MIRROR MATTER IN ORTHO-POSITRONIUM DECAY SEARCHES USING THE J-PET DETECTOR*

Justyna Mędrala-Sowa, Elena Perez del Rio, Paweł Moskal

on behalf of the J-PET Collaboration

Faculty of Physics, Astronomy and Applied Computer Science
Jagiellonian University, 30-348 Kraków, Poland
and
Centre for Theranostics, Jagiellonian University, 31-501 Kraków, Poland

Received 15 August 2024, accepted 4 October 2024,
published online 27 November 2024

Positronium (Ps), governed by Quantum Electrodynamics (QED), provides a rich domain for exploring fundamental physics. Monte Carlo simulations of its decay provide insights into various aspects of particle physics. The development of J-PET, an innovative tomography system at the Jagiellonian University using high-resolution scintillator detectors, facilitates interdisciplinary studies encompassing fundamental physics tests, medical research, and quantum entanglement measurements but also enhances our capacity to investigate positronium decays in pursuit of potential dark matter (DM) candidates, a lingering enigma within the current Standard Model (SM) framework. In our research, we employ the J-PET detector to study ortho-positronium (o-Ps) decays as a part of our ongoing quest for the discovery of DM. Our primary goal is to explore mirror matter, which seeks to restore parity invariance and is proposed as a candidate for the Universe's DM. Our study aims to push the boundaries of precision measurement in the decay width of o-Ps to three gamma quanta, contributing to our understanding of the elusive nature of dark matter. The article presents the preliminary lifetime distribution of o-Ps as a search for mirror matter obtained from data collected during a portion of a long-term measurement conducted with the J-PET detector in 2020. The long-term aim of the study is to achieve 10^{-6} lifetime sensitivity.

DOI:10.5506/APhysPolBSupp.17.7-A8

1. Introduction

Dark matter and dark energy play a key role in cosmology. Dark matter makes up most of the Universe's matter, so it can be assumed that there is

* Presented at the 5th Jagiellonian Symposium on *Advances in Particle Physics and Medicine*, Cracow, Poland, June 29–July 7, 2024.

a rich so-called 'hidden sector' potentially linked to the SM by intermediate particles. These potential candidates can be investigated in colliders [1–4] and through cosmological experiments [5]. However, detection has remained unsuccessful despite extensive efforts.

The minimal realization of the 'hidden sector' model is Dark Photon [6], a force carrier between SM and DM. It can be searched for in Ps decays [7] and some preliminary studies have been performed with the J-PET detector already [8].

1.1. Mirror matter

Mirror matter is a hypothetical form of matter predicted to exist alongside known matter [9]. It consists of particles that are reflections of those in the SM that have opposite chirality and interacts very weakly with ordinary matter. This makes mirror matter an excellent candidate for DM, potentially explaining the invisible mass in the universe.

Mirror matter can be searched for in the Ps system, which is a simple bound state consisting of an electron and a positron and is therefore an excellent candidate for QED testing [10, 11]. It is proposed that o-Ps (the triplet state of Ps with $l = 0$ and $s = 1$) could oscillate into its mirror partner [12], which would then decay into mirror photons, leaving no detectable signal in the detector. If o-Ps undergoes oscillation, it will lead to an increased lifetime. A discrepancy in the measured lifetime to the prediction made by QED could indicate the existence of processes not accounted for in positronium theory.

The decay of o-Ps is accurately described by nonrelativistic quantum electrodynamics (NRQED). Using this theory, the o-Ps decay rate has been precisely calculated [13]

$$\Gamma = 7.039979(11) \times 10^6 \ \mathrm{s}^{-1} \,. \tag{1}$$

The most accurate measurement to date is [14]

$$\Gamma = 7.0401 \pm 0.0007 \times 10^6 \ \mathrm{s}^{-1} \tag{2}$$

which is two orders of magnitude less accurate than the calculated value.

2. Detector

The J-PET detector at the Jagiellonian University features axially arranged plastic scintillator strips [15], programmable electronics [16], and a triggerless data acquisition system [17]. It is specialized in registering annihilation photons and serves various purposes [18], including lifetime measurements, symmetry tests [19, 20], quantum entanglement studies [21, 22], and medical imaging [23–27]. Collaborative efforts, such as CPT-violating angular correlation searches, yield highly precise results [20, 28].

