# PERSPECTIVE OF CP VIOLATION SEARCH BY MODULAR J-PET DETECTOR IN THE ORTHO-POSITRONIUM DECAY*

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The positronium atom, a bound state of electron and positron, is a suitable leptonic test site for Charge-Parity (CP) discrete symmetry research. According to the Standard Model, the photon–photon interaction in the final state due to the vacuum polarization may mimic CP violation of the order of $10^{-9}$, while weak interaction effects lead to a violation of the order of $10^{-14}$. So far, the experimental limits on CP symmetry violation in the decay of o-Ps are set at the level of $10^{-3}$. The J-PET detector can be used to explore discrete symmetries by looking for probable non-zero expectation values of the symmetry-odd operators, constructed from spin of ortho-Positronium (o-Ps) and momentum, and polarization vectors of gamma ($\gamma$) quanta resulting from o-Ps annihilation. The upgraded version of the J-PET detector, with an additional fourth layer of detection modules increases signal acceptance, which allows to triple the efficiency of $\gamma$ quanta detection for CP discrete symmetry studies.

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## 1. Introduction

Charge conjugation (C) and parity (P) operators are combined to create one of the discrete symmetries in the Universe, known as the CP discrete symmetry [1, 2]. The Standard Model value of CP symmetry violation in weak interactions seems insufficient to explain the observed predominance of matter over antimatter in the Universe [3–5]. Strong and electromagnetic

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interactions are both symmetric under the operators C and P, proving that they are likewise symmetric under the product CP [1, 2]. In positronium decay, the photon–photon interactions in the final state due to the vacuum polarization may mimic CP symmetry violation of the order of $10^{-9}$ according to the Standard Model prediction [2, 6, 7]. Many particle physics experiments were conducted in the search of CP symmetry violation effects in hadrons [8, 9] and in leptonic systems [10–12]. The most recent experimental limits on CP violation in positronium decays are set at the level of $10^{-3}$ [13] and CPT violation limits in the o-Ps decay are set at the level of $10^{-4}$ [14, 15]. Searches for the CP discrete symmetry violations are still going on and we are aiming at improving these experimental symmetry violation limits using our new modular J-PET detector [14].

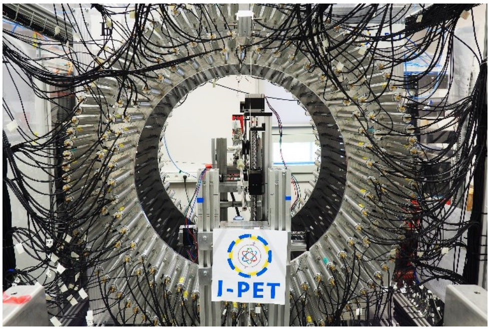
## 2. Jagiellonian-Positron Emission Tomography

The Jagiellonian-Positron Emission Tomography (J-PET) is the first PET scanner designed using plastic scintillator strips, which makes it inexpensive for uses in both scientific research and medical applications [16–25]. The capacity of the J-PET detector to monitor the polarization and momentum direction of the annihilation photons is one of its distinguishing properties [2, 21]. Recently, the J-PET Collaboration has constructed the modular J-PET detector which offers greater statistics of $\gamma$ quanta in a shorter measurement period to considerably improve the precision of experimental measurement values [14, 28–32].

### *2.1. 3-layer J-PET detector*

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 3-layer J-PET detector (Fig. 1 (left)) [16–20]. Each scintillator in the J-PET scanner is optically connected with Hamamatsu R9800 vacuum tube photomultipliers at each end, which read out the optical signals from the scintillators [16–20]. The sides of scintillator strips are wrapped with reflective foil to reduce photon losses [20–24, 26, 27]. Although the J-PET detector was designed for medical imaging applications, its outstanding angle resolution of roughly one degree and time resolution of about 250 ps allows us to measure relative angles between the interacting photons [2, 29–33]. These features enable the J-PET detector to investigate ortho-Positronium (o-Ps) to $3\gamma$ events with a reduction of $e^+e^- \to 2\gamma$ background events by a factor of $10^4$, while rejecting only 3% of signal events [2, 20, 28, 34–36].

Figure 1 (right) shows o-Ps $\to 3\gamma$ decay and the momentum of 3 primary annihilation photons are marked with $\vec{k}_1$, $\vec{k}_2$, $\vec{k}_3$ (where $|\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3|$), while the secondary scattered photon is denoted with $\vec{k}'_1$ [2, 28].



