CP Discrete Symmetry study in the decay of ortho-Positronium atom using the J-PET detector.

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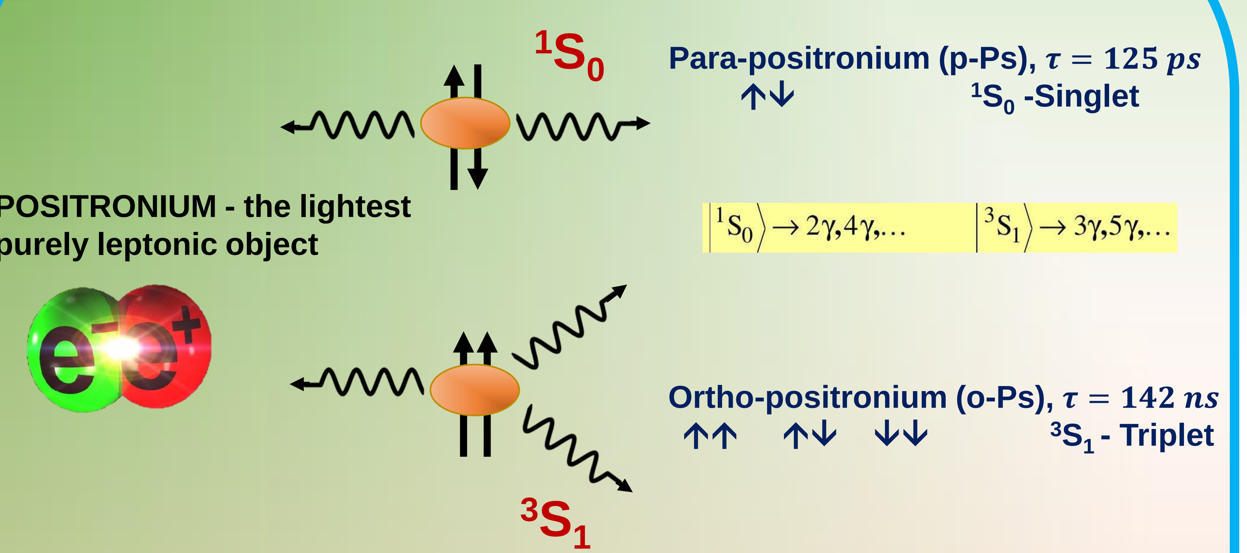
Introduction:

One of the unique features of the J-PET detector is its ability to measure polarization direction of the annihilation photons [1, 2]. And also, we can use J-PET detector as a standard way to study the momentum and spin direction of the annihilation photons [1,3]. The Standard Model predicts that the photon–photon interactions and weak interactions will mimic the symmetry violation in the order of 10^{-9} and 10^{-13} respectively [1-2,4]. Positronium atom is a unique laboratory to test CP discrete symmetry involving correlations of photons momenta originating form ortho-positronium (o-Ps) annihilation [6-9].

Discrete-Symmetry Tests in the Leptonic Sector



- Interaction between electron-positron pair leads to direct annihilation into photons or creation of a bound state called Positronium [1].
- As an atom bound by a central potential, it is a parity eigenstate, and as an atom built out of an electron and an anti-electron, it is an eigenstate of the charge conjugation operator [1-4].

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

Table 1. Discrete symmetry odd-operators constructed using spin orientation of the o-Ps as well as polarization and momentum directions of the annihilation photons [1].

