Search for *CPT*-Odd Decays of Positronium

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(Received 11 July 2003; published 23 December 2003)

We have limited a *CPT*-violating correlation in annihilations of polarized ortho-positronium. We searched for an asymmetry in the triple correlation $\vec{s} \cdot (\vec{k}_1 \times \vec{k}_2)$, where $\vec{k}_1$ and $\vec{k}_2$ are the two largest photon momenta, and $\vec{s}$ is the spin of the positronium. Using the Gammasphere array of Compton-suppressed high-purity germanium detectors, we detected 2.65×10^7 events of ortho-Ps annihilation. The amplitude of a *CPT*-violating asymmetry in the data set is found to be 0.0026 ± 0.0031, a factor of 6 smaller than previous experiments.

DOI: 10.1103/PhysRevLett.91.263401 PACS numbers: 36.10.Dr, 11.30.Er, 24.80.+y

Positronium (Ps), the bound state of an electron and a positron, is an eigenstate of the charge conjugation operator (C), and as in other atoms, states of Ps are parity eigenstates. Because its states are nominally eigenstates of the CP operator (unlike stable atomic systems which are just P eigenstates), the Ps atom allows tests of the combined symmetry CPT in decay correlations, analogous to tests of T symmetry in other systems (e.g., in beta decay). Ps has been recognized as a useful system for tests of the discrete fundamental symmetries C, P, and T [1]. Although the standard model respects CPT, some extensions to the standard model (such as string theory) contain nonlocal interactions which violate CPT symmetry or Lorentz invariance. CPT-odd observables have been suggested as experimental signatures of new physics [2]. A theoretical framework for describing CPT or Lorentz violating effects was suggested in Refs. [2,3]. This formalism obtains parameters for an effective QED-like model as a limit to a generalized standard model extension. Recent low-energy searches for CPT or Lorentz violating observables focus on comparative matter/antimatter properties and high precision QED tests. Reference [4] pointed out that few predictions of the effective QED model for scattering or decay processes have been tested. There was one search for Lorentz invariance violation in (o-Ps $\rightarrow 3\gamma$), motivated by the ortho-positronium lifetime puzzle [5]. Theoretical implications of the CPT-odd triple correlation $\vec{s} \cdot (\vec{k}_1 \times \vec{k}_2)$ for polarized positronium were suggested in Ref. [1], which also pointed out that CP violating phases in neutrino mixing (currently an active area of speculation) would result in no observable CPT-odd triple correlation of o-Ps decay, if this were the sole source of CP violation beyond the standard model. Two experiments [6,7] have searched for this triple correlation. There has been one high-energy search for a similar observable in Z^0 decays [8]. A reappraisal for o-Ps within the new effective QED formalism seems desirable, and interest in CPT violating theories motivated the experiment described here.

The CP-even but T-odd decay signature for o-Ps considered here, $\vec{s} \cdot (\vec{k}_1 \times \vec{k}_2)$, was suggested in Refs. [1,9]. o-Ps annihilates mainly to three coplanar photons, which can be labeled γ_1, γ_2, and γ_3 in order of decreasing energy. The quantity $(\vec{k}_1 \times \vec{k}_2)$ formed from the two ordered largest photon momenta defines a vector normal to the decay plane. A nonzero CPT-odd correlation would give rise to an up/down asymmetry of this plane with respect to the initial spin direction. Previous experiments have limited this correlation to about 2% [6,7] by searching for an up-down asymmetry in planar arrays of NaI gamma-ray detectors as the o-Ps spin direction is reversed. These experiments measured $A = (N_{\rm up} - N_{\rm down})/(N_{\rm up} + N_{\rm down})$ by detecting two of the three annihilation gamma rays. If the average polarization of the o-Ps in the experiment is $\langle P \rangle$, then the amplitude of the angular correlation between spin and decay plane (C) is related to the observed count asymmetry by $C = A/\langle P \rangle$. The detector geometry of these experiments determines the sensitivity to the triple correlation. The present experiment used a 4π array of high-purity germanium detectors. In our case, all three annihilation photons γ_1, γ_2, and γ_3 are detected, and the decay plane can be reconstructed to calculate its orientation with respect to the initial spin axis. Because any of the detectors in the array can detect any of the three photons, this experiment is less sensitive than previous experiments to geometric asymmetries of the counter arrangement, or asymmetries in detector efficiencies.

