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Search for short-lived neutral bosons in orthopositronium decay

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We searched for an exotic decay of orthopositronium into a single photon and a short-lived neutral boson Φ^0 in hitherto unexplored mass region below $300\,\mathrm{keV}/c^2$. A high-resolution measurement of the associated photon energy spectrum was carried out with a germanium detector to discriminate the expected sharp peak of this decay from the broader peak of the pick-off annihilations. No evidence of such decay was observed, resulting in the upper-limits on the branching ratio of 3.0×10^{-4} ($m_{\Phi^0} < 500\,\mathrm{keV}/c^2$). This clearly rules out the possibility of this exotic decay mode explaining the reported discrepancy in the orthopositronium decay rate.

1. Introduction

Measurement of the decay rate of orthopositronium (o-Ps) in vacuum cavities at a 200 ppm accuracy level [1] was found to be 1400 ppm larger than QED theoretical predictions [2]. This discrepancy is consistent with results from precision experiments carried out over the last 18 years in low-pressure gases [3], in vacuum cavities [4], and SiO_2 powders [5]. QED calculations include only corrections up to order α, and therefore higher-order corrections may account for this difference. However, several estimations of the higher-order corrections are only 150 ppm [6], being about 9 times less than the level which would explain the discrepancy. Another possibility exists that o-Ps has a novel decay channel which could be proven by finding a corresponding branching ratio. In this respect, we consider o-Ps to be an attractive and promising hunting field to search for exotic phenomena.

Various exotic o-Ps decay modes have been investigated to explain this discrepancy, though none have been found thus far. A review of previous studies directed at elucidating possible exotic decay follows. The decay into a single photon and a long-lived, weakly-interacting particle X^0 has been ruled out at a 1 ppm sensitivity level [7], while that into a photon and a short-lived, spin-zero boson Φ^0 was excluded at a level of 400 ppm in the m_{Φ^0} region from 300 to $900\,\mathrm{keV}/c^2$ [8]. In another experiment, the Φ^0-mass region below $30\,\mathrm{keV}/c^2$ was also ruled out at 28 ppm [9]. The decay into two photons, being forbidden by space-rotational invariance and by the charge-conjugation invariance of QED (C-invariance), was excluded at a level of 233 ppm [10,11], as was C-violated decay into four photons [12]. Moreover, an exotic decay mode into only non-interacting particles was excluded at 3 ppm [13]. Finally, the three-body final state mode [#1] in which o-Ps decays into two photons and a long-lived, weakly-interacting vector-boson $\gamma^\dagger$ (e.g., a paraphoton [14]) was recently ruled out at 10 ppm [15]. Therefore, we consider that the following three possibilities to be the best remaining decay mode candidates:

(1) o-Ps decays into a single γ and a spin-zero neutral boson Φ^0, where the Φ^0-mass is between 30 and $300\,\mathrm{keV}/c^2$ and the Φ^0 is abnormally short-lived, immediately decaying into two photons.

(2) o-Ps decays into $\gamma\Phi^0$, where Φ^0 is heavier than $900\,\mathrm{keV}/c^2$ and has an effective coupling to photons

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[#1] If a long-lived, weakly-interacting vector-boson $\gamma^\dagger$ is parity-odd for charge-conjugation, this three-body final state decay would be the lowest-order contribution. Because the γ energy spectrum from this decay has no peak corresponding to the mass of $\gamma^\dagger$, peak-hunting experiments [8,9] have no sensitivity for this mode.

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the same as in (1).

(3) o-Ps decays into three photons via an exotic intermediate state.

In (1) and (2), because Φ^0 has an effective coupling to photons, Φ^0 and a single photon are also produced from the *s*-channel annihilation of o-Ps. Hence, even if Φ^0 has no coupling to an electron like a hadronic axion, o-Ps could decay into a single photon and a Φ^0 boson; with this decay channel accounting for the decay rate discrepancy. Here, we search for decay mode (1) by applying a peak-hunting method to an inclusive γ-energy spectrum of o-Ps decay.

