J-PET DETECTOR APPROACH FOR TESTING CP SYMMETRY IN THE ORTHO-POSITRONIUM ANNIHILATION*

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Positronium is a suitable leptonic system to test Charge-Parity (CP) discrete symmetry involving the correlations of photons momenta originating from ortho-positronium (o-Ps) annihilation. The photon–photon interaction in the final state due to the vacuum polarization may mimic CP symmetry violation of the order of 10^{-9}, while weak interaction effects lead to a violation of the order of 10^{-14} according to the Standard Model prediction. So far, the experimental limits on CP symmetry violation in the o-Ps decay are set at the level of 10^{-4}. One of the unique features of the J-PET detector is its ability to measure the polarization direction of the annihilation photons without the magnetic field. The J-PET detector can be used to explore discrete symmetry by looking for probable non-zero expectation values of the symmetry-odd operators, constructed from spin of ortho-Positronium and momentum, and polarization vectors of gamma (γ) quanta resulting from o-Ps annihilation. In this work, the J-PET detector experimental and analysis method to improve the sensitivity level at least by one order for CP discrete symmetry studies in the o-Ps decay via symmetry odd operator $(\vec{\epsilon}_i \cdot \vec{k}_j)$, where $\vec{\epsilon}_i$ and $\vec{k}_j$ are reconstructed polarization and momentum vectors of photons from the o-Ps decays, respectively, will be presented.

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1. Introduction

The Standard Model value of CP symmetry violation seems insufficient to explain the observed predominance of matter over antimatter in the Universe [1–3]. Strong and electromagnetic interactions are both symmetric under C and P, proving that they are likewise symmetric under the product CP [3–6]. In positronium decay, the photon–photon interactions in the final state due to vacuum polarization may mimic CP symmetry violation of the order of 10^{-9} according to the Standard Model prediction [2, 7–14]. The motivation for the search of CP symmetry violation effects in positronium decay is further encouraged by the many particle physics experiments conducted in the search for CP symmetry violation effects in hadronic [15, 16] and leptonic systems [17–21]. The three-photon annihilation of the ortho-positronium (o-Ps) will provide insight into CP and even CPT-violating effects through certain angular correlations between the o-Ps spin and momenta of annihilation photons [2, 7, 9, 12]. The limitations of previous experiments were overcome by the 3-layer J-PET detector due to its much higher granularity, which improved the world result and reached the statistical precision of the order of 10^{-4} for CP and CPT discrete symmetry tests [11, 12, 22, 25]. The reported result is the present best upper limit on the discrete symmetry violation in the decay of o-Ps, leaving us 5 orders of more statistical sensitivity to be explored in this aspect.

One of the unique features of the J-PET detector is its ability to measure the polarization and momentum vector direction of the annihilation photons without the magnetic field. This enables us to explore the CP discrete symmetry by looking for probable non-zero expectation values of the CP symmetry-odd operator (Table 1) constructed from the momentum and polarization vectors of γ quanta resulting from o-Ps decay. As a bound system constrained by a central potential, o-Ps is an example of a parity operator (P) eigenstate, and as an atom built out of an electron and an anti-electron (positron), it is an eigenstate of the charge conjugation operator (C), therefore, it also has CP eigenstate [2, 23, 24], which makes o-Ps as one of the perfect leptonic bound systems to study discrete symmetries [2].

Table 1. Discrete symmetry-odd operator constructed using 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 [2, 13].

