TOWARDS IMPROVING THE SENSITIVITY OF THE CPT SYMMETRY IN POSITRONIUM DECAYS WITH THE MODULAR J-PET DETECTOR*

N. Chug†, A. Gajos

on behalf of the J-PET Collaboration

Faculty of Physics, Astronomy, and Applied Computer Science
Jagiellonian University, Kraków, Poland
and
Center for Theranostics, Jagiellonian University, Kraków, Poland

Received 27 September 2022, accepted 4 November 2022, published online 23 November 2022

The Jagiellonian Positron Emission Tomograph (J-PET) is the first plastic scintillator-based tomographic device used to test discrete symmetries in the charged leptonic sector. One of such tests is for the CPT symmetry, under the combined transformation of charge, parity, and time reversal in the decays of positronium atoms. J-PET performed its first measurement for the CPT symmetry test by searching for non-vanishing CPT-violating angular correlations between the spin and orientation of the decay plane of ortho-positronium (o-Ps) atoms, which is the triplet state of positronium. The sensitivity of testing CPT symmetry with the J-PET detector reaches the precision level of 10^{-4}. Here, we will discuss the prospects of improving the sensitivity of this test beyond the level of 10^{-4} by enhancing the photon registration efficiency using a new layer of densely packed plastic scintillators and a spherical annihilation chamber as a positronium production medium.

DOI:10.5506/APhysPolBSupp.15.4-A6

1. Introduction

The validation of fundamental symmetries of Nature relies greatly on experimental precision [1]. The CPT symmetry which is an invariance under

* Presented at the 4th Jagiellonian Symposium on *Advances in Particle Physics and Medicine*, Cracow, Poland, 10–15 July, 2022.

† Corresponding author: `neha.chug@doctoral.uj.edu.pl`

a product of charge, parity, and time reversal transformation, is considered to be an exact symmetry. However, there are many experimental tests that search for its violation in different particle systems [2]. One of such experimental tests of CPT involving electromagnetic interactions is using positronium, which is a bound state of charged leptons (e^- and e^+).

Measurements on a single e^- and e^+ system showed that the CPT symmetry is invariant at the precision level of 10^{-22} [3, 4] in elementary leptonic systems. Quantum electrodynamics (QED) does not allow any violation in the CPT symmetry. QED is verified by the comparison of its predictions with the measurements of positronium fine structure constant and electric magnetic moment to the precision of 10^{-12} [5, 6]. However, the recent measurements of a deviation from QED predictions in the atomic spectroscopy of positronium [7] indicate that it would be worth to investigate in the positronium atom which is an unstable bound state of e^- and e^+.

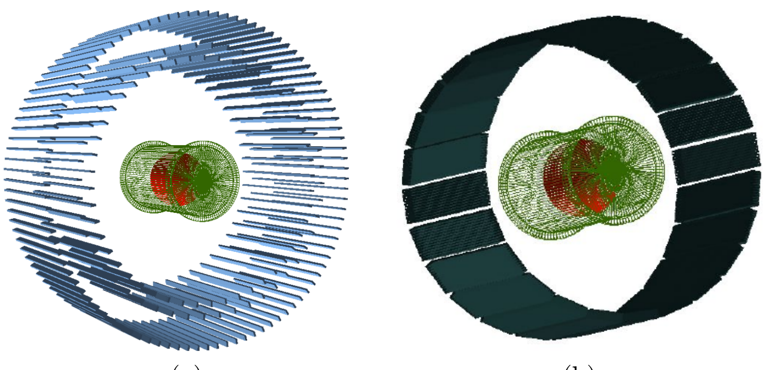
The CPT symmetry violation in positronium decays can also be sought in the non-vanishing angular correlations that come to be odd under the combined transformation of C, P, and T. The search for CPT violating angular correlations is done in the annihilation of ortho-positronium (o-Ps), a $^3S_1$ state of positronium, into three photons [8]. The experimentally tested CPT-violation operator in o-Ps decays is $\vec{S}\cdot(\vec{k_1}\times\vec{k_2})$. It represents the angle between the spin and decay plane orientation of the ortho-positronium atom obtained from the momenta of two most energetic photons. The measurement of the non-zero expectation value of the CPT-odd angular correlation would be an indication of CPT symmetry breaking. It is completely a model-independent approach to search for CPT violation.

The first direct search for CPT invariance using the angular correlation operator was done in 1988 [9]. The most precise CPT symmetry test was performed with the Gammmasphere detector built of germanium detectors, by detecting three annihilation photons and measuring the expectation value of the CPT-odd angular correlation operator. It resulted in no observation of the CPT symmetry breaking at a precision level of 10^{-3} [10], six orders of magnitude larger than the intrinsic sensitivity limit of the method due to radiative corrections which is expected at a precision level of 10^{-9} [8, 11].

