CP SYMMETRY STUDY USING MOMENTUM AND POLARIZATION OF PHOTONS FROM THE ORTHO-POSITRONIUM ANNIHILATION*

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The Jagiellonian-Positron Emission Tomography (J-PET) is distinguished by its ability to determine the polarization plane of photons emitted during the positronium annihilation. According to the Standard Model prediction, photon–photon interactions in its final state due to vacuum polarization can mimic CP symmetry violation at a magnitude of approximately 10^{-9}, which is significantly larger than the predicted value of the order of 10^{-14} for weak interactions. Currently, with the help of the J-PET detector, experimental limits on CP symmetry violation in o-Ps decay are set at a precision value of the order of 10^{-4}. The J-PET detector measures the polarization direction of annihilation photons without a magnetic field and can investigate discrete symmetry by examining non-zero expectation values of symmetry-odd operators, constructed from the momentum and polarization-related vectors of gamma (γ) quanta coming from the o-Ps annihilation. This work focuses on studying the CP symmetry in o-Ps decay and the initial operator plot derived from data collected over 250 days using the J-PET detector. The primary objective of this experiment is to enhance statistical significance in fundamental symmetry studies and refine the precision of CP symmetry tests. The study utilizes the CP symmetry-odd operator $(\vec{\epsilon}_i \cdot \vec{k}_j)$, where $\vec{\epsilon}_i$ and $\vec{k}_j$ represent the reconstructed polarization-related and momentum vectors of the photons emitted from o-Ps decay.

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1. Introduction

Positronium is a fundamental atom composed of an electron (e^-) and a positron (e^+) [1]. Electrons and positrons are leptons that interact with electromagnetic and weak forces [1, 2]. Positronium is a fully leptonic atom since it is made up entirely of electrons and positrons [1–4]. When an e^+e^- pair interacts, it can either directly annihilate or create a bound state known as a positronium atom [1–6]. Positronium, being a bound system confined by a central potential, is an example of a parity operator (P) eigenstate. Because it is made up of an electron and an anti-electron(positron), positronium is also an eigenstate of the charge conjugation operator (C), hence it is also a CP eigenstate [1, 6–10]. This makes positronium an ideal leptonic-bound system for studying discrete symmetries [1–7]. Positronium can exist in the singlet state (p-Ps) or triplet (o-Ps) states with the spin equal to zero (0) and one (1), which can annihilate into an odd or even number of photons, respectively [1–6]. In a vacuum, the mean lifetime value for the ground states of p-Ps is 0.125 ns and o-Ps is about 142 ns [1]. Such large differences in lifetimes enable a very efficient experimental disentangling of these states [1]. The polarization properties of positronium annihilation photons can be used in many research studies, including PET imaging, quantum entanglement, discrete symmetry, and positron-based molecular spectroscopy studies [11–20]. Due to the vacuum polarization effect, the final-state interaction of photons emitted in the o-Ps decay mimics CP symmetry violation and its Standard Model predicted value is of the order of 10^{-9} [1, 4–7]. Many particle physics experiments in the world are searching for these kinds of CP symmetry-breaking phenomena in hadrons [21, 22] and leptonic systems [23–28]. Previous research on CP symmetry in the o-Ps atom decay used odd-symmetry operators constructed from photon momenta ($\vec{k}_i$) and positronium spin ($\vec{S}$) vectors [1, 6, 7, 29]. This study utilizes the CP symmetry-odd operator ($\vec{\epsilon}_i \cdot \vec{k}_j$), where $\vec{\epsilon}_i$ and $\vec{k}_j$ represent the reconstructed polarization-related and momentum vectors of the photons emitted from the o-Ps decay [1, 6]. In the recent CP symmetry studies in positronium decays using the J-PET detector, the mean expected value of the operator correlation was determined to be $\langle \vec{\epsilon}_i \cdot \vec{k}_j \rangle = 0.0005 \pm 0.0007_{\mathrm{stat}}$ [6], and experiments are still going on to improve the sensitivity value by one order of magnitude.

