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Mirror Matter: Towards Precise Measurement of Ortho-Positronium Lifetime

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Positronium (Ps), an exotic atom composed of an electron and a positron, provides a unique system for testing fundamental physics and verifying quantum electrodynamic predictions. At Jagiellonian University, the J-PET detector enables high-precision studies of positronium decays and the search for dark matter. This work focuses on mirror matter, a hypothetical dark matter candidate, by comparing measured o-Ps lifetimes with quantum electrodynamic predictions to probe potential deviations.

topics: mirror matter, ortho-positronium (o-Ps), Jagiellonian-positron emission tomograph (J-PET), dark matter (DM)

1. Introduction

Mirror matter is a hypothetical form of matter proposed to restore parity symmetry [1], consisting of counterparts of Standard Model particles with opposite chirality. It interacts only very weakly with ordinary matter, which makes it a plausible dark matter (DM) candidate. DM does not emit or absorb light but reveals its presence through its gravitational effects on structures in the Universe.

In the positronium system, mirror matter can be studied through its triplet state $^3S_1$, called ortho-positronium (o-Ps). This triplet state ($l = 0, s = 1$) may oscillate into its mirror counterpart [2], which would then decay into undetectable mirror photons. The o-Ps decay into 3 photons has an accurately calculated lifetime derived from quantum electrodynamic (QED) [3], and a precise comparison to this value can show a hint of the mirror matter contribution.

2. J-PET detector

The Jagiellonian positron emission tomograph (J-PET) detector at the Jagiellonian University consists of axially arranged plastic scintillators [4] for detecting annihilation photons [5]. It is used in lifetime measurements, symmetry tests [6, 7], quantum entanglement studies [8], and medical imaging [7, 9–11].

Data are collected with two prototypes, namely a barrel-shaped detector with three cylindrical layers [12] and a modular detector allowing flexible configurations [7, 9, 13, 14]. In the modular setup, the strips are read out by silicon photomultipliers (SiPMs), while the compact design further enhances photon detection efficiency and timing resolution [5].

For this study, the modular detector incorporates a small PA6 production chamber [15] containing a ^{22}Na source (1.2 MBq) coated with porous XAD4 polymer [16] to enhance positronium production. Dedicated analysis tools and a Monte Carlo generator based on Geant4 toolkit [7, 17–19] were employed.

3. Analysis

This study focuses on precisely measuring the lifetime of o-Ps, which decays predominantly into three photons (o-Ps $\rightarrow 3\gamma$). The ^{22}Na source undergoes β^+ decay, providing positrons and a 1274 keV photon as the start signal for each event.

The backgrounds include random (accidental) coincidences arising from uncorrelated signals, cosmic rays, scattered photons, and pick-off events in which o-Ps annihilates through interaction with surrounding matter. The decays of o-Ps into invisible products have a negligible Standard Model background.

3.1. Data selection

Events corresponding to the o-Ps $\rightarrow 3\gamma + \gamma_{\text{prompt}}$ decay were selected based on the number and topology of detected hits. Only events with at least four hits were considered, with at least three assigned to the annihilation region and one to the prompt gamma region, as illustrated in Fig. 1.

To suppress background, the sum of the two smallest angles between detected photons is used, where o-Ps events are expected with higher purity [20]. Furthermore, the time difference between annihilation hits was required to be less than 3 ns, since the photons are emitted contemporaneously, and the distance of the source from the plane defined by the three annihilation hits was limited to less than 8 cm (Fig. 2) to satisfy the coplanarity condition. This relatively wide time window accounts for the detector's time resolution and ensures that most of the annihilation photons emitted simultaneously are included.

To further increase sample purity, only events falling within the "signal box" shown in Fig. 3a were selected. The signal box is defined by the criterion $\theta_1 + \theta_2 > 190°$, which favours events consistent with three-photon annihilations while rejecting the background from 2γ decays.

