Search for very weakly interacting, short-lived, *C*-odd bosons and the orthopositronium decay rate problem

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The discrepancy between theory and experiment for the orthopositronium (o-Ps) decay rate could be resolved by an exotic decay branch o-Ps$\rightarrow X^0\gamma\gamma$, where X^0 is a low-mass C-odd boson. An experimental search for X^0 is reported in which Compton-like interactions with electrons or decay γ rays ($X^0\rightarrow 3\gamma$) could be detected. None are observed and sensitive, but model-dependent limits are set (for two specific models). One model, testable by this method, allows the good agreement between theory and experiment for the parapositronium decay rate to be reconciled with the disagreement for the o-Ps decay rate. [S1050-2947(97)03402-1]

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Precision experimental tests of theoretical predictions from quantum electrodynamics (QED) have yielded uniformly reasonable agreement between theory and experiment with one notable exception. Two recent measurements [1,2] of the vacuum decay rate ($\lambda_T = 1/\tau_t$) of ground-state, triplet positronium ($S=1$, termed orthopositronium or o-Ps) are in mutual agreement and when combined differ from the theoretical prediction [3] by more than ten standard deviations ($>10\sigma$). The QED theoretical value for λ_T, calculated through relative order $\alpha^2\ln\alpha$ radiative corrections [3], is $\lambda_T^{\rm th} = 7.03830 \pm 0.000\,07\ \mu s^{-1}$ ($\tau_t = 142.08$ ns). The first experiment [1] uses o-Ps formed in gases at a variety of densities. The vacuum decay rate was determined by extrapolating to zero density yielding $\lambda_T = 7.0514 \pm 0.0014\ \mu\mathrm{s}^{-1}$ (200 ppm uncertainty). The disagreement with theory is 9.4σ.

The second experiment [2] uses the systematically different, vacuum technique. The o-Ps is formed from a slow positron beam (<1 keV) incident on a fumed MgO surface. The o-Ps is contained in an evacuated cavity with minimal perturbation from the fumed MgO walls. The result, $\lambda_T^{\rm vac} = 7.0482 \pm 0.0016\ \mu\mathrm{s}^{-1}$ (230 ppm uncertainty), agrees reasonably well with the previous gas experiment [1] and disagrees with theory by 6.2σ.

Another recent decay rate experiment [4] uses magnetic mixing to perform a measurement of the singlet state, parapositronium decay rate (λ_S). The λ_S result, obtained in gases, agrees at the 215 ppm level with the QED theoretical prediction for λ_S calculated through the same order of radiative corrections as λ_T. A byproduct of the λ_S experiment [4] is another independent λ_T measurement (both decay rates are fitted simultaneously) that agrees with the two previous λ_T measurements at the 300 ppm level.

Very recently, another method for measuring λ_T has been introduced [5] that uses fine-grained SiO_2 powder as the o-Ps formation medium. The measurement relies upon an energy spectroscopic technique to correct for a roughly 1% shift in λ_T due to o-Ps collisions with the powder grains. The quoted result, $\lambda_T = 7.0398 \pm 0.0029$ (414 ppm uncertainty) differs by 3.6σ and 2.5σ from [1] and [2], respectively, and agrees with theory. We note that this experiment has not been systematically tested at the same level of precision as [1,2]. Furthermore, the conjecture in [5] that both [1,2] suffer from a common uncompensated systematic shift in λ_T due to a possible time dependent 2γ decay rate as the o-Ps slows down to thermal energies, had already been refuted. In fact, [6] used the same technique as [5] uses for its 1% subtraction to test the very apparatus of [2] for anomalous 2γ events. None were found. Thus the decay rate discrepancy remains unresolved.

As pointed out in [2], if the λ_T discrepancy is attributed to the uncalculated, order $(\alpha/\pi)^2$ radiative correction term, then this term would have a large coefficient (250 ± 40). Recent theoretical calculations [7] on portions of the order $(\alpha/\pi)^2$ corrections to λ_T have been completed. Some have yielded partial coefficients as large as 50, but it appears that 250 ± 40 should be considered to be anomalously large until the complete order α^2 calculation is finished.