2. Experimental procedure

The Jagiellonian-Positron Emission Tomograph (J-PET) is the first PET scanner to use plastic scintillator strips, making it more cost-efficient and portable [30–38]. Due to good timing characteristics and high granularity properties, plastic scintillators are being used as detecting elements to identify gamma scatterings [30–39]. The J-PET detector is distinguished by its ability to perform positronium imaging [40, 41] and to measure the polarization direction of photons emitted during the positronium annihilation [6, 30–35]. The 192 plastic scintillator strips (EJ230, $500 \times 19 \times 7$ mm^3, form concentric layers of 48 modules on a radius of 425 mm, 48 modules on a radius of 467.5 mm and 96 modules on a radius of 575 mm) make up the three layers of the J-PET detector (Fig. 1, left) [30–33, 35, 38]. Each scintillator in the J-PET scanner is optically connected with the Hamamatsu R9800 vacuum tube photomultipliers (PMTs) at each end, which read out the optical signals from the scintillators [30–33, 37, 38]. The sides of scintillator strips are wrapped with reflective foil to reduce photon losses [30–33, 37, 38].

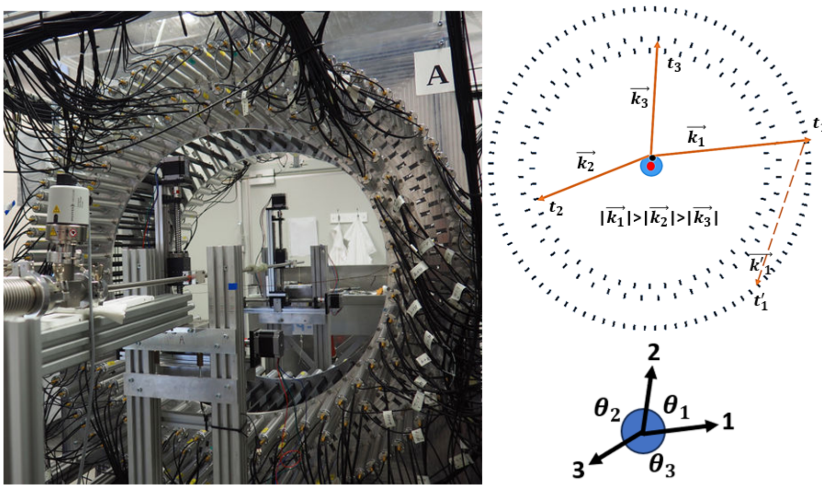

Fig. 1. Left: Photograph of the 3-layer J-PET detector [30]. Right: Cross-sectional view of the J-PET detector with a point-like ^{22}Na source at the center (red) covered in the XAD-4 porous polymer (blue) and inside schematic shows the o-Ps atom (black dot) decay [30].

The main aim of this experimental run was to increase the statistics for the discrete symmetry studies in the o-Ps decay. During the data measurement performed in 2020/2021 (250 days), a small annihilation chamber made of plastic PA6 (polyamide) with a density of 1.14 g/cm^3 was used. The positron source used was a ^{22}Na source with an activity of 0.702 MBq sandwiched between 3 mm thickness XAD-4 porous material where the o-Ps are formed. A small annihilation chamber with the ^{22}Na source inserted into its center was placed within the 3-layer J-PET detector and four thresholds (30, 80, 190, and 300 mV) were set to each PMT. The positrons emitted by the sodium source ($^{22}\text{Na} \to {}^{22}\text{Ne}^* + e^+ + \nu_e$) interact with electrons in the cylindrical layer of the XAD-4 porous material target to form the spin-linear polarized ortho-positronium (o-Ps) which annihilates into 3γ quanta (o-Ps $\rightarrow 3\gamma$) [1, 42–45]. The position of annihilation photon interactions in scintillator strips allowed us to reconstruct their momentum and polarization-related vectors which are used to study CP symmetry violation by determining the expectation values of the CP symmetry odd operator listed in Table 1 [1, 6, 42, 45].

