Developing analysis criteria for studies of CP symmetry with photons from o-Ps decay and Compton scattering with the Modular J-PET Detector

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1. Abstract

Charge conjugation (C) and parity (P) transformation, both discrete symmetries, are coupled to generate Charge-Parity (CP) symmetry [1-8]. Charge conjugation (C) exchanges particles with their antiparticles, whereas parity (P) reflection reverses spatial coordinates [1-8]. Positronium is a suitable leptonic bound system to test CP discrete symmetry involving the correlations of photons momenta originating from ortho-Positronium (o-Ps) annihilation [1-8]. This work aims on developing new analysis criteria towards improving the sensitivity level for CP discrete symmetry studies in o-Ps decay. After the analysis selection chain, expectation value of CP odd operator ($\boldsymbol{\varepsilon_i} \cdot \mathbf{k_j}$) will be calculated for each event, with three hits from o-Ps → 3γ decay and a fourth hit assigned as scattering to one of the annihilation photons. The goal is to achieve substantial (factor of 2 or more) improvement compared to previously published mean expectation value result of 0.0005±0.0007 for the operator ($\boldsymbol{\varepsilon_i} \cdot \mathbf{k_j}$) [7]. These studies will be carried out using the modular J-PET tomograph that has 20 times higher sensitivity for o-Ps registration [7, 9]. The modular J-PET tomograph is a newly developed, flexible, and portable variant of the J-PET detection system [9].

2. Aim: To identify o-Ps events and construct CP odd operator for symmetry studies

Operator	C	P	T	CP	CPT
$\varepsilon_i \cdot k_j$	+	-	-	-	+

Three independent CP odd operators.

$$\varepsilon_1.k_2 = \varepsilon_1.(C - k_1 - k_3) = \varepsilon_1.C - \varepsilon_1.k_1 - \varepsilon_1.k_3 = \varepsilon_1.C - \varepsilon_1.k_3$$

$$\varepsilon_2.k_3 = \varepsilon_2.(C - k_2 - k_1) = \varepsilon_2.C - \varepsilon_2.k_2 - \varepsilon_2.k_1 = \varepsilon_2.C - \varepsilon_2.k_1$$

$$\varepsilon_3.k_1 = \varepsilon_3.(C - k_3 - k_2) = \varepsilon_3.C - \varepsilon_3.k_3 - \varepsilon_3.k_2 = \varepsilon_3.C - \varepsilon_3.k_2$$