Another explanation has been proposed to resolve the λ_T discrepancy. Since the measured decay rates are greater than theory, a forbidden or exotic decay branch of o-Ps, not included in the QED calculation of o-Ps $\rightarrow 3\gamma$, could be causing the discrepancy [8,9]. The investigated decay branches include: (1) o-Ps $\rightarrow \gamma + A^0$, where A^0 is a neutral pseudoscalar; (2) o-Ps $\rightarrow 2\gamma$, forbidden by angular momentum conservation; (3) o-Ps $\rightarrow 4\gamma$, forbidden by charge conjugation (C) conservation; (4) o-Ps $\rightarrow$ ''nothing,'' i.e., decay to undetected products; (5) o-Ps $\rightarrow 1\gamma$, forbidden by momentum conservation [6]. The limits set by these experiments exclude all these mechanisms as explanations of the λ_T discrepancy.

Recently, we proposed another exotic decay branch involving a light, neutral, C-odd boson: o-Ps $\rightarrow 2\gamma + X^0$($\eta_3 \equiv R_{\gamma\gamma X}/R_{\gamma\gamma\gamma}$) [8]. The axion searches discussed above do not directly test for the X^0 since o-Ps $\rightarrow \gamma + X^0$ is forbidden by C conservation [$C(o-Ps) = C(\gamma) = C(X^0) = -1$, $C(A^0) = +1$]. The properties of the X^0 were specifically chosen to avoid exclusion by any of the above experiments. We reported an experimental search for evidence of this X^0 [8] using low energy e^+e^- direct annihilation, $e^+e^- \rightarrow \gamma + X^0$. That experiment set limits at a few ppm on the $\gamma + X^0$ branching ratio (compared to 2γ, $\eta_2 \equiv R_{\gamma X}/R_{\gamma\gamma}$) over the range of X^0 masses 100 keV to 1 MeV under the assumption that the X^0 is both long lived and noninteracting. This article experimentally addresses the

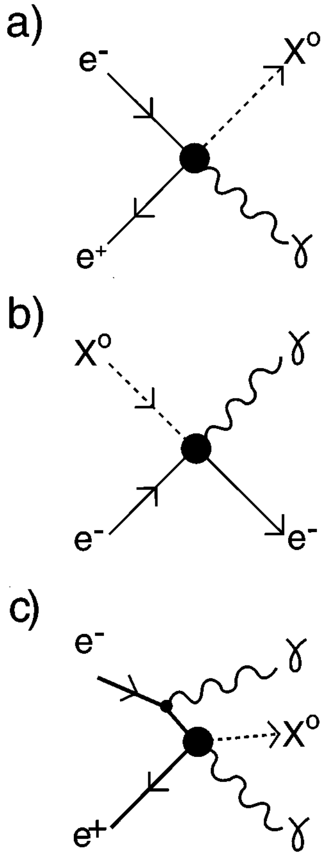

FIG. 1. X^0 interactions. In (a), the X^0 participates in e^+e^- direct annihilations occurring in the source region in this experiment. Rotating (a) to form (b) implies the X^0 interacts with electrons in a process similar to Compton scattering, experimentally occurring in a Ge detector. In (c), the λ_T discrepancy is assumed to be due to an exotic decay branch involving the X^0 as in (a) with a conventional electromagnetic photon coupling in addition.

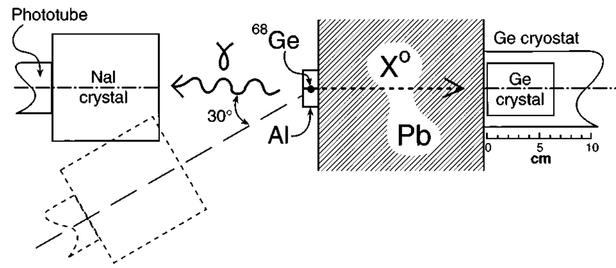

FIG. 2. Experimental apparatus. A penetrating X^0, produced by e^+ from the ^{68}Ge source ($e^+e^- \rightarrow \gamma + X^0$), reaches the Ge detector and infrequently interacts with it. The accompanying γ ray is detected in the NaI crystal. The dashed line at 30° indicates the background run position of the NaI detector.

lifetime and interactions of the X^0 and presents the first direct limits on an X^0 with a mass under 100 keV.

In order to avoid inconsistencies with other experiments (e.g., electron $g-2$) we assume that there is no direct interaction of the X^0 with electrons as shown in Fig. 1(b) of [8]. However, the existence of the decay $e^+e^- \rightarrow \gamma + X^0$ [Fig. 1(a)] would dictate that the X^0 *will* interact at least weakly with matter [8], as shown in the related Feynman diagrams in Figs. 1(a) and 1(b). The similarity of Fig. 1(b) to Compton scattering ($\eta_c \equiv R_{X\gamma}/R_{\gamma\gamma}$) implies that a normal Ge detector has a very small, but nonzero, efficiency for measuring the total energy of an X^0. Nevertheless, this X^0 will still have a high probability for traversing significant amounts of shielding, 15 cm of Pb in this experiment (see Fig. 2). The shielding is used to absorb the 511 keV γ rays from normal 2γ final states of direct e^+e^- annihilation. The λ_T discrepancy is attributed to an X^0 contribution to o-Ps decay as shown in Fig. 1(c).

