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Angular-correlation test of *CPT* in polarized positronium

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Polarized triplet positronium, formed in the ground state with a polarized slow-e^+ beam, is used for an experimental test of *CPT* (charge-conjugation–parity–time-reversal) invariance. The angular correlation $\hat{\mathbf{S}}\cdot\hat{\mathbf{k}}_1\times\hat{\mathbf{k}}_2$ was measured (where $\mathbf{S}$ is the positronium spin angular momentum and $|\mathbf{k}_1|>|\mathbf{k}_2|>|\mathbf{k}_3|$ are the momenta of the three decay γ rays). It is expected to have zero amplitude if *CPT* is conserved. No effect was found in the experiment at the 2.3% level of uncertainty in the coefficient of the angular correlation. Information gained from a study of the systematic effects, along with straightforward improvements in the apparatus, would allow a 0.1% measurement. Other possible angular correlations using polarized and aligned positronium, including tests of *CP* invariance, are discussed.

I. INTRODUCTION

Since the prediction[1] and discovery[2] of parity violation in 1956 and 1957, investigations of discrete symmetries have assumed an important role in physics. Along with the parity-inversion (*P*) tests just mentioned, charge-conjugation (*C*) and time-reversal (*T*) tests have presented many interesting and sometimes unresolved problems. These tests[3,4] can investigate the discrete symmetries either individually or in various combinations such as *CP* or *CPT*; the latter being the topic of this paper.

The invariance of *CPT* is the subject of an important theorem in quantum field theory. First proved over thirty years ago by Bell,[5] the theorem simply states that *CPT* is a good symmetry for *all* spin-0, -$\frac{1}{2}$, and -1 field theories. The assumptions required to prove the *CPT* theorem are all quite fundamental: locality, as well as Lorentz invariance of the field theory. Any observed violations of *CPT* invariance would have profound consequences for modern theoretical particle physics.

All previous experimental tests of *CPT* invariance have been concerned with the equality of various properties between a particle and its antiparticle.[4,6] These properties include the masses of the particles, the decay lifetimes, and the magnetic moments (g factors).[4] Some very precise and important tests include the comparison of the g factors of the electron and positron and also of the muon and antimuon. Another important *CPT* test is in the system of neutral kaons where a mass difference between K^0 and $\bar{K}^0$ would lead to a difference in the phases (ϕ_{+-} and ϕ_{00}) of the *CP*-violating parameters η_{+-} and η_{00} for K_L^0 decay.[7] Present measurements[8] of this effect show a two-standard-deviation *CPT*-violating signal: $\phi_{+-}-\phi_{00}=(12.6\pm6.2)^\circ$.

Our experiment is concerned with an angular correlation in the 3γ decay of spin-polarized positronium (Ps) as a test of *CPT* invariance.[9] This is the first direct search for *CPT* violation with angular correlations; it is also the first explicit use of polarized triplet ($S=1$) Ps. Although there have been many studies[10,11] using polarized positrons (e^+) from β decay to form Ps, in fact, all these previous investigations have measured only the asymmetry of formation rates into the various Ps substates (ground-state singlet and triplet). No explicit use was made of the fact that the triplet Ps is itself polarized.

We employ polarized triplet Ps in the ground state to measure a particular angular correlation of its annihilation radiation, as first suggested by Bernreuther and Nachtmann.[12] This angular correlation is

$$\hat{\mathbf{S}}\cdot\hat{\mathbf{k}}_1\times\hat{\mathbf{k}}_2\ , \tag{1}$$

where $\mathbf{S}$ is the Ps spin and $\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3$ are the momenta of the three annihilation γ rays in the decay of triplet Ps, with the requirement

$$|\mathbf{k}_1|>|\mathbf{k}_2|>|\mathbf{k}_3|\ . \tag{2}$$

Notice that the quantity $\hat{\mathbf{k}}_1\times\hat{\mathbf{k}}_2$, which appears in Eq. (1), defines a normal to the decay plane of the three γ rays. Hence, Eq. (1) can be simply thought of as a correlation between the spin and the decay plane.

