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Mirror Matter in Positronium Decay Searches with the J-PET Detector

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The positronium (Ps) atom, a bound state of an electron and a positron, is a fascinating system for fundamental physics research. Its properties, well-described by Quantum Electrodynamics (QED) within the Standard Model (SM), make it an ideal candidate for precise tests. The J-PET setup at Jagiellonian University, based on plastic scintillator detectors with high angular and timing resolutions, enables multidisciplinary studies including tests of symmetries, quantum entanglement, and the search for Dark Matter through positronium decays.

This work focuses on current searches for Dark Matter (DM) involving ortho-Positronium (o-Ps) decays using the J-PET detector. The primary goal is to investigate Mirror Matter, a proposed type of matter that could restore parity invariance and serve as a potential DM candidate. This study aims to achieve unprecedented precision in measuring the o-Ps decay to three gamma quanta, comparing results to QED predictions in the search for elusive DM.

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1. Introduction

Dark matter and energy are one of the unsolved mysteries in cosmology nowadays. Most of the matter of the Universe is dark matter itself. Given the wide range of known particles, one could assume that there is a rich so-called "hidden sector" potentially linked to SM by intermediate particles [1]. These potential candidates can be searched for in colliders [2–5] and through cosmological experiments [6].

The simplest version of the "hidden sector" model is represented by the dark photon [7], a potential force carrier between the Standard Model (SM) and dark matter (DM). This particle can be studied in Ps [8] decays, and preliminary studies have already been carried out using the J-PET [9] detector.

1.1 Mirror Matter

Mirror matter is a hypothetical type of matter that can exist alongside ordinary matter [10]. Mirror matter corresponds to a complementary set of particles to those of the SM but with opposite chirality. It was conceived as an explanation to restore parity invariance and it is theoretized to interact very weakly with ordinary matter. These properties make mirror matter a strong candidate for dark matter, potentially responsible for the invisible mass in the universe.

The positronium (Ps) system, a simple bound state of electron and positron, offers a promising environment for searching for mirror matter and serves as an ideal candidate for testing quantum electrodynamics (QED) [11, 12]. It has been suggested that o-Ps (a triplet state of Ps with $l = 0$ and $s = 1$) could oscillate into its mirror equivalent [13], which would then decay into mirror photons, leaving no detectable trace in the detector. If such oscillation occurs, it would result in a modification of the lifetime of the o-Ps. Thus, any deviation of the observed lifetime of o-Ps from QED's predictions could reveal the presence of unknown processes beyond standard positronium theory.

The decay of ortho-positronium (o-Ps) is accurately described by non-relativistic quantum electrodynamics (NRQED). In this framework, the decay rate of o-Ps has been calculated as [14]:

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

2. Detector

The J-PET detector is equipped with axially aligned plastic scintillation strips [15], programmable electronics [16] and a triggerless data acquisition system [17]. The detector is specifically designed to detect annihilation photons and has many applications: lifetime measurements, symmetry tests [18], quantum entanglement studies [19] and medical imaging [20]. Joint projects, such as the search for angular correlations that violate CPT, are yielding very accurate results [21, 22]. With a time resolution of 380 ps and a position resolution of 4.6 cm (FWHM) [23], the J-PET minimizes pile-up events, enhancing the detection of higher positronium rates and improving the statistical accuracy of decay studies [24].

At this point, two prototypes have been developed: a barrel detector with plastic scintillators arranged in three cylindrical layers [23] and a modular design [25–27]. In the modular configuration, the scintillation strips are read out by silicon photomultipliers (SiPMs), which significantly improves the single photon detection efficiency and time resolution [28]. 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.

The data used for the analysis presented in this article comes from the barrel detector. Inside the detector there is a small cylindrical production chamber coated with a porous material that enhances positron formation [29]. Data are sampled at four fixed voltage thresholds: 30, 80, 190, 300 mV [16]. The measurements took place over 250 days, starting in April 2020 and the preliminary analysis included in this publication covers 55 hours.