- **The expectation value of the operator as a measure of observed asymmetry is given by the equation below [1].**

$$Cosine(\alpha) = \frac{\vec{\epsilon}_i \cdot \vec{k}_j}{|\vec{\epsilon}_i||\vec{k}_j|} \qquad Where, \vec{\epsilon}_i = \vec{k}_i \times \vec{k}_i'$$

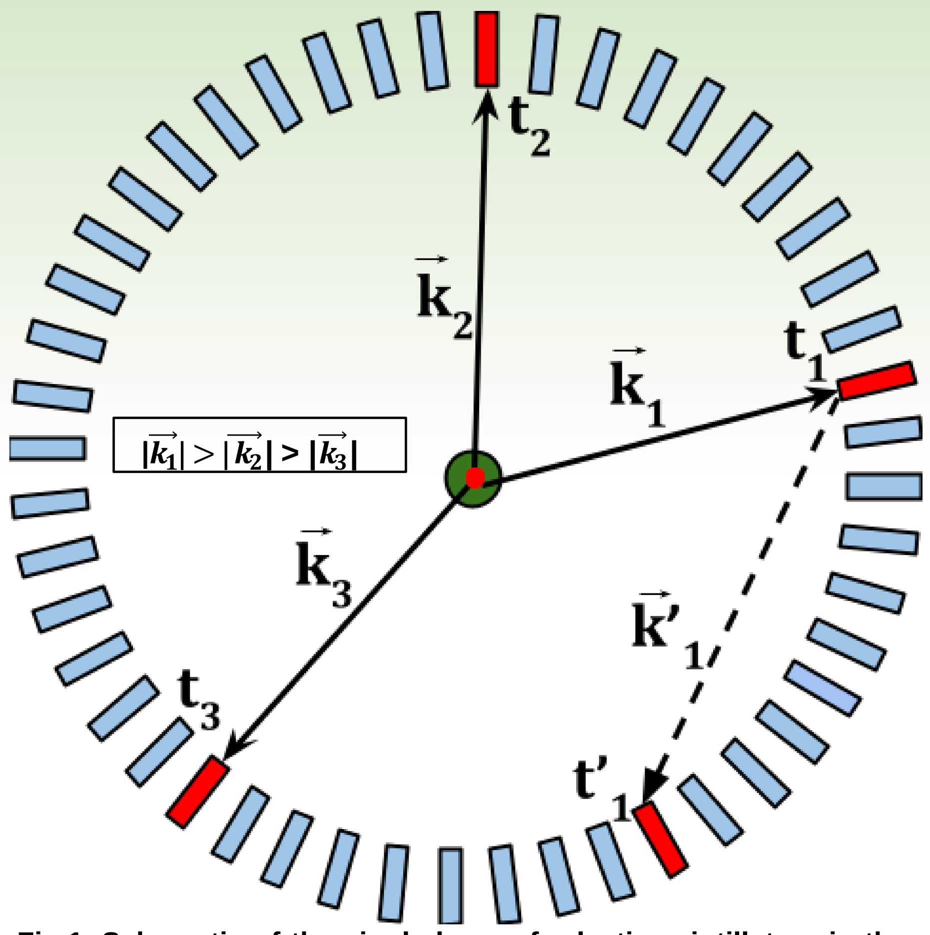


Fig.1. Schematic of the single layer of plastic scintillators in the J-PET detector as the blue ring. Superimposed arrows indicate gamma photon originating from the annihilation photons from ortho-positronium decay ($\vec{k}_1$, $\vec{k}_2$ and $\vec{k}_3$) and secondary scattered photon ($\vec{k}_1'$). The photon interaction time is denoted as t_1, t_2, t_3 and t_1' respectively.

Fig.2. The linear polarization direction of the primary annihilation photon is given as $\vec{\varepsilon} = \vec{k} \times \vec{k}'$ [1].

J-PET Detector

- The J-PET detector consists of 192 plastic scintillator strips (EJ230) of dimensions 500 × 19 × 7 mm^3 each, forming concentric layers (48 modules on radius 425 mm, 48 modules on radius 467.5 mm and 96 modules on radius 575 mm) [1-3,5-6].
- Each scintillator in the J-PET scanner is optically connected with Hamamatsu R9800 vacuum tube photomultipliers (grey) at each end.
- Gamma quanta from Positronium annihilation interact with plastic scintillator strips and cause emission of photons from the visible light spectrum [5-6].
- The optical signal from the scintillators is read out at both of its ends by the photomultipliers (PMT) in the J-PET detector [5,10].
- In order to decrease photon losses the sides along a scintillator strips are covered with reflective foil.

