Search for Long-Lived Neutral Bosons in Orthopositronium Decay

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We have searched for orthopositronium decay into γ plus a feebly interacting boson X^0, by looking for a narrow peak in the energy spectrum of a single γ taken under the condition of no additional γ detected in a hermetic photon detector. No evidence of such decay is observed, resulting in a new upper limit on the branching ratio of 1.1×10^{-6}, which is a factor of 60 more stringent than previous limits in the m_X region below 30 keV. This experiment rules out the existence of light ($m_X<800$ keV) Goldstone-like bosons having electron-coupling constants α_{Xee} larger than 1.1×10^{-11}.

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The possible existence of feebly interacting light neutral bosons (hereafter denoted as X^0) has been conceived by many recent theories which extend the standard model. For example, these theories often contain global continuous symmetries which are broken at very high energy to reproduce the low-energy region of the standard model. A massless spin-zero boson appears as a Goldstone boson when such a global symmetry suffers spontaneous symmetry breaking. If the symmetry is not explicitly exact, the resulting pseudo-Goldstone boson acquires a small mass, which is inversely proportional to E_X, the energy scale of the symmetry breakdown. The coupling constants of the bosons to leptons and quarks are also expected to be inversely proportional to E_X. Therefore, searches for light, feebly interacting bosons might provide new windows to explore the physics of ultrahigh-energy scales not directly accessible by present accelerators. Famous examples of such Goldstone-like bosons are the dilatons and axions.

Besides cosmological and astrophysical considerations, which often contain various ambiguities, there exist only a few direct experimental methods to search for such light, feebly interacting neutral bosons. Beam-dump experiments[1] are powerful in searching for such bosons, but are not sensitive to bosons lighter than MeV, because the expected decay length of such light bosons becomes much longer than the typical distance between target and detector. Orthopositronium (*o*-Ps) decay into γX^0 provides another direct method, which in principle is sensitive down to zero-mass bosons. Furthermore, space rotational invariance forbids the 2γ decay of *o*-Ps and slows the *o*-Ps decay rate by 3 orders of magnitude relative to that of parapositronium. The branching ratio of a rare decay such as γX^0 will then be enhanced by the same factor and might eventually reach a detectable level. We report here on a new search of *o*-Ps decay into γX^0. The concept of our experiment is to search for single monochromatic γ rays, whose energy is measured by a high-resolution germanium detector. A hermetic photon detector detects any additional γ ray and provides the veto signal to normal *o*-Ps decays as well as to pickoff[2] events, in which *o*-Ps collides with an atomic electron of the target material or of the gas, causing annihilation into 2γ.

The setup of the experiment is illustrated in Fig. 1. A ^{68}Ge-Ga positron source with an activity of 0.6 μCi is deposited in a small cup (diameter 3 mm and height 3 mm) made of a plastic scintillator (NE104) of thickness 700 μm. Most of the positrons pass through the scintillator, giving light pulses to a photomultiplier (Hamamatsu H-3165-04), and stop in silica aerogel of density 0.1 g/cm^3 to form positronium atoms. In order to minimize the pickoff probability, the source and scintillator are placed in an evacuated (10^{-4} torr) container made of CsI scintillator, which is a part of the active veto counter. In this way, the materials in front of the veto scintillator are minimized to reduce the attenuation of the photons. The energy of a γ ray from *o*-Ps decay is measured by a large-volume (196 cm^3) coaxial germanium crystal of high purity (Ortec GEM38195), with energy resolution of 0.9 and 1.2 keV FWHM at 122 and 511 keV, respectively.