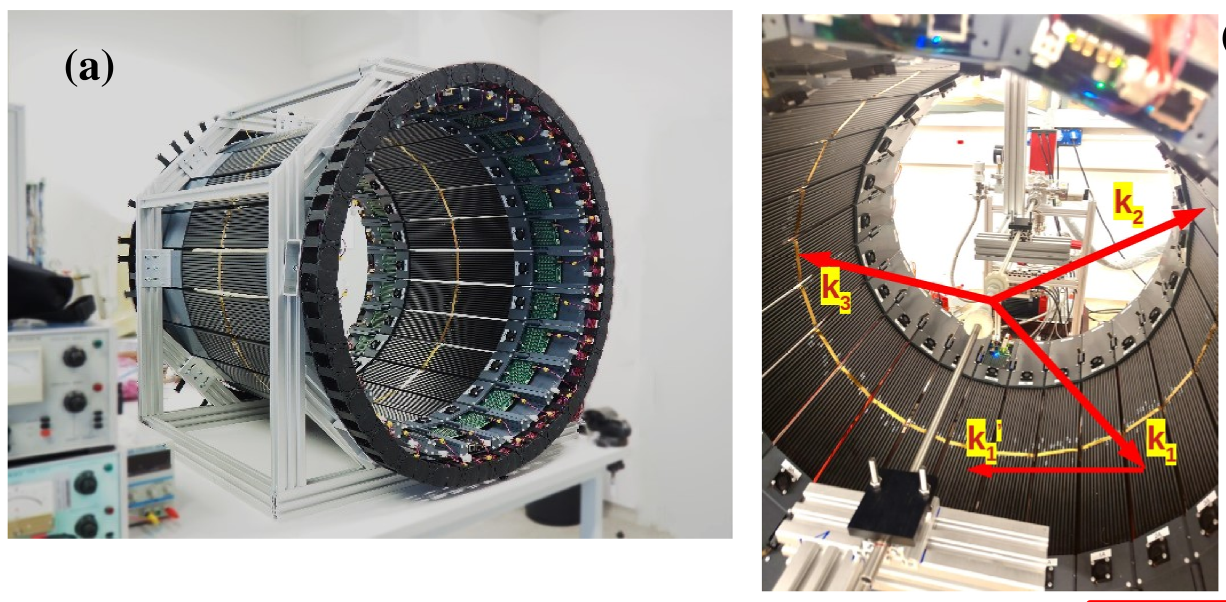


Fig.1. (a) Schematic of arrangement of plastic scintillators in the Modular J-PET detector.
(b) Superimposed arrows indicate momentum vector direction of primary photons from o-Ps decay (k_1, k_2, k_3) and secondary scattered photon (k_1').

The expectation value of the operator, as a measure of observed asymmetry is [1,7],

$$\cos\theta = \frac{\vec{\varepsilon}_i \cdot \vec{k}_j}{\left(\left|\vec{\varepsilon}_i\right| \cdot \left|\vec{k}_j\right|\right)}$$

3. Experimental Setup

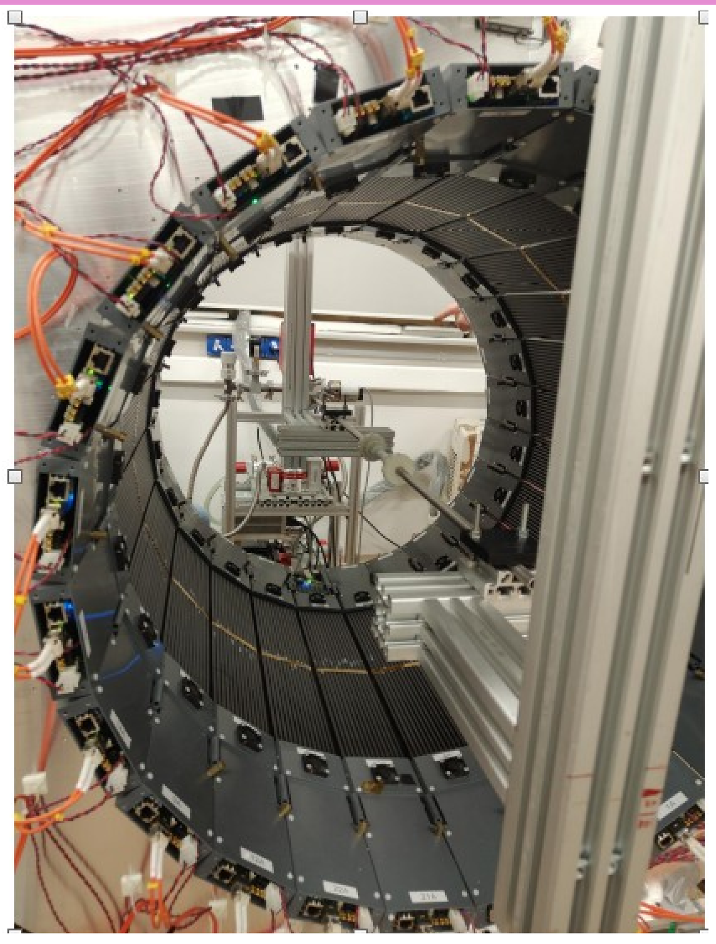


Fig.2. Modular J-PET detector with small annihilation chamber placed at its centre.