Table 1. CP discrete symmetry odd operators which are independent of each other. One of the CP discrete symmetry operators is $\vec{\epsilon}_1 \cdot \vec{k}_2$ which can be constructed using the linear polarization direction ($\vec{\epsilon}_1 = \vec{k}_1 \times \vec{k}_1''$) of the most energetic annihilation photon and momentum directional vector ($\vec{k}_2$) of the second annihilation photon (where $|\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3|$) from the same o-Ps decay event [6, 32]. The operator $\vec{\epsilon}_1 \cdot \vec{k}_2$ is odd under Parity (P), Time (T), and CP transformation which is marked using the '$-$' sign [1, 6, 42, 45]. Similarly, other two operators $\vec{\epsilon}_1 \cdot \vec{k}_3$ and $\vec{\epsilon}_2 \cdot \vec{k}_3$ can be constructed.

Operator	C	P	T	CP	CPT
$\vec{\epsilon}_1 \cdot \vec{k}_2$, $\vec{\epsilon}_1 \cdot \vec{k}_3$, $\vec{\epsilon}_2 \cdot \vec{k}_3$	$+$	$-$	$-$	$-$	$+$

3. Preliminary result

The signal event considered during this study was o-Ps $\rightarrow 3\gamma + 1\gamma$ scattered from the primary annihilation (as shown in Fig. 1, right), which was selected based on several selection criteria [6, 46]. The coplanarity of momenta and common emission time of these annihilation photons are used to identify them [6, 46]. The major background contribution to our signal comes from p-Ps $\rightarrow 2\gamma$ and cosmic radiation, which are suppressed by the requirement of the TOT range, TOT < 80 ns was selected [46, 47].

The J-PET detector's main characteristic is its rapid timing features derived from plastic scintillators, which enable the determination of the relative azimuthal angles between interacting photons [1, 6, 46, 47]. Using this detector feature, a huge background of $e^+e^- \rightarrow 2\gamma$ was suppressed by taking the condition that the sum of the two least relative azimuthal angles between reported annihilation photons for o-Ps $\rightarrow 3\gamma$ must exceed 200° (Fig. 2) [6, 47]. The assignment of the scattered photon to one of the selected o-Ps $\rightarrow 3\gamma$ candidates is based on the smallest scatter test value (STV) and is calculated by the formula ($\mathrm{STV}_{i,\mathrm{scat}} = (t_{\mathrm{scat}} - t_i) - \frac{\vec{r}_{\mathrm{scat}} - \vec{r}_i}{c}$) where, time and position of interaction on the scintillator strip for i^{th} annihilation hit are t_i, $\vec{r}_i$ ($i = 1, 2, 3$ for hit1, hit2, and hit3 in an event) and that for scatter hit from i^{th} annihilation hit is t_{scat}, $\vec{r}_{\mathrm{scat}}$ [6, 46]. Those hits information that survived after applying the above-mentioned selection condition are considered for the construction of CP odd operators (Table 1) [1, 6, 46]. The momentum direction of the annihilation photon is identified based on the known annihilation point (source position assumed to be at the center of the detector) and the reconstructed point of interaction with scintillator strips due to good timing resolution [6, 20, 46, 47].

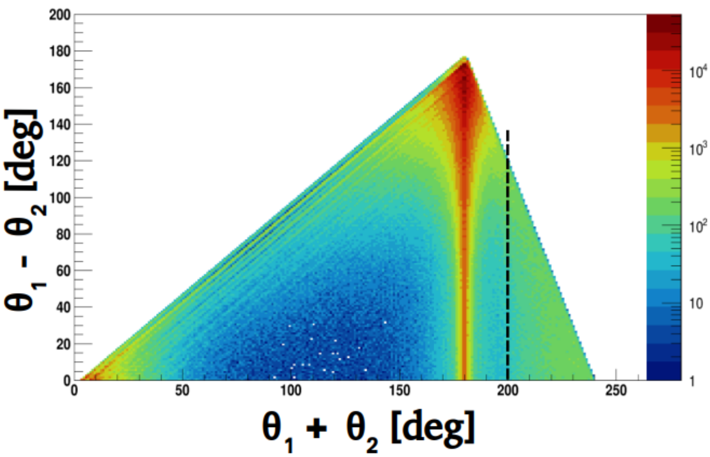

Fig. 2. Sum of two smallest angles between photons from o-Ps $\rightarrow 3\gamma$ decay *versus* their difference plot. Events selected for further analysis are from the region where the sum of two smallest angles $\geq 200°$.