The source and the germanium detector are surrounded by a hermetic veto detector consisting of 21 CsI

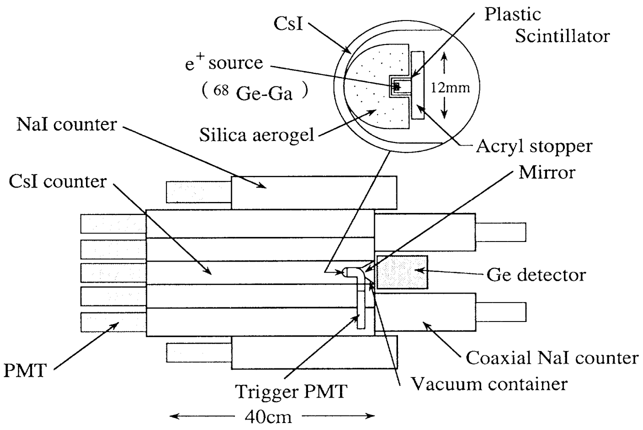

FIG. 1. Setup of the experiment.

counters of dimensions 60×60×440 mm each, 18 NaI scintillators of dimensions 65×65×300 mm each, and a coaxial NaI counter with thickness 80 mm and length 220 mm.

Data acquisition is started by the trigger pulse from the β^+ emission. For this purpose, the pulse from the plastic scintillator is discriminated, one output of which gives a start signal to a 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 germanium detector is fed through a fast filter amplifier (Ortex FFA 579) into a constant-fraction discriminator (Ortec CFD 583), whose outputs are used as the stop signal for the TAC and as the delayed coincidence to the trigger pulse. The FFA and CFD are adjusted to obtain a good time resolution of 5 nsec rms. Signals from the CsI and NaI counters are discriminated with an energy threshold of 20 and 5 keV, respectively. The outputs of the discriminators are logically added and used as veto signals. Another output from the germanium detector is amplified by a spectroscopy amplifier (Ortec 673), whose outputs are recorded by two pulse-height analyzers (SEIKO MCA7800), one gated by the delayed coincidence with the veto signals, and the other by the corresponding accidental coincidence. Energy calibration is performed by using line γ rays from ^{51}Cr, ^{57}Co, ^{137}Cs, and ^{85}Sr.

Figure 2 shows the time spectrum between the pulses from the plastic scintillator and the germanium detector, for the energy window of the germanium detector set at 400–500 keV. The sharp peak of the prompt annihilations is followed by the exponential decay of o-Ps and subsequently by the constant accidentals. By fitting this spectrum with $A\exp(-t/\tau)+B$, a measured decay time (τ) of 138.0 ± 1.3 nsec is consistently obtained for various time spans. 70 nsec is required after the prompt peak to reach this asymptotic value of the lifetime. In order to obtain a pure sample of o-Ps decays, the delayed coincidence is required to be such that the germanium signal arrives between 120 and 260 nsec later than the prompt annihilations, as indicated in Fig. 2. To measure and subtract the accidental contributions, the accidental coincidence is defined within the time window 1000–1420 nsec later than the prompt peak. The accidental time window is chosen to be 3 times wider than the delayed coincidence in order to reduce the statistical error of the accidental spectrum.

The singles energy spectrum of the germanium detector is shown as curve a in Fig. 3. The strong peak at 511 keV is due to the prompt annihilations. Curve b in Fig. 3 is the germanium energy spectrum which is taken with delayed coincidence (the accidental contributions are subtracted). The energy spectrum (hereafter denoted "o-Ps spectrum") consists of the 3γ decays of o-Ps and the pickoff annihilations. Finally, data are collected for a total of 5.51×10^6 sec with the veto from CsI and NaI counters imposed on the delayed coincidence as well as on the accidental coincidence. During this data taking, the room temperature is controlled to ±0.5 °C in order to obtain good stability. We have performed a stability and resolution check of the germanium detector every ten days. The resulting spectrum is shown as curve c in Fig. 3 ("delayed spectrum with veto").