The detector has two configurations: a barrel detector with plastic scintillators in three cylindrical layers [29] and a modular design allowing flexible configurations [30–32]. In the modular setup, scintillator strips are read out by silicon photomultiplier matrices (SiPMs), significantly enhancing single-photon detection efficiency and time resolution [18].

With a time resolution of around 380 ps and a position resolution of 4.6 cm (FWHM) [33], the J-PET detector effectively reduces pile-up events, improving the detectability of higher positronium production rates. This capability enhances statistical accuracy in positronium decay studies [33].

The experiment uses a special chamber coated with a porous material that enhances positron formation. The material selected for this experiment is the polymer XAD4 [34].

The results presented in this article are based solely on data collected by the barrel detector, which consists of three cylindrical layers made of plastic scintillators [15, 29]. Inside, there was a small cylindrical production chamber made of PA6 (poliamide) [35]. The pressure inside was $\sim 1.5 \times 10^{-4}$ Pa [19]. The data were sampled at four fixed voltage thresholds: 30, 80, 190, 300 mV [16]. The measurement was conducted for over 250 days starting in April 2020, while the preliminary presented data covered 55 hours.

Currently, measurements are being conducted with the modular configuration. The improved time resolution from this setup is expected to further refine the results discussed here.

To search for o-Ps, dedicated tools and a Monte Carlo generator [23] based on Geant4 [36–38] are employed in the analysis.

3. Analysis

The J-PET experiment uses the ^{22}Na isotope as a positron source. This isotope undergoes β^+ decay to excited ^{22}Ne. Shortly after the beta decay, a photon with an energy of 1274 keV is emitted from the excited neon, marking the start of the event. A source with an activity of 0.702 MBq was used for this research.

This research concentrates on precise determination of the o-Ps lifetime. o-Ps is the triplet state ($l = 0$ and $s = 1$) of positronium, which annihilates into an odd number of photons greater than one. o-Ps mainly decay into 3 photons. Consequently, events with exactly three annihilation photons and one prompt gamma were investigated.

3.1. Main background sources

The o-Ps oscillation has a minimal background from Standard Model processes. However, it is crucial to account for various processes inherent in the data itself, mostly: random coincident events, cosmic rays, scattered photons, pick-off — events where positron from positronium annihilate with a different electron from the detector volume.

3.2. Monte Carlo

MC samples were generated and analyzed, enabling the exploration of data and sources of background to be properly identified and characterized. The deposited energy distribution was created for different types of the events, see Fig. 1.

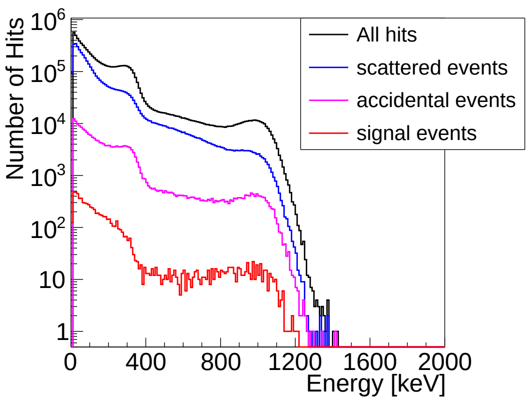

Fig. 1. Deposited energy distribution for the generated MC sample (black histogram). The hits are categorized according to the MC generation as: scatter events (blue), accidental events (magenta), and signal events (red).

Signal events were reconstructed with the following conditions:

1. a number of the hits equals 4: exactly one prompt gamma and 3 annihilation hits, selected with the energy cut,
2. deposited energy is used to discriminate the annihilation gammas ($E_{\mathrm{dep}} < 400$ keV) and the prompt gammas ($E_{\mathrm{dep}} > 450$ keV),
3. sum of the two smallest angles between annihilation hits $\geq 190°$, which suppress events with annihilation into two photons.

3.3. Data

The conditions imposed on the data are the same as for MC. The final, additional step was to reconstruct the annihilation point with the trilateration method. The outcome of reconstruction is shown in Fig. 2. Data from 55 hours of measurements was analyzed.