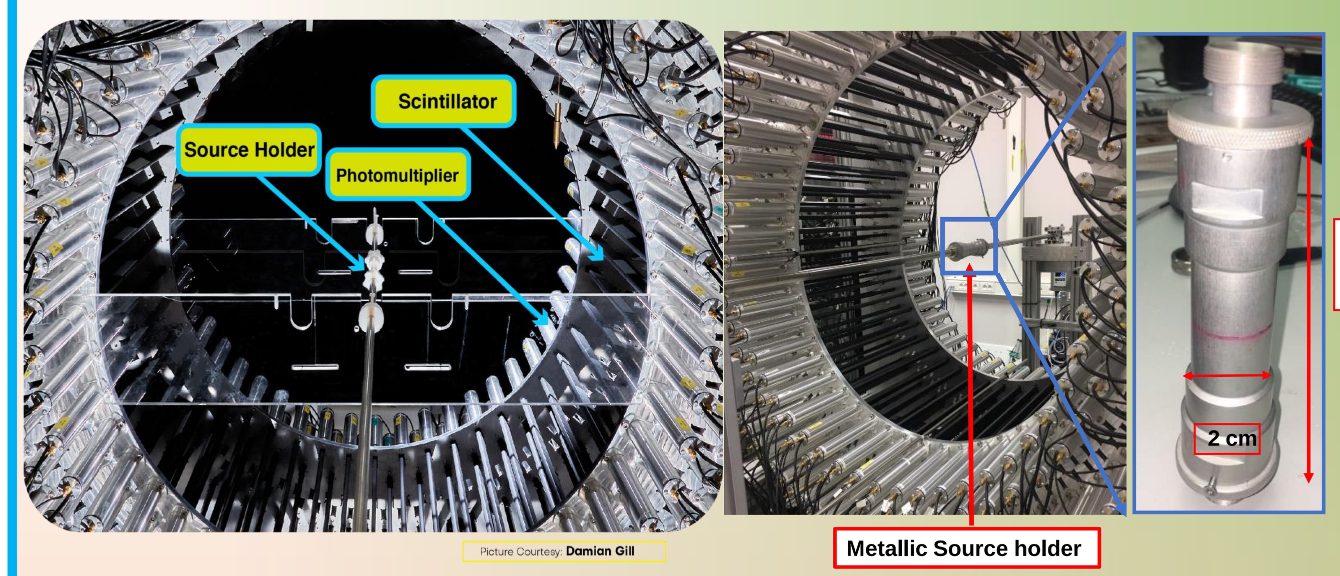


Fig.3. J-PET Detector and source holder placed inside it.

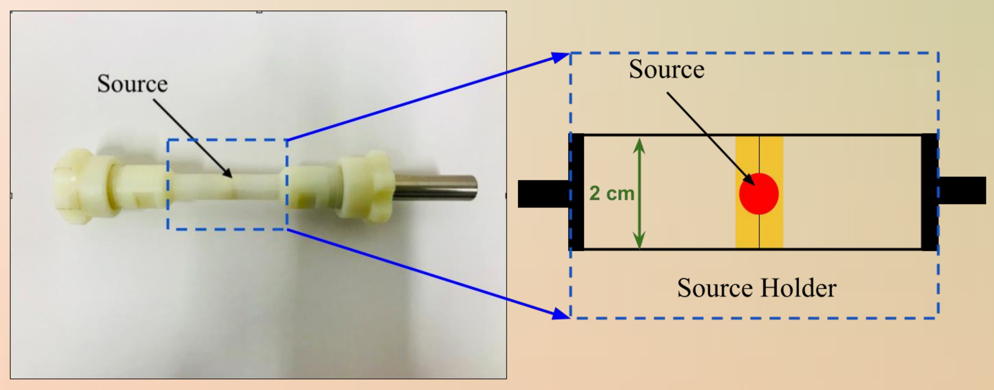


Fig.4. (Left) The real picture of the source holder. (Right) The schematic of the source holder with a point-like source (red) covered with XAD-4 (yellow) in the center.