The γX^0 decays of o-Ps would appear as a narrow peak in the delayed spectrum with veto. Since the intrinsic width of the bosons of the search is expected to be ex-

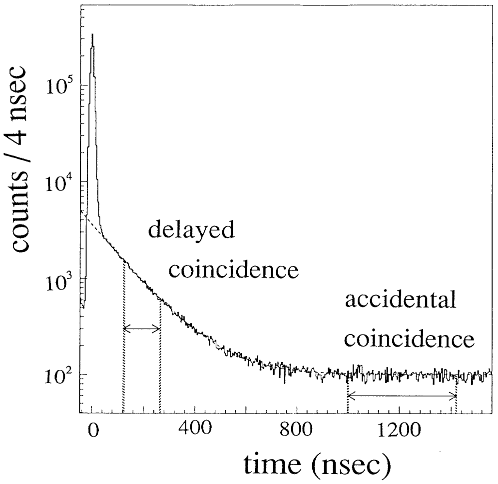

FIG. 2. Time difference distribution between the plastic scintillator and the germanium pulses. The dashed line is the decay curve obtained by the fitting.

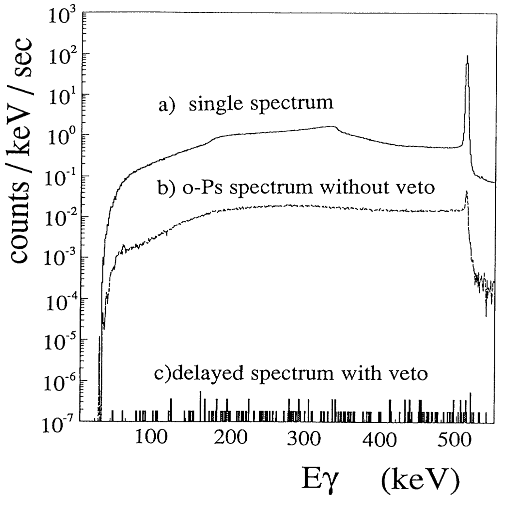

FIG. 3. γ-ray energy spectra detected by the germanium detector. The vertical scale is the absolute counting rate per keV per second. Curve a, the singles (all times) spectrum. Curve b, "orthopositronium spectrum" taken with delayed coincidence. The accidental contribution is subtracted. Curve c, the spectrum taken with the veto from the CsI and NaI counters imposed on the delayed spectrum.

tremely 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[2] in an aerogel very similar to the one used in this experiment and is known to decrease rapidly to 0.03 eV within 60 nsec after formation. The Doppler broadening due to this thermal kinetic energy would contribute negligibly to the width of the peak. Therefore we assume that the shape of the peak would be Gaussian, of a width determined by the energy resolution of the germanium detector.

No statistically significant peak is detected in the delayed spectrum with veto except for the 6 events at 511 keV. This peak is very likely not due to γX^0 decays but due to the accidental contributions and due to the pickoff annihilations, for the following reasons. First, the expected accidental contribution is estimated to be 4.7 ± 1.3 events, deduced from the 14 events observed at 511 keV in the accidental spectrum with veto after proper normalization by the relative width of the time windows. Second, a Monte Carlo simulation predicts that the pickoff annihilations will fake 1.3 ± 0.5 single-γ events, in which one of the 2γ penetrates through the photon-veto counters. Thus there is no significant signal of γX^0 decays. We take a conservative attitude in this paper and obtain upper limits by assuming that the events in the delayed spectrum with veto could all be due to γX^0 decays.

The branching ratio $B_{rX}(k)$ can be obtained from the upper limit of the number of γX^0 events under a peak at energy k, which we denote $n_{rX}(k)$, by using the formula

$$n_{rX}(k) = N_{\text{ortho}} B_{rX}(k)\epsilon(k) ,$$

where $\epsilon(k)$ is the absolute peak efficiency of the germanium detector in our setup for a γ ray of energy k. N_{ortho}, the total number of *o*-Ps decays which occur within the timing by the delayed coincidence, is determined by the following two ways. First, the ratio of N_{ortho} to the corresponding number of the pickoff annihilations (N_{pick}) is given by

$$N_{\text{ortho}}/N_{\text{pick}} = \tau_0^{-1}/(\tau_{\text{obs}}^{-1} - \tau_0^{-1}) ,$$

where τ_0 and τ_{obs} are, respectively, the intrinsic decay time of *o*-Ps in vacuum [we use the value of 142 nsec (Refs. 3 and 4)] and the decay time measured in our experiment (138 nsec), which is shorter than τ_0 as a result of the pickoff annihilations. N_{pick} can be determined from the number of the pickoff events (denoted by n_{pick}) under the peak at 511 keV in the *o*-Ps spectrum by the following formula:

