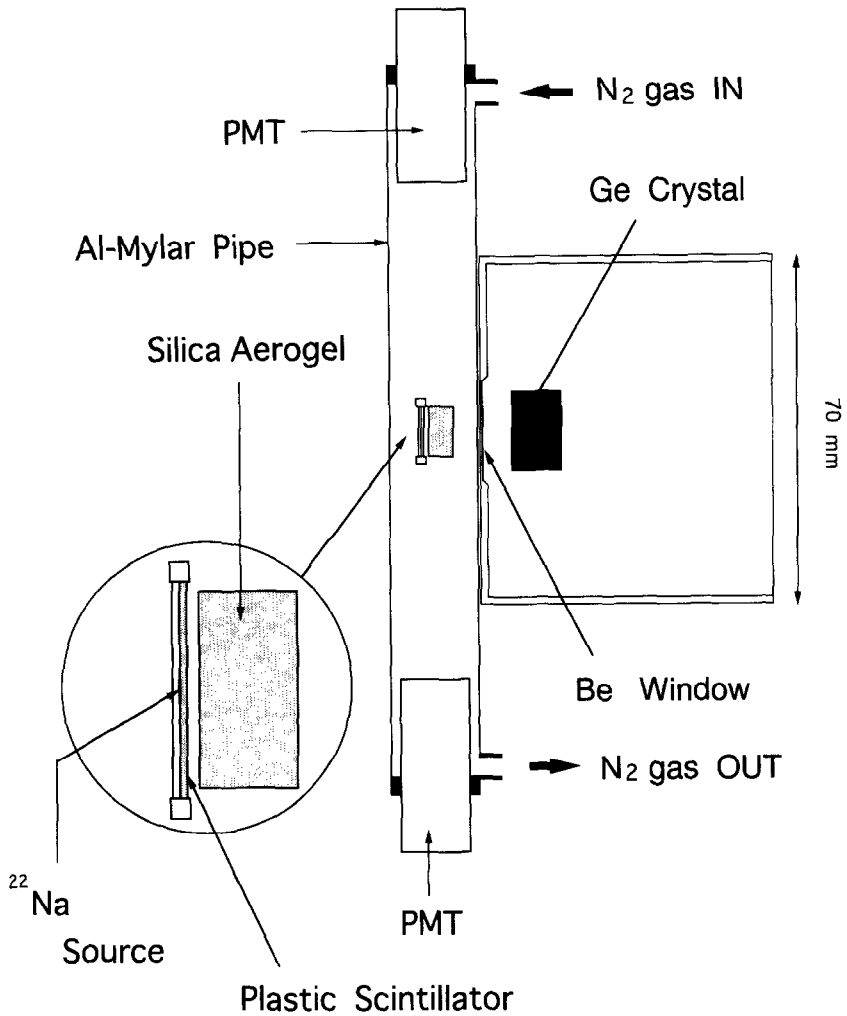

Fig. 1. A schematic view of the experimental setup. Circular inset: a magnified view of the source region.

silica aerogel, they form positronium-atoms for about 20% of cases. The total efficiency of o-Ps formation in our set-up was measured to be 3.0% per β^+decay.

The energy of the photon from the decay of o-Ps is measured by a planar high-purity germanium detector (diameter 16 mm, thickness 10 mm, Ortec GLP-16195/10-P). The germanium detector has a thin Be window of thickness 0.13 mm, which results in a high efficiency to low-energy photons down to 5 keV. The energy resolution and the absolute peak efficiencies of the germanium detector are determined as a function of the photon energy by using the line γ peaks from various sources of known strength, i.e., ^{22}Na, ^{57}Co, ^{133}Ba, ^{152}Eu, ^{210}Pb and ^{226}Ra, placed at the source position. The energy resolution obtained is 270, 525 and 828 eV FWHM at 14.4, 136.5 and 356.0 keV, respectively.

