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## Systematic Study of Positronium Production Medium in the J-PET Experiment for the CPT Symmetry Test

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The Jagiellonian positron emission tomograph (J-PET) is a novel technology employed to detect multiple photons from positronium annihilation. It employs plastic scintillator strips optimized for the detection of photons in the sub-MeV energy range. The experimental setup consists of a positron-emitting source surrounded by chambers coated with porous materials to facilitate positronium formation. Owing to its large geometrical acceptance and high angular resolution, J-PET enables the reconstruction of various kinematic configurations of positronium annihilations, allowing for precise measurements of angular correlations in ortho-positronium decays. The detector has already demonstrated high sensitivity in charge-parity and charge-parity-time symmetry tests based on such correlations. In the present work, we report a systematic study of the effects of non-uniformity in porous materials used for positronium production in the J-PET setup, performed in the context of a charge-parity-time symmetry test. The systematic uncertainty obtained from this study is  $0.59 \times 10^{-5}$ , and contributes negligibly to the total uncertainty of the charge-parity-time symmetry test.

topics: charge-parity-time (CPT) symmetry, positronium, uncertainty, Jagiellonian positron emission tomograph (J-PET)

### 1. Introduction

This work concerns charge-parity-time (CPT) symmetry tests using the Jagiellonian positron emission tomograph (J-PET) scanner — a tabletop detection system [1–3]. The Standard Model (SM) of particle physics rests upon the foundational principles of CPT and Lorentz symmetry. Any violation of CPT symmetry would imply a violation of Lorentz invariance, as predicted by the Standard Model extension (SME) [4, 5]. Therefore, investigating potential CPT-violating effects provides a sensitive probe into physics beyond the Standard Model.

CPT symmetry, a product of charge conjugation, parity, and time reversal, is one of the fundamental symmetries and has been preserved in all physical processes observed to date. Numerous experimental approaches have been and continue to be developed to test its validity across different particle systems [6]. Despite the lack of a direct violation, these tests have established stringent experimental limits. Most CPT symmetry tests involve precise comparison of fundamental properties

of particle-antiparticle pairs, such as mass, lifetime, electric charge, and magnetic moment [7]. In addition to these direct comparisons, CPT symmetry can also be probed by studying particle interactions. One of such tests is electromagnetic interactions in the three-photon decays of the positronium [1, 8].

Positronium (Ps), a purely leptonic bound state of an electron and a positron, presents a unique investigative tool for precision tests of quantum electrodynamics (QED) and discrete symmetries [9, 10]. Recent high precision measurements of the fine-structure of positronium have revealed discrepancies between experimental results and QED predictions [11]. These discrepancies highlight the importance of further investigations into the structure and interactions within the positronium [12]. The triplet state, ortho-positronium (o-Ps), decays predominantly into three photons, offering a model-independent framework to probe CP and CPT invariance through angular correlations between the o-Ps spin and photon momenta [1, 8, 13]. Any deviation from the expected symmetry conservation would manifest as a non-zero expectation value of CPT-odd operators.

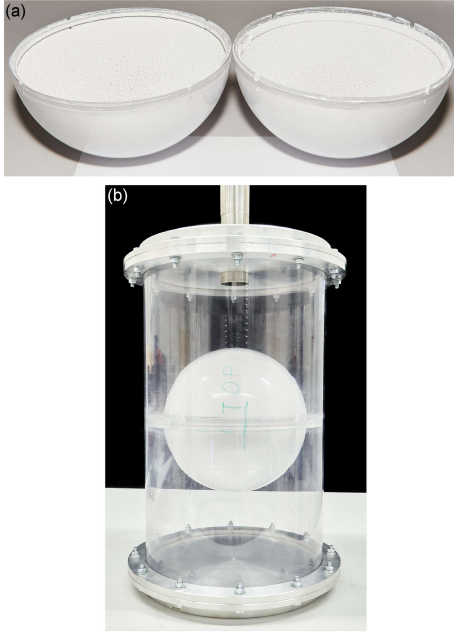


Fig. 1. Spherical annihilation chamber used for positronium production in the J-PET experiment [22]. (a) Two hemispheres coated with a layer of porous silica on their inner walls, joined to form a sphere-shaped chamber. (b) Spherical chamber assembled inside a cylindrical tube.