The apparatus depicted in Fig. 2 employs a 10.2 cm $\times$10.2 cm diameter NaI γ-ray detector to tag annihilation events including possible $\gamma + X^0$ events. From momentum conservation the X^0 would be emitted toward the Ge detector (Ge crystal size 6.4 cm $\times$5.2 cm diam). Since the goal is to search for a light X^0($<$100 keV), the accompanying γ-ray energy will be in the range 506.1–511.0 keV (see Eq. (1) in Ref. [8]) and the NaI energy acceptance window is set at 511 $\pm$ 50 keV. We search for a signal in the Ge detector in the energy range 511.0$\pm$4.4 keV in fast timing coincidence (window $\sim$ 30 ns) with that of the NaI detector. (Later in this article, we discuss the energy window above 511 keV in the Ge spectrum.) The source is $\sim$50 μCi of ^{68}Ge electroplated on Ni foil. The ^{68}Ge is sandwiched between two pieces of Al alloy, each 6.4 mm thick.

When the 15 cm of Pb is in place, we calculate an attenuation for 511 keV γ rays to about 10^{-11}. To check this calculation, we repeated the procedure with a ^{60}Co source. Because of the higher energies of the ^{60}Co γ rays (1173 and 1332 keV), a measurable flux penetrates the Pb shield. Experimental ratios of rates, with and without the Pb, agreed with those predicted within a factor of two. We conclude that the 15 cm Pb shield is thick enough to reduce the transmitted 511 keV γ-ray flux to a negligible level.

The apparatus is calibrated by counting with the 15 cm Pb shield removed from between the source and Ge detector. A rate of 1700 {850} Hz is observed for 511 keV photopeak events in the Ge detector in coincidence with the NaI full energy deposition events. (The numbers in curly brackets indicate results from a repetition of this experiment with a less intense source.) During calibration, either of the two γ rays can be detected in each detector, hence the annihilation rate of 850 {425} Hz (half the detected event rate) is taken for normalizing the process $e^+e^- \rightarrow \gamma + X^0$, in which the single γ ray can only be detected in the NaI.

With the Pb in place, the observed ''signal'' rate is $107 \pm 16\{88 \pm 21\}\mu$Hz with, we assert, accidental coincidences dominating the event rate. To verify this assertion, two types of background runs are performed. First, the fast-timing window is moved by 105 ns out of coincidence. A rate of $132 \pm 21\{83 \pm 34\}\mu$Hz is observed for this configuration, confirming that accidental coincidences are dominating the rates. A second type of background run involves leaving the timing in coincidence, but moving the NaI detector. In the initial configuration, the NaI, source, and Ge are collinear to search for back-to-back decay products. Moving the NaI by 30° with respect to the former collinear line (see Fig. 2), the back-to-back criterion is removed. A rate of $105 \pm 25\{82 \pm 31\}$ μHz is observed in this ''momentum-violating'' second type of background run.

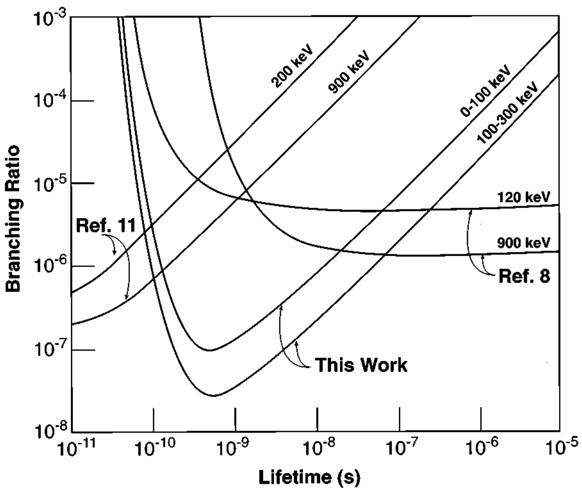

FIG. 3. Limits on a short-lived X^0. On the vertical axis, branching ratio limits (1σ) on $e^+e^- \rightarrow \gamma + X^0$ compared to $e^+e^- \rightarrow 2\gamma$ are displayed as a function of the X^0 lifetime on the horizontal axis. The limits come from experiments described in Refs. [8] and [11] and in this paper. Two curves are shown for each experiment demonstrating the weak dependencies on the labeled X^0 rest mass. The excluded regions are in the upper part of the graph.

