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Improved test of CPT invariance in ortho-positronium decays at J-PET

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Symmetry violation under the combined transformation of charge (C), parity (P), and time reversal (T) in the charged leptonic sector can be sought through the non-vanishing expectation value of certain angular correlation operators that are odd under the CPT transformation. Here, we discuss the experimental approach for a CPT symmetry test by measuring angular correlations between the spin and momenta of photons originating from ortho-positronium (o-Ps→3γ) decays. This experiment is performed with the J-PET detector which measures a broad range of kinematical configurations of ortho-positronium annihilation into three photons and is the first experiment to determine the full range of the CPT-odd angular correlation. A novel technique to estimate the spin of ortho-positronium and momenta of annihilation photons for a single recorded ortho-positronium event allowed J-PET to measure the expectation value of CPT symmetry odd angular correlation operator at the precision level of 10^{-4}, a factor of three better than the previous best result. There are new measures and perspectives for J-PET in improving the sensitivity to CPT violating effects beyond the level of 10^{-4} by increasing the efficiency for detection of photons from ortho-positronium decays by means of using a new modular J-PET detector and spherical annihilation chamber.

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1. Introduction

The J-PET detector is the first positron emission tomography device built from plastic scintillators that can be used as a multi-purpose detector [1–3]. It detects photons of around 1 MeV energy range via Compton scattering from annihilations of positronium which is a bound state of e^- and e^+. This property enables it to perform research in the multidisciplinary range of studies including the fundamental search for discrete symmetries [4, 5], entanglement of photons [6, 7], positronium imaging [8, 9] etc. J-PET consists of cylindrical shaped 192 plastic scintillators strips arranged axially in three concentric layers with photomultiplier tubes as a readout on two ends of each scintillator strip [10–13]. J-PET allows for exclusive registration of a broad range of kinematical configurations of multi-photon annihilations with large geometrical acceptance, high angular (1°), and timing resolution (250 ps) [14, 15]. The main aim of this work is to perform the CPT symmetry test in the three-photon annihilation of ortho-positronium atom with the J-PET detector. The study has already been performed with the J-PET [16] but we want to push the previously set experimental limit of the CPT symmetry test in positronium decays from the measurements with the upgraded J-PET detector.

2. CPT symmetry test in positronium decays

Discrete symmetry violation in positronium decays can be sought for studying certain non-vanishing angular correlation operators which come to be odd under particular symmetry transformations, as shown in Table 1 [17, 18]. These operators involve the spin information of ortho-positronium and the momenta of three annihilating photons ordered by their magnitude $|\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3|$. Any signature of violation of discrete symmetry would come as a non-zero expectation value of such odd operators [19].

Table 1: Angular correlation operators in the three-photon decay of ortho-positronium. '+' and '-' denote whether an operator is even or odd under a given symmetry transformation.

Operators	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	-	+	-	-
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	-	+	-
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$	+	-	-	-	+

An experimental test of the CPT symmetry invariance using odd angular correlation operator $\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$ has already set an upper limit for the respective symmetry violation in positronium decays [20]. But there are still six orders of magnitude differences in the best experimental obtained limit and the expected limit for sensitivity to the CPT violation due to photon-photon interaction [17, 21]. To explore this sensitivity gap, measurements were done by a J-PET detector to test this CPT symmetric odd operator in the annihilations of the triplet state of positronium. This test reached a sensitivity beyond the upper limits defined by previous experiments and found no CPT violation at the precision of 10^{-4} [16].

3. Experimental setup and methodology

The first J-PET measurement of the CPT odd operator $\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$ was done with a three-layer J-PET (192 scintillators) detector and a cylindrical annihilation chamber, by using the method described in ref [4]. ^{22}Na source of 10 MBq activity was used and placed in the center of cylindrical annihilation chamber [24]. The inner walls of the chamber were coated with a layer of porous silica to enhance the ortho-positronium (o-Ps) formation probability. The full chamber setup was placed at the center of the detector and vacuumed to minimize the scattering of positrons before interacting with porous silica to form positronium. This study requires the registration of three photons from o-Ps annihilation. To meet this requirement, positrons (e^+) from a β^+ source undergo interactions with porous silica material, which lead to the formation of o-Ps, as presented in Fig. 1. The trilateration method is used to reconstruct the annihilation point of three photons [25]. Once the annihilation point is determined, it is used to estimate the spin $\vec{S}$ direction of o-Ps along the direction of flight of the positron for each detected event. The measurement demonstrates the potential of J-PET in estimating the expectation value of the CPT odd operator, $\hat{S} \cdot (\hat{k_1} \times \hat{k_2})$ and reached the sensitivity of CPT symmetry test in positronium decays at the precision level of 10^{-4} [16].