The experiment was performed using the Gammasphere array at the 88" Cyclotron at Lawrence Berkeley National Laboratory [10]. Gammasphere consists of 110 Compton-suppressed high-purity germanium detectors surrounding an 18 cm radius target chamber. The positronium source, data acquisition electronics, and trigger were similar to a previous experiment using unpolarized positronium [11]. Polarized ortho-positronium was produced using 10 μCi sources of ^{68}Ge and ^{22}Na. Both sources were composed of activity deposited on thin (1 mg/cm^2) kapton foil, covered with adhesive and a second kapton foil. The source was placed 1 mm below a thin (0.2 mm) plastic scintillator and a hemisphere of silicon dioxide aerogel. The aerogel acts as a moderator to slow the positrons and as a medium for forming ortho-Ps. Two different aerogels were used, with density 0.1 g/cm^3 for the ^{22}Na source and 0.3 g/cm^3 for the ^{68}Ge. Each hemisphere had a diameter of 58 mm. Different densities were used to match the range of the β decay positrons to produce similar distributions of o-Ps in the gels. Positrons from β decay are polarized along their momentum with $\vec{P} = +\vec{v}/c$. Upward directed and polarized positrons deposit roughly 70 keV of energy in the thin scintillator. Scintillation light was piped to a photomultiplier tube (PMT) (Hamamatsu R1450), and the PMT pulse was used as a trigger for the Gammasphere electronics as in Ref. [11]. Downward-going positrons (with the opposite polarization) from the source are stopped in the aluminum target chamber and cannot form ortho-Ps. The probability that downward-going positrons backscatter from the target backing is small (less than 3%), and the probability that positrons striking the target chamber scatter back into the scintillator and aerogel is negligible ($<10^{-3}$). The average polarization can be estimated from the average velocity of the positrons emitted in the β decays. For ^{22}Na, $\langle P\rangle = \langle v\rangle/c \approx 67\%$, while for ^{68}Ga, $\langle P\rangle \approx 90\%$. There is a $\approx 1\%$ correction to these values because low-energy positrons are stopped by the scintillator and do not form o-Ps. The positrons are somewhat depolarized by multiple scattering as they stop in the aerogel. This reduces the average polarization of the population of slowed positrons which form positronium. Such effects have been measured and simulated in Ref. [12]. Based on the simulations presented in [12], the net depolarization of the positrons from ^{68}Ge is 17% and 8% for ^{22}Na as they stop in the scintillator and aerogel. The polarization of the ortho-positronium formed is (from statistics) simply 2/3 times the average slow positron polarization [6]. The magnitude of the source polarization is reduced by accepting all upward positrons in a solid angle of $\approx 2\pi$, but this effect is accounted for in the data analysis. The experiment's sensitivity to a CPT-odd asymmetry was calculated using a Monte Carlo simulation which allowed initial Ps polarizations in all directions which could be formed in the source. The positronium polarization used in the analysis is $\langle P\rangle = 0.41$ for the ^{22}Na source and $\langle P\rangle = 0.50$ for the ^{68}Ge source. A true asymmetry signal should scale slightly differently for the two o-Ps sources.

The o-Ps decay planes have a CPT-allowed distribution with respect to the spin direction. The o-Ps decay rate (Γ) as a function of the angle θ between spin and decay plane is [9]

$$\frac{d\Gamma}{d\theta} \propto \frac{1}{2}(3 - \cos^2\theta). \qquad (1)$$

In principle, this distribution of decay planes is detectable in Gammasphere. However, the source geometry accepts upward directed positrons with polar angles with respect to the aerogel hemisphere axis of up to $\theta_{max} = 83°$. The term proportional to $(\cos^2\theta)$ in the phase space distribution of Eq. (1) averages nearly to zero when averaged over positron emission angles up to θ_{max}, resulting in a nearly isotropic annihilation pattern.