Within QED, CPT symmetry is preserved in positronium decays, though higher-order effects, such as photon final-state interactions, may mimic apparent violations at the precision level of  $10^{-9}$  [14]. While the weak interaction amplitude in Ps due to parity mixing and weak decays of its state may mimic CPT violation at the precision of  $10^{-12}$  [8, 14]. Experimental investigations of such tests have so far verified CPT invariance with a precision of  $0.00067 \pm 0.00095$  [2]. Further advancements in experimental techniques are imperative to achieve even higher precision level for such tests [15].

## 2. Experimental details

In this study, we report a systematic check for the measurement that was conducted for the CPT symmetry test in the years 2021–2022 with the Jagiellonian positron emission tomograph (J-PET) [16–21]. The measurement data were analyzed in view of testing the CPT symmetry in three-photon annihilations of the o-Ps atom using the angular correlation operator. The CPT-odd angular correlation operator is studied, defined as  $\mathbf{S} \cdot (\mathbf{k}_1 \times \mathbf{k}_2)$  between the spin of ortho-positronium (o-Ps) and the normal to the decay plane of its annihilation photons. Here,  $\mathbf{k}_1$  and  $\mathbf{k}_2$  represent the

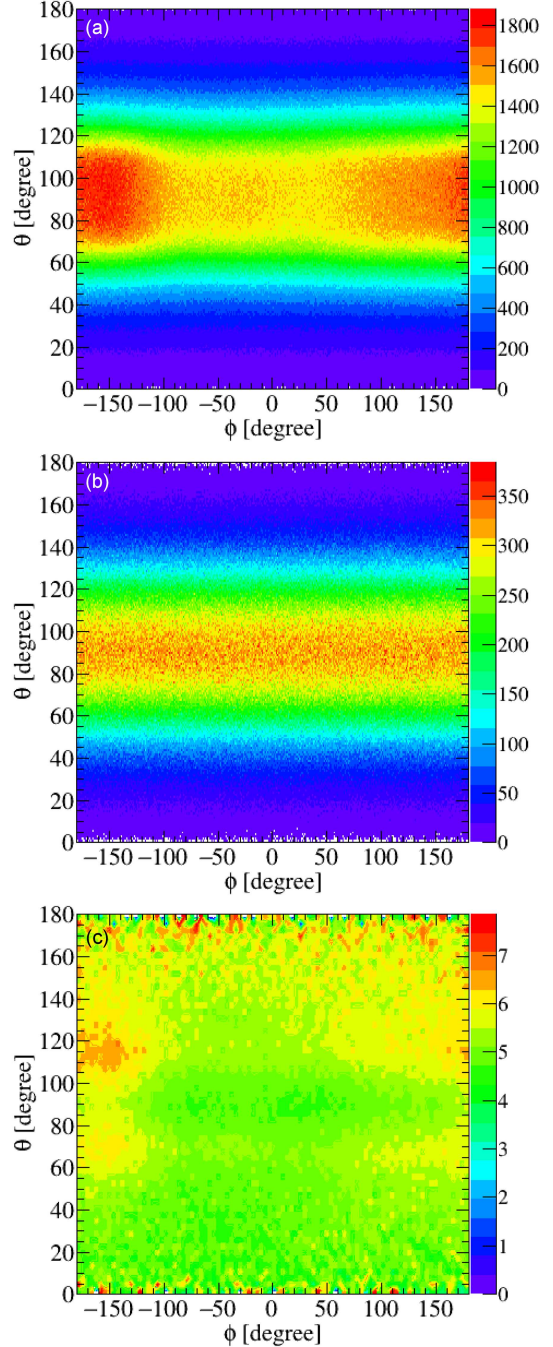


Fig. 2. Two-dimensional (2D) angular map consisting of azimuthal angle  $\phi$  and the polar angle  $\theta$  for the ortho-positronium annihilation points reconstructed from (a) experimental data and (b) Monte Carlo simulations. Panel (c) shows the angular distribution of the ratio between experimental data and MC simulations.

momentum vectors of the two most energetic annihilation photons from the o-Ps decay. The measurement was performed with the J-PET detector and a spherical-shaped annihilation chamber. The final results from these CPT symmetry measurements using J-PET have been reported in an article [3].