Averaging the two types of background runs, and reducing the error since they are independent, yields $121 \pm 16\{82 \pm 23\}$ μHz. Subtracting this from the signal, we obtain $-14 \pm 22\{6 \pm 31\}$ μHz as the value for the rate of X^0 production in the source combined with detection in the Ge crystal. Dividing the X^0 production-and-detection rate by the 850 {425} Hz no-Pb rate and correcting for the change in the Ge photopeak fraction between the X^0 and a 511 keV γ ray, the result is equated to $\eta_2 \eta_c$ [recall $\eta_2 \equiv R_{\gamma X}/R_{\gamma\gamma}$ for Fig. 1(a), production, and $\eta_c \equiv R_{X\gamma}/R_{\gamma\gamma}$ for Fig. 1(b), detection]. The inferred limit, averaging the two runs, is $\sqrt{\eta_2 \eta_c} < 100$ ppm.

If we assume that $\sqrt{\eta_2 \eta_c}$ is approximately η_3 (recall for o-Ps, $\eta_3 \equiv R_{\gamma\gamma X}/R_{\gamma\gamma\gamma}$), this 100 ppm result excludes the possibility that a low mass X^0 is causing the λ_T discrepancy in the gas [1] and vacuum [2] experiments, which would require $\eta_{\mathrm{ave}} = (1650 \pm 150)$ ppm, differing by 9.2σ from our current observation. Within the theory presented here and in Ref. [8], a direct experimental test has been performed to search for light (0–100 keV), C-odd bosons from e^+e^- direct annihilation. The results of this test demonstrate that these bosons cannot be causing the λ_T discrepancy. As pointed out in [8], indirect limits on C-odd bosons can also be inferred from the work of Asai *et al.* [10]. By considering the so-called ''pick-off'' process (a process related to direct annihilation) affecting the decay rate of o-Ps in their experiment, 40 ppm limits can be obtained on the C-odd boson branch. These indirect 40 ppm limits corroborate our direct 100 ppm limits derived above.

Finally, we address the experimental assumption [8] of a long lifetime for the X^0. Since it is a C-odd boson, the most natural decay mode for the X^0 is into three photons, each of which is also C odd. If the X^0 could decay quickly into 3γ, then a four photon measurement [11] by Adachi *et al.* has experimental sensitivity to the direct annihilation process $e^+e^- \rightarrow \gamma + X^0$, followed by $X^0 \rightarrow 3\gamma$. A limit of 3.3×10^{-7} at 90% confidence is quoted by Adachi *et al.* for the branching ratio $e^+e^- \rightarrow \gamma + X^0$ compared to 2γ decay if 200 keV $< M_{X^0} <$ 900 keV. In Fig. 3, these limits are displayed as a function of the X^0 lifetime τ. The Adachi *et al.* experiment loses sensitivity at longer lifetimes because the velocity (v) of the X^0 carries it out of view of the detectors if $v\tau \gtrsim 1$ cm for the X^0 [11].

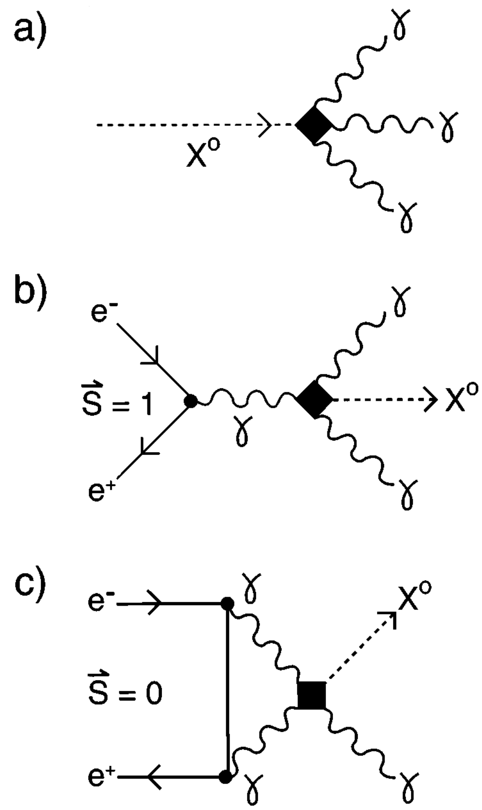

FIG. 4. The 3γ decay of the X^0. Another possible fundamental vertex for the X^0 is depicted in (a). This model differs significantly from Fig. 1. The λ_T discrepancy, due to a branch shown in (b), is expected to be fractionally much larger than any λ_S discrepancy arising from (c), based on counting powers of α.