- Positronium atom is formed in the center of J-PET detector using the β-emitter ^{22}Na source placed inside a small chamber.
- The ^{22}Na source is sandwiched between an aerogel material.
- Time Over Threshold (TOT) is adopted as a measure of energy deposition.
- The signals are measured by using the trigger-less data acquisition [6,9-10].

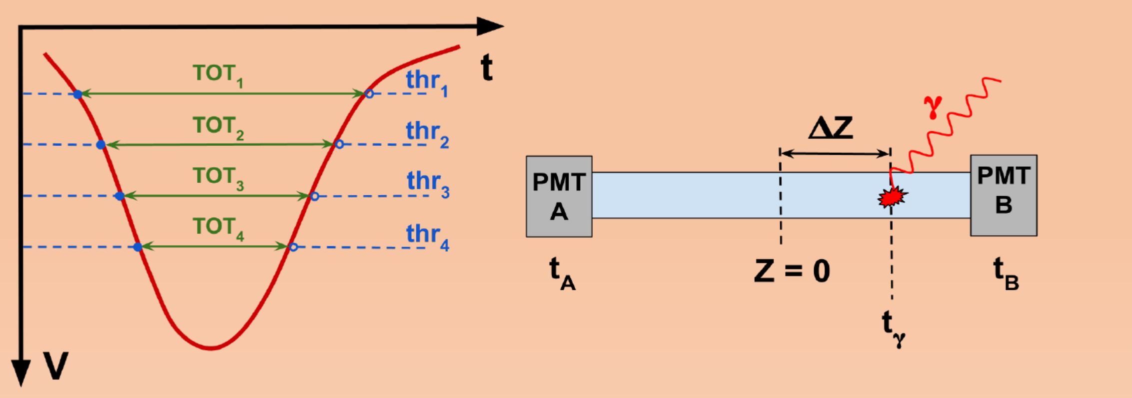


Fig.5. Left: Four voltage threshold levels are applied from the recorded signal (blue lines). Recorded times at both PMT's (t_A and t_B) are used for the determination of the gamma quantum interaction time (t_{Hit}) and place (Z_{Hit}) along the scintillator strip. The value of deposited energy corresponds to the sum of registered times over threshold (TOT) for all thresholds crossed by the signal. Right: The incident gamma quantum (red) interacts with the detector strip, causing photons to be emitted, which are then detected by photomultipliers (PMT) [1,6].

Main 4 stages of analysis

Step 1 : Segregation of Signal, Background, mis-Reconstructed Signal.

Step 2: Identify Favorable Hits per Event.
Selection of good hits from the event.
- Lower Energy Threshold >= 31 keV
- |Z - Interaction Position| <=23 cm
- Cosmic Threshold <=17 ns

Step 3: Identification of three Primary Hits.
Selection of good primary-hits from the event.
- Angle 3D Sum >=190 degrees
- Emission Time <=1.4 ns
- Distance of the Annihilation plane <=4 cm

Step 4: Correlate Scattered Hits to Parent.
Selection of good scatter hit and assignment from the event, reduction of background by cut (Scatter Test Correlation).

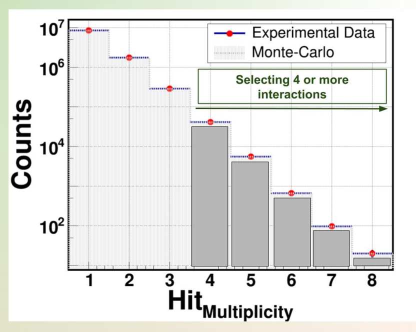


Fig.6. The distribution of number of photon interactions (hits) recorded within each event (Hit Multiplicity).