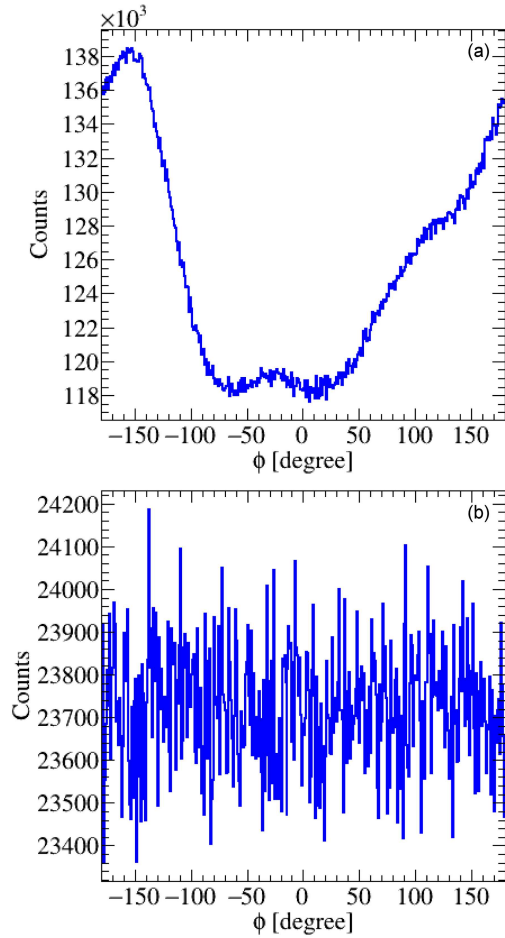


Fig. 3. Distribution of azimuthal angles associated with identified o-Ps annihilation points on XY detector plane for (a) experimental data and (b) MC simulations.

The spherical chamber, used as the medium for positronium production, consisted of two hemispheres that had been joined to form a sphere ( $R = 10$  cm), as shown in Fig. 1 (see also [22]). There is a layer of porous silica coating ( $\approx 2$  mm) on the inner walls of the chamber. As the measurement lasted for one year, the coating of porous material became non-uniform over time. We studied the effect of non-uniform thickness of porous layer on the CPT-odd angular correlation operator using J-PET.

### 3. Systematic check on porous silica uniformity

Any potential asymmetry that might arise from the non-uniform thickness of the porous silica used in the annihilation chamber was investigated. The polar ( $\theta$ ) and azimuthal ( $\phi$ ) angles of the reconstructed annihilation points of the identified o-Ps  $\rightarrow 3\gamma$  decays were analyzed to access the

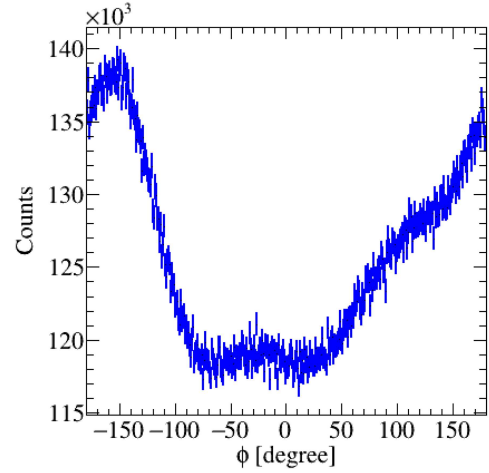


Fig. 4. The distribution of azimuthal angles from Monte Carlo simulations after rescaling with the correction weights. The weighted MC distribution is consistent with the one from experimental data, as shown in Fig. 3a.

uniformity of porous material and to model the effect of the target material thickness on positronium formation. The annihilation points of the identified o-Ps events were reconstructed using the trilateration method [23]. The distributions from these angular variables, termed as two dimensional angular map, are shown in Fig. 2a (for the experimental data) and Fig. 2b (for the Monte Carlo simulations). Note that  $\theta$  denotes the angle with respect to the detector axis  $Z$ , while  $\phi$  is the azimuthal angle in the XY plane measured from the  $X$  axis. The experimental data exhibit more annihilation events in the region of  $\theta$  angles from  $60^\circ$  to  $120^\circ$ , whereas the MC distribution is uniform across these angles range. This localized excess is also visible in the data-to-MC ratio map in Fig. 2c.

