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Exploring the limits of CPT symmetry in ortho-positronium decays with J-PET

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The CPT symmetry is one of the most fundamental symmetries in physics. Any violation of this symmetry would have profound implications for our understanding of the universe. In this study, we report the CPT symmetry tests in 3γ decays of polarised $^3S_1$ positronium using the Jagiellonian Positron Emission Tomography device. The J-PET experiment allows sensitive and precise tests of CPT symmetry by measuring the angular correlation between the spin of ortho-positronium and the momenta direction of the annihilation photons emitted in ortho-positronium decay. The potential of J-PET in determining the full range of the expectation value of this correlation has improved the precision of the CPT symmetry test to 10^{-4} already. The accuracy of this previous measurement was limited by statistics only. The new test is based on the increased statistics due to the modified experimental setup aiming at the improvement of detection efficiency and due to the usage of different positronium production chambers. The high precision of this test would open the possibility of exploring the limits of CPT symmetry validity in the charged leptonic sector. In this work, we discuss the evaluation of background sources in the CPT symmetry test with J-PET which is a crucial factor in improving the precision of such studies.

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1. Introduction

Experimental tests of the CPT (charge-parity-time reversal) symmetry unfold the probes in understanding the fundamental physics [1]. The investigation of such a test could result in either symmetry breaking which opens the possibility of new physics, or symmetry invariance which sets the experimental precision limit of its validation. This study focuses on testing the CPT symmetry in electromagnetic interactions using a polarized Positronium (Ps) atomic system. The test can be done using the CPT violating angular correlation in 3γ decays of polarized $^3S_1$ Ps defined as $O_{CPT} = \vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$ [2]. This CPT-odd quantity represents the correlation between the spin of ortho-positronium (o-Ps) and the momenta of the two most energetic annihilation photons. Its invariance can be tested to the precision of $O(\mathcal{CPT}) = 10^{-9}$ which comes from the effect of the final state interaction of photons [3, 4].

2. Measurements with J-PET

Jagiellonian Positron Emission Tomograph (J-PET) is the first plastic scintillator-based PET scanner designed for a wide range of studies from discrete symmetry tests in fundamental physics [5–7] to medical imaging [8–12]. It consists of 192 plastic scintillator strips arranged cylindrically in three concentric layers that detect the photons from the annihilations of positronium atoms using the Compton scattering effect [13, 14]. To avoid any bias in the recorded sample of events, J-PET's data acquisition operates in a triggerless mode [15]. The electric signals from the photomultipliers are sampled in the time domain at four different voltage thresholds, which allows for an estimation of the deposited energy of the photon using the time over threshold (TOT) method [16].
The positronium needed for the CPT symmetry test is produced using e^+ from a point like ^{22}Na (β^+) source (1.1 MBq activity) placed at the center of a spherical-shaped annihilation chamber (R=10 cm). The chamber wall is coated with a layer of porous silica (3 mm thick) where e^+ thermalize and form positronium [17]. Spin polarization of o-Ps is estimated using the longitudinal polarization of e^+ from β decay for a single o-Ps event. The Trilateration method of reconstructing the annihilation point of o-Ps decaying to three photons is further used to estimate the momentum direction of the annihilation photons [18]. More than one year of measurement is done with this prototype of a spherical annihilation chamber inside the three-layer J-PET detector for the CPT symmetry test.

3. Background evaluation

The signal event in this study is o-Ps$\to 3\gamma$ where 3γ interactions are recorded in the J-PET detector. The Monte Carlo simulations-based study is performed with a similar experimental setup as described above to evaluate the different backgrounds that can mimic the signal events from o-Ps. The different background components studied along with the signal are represented in Figure 1. The relative angles between the recorded photons in three-dimensional space are defined to distinguish the different topologies of 3γ events detected in the setup as explained in the figure. The sum and difference of these two smallest relative angles are plotted for the experimental data and compared with the simulated signal and the respective background events as shown in Figure 2. This distribution enables the discrimination of the major background arising from 2γ annihilations and the secondary Compton scatterings in the detector over the o-Ps annihilation in the experimental data.

