PROCEEDINGS OF SCIENCE

Estimating background for decays of positronium with J-PET using Machine Learning Algorithms

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Being governed by electromagnetic interaction, the bound state of electron and positron forms a metastable state-Positronium. Test for bound state QED could be carried out by probing the decay rates of Positronium. In particular the Ps triplet state, the ortho-Positronium, which predominantly decays into three gamma quanta. Based on QED calculations, the rate for oPs decaying into a higher number of photons is by six orders of magnitude smaller compared to 3gamma decay. However, higher decay channels could be probed using the multi-purpose Jagiellonian PET (J-PET) detector. J-PET is a plastic-scintillator based, multi-discipilinary PET tomograph extending its reach from biomedical application to active fundamental studies like CPT invariance, photon entanglement and mirror matter searches. In this work we will present the capabilities of J-PET and preliminary studies of the multi-photon decays of oPs and aim to put stringent limits in this rare decay.

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1. Introduction

Positronium (Ps), a two body bound state of an electron and positron, is well understood within the framework of Quantum Electrodynamics (QED) [1, 2]. In its ground state, positronium can exist as either para-positronium (the singlet state, pPs), with a lifetime of 125 ps, or ortho-positronium (the triplet state, oPs), with a lifetime of 142 ns in the vacuum. As a purely leptonic system and with the absence of hadronic components, positronium provides an ideal and clean testing ground for QED and high-precision studies. As per the QED, the Parity (P) and charge parity (C) is conserved in this exotic leptonic system. Respecting the charge conjugation symmetry, oPs can decay into an odd number of gamma quanta [3, 4]: oPs $\rightarrow 3\gamma, 5\gamma, 7\gamma$, and so on. These decay channels provide a sensitive probe to test the accuracy of QED. The probability of higher number of photons in the final state decay products of oPs is expectedly small as per QED calculations [5]. However, these rare decays can test the QED to a higher power of the fine-structure constant, α. At the tree level, QED predicts the branching ratio of oPs decaying into 5 photons as [6]:

$$BR(o-Ps \rightarrow 5\gamma) = 0.9591(8) \times 10^{-6}. \tag{1}$$

Previous experimentally obtained bounds on branching ratio by Matsumoto *et al.* [6] equals:

$$BR(o-Ps \rightarrow 5\gamma) = [2.2^{+2.6}_{-1.6} \pm 0.5] \times 10^{-6}, \tag{2}$$

and obtained by Vetter and Freedman [7] is equal to:

$$BR(o-Ps \rightarrow 5\gamma) = [1.67 \pm 0.99 \pm 0.37] \times 10^{-6}. \tag{3}$$

Evidently, the experimental results are less precise than that of the QED calculation. Having this discrepancy as the motivation, we aim to perform a more sensitive study, updating and improving the current limits, by using the potential of the Jagiellonian Positron Emission Tomograph (J-PET) for multi-photon decays of oPs has been explored [8–12, 14].

2. Measurement with the Jagiellonian Positron Emission Tomograph (J-PET)

The present study utilized the multipurpose Jagiellonian Positron Emission Tomography (J-PET) scanner, designed for both fundamental physics research [8, 9, 11, 12] and medical diagnostics [13–15]. Arranged in three concentric cylindrical layers, the scanner consists of 192 plastic scintillator strips, each with dimensions of $50 \times 1.9 \times 0.7$ cm^3 [16]. The radii of each layer is 42.5 cm, 46.75 cm, and 57.5 cm along the scanner's longitudinal axis. The scintillators are coupled at both ends to Hamamatsu R9800 photomultiplier tubes (PMTs) to collect photons.