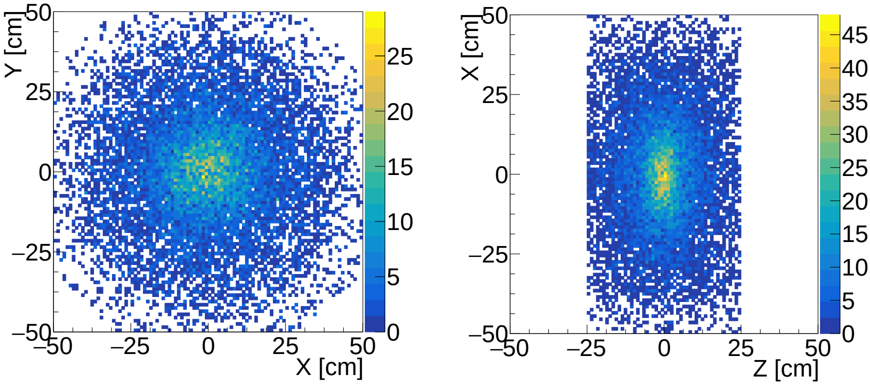

Fig. 2. The reconstructed vertices coordinates on the XY (left), corresponding to the basis of the cylinder (barrel), and XZ plane (right), where Z is defined as the axis of the cylinder.

The lifetime spectrum is then created by subtracting the time of the prompt gamma registration from the average registration time of the annihilation hits after refining the selection by reconstructing the vertices. This greatly removes the backgrounds together with the oPs selection, as can be seen in the red spectrum in Fig. 3. The lifetime is compared to the lifetime without any selection criteria (black histogram) to show the improvement.

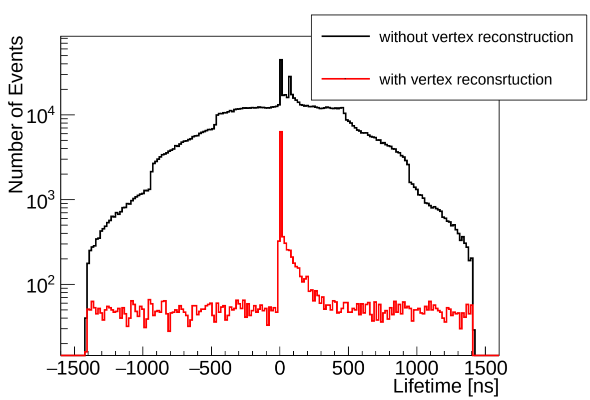

Fig. 3. The reconstructed lifetime of o-Ps from J-PET data.

In the lifetime spectrum, the longest-lived components, with lifetimes exceeding 1 ns, are associated with the o-Ps decay. The obtained lifetime spectrum is consistent with expectations for the XAD4 material. Figure 4 shows the shorter-lived components of o-Ps. For XAD4, the following lifetimes and intensities are determined [34]:

1. $I = 3.3(6)\%\,, \qquad \tau = 2.45(25)$ [ns] ,
2. $I = 2.8(5)\%\,, \qquad \tau = 10.2(6)$ [ns] ,
3. $I = 44.8(4)\%\,, \qquad \tau = 90.8(12)$ [ns] .

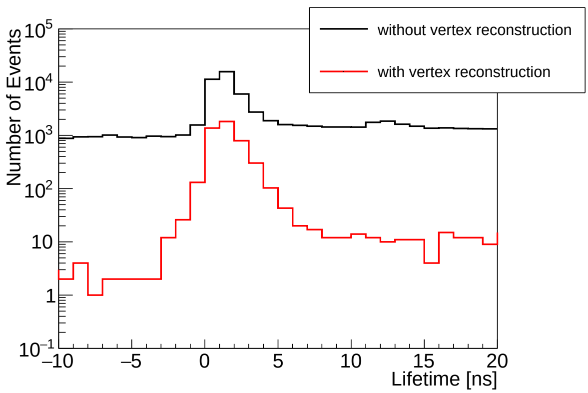

Fig. 4. The reconstructed lifetime of o-Ps from J-PET data in the range from −10 ns to 20 ns.

4. Summary

The main goal of the research is to study mirror matter, a new type of matter and a potential dark matter candidate. The research is currently being conducted using the J-PET detector, specifically designed to precisely measure annihilation processes. With this detector, it is possible to precisely determine the lifetime of the positronium, which is a desired result of the ongoing research. The present study aims (in the long term) at a sensitivity of the order of 10^{-6} to be able to compare to the QED expectations. The analysis of the Monte Carlo samples was conducted to enable the calculation of systematic errors.