The data analysis is performed by using the J-PET Framework [20] and Monte Carlo simulations using J-PET-Geant [30–32] based generator.

3. Analysis

The J-PET experiment uses the isotope ^{22}Na, which decays β^{+} to excited $^{22}Ne^{*}$. This decay leads to the emission of a photon with an energy of 1274 keV from the excited neon, which is contemporary to the emission of the β^{+} particle, flagging the start time for the Ps formation. A source with an activity of 0.702 MBq was used for the study.

The main focus is on precise measuring the lifetime of o-Ps, the triplet state of positronium ($l = 0$, $s = 1$), which typically decays into three photons. Therefore, events with exactly three annihilation photons and one gamma photon were analyzed.

3.1 Main background sources

The o-Ps decay to invisible can be mimic in the SM only by the decay to neutrino-antineutrino, with an extremelly rare ocurrence. However, the final state can be shadowed by several background sources: random coincidences, cosmic rays, scattered photons and pick-off events in which a positron from positronium annihilates with another electron in the detector volume.

3.2 Monte Carlo

Monte Carlo samples were generated and analyzed, allowing for thorough data exploration and accurate identification and characterization of background sources.

The deposited energy distribution was created for different types of the events and shown in Fig 1. The distribution shows that the population of random and scattered events is larger than the population of signal events, so correctly identifying the type of events in the data is vital.

Signal events were reconstructed based on the following criteria:

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

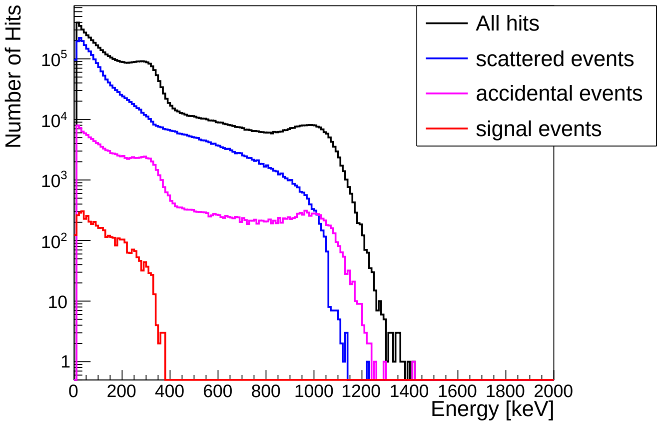

Figure 1: Deposited energy distribution for generated MC sample (black histogram). The hits are categorized according to the MC generation as: scatter events (blue), accidental events (magenta), and signal events (red).

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 [33]. In the experiment, the source was in the center of the detector, so a cut was additionally applied to the determined annihilation point. The annihilation point must be roughly in the center of the detector, but a certain spatial resolution must also be assumed. The outcome of reconstruction with cuts is shown in Fig. 2.

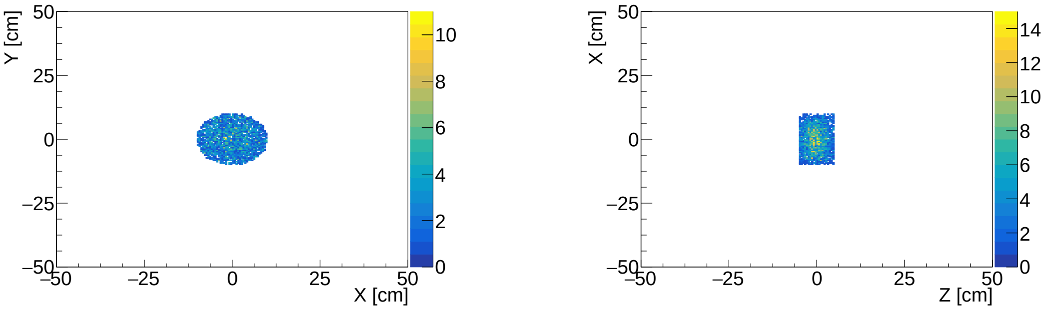

Figure 2: The reconstructed vertices coordinates with applied spatial cut on the XY (left), corresponding to the basis of the cylinder (barrel), and XZ plane (right), where Z is defined as the axis of the cylinder.