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

The distinguishing properties and geometry of the J-PET detector allow us to design the positronium source so that the vector polarization of generated o-Ps can be identified [2, 8, 25–27]. Due to parity violation in the β-decay, the positron emitted from the source will be longitudinally polarized [2]. The positrons emitted through β-decay by the source will interact with electrons in the cylindrical layer of the XAD-4 porous material target, to form the spin-linear polarized ortho-positronium [2, 11, 12, 28]. The position of annihilation γ quanta interactions in scintillator strips allows us to reconstruct their momentum and polarization vectors that are used to construct the CP symmetry-odd operator $(\vec{\epsilon}_i \cdot \vec{k}_j)$ [2, 9–11, 25]. Throughout the analysis, authors used the discrete symmetry-odd operator $(\vec{\epsilon}_1 \cdot \vec{k}_2)$, where $\vec{k}_2$ is the momentum vector direction of the second most energetic o-Ps annihilation photon (here, $|\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3|$, which is ordered based on the energy of annihilation photons), $\vec{\epsilon}_1$ is the linear polarization direction of the first annihilation photon, which can be obtained knowing the momentum vector direction of the first annihilation photon $(\vec{k}_1)$ and direction of its scattering in the detector $(\vec{k}'_1)$ *i.e.*, $(\vec{k}_1 \times \vec{k}'_1)$. The momentum vectors of three annihilated gamma photons $(\vec{k}_1, \vec{k}_2, \vec{k}_3)$ and scattered primary photon $(\vec{k}'_1)$ are shown in Fig. 1 (right).

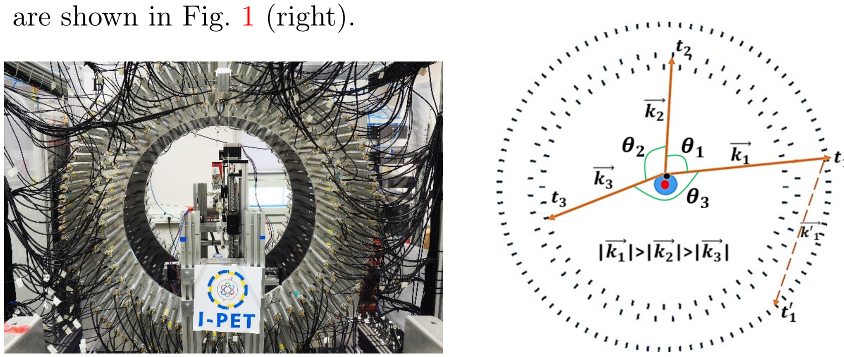

Fig. 1. Left: Photography of a 3-layer J-PET detector [8]. Right: Cross-sectional view of a J-PET detector with the point-like ^{22}Na source at the center (red) covered in XAD-4 porous polymer (blue) and the inside scheme shows o-Ps atom (black dot) decay [8].

J-PET is the only detector now enabling the studies of discrete symmetries using the polarization of photons from the positronium decay without using the magnetic field [2, 27, 28]. In order to construct the discrete symmetry-odd operator $(\vec{\epsilon}_1 \cdot \vec{k}_2)$, we measure the angle θ between $(\vec{\epsilon}_1)$ and $(\vec{k}_2)$ from the same decay event. The value of the CP-odd operator (Table 1) is given by the equation, $\cos\theta = \frac{\vec{\epsilon}_1 \cdot \vec{k}_2}{|\vec{\epsilon}_1| \cdot |\vec{k}_2|}$. The expectation value of the operator gives the measure of the CP discrete symmetry violation [2, 11, 13, 28].

2. Experimental setup and data sample

The Jagiellonian Positron Emission Tomography (J-PET) is the first PET scanner designed using plastic scintillator strips, which makes it inexpensive for use in both scientific research and medical applications [8, 29–36]. 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) [8, 28–33]. Each scintillator in the J-PET scanner is optically connected with Hamamatsu R9800 vacuum tube photomultipliers (PMTs) at each end, which read out the optical signals from the scintillators [8, 28–33]. The sides of scintillator strips are wrapped with reflective foil to reduce photon losses [8, 28–33]. Although the J-PET detector was designed for medical imaging uses, it allows us to measure relative azimuthal angles between the interacting photons [2, 37–40]. These features enable the J-PET detector to investigate o-Ps annihilation into 3γ events (Fig. 1, right), with a considerable reduction of background events for the CP discrete symmetry studies [2, 13, 28].

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 and placed at the center of the small annihilation chamber [41]. This whole setup was placed within the Big Barrel (J-PET detector with 3 layers) and four thresholds (30, 80, 190, and 300 mV) were set to each PMTs. The main aim of this experimental setup is to increase the statistics for the discrete symmetry studies. The positrons emitted by the source through β-decay 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 $\rightarrow 3\gamma$) [42]. The position of annihilation photon interactions in scintillator strips allowed us to reconstruct their momentum and polarization vectors which are used to study CP symmetry violation by determining the expectation values of the CP symmetry odd operator listed in Table 1. The data analysis steps and preliminary results are presented in the next section.