To further investigate this effect, the  $\phi$  angles for the data and simulations are compared in Fig. 3. A uniform  $\phi$  distribution would indicate uniform coating thickness, whereas the data reveal noticeable non-uniformity, shown in Fig. 3a.

Correction weights were derived from the 2D angular map by calculating bin-by-bin the ratio of the event counts in the data to the simulations (with a bin size of  $4^\circ$ ). These weights were applied to the MC sample to reproduce the observed non-uniformity, as shown in Fig. 4, and to evaluate its impact on the final CPT-odd angular correlation. After applying the 2D angular weights, the Monte Carlo distributions reproduce the angular structures observed in the data. To quantify the systematic uncertainty associated with the non-uniformity of porous silica, the unweighted and weighted MC distributions of the CPT-odd operator were compared, and their corresponding ratios were evaluated, as shown in Fig. 5a and b, respectively.

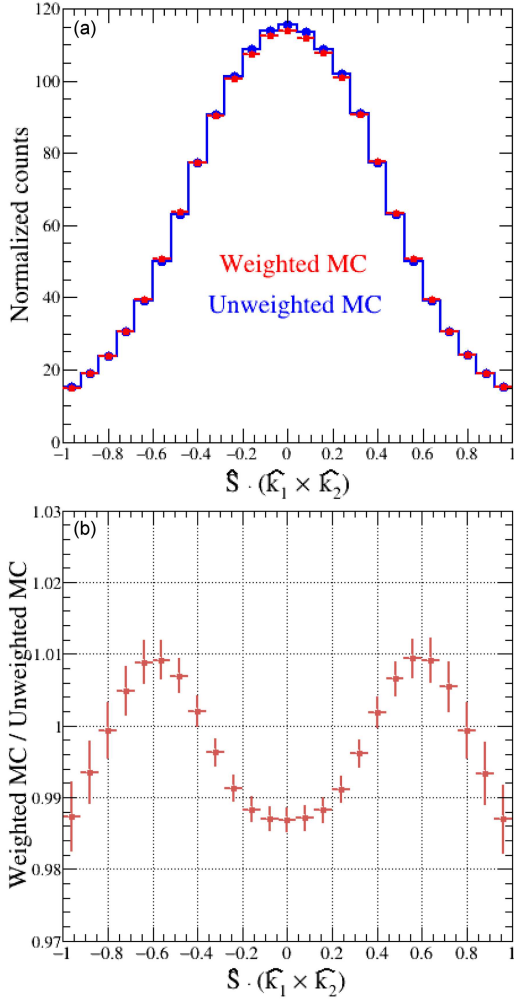


Fig. 5. (a) Distribution of the CPT-odd angular correlation operator  $\mathbf{S} \cdot (\mathbf{k}_1 \times \mathbf{k}_2)$  for weighted and unweighted MC simulations. (b) The corresponding ratio of weighted to unweighted Monte Carlo distributions as a function of angular correlation.

#### 4. Conclusions

In this work, we investigated the impact of the non-uniform thickness of target material used for positronium formation on CPT-odd observables measured with the J-PET detector. The estimated systematic shift due to spatial non-uniformity in the MC sample amounts to be 0.0000059, which is negligible compared to the final statistical uncertainty of the measurement [3]. After applying the correction weights, no statistically significant change in the expectation value of the CPT-odd operator is observed.

It is important to note that the non-uniformity of the target material affects the production of o-Ps annihilations in the experimental setup. The concentration of o-Ps annihilations is not uniform over the entire spherical chamber, as shown in Fig. 2.

