FEASIBILITY OF ORTHO-POSITRONIUM LIFETIME STUDIES WITH THE J-PET DETECTOR IN CONTEXT OF MIRROR MATTER MODELS*

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We discuss the possibility to perform the experimental searches for invisible decays in the ortho-positronium system with the J-PET detector.

1. Introduction

In spite of the remarkable success of the Standard Model (SM) of particles, whose precise predictions have been confirmed by many experiments, SM fails to explain all features of Nature and still several important questions remain without answers. One of such open puzzles is the existence and the nature of the so-called dark matter (DM) which is believed to be described by new particles.

DM is called *dark* because it does not interact with electromagnetic forces, which makes its experimental observation extremely difficult. However, since DM particles have invariant mass, they can act on the ordinary matter via the gravitational force. Indeed, several astrophysical observations have been interpreted as indirect evidence of the DM existence [1–5].

In laboratories, many attempts have been performed to detect the DM particles [6–9]. However, so far, neither direct nor indirect experimental evidence has been found.

In mirror matter (MM) models, the mirror (spatial parity-) counter-partners for the ordinary SM particles are introduced. Since such objects would interact with SM matter mainly via gravitational force, the mirror particles seem to be natural DM candidates.

The search for mirror matter particles can be carried out in the so-called invisible decays of positronium (Ps). Ps is a bound state of electron and positron. Its ground state has two possible configurations, a singlet state $^1S_0$, para-positronium (p-Ps), where the spins of the electron and the positron are anti-parallel, and the $^3S_1$ triplet, ortho-positronium (o-Ps), where the spins are parallel. Being a purely leptonic system, Ps is precisely described by Quantum Electrodynamics (QED) with very small radiative corrections from Quantum Chromodynamics (QCD) and weak interaction effects. Those properties make it an attractive system for various experimental tests [10, 11]. Assuming MM model, o-Ps can oscillate into its parity-partner mirror o-Ps′, which consequently decays into mirror photons not detectable in the laboratory. Experimentally, this process would increase the observed o-Ps decay rate.

In this contribution, we discuss the feasibility of the measurement for the mirror matter in the invisible decays with the J-PET device. The article is structured in the following way: In Section 2, we shortly discuss the mirror oscillations phenomena in the context of Ps invisible decays. In Section 3, the experimental methods are briefly described. Next, in Section 4, the J-PET detector is introduced. The experimental prospects are discussed in Section 5. Finally, Section 6 contains the outlook.

2. Mirror matter and invisible decays

The concept of MM was first introduced by Lee and Yang [12] in the famous paper in which they proposed a series of experiments that led to the confirmation of spatial parity violation in weak interactions [13, 14]. To restore the spatial parity symmetry in a larger sense, Lee and Yang suggested the existence of parity reflected counter-partners of the ordinary matter.

This idea was further developed into MM models [15, 16], in which the hidden mirror sector contains not only particles but also interactions. The mirror world would consist of the parity reflected states (*e.g.* right-handed for mirror particles and left-handed for antiparticles) of every ordinary particle from SM.

Apart from the gravity, MM could interact with ordinary matter via a mixing mechanism, as proposed by Glashow [17], to explain the experimental results of o-Ps decays. In this model, the invisible decay of o-Ps can proceed through the annihilation into a virtual single photon, which oscillates into a mirror photon, connecting o-Ps and the corresponding mirror o-Ps′ partner via the kinetic term

$$\mathcal{L} = \epsilon F^{\mu\nu} F'_{\mu\nu} \,, \tag{1}$$

where ϵ, $F^{\mu\nu}$ and $F'_{\mu\nu}$ are the mixing parameter and field tensors for electromagnetism and mirror electromagnetism, respectively [17].

We can express the probability that an o-Ps does not change its states in a time t, assuming that it was in the o-Ps state at $t = 0$, as

$$P(t) = e^{-\Gamma t} \times \cos^2(2\pi\epsilon f t) \,, \tag{2}$$

where Γ and f are the decay rate of o-Ps into three photons and the contribution to the ortho–para splitting from the one photon annihilation diagram involving o-Ps ($f = 8.7 \times 10^4$ MHz), respectively. The inclusion of oscillation process would lead to the increase of the measured lifetime. The complementary probability that o-Ps oscillates into the mirror state in the time t is given by

$$P'(t) = e^{-\Gamma t} \times \sin^2(2\pi\epsilon f t) \,. \tag{3}$$

The branching ratio BR(o-Ps → invisible) can be expressed as an average probability over a long time of measurement

$$\mathrm{BR(o\text{-}Ps \to invisible)} = \Gamma \times \int_0^\infty P'(t)\mathrm{d}t = \frac{2(2\pi\epsilon f)^2}{\Gamma^2 + 4(2\pi\epsilon f)^2} \,. \tag{4}$$