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

The second method is to determine N_{ortho} directly from the rate of 3γ decays. This is performed by comparing a part of the *o*-Ps spectrum (between 400 and 500 keV where the 3γ decays dominate) with the theoretical spectrum[3] of the 3γ decays folded by the energy-dependent efficiency. Both values of N_{ortho} thus obtained agree within the estimated error of 10%. It should be noted that the final $B_{rX}(k)$ thus determined depends only on the relative efficiency of the germanium detector, and not on the absolute efficiency.

The resulting upper limit of the *o*-Ps→ γX^0 branching ratio at the 90%-confidence level is shown in Fig. 4(a) as a function of m_X. As seen in this figure, a new upper limit on the γX^0 decay branching ratio of 1.1×10^{-6} is obtained, which is a factor of 60 times more stringent than the previous limits[5,6] in the mass region of m_X below 40 keV. The coupling constant of the X^0 bosons to the electron ($\alpha_{Xee} = g_{Xee}^2/4\pi$) is associated with the branching ratio by the following formula:[7]

$$\alpha_{Xee} = \frac{2(\pi^2-9)}{3\pi}\alpha^2 B_{rX}\left[1-\left(\frac{m_X}{2m_e}\right)^2\right]^{-1}$$

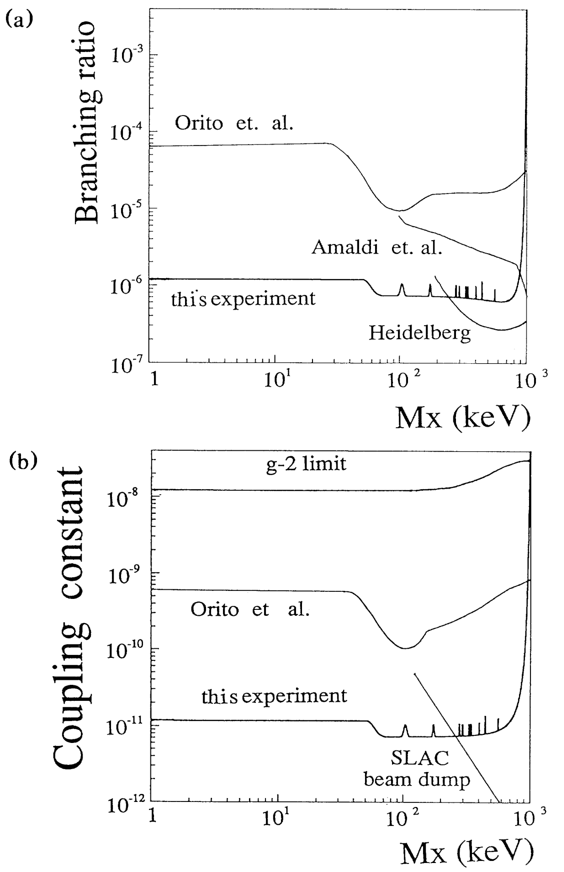

FIG. 4. (a) The resulting upper limits at 90%-confidence level on the branching ratio of γX^0 decay compared to the existing limits (Refs. 5 and 6). (b) The resulting upper limits at 90%-confidence level on the electron-coupling constant compared to the existing limits (Refs. 1 and 8). The limit of the SLAC beam-dump experiment is converted by using the relation (Ref. 9) between α_{Xee} and the decay time of $X^0 \to 2\gamma$.

(for scalar and pseudoscalar). The corresponding upper limit on α_{Xee} in the scalar and pseudoscalar case is shown in Fig. 4(b) as a function of m_X. This experiment rules out the existence of long-lived, light ($m_X < 800$ keV) scalar and pseudoscalar bosons with α_{Xee} larger than 1.1×10^{-11}.

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