The detection of this $\gamma\Phi^0$ decay mode is generally believed to be difficult due to the background of the "pick-off" process in which o-Ps collides with the atomic electrons of the target material or residual gas, causing annihilations into two photons. We overcome this obstacle by reducing the pick-off contribution to 0.8% of the vacuum decay rate by selecting a special low-density silica powder 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 $\gamma\Phi^0$ decay from the peak of the pick-off 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 γ peak from the $\gamma\Phi^0$ decay might be affected by the Doppler effect due to the non-zero velocity of the decaying o-Ps , as well as by the total decay width of the Φ^0 boson, $\Gamma^{\mathrm{tot}}_{\Phi^0}$. The velocities of the o-Ps have been measured as a function of time in various silica aerogels [16,17] and powders [17], including some powders similar to one used in this experiment. These measurements show that the positronium (Ps), after being repelled out of the silica grain into a vacuum void with a 0.85 eV kinetic energy, rapidly slows down to an average kinetic energy of 0.4 eV within a few ns. Subsequently, elastic collisions with the surface silica atoms gradually slow it down towards thermal velocity. According to these measurements, this relaxation process is the same in aerogel and powder, and it appears to be simply governed by the number of collisions, probably because only a limited number of atoms are directly involved in the collisions. A model [17] of the relaxation process based on these assumptions fits all the available data rather well [18]. This model, applied to the powder used in this experiment, predicts the average kinetic energy of o-Ps to be about 0.05 eV in our time window of 120 to 300 ns after formation. Doppler-broadening due to this amount of kinetic energy is negligible in comparison to the energy resolution of the germanium detector. On the other hand, $\Gamma^{\mathrm{tot}}_{\Phi^0}$ is estimated to be smaller than 0.001 eV (for $m_{\Phi^0} < 300\,\mathrm{keV}/c^2$), which is the calculated value corresponding to the reported discrepancy of the o-Ps decay rate. The resultant broadening effect due to the $\Gamma^{\mathrm{tot}}_{\Phi^0}$ will also be negligible with respect to the detector resolution. Therefore, taken together, we should expect that the γ peak from the $\gamma\Phi^0$ decay is sharp and has a width determined by the detector's resolution.

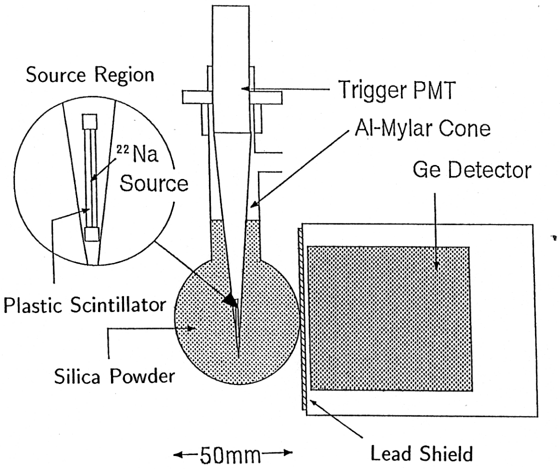

Fig. 1. Diagram of experimental setup. Circular inset: a magnified view of the source region.

2. Experimental setup

Fig. 1 shows a diagram of the experimental setup, being similar to one used in our previous experiment [10]. A ^{22}Na positron source 0.02 at μCi with a 2 mm spot diameter is sandwiched between two sheets of plastic scintillator (NE104), each with a diameter of 12 mm and thickness of 100 μm. The source is held by a cone made of 20 μm thick aluminized-mylar (Al-Mylar), and is situated at the center of a vacuum container made of 500 μm thick glass and having a 48 mm diameter. The container is filled with the silica powder (density: $0.035\ \mathrm{g\,cm^{-3}}$) and evacuated to 10^{-2} Torr. Most of the emitted positrons pass through the scintillator, transmitting a light pulse to a photomultiplier (Trigger PMT; Hamamatsu H-3165-04) and forming Ps when stopped in the silica powder.

The energy of the γ produced by the decay of o-Ps is measured by a high-purity coaxial germanium crystal (diameter: 61 mm, thickness: 69 mm, Ortec GEM 38195). The germanium detector's energy resolution and absolute peak efficiencies are determined as a function of γ energy using the line γ peaks from various known-strength sources, i.e., ^{57}Co, ^{85}Sr, ^{22}Na, ^{60}Co, and ^{152}Eu, 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 2.08 mm thick lead sheet is placed in front of the detector to eliminate the contribution of the two low-energy γ's from the three-photon decay of o-Ps.

The trigger and the data-acquisition system with CAMAC are described as follows. The output of the scintillator pulse discriminator provides both the start signal to the time-to-digital converter (TDC) (Hohshin C006) and the trigger signal to the CAMAC system. 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 output is used as the stop signal for the TDC. The differential and integral time of the fast-filter amplifier are optimized in order to obtain a good time resolution of 6 ns rms. The other preamplifier output is amplified by a spectroscopy amplifier (Ortec 673), whose output is fed to the amplitude-to-digital converter (ADC) (Hohshin C011) to record the energy information. To enable off-line analysis, the TDC and ADC data-sets are recorded for all triggered β^+.