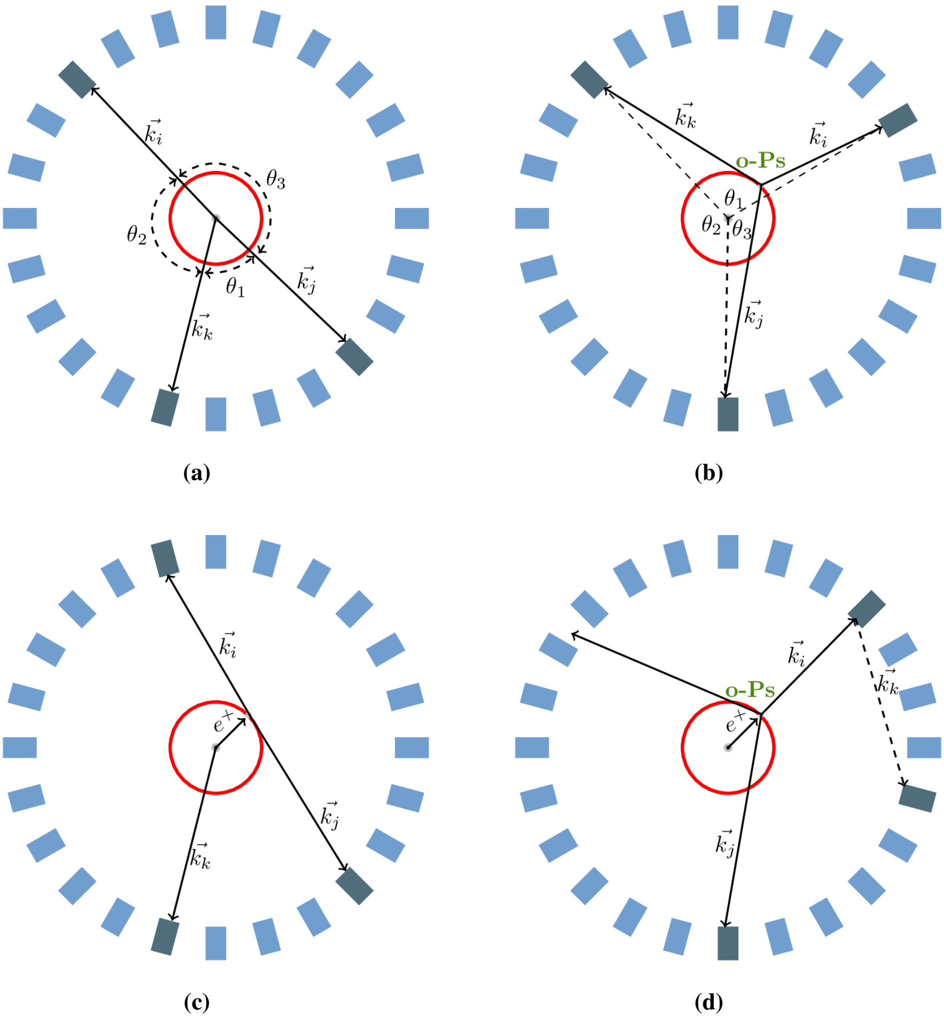

Figure 1: Schematic representation of the different topologies of events recorded in the J-PET detector where the red sphere represents the spherical annihilation chamber at the center of the detector in the transverse plane. Only a few scintillation modules in one layer of J-PET are shown. The modules where three photons interact in the detector are marked in dark blue color. These are the events with 3γ interactions in the detector where (a) 2γ from direct e^- and e^+ annihilation with the de-excitation photon (1.2 MeV) (b) all the three photons are from o-Ps annihilation (signal) (c) 2γ from para-positronium annihilation on the wall of spherical annihilation chamber along with the de-excitation photon and (d) 3γ annihilation where two of its primary photons recorded and the third photon is the secondary Compton scattering in the detector. θ_1, θ_2, and θ_3 in (a) and (b) represent the relative angle between the three recorded photons calculated from the center of the detector.