The limits on a short-lived X^0 from the Adachi *et al.* study complement those that can be obtained from Ref. [8], also indicated in Fig. 3. In the latter study, the X^0 must survive for at least roughly 1 ns to distance the 3γ decay site from the ''veto'' detector (a 10 cm thick NaI crystal). A shorter-lived X^0 decaying in or around the veto detector, so as to trigger it, would not yield a recorded event [8].

For the experiment described in this paper, there would be sensitivity to the 3γ decay of a light, short-lived X^0, if the X^0 were to decay in or just in front of the Ge detector (see Fig. 2). This measurement would require that the total energy of the 3γ be deposited in the Ge detector. A reanalysis has been performed of the experimental results presented and analyzed earlier in the context of Fig. 1. The new analysis assumes the Ge detector signals are due to a short-lived $X^0 \rightarrow 3\gamma$ decay with the 3γ absorbed in the Ge rather than the Compton-like process shown in Fig. 1(b). As before, a correction is applied for the Ge photopeak efficiency for 3γ. The results of the new analysis in the mass range $0 < M_{X^0} < 100$ keV are also shown in Fig. 3, where over a certain range of lifetimes (roughly $10^{-10}-10^{-7}$ s) the best limits come from the present experiment.

Also displayed in Fig. 3 are limits in the mass range 100 keV $< M_{X^0} < 300$ keV. These limits arise from the same Ge coincidence spectra described earlier but with the analysis repeated in the energy region just above 511 keV. For large X^0 mass, significantly more energy is deposited in the Ge (X^0) detector than in the NaI(γ) detector. With $M_{X^0}=300$ keV, the recoiling γ-ray energy is 467 keV, still sufficient to occasionally trigger the NaI detector. After the background subtraction, no peaks or excess events were observed in the Ge coincidence spectra immediately above the 511 keV peak, thereby yielding the limits shown in Fig. 3.

If the process $X^0 \rightarrow 3\gamma$ is taken as the more fundamental vertex [see Fig. 4(a), note this differs significantly from Fig. 1], then a prediction, based on the λ_T discrepancy, can be made for where the X^0 should appear on Fig. 3. Triplet and singlet annihilations involving the X^0 are depicted in Figs. 4(b) and 4(c), respectively. By requiring the (1650 ± 150) ppm λ_T discrepancy to be totally due to Fig. 4(b), a branching ratio for singlet annihilation [Fig. 4(c)] of about 10^{-7} to 10^{-8} is indicated by crudely counting powers of α. A precise calculation of the branching ratio, including all phase space factors, etc., is beyond the scope of this paper. The crude prediction of 10^{-7} to 10^{-8} branching is not well tested by the best limits shown in Fig. 3 [12]. The diagrams in Fig. 4 could also provide a consistent explanation of the agreement with QED theory for the recent λ_S measurement [4] and the disagreement of the three λ_T measurements [1,2,4] with the same theory. Again, simply counting powers of α in Figs. 4(b) and 4(c) would predict a much smaller fractional discrepancy for λ_S compared to that for λ_T, roughly 10^4 to 10^5 smaller.

In conclusion, we have performed a direct experimental search for exotic decays involving light, C-odd bosons contributing to e^+e^- annihilation. A C-odd boson decay branch causing the λ_T discrepancy is arguably the last in a long list of possible exotic decay branches. All decays of the type $n\gamma$ ($n=0,1,2,4,5$) have been excluded as the cause of the λ_T discrepancy, and the particle decays (A^0 and X^0) encompass all the quantum numbers of the o-Ps system. Our C-odd boson results can be compared to the λ_T discrepancy, but not in a model-independent fashion. If we assume that the Ge detector responds to an interaction of the form of Fig. 1(b), exotic C-odd bosons of any mass cannot be causing the λ_T discrepancy. However, if Fig. 4 is the correct description of X^0 interactions, then the λ_T discrepancy could be due to Fig. 4(b) and the limits shown in Fig. 3 are not quite sensitive enough to reveal the C-odd boson. We are pursuing further experiments along these lines.

Note added in proof. Recently, another search [13] for the X^0 from low energy e^+e^- annihilation, similar in design to [8], yielded the limit of 2×10^{-6} for X^0 masses in the range zero to 200 keV, improving on our limits (see Fig. 3) for $\tau > 35$ ns.

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