First Test of *CP* Invariance in the Decay of Positronium

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The 3γ decay of spin-aligned triplet positronium (Ps) is used for a test of *CP* invariance (charge conjugation and parity). This is the first use of the Ps atom to investigate the *CP* symmetry. The angular correlation $(\hat{\mathbf{S}}\cdot\hat{\mathbf{k}}_1)(\hat{\mathbf{S}}\cdot\hat{\mathbf{k}}_1\times\hat{\mathbf{k}}_2)$ was measured, where $\mathbf{S}$ is the Ps spin and $|\mathbf{k}_1|>|\mathbf{k}_2|>|\mathbf{k}_3|$ are the γ momenta. If this correlation has a nonzero amplitude, *CP* is not conserved. No amplitude was found at the 1.5% level of uncertainty.

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There is still no single theoretical model, after one quarter century of speculation [1], that resolves the origin of *CP* violation (charge conjugation and parity) in neutral kaons [2]. Partly, this is because, in spite of numerous experiments using other particles and systems [3,4], the phenomenon of *CP* nonconservation has been observed, thus far, only in the K^0-$\bar{K}^0$ system. Observation of *CP* violation in other particle systems would be very important for identifying the *CP*-violating mechanism.

In this Letter, we present the first results from a new type of experiment, in a previously unused system, positronium (Ps), for investigating *CP* nonconservation [5]. All currently viable theories of *CP* violation would predict very small effects in the Ps system [6]. The theoretical focus is naturally on the strongly interacting neutral-kaon system. Great uncertainty still exists on the real, underlying phenomena responsible for *CP* violation and how they would effect a purely leptonic system (Ps) [6].

In our new experiment, we are investigating the *CP*-violating angular correlation [7,8]

$$C_{CP}(\hat{\mathbf{S}}\cdot\hat{\mathbf{k}}_1)(\hat{\mathbf{S}}\cdot\hat{\mathbf{k}}_1\times\hat{\mathbf{k}}_2)\,, \quad (1)$$

where C_{CP} is the amplitude (related to *CP* nonconservation), $\mathbf{S}$ is the spin of the triplet Ps atom, and $\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3$ are the momenta of the three annihilation γ rays, with

$$|\mathbf{k}_1|>|\mathbf{k}_2|>|\mathbf{k}_3|\,. \quad (2)$$

Our experiment is similar to a previous study [7] by Arbic *et al.* Arbic *et al.* searched for a *CPT*-violating (*T* denotes time reversal) angular correlation in the decay of spin-polarized triplet Ps. Previous β-decay investigations have used several different *T*-violating (hence also *CP*-violating) angular correlations [9].

The discrete symmetry properties of Eq. (1) can be seen as follows (see also Arbic *et al.*). All five vectors in Eq. (1) change sign under the time-reversal (*T*) operation, and hence it is *T* odd (i.e., if the angular correlation is present, then *T* is violated). The angular correlation in Eq. (1) is also *P* odd, since there are three vectors, the momenta, that change sign under the *P* (parity) operation; $\mathbf{S}$, being an axial vector, does not change sign under *P*. Since the decay of triplet Ps ($C=-1$) into three γ rays (each with $C=-1$) conserves *C* (charge conjugation), we conclude that the correlation in Eq. (1) is *CP* odd and *T* odd and not necessarily *CPT* violating. Hence, if we find a nonzero amplitude C_{CP} for the angular correlation in Eq. (1), it would be a clear signal of *CP* violation in Ps decay. Notice that radiative corrections and final-state interactions which could mimic a *CP* violation in this case are very small (2×10^{-10}) since there are no charged particles in the final state (see, e.g., Refs. [7] and [8] and references therein).

Since the $\hat{\mathbf{S}}$ appears twice in Eq. (1) (in antisymmetric combination, see Ref. [8]) we do not require a simple vector polarization, as in Arbic *et al.*, but rather a particular tensor polarization or alignment, P_2:

$$P_2=\sum_{m=0,\pm1}N_m(3m^2-2)\Big/\sum N_m\,, \quad (3)$$

where N_m are the populations of triplet Ps atoms with $m_s=0,\pm1$. We note that one can have alignment without (vector) polarization and vice versa.

Our experimental design (see Fig. 1) uses rare-earth (Nd-Fe-B) permanent-magnet disks [10] and iron flux returns to generate a magnetic field of approximately 4 kG to perturb the Ps spin states [11], thereby creating the required spin alignment. With no external $\mathbf{B}$ field, Ps is formed in four states: one singlet ($\mathbf{S}=0$, $m_s=0$, $\tau=0.12$ ns) and three triplet ($\mathbf{S}=1$, $m_s=0,\pm1$, $\tau=142$ ns) states. An external $\mathbf{B}$ field will perturb and mix the two $m=0$ Ps states. This mixing gives rise to two new states, the perturbed singlet and perturbed triplet. The $m=\pm1$ states are not affected by the field.