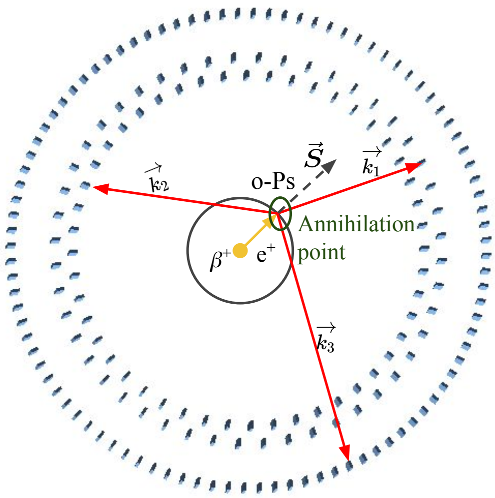

Figure 1: Schematic view of a 3-photon o-Ps annihilation event recorded in the prototype of 3-layer J-PET detector. ^{22}Na source (yellow dot) emitting β^+ is placed inside the vacuum-filled annihilation chamber coated with silica aerogel.

4. Improved CPT symmetry test with J-PET

J-PET has upgraded the detection setup with a view to improving the sensitivity of the CPT symmetry test in o-Ps decays by replacing the cylindrical annihilation chamber for positronium production with a spherical-shaped chamber. It results in increasing the positronium production by a factor of 1.5 [26]. Over one year of testing, measurements were conducted with a spherical annihilation chamber inside the 3-layer J-PET detector using ^{22}Na source with activities of 1 and 4 MBq. These measurements resulted in the identification of o-Ps events in the collected data after comparing the distribution of Monte Carlo simulations for o-Ps→ 3γ events [27]. A new compact detection system has also been developed using 24 modules of 13 densely packed strips of plastic scintillators with silicon photomultiplier readout, termed the Modular J-PET [28]. The modules can be arranged in single or multiple layers. The higher granularity of Modular J-PET results in increasing the efficiency of the registration of photons. Comparison studies of different Modular J-PET detector geometries as single and multiple layers with already existing 3-layer J-PET detector were done using MC simulations. Parameters like the registration efficiency of photon and secondary Compton scatterings recorded in different detector geometry were compared. The studies conclude that the use of a single layer would be beneficial for the improved CPT symmetry test due to its higher registration efficiency of 3γ from o-Ps decays than 3-layer J-PET detector and the lower probability of inter-detector scatterings compared to multiple layer detectors. [29].

5. Summary

J-PET has performed its first CPT symmetry test with precision improved by a factor of three [16] with respect to the best-known previous experimental results [20]. Around 2 million of o-Ps events were collected from 30 days of measurement for this test in 2018. After this, separate experiments were conducted with the same detector and the new annihilation chamber collected much higher statistics as shown in Fig. 2. Around 60,000 o-Ps events per day were identified. In December 2022, measurements with the modular J-PET and spherical annihilation chamber started with the aim to reach the sensitivity of the CPT symmetry test at the precision of 10^{-5}.

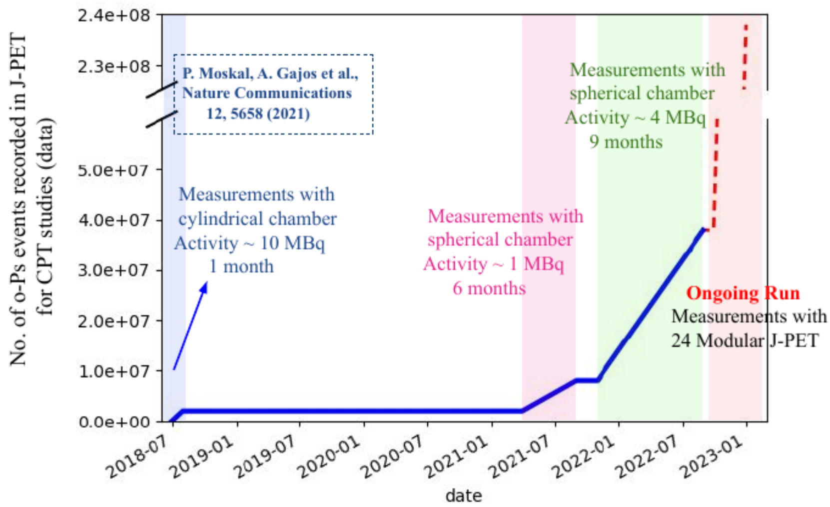

Figure 2: Outlook of a total number of ortho-positronium events recorded in J-PET device in its different experimental runs conducted so far for discrete symmetry studies with large annihilation chambers (cylindrical and spherical) at different source activities. Flat lines indicate intervals where measurements with another chamber were conducted. The last column (red) shows a prediction about the ongoing measurements with Modular J-PET and spherical annihilation chamber through which we want to collect two hundred million of o-Ps events which would be 100 times more statistics than the first measurement with J-PET [16].

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