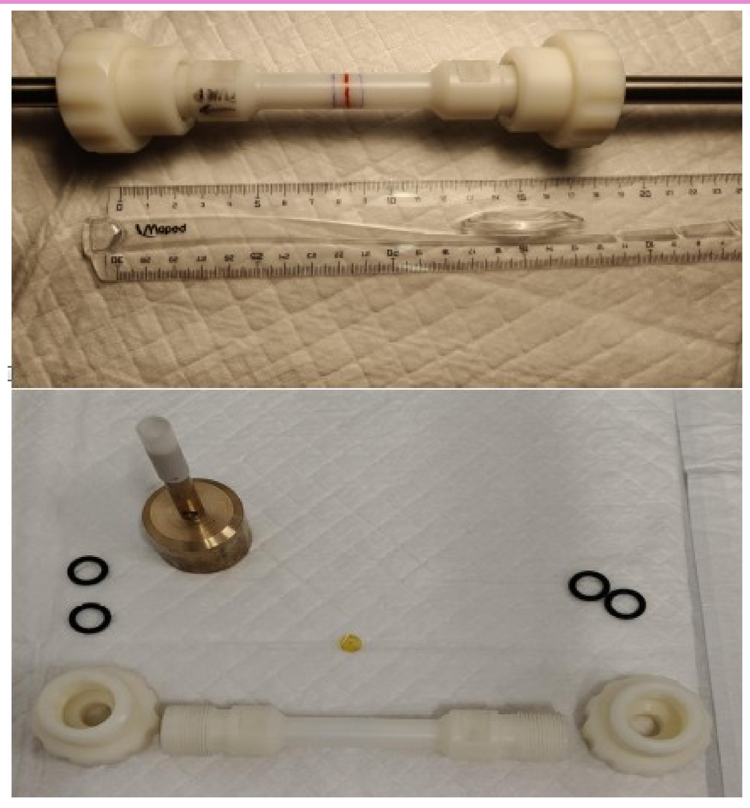


Fig.3. Small annihilation chamber (PA6 material) and sodium source of activity 5.541 MBq. Source is sandwiched between XAD-4 material and placed at the centre of the small annihilation chamber.

Data collected for 138 days.

4. Analysis Scheme

Step 1: Identify Favorable Hits per event:

- |Z Interaction Position| <= 23 cm
- 3ns*V < TOT < 8ns*V
- Hits per event >= 4

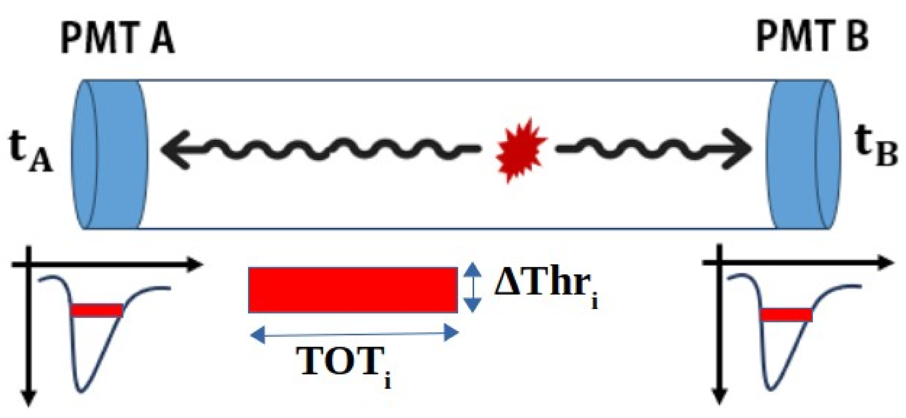


Fig.2. The incident gamma quantum (red) interacts with the detector strip.