3. Data analysis and results

To test CP symmetry in the o-Ps $\rightarrow 3\gamma$ decay, the experimental data analysis as well as MC simulations have been performed. Several selection criteria have been applied to select the signal process which was o-Ps $\rightarrow 3\gamma$ + 1γ scattered from primary annihilation. As a first analysis step, events selection with hits number exactly equal to 4 in a single event was selected.

To identify favorable hits per event, *i.e.*, 3 annihilations and one scattered, cut on the time over threshold (TOT) were performed. TOT is considered as the measure of energy deposited once a photon hits the scintillator strips. Photon hits on the scintillator strips are read by PMTs as optical signals and for each signal (Fig. 2 (a)), a TOT value was calculated as the sum of TOT values calculated at each threshold 'thr_i' (i = 30, 80, 190, and 300 mV) applied to PMTs (Fig. 2 (b)). The rectangular method calculates

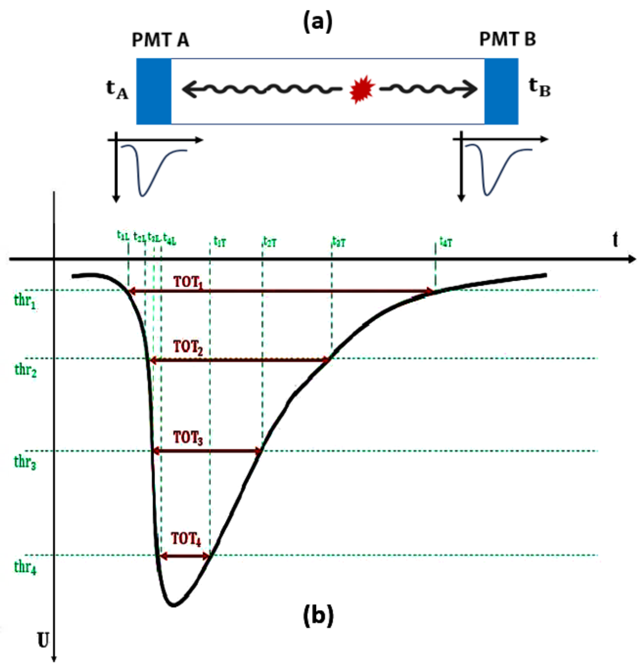

Fig. 2. (a) The incident gamma quantum (red) interacts with the detector strip. (b) Signal received by PMT-B and $\mathrm{TOT_B} = \sum_{i=1}^{4} \mathrm{TOT}_i$ where, TOT_i is TOT calculated as the area of a rectangle that can be constructed at each threshold applied. Similarly, we can calculate $\mathrm{TOT_A}$. TOT of the single-photon hit is $\mathrm{TOT_{hit}} = \mathrm{TOT_A} + \mathrm{TOT_B}$.

the TOT of the signal approximating it to the area of the rectangle that can be constructed at each threshold applied to PMTs. The major background contribution to our signal comes from p-Ps $\to 2\gamma$ and cosmic radiation, which are suppressed by the requirement of the TOT range. TOT < 80 ns was selected (Fig. 3) for experimental data [13, 28] and energy deposition region between 31 keV–400 keV was selected while analyzing MC simulation data (Fig. 4) [43].

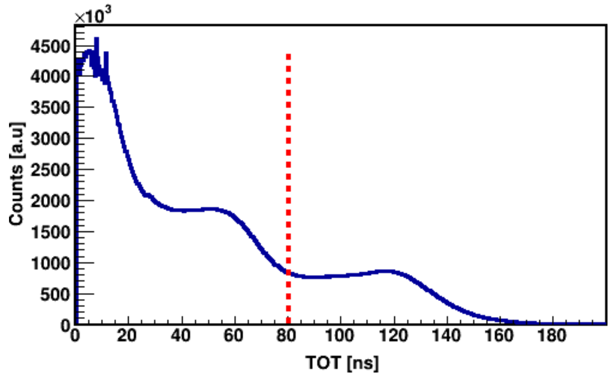

Fig. 3. Time over Threshold (TOT) spectrum.