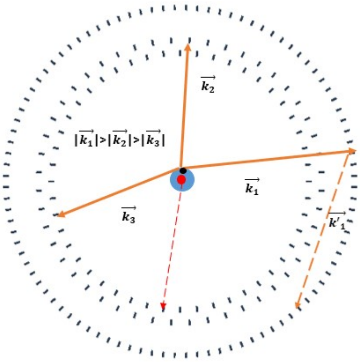
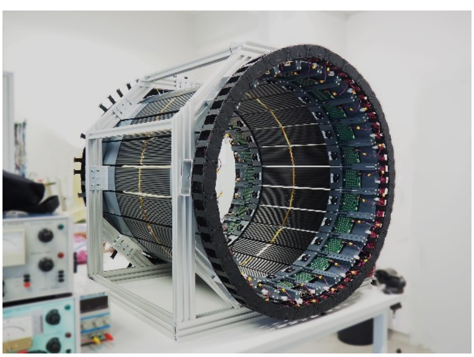




Fig. 1. Left: Photograph of 3-layer J-PET detector [20] and right: its cross-sectional view with a point-like $^{22}$Na source at the center (red) covered in the XAD-4 porous polymer (blue) [20]. The solid arrows show o-Ps (black dot) $\to 3\gamma$ decay and the momentum of 3 primary annihilation photons are marked with $\vec{k}_1$, $\vec{k}_2$, $\vec{k}_3$ and the secondary scattered photon is denoted with $\vec{k}'_1$ [2, 35]. The red dotted arrow indicates a prompt $\gamma$ quantum from de-excitation of the daughter nucleus $^{22}$Ne originating from the $^{22}$Na decay [15, 37].

### *2.2. Modular J-PET detector*

The modular J-PET detector (Fig. 2 (left)) is a newly developed, flexible, and portable variant of the J-PET detector that can be fitted within the 3-layer J-PET detector as shown in Fig. 2 (right) [14, 20].



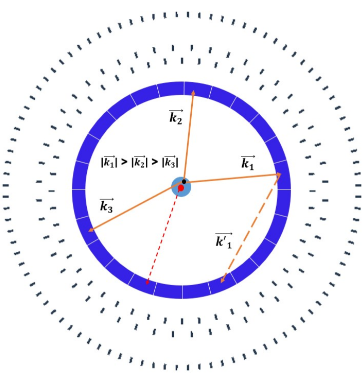



Fig. 2. Left: Photograph of the modular J-PET detector. Right: Cross-sectional view of the modular layer J-PET detector (blue rectangles) fitted inside the 3-layer J-PET detector.

This 4-layer arrangement of detection modules in the modular J-PET detector increases the acceptance of signal events to evaluate the CPT and CP discrete symmetry violations in the o-Ps annihilation process [14, 29]. The modular J-PET detector consists of 24 detection modules and each module is comprised of 13 strips of BC404 plastic scintillators with dimensions of $6 \times 25 \times 500$ mm$^3$ and they are wrapped in Vikuiti ESR and Pokalon 100B foils [19]. Each scintillator strip is read out at both ends by arrays of 1 matrix Hamamatsu Silicon PhotoMultipliers (SiPMs) [30]. Inserting of the modular detector layer inside the 3-layer J-PET prototype reduces the photons losses through gaps and is capable of performing positronium decay imaging with increased multi-photon registration probability [14, 29, 33]. The enhanced o-Ps to $3\gamma$ decay events detection efficiency by the modular J-PET detector allows for the discrete symmetry violation study at a precision level of $10^{-5}$ [14, 28].

## 3. CP Discrete symmetry study in the leptonic sector

In 1933, Anderson discovered the positron in the cosmic ray showers, which is an antiparticle of an electron [38, 39]. An ortho-Positronium (o-Ps) is a bound state formed between a positron and an electron with spin equal to 1 (figure 3) [2, 39].

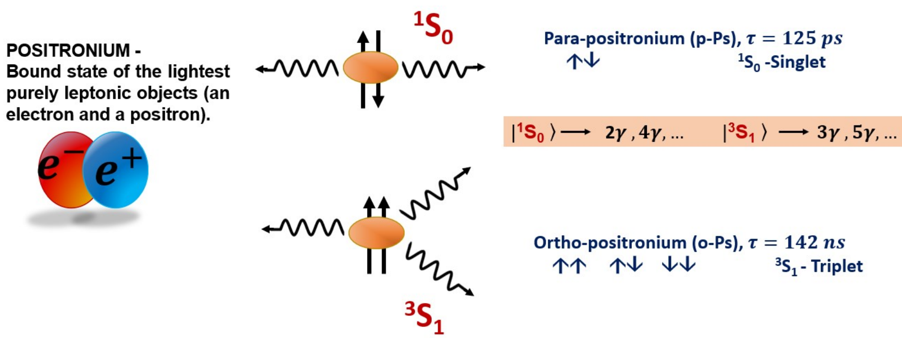



Fig. 3. Interaction between $e^-$–$e^+$ pair leads to direct annihilation into prompt $\gamma$ or creation of a bound state called positronium, which can be formed in two spin configurations and later get annihilated into either odd or even number of photons (o-Ps $\to 3\gamma, 5\gamma, \ldots$ and p-Ps $\to 2\gamma, 4\gamma, \ldots$) [1, 2, 39].