The source was inserted into the target chamber of Gammasphere through an access port located at $(\theta, \phi) = (63.4°, 180.0°)$ with respect to the beam line axis of the array. The source could be rotated in Gammasphere, and four different positions were used to guard against any artificial asymmetry. The different Ps spin orientations are denoted 0°, 90°, 180°, 270°, corresponding to a rotation angle of the source about a great circle of the detector array. During the experiment, several detector modules were missing from the array in the beam-forward direction (a common configuration for other Gammasphere experiments). According to the Monte Carlo simulations, even this large asymmetry caused by six missing Ge detectors in one portion of the array causes no large asymmetry in the CPT-odd signature at the level of the statistical uncertainty of the simulations, $C \approx 0.002$.

As in Ref. [11], the experiment used a two level trigger to detect Ps decay events. The trigger selected events with hits in three or more Gammasphere detector modules (in which the Compton-suppressing bismuth germanate detectors did not fire) and a hit in the positron detector, all occurring within a 1 μs timing window. A time to amplitude converter (TAC) for each Ge detector records the time between the beta detector PMT pulse and the Gammasphere detector hits. The timing resolution and the time-coincidence condition was determined in the same manner as in Ref. [11]. The events satisfying the trigger condition were written to tape for off-line analysis. The energy deposited, the TAC output, and a detector identifier are recorded for each hit. The 36 d run had a live time of 2.65×10^6 s. Approximately 3.98×10^9 events were written to tape. Of these, 2.65×10^7 passed cuts to qualify as (o-Ps $\rightarrow 3\gamma$) annihilation events. Statistics for seven runs with the two different o-Ps sources and different spin directions in Gammasphere are summarized in Table I. The cuts applied to the data to select valid (o-Ps $\rightarrow 3\gamma$) events were essentially the same as those in experiment [11]. Three-photon events must have a correct energy sum (1022.0 ± 5.0 keV), a low momentum sum ($|\sum \vec{p}\,| < 150$ keV$/c$), coincident photon arrival times, no colinear detector modules, and a coplanar event geometry. The coplanar condition selects against o-Ps decays occurring outside the aerogel volume, rejecting any decay events from scattered positrons with incorrect polarization which form o-Ps elsewhere in the source chamber. The o-Ps population is further identified as events with mean times greater than 9 ns after the initial scintillator detector trigger. $2.8\% \pm 1.4\%$ of the events in the data are caused by (P-Ps $\rightarrow 2\gamma$) decays in which a photon scatters. Monte Carlo simulations of such scattered events suggest that they result in an approximately isotropic distribution of false decay planes ($C_3 = +0.01 \pm 0.02$), resulting in a negligible correction to the final asymmetry measurements.

TABLE I. Statistics for data runs with two isotopes and different angular orientations in Gammasphere of the Ps source. The last column lists the number of counts in each run passing cuts (described in text) to qualify as (o-Ps $\rightarrow 3\gamma$) annihilation events.

Run	Source	Angle	(o-Ps $\rightarrow 3\gamma$) events
1	^{22}Na	0	825 167
2	^{22}Na	180	1 060 628
3	^{22}Na	90	335 167
4	^{68}Ge	0	3 093 038
5	^{68}Ge	180	3 544 346
6	^{68}Ge	90	3 948 792
7	^{68}Ge	270	1 766 862

For each valid (o-Ps $\rightarrow 3\gamma$) event, the triple product was calculated with three different weightings suggested in Ref. [1]:

$$\vec{s} \cdot (\vec{k}_1 \times \vec{k}_2) W_i(\vec{k}_1, \vec{k}_2). \tag{2}$$

$W_i(\vec{k}_1, \vec{k}_2)$ is a weighting factor for the decay plane normal vector which depends on the photons' momenta:

$$W_1 = 1/|\vec{k}_1 \times \vec{k}_2|, \tag{3}$$

$$W_2 = 1/(|\vec{k}_1||\vec{k}_2|), \tag{4}$$

$$W_3 = 1. \tag{5}$$

In the absence of a specific model for a CPT-violating correlation, the choice of the weighting function is arbitrary.