We acknowledge support from the National Science Centre (NCN), Poland through grants Nos. 2019/35/B/ST2/03562 and 2020/38/E/ST2/00112, the Ministry of Education and Science, Poland through grant No. SPUB/SP/490528/2021, and the SciMat and qLife Priority Research Area budget under the auspices of the program Excellence Initiative — Research University at the Jagiellonian University.

REFERENCES

[1] E. Perez del Rio, *Acta Phys. Pol. B* **47**, 461 (2016).

[2] NA62 Collaboration (E. Cortina Gil *et al.*), *J. High Energy Phys.* **2019**, 182 (2019).

[3] P. Ilten *et al.*, *Phys. Rev. Lett.* **116**, 251803 (2016).

[4] KLOE-2 Collaboration (A. Anastasi *et al.*), *Phys. Lett. B* **784**, 336 (2018).

[5] R. Foot, *Phys. Lett. B* **789**, 592 (2019).

[6] BaBar Collaboration (J.P. Lees *et al.*), *Phys. Rev. Lett.* **119**, 131804 (2017).

[7] P. Fayet, M. Mezard, *Phys. Lett. B* **104**, 226 (1981).

[8] J. Mędrala-Sowa, E. Perez del Rio, W. Krzemień, *Acta Phys. Pol. B Proc. Suppl.* **17**, 1-A5 (2024).

[9] T.D. Lee, C.N. Yang, *Phys. Rev.* **104**, 254 (1956).

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

[11] S.D. Bass, S. Mariazzi, P. Moskal, E. Stępień, *Rev. Mod. Phys.* **95**, 021002 (2023).

[12] P. Crivelli *et al.*, *J. Instrum.* **5**, P08001 (2010).

[13] G.S. Adkins, R.N. Fell, J. Sapirstein, *Ann. Phys. (N.Y.)* **295**, 136 (2002).

[14] Y. Kataoka, S. Asai, T. Kobayashi, *Phys. Lett. B* **671**, 219 (2009).

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

[16] M. Pałka *et al.*, *J. Instrum.* **12**, P08001 (2017).

[17] G. Korcyl *et al.*, *IEEE Trans. Med. Imaging.* **37**, 2526 (2018).

[18] P. Moskal *et al.*, *Phys. Med. Biol* **61**, 2025 (2016).

[19] P. Moskal *et al.*, *Nat. Commun.* **15**, 78 (2024).

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

[21] P. Moskal *et al.*, *Eur. Phys. J. C* **78**, 970 (2018).

[22] P. Moskal *et al.*, `arXiv:2407.08574 [nucl-ex]`.

[23] P. Moskal *et al.*, *Sci. Adv.* **7**, abh4394 (2021).

[24] M. Das *et al.*, *Bio-Algorithms Med-Systems* **19**, 87 (2023).

[25] S. Parzych, *Bio-Algorithms Med-Systems* **19**, 80 (2023).

[26] E.Y. Beyene *et al.*, *Bio-Algorithms Med-Systems* **19**, 101 (2023).

[27] T. Kaplanoğlu, P. Moskal, *Bio-Algorithms Med-Systems* **19**, 109 (2023).

[28] J-PET Collaboration (E. Perez del Rio), *PoS* **(EPS-HEP2021)**, 697 (2022).

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

[30] F. Tayefi Ardebili, S. Niedźwiecki, P. Moskal, *Bio-Algorithms Med-Systems* **19**, 133 (2023).

[31] P. Moskal *et al.*, *Sci. Adv.* **10**, adp2840 (2024).

[32] P. Moskal, E.Ł. Stępień, *PET Clin.* **15**, 439 (2020).

[33] K. Dulski *et al.*, *Nucl. Instrum. Methods. Phys. Res. A* **1008**, 165452 (2021).

[34] B. Jasińska *et al.*, *Acta Phys. Pol. B* **47**, 453 (2016).

[35] M. Gorgol *et al.*, *Acta Phys. Pol. B* **51**, 293 (2020).

[36] J. Allison *et al.*, *IEEE Trans. Nucl. Sci.* **53**, 270 (2006).

[37] J. Allison *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **835**, 186 (2016).

[38] S. Agostinelli *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **506**, 250 (2003).