The *CPT* properties of Eq. (1) can be seen as follows. The angular correlation shown in Eq. (1) contains three vectors all of which change sign under the *T* operation;[13] hence it is *T* odd (i.e., if the angular correlation is present, then *T* is violated.) Equation (1) is *P* even since only the two momenta change signs under *P*; $\mathbf{S}$ being an axial vector does not change sign under *P*. This therefore renders Eq. (1) as P even (i.e., if the angular correlation is present, then P may or may not be violated.) Finally, triplet Ps ($^3S_1$) is an eigenstate of C with an eigenvalue[14] of -1. Also, the photon has $C=-1$. Therefore, in the 3γ Ps($^3S_1$) decay C is conserved, which allows us to conclude that the angular correlation is C even.[15] Combining these results gives an overall *CPT*-violating sensitivity for the term shown in Eq. (1).

There are two restrictions on using Eq. (1) as a *CPT* test. First, there are normal electromagnetic interactions among the particles in the final state that can mimic the *CPT*-violating signal. This effect, in the absence of unknown interactions, will be shown later in this paper to be very small. Second, an interaction that causes an anomalous mixing of Ps states could also mimic a *CPT* violation. Such an interaction would be *CP* violating and quite interesting in its own right.

II. THE EXPERIMENT

The Ps needed for our *CPT* test is produced using a "slow"-e^+ beam as shown[11] in Fig. 1. High-energy ($\approx$200 keV) "fast" e^+ are obtained from a ^{22}Na source and thermalize in a tungsten vane moderator.[11] About 1 in 10^3 of all e^+ diffuse to the surface, where they are expelled by the negative work function into the vacuum with an energy of order 2 eV. These slow e^+ are then accelerated and focused to form a beam.

The experiment depicted in Fig. 1 measures the polarization of the slow-e^+ beam.[11] The e^+ from the source are initially longitudinally polarized ($\mathcal{P}_L=\beta=v/c$) due to parity violation in nuclear β decay. This initial polarization is, by and large, retained in the moderation process.[11] A low-Z, 30-mg/cm^2 absorber placed between the source and moderator reduces the beam intensity by a factor of 4 while increasing the beam polarization. The spin rotator shown in Fig. 1 is a Wien filter that allows the periodic reversal of the slow-e^+ spin during the experiments. The slow-e^+ polarization measurement is based on Ps formation in a magnetic field.[11,16] The result of the measurement for our beam and the source used in the *CPT* experiment is

$$\mathcal{P}_{e^+}=0.39\pm0.02 \ . \tag{3}$$

This polarization was selected by choosing the absorber thickness to maximize $\mathcal{P}^2 I$ (the standard quality factor), where I is the e^+ beam intensity.[17] For the angular-correlation experiment described next, the intensity is $I\cong 10^5\ e^+$/sec.

In the *CPT*-invariance experiment, the e^+ polarimeter was removed from the slow-e^+ beam. A 50-G magnetic guiding field directed the slow-e^+ beam at 450 eV into the Ps confinement cavity shown in Fig. 2. The beam enters through a 5-mm-diameter hole in one end of the Ps confinement cavity. At the other end, the beam strikes an MgO-fumed CEMA detector (channel electron multiplier array),[18] which performs three functions: First, the CEMA provides a timing signal derived from secondary electrons to mark the arrival of an e^+. Second, in conjunction with a phosphor screen,[19] the CEMA permits viewing and analysis of the spatial distribution of the e^+ beam when striking the CEMA front surface. Finally, Ps is formed on the CEMA surface with an efficiency of 27% and is emitted into the vacuum in the cavity where it is reflected by the MgO lining when striking the walls. It is estimated that approximately five wall collisions occur during one Ps lifetime.[20] A lack of spin-exchange quenching during the wall collisions has been observed in previous experiments,[11,21] indicating that if Ps is polarized when it is formed, it will remain polarized when confined in the cavity. The formation of polarized Ps occurs when the initial e^+ are polarized, even if the e^- are unpolarized. The degree of triplet Ps polarization is calculated (see Appendix) to be