$$TOT_{signal} = \sum_{i=1}^{4} TOT_i \cdot \Delta Thr_i$$

$$\text{Where}, \Delta Thr_i = Thr_i - Thr_{i-1}$$

$$Thr_0 = 0$$

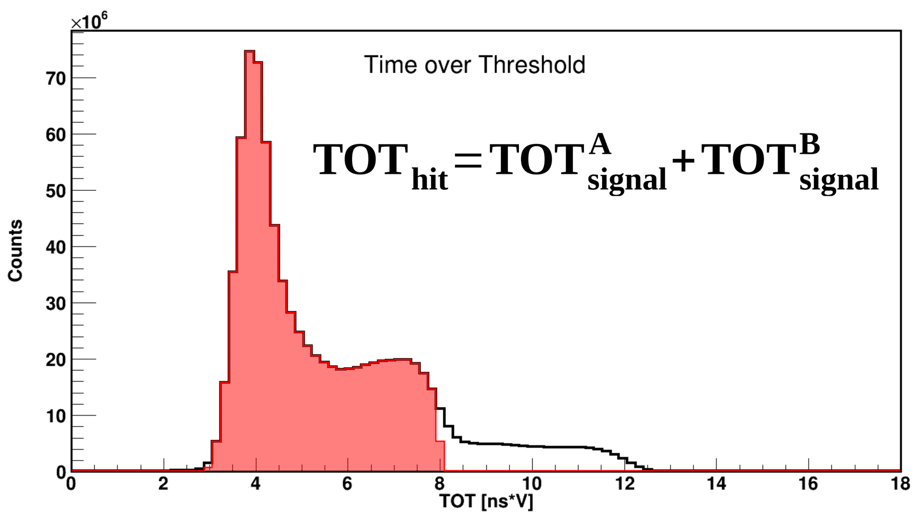


Fig.4. TOT (Time over Threshold) plot.

Step 2: Identification of three Primary annihilation

- $DOP = |A.S_x + B.S_x + C.S_x + D| / (A^2+B^2+C^2)^{1/2}$

  where Ax + By + Cz + D = 0 is annihillation plane equation.
  (S_x, S_y, S_z) is the source position.
- Emission Time difference

  $ETS = t_{hit} - d_{hit}/c$

$$R = \sqrt{(ETS^2 + DOP^2)}$$

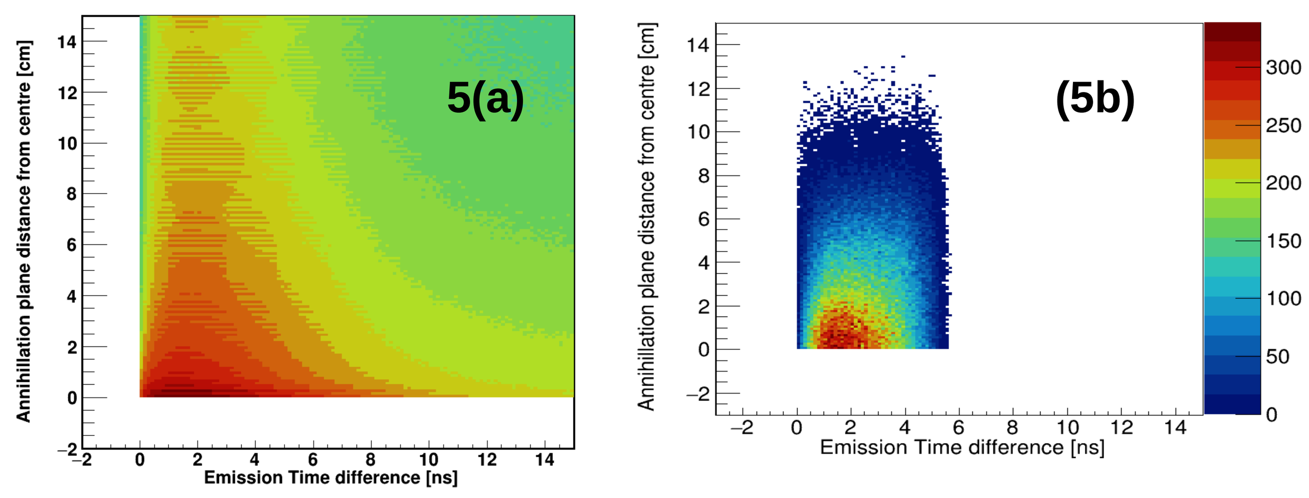


Fig.5. ETS is calculated as a difference between the last and first emission time of o-Ps → 3γ photons. DOP is calculated from the centre of the detector. Fig.5(a) Before and Fig.5(b) After selecting events with smallest R value.