Values of ϵ between $\sim 10^{-10}$ and $\sim 4 \times 10^{-9}$, constraint by DM models aiming to explain the DAMA anomaly [18], correspond to branching ratio expectations between 5×10^{-10} and 2×10^{-7}. These calculations do not consider incoherent processes (*e.g.* collisions with matter), and thus apply only to o-Ps decays in vacuum. Another constraint can be determined from the prediction of the primordial ^{4}He abundance by the SM and it gives $\epsilon \leq 3 \times 10^{-8}$ [19].

In principle, the experimental confirmation of the invisible o-Ps decays can be interpreted not only in the frame of the MM models but also in context of other new physics scenarios, *e.g.* milli-charged particles and extra space-time dimensions [20].

3. Experimental methods

The search for invisible decays is a major focus for Ps decay experiments [21–25]. The process allowed by SM that would mimic the new physics invisible decays has an experimentally negligible branching ratio BR(o-Ps $\to$ $\nu_e\bar{\nu}_e$) $< 10^{-18}$ [26].

So far, two types of experimental methods have been used. The first one is based on the precise measurement of the o-Ps decay rate looking for a difference relative to the QED predictions due to some unconventional processes, *e.g.* due to the oscillation of the o-Ps into the mirror world. The second, a direct search approach, relies on the definition of a *no-signal* region in some experimental distribution, *e.g.* the sum of the energies deposited by the o-Ps decay products, which corresponds to detector response not connected with any physical processes but, *e.g.* with detector noise or other nuisance phenomena. The observation of any excess in the *no-signal* region could be interpreted as a manifestation of the invisible decay mode.

The *no-signal* method was used in two independent measurements by the ETH Zürich group. They established the most accurate constraint on a possible invisible decay of o-Ps in vacuum [25] up to now[1]

$$\mathrm{BR(o\text{-}Ps \to invisible)} < 5.0 \times 10^{-4}\,, \qquad 90\%\,\mathrm{C.L.} \tag{5}$$

which can be interpreted as a constraint on the mixing parameter: $\epsilon < 3.1 \times 10^{-7}$.

The most accurate measurements of the o-Ps decay rate are consistent with each other and with the theoretical prediction known up to two-loop ($\mathcal{O}(\alpha^2)$) corrections (see Eq. (1) in [10]).

The Tokyo group [28] obtained

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

with the o-Ps produced in SiO_2 powder, whereas Ann Arbor group [29] measured:

$$\Gamma = 7.0404 \pm 0.0010 \pm 0.0008 \times 10^6 \ \mathrm{s}^{-1} \tag{7}$$

with a slow positron beam on silica target. These results are consistent with the QED theory predictions, with the caveat that the present experimental uncertainties on the decay rate are about 100 times larger than the theoretical error, and thus the sensitivity needed to test the o-Ps mirror component.

In experiments, o-Ps is typically formed not in the vacuum, but in some kind of material where it can interact with the environment. Since the interaction of mirror o-Ps′ with the standard matter is negligible, it follows

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[1] There is a new result from the ETHZ group in e-print [27] updating the BR measurement to $\mathcal{O}(10^{-5})$.

that one has to consider interaction of just the normal o-Ps with the host material. The net oscillation effect can be suppressed by these processes, *e.g.* scattering with the gas molecules or with the cavity walls [30]. These effects must be taken into consideration when performing the experiment because they effectively reduce the experimental sensitivity for extracting the mixing term.

4. J-PET detector

The J-PET (Jagiellonian-Positron Emission Tomography scanner) is a high acceptance multi-purpose detector optimized for the detection of photons from positron–electron annihilation. Originally designed as a medical scanner, the J-PET detector has several advantages such as very good timing resolution [31], possibility of data taking in the continuous mode (triggerless) [32, 33], fully digital front-end electronics [34], and efficient discrimination between different Ps decay channels [35]. These make it suitable in a broad scope of interdisciplinary investigation, *e.g.* medical imaging [36, 37], fundamental symmetry tests [11] and quantum entanglement studies with o-Ps [38].

