Search for exotic decays from low-energy e^+e^- direct annihilation

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A new exotic-decay candidate is proposed to resolve the orthopositronium decay rate discrepancy. A search has been performed for the process $e^+e^- \to \gamma + X^0$, where the X^0 is a long-lived, low-mass boson that interacts very weakly with matter and has a charge conjugation eigenvalue $C = -1$. No evidence for the X^0 has been found in this experiment, with essentially the entire X^0 mass range from 0.1 to 1 MeV being excluded as the cause of the decay rate discrepancy. Previous results from other experiments are analyzed for sensitivity to this X^0.

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The vacuum decay rate (λ_T) of ground state triplet positronium [$^3S_1$, called orthopositronium (o-Ps)] has been precisely measured in two systematically different experiments [1,2]. The first experiment [1] measured the decay rate of o-Ps formed in gases and extrapolated to zero gas density to obtain λ_T. The experimental result, $\lambda_T^{\rm gas} = 7.0514 \pm 0.0014\ \mu s^{-1}$ (200 ppm uncertainty), differed by 9.4 standard deviations (σ) from the theoretical QED prediction [3], $\lambda_T^{\rm th} = 7.038\,30 \pm 0.000\,07\ \mu s$, calculated through order $\alpha^2 \ln\alpha$ corrections. The most recent o-Ps decay rate measurement [2] used the so-called vacuum technique where a slow positron beam is used to form o-Ps in an evacuated, MgO-coated cavity. This systematically different experiment yielded $\lambda_T^{\rm vac} = 7.0482 \pm 0.0016\ \mu s^{-1}$ (230 ppm uncertainty) in strong disagreement with theory (by 6.2 σ) and in reasonable agreement with the gas experiment [1]. It is noted in [2] that, if the disagreement is attributed to the uncalculated $(\alpha/\pi)^2$ term, the coefficient of that term would be large (250 ± 40).

Since both gas and vacuum experiments find a decay rate that is greater than theory, it has been suggested that an additional forbidden decay or exotic decay branch, not included in the QED calculations, could be the cause of the disagreement. A number of direct searches, all negative, have been performed for several different forbidden or exotic decay modes of o-Ps. These include searches for a pseudoscalar, axionlike neutral boson A^0 which replaces two γ rays from the normal 3γ decay of o-Ps [4], o-Ps $\to \gamma + A^0$. Upper limits (at 90% confidence) on this branch compared to 3γ are currently at the 1 ppm level for A^0 masses between 0 and 800 keV and the mass range from 0 to about 950 keV is definitely excluded as being the cause of the 1650 ppm λ_T discrepancy. Searches for the angular momentum violating decay, o-Ps $\to 2\gamma$, have been performed in several recent experiments [5]. At the 350 ppm level, the 2γ branch is excluded, with a 90% confidence level. Similarly, the C-forbidden (C-charge conjugation) branch, o-Ps$\to 4\gamma$, has been excluded at the 8 ppm level at 1σ [6]. Finally, the disappearance or the decay of o-Ps into undetected products o-Ps $\to$ nothing [7]), possibly "millicharged" particles [8], has been shown to be absent at the 3 ppm level with 90% confidence.

In this paper, we introduce a new exotic-decay candidate for explaining the λ_T discrepancy that could have been missed in earlier experiments. A massive scalar (vector)$C = -1$ boson, the X_S^0 (X_V^0) could infrequently replace one photon from normal o-Ps decay: o-Ps $\to 2\gamma + X^0$. (There are hadronic analogues to both X_S^0 and X_V^0.) The axion searches discussed above do not directly test for the X^0 since o-Ps $\to \gamma + X^0$ is forbidden by C conservation [$C(o\text{-Ps}) = C(\gamma) = C(X^0) = -1$, $C(A^0) = +1$]. If observed, the X^0 could be identified with the light vector C-odd bosons predicted by various theories extending the standard model [9]. Unfortunately, the three-body final state in o-Ps decay ($2\gamma + X^0$) would greatly complicate a direct X^0 search. A simpler and perhaps equivalent procedure is to search for the X^0 in direct positron-electron (e^+e^-) annihilation. The usual decay $e^+ + e^- \to 2\gamma$ could have a competing exotic decay mode, $e^+ + e^- \to \gamma + X^0$, at about the same 10^{-3} branching ratio as the λ_T discrepancy. At this level, such a new particle and its effects may have escaped detection even in the high-energy pion and kaon experiments designed to search for a particle with the same quantum numbers as the X^0 [10].