- Relative angle cut, $\theta_1 + \theta_2 > 210^0$ and $\theta_2 - \theta_1 < 70^0$

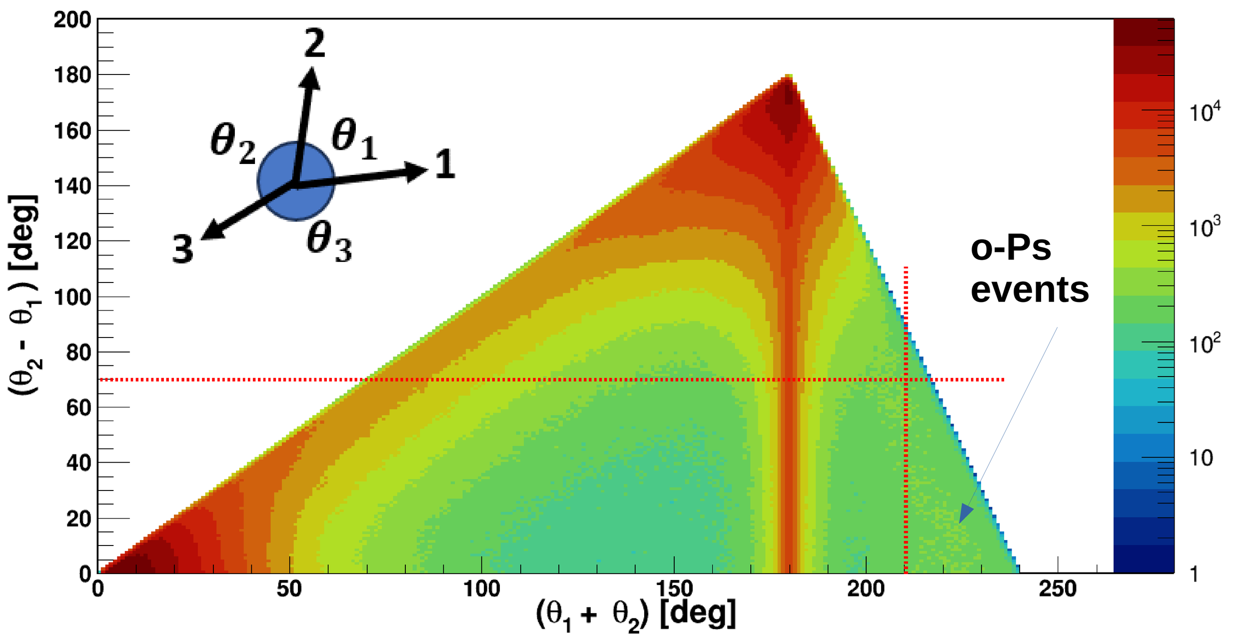
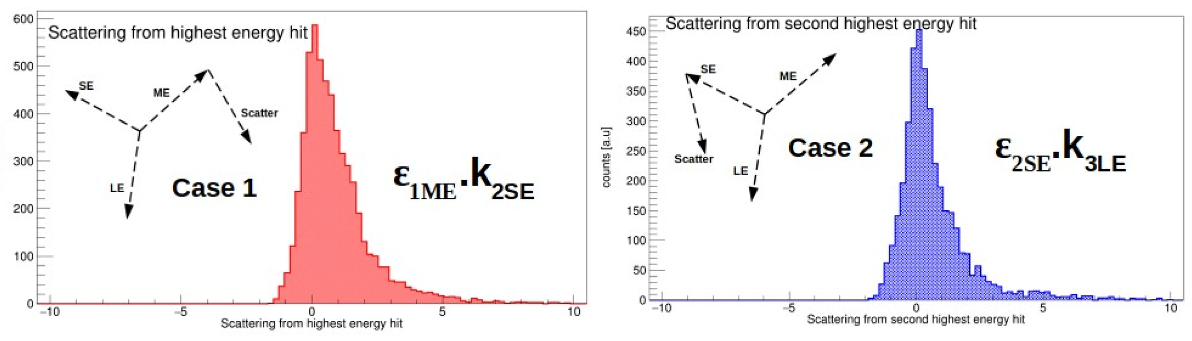


Fig.7. Sum of two smallest angles between photon momentum vectors from o-Ps → 3γ decay vs their difference.