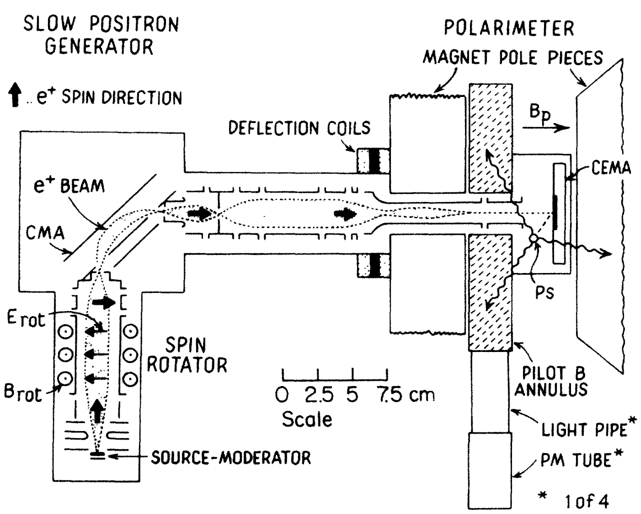

FIG. 1. Polarized slow-e^+ beam. Polarized positrons from a radioactive source are moderated to about 2 eV. A slow-e^+ beam is formed by accelerating and focusing the 2-eV positrons. Spin reversals are performed by a Wien-filter spin rotator. The slow-e^+ beam is then focused into a positron polarimeter after being bent by a cylindrical mirror analyzer (CMA).

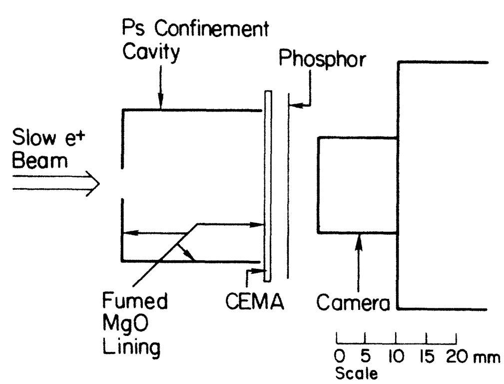

FIG. 2. Ps confinement cavity. The slow-e^+ beam enters the cavity through a hole on the left and strikes the CEMA on the right where Ps is formed and diffuses into the cavity. The MgO lining prevents the Ps from quenching during collisions with the walls. The camera, phosphor, and a computer digitization system permit viewing and analysis of the shape and position of the slow-e^+ beam. Video images are digitized and stored in an IBM-PC computer for later analysis.

$$\mathcal{P}_{Ps}=\tfrac{2}{3}\mathcal{P}_{e^+} \quad (4)$$

when there are no large external magnetic fields greater than ~ 1 kG. The 50-G field in our experiment changes this relationship by less than 10^{-3}

Three NaI detectors, 5.08 cm diameter $\times$ 5.08-cm crystals coupled to Amperex XP-2020 photomultiplier tubes, are arranged outside the vacuum pipe which surrounds the Ps cavity, as shown in Fig. 3. The Pb shielding improves the peak-to-Compton ratio in the NaI detectors. The holes in the shield permit each detector a solid angle of about 2.5% of 4π sr. Standard fast-slow electronics is used to process the NaI detector outputs. Fast timing signals select coincident γ events in two (one on the left and either one on the right in Fig. 3) of the NaI detectors. The time resolution is 4 ns full width at half maximum (FWHM). The slow energy signals further require one scintillator to detect the highest-energy γ ray (400–500 keV) while the other detector must detect the second highest-energy γ ray (300–400 keV). The lowest-energy γ ray (<300 keV) is not observed. The average energy resolution ($\Delta E/E$) for our NaI detectors is about 11% at 511 keV. The angle between the centers of the two detectors is 145°. This geometry was chosen on the basis of the normal QED 3γ phase space for the energy windows that are used.[22] However, decays mediated by a symmetry-violating interaction can possess phase-space distributions constrained only by momentum and energy conservation, which could be unlike that of QED. Coincidences between the detector on the left and the upper detector on the right (Fig. 3) imply the normal to the decay plane ($\hat{\mathbf{n}}\sim\hat{\mathbf{k}}_1\times\hat{\mathbf{k}}_2$) points into the page in Fig. 3. A coincidence between the left detector and the lower one on the right makes the normal point out of the page. Reversals of the normal to the decay plane occur randomly while running, depending on which detector on the right gets a signal. Thus, the decay-plane normal is effectively reversed in a random manner at half the data rate on the average during a typical run.

