ADVANCEMENTS IN THE STUDIES OF MULTI-PHOTON DECAYS OF ORTHO-POSITRONIUM WITH J-PET*

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Based on plastic scintillators, Jagiellonian PET (J-PET) is a multidiscipilinary PET scanner having a wide range of applications. With the potential of J-PET to register multiphotons, we aim at exploring the rare and forbidden decay channels of the Positronium triplet state, the ortho-Positronium (o-Ps). The o-Ps decaying into a higher number of photons than the predominant mode (o-Ps $\rightarrow 3\gamma$) is six orders of magnitude smaller than expected from the Quantum Electrodynamics (QED) calculations. In this article, we intend to present the status of the preliminary studies of the multi-photon decays of ortho-Positronium. We will explain toy Monte Carlo simulations involving 4- and 5-gamma decays of the o-Ps, together with a preliminary estimation of a J-PET-like detector efficiencies for these channels.

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1. Introduction

The ortho-positronium (o-Ps) is the triplet state of the Positronium (Ps), a bound electron–positron atom, characterized by spin equal to one. Non-relativistic Quantum Electrodynamics (nrQED) effectively describes its properties [1, 2]. With a lifetime of 142 ns in the vacuum, this exotic particle provides numerous opportunities to test fundamental symmetries such as C, CP, and CPT. Additionally, the o-Ps serves as a sensitive probe for testing QED with high precision.

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Due to the absence of hadronic components in its constituents, the decay of o-Ps is predominantly governed by electromagnetic interactions, which preserve charge conjugation parity. Under charge conjugation symmetry, the o-Ps can decay into an odd number of gamma quanta: o-Ps $\rightarrow 3\gamma, 5\gamma, 7\gamma$, and so on. Therefore, investigating the o-Ps $\rightarrow 5\gamma$ decay channel allows for testing Quantum Electrodynamics with greater precision, while measuring the o-Ps $\rightarrow 4\gamma$ decay serves as an indicator of charge conjugation parity (C) violation.

1.1. Precision test of Quantum Electrodynamics (QED)

Under the QED formalism, the decay rate up to the two-loop level is well described by the following equation [3]:

$$\begin{aligned}\Gamma(\text{o-Ps} \rightarrow 3\gamma, 5\gamma) \;=\; & \frac{2(\pi^2-9)\alpha^6 m_e}{9\pi}\left[1 - A\frac{\alpha}{\pi} + \frac{\alpha^2}{3}\ln\alpha + B\left(\frac{\alpha}{\pi}\right)^2\right. \\ & \left. -\frac{3\alpha^3}{2\pi}\ln^2\alpha + C\frac{\alpha^3}{\pi}\ln\alpha + D\left(\frac{\alpha}{\pi}\right)^3 + \ldots\right]. \qquad (1)\end{aligned}$$

The coefficient A evaluates to be 10.286606(10), B is 44.87(26) for 3γ contribution. If taken into account 5γ, B is equal to 45.06(26). The coefficient C is $-5.517025(03)$ and D remains to be determined. By incorporating all known coefficients and ignoring the term proportional to the unknown coefficient, the theoretical decay rate is given by [3]

$$\Gamma_{\text{o-Ps}} = 7.039979(11) \times 10^6\ \text{s}^{-1}\,. \qquad (2)$$

The experimentally obtained results align well with the theoretical predictions within the bounds of experimental uncertainties obtained in SiO_2 [4] and vacuum [5]. However, the current QED calculation is 100 times more precise than the experimental observations

$$\Gamma_{\text{exp.}} \;=\; 7.0401 \pm 0.0007 \times 10^6\ \text{s}^{-1}(\text{SiO}_2)\,, \qquad (3)$$

$$\Gamma_{\text{exp.}} \;=\; 7.0404 \pm 0.0010 \pm 0.0008 \times 10^6\ \text{s}^{-1}(\text{vacuum})\,. \qquad (4)$$

The branching ratio of o-Ps decaying into 5 photons tests QED to a higher power of the fine-structure constant, α. At the tree level, the branching ratio has been theoretically calculated and reported in Refs. [6, 7]. QED predicts the branching ratio as [8]

$$\text{BR}(\text{o-Ps} \rightarrow 5\gamma) = 0.9591(8) \times 10^{-6}\,. \qquad (5)$$