Then the expectation value of the CP odd operators $(\vec{\epsilon}_1 \cdot \vec{k}_2)$, $(\vec{\epsilon}_1 \cdot \vec{k}_3)$, and $(\vec{\epsilon}_2 \cdot \vec{k}_3)$ are calculated by the following equations: $\cos\theta_{12}(\vec{\epsilon}_1, \vec{k}_2) = \frac{\vec{\epsilon}_1 \cdot \vec{k}_2}{|\vec{\epsilon}_1| \cdot |\vec{k}_2|}$, $\cos\theta_{13}(\vec{\epsilon}_1, \vec{k}_3) = \frac{\vec{\epsilon}_1 \cdot \vec{k}_3}{|\vec{\epsilon}_1| \cdot |\vec{k}_3|}$, $\cos\theta_{23}(\vec{\epsilon}_2, \vec{k}_3) = \frac{\vec{\epsilon}_2 \cdot \vec{k}_3}{|\vec{\epsilon}_2| \cdot |\vec{k}_3|}$ respectively (Fig. 3 (a), (b), (c)) [1, 5, 45]. The mean expectation values obtained for $\cos\theta_{12}(\vec{\epsilon}_1, \vec{k}_2)$, $\cos\theta_{13}(\vec{\epsilon}_1, \vec{k}_3)$, and $\cos\theta_{23}(\vec{\epsilon}_2, \vec{k}_3)$ are of the order of 10^{-3}. These are the preliminary results obtained from the 2% of the newly collected 3-layer J-PET detector data sample (RUN11 data) analysed and aiming to improve the mean expectation value of the operator of the order of 10^{-5} after analysis of 100% of data. The next step will be the signal selection criteria optimization and correction for efficiency. New data-taking campaigns using the modular version of the J-PET detector are in progress now intending to improve the already published result [6].

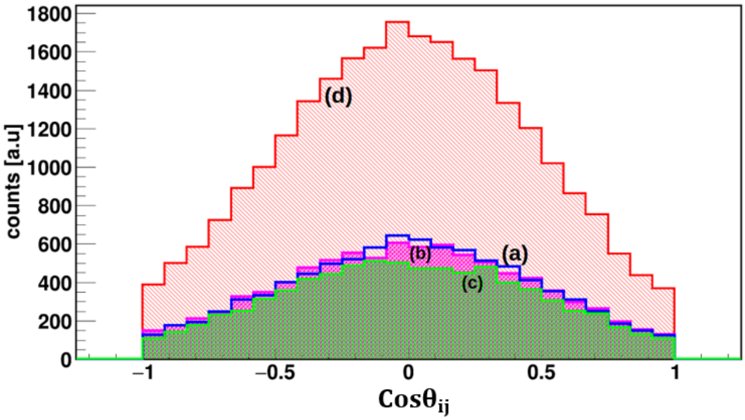

Fig. 3. Preliminary result from 2% of RUN11 data analysed. The expectation values of the CP odd operator: (a) $\cos\theta_{12}(\vec{\epsilon}_1, \vec{k}_2)$, (b) $\cos\theta_{13}(\vec{\epsilon}_1, \vec{k}_3)$, (c) $\cos\theta_{23}(\vec{\epsilon}_2, \vec{k}_3)$, (d) single histogram filled with $\cos\theta_{12}$, $\cos\theta_{13}$, and $\cos\theta_{23}$ values.

4. Conclusion

So far, reached statistical precision for CP discrete symmetry studies in the o-Ps decay is of the order of 10^{-4} [6]. In the coming year, with an increase in source activity and measurement duration, the most recently updated modular version of the J-PET detector may realistically increase the acquired photon statistics by a factor of 100. This is required to achieve the sensitivity level of 10^{-5} for the CP symmetry violation studies and needs to check our signal efficiency [6, 46].

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