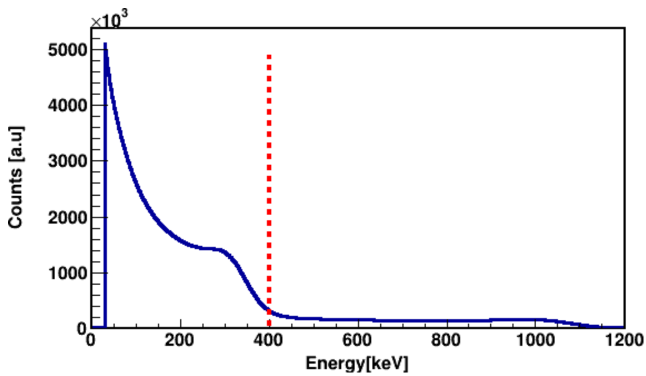

Fig. 4. Energy deposition (Edep) spectrum.

Hits from o-Ps $\rightarrow 3\gamma$ decay are identified based on the comparison of their emission time (emission time spread (ETS) $\leq$ 1.5 ns (Fig. 5)), the distance of annihilation plane (DOP) from the center (DOP $\leq$ 4 cm), and in this plane angular correlation between annihilation photons (sum of the smallest angle between annihilation hits $\geq 200^{\circ}$ (Fig. 6)) [28].

The comparison of experimental data and simulations allowed us to set an appropriate selection criterion in the analysis allowing for effective separation of the investigated o-Ps $\rightarrow 3\gamma$ along with one primary scattered gamma signal candidates from the backgrounds. Monte-Carlo studies were performed to check possible background events such as p-Ps $\rightarrow 2\gamma$ events with 2 scatterings (Fig. 7 (a)), events with multiple scattering of a single photon between active elements of the detector (Fig. 7 (b)), o-Ps $\rightarrow 3\gamma$ with primary scatterings with at least one of the primary γ that was not registered (Fig. 7 (c) and (d)), events that can mimic signal events (Fig. 8 (a)).

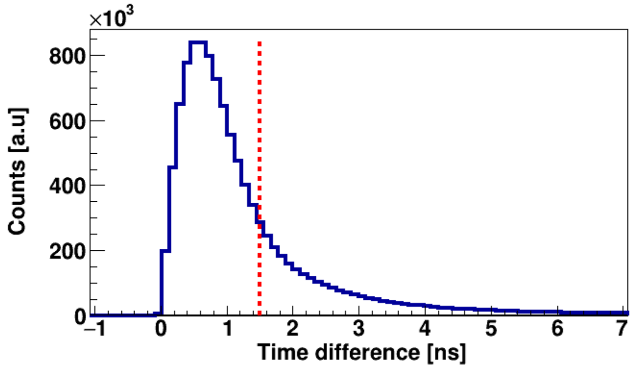

Fig. 5. Emission time spread (ETS) is calculated as an emission time difference between the last and first γ of the o-Ps $\rightarrow 3\gamma$ decay.

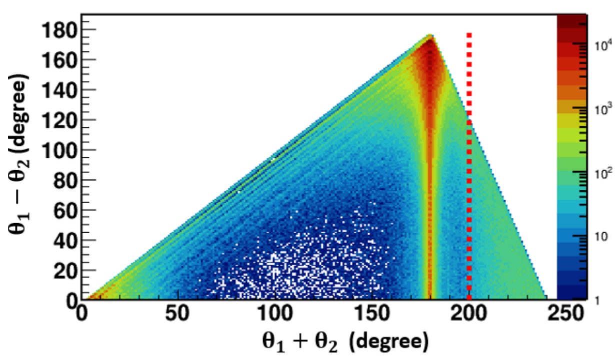

Fig. 6. Sum of two smallest angles between photon momentum vectors from o-Ps $\rightarrow 3\gamma$ decay $\geq 200°$.