Fig. 2 shows the time spectrum between the scintillator and germanium signals for a germanium detector energy window from 400 to 480 keV. An initial, sharp peak of prompt annihilation is followed by the exponential decay of o-Ps and subsequently by the constant accidentals. The time spectrum fits to an exponential function plus a constant term, and a decay time of 141.0 ± 0.2 ns is consistently obtained for various time spans. Note this is the measured lifetime value, and not the lifetime of o-Ps in a vacuum. The asymptotic value of the measured lifetime is reached about 120 ns after the prompt peak, being consistent with the previously mentioned model [17] of the relaxation process. In order to obtain a pure sample of o-Ps decay, a delayed gate is employed (fig. 2), i.e., the germanium signal should arrive between 120–300 ns after the prompt annihilation. To measure and subtract the accidental contributions, the accidental gate is taken from 2000 to 3800 ns following the prompt peak.

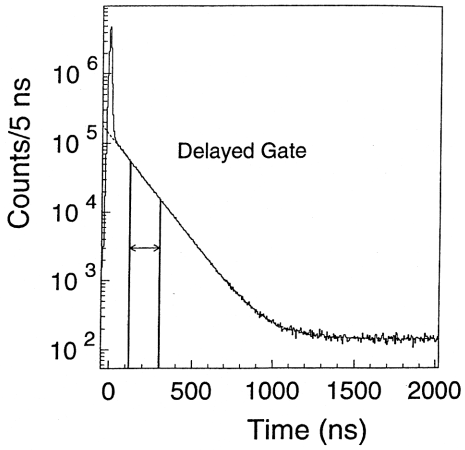

Fig. 2. The time spectrum between the scintillator and germanium detector signals for a 400 to 480 keV energy window.

3. Results and discussion

The TDC and ADC data-sets were collected from 24 runs for a total 1.28×10^7 s, during which time the room temperature was controlled ±0.3°C to ensure stability of the amplifiers and ADC. The narrow width (1.8 keV FWHM) of the observed accidental 1275 keV line γ peak indicates excellent energy resolution and stability were obtained throughout the data-taking period. The resultant two spectra within the delayed and accidental gates are shown in fig. 3a, where the accidental contribution in the energy region of interest is small because of the low activity of the positron source.

Fig. 3b shows the delayed-gate spectrum following subtraction of the accidental contribution; thereby representing the photon-energy spectrum from a pure sample of o-Ps (termed here as the "o-Ps spectrum"). This spectrum is comprised of a high peak around 511 keV and a flatter spectrum from the 3γ decay of o-Ps.

A simulated energy spectrum of the 3γ decay, termed here as "3γ simulation spectrum", was calculated by a Monte Carlo simulation in which

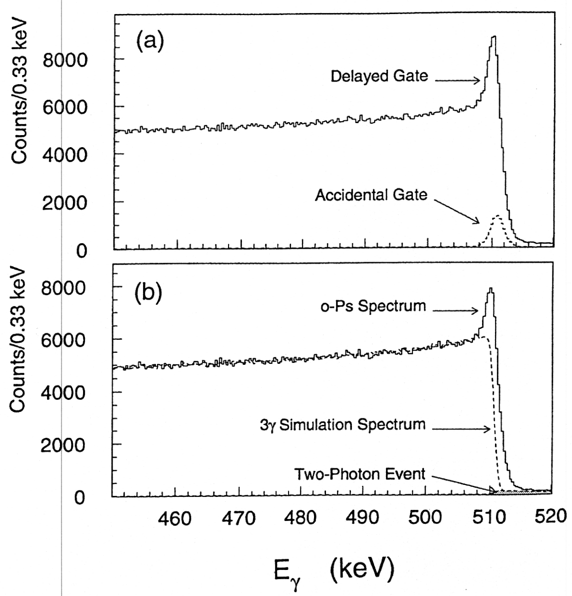

Fig. 3. (a) The photon energy spectra measured within the delayed and accidental gates. The accidental spectrum is normalized by the widths of the delayed time windows. (b) The o-Ps spectrum after subtracting the accidental contribution. The dotted line, nearly indistinguishable from the observed data below 508 keV, shows the simulated spectrum from the 3γ decay of o-Ps, and the lower hatched spectrum is due to the events in which two low-energy photons from a 3γ decay simultaneously hit the detector.

the setup geometry and various material properties are reproduced in detail. For every simulated event, three photons are generated according to an order-α-corrected energy spectrum [19]. Successive photoelectric or Compton interactions of every γ are then followed through the materials until all its energy is dissipated. Consequently, events in which multiple photons hit or scatter into the detector are properly included in the simulation, although the contribution of such events is small in the energy region of interest as indicated by fig. 3b. The response function of the detector as a function of the incident photon energy is deduced from the measured spectra of monochromatic γ rays emitted from ^{137}Cs (662 keV), ^{85}Sr (514 keV) and ^{113}Sn (392 keV) and is folded in the simulation. Thus, the contribution from simulated photons is stable against various systematic errors; e.g., it only depends on the relative efficiency of the detector and not on its absolute efficiency.