The search has been extended using the J-PET detector constructed from plastic scintillators with better timing and angular resolution (250 ps and 1°, respectively) of recording o-Ps $\rightarrow 3\gamma$ decays as compared to Gammasphere with 4.6 ns and 4°, respectively [12]. The higher granularity of the J-PET detector allowed it to extend the precision limit of testing CPT symmetry to 10^{-4} [13]. In this work, we will present J-PET's first CPT test as well as different measures for improving the sensitivity of this test to the precision level of 10^{-5}.

2. Experimental test of CPT with J-PET

The Jagiellonian Positron Emission Tomograph is built of 50 cm long strips of EJ-230 plastic scintillators where 192 scintillators are arranged cylindrically in three concentric layers with radii of 42.5 cm, 46.75 cm, and 57.5 cm [14–16]. There are PMTs mounted on two ends of each scintillator. This setup detects photons via the Compton scattering in 1 MeV range [17–22]. For this measurement, ^{22}Na source of 10 MBq activity was placed in the center of a cylindrical annihilation chamber [23]. There is a porous silica R60G coating on the inner walls of the annihilation chamber where positrons from the source interact with electrons to form positronium. The entire chamber is positioned inside the J-PET detector as shown in Fig. 1 (a), and is vacuumed to minimize the scatterings of positrons before they reach the porous silica material [24, 25]. The positronium annihilation location as the common emission point of the three photons from o-Ps decay recorded in J-PET is reconstructed using a trilaterative approach [26]. On each event, the spin of o-Ps event recorded in the detector is estimated along the direction of flight of positron based on the longitudinal polarization of positrons from ^{22}Na source and that allows the J-PET to determine the full range of the CPT-odd angular correlation between o-Ps spin and plane of its annihilation [27]. This experiment measured 2 million events of o-Ps annihilation and obtained the amplitude of CPT-violating asymmetry to be 0.00067 ± 0.00095 [13].



(a) (b)

Fig. 1. Visualization of (a) the 3-layer J-PET with spherical annihilation chamber at the center and (b) The 24-Modular J-PET detector with spherical annihilation chamber placed in its center in Geant4.

3. Future endeavours of CPT symmetry test with J-PET

J-PET is working on detector upgrades to improve the sensitivity of CPT symmetry test in ortho-positronium decays. The first upgrade is the use of the spherical annihilation chamber to increase the positronium production in the J-PET. A new set of measurements is being already performed with a spherical annihilation chamber of a radius 10 cm and the 3-layer J-PET detector as shown in Fig. 1 (a) which resulted in an increase in the positronium production rate by a factor of 1.5 as compared to the previous measurements [28].

The second upgrade is a new Modular J-PET detector (Fig. 1 (b)) consisting of 24 modules of densely packed plastic scintillators with SiPM readouts. The higher granularity of the Modular J-PET detector would result in an increase in efficiency for the detection of three photons from o-Ps decays [27]. It is estimated from the Monte Carlo simulations that the registration efficiency of photons from o-Ps annihilation in the 24-Modular J-PET detector is higher than in the case of the 3-layer J-PET detector as shown in Fig. 2.

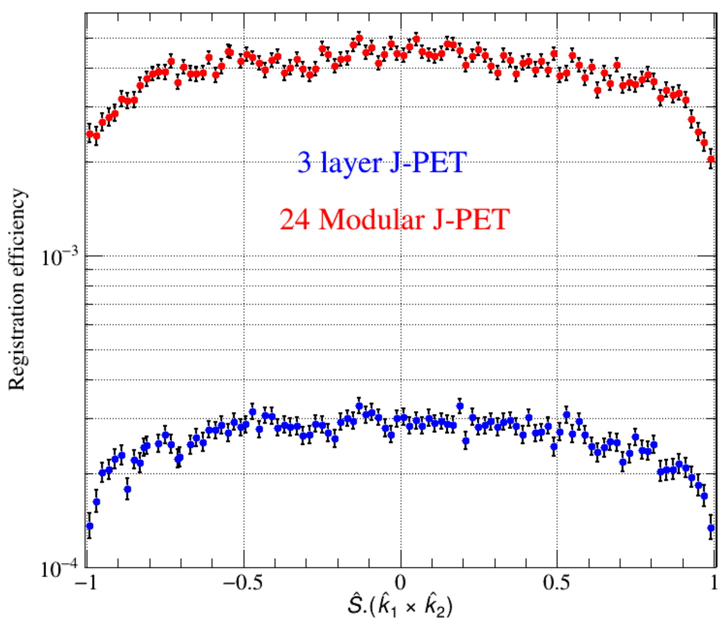


Fig. 2. Distribution of the increased registration efficiency of o-Ps $\rightarrow 3\gamma$ events in the case of the 24-Modular J-PET as compared to the 3-layer J-PET detector geometry using a spherical annihilation chamber for $\vec{S} \cdot (\vec{k_1} \times \vec{k_2})$ operator based on the Monte Carlo simulations.