Figure 7 shows the sum of the smallest angle between annihilation hits *versus* their difference plots for the simulation of background contribution, while Fig. 8 (a) presents this sum for the MC signal events and Fig. 8 (b) for MC including all possible physics processes. The assignment of the remaining scattered photon to one of the selected o-Ps $\rightarrow 3\gamma$ candidates is based on the smallest scatter test value (STV) (Fig. 9). STV between i^{th} hit and a scatter hit (scat) is calculated by the formula ($\text{STV}_{i.\text{scat}} = (t_{\text{scat}} - t_i) - \frac{\vec{r}_{\text{scat}} - \vec{r}_i}{c}$), where time and position of interaction on 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 $t_{\text{scat}}, \vec{r}_{\text{scat}}$.

Finally, by following the above-described selection criteria, signal events *i.e.*, o-Ps $\rightarrow 3\gamma$ with at least one primary scattered photon were selected. For every selected signal event, the momentum vectors and polarization vectors for the annihilation photons were reconstructed using the hit position

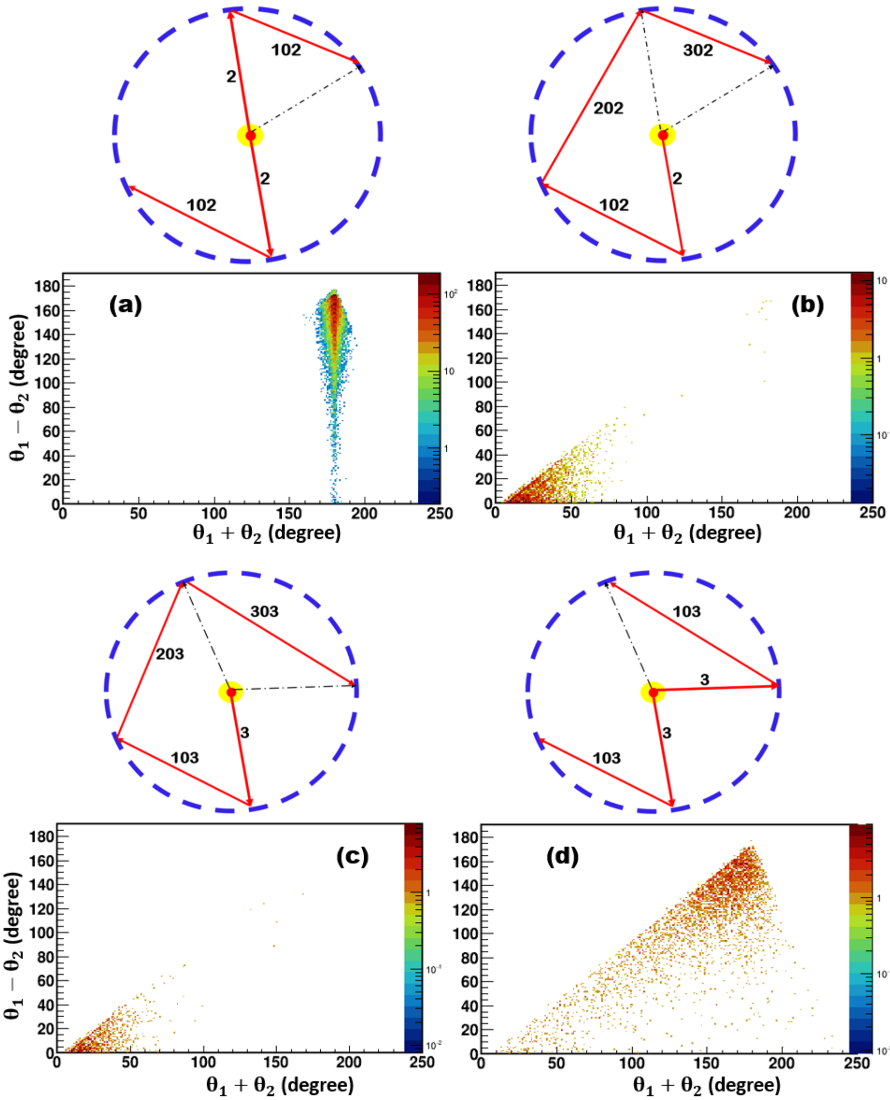

Fig. 7. Sum of the smallest angle between annihilation hits *versus* their difference plots for the simulation of background events.

information from the detector [12, 13]. Then the value of the CP-odd operator $(\vec{\epsilon}_1 \cdot \vec{k}_2)$ is calculated by equation $\cos\theta = \frac{\vec{\epsilon}_1 \cdot \vec{k}_2}{|\vec{\epsilon}_1| \cdot |\vec{k}_2|}$. The $\cos\theta$ plot for 13% of the collected data sample is presented in Fig. 10. Next step will be the signal selection criteria optimization and correction for efficiency.