Step 3: Correlate Scattered Hits to Parent:



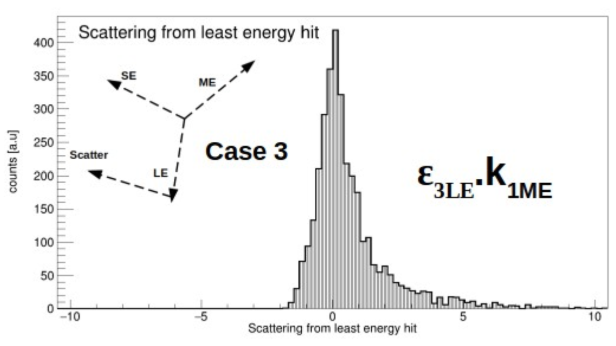


Fig.8. The assignment of scattered photon to one of o-Ps → 3γ candidates is based on the smallest scatter test value.

$STV = (t_{hit} - t_{sca}) - (d_{hit} - d_{scat})/c$

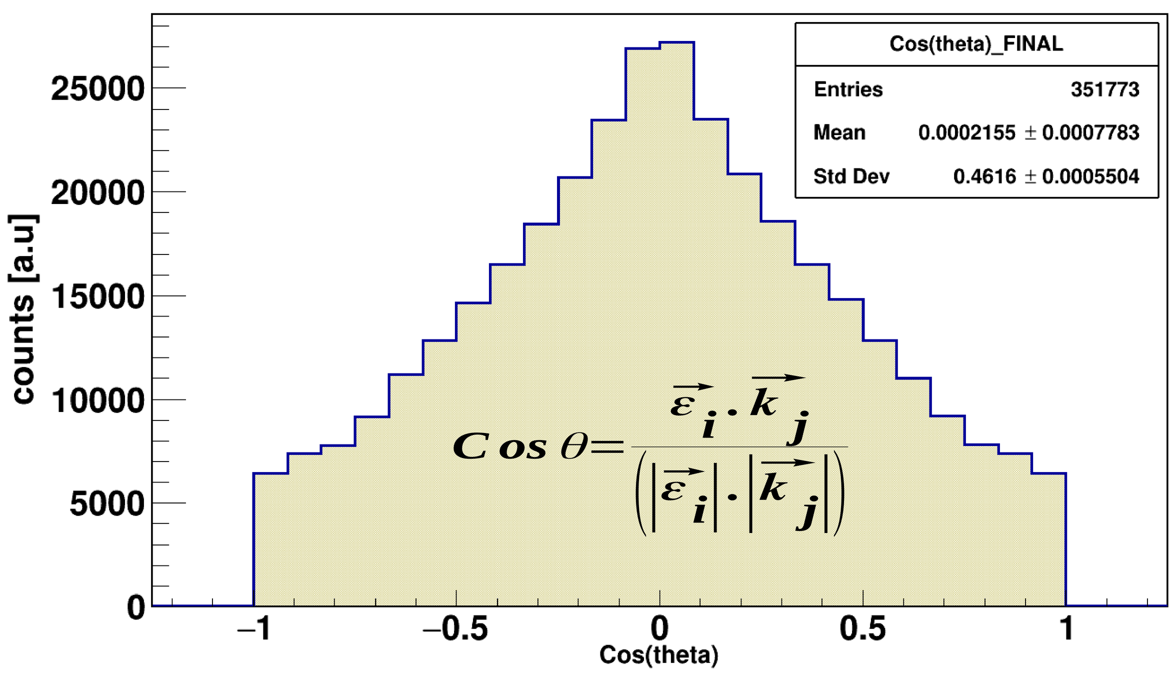


Fig.9. Cosθ plot. Preliminary result from 0.3% of Modular Data analysed.

Estimated preliminary Modular data result:
Mean expectation value error from 0.3% of data = 0.00077
Mean expectation value error from 100% of data = 0.00004

Big Barrel Data result (published in 2024) [7]:
Mean expectation value error = 0.0007

6. References

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7. Acknowledgement

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5. Future Plan

- Monte-Carlo simulation studies for the fine tuning of selection cut values in-order to select signal events for constructing CP symmetry odd operator.
- Analyze the whole data from Modular measurement by utilizing the CYFRONET resources/cluster in frame of PLGRID grant.
- My aim is to improve the statistical sensitivity of the CP discrete symmetry up to a level below 10^{-4} using the Modular J-PET detector.