The histogram of the correlation $\vec{s} \cdot (\vec{k}_1 \times \vec{k}_2) W_3$ is shown in Fig. 1 for one of the seven data runs, compared to the asymmetric annihilation radiation pattern predicted from the Monte Carlo simulations for an artificial CPT-odd correlation with $C_3 = 1$. The antisymmetric part of each data histogram about $\theta = 0$ was calcluated:

$$A(\theta) = \frac{N(\theta) - N(-\theta)}{N(\theta) + N(-\theta)}, \tag{6}$$

where $N(\theta)$ is the number of counts in the bin for $\theta = \cos^{-1}[\vec{s} \cdot (\vec{k}_1 \times \vec{k}_2) W_i(\vec{k}_1, \vec{k}_2)]$. This procedure generated a series of measurements of $(N_{\mathrm{up}} - N_{\mathrm{down}})/(N_{\mathrm{up}} + N_{\mathrm{down}})$ for all possible orientations θ of the decay plane.

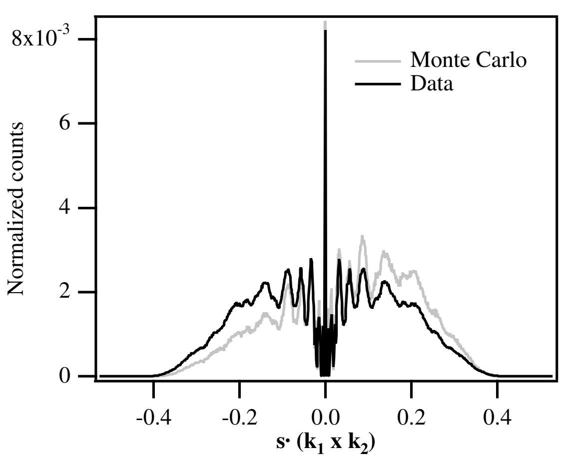

FIG. 1. Data histogram of $\vec{s} \cdot (\vec{k}_1 \times \vec{k}_2) W_3(\vec{k}_1, \vec{k}_2)$ for events from run 7 (see Table I), compared to a Monte Carlo generated histogram which includes a CPT-odd correlation of amplitude $C_3 = 1$. The peak features are caused by the angular arrangement of the Gammasphere detectors in a regular array.

The asymmetry as a function of θ in the data was then compared to a Monte Carlo generated simulation of a CPT-odd signal. This step accounted for the sensitivity of the Gammasphere array to any CPT-odd signal, given the source and detector geometry. The Gammasphere simulation software [13] (based on GEANT 3.2) includes active (detector) and passive materials in Gammasphere (including nonfunctioning or missing detectors), the Ps source geometry and composition, detector energy thresholds, and resolution. Simulated three-photon annihilation events were generated using a recursive algorithm which produces two correlated angles (in a plane) between two of the three photons, weighted by the kinematic phase space of the (o-Ps $\rightarrow 3\gamma$) decay. The decay plane was then oriented with respect to an inital spin direction of the positron (which was averaged over all positron momenta accepted by the source geometry). The decay plane orientation can include an isotropic distribution, a CPT-odd antisymetric ($\cos\theta$) term, and a CPT-even term proportional to $\cos^2\theta$, separated from Eq. (1). Separate Monte Carlo histograms were generated for each angular orientation ($0°, 90°, 180°, 270°$) of the source in the detector array. The randomized annihilation vertex position was generated from range calculations of the beta-decay positrons in aerogel. Simulated data events were subjected to cuts identical to the real data. Histograms of the triple correlations $\vec{s} \cdot (\vec{k}_1 \times \vec{k}_2) W_i$ were generated from the Monte Carlo events with an initial CPT-odd distribution of decay planes. These histograms act as the templates for comparison with the data to search for a CPT-odd signature.

To extract the asymmetry amplitude from the data, we calculated $A(\theta)_{\mathrm{data}}/A(\theta)_{\mathrm{Monte\ Carlo}}$, the ratio of the odd part of the data about $\theta = 0$ to the odd part of the simulated data (generated with CPT-odd asymmetry $C_i = 1$). This ratio was then averaged over all angles θ to derive an asymmetry average for each data set. These averages were divided by the o-Ps polarization to arrive at C_1, C_2, and C_3: $C_i = A_i/\langle P \rangle$. The CPT-odd asymmetry amplitudes C_1 are shown for each of the seven data sets in Fig. 2. The measured asymmetries for each of the three weightings, averaged over all seven data sets, are summarized in Table II.