The J-PET device is made of plastic scintillators. The current prototype is built from three cylindrical layers (radius of 42.5, length of 50 cm). Light signals from each strip are converted to electrical signals by photomultipliers placed at opposite ends of the strip [39–41].

Presently, a new innermost layer is being installed and commissioned, with the start of data acquisition of the full 4-layer setup planned for the 2019 winter [36]. This fourth layer, see Fig. 1 (left) is read out by matrices of silicon photomultipliers (SiPM), which is expected to triple the efficiency for the single-photon detection and improve the time resolution by about a factor of 1.5 [31]. In addition, the new setup allows to recombine the modules into various arrangements that can be adapted for dedicated physics measurements. *E.g.* the setup in Fig. 2 (right) contains two modular layers. Future measurements will be carried out with the fully equipped detector.

5. J-PET prospects

The J-PET detector is suited to perform the precise measurement of o-Ps lifetime using the decay process o-Ps $\rightarrow 3\gamma$. The results will be confronted with high precision QED calculations. Any significant discrepancy between theoretical predictions and the measurement would point into the direction of new physics and might be interpreted in the frame of MM models.
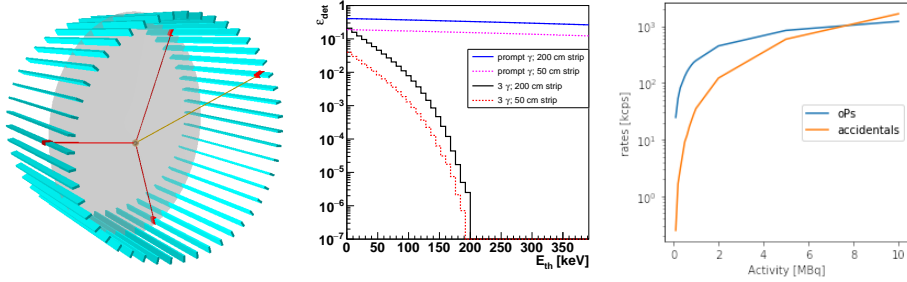
Fig. 1. Left: Inner thin layer of the J-PET detector with superimposed decay plane of o-Ps $\rightarrow 3\gamma$ process. Lines inside the plane indicate annihilation photons and the line pointing out the $\gamma_{\text{de-ex}}$. Center: Registration efficiency for $\gamma_{\text{de-ex}}$ (upper lines) and o-Ps $\rightarrow 3\gamma$ as a function of the energy-loss threshold, estimated for a single-layer setup. The dashed and solid lines indicate efficiencies for 50 cm and 200 cm strip length, respectively [36]. Right: Estimated rates of produced accidental and o-Ps events as a function of the source activity. The registration efficiency is not included in the estimate.
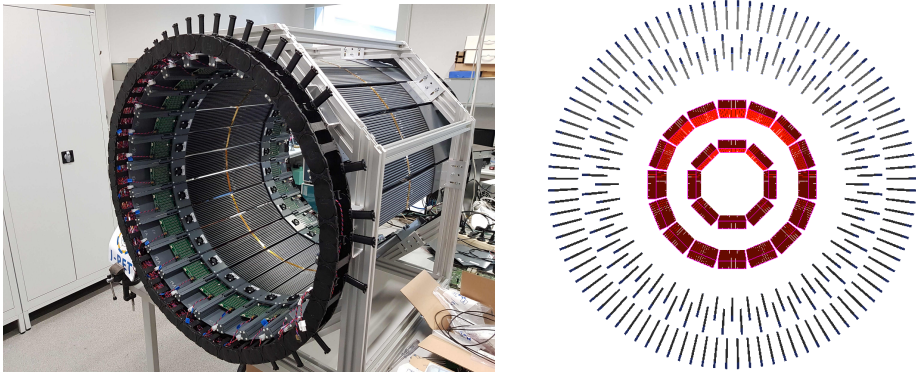

Fig. 2. Left: The fourth layer of the J-PET detector. Right: J-PET detector scheme with modules from the 4th layer rearranged into 2 internal layers.

In the J-PET experiments, a ^{22}Na source can be used. The Na isotope decays through β^+ transitions, emitting a positron that slows down in its interactions with matter, reaching thermal energies. Then it undergoes free annihilation or forms positronium.