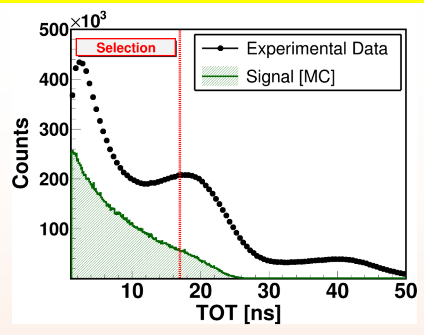


Fig.7. Energy deposited by interacting photons in the plastic scintillators as a function of Time over Threshold.

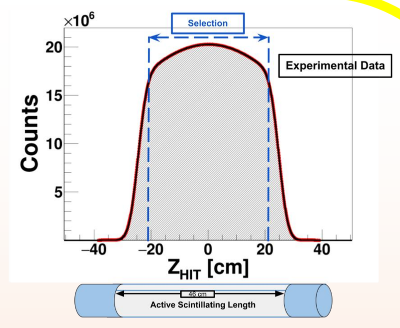


Fig.8. Distribution of the hit interaction position along the axial direction with a schematic indicating the active scintillating region in a single J-PET detector module.

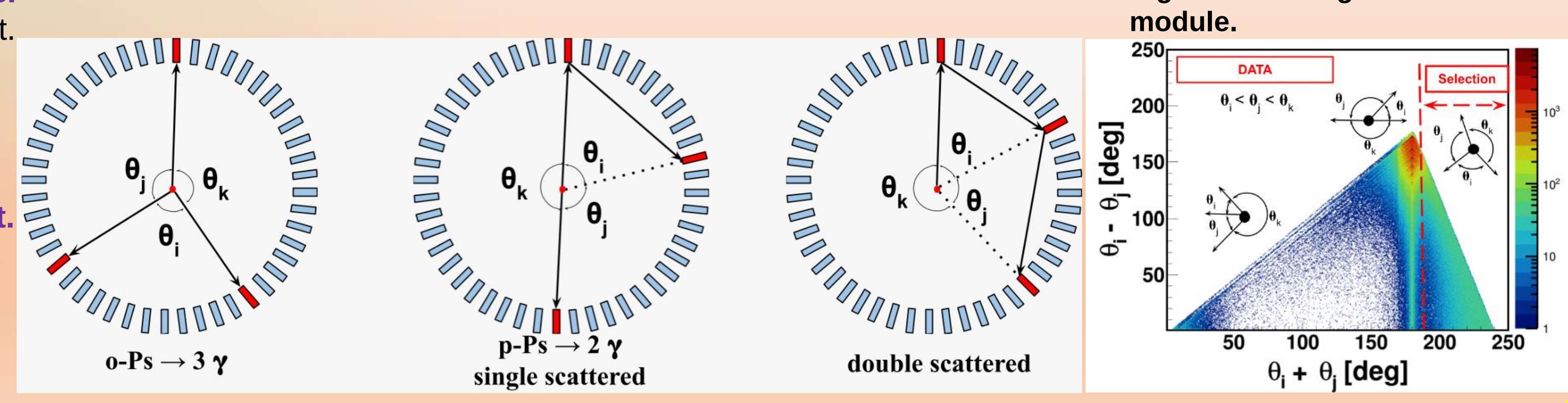


Fig.9. Relative Azimuthal Angle to Segregate Signal from Background.

Summary and Preliminary results

- **Experimental measurement performed for 122 days. The collected data is equivalent to 24 × 10^6 events of o-Ps→ 3γ + γ ′ and the expectation value of the symmetry odd-operator is presented below.**

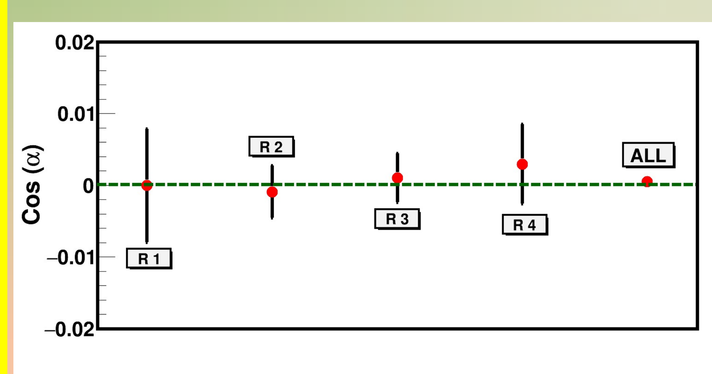


Fig.10. Expectation value of the discrete symmetry odd-operator with its statistical sensitivity for the four parts of the experimental data measured and the total weighted average of the preliminary result.