Previous experimentally obtained bounds on branching ratio by Matsumoto *et al.* [8] equals

$$\text{BR}(\text{o-Ps} \rightarrow 5\gamma) = \left[2.2^{+2.6}_{-1.6} \pm 0.5\right] \times 10^{-6}\,, \qquad (6)$$

and by Vetter and Freedman [9] is equal to

$$\mathrm{BR}(\text{o-Ps} \to 5\gamma) = [1.67 \pm 0.99 \pm 0.37] \times 10^{-6} \,. \tag{7}$$

The BR(o-Ps $\to 5\gamma$) determined experimentally is by several orders of magnitude less precise than it is estimated theoretically. This disparity emphasizes the need to explore this rare decay channel further to achieve higher precision.

1.2. Charge conjugation parity test

Under charge conjugation parity (C), the eigenvalue of ortho-Positronium (o-Ps) is -1. This imposes a restriction that the number of photons in the final state of o-Ps decay must be odd [10, 11]. Therefore, any decay of the o-Ps into an even number of photons would violate charge conjugation invariance. The branching ratio for these decays under the Standard Model (SM) calculation is of the order of 10^{-10}–10^{-9} [12]. Observation of a branching ratio greater than predicted by the SM would suggest a violation of C symmetry [13, 14]. The present limits on this decay mode is found to be: BR(o-Ps $\to 4\gamma$/o-Ps $\to 3\gamma$) $< 2.6 \times 10^{-6}$ at 90% C.L. [15].

With the triggerless data acquisition of the Jagiellonian Positron Emission Tomograph (J-PET), it is possible to retrieve the multi-photon events produced during o-Ps decay. The properties of the J-PET detector enabling multi-photon detection were described in Refs. [16–20]

In this article we have presented the possibility of utilizing the potential of J-PET to perform the QED and C test [16, 21–25].

2. Monte Carlo model for rare decay

In order to investigate the rare and forbidden decays of o-Ps, we need a reliable Monte Carlo model to compare with the data and extract the branching ratios. The first preliminary study with the simplified Monte Carlo (MC) simulated data for the efficiency determination were reported in Ref. [26]. In this article, all the possible contributions to the efficiency such as the acceptance of J-PET-like cylindrical configuration, interaction probability with the plastic scintillator and the Compton scattering of photons within the scintillator have been implemented. As a continuation of the above work, the proposed method for efficiency determination was further planned to be examined using more sophisticated tools. The very own developed MC architecture of J-PET based on Geant4 [27] and ROOT [28] was used for this purpose. This dedicated simulation toolkit, JPET-Geant, aptly simulates the passage of photons generated during radioactive decay of Na-22 through the detector material. JPET-Geant considers the geometrical constraints of J-PET, the actual material involved in the detector configuration, the generation of primary particles, and their subsequent scatterings in the detector. This simulation also gives the response of the sensitive components of the detector. In a nutshell, with JPET-Geant more realistic simulation of the processes involved in the detector has been considered.

The existing architecture of JPET-Geant includes the dominant decay modes of the Positronium (direct annihilation, 3γ, 2γ *etc.*). However, the higher decay modes for the concerned Ps configuration were not included. Events for the rare decay were generated in pure phase space using the ROOT TGenPhaseSpace [28] event generator. This tool enables the simulation of the kinematics of the decay products under the constraints of energy and momentum conservation. The next step is the inclusion of the forbidden decay to 4γ quanta. Currently, the simulation is conducted for the o-Ps $\rightarrow 5\gamma$ decay mode. The generated daughter particles, in this case, the five gamma photons, were transported through the detector medium. This step is crucial for simulating the interaction of the gamma quanta with the plastic scintillator, the key component of the JPET detector. This step helps in understanding the sensitivity and accuracy of the detector setup in capturing the five-photon events.