The Ps is produced mostly in the ground state, forming p-Ps or o-Ps with probabilities of 25% and 75%, respectively. However, the interactions with the surrounding matter can lead o-Ps to spin inversion or to pick-off processes

and, as a result, significantly decrease the relative ratio of $3\gamma/2\gamma$ annihilation. In the J-PET setup, an amberlite porous polymer XAD-4 (CAS 37380-42-0) material placed in a vacuum chamber increases the effective yield of annihilation into 3γ to 29% [42].

The β^+ decay from Na source is followed — after few picoseconds — by the emission of a monochromatic photon of 1.27 MeV ($\gamma_{\text{de-ex}}$) from the de-excitation of neon nucleus. The de-excitation gamma registration time enables to set a window for the registration of the annihilation photons and for lifetime measurements.

The events can be efficiently reconstructed and separated using the angular and timing resolution of the J-PET detector. Subsequent constraints in hit position, energy and time allow to disentangle the de-excitation from the annihilation photons, at the same time, that 3γ and 2γ events can be selected. Besides, due to the kinematic constraints of the decay, the vertex can be precisely reconstructed using the trilateration technique [43], see Fig. 1 (center).

In order to reduce the main source of background, consisting of pick-off events, a selection based on two-photon events can be performed in the same data sample. This would allow to evaluate and subtract the background component directly from data.

To better distinguish between the multi-photon decays categories, we plan to use Machine Learning (ML) algorithms, such as Boosted Decision Trees (BDT) or Artificial Neural Networks (NN). In this way, the sample can be used to train on two photon events in order to properly separate the pick-off from the interesting three-photon decays. A similar method has been already proposed by the ETHZ group [44], showing a good separation between the two categories of events.

The level of the statistical uncertainty that can be achieved is inversely proportional to the number of generated Ps multiplied by the registration efficiency for the given process. The BR(o-Ps $\rightarrow$ X) can be expressed as BR $\approx \frac{1}{N_{\text{Ps}} \times \epsilon_X}$.

The advantage of the short signals formed in the plastic scintillators (of the order of few ns) allows to significantly reduce the pile-up problems present in the previous experiments [25, 29, 45] and, therefore, to choose sources with higher activities. The estimate of the accidental coincidence rate together with the o-Ps production rate is shown in Fig. 2 (right). The accidental event is defined as an event in which more than o-Ps decays take place in the 200 ns frame calculated with respect to the time of the de-excitation gamma. For the further estimates, we use a 1 MBq source to keep the signal-to-background ratio reasonable for the measurement.

With this assumption in one year of data taking with J-PET detector, we expect to have about $N_{\text{o-Ps}} \approx 10^{13}$ o-Ps, and about the same amount of p-Ps produced.

As mentioned above, the current best experimental accuracy of lifetime measurement 10^{-4} is 100 times less precise than the theoretical calculations [10]. To reach the statistical uncertainty below 10^{-4}, one needs to reconstruct 10^9 o-Ps events. For this purpose, the new modular J-PET needs to be used in a double-layered configuration, see Fig. 2 (left). This arrangement corresponds roughly to an increase of detection efficiency for a single photon of about a factor of 2. Taking into account the estimated number of o-Ps generated using the J-PET setup ($\approx 10^{13}$) and the efficiency for the detection of annihilation photons (2%) and of the de-excitation photon (about 20%), see Fig. 1 (right), together with the double-layered configuration, a sensitivity below 10^{-5} could be reached after two years of data taking using the J-PET detector.

6. Summary and outlook

In this article, we discussed the capability of the J-PET detector to perform searches of o-Ps invisible decays with the precise measurement of o-Ps lifetime distribution. After two years of data taking the expected sensitivity would allow for more precise tests of the QED predictions. Any possible discrepancy between the measured and predicted o-Ps decay rate could be interpreted in terms of invisible decays, with possible MM model interpretation. The estimated statistical sensitivity is rather conservative and can be largely improved by adding a new set of layers, which would further increase the detection efficiency. Currently, we carry out the studies of the ML-based method for the pick-off background subtraction.

Another possibility to decrease the background and increase the experimental reach of the measurement is the implementation of a tagger system for the positrons emitted by the source, based on SiPM and scintillator fibers. Finally, the proposed search can be extended to the measurement carried out not only with radioactive sources but with a positron beam. The new version of the modular J-PET detector is highly portable and would allow transporting the device to facilities with positron beams such as *e.g.* Trento Institute of Fundamental Physics and Applications, in Italy or ETH Zürich in Switzerland, to perform new and independent measurements.

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