4. Conclusions

The measurement of the CPT-odd operator $\vec{S} \cdot (\vec{k_1} \times \vec{k_2})$ requires the spin direction $\vec{S}$ of decaying ortho-positronium and the momenta of two most energetic annihilation photons. The novel technique to estimate the spin of o-Ps for a single recorded event allows J-PET to measure the expectation value of CPT-odd correlation over its entire range of values. Around 2 million signal events were collected from the 26 days measurement of the first CPT test with the three-layer J-PET and a cylindrical annihilation chamber. It is estimated from the MC simulations that the desired statistics required for reaching the sensitivity of 10^{-5} with J-PET can be obtained in 4 months of data taking using the Modular J-PET detector and a spherical annihilation chamber.

This work was supported by the Foundation for Polish Science through TEAM POIR.04.04.00-00-4204/17, the National Science Centre, Poland (NCN) through 2019/35/B/ST2/03562, and the Jagiellonian University MNS grant No. 2021-N17/MNW/000013 and Research support module No. 2022-RSM/6/CN, and SciMat and qLife Priority Research Areas budget under the program Excellence Initiative — Research University at the Jagiellonian University.

REFERENCES

[1] M.S. Sozzi, *J. Phys. G: Nucl. Part. Phys.* **47**, 013001 (2020).

[2] V.A. Kostelecký, `arXiv:hep-ph/9810365`.

[3] R.S. Van Dyck Jr., P.B. Schwinberg, H.G. Dehmelt, *Phys. Rev. Lett.* **59**, 26 (1987).

[4] H. Dehmelt, R. Mittleman, R.S. Van Dyck Jr., *Phys. Rev. Lett.* **83**, 4694 (1999).

[5] D. Hanneke, S. Fogwell, G. Gabrielse, *Phys. Rev. Lett.* **100**, 120801 (2008).

[6] R.H. Parker *et al.*, *Science* **360**, 191 (2018).

[7] L. Gurung, T.J. Babij, S.D. Hogan, D.B. Cassidy, *Phys. Rev. Lett.* **125**, 073002 (2020).

[8] W. Bernreuther, U. Low, J.P. Ma, O. Nachtmann, *Z. Phys. C* **41**, 143 (1988).

[9] B.K. Arbic *et al.*, *Phys. Rev. A* **37**, 3189 (1988).

[10] P.A. Vetter, S.J. Freedman, *Phys. Rev. Lett.* **91**, 263401 (2003).

[11] S.D. Bass, *Acta Phys. Pol. B* **50**, 1319 (2019).

[12] P. Moskal *et al.*, *Acta Phys. Pol. B* **47**, 509 (2016).

[13] P. Moskal *et al.*, *Nat. Commun.* **12**, 5658 (2021).

[14] S. Niedźwiecki *et al.*, *Acta Phys. Pol. B* **48**, 1567 (2017).

[15] P. Moskal *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **764**, 317 (2014).

[16] P. Moskal *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **775**, 54 (2015).

[17] K. Dulski *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **1008**, 165452 (2021), .
[18] P. Moskal *et al.*, *Sci. Adv.* **7**, eabh4394 (2021).
[19] P. Moskal, E. Stepien, *PET Clin.* **15**, 439 (2020).
[20] P. Moskal *et al.*, *Nature Rev. Phys.* **1**, 527 (2019).
[21] S. Sharma *et al.*, *EJNMMI Phys.* **7**, 39 (2020).
[22] G. Korcyl *et al.*, *IEEE Trans. Med. Imag.* **37**, 2526 (2018).
[23] M. Gorgol *et al.*, *Acta Phys. Pol. B* **51**, 293 (2020).
[24] A. Gajos *et al.*, *Acta. Phys. Pol. A* **137**, 126 (2020).
[25] A. Gajos *et al.*, *Adv. High Energy Phys.* **2018**, 8271280 (2018).
[26] A. Gajos *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **819**, 54 (2016).
[27] A. Gajos, *Symmetry* **12**, 1268 (2020).
[28] J-PET Collaboration (N. Chug, A. Gajos), *PoS* **(PANIC2021)**, 440 (2022).