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CPT symmetry test in positronium annihilations with the J-PET detector

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Discrete symmetry under combined transformation of charge, parity and time reversal (CPT) can be tested in the decays of positronium atom, the lightest bound system built of charged leptons. Jagiellonian Positron Emission Tomograph (J-PET) device constructed from plastic scintillators, detects the photons originating from electron positron annihilation. This feature enables J-PET to study CPT symmetry in the three photon annihilations of the triplet state of positronium. Signs of violation of the CPT symmetry can be sought as a non-vanishing expectation value of an angular correlation operator that is odd under CPT transformation. A technique to estimate the spin of ortho-positronium and momenta of annihilation photons for single recorded ortho-positronium annihilation events allows J-PET to measure the expectation value of a CPT symmetry odd angular correlation operator. J-PET measures a broad range of kinematical configurations of ortho-positronium annihilation to three photons and is the first experiment to determine the full range of the CPT-odd angular correlation.

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1. Introduction

Discrete symmetries violation can be tested by searching for breaking of any of charge conjugation (C), parity (P), time reversal (T) symmetries and their combinations CP and CPT [1, 2]. Small violations of all of the above symmetries except for CPT were already observed in certain interactions e.g. in the hadronic sector [3]. Whereas in the leptonic sector, long baseline neutrino oscillation experiments have observed the first evidence of CP violation in neutral leptons at a level of 3σ [4], it would be exciting to observe similar evidence with charged leptons.
The first direct search for CPT invariance in the positronium system was done using the angular correlations in the 3γ decay of polarized positronium [5]. The most precise test of CPT symmetry in ortho-positronium (o-Ps) decay to 3γ decay has reached a precision level of 10^{-3} with no observation of CPT violation [6]. This result is still about six orders of magnitude larger than the possible contribution from the radiative corrections which may mimic the CPT symmetry violation at the level of 10^{-9} [7]. With the J-PET detector the precision limit has been extended to 10^{-4} with no CPT violating effects [8]. In this work, we present the methods of performing the CPT symmetry test with ortho-positronium annihilations using the J-PET detector with an enhanced sensitivity aiming to reach the 10^{-5} level.

2. CPT Symmetry test with J-PET

J-PET is the first Positron Emission and Positronium Tomography device build from 50 cm long cylindrical plastic scintillators arranged concentrically in three layers [9–13]. It consists of 192 plastic scintillators with PMTs on both ends [14, 15]. In J-PET, signals are processed through multi-threshold system and data is collected in a trigger-less mode [16]. It allows for exclusive registration of a broad range of kinematical configurations of three-photon annihilations with large geometrical acceptance and high angular resolution. Annihilation chambers are used for the production of positronia which makes this device useful in the studies of fundamental search for discrete symmetries [17–19].
The measurement of the CPT asymmetric angular correlation operator in ortho-positronium annihilations is done by estimating the direction of spin $\vec{S}$ of decaying ortho-positronium using the intrinsic polarization of positrons from a β^+ source and the final state momenta of three annihilating photons ordered by their magnitude $|\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3|$. The CPT violation sensitive operator is given by $\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$. It requires the registration of three photons from ortho-positronium annihilation in the J-PET detector. To meet this condition, positrons e^+ from a ^{22}Na source had a chance to form ortho-positronium on interacting with R60G porous silica coated on the inner walls of an annihilation chamber in vacuum. The direction of flight of each of three recorded photons is used to reconstruct the annihilation point of o-Ps$\rightarrow 3\gamma$ decay using trilateration reconstruction method [20]. J-PET has already performed a CPT symmetry test in positronium decays and reached a sensitivity which is better than the previous best known result by a factor of more than two [8]. This measurement was done using a cylindrical annihilation chamber but to increase the production of o-Ps$\rightarrow 3\gamma$ events in J-PET, a new set of measurements is being performed with a spherical annihilation chamber inside the 3 layer J-PET detector as shown in Fig. 1.