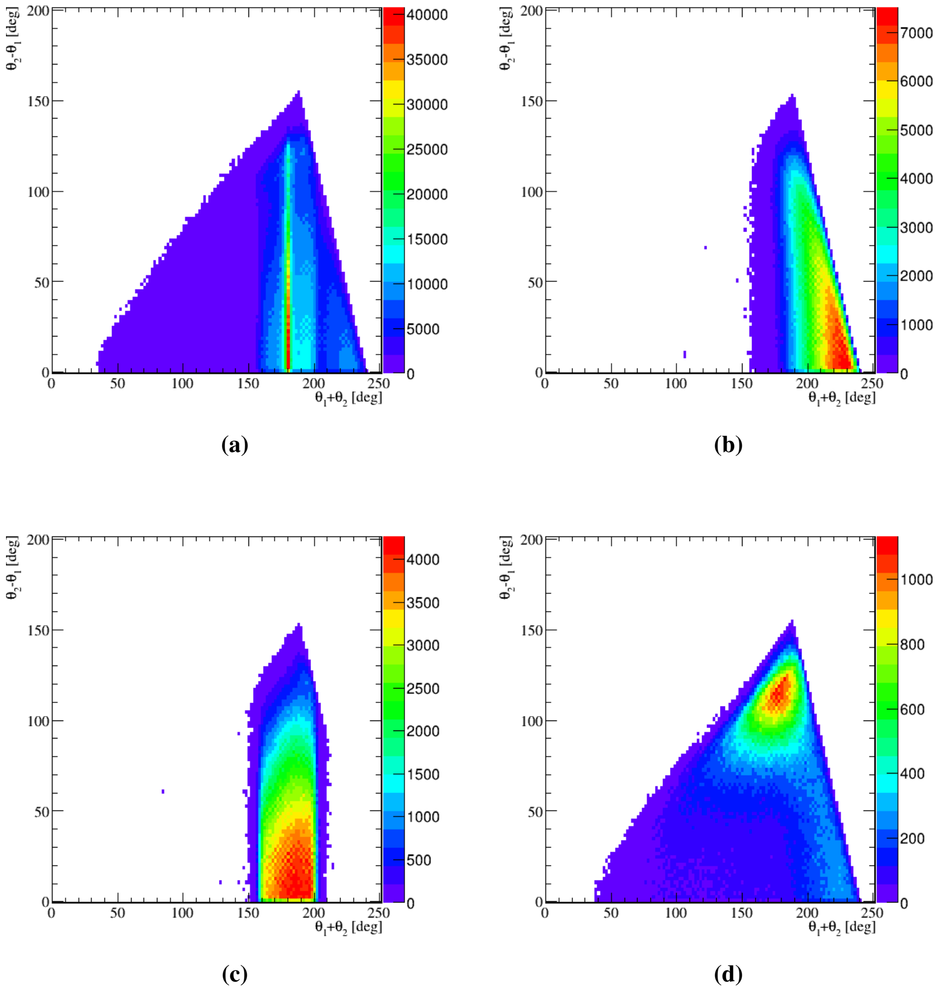

Figure 2: The relative distribution of the sum and difference of two smallest angles between the 3γ recorded in the detector taken from the center of the detector frame as shown in Figure 1 (a) and (b). The relative distribution of angles for **(a)** experimental data compared with MC simulated events **(b)** o-Ps$\rightarrow 3\gamma$, **(c)** p-Ps$\rightarrow 2\gamma$ from the walls of the annihilation chamber, and **(d)** 3γ or 2γ annihilation with secondary Compton scattering. In experimental data the maximum concentrated region at $\theta_1 + \theta_2 = 180°$ is from the direct annihilation of $e^+e^-\rightarrow 2\gamma$ events from the ^{22}Na source as represented in Figure 1 (a). While the band around $180° < \theta_1 + \theta_2 < 200°$ comes from the other background events like p-Ps$\rightarrow 2\gamma$ annihilation and $2\gamma/3\gamma$ annihilations with secondary Compton scatterings in the detector. The rightmost region of $\theta_1 + \theta_2 > 200°$ in data is identified as o-Ps signal events.

4. Conclusion and Future Perspectives with J-PET

The J-PET detector has made significant progress in testing CPT symmetry in positronium annihilations using $\vec{S} \cdot (\vec{k_1} \times \vec{k_2})$. The first CPT symmetry test performed with J-PET has achieved a precision of 10^{-4}, a factor of three better than the previous best-known result [7, 19]. A similar test was performed with the improved positronium production medium as described in this work resulting in obtaining four times more signal events in the measurement. The discrimination of background events based on MC simulation has resulted in more than 50 percent signal purity in the study. J-PET has been working towards improving the sensitivity of these studies with the new Modular J-PET detector [20–22]. This new upgrade has 24 modules of densely packed plastic scintillators with SiPM readouts that can be arranged cylindrically in a single or multi-layer setup [23]. The higher granularity of the detector would result in improving the detection efficiency of 3γ from o-Ps which is an important factor in reaching the sensitivity of CPT symmetry to the precision level of 10^{-5}.

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