Figure 1 shows the index of the photon generated in JPET-Geant simulation based on their origin. 1 refers to the generated de-excitation photon and 5 refers to the 5γ decay of o-Ps. The formation of Ps atoms in XAD4 hap-

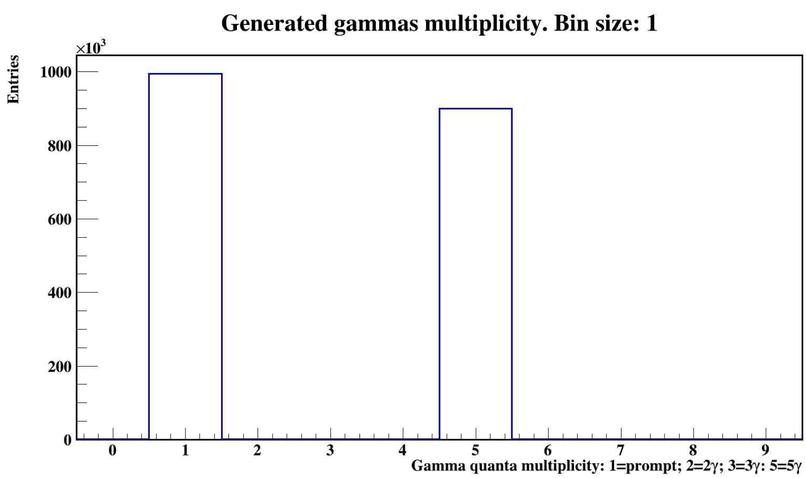

Fig. 1. The generated hits (5 photons and de-excitation (prompt) photon) in the JPET-Geant simulation. The simulations assumed the decay scheme of the Na-22 source. In addition to the prompt photon, based on the decay channels of Ps, it could decay into 2γ , 3γ, and 5γ. In this study, the o-Ps is simulated to annihilate only into 5γ.

pens simultaneously with the emission of a de-excitation (prompt) gamma from the neon. We register the de-excitation gamma along with the 5γ from the o-Ps decay in the detector.

Characterization of the signal based on kinematic variables, background discrimination, and efficiency evaluation has been conducted using this MC simulation in parallel to data analysis. Figure 2 illustrates the energy deposition distribution of 5γ events in J-PET scintillators, generated using JPET-Geant simulations. The insert displays the same spectrum in the logarithmic scale. Above about 300 keV, a clear spectrum from Compton scattering of prompt gamma is visible, while below about 300 keV, the spectrum from 5γ is dominating. Above 1061.2 keV, multiple scatterings and few events due to the photoelectric interaction of prompt gamma are visible.

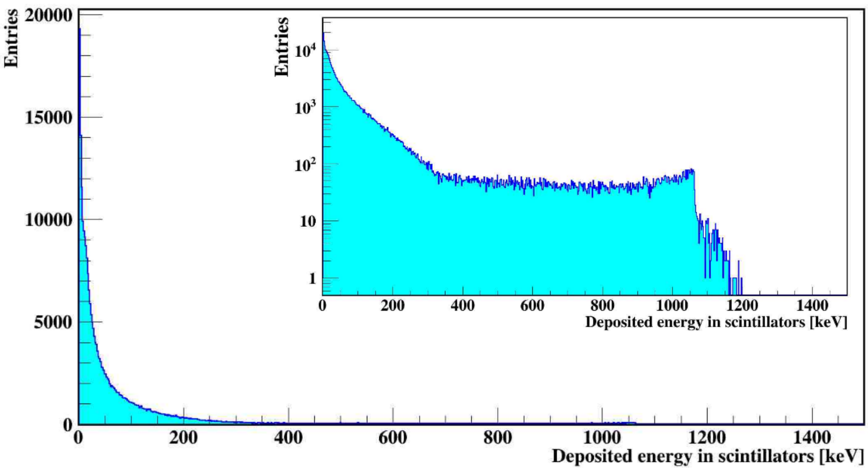

Fig. 2. A simulated deposited energy distribution of o-Ps $\rightarrow 5\gamma$ in JPET-Geant. The inserted plot presents the same spectrum in the logarithmic scale.

3. Conclusions

In this report, we present the recent advancements in the context of Monte Carlo simulations which prove to be a crucial step in this study of multi-photons. In this work we have utilized the Geant4 toolkit along with TGenPhaseSpace for successful simulation of the rare decay of ortho-Positronium. In the restrictive available range of deposited energy, the possibility of discerning the signal candidates seems to be a real challenge. Precission limits of the order of $\mathrm{BR}(10^{-6})$ are expected to be achieved with the J-PET detector. The ongoing analysis is focused on the enhancement of the signal over the background, a clear limitation in the previous results. The next step will be searching for the o-Ps decay into 4γ, forbidden due to C-parity.

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[28] `https://root.cern.ch/doc/v608/classTGenPhaseSpace.html`