Experimentally, we separate these various Ps states on the basis of their differing lifetimes in the applied external $\mathbf{B}$ field. The unperturbed, $m=\pm1$ states, still have a vacuum lifetime $\tau=142$ ns. The field-perturbed, $m=0$ triplet state has a new lifetime $\tau\cong30$ ns in our experimental configuration [12]. By observing the time-resolved decay spectrum of Ps and using the difference in lifetimes to separate the various states, according to Eq. (3) we obtain a selectable alignment whose magnitude depends on the annihilation delay time from Ps formation.

A 10-μCi ^{68}Ge source, electroplated on Ni foil, supplies the positrons (e^+). Ps formation takes place when

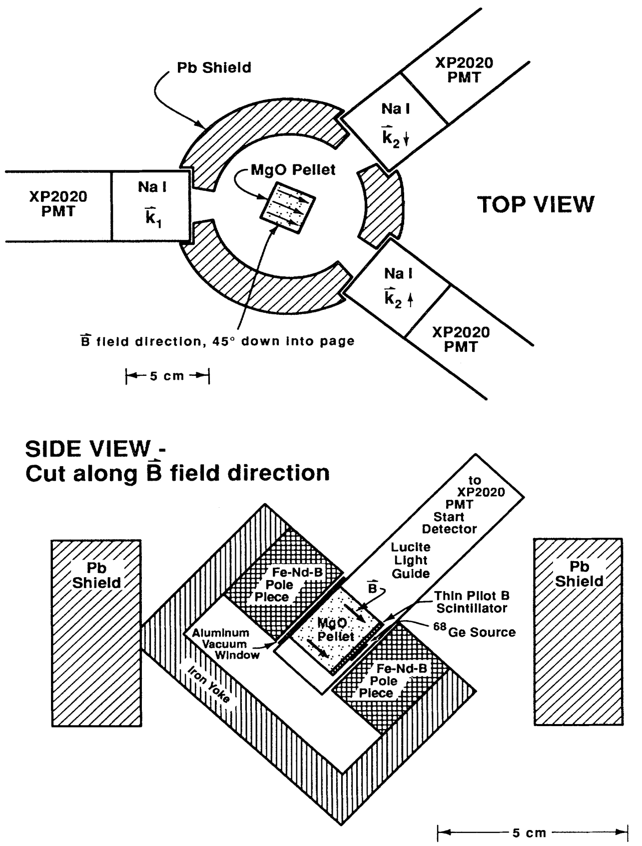

FIG. 1. Experimental apparatus. Spin-aligned Ps is formed in MgO powder from ^{68}Ge e^+ in the presence of a magnetic field. Annihilation γ rays are detected using three NaI scintillators.

the e^+ stop in an evacuated, compressed pellet of fine-grained MgO powder. Between the MgO and the ^{68}Ge is a thin (0.5 mm) plastic scintillator coupled to an Amperex XP-2020 photomultiplier tube that provides a timing signal (detected rate $R=10^5$ Hz) to denote an e^+ arrival. The magnetic field has about $\pm 10\%$ uniformity over the volume of the MgO. The observed unperturbed and perturbed triplet lifetimes are 125 and 30 ns, respectively, in accordance with expectations [11].

The annihilation radiations are observed in three 5.08 cm$\times$5.08 cm diam NaI crystals, each coupled to a magnetically shielded Amperex XP-2020 photomultiplier tube. The NaI detectors are mounted in a Pb shield that surrounds the magnet assembly and Ps source. The three NaI detectors are coplanar with two detectors symmetrically placed at $\pm 145°$ from the third detector (see Fig. 1). The direction of the normal to the decay plane ($\hat{\mathbf{k}}_1 \times \hat{\mathbf{k}}_2$) is at 45° from the magnetic-field direction. The angle between $\hat{\mathbf{k}}_1$ and the magnetic field is about 55°. Holes in the Pb shield are shaped in a manner which permits the NaI detectors to view the Ps decay region, with a solid angle for each of $\sim 2\%$ of 4π sr, while minimizing the effects of γ-ray Compton scattering near the edges of the NaI crystals. The average energy resolution of the NaI detectors is 9.5% FWHM at 511 keV; the average rate is about 7 kHz. The time resolution for 511-511 coincidences between two NaI detectors is 3.9 ns (FWHM).