The trigger and the data acquisition system is arranged as follows. The pulses from the two photomultipliers are discriminated individually and the coincidences between them provide the start signals to the time-to-digital converter (TDC; LeCroy 2228A), as well as the trigger signals to the CAMAC system. One output from the preamplifier of the germanium detector is fed through a fast-filter amplifier (Ortec 474) with an integration time of 100 nsec, into the peak hold

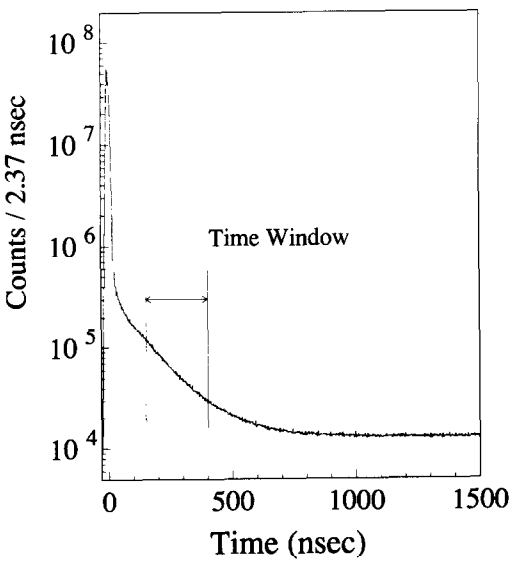

Fig. 2. The time spectrum between the scintillator and germanium detector signals.

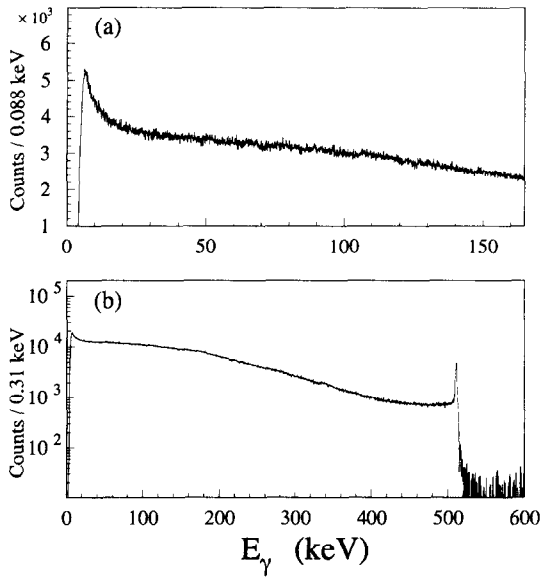

Fig. 3. The o-Ps spectra after subtracting the accidental contribution. (a) Below 160 keV. (b) Up to 600 keV.

analog-to-digital converter (ADC-1; Hohshin C008), and also into a discriminator whose output is used as the stop signal for the TDC. The other preamplifier output is amplified by a shaping amplifier (Ortec 572) with an integration time of 3 μsec. One output of the shaping amplifier is fed into the peak-hold analog-to-digital converter (ADC-2; Hohshin C011), to record the information of the low-energy region below 160 keV. The other output of the shaping amplifier is attenuated and fed into the other input of the ADC-2, to record the energy information in a wider range up to 600 keV. If the TDC stop signal is not generated within 5 μsec after the trigger, the data readout is terminated and the system is cleared to accept the next trigger.

The data were collected from 10 runs for a total of 2.26×10^6 sec. Throughout the data taking period, the room temperature was controlled to ± 0.4°C. The energy calibrations and the measurements of the energy resolution were carried out at intervals of 7 days. In addition, the position and the width of the 511 keV annihilation line were monitored by offline analysis of the data, which showed a stable peak position within 0.03 keV and a constant energy resolution throughout the data taking period.

The offline selection and calibration process is as follows. In order to eliminate the pile-up effects, we demand the consistency between two ADC values with different integration time: If the ratio of the two values deviates from the central value by more than 6%, the event is rejected as being affected by the pile-up. This selection has an efficiency of 92%. The time walk of the discriminator output is corrected by using the pulse height information from the ADC-2. The nonlinearity of the TDC is corrected by using a flat spectrum between random triggers and clock signals.

Fig. 2 shows the time spectrum between the scintillator and germanium signals. A sharp peak of the prompt annihilations is followed by the exponential decay of o-Ps and subsequently by the constant accidentals. The time spectrum fits well to an exponential function plus a constant term. A decay time of 134.2 ± 0.4 nsec is consistently obtained for various time spans if the fitting starts more than 150 nsec after the prompt peak. To obtain a pure sample of the o-Ps decay, we select the events in the time window between 150 and 400 nsec after the prompt annihilations. The accidental contribution is measured by using the events in the time-window between 2000 and 3200 nsec after the prompt peak.