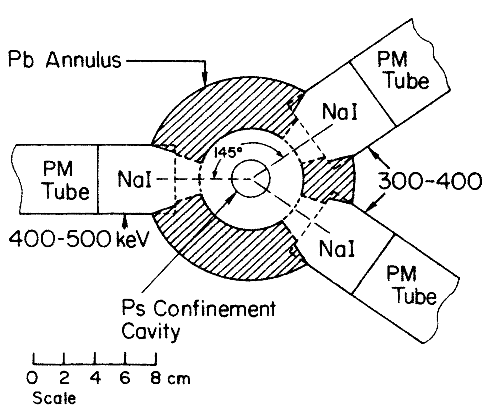

FIG. 3. NaI detector array. Three NaI scintillators, situated in the plane perpendicular to the e^+ beam direction, detect γ rays from the 3γ decay of Ps. The highest-energy γ ray is detected on the left, the second highest by one of the detectors on the right. The lowest-energy γ ray is not observed. The photomultiplier tubes are denoted PM Tube.

The fast-timing signal from the CEMA is used with the NaI fast-timing coincidence signals to select decay events due to triplet Ps($\tau_T\cong 135$ ns), as opposed to singlet Ps and direct annihilations of $e^+(\tau_S\cong\tau_{dir}\cong 120$ ps). By selecting γ events that are delayed with respect to the CEMA signal, the longer-lived triplet Ps can be isolated. The delay time is selected to be between 20 and 200 ns. The lifetime of the triplet Ps in the confinement cavity is measured to be 135(2) ns, very close to the vacuum lifetime of 142 ns.

This experiment incorporates frequent reversals of the Ps spin and the normal to the decay plane. These frequent flips are intended to average out any effects due to drift instabilities, e.g., electronics, detector gains, or e^+ beam position. The Ps polarization is reversed every four minutes during a typical one-day run, with a 30-second waiting period after each flip to allow the spin rotator fields to stabilize prior to the next 3.5 minutes of data acquisition. One further reversal is also routinely used in these measurements. At approximately daily intervals, the two detectors on the right side of Fig. 3 are physically interchanged to average out any differences in their efficiencies, resolution, etc. In addition, the previously mentioned random reversal of the decay-plane normal is used, making a total of three independent flips.

III. RESULTS

Data were taken over a period of eight weeks which included setting up, systematic tests, and other related experiments. A typical data run involves counting delayed coincidence events N, with the energy cuts, for the detector pairs that give the normal to the decay plane parallel (+) and antiparallel (−) to the spin direction. From these simultaneous measurements, an asymmetry is defined:

$$A\equiv\frac{N_+-N_-}{N_++N_-} . \quad (5)$$

Separate counters record events for the opposite spin direction and another asymmetry is so generated. Averaging the asymmetries from the two spin directions tends to cancel out systematic effects due to instrumental asymmetries. The final measured asymmetry, appropriately averaged to eliminate systematics, is found to be $A=+0.0017\pm 0.0017$. The average coincidence counting rate is about 0.5 Hz, and the total number of coincidences is 3.5×10^5. Accidental random coincidences, due to finite detector time resolution, are present at the level of 10^{-5} of the true coincidences, a negligible effect.

The most important systematic effect that was identified is the effect upon A due to a difference in the e^+-beam position between the two spin directions when striking the CEMA. This positional difference is due to differences in the magnetic fringing fields of the Wien filter when reversing field directions. The systematic effect on A is caused by changes in the geometrical solid angle for the various NaI detectors when the beam shifts position. This effect does not cancel during the averaging process described above. A set of electrostatic deflection plates, in combination with the phosphor screen and image analysis system, allows us to adjust the location of the centroid of the e^+ beam with better than 0.02 mm uncertainty.

To quantify the systematic effect, we performed several runs where the difference in beam location for the two spin directions was intentionally made large by means of the electrostatic deflection, with a maximum of 2 mm difference in the beam centroids. The results are shown in Fig. 4. Clearly, a large effect is indicated by these tests, but during our normal running conditions positional shifts were adjusted to be $\lesssim 0.1$ mm so that the systematic effect on the asymmetry is $\lesssim \pm 1\times 10^{-3}$. The size of the systematic effect roughly corresponds to the calculated change in the geometrical solid angle of the NaI detectors with the change in beam location. Other systematic effects appear either very small in comparison to the above and/or are canceled out by the system of multiple reversals. Slow secular drifts in the beam positions, typically of order 0.1 mm/day were observed. These drifts are believed to have their origins in long-term instabilities in the magnetic guiding field and have a negligible effect on our results.