Run	Expectation value (10^{-4})	Weighted Average (10^{-4})
R1	-1 ± 79	5.2 ± 6.7
R2	-9 ± 36	
R3	10 ± 34	
R4	29 ± 56	

Table 2: Summary of the obtained expectation value result.

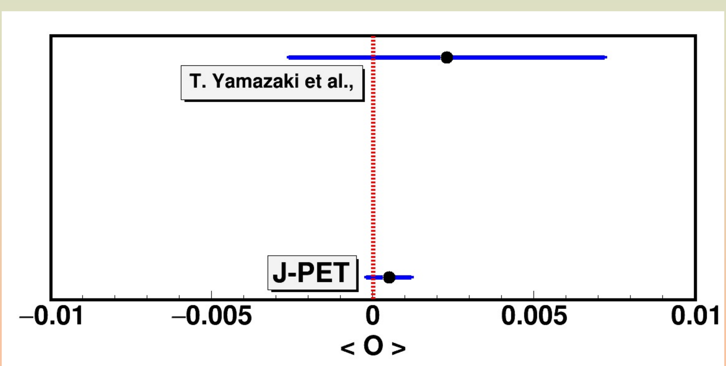


Fig.11. The expectation value determined with the analysis is improved three times more precise than the best classified measurement for CP violation in the charged leptonic sector until now [8] as shown in Fig.11.

Future Research Tasks

Main aim in future is to test the CP discrete symmetry in the decay of ortho- Positronium atom using Modular J-PET Detector.

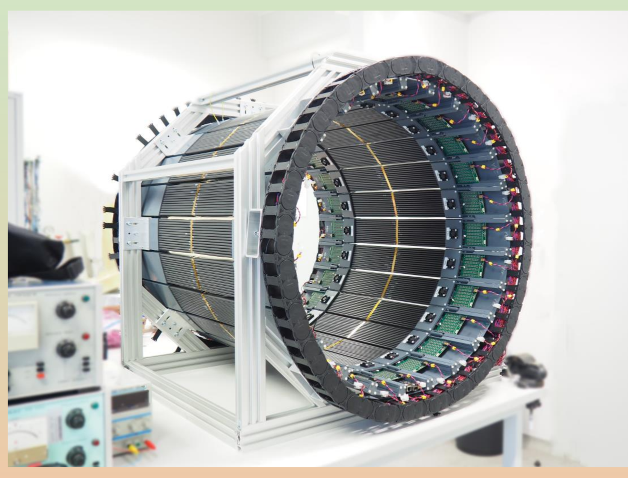


Fig.12. Modular J-PET Detector

- The Modular J-PET detector consists of 24 detection modules. Each module is made of 13 strips of 13 BC-404 plastic scintillators with dimensions of 6x25x500 mm^3. Each scintillator strips are readout at both sides by arrays of 1x4 silicon photomultipliers (SiPMs).
- To be a part of upgrading the detector here we have 4 layers instead of three. This will increase the acceptance by 20%.
- Because of the 20 times higher efficiency of the modular J-PET detector I will be able to select 5 hit events (3 annihilation, 1 polarization and 1 prompt photon), this will enable me to decrease the background with respect to previous experiments and I will be able to distinguish between o-Ps and (p-Ps and direct annihilation) via measurement of the time difference between the prompt photon and annihilation photons.

With the successful measurement we are expecting to improve the statistical sensitivity of the discrete symmetry up to a level below 10^{-4} and estimated at least by 10^{-5}.

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