The lifetime spectrum is generated by subtracting the recording time of the gamma prompt from the average recording time of the annihilation hits, after refining the selection by reconstructing the vertices and assuming their locations. This process significantly reduces background noise in combination with ortho-Positronium (o-Ps) selection, as illustrated by the green spectrum in Fig. 3. The vertex reconstruction alone, which requires the 3 annihilation hits to be on a single plane and the designated annihilation point to be inside the detector, significantly reduces events erroneously assumed to be o-Ps in a single time window. The lifetime is then compared to the spectrum without any selection criteria (shown as a black histogram) to highlight the improvement achieved.

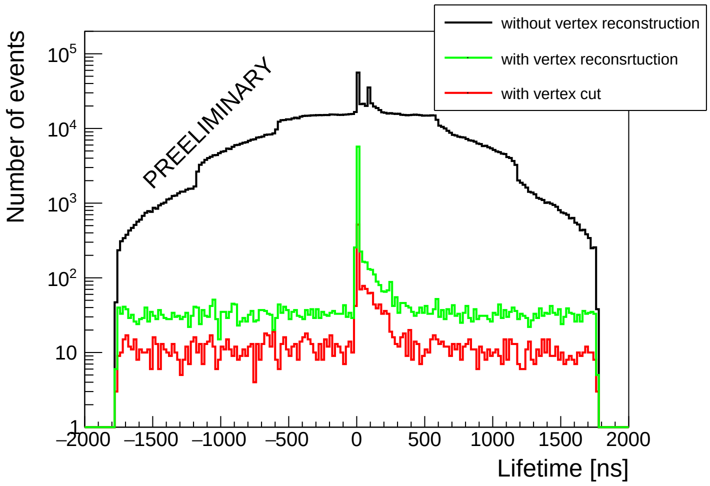

Figure 3: The reconstructed lifetime of o-Ps from J-PET data with applied vertex reconstruction (red) and spatial cut on vertex (green).

Although random background events persist, vertex reconstruction effectively lowers background levels while preserving the exponential decay component. However, further statistical improvement is required. While the application of vertex cuts reduces random events, a noticeable bulk remains around zero. The slow exponential component of o-Ps decay must be accurately fitted.

Table 1 compares the theoretical and experimental values obtained so far. The J-PET system is anticipated to yield up to $O(10^5)$ or lower.

Table 1: Comparison of the theoretical, experimental, and order of magnitude of the expected decay rate.

	Theory	Experiment	Expectation J-PET modular
Γ (s^{-1})	$7.039979(1) \times 10^6$ [14]	$7.0401 \pm 0.0007 \times 10^6$ [35]	$\leq O(10^5)$ [37]
		7.0404 ± 0.0010 ± 0.0008 × 106 [36]	

4. Summary

The main goal of this research is to study mirror matter, a new form of matter that may serve as a dark matter candidate. Currently, this research is being conducted using the J-PET detector, specially designed to measure annihilation processes precisely. Using this advanced detector, scientists can accurately assess the positronium lifetime, a critical outcome of the ongoing study.

In the long term, the study aims to achieve a sensitivity level of 10^{-6}, which will enable meaningful comparisons with quantum electrodynamics (QED) predictions. Monte Carlo simulations are used to define the selection criteria and properly account for the systematical uncertainties. This thorough approach will enhance the understanding of mirror matter and its implications in the context of dark matter research.

Future modifications include the use of various analysis techniques. The intention here is to use machine learning. Preliminary analysis has shown that this makes it possible to increase the sensitivity [34]. In addition, a tracking detector is being considered to reduce scattering by being placed near the source and accurately tracking the signals.

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