As seen in fig. 3b, the 3γ simulation spectrum reproduces well the o-Ps spectrum over a wide energy region below 508 keV. The sharp falloff of this spectrum at 511 keV is due to the phase-space cutoff. Therefore, the sharp falloff is almost entirely determined by the energy resolution and has no ambiguity; providing that the absolute energy scale and response function are properly obtained. One potential problem could have been the contribution of events in which two low-energy photons from a 3γ decay simultaneously hit the detector. Although such events are taken into account in the simulation, their occurrence would cause the detected energy spectrum to abruptly increase above 511 keV, and be more vulnerable to systematic errors of the simulation. However, as seen in the lower hatched histogram in fig. 3b, the simulation results show that such events are reduced to a negligible level by the lead shield placed in front of the detector.

The pick-off annihilation spectrum must be known to carry out a detailed investigation around the 511 keV peak. For this purpose, a total of 7.2×10^5 s of "enhanced pick-off" runs were performed, being accomplished by attaching a 3 mm thick slab of silica aerogel (density: 0.2 $\mathrm{g\,cm^{-3}}$, diameter: 14 mm) to each side of the Al-mylar cone holding the positron source. In this setup, most of the positrons stop in the silica aerogel instead of the silica powder; enhancing the pick-off peak by a factor of 11.9 relative to the 3γ decay. The "pick-off spectrum" is then obtained by subtracting the corresponding accidental and 3γ contributions, and shows a broad peak (2.8 keV FWHM) at 511 keV.

Narrow peaks from the $\gamma\Phi^0$ decay were searched for as described next. We fit the o-Ps spectrum with function $\boldsymbol{a}P(k) + \boldsymbol{b}G(k) + \boldsymbol{f}S(k, m_{\Phi^0})$ by freely varying the fitting parameters $\boldsymbol{a}$, $\boldsymbol{b}$, and $\boldsymbol{f}$; where $k, P(k), G(k)$, and $S(k, m_{\Phi^0})$ respectively represent the photon-energy, pick-off spectrum, 3γ simulation spectrum, and an expected peak-function of $\gamma\Phi^0$ decay. The expected peak-function has a narrow peak (1.3 keV FWHM at $k=511$ keV) at photon-energy $k = m_e(1 - (m_{\Phi^0}/2m_e)^2)$, and its shape was deduced from the measured spectra of monochromatic γ rays. For all m_{Φ^0} below 500 keV/c^2, a region corresponding to the photon energy of the narrow peak from 390 to 511 keV; $\boldsymbol{a}$, $\boldsymbol{b}$, and $\boldsymbol{f}$ were obtained and the $\boldsymbol{f}$ parameters were statistically found to be consistent with zero.

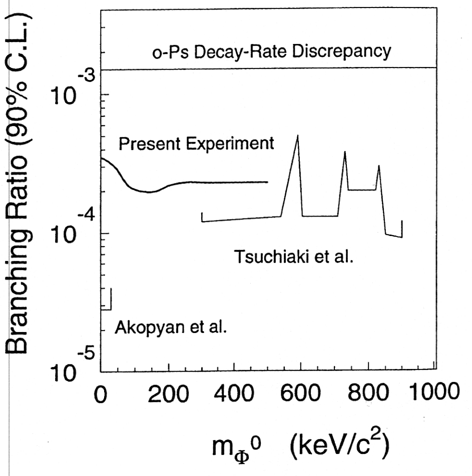

Fig. 4. The resultant upper-limits at 90% C.L. on the branching ratio of $\gamma\Phi^0$ decay in comparison with the existing limits [8,9].

No statistically significant peak from the $\gamma\Phi^0$ decay was detected in the energy region above 390 keV. Our resultant upper-limits on the $\gamma\Phi^0$ branching ratio are shown as a function of m_{Φ^0} in fig. 4 at a 90% confidence level. As indicated, we obtained new upper-limits on the $\gamma\Phi^0$ branching ratio of o-Ps in the mass region of Φ^0 from 30 to 300 keV/c^2. Since our upper-limits are 3.0×10^{-4}, a factor of 5 below the level which would explain the reported decay rate discrepancy, we conclude that the $\gamma\Phi^0$ ($m_{\Phi^0} < 900\,\mathrm{keV/c^2}$) decay of o-Ps is not the source of this discrepancy.

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