We assume here that the Feynman diagram for the direct annihilation into X^0 is shown in Fig. 1(a). The photon line is directly attached to the X^0-e vertex in order to avoid the inconsistencies with other precision experiments (e.g., e^- $g - 2$) that would result from a simple X^0-e vertex [Fig. 1(b)]. The X^0 contribution to o-Ps decay is thus assumed to be as in Fig. 1(c) where there is one extra normal electromagnetic e-γ vertex compared to Fig. 1(a).

If the e^+ and e^- velocities are low at annihilation, the direct process $e^+e^- \to \gamma + X^0$ yields a back-to-back, momentum-conserving final-state pair in the laboratory frame. For β decay e^+ in metals, about 97% thermalize before annihilating to 2γ. The lab γ-ray energy can then be related to the X^0 rest mass m:

$$E_\gamma = m_e \left[1 - \left(\frac{m}{2m_e}\right)^2\right]. \qquad (1)$$

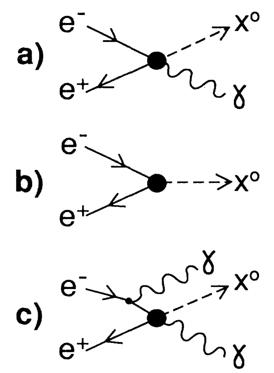

FIG. 1. In (a), the X^0 and γ are created at one vertex, avoiding consistency problems inherent in process (b). In (c), the decay o-Ps$\rightarrow 2\gamma + X^0$ is depicted.

The experimental apparatus is shown schematically in Fig. 2. We use a high-resolution [1.88 keV full width at half maximum (FWHM) at 1332 keV], 28% efficiency (64 mm $\times$ 52 mm diameter), Ge γ-ray detector to search for the single photon decay manifested as a peak between 0 and 511 keV in the energy spectrum. The e^+ are supplied by a $\approx 1\mu$Ci ^{68}Ge source contained between 6.4 mm and 0.004 mm Al alloy pieces. A 2.66 keV FWHM peak is observed at 511 keV, indicative of the well-known Doppler broadening from motion of the annihilation electron, an effect that also applies to X^0 production.

The major source of background noise in this experiment is the normal process $e^+e^- \rightarrow 2\gamma$. A 511 keV γ ray interacting in the Ge detector has about a 70% probability of incomplete energy deposition. Thus, the entire energy spectrum from 0 to 511 keV is contaminated with both a continuum and a peak from 2γ decays. To reduce the 2γ background, a 10.2 cm $\times$ 10.2 cm diameter NaI detector is placed on the opposite side of the source (thin Al piece toward the NaI) from the Ge detector as shown in Fig. 2. Back-to-back 2γ events are "vetoed" by rejecting all events in the Ge detector that have a coincident signal in the NaI detector. The assumption being made is that the X^0 is long-lived, noninteracting, and goes through the NaI. Singles counting rates are 2.8 kHz and 8.5 kHz for the Ge and NaI detectors, respectively.

Figure 3 presents the Ge energy spectra with the NaI veto requirement and in the singles mode. Much of the

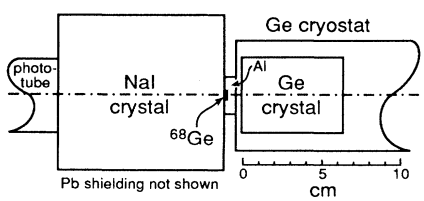

FIG. 2. Experimental apparatus. Positrons from a ^{68}Ge source directly annihilate in metallic Al. The Ge detector searches for single photon decays manifested as a peak in the energy spectrum. The NaI detector acts as a veto to reduce noise, rejecting Ge events that have a coincident γ ray interacting with the NaI.