Several tests and calculations were done to determine the relation between the measured asymmetry and the coefficient of the angular correlation in Eq. (1) which we call, following Nachtmann,[23] C_n:

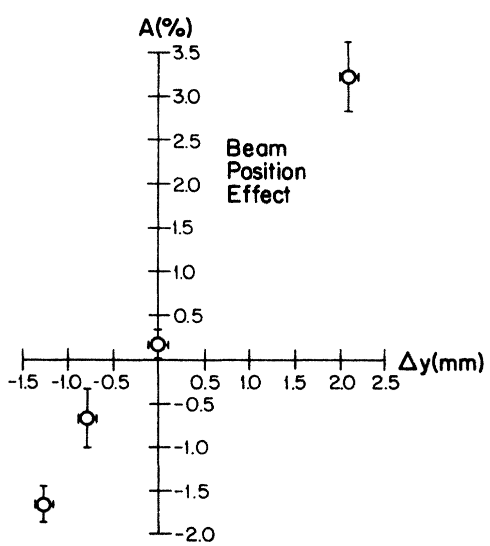

FIG. 4. Systematic effect of e^+-beam position. An instrumental asymmetry, due to e^+-beam position differences for the two spin directions, is clearly present. By ensuring that the e^+ beam has the same spatial distribution and centroid location for both spin directions, the systematic uncertainty in the asymmetry [Eq. (5)] due to this effect can be reduced to below 1×10^{-3}. The horizontal axis on this graph, Δy, corresponds to relative vertical displacements in Fig. 3. The indicated horizontal error bars in this figure are the rms spread due to drifts in the beam position.

$$C_n(\hat{\mathbf{S}}\cdot\hat{\mathbf{k}}_1\times\hat{\mathbf{k}}_2) \ . \tag{6}$$

We define an analyzing power $S_{\rm an}$ that relates the measured asymmetry to the angular-correlation coefficient

$$S_{\rm an}\equiv\frac{A}{C_n} \ . \tag{7}$$

One test measured the occurrence of two back-to-back 511-keV annihilation photons (from, e.g., singlet decay) mimicking a true triplet event. If one of the 511-keV γ-rays compton scatters and deposits only part of its energy in the scintillator that is used to detect the second highest-energy γ ray from triplet decay (300–400 keV), it can pass the energy cuts. The delayed coincidence requirement can be met by either insufficient e^+-γ timing resolution or quenching of a triplet Ps atom during a wall collision. (The lifetime measurement implies this occurs in a maximum of 4% of the triplet decays.) We find that 8% of the events are due to two 511-keV γ rays and have so corrected the results. The finite solid angle of the NaI detectors, the polarization of the Ps, the finite size of the Ps confinement cavity, the average angle between the Ps spin and the normal to the decay plane, and the degree of overlap in the energy windows for the γ rays are additional factors that enter into $S_{\rm an}$ and have been calculated. Another calculation was done to account for the difference in the γ-ray directional angular correlation from the $m=0$ and $m=\pm 1$ states of triplet Ps.[22]

Putting all these effects together, we find for this experiment that the analyzing power is given by

$$S_{\rm an}=0.085\pm 0.012 \ . \tag{8}$$

Combining this with the asymmetry corrected for the systematic effect of beam position yields our value for the angular correlation coefficient

$$C_n=+0.020\pm 0.023 \ . \tag{9}$$

This final result includes both statistical and systematic uncertainties and is consistent with *CPT* invariance.[24]

IV. DISCUSSION AND CONCLUSIONS

One final correction involves the effect of final-state interactions, so-called radiative corrections that can mimic a true *CPT*-violating signal, as mentioned previously. Since there are no charged particles in the final state, electromagnetic radiative corrections can appear only through the virtual creation of pairs of charged particles (e.g., e^+, e^-). This implies these correction terms will appear in a high order of α. Nachtmann[23] has calculated the radiative corrections using standard perturbative QED and finds

$$C_n^{\rm QED}\cong\left[\frac{\alpha}{2\pi}\right]^2 6\times 10^{-4}\cong 9\times 10^{-10} \ , \tag{10}$$

a number far below our experimental sensitivity.