3.2. Event categories in MC

Monte Carlo (MC) samples were prepared to support the machine learning-based event selection. The distributions shown in Fig. 4 represent the simulated distributions of the distance from the plane defined by the detected hits and the sum of the two smallest angles between these hits. Each distribution is presented for four event categories: full MC, randoms, background, and the 3-gamma signal.

Because the random and signal categories appear with much lower counts than the background, they are additionally presented in the top-left insets in Fig. 4a and b, where a magnified range allows their structures to be seen more clearly. The randoms category includes events in which not all hits originate from the same vertex, while the background category corresponds to events in which not all hits carry the expected tagging (3 for o-Ps and 1 for the prompt gamma).

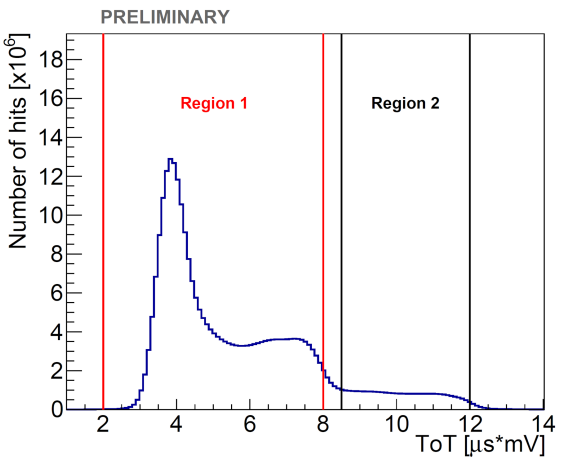

Fig. 1. Time-over-threshold (ToT) distribution for all registered hits. Region 1 corresponds to annihilation hits, and Region 2 to the prompt gamma γ_{prompt}.

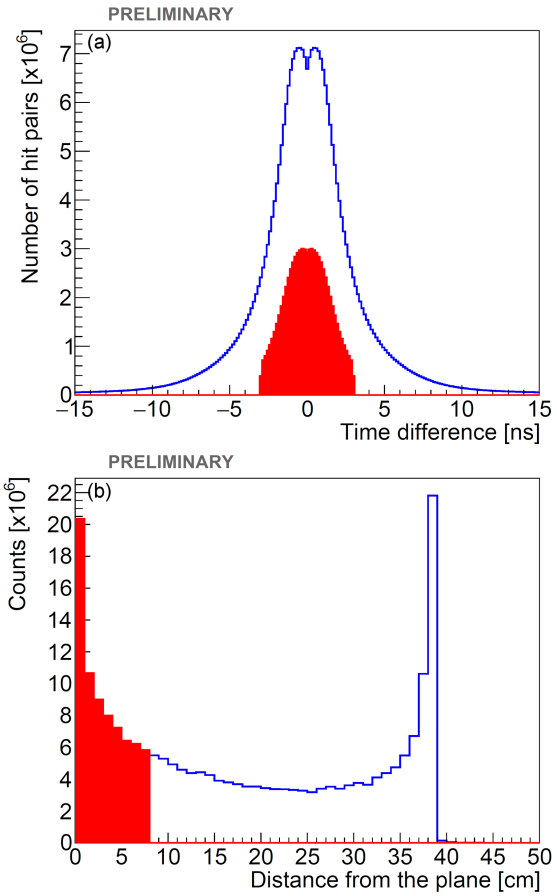

Fig. 2. Time difference between annihilation hits (a) and distance of the source from the 3-hit plane (b). Red histograms denote variable ranges after cuts.

4. Conclusions

This research focuses on the search for mirror matter, a hypothetical dark matter candidate, using the J-PET detector. The current analysis targets to precisely measure the o-Ps lifetime, aiming for a sensitivity to decay rates below 10^{-5}, to test the predictions of QED. Data collection is ongoing, intending to improve the precision of the o-Ps