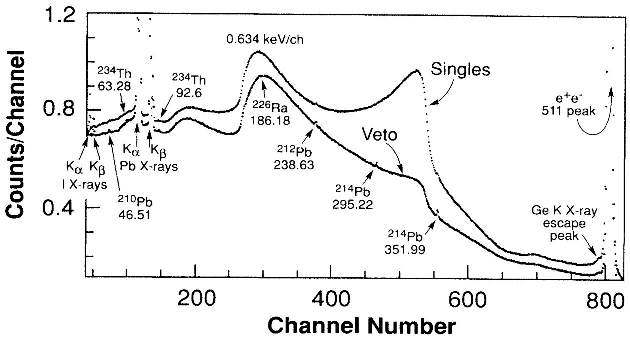

FIG. 3. Ge energy spectra. Portions of the Ge γ-ray energy spectra are displayed, with both veto and singles spectra shown for comparison. The peak energies are given in keV, labeled γ-ray peaks (except 511 keV) are due to ambient background, the x rays are from fluorescence, veto inefficiency gives the 511 peak. Over 300 h of live-time acquisition were required to obtain these spectra. The vertical scale is in units of millions of counts.

veto spectrum is explained by inefficiencies in the veto process, permitting the recording of normal 511 keV γ rays that interact in the Ge detector. The difference in shapes between the two compton distributions shown in Fig. 3 can be understood as follows: 511 keV γ rays that enter the Ge detector and backscatter (i.e., the reemitted compton γ ray goes toward the NaI) can activate the veto, reducing the relative size of the compton edge in the veto spectrum. With lower energies deposited in the Ge crystal ($\leq$ 200 keV), the reemitted compton γ ray when escaping the Ge misses the NaI detector.

Accounting for all the peaks in the veto spectrum of Fig. 3 allows us to set limits on the X^0 over a wide mass range. These 1σ limits on the branching ratio $\eta_2 \equiv R_{\gamma X}/R_{\gamma\gamma}$ are displayed in Fig. 4 as a function of the X^0 rest mass. In any model, η_2 may be related to

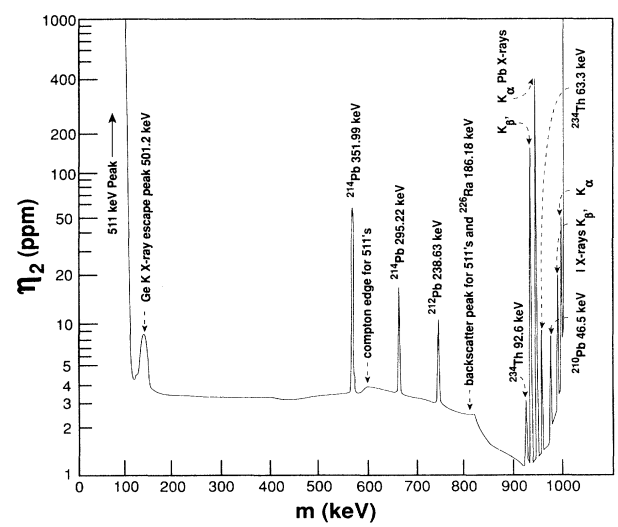

FIG. 4. Limits on the X^0. Upper limits (1σ) on the decay branch with an X^0 are plotted as a function of X^0 mass, m. The direct limits from the present experiment are shown.

the branching ratio in o-Ps, $\eta_3 \equiv R_{\gamma\gamma x}/R_{\gamma\gamma\gamma}$, depending on m. Neglecting differences in the momentum dependence of the matrix elements and considering only the available final-state phase space, $\eta_2 \approx \eta_3$ for $m \ll 2m_e$ and $\eta_2 > \eta_3$ as $m \to 2m_e$. Thus, the limits on η_2 can be roughly interpreted as η_3 limits; these limits extend over almost the entire mass range from 100 keV to 1 MeV. The loss in sensitivity below $m = 100$ keV is due to the presence of the 511 keV photopeak in the vetoed spectrum and inaccuracies in our knowledge of the actual veto efficiency.