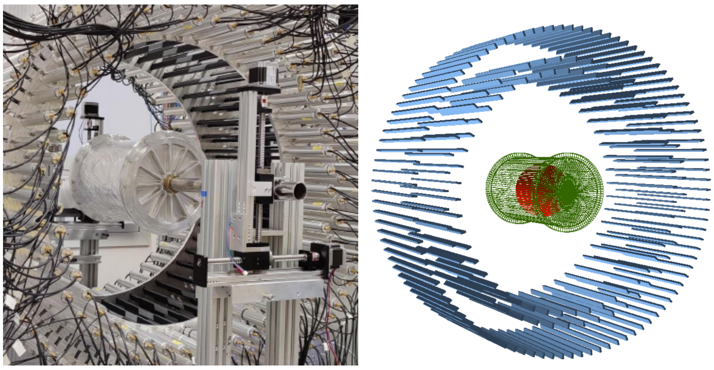

Figure 1: Experimental setup of 3 layer J-PET with spherical positronium annihilation chamber installed (left) and visualization of experimental setup geometry in Geant4 (right).

3. Identification of o-Ps events

The J-PET detector measures energy deposition of interacting photons through a Time Over Threshold (TOT) method due to good time resolution of the detector (~250 ps) [21]. This method can identify the annihilation photons (511 keV) and the deexcitation photon (1.27 MeV) based on the Compton edge for 511 keV photons. The possible background components that can mimic the 3γ events are the Compton secondary scattered photons originated from $e^+e^-\to 2\gamma$ events in the detector due to plastic scintillators and the 2γ annihilations $e^+e^-\to 2\gamma$ directly from β^+ source placed at the center of the chamber along with a de-excitation photon. Evidence for identification of o-Ps events in J-PET from ongoing data analysis is from the distributions shown in Fig. 2 where the selected region for 3γ from o-Ps (left) is compared with MC simulation for o-Ps$\to 3\gamma$ events (right).

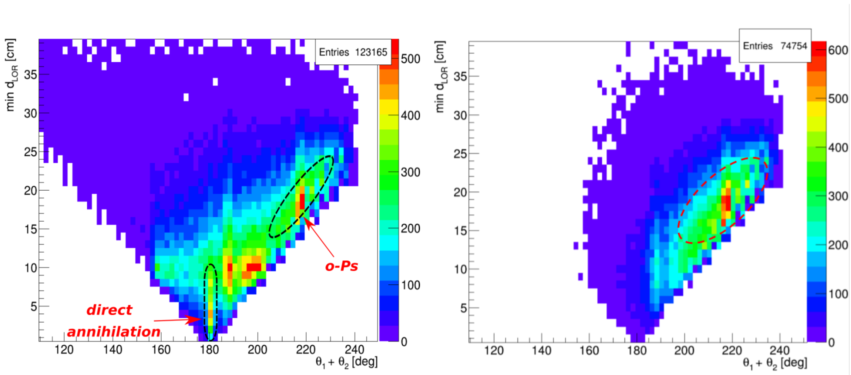

Figure 2: Distribution of minimum distance between source position and hypothetical 2γ annihilation point on LOR v/s sum of two smallest angles between photons' momenta for data (left) and MC simulations only of o-Ps$\to 3\gamma$ events (right). The structure marked with an ellipse which corresponds to pure o-Ps$\to 3\gamma$ events is clearly visible in the collected data. The enhancement near $\theta_1 + \theta_2 = 190°$ and $200°$ in data (left) is due to the scattering of photons on the inner walls of the spherical annihilation chamber. The split in this enhanced region (near $\theta_1 + \theta_2 = 192°$) is due to lower detection efficiency of photons at some particular angles due to sparse geometry of the detector that can also be seen in the same region (near $\theta_1 + \theta_2 = 192°$) on the right plot for MC simulations.

4. Conclusions and Perspectives

The J-PET detector has reached a precision level of 10^{-4} for CPT violating effects in o-Ps→3γ decays [8]. It is being worked on to further improve the sensitivity for CPT symmetry test by upgrading the existing 3 layer J-PET with a fourth layer of densely packed plastic scintillator strips with silicon photomultiplier readouts and using a spherical annihilation chamber. Ongoing measurements with this spherical chamber give a positronium production rate about 1.5 times higher than in the previous experiment with cylindrical chamber and we are able to identify o-Ps→ 3γ events with the new chamber. Having an additional fourth layer of scintillators will increase the geometrical acceptance of the detector resulting in increasing the detection efficiency of registration of 3γ from ortho-positronium with respect to previous 3 layer J-PET detector by a factor of about 64. With these improvements, J-PET should be able to reach a precision level of 10^{-5} for the CPT symmetry test.

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