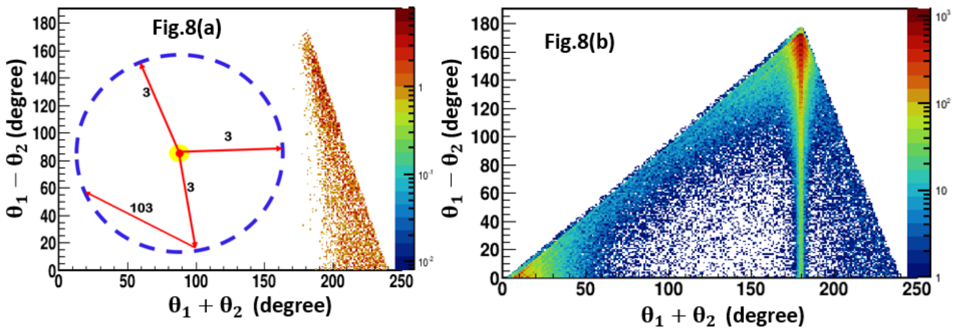

Fig. 8. (a) Sum of the smallest angle between annihilation hits *versus* their difference for MC signal events *i.e.*, o-Ps $\to 3\gamma$ with one primary scattering and (b) for MC including all possible physics processes.

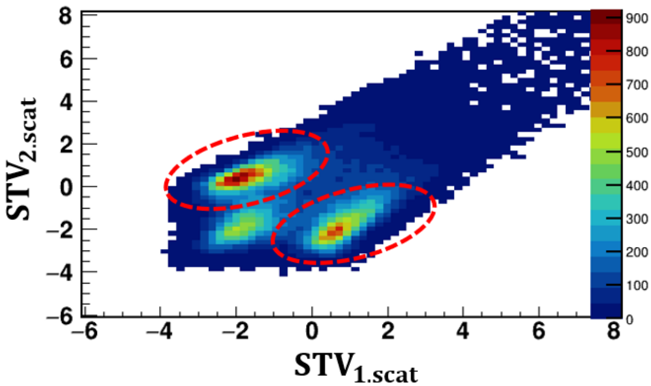

Fig. 9. The assignment of scattered γ hit to one of o-Ps $\to 3\gamma$ hit is based on the smallest scatter test value.

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, which is required to achieve the sensitivity level of 10^{-5} for the CP symmetry violation studies and need to check our signal efficiency.

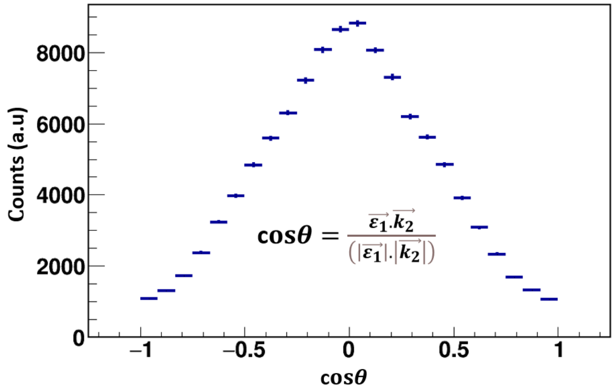

Fig. 10. $\cos\theta$ value of the CP-odd operator $(\vec{\epsilon}_1 \cdot \vec{k}_2)$ is given by the equation, $\cos\theta = \frac{\vec{\epsilon}_1 \cdot \vec{k}_2}{|\vec{\epsilon}_1| \cdot |\vec{k}_2|}$. Preliminary result from 13% of RUN11 data analysed.

4. Conclusion

So far, reached statistical precision for CP discrete symmetry studies is of the order of 10^{-4} [28]. In the years 2024/2025, we are aiming to improve the sensitivity level at least by one order for CP discrete symmetry studies in the o-Ps atom decay with the help of the Modular J-PET detector [44].

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