A standard fast-slow NIM electronics system is used to select decay events according to a number of criteria. The symmetrically placed pair of NaI crystals detects γ-ray energies in the range of 300–390 keV, defining the direction $\hat{\mathbf{k}}_2$ used in Eq. (1). The remaining NaI crystal is set to the energy range 410–480 keV, defining the $\hat{\mathbf{k}}_1$ direction. A fast-timing coincidence between the $\hat{\mathbf{k}}_1$ detector and one of the $\hat{\mathbf{k}}_2$ detectors is also required, along with the energy cuts, to trigger the recording of a decay event. The recorded quantity is the lifetime spectrum of the Ps atoms, as measured by a standard time-to-amplitude-converter–multichannel-analyzer (TAC-MCA) system started with the plastic-scintillator signal and stopped by one of the NaI detectors (the $\hat{\mathbf{k}}_1$ detector). Two such lifetime spectra are alternately acquired first for one $\hat{\mathbf{k}}_2$ detector and then flipping to the other $\hat{\mathbf{k}}_2$ detector. This flip has the effect of reversing the decay-plane normal ($\hat{\mathbf{k}}_1 \times \hat{\mathbf{k}}_2$) and is essential for canceling out systematic effects and electronic drifts. The $\hat{\mathbf{k}}_2$ reversal is performed 1000 times per day and is controlled by the programmable MCA (Tracor-Northern 1710) that also analyzes and stores the TAC signals.

Two Ps lifetime spectra ($\hat{\mathbf{k}}_1 \times \hat{\mathbf{k}}_2$ up and $\hat{\mathbf{k}}_1 \times \hat{\mathbf{k}}_2$ down) are thus built up over the course of about one-half day when the running is stopped, the data recorded, detector gains monitored and adjusted, and a new run started. We analyze these spectra by forming asymmetries using the background-corrected number of counts in two time windows. The first time window is from 10.3 to 64.6 ns after Ps formation. A large fraction of the counts in this window is due to decays of perturbed Ps ($m=0$), and from Eq. (3), the $m=0$ states contribute negative alignment. The second time window is from 65 to 270 ns after Ps formation; here the majority of counts is due to unperturbed Ps ($m=\pm 1$) decay, and Eq. (3) yields positive alignment. Acquiring the data in this fashion gives a reversal of the Ps spin alignment on the average at one-half the data rate or about an average of 4 s between flips. Again, as with the $\hat{\mathbf{k}}_2$ flip, the alignment reversal is used to cancel out systematic effects and drifts. Two asymmetries, A_u and A_p are formed for the unperturbed and perturbed windows, respectively, according to the relation

$$A=\frac{N^+-N^-}{N^++N^-}, \tag{4}$$

where N is the number of counts in the window corrected for random background and the + and − superscripts indicate the reversal of the decay-plane normal. The difference in the asymmetries for the perturbed and unperturbed Ps windows,

$$\bar{A}=(A_u-A_p)/2\,, \tag{5}$$

gives a systematic-free [13] and drift-free result at our present level of sensitivity.

Three other flips (reversals) are also used in our experiment, to check for unknown systematic effects. First, periodically, the two NaI detectors that are used to define $\hat{\mathbf{k}}_2$ are physically interchanged in order to average out any differences in their resolution, efficiency, etc. As another flip, the direction of the magnetic field was reversed by physically turning over the permanent-magnet pole caps. The final flip was to turn over the Pb shield surrounding the magnet. This inversion has the effect of moving the $\hat{\mathbf{k}}_1$ detector from one side of the magnet yoke to the other side (see Fig. 1). All of these tests are summarized in Table I. The first entry in Table I differs from zero by two standard deviations; the other three entries are all less than one standard deviation from zero. A χ^2 analysis of these four values gives 37% probability for a data set to have scatter from the mean greater than the scatter observed in our four measurements. Therefore, we consider the single, two-standard-deviation run to be a normal, statistical fluctuation in the data.

The measured asymmetries for each of the four tests in Table I have been averaged together to get a final asymmetry:

$$A_{\rm stat}=-0.0004\pm0.0010\,. \tag{6}$$

The quoted error in this result is due to counting statistics only. The data used to obtain $A_{\rm stat}$ show a χ^2 distribution from the mean for 63 runs of 61.9 for 62 degrees of freedom, again indicating a nominally statistical distribution of the data.

Our calculations show that all known systematic effects in the present apparatus are negligible at the current level of statistical uncertainty [Eq. (6)]. Table II summarizes the expected systematic effects that could influence the final asymmetry. Clearly, a large number of other possible systematic effects are eliminated by the system of flips and reversals. Notable exceptions are the uncertainties introduced by the correction for accidental, random background events and diffusion of the Ps atoms during their lifetime in the MgO pellet [14], both quantified in Table II. Correcting Eq. (6) for these effects gives a final asymmetry:

$$A_{\rm final}=-0.0004\pm0.0011\,. \tag{7}$$

Several calculations, supplemented by experimental tests, were done to determine the relation between the measured asymmetry [Eq. (7)] and the coefficient of the angular correlation C_{CP} [Eq. (1)]. We define an analyzing power $S_{\rm an}$ that relates asymmetry and correlation coefficients:

$$S_{\rm an}=A/C_{CP}\,. \tag{8}$$

To determine $S_{\rm an}$, one test measured the occurrence of two back-to-back 511-keV annihilation photons (from, e.g., collisional quenching of unperturbed triplet Ps or magnetic quenching of perturbed triplet Ps) mimicking a true 3γ triplet event. If one of the 511-keV γ rays Compton scatters and deposits only part of its energy in the scintillator that is set for 300–390 keV ($\hat{\mathbf{k}}_2$), this event could pass the energy cuts. It was determined that 3.8% of the events in the unperturbed-Ps time window were due to 2γ events, while the percentage was 12.8% for the perturbed Ps with a corresponding dilution of the alignment in these windows. Additional factors that enter in $S_{\rm an}$ include (i) finite solid angle of the NaI detectors (0.96), (ii) finite size of the Ps source (roughly uniform distribution over the volume of the MgO pellet, 0.97), (iii) uniformity of the **B** field over the MgO pellet (0.998), (iv) spin alignment of the Ps including the 2γ dilution (0.37), (v) the average angles between the magnetic-field axis ($\hat{\mathbf{S}}$) and the directions $\hat{\mathbf{k}}_1$ (55°) and $\hat{\mathbf{k}}_1\times\hat{\mathbf{k}}_2$ (45°) and between $\hat{\mathbf{k}}_1$ and $\hat{\mathbf{k}}_2$ (145°), (vi) stability and degree of overlap in the energy windows for the γ rays (0.9), and (vii) the γ-ray directional angular correlation from the $m=0,\pm1$ states of triplet Ps (0.995) [15]. Various tests and calculations have been performed to quantify these factors. Putting all these effects together, the final result for the analyzing power is

$$S_{\rm an}=0.072\pm0.015\,. \tag{9}$$

Combining this analyzing power with the final result for the asymmetry [Eq. (7)], we obtain the angular correlation coefficient

$$C_{CP}=-0.0056\pm0.0154\,. \tag{10}$$

This final result contains both statistical and systematic uncertainties and is consistent with *CP* invariance.

It could be argued that our present experimental uncertainty of 1.5×10^{-2} is insufficient to observe a *CP*-

TABLE I. Measured asymmetries under differing conditions.

Test Conditions	Asymmetry A
Initial configuration	-0.0040 ± 0.0020
Interchanged $\hat{\mathbf{k}}_2$ detectors	-0.0002 ± 0.0019
Reversed **B**	$+0.0011\pm0.0020$
Inverted Pb shield	$+0.0022\pm0.0024$
Wt. average	-0.0004 ± 0.0011

TABLE II. Systematic effects on A.

Systematic	Effect on A
Background correction	±0.0004
Ps diffusion	±0.0001

violating effect that in neutral kaons is characterized by $\eta = 2.3 \times 10^{-3}$. However, it cannot be said that one result would preclude the other in a model-independent manner [16]. In fact, as discussed in the introduction, the real mechanism behind *CP* violation is still unclear, and may give results in the Ps system which are larger than the neutral-kaon results. For example, if the origin of *CP* violation lies in the leptonic sector rather than the hadronic, as usually assumed, then a Ps experiment might observe a large *CP*-violating effect.

We are planning to pursue the experiment described in this paper with a new apparatus. When designing the scale-up of the present experiment, our principal concern has been the possibility of a shadowing systematic (unobserved as yet, but conceivably a relatively large percentage of our current uncertainty) due to the proximity of the magnet pole pieces. Since the pole pieces are dense enough to act as effective γ-ray shielding between the Ps source (the MgO pellet) and the NaI γ-ray detectors, each detector is effectively viewing somewhat different parts of the MgO pellet, with other parts shadowed. An iron NMR electromagnet with 12-in.-diam pole pieces has been used in our laboratory for Ps lifetime studies [17]. A 23.5-cm-wide gap gives a maximum field at the center of the gap of 4.5 kG, which we calculate is the optimum magnetic field for this angular correlation experiment. The increased field volume eliminates concern over the shadowing systematic [18]. With the use of this magnet and other straightforward improvements, such as the use of more γ detectors, we anticipate an order of magnitude increase in the sensitivity of our experiment. These results would be numerically competitive with neutral-kaon *CP* violation.

In conclusion, we have performed the first test of *CP* invariance using Ps. This test is based on a *CP*-violating and *T*-violating angular correlation in the decay of polarized Ps. Our results indicate no *CP* violation at the level of 1.5% uncertainty in the angular correlation coefficient. The straightforward improvements, some of which are discussed above, should yield an experimental limit on the coefficient below the 0.1% level.

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