It could be argued that our 2% null result for C_n [Eq. (9)] is not very precise in light of the sensitive tests of *CPT* (e^--e^+ and μ^--$\mu^+ g$ factors, or neutral kaons).[4] However, this comparison should be made with respect to a *CPT*-violating model, which is not practical since such theories are rarely, if ever, discussed. As noted before, the assumptions required to prove the *CPT* theorem are Lorentz invariance and locality. Theories constructed to violate these assumptions frequently are not gauge invariant.[25] The use of specific models that violate *CPT* to calculate observables is beyond the scope of this paper. Hence, we cannot directly compare our result with previous *CPT* tests.

One theoretical observation can be made about our result that is not applicable to the previous experiments. Our experiment is the first to use an angular correlation and, in particular, a *T*-odd angular correlation. All *T*-odd angular correlations are the result of the interference of the matrix elements of two separate interactions having the same final state. The use of interference effects is widely utilized to enhance symmetry-violating behavior by measuring the product of a symmetry-forbidden matrix element with an allowed and thus large matrix element instead of measuring the direct symmetry-violating effect given by the square of its matrix element. This argument makes it possible that our experiment has enhanced or even unique sensitivity to *CPT*-violating effects compared with the previous *CPT* tests. To become sensitive to these possible effects, we will have to increase the accuracy of our experiment.

Much more accurate versions of this experiment are easy to envision. The most obvious place for improvement is in the NaI detector array. There are a number of detector arrays used for high-energy or heavy-ion physics that are based on multiple (>100) independent NaI crystals.[26] These arrays feature nearly 4π sr of coverage and flexible computer control for choosing triggers to store events. Recently, one such array (the Darmstadt-Heidelberg "crystal ball") has been used off line for low-energy positronium studies.[27] Application of such an array to this experiment would enable several improvements, starting with a 20-fold increase in the Ps rate, virtually 100% efficiency in reconstructing the decay plane of the annihilation γ rays, and better information on the effects due to γ-ray scatterings in the NaI detectors with only partial energy deposition. Overall, a factor of 30 reduction in the present uncertainty for C_n is a realistic goal. The effects of the beam position systematic (Fig. 4) could be reduced by a factor of at least 30 by continuous monitoring of beam position while running rather than just observing the position at the beginning and end of day-long runs, as done with our experiment.

There are other interesting angular correlations that could be measured using the polarized Ps technique developed here. For example, the *P*-violating and *CPT*-violating angular correlation

$$\hat{\mathbf{S}}\cdot\hat{\mathbf{k}}_1 , \tag{11}$$

or the *T*-violating and *P*-violating, but *CPT*-conserving angular correlation

$$(\hat{\mathbf{S}}\cdot\hat{\mathbf{k}}_1)(\hat{\mathbf{S}}\cdot\hat{\mathbf{k}}_1\times\hat{\mathbf{k}}_2) \tag{12}$$

could be measured in straightforward extensions of the experiment presented here. Since Eq. (12) contains two $\hat{\mathbf{S}}$'s it requires aligned as opposed to polarized Ps. Experimentally, aligned triplet Ps can be obtained by magnetic quenching using an external field of a few kG. With the addition of a circular polarization ($\hat{\boldsymbol{\varepsilon}}$) measurement of one of the decay γ rays, one could search for the *T*-violating and *P*-violating, but *CPT*-conserving angular correlation

$$\hat{\mathbf{S}}\cdot\hat{\boldsymbol{\varepsilon}}_1\times\hat{\mathbf{k}}_2 . \tag{13}$$

In addition, there are a number of allowed angular correlations that are expected to appear in polarized and aligned Ps decay[22,28] which have never been experimentally measured and can serve as tests of bound state QED.

In conclusion, we have performed the first measurement of a *CPT*-violating angular correlation, and at the same time, made the first use of polarized Ps. The coefficient of the angular correlation was found to be zero at the 2.3% level, indicating no *CPT* violation. Prospects are excellent for improving this measurement by more than an order of magnitude in the near future. Other interesting experiments, using the angular-correlation and polarization techniques developed here, are also possible.