Positronium exists in the singlet state (p-Ps) and triplet (o-Ps) states with spin equal to zero (0) and one (1), respectively [2]. In vacuum, the mean lifetime value of the ground states of p-Ps is 0.125 ns and o-Ps is about 142 ns [2]. In a medium, o-Ps pick-off annihilation process may occur when a positron ($e^+$) from o-Ps annihilates directly with an electron from the material outside, which may reduce the o-Ps mean lifetime even up to a few nanoseconds [2, 39–41]. As a bound system constrained by a central potential, positronium is an example with a parity operator (P) eigenstate, and it is built of an electron and an anti-electron (positron) so, positronium is an eigenstate of charge conjugation operator (C), therefore, it is also a CP eigenstate [2, 40, 41]. So, o-Ps is a perfect leptonic bound system to study discrete symmetries. The unique feature of the J-PET detector which allows the study of CP symmetry violation is the measurement of the polarization direction of o-Ps annihilation photons [2]. Distinguishing the geometry and properties of the J-PET detector allows us to design the positronium source so that the vector polarization of generated o-Ps can be identified [2, 20, 28]. Due to parity violation in the $\beta$ decay, the positron emitted from the $^{22}$Na source will be longitudinally polarized [2] and they will interact with electrons in the cylindrical layer of the XAD-4 porous material target to form the spin-linear polarized ortho-Positronium [2, 20, 28]. The timing and position information of o-Ps annihilation photon interactions in the scintillator strips allow us to reconstruct the annihilation position using the trilateration method, and hence their momentum and polarization vector [2, 14, 34]. The reconstructed annihilation photon momentum and polarization vector can be used then to study CP symmetry violation by determining the expectation values of the CP symmetry odd operator listed in Table 1 [2, 6, 7, 42].

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 (in decreasing energy order) annihilation photon from the same o-Ps decay event [2, 42].

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

The value of the CP operator (Table 1) is given by equation (1) [2, 35]

$$\cos(\alpha) = \left(\vec{\epsilon}_1 \cdot \vec{k}_2\right) \Big/ |\vec{\epsilon}_1| \left|\vec{k}_2\right| \,, \tag{1}$$

where ($\alpha$) is the angle between the linear polarization direction of the most energetic annihilation photon ($\vec{\epsilon}_1$) and momentum directional vector of the second annihilation photon ($\vec{k}_2$) from the same o-Ps decay event. The mean of $\cos(\alpha)$ values is used as a measure of the CP symmetry violation [2, 35].

So far, the experimentally reached non-zero expectation value limit for CP and CPT symmetry violation in the o-Ps annihilation has a precision between $10^{-2}$ and $10^{-3}$, respectively [13, 15, 28]. The statistical uncertainty of the number $N$ of recorded o-Ps into $3\gamma$ decay events and analyzing power of the detector roughly reflects the sensitivity to the discrete symmetry violation parameter [28]. J-PET's objective to reach a sensitivity value exceeding $10^{-3}$, which demands the value of $N$ at least of the order of $10^7$ was achieved with three months of continuous measurements using a 10MBq sodium source [14, 28, 35]. In the year 2021, the limitations of the previous experiments were overcome by the 3-layer J-PET detector due to its much higher granularity which improved the world result and reaches the statistical precision of the order of $10^{-4}$ for CPT and CP discrete symmetry [14, 29, 35]. 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 [14, 29, 35]. With an increase in source activity or 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 our CP symmetry violation studies [39, 42, 43].

## 4. Conclusion

The enhanced multiphoton detection efficiency of the modular version of the J-PET detector will help to improve the o-Ps annihilation $\gamma$ quanta registration probability and will provide larger statistics of o-Ps decay events in a shorter duration of time for the CP discrete symmetry study. The tests of CP symmetry with the modular J-PET detector are planned for the year 2023. We will aim at achieving the sensitivity at the level of $10^{-5}$ for the CP discrete symmetry test by combining the J-PET detector with an additional modular layer of fully digital readout system-based SiPMs, which would enable three times higher single photon detection efficiency.

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