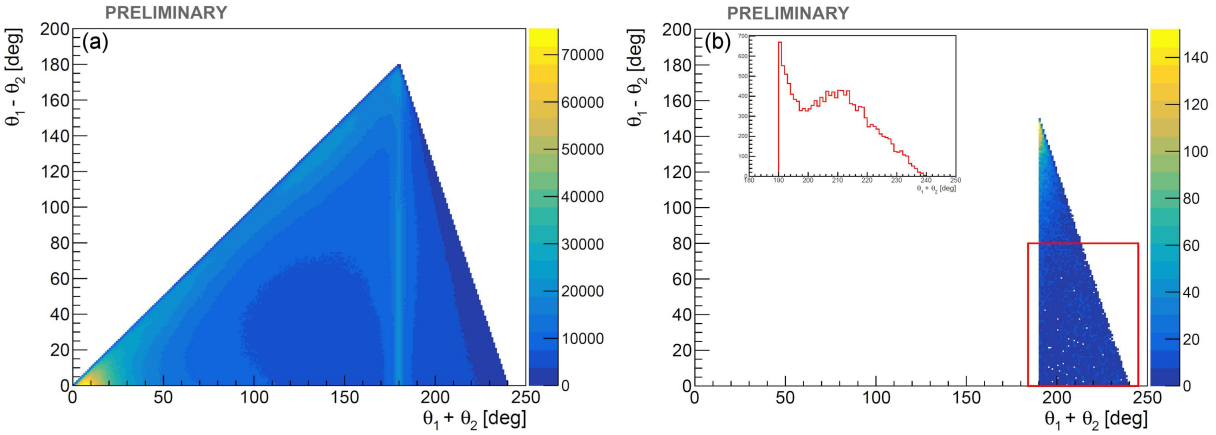

Fig. 3. Angle distributions before (a) and after (b) applying the 190° cut. In the top-left corner of panel (b), the inset shows the projection onto the sum of the two smallest angles, $\theta_1 + \theta_2$, which shows the signal region after the box cut is applied.

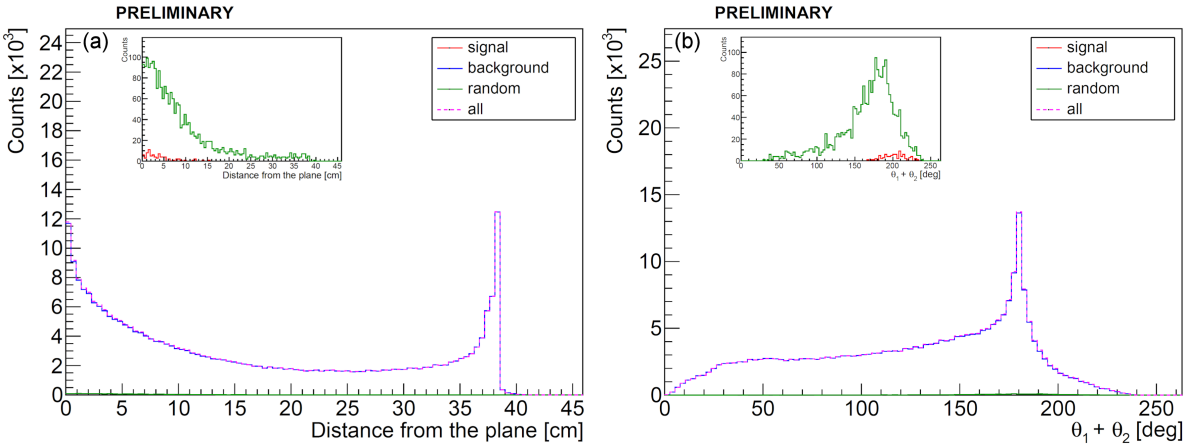

Fig. 4. (a) Distribution of the distance of the hits from the plane defined by the annihilation photons for different MC event categories: all, randoms, background, and signal. (b) Distribution of the sum of the two smallest angles between detected hits for the same categories. Insets in the top-left corners of both panels show a magnified view of the low-value region, improving the visibility of the random and signal components.

lifetime measurement by roughly an order of magnitude compared to previous experiments [21]. Monte Carlo simulations are employed to evaluate systematic effects and optimise event selection, providing a quantitative estimate of the expected improvement compared to the current state of the art.

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