As discussed earlier, an axion search in the decay of orthopositronium [4] sets limits at the 1 ppm level. This experiment places no direct limit on the X^0 since o-Ps$(^3S_1) \to \gamma + X^0$ is precluded by C conservation. However, 3% of the delayed annihilations were due to "pick-off" of electrons from collisions which, since the positron and electron are not in a relative $^3S_1$ state, can annihilate to 2 γ rays or to $\gamma + X^0$. Thus the axion limits can be interpreted as $\eta_2 < 40$ ppm over the mass range m: $0 - 800$ keV. Combining the results of our experiment with those deduced from Ref. [4], 40 ppm or better limits are placed over the mass range m: 0–930 keV for both X_S^0 and X_V^0, with the best limits over most of the mass range coming from our experiment.

Other experiments that involve annihilation from $^1S_0$ states can also be interpreted to place limits upon η_2 for only a vector X_V^0. The decay of a singlet state $(^1S_0) \to \gamma + X_S^0$ is precluded by momentum and angular momentum conservation. In a recent result [11], the decay rate of the singlet ground state [parapositronium (p-PS)] derived from a magnetic mixing experiment is found to be in agreement with theory at the 215 ppm level. This result implies a 215 ppm 1σ upper limit on an X_V^0 branch, independent of its mass. In another axion search [12] 50% of the orthopositronium was quenched to 2 γ's. The 2γ component was presumably due to the presence of one atmosphere of air (in particular, 21% O_2) in the experiment. The paramagnetic O_2 provides spin exchange in collisions which converts o-Ps$(^3S_1)$ to p-Ps$(^1S_0)$. Limits on a vector X_V^0 similar to ours in Fig. 4 can be obtained from interpretation of this measurement. Finally, limits on a *short-lived* $X^0(\tau \leq 1$ ns) were derived from existing measurements [13]. From C conservation, the most plausible decay mode for the X^0 is into three photons. A recent experiment [13] measures the branching ratio (BR) for low-energy e^+e^- direct annihilation into four photons, BR = 1.48(18) ppm, in excellent agreement with the QED theoretical calculation. The agreement between theory and experiment precludes $e^+e^- \to \gamma + X^0 \to 4\gamma$, a short-lived X^0 contributing to e^+e^- direct annihilation. The authors of [13] quote a 3.3×10^{-7} branching ratio limit with 90% confidence for a short-lived X^0 in the mass range between 200 and 900 keV.

Limits on η_2 could also be derived by relating (as shown in the Feynman diagrams, Fig. 5) the production process

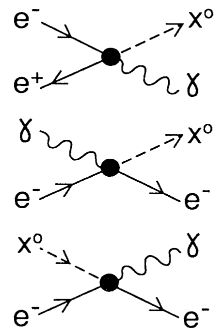

FIG. 5. X^0 interactions. Direct e^+e^- annihiliation to $\gamma + X^0$ is related to compton-scattering-like diagrams involving $X^0 \leftrightarrow \gamma$.

$e^+e^- \to \gamma + X^0$ to the compton-scattering-like process

$$\gamma + e^- \leftrightarrow e^- + X^0. \tag{2}$$

The presence of this latter process shows that the X^0 would not be totally noninteracting as assumed above. For example, limits can be placed by considering γ rays from an intense source scattering via Eq. (2) with the arrow taken in the forward direction, followed by propagation of the resulting X^0 through a large amount of shielding to the attenuate the γ-ray flux, and interaction of the X^0 in a standard γ-ray detector via the inverse process in Eq. (2), see Fig. 5 bottom. This second-order process could place better limits at low X^0 masses than those considered above, however, these limits will be highly model dependent. We are pursuing several experiments along these lines.

In conclusion, the experimental branching ratio limits on the η_2 presented in this paper are quite precise (a few ppm) over most of the allowed X^0 mass range above 100 keV. The λ_T discrepancy between theory and the averaged vacuum and gas experiments would correspond to $\eta_{3\text{ave}} = (1650 \pm 150)$ ppm. The results for η_2 presented in Fig. 4 are sufficiently below $\eta_{3\text{ave}}$ to preclude exotic decay branches involving massive (0.1–1 MeV), $C = -1$ bosons from explaining the orthopositronium decay rate discrepancy. In addition, by interpreting results from previous experiments, the excluded X^0 mass range has been extended to include 0 to 100 keV, and the possibility of a short-lived X^0 has been excluded. The assumption of a noninteracting X^0 will be quantitatively discussed in a forthcoming publication.

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