Nevertheless, this uneven production of o-Ps events in the J-PET detector has an insignificant impact on the distribution of CPT-odd observables.

These results are particularly relevant in the context of future high-precision CPT symmetry studies with the modular J-PET detector, as described in [24–27]. Using modular J-PET detector, data for CPT studies with four-fold higher statistics compared to previous J-PET measurements have already been collected.

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#### References

- [1] P. Moskal, D. Alfs, T. Bednarski et al., *Acta Phys. Pol. B* **47**, 509 (2016).
- [2] P. Moskal, A. Gajos, M. Mohammed et al., *Nat. Commun.* **12**, 5658 (2021).
- [3] N. Chug, S.D. Bass, E.Y. Beyene et al., *Phys. Rev. D*, (2025) (accepted for publication).
- [4] D. Colladay, V.A. Kostelecký, *Phys. Rev. D* **55**, 6760 (1997).
- [5] D. Colladay, V.A. Kostelecký, *Physical Review D* **58**, 116002 (1998).
- [6] A. Kostelecky, arXiv:hep-ph/9810365 (1998).
- [7] M.S. Sozzi, *J. Phys. G Nucl. Part. Phys.* **47**, 013001 (2019).
- [8] W. Bernreuther, U. Löw, J.P. Ma, O. Nachtmann, *Z. Phys. C* **41**, 143 (1988).
- [9] S.D. Bass, *Acta Phys. Polon. B* **50**, 1319 (2019).
- [10] S.D. Bass, S. Mariazzi, P. Moskal, E. Stepień, *Rev. Mod. Phys.* **95**(2), 021002 (2023).
- [11] L. Gurung, T.J. Babij, S.D. Hogan, D.B. Cassidy, *Phys. Rev. Lett.* **125**, 073002 (2020).
- [12] G.S. Adkins, D.B. Cassidy, J. Pérez-Ríos, *Phys. Rep.* **975**, 1 (2022).

- [13] P.A. Vetter, S.J. Freedman, *Phys. Rev. Lett.* **91**, 263401 (2003).
- [14] B.K. Arbic, S. Hatamian, M. Skalsey, J. Van House, W. Zheng, *Physical Review A* **37**, 3189 (1988).
- [15] H.W. Park, D.W. Jeong, J. Jegal, A. Khan, H.J. Kim, *J. Instrum.* **18**, P03011 (2023).
- [16] P. Moskal, S. Niedźwiecki, T. Bednarski et al., *Nucl. Instrum. Methods Phys. Res. A* **764**, 317 (2014).
- [17] S. Niedźwiecki, P. Białas, C. Curceanu et al., *Acta Phys. Pol. B* **48**, 1567 (2017).
- [18] P. Moskal, N. Zoń, T. Bednarski et al., *Nucl. Instrum. Methods Phys. Res. A* **775**, 54 (2015).
- [19] P. Moskal, K. Dulski, N. Chug et al., *Sci. Adv.* **7**, eabh4394 (2021).
- [20] P. Moskal, E. Czerwiński, J. Raj et al., *Nat. Commun.* **15**, 78 (2024).
- [21] P. Moskal, D. Kumar, S. Sharma et al., *Sci. Adv.* **11**, eads3046 (2025).
- [22] M. Gorgol, B. Jasińska, M. Kosior, E. Stepień, P. Moskal, *Acta Phys. Pol. B* **51**, 293 (2020).
- [23] A. Gajos, D. Kamińska, E. Czerwiński et al., *Nucl. Instrum. Methods Phys. Res. A* **819**, 54 (2016).
- [24] P. Moskal, J. Baran, S. Bass et al., *Sci. Adv.* **10**, eadp2840 (2024).
- [25] F. Tayefi Ardebili, S. Niedźwiecki, P. Moskal, *Bio-Algorithms Med-Syst.* **19**, 132 (2023).
- [26] F. Tayefi Ardebili, P. Moskal, J-PET Collaboration, *Bio-Algorithms Med-Syst.* **20**, 1 (2024).
- [27] P. Moskal, E. Stepień, A. Khreptak, *Bio-Algorithms Med-Syst.* **20**, 55 (2024).