Figs. 3a and 3b show the measured energy-spectra from the o-Ps decay (o-Ps spectrum), thus selected and the accidental contribution being subtracted. The two-body decay into a photon and X^0 (γX^0 decay)

would appear in this o-Ps spectrum as a narrow peak on a smooth background. The peak position k_p is related to the X^0 mass, m_{X^0}, by

$$k_p = m_e \left[1 - \left(m_{X^0}/2m_e\right)^2\right] ,$$

where m_e is the electron mass.

Peaks in the o-Ps spectrum have been searched for by scanning k_p with a step of 0.088 keV from 10 to 160 keV, corresponding to the m_{X^0} region from 847 to 1013 keV/c^2. At each k_p, the o-Ps spectrum was fitted with the function

$$S(k) + n(k_p)P(k) ,$$

where $S(k)$ and $P(k)$ represent the smooth background spectrum and the normalized peak function, respectively. The fitting parameter $n(k_p)$ corresponds to the number of photons from the γX^0 decay events under the peak at k_p. The background spectrum $S(k)$ is obtained at each k_p by fitting the o-Ps spectrum (excluding the region within 2.5 times the FWHM of the peak position) with a polynomial function of up to seventh order. Since the intrinsic width of X^0 is expected to be extremely small, the observable width of the peak would be dominated by the energy resolution of the detector and by the thermal motion of o-Ps. The thermal kinetic energy of o-Ps has been measured in an aerogel similar to the one used in this experiment and is known to decrease to about 0.04 eV within 60 nsec after formation [11,12]. The Doppler broadening due to this thermal kinetic energy would contribute negligibly to the peak width. Therefore the shape of the peak is assumed to be Gaussian, of a width determined by the energy resolution of the germanium detector.

No statistically significant peak beyond 4 standard deviations was detected in the o-Ps spectrum, except for the one at 511 keV, resulting in upper limits on $n(k_p)$. This peak at 511 keV (seen in Fig. 3b) is clearly due to the pick-off annihilations, in which the orthopositronium atoms collide with the atomic electrons of the target material causing annihilations into two photons.

The limits on $n(k_p)$ can be converted into the corresponding limits on the branching ratio of the γX^0 decay, $\mathrm{Br}(k_p)$, by using the formula

$$\mathrm{Br}(k_p) = \frac{n(k_p)}{\epsilon(k_p)\, N_{\mathrm{ops}}} ,$$

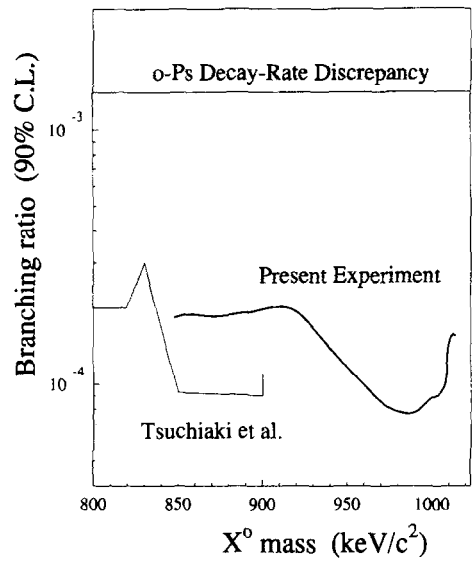

Fig. 4. The resultant upper limits at 90% C.L. on the branching ratio of γX^0 decay in comparison with the existing limits [8].

where $\epsilon(k_p)$ is the absolute peak efficiency for a γ-ray of energy k_p.

N_{ops} represents the total number of the o-Ps decays occurring within the 150–400 nsec time-window, and is determined by fitting the "Compton-free" region of the o-Ps spectrum (between 400 to 490 keV, where the three-photon decays dominate) with the theoretical spectrum [13] of the three-photon decay folded with the energy-dependent efficiency. It should be noted that the $\mathrm{Br}(k_p)$ thus obtained has a small systematic error, being dependent only on the relative values of the efficiencies, not on their absolute values.

The resulting upper limits at a 90% confidence level on the branching ratio of γX^0 decay are shown in Fig. 4 , as a function of m_{X^0}. As indicated in this figure, new upper limits on the γX^0 branching ratio in the mass range of X^0 from 900 to 1013 keV/c^2 have been obtained. Since our upper limits are at least a factor of 7 below the level which would explain the reported discrepancy of the o-Ps lifetime, we conclude that the o-Ps decay mode of γX^0 in the mass region below 1013 keV/c^2 cannot explain the reported discrepancy of the orthopositronium decay rate.

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