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APPENDIX

In this appendix we calculate the polarization of triplet Ps which was formed from polarized positrons and unpolarized electrons. The assumption is made that there is no external magnetic field.

The spin states of Ps formed in the ground state may be written as

$$|\mathbf{S}|=0(\text{singlet})\ m_s=0:\ \ \psi_S=\frac{1}{\sqrt{2}}(\downarrow\ddagger-\uparrow\ddagger)\,,$$

$$|\mathbf{S}|=1(\text{triplet})\begin{cases} m_s=0:\ \ \psi_T(m=0)=\dfrac{1}{\sqrt{2}}(\downarrow\ddagger+\uparrow\ddagger) \\ m_s=1:\ \ \psi_T(m=+1)=\uparrow\ddagger \\ m_s=-1:\ \ \psi_T(m=-1)=\downarrow\ddagger , \end{cases} \tag{A1}$$

where $\uparrow(\downarrow)$ is the electron spinor for spin up (down) and a bar through the arrow denotes the positron. For unpolarized positrons and electrons, each of these four states is equally populated. Now consider using completely polarized positrons ($\ddagger$) and unpolarized electrons ($\frac{1}{2}\uparrow+\frac{1}{2}\downarrow$) to form Ps. In this case, two states are equally populated:

$$\Updownarrow + \uparrow \rightarrow \Updownarrow\uparrow \ , \tag{A2a}$$

$$\Updownarrow + \downarrow \rightarrow \Updownarrow\downarrow \ . \tag{A2b}$$

State (A2a) is an eigenstate of Ps, the $m_s = +1$ triplet state. However, state (A2b) is an equal combination of singlet and $m = 0$ triplet states. Therefore, the fraction of $m = +1$ triplet states (f_1) is $\frac{1}{2}$ and the fraction of $m = 0$ triplet states (f_0) is $\frac{1}{4}$. The polarization of triplet Ps formed from completely polarized positrons is then

$$\mathcal{P}_{\rm Ps} = \frac{f_1 m_s(+1) + f_0 m_s(0)}{f_1 + f_0} = \frac{\frac{1}{2}+0}{\frac{1}{2}+\frac{1}{4}} = \frac{2}{3} \ . \tag{A3}$$

This argument for partially polarized positrons carries over to give Eq. (4).

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[24]We note that this experiment is also sensitive to the angular correlation:

$$(\hat{\mathbf{k}}_1 \cdot \hat{\mathbf{k}}_2)(\hat{\mathbf{S}} \cdot \hat{\mathbf{k}}_1 \times \hat{\mathbf{k}}_2)$$

and our results set a 3.0% limit on the coefficient of this correlation. The symmetry properties of this angular correlation are exactly the same as $\hat{\mathbf{S}} \cdot \hat{\mathbf{k}}_1 \times \hat{\mathbf{k}}_2$. So, in effect, nothing noteworthy is gained by considering this new correlation.

[25]Violations of Lorentz invariance are considered in J. G. Vargas and D. G. Torr, Found. Phys. **16**, 1089 (1986) and references therein. A nonlocal model for a QED-like theory is

$$\mathcal{L} = ie \int dx' \bar{\psi}(x') A_\mu(x') \gamma^\mu \psi(x') w(x,x') \ .$$

The simplest form for the function $w(x,x')$ would vanish sufficiently rapidly to render the action finite at all x and could then depend on a single parameter—some fundamental distance scale.

[26]G. Gidal, B. Armstrong, and A. Rittenberg, LBL-91 supplement UC-37 (1983) (unpublished); H. C. Griffin and A. Hallin (private communication).

[27]W. Wahl, Ph.D. dissertation, Ruprecht-Karl-Universitat, Heidelberg, 1985; (unpublished).

[28]Three example of allowed angular correlations are (1) $\hat{\mathbf{S}} \cdot \hat{\boldsymbol{\varepsilon}}_1$, (2) $(\hat{\mathbf{S}} \cdot \hat{\mathbf{k}}_1)(\hat{\mathbf{S}} \cdot \hat{\mathbf{k}}_2)$, and (3) $(\hat{\mathbf{S}} \cdot \hat{\mathbf{k}}_1)(\hat{\boldsymbol{\varepsilon}}_1 \cdot \hat{\mathbf{k}}_2)$.