Past searches for the CPT-odd signal were susceptible to displacements of the source when the spin direction was reversed, causing a false count rate asymmetry. In the experiment of Arbic *et al.* [6], this effect limited the final result to an asymmetry amplitude of about 2.0%. In

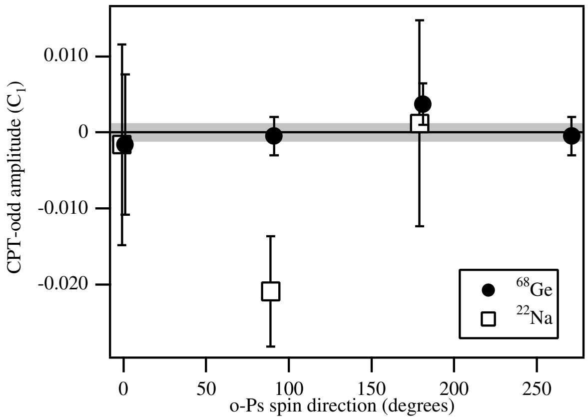

FIG. 2. Asymmetry averages (C_1) for each of the seven data sets in Table I.

Gammasphere, because any detector can detect any of the three photons, geometric asymmetries are greatly suppressed. It is possible to detect events with decay planes ($\vec{k}_1 \times \vec{k}_2$) in any orientation with respect to the spin rather than merely parallel or antiparallel, as in previous experiments. A true CPT-odd asymmetry would have a distribution of the decay planes with respect to the spin proportional to $\cos\theta$. The angular segmentation and matched detector characteristics limit the sensitivity to false signals, since no detector mismatches are likely to produce a simple, robust $\cos\theta$ distribution of detected three-photon events. Tests of displacements of the Ps source in Gammasphere were performed to estimate false CPT-odd signals. Monte Carlo data with the Ps source displaced by 1 cm from the center of Gammasphere were compared to Monte Carlo data with no displacement and to the real data. Tests of angular displacements of the source of 2° (equivalent to misidentifying the inital o-Ps polarization direction) were also performed. The resulting Monte Carlo data had no resolved CPT-odd asymmetry greater than $C_3 \approx 0.002$.

To estimate the polarization of the o-Ps sample, the observed decay correlation histograms $\vec{s} \cdot (\vec{k}_1 \times \vec{k}_2) W_3$ of ^{22}Na data were subtracted from ^{68}Ge data. This should isolate the $\cos^2\theta$ part of the normal plane distribution from Eq. (1), which is proportional to the o-Ps polarization. The amplitude of this artificial "purely polarized sample" histogram is consistent with the Monte Carlo generated distribution which includes the polarizations of the ^{22}Na and ^{68}Ge positrons as above. The uncertainty in $\theta_{\max} = (83 \pm 5)°$ produces a 30% uncertainty in this polarization measurement. There is no particular reason to doubt the calculated values of the o-Ps polarization, and uncertainty from the o-Ps polarization is not included in the CPT-odd correlation coefficients C_i, since they are dominated by statistical uncertainty. The results for C_2 in Table II represent an improvement over the previous measurements [6,7] of the CPT-odd decay correlation. Both of these experiments calculated limits for the correlation amplitude C_2, and the results for C_1 and C_3 represent a more substantial improvement in a limit to a potential CPT-violating decay asymmetry.

TABLE II. Amplitudes of the measured correlation amplitudes C_i for each weighting $W_i(\vec{k}_1, \vec{k}_2)$, averaged over several spin orientations.

	C_1	C_2	C_3
^{22}Na	−0.0132(57)	−0.0006(92)	0.0004(57)
^{68}Ge	0.0008(15)	0.0134(83)	0.0038(30)
Both	−0.0001(14)	0.0071(62)	0.0026(31)
Ref. [6]	···	0.0200(230)	···
Ref. [7]	···	0.0140(190)	···

A. O. Macchiavelli, R. Clark, P. Fallon, and D. Ward helped with Gammasphere data acquisition and experiment design. E. Norman prepared the ^{22}Na source. Ocellus Corp. provided the aerogels. This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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