A radioactive isotope was used as a positron source for the measurement, specifically Na-22, encased in a small plastic chamber [17]. The interior of the chamber is coated with porous XAD-4 material to enhance the production of three-gamma decays from ortho-positronium (oPs), relative to the two-gamma annihilation events that result from pick-off processes with the surrounding material [18]. XAD-4 contributes to this enhancement by supporting the formation of different oPs components, which originate from the variety of pore structures present in the material. As detailed in [18], the overall positronium formation probability in XAD-4 is determined by the combined intensities of these components, amounting to 50.8%. Of the formed positronium, the fraction decaying via the three-gamma channel constitutes approximately 29% of all positronium decays. In 90% of cases, Na-22 undergoes β^+ decay, emitting a positron and an excited neon atom. The excited neon atom then de-excites to its ground state, emitting a prompt photon with an energy of 1274 keV. On the other hand, emitted positron thermalizes in the porous material and forms positronium[1]. The emission of the de-excitation photon occurs on average about 1.6 ps after the positron emission [19], so the time of prompt photon emission can be considered the time of Ps formation. Photons resulting from the positronium annihilation interact with the plastic scintillator via Compton scattering, producing scintillation light detected by the PMTs. The electrical signals from the PMTs are sampled at four voltage thresholds at both the leading and trailing edges using specialized digital front-end electronics. The time obtained from these multi-threshold sampled signals are used to determine the location of the photon interaction. Data acquisition from the detector operates in a triggerless mode [20], allowing the same data to be used for multiple studies. The stored data is processed through offline reconstruction using a dedicated framework developed for J-PET data analysis [13].

3. Background characterization in multiphoton decay of o-Ps

A study was conducted to estimate the registration efficiency of photons in the J-PET detector, which is crucial for determining the branching ratio. This study focused on higher-order decays

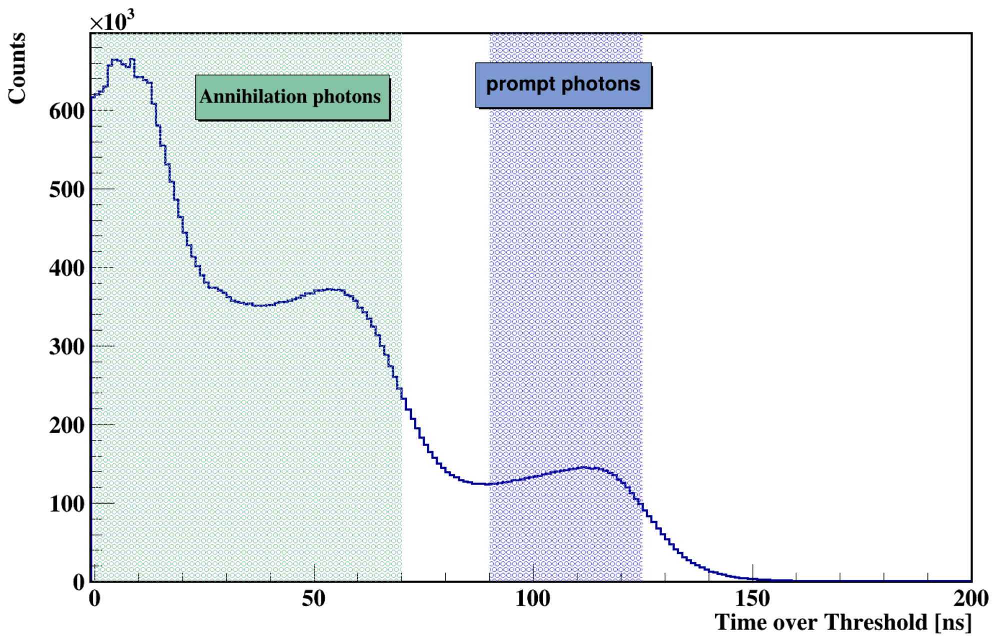

Figure 1: The time over threshold (TOT) distribution of registered hits in the detector. The annihilation hits lie between 0 to 70 ns, while the prompht hits occupy the higher TOT range of 90 to 125 ns.

of ortho-positronium (oPs) through simplified Monte Carlo simulations, with preliminary results reported for oPs decaying into four and five gamma photons [21], where the former being a forbidden decay mode of oPs. The challenge in studying the oPs rare decay to 5 gammas comes from the signal separation from the background. The background originates from photons scattering in the detector in combination with other decay modes. The major background sources in the experiment arise from the combination of photons arises due to the interaction of e^+ from oPs with one of the electrons from the surrounding bulk material having anti-parallel spin ($\gamma_{pickoff}$), different annihilation photons (2γ, 3γ), scattered photons ($\gamma_{scat.}$), and ,prompt photons (γ_{prompt}) during the decay process of $oPs \rightarrow 5\gamma$. The possible list of backgrounds is as follows.

- $$pPs \longrightarrow 2\gamma + 2\gamma_{scat.} + \gamma_{prompt}$$
- $$oPs \longrightarrow 3\gamma + \gamma_{scat.} + \gamma_{prompt}$$
- $$e^+e^- \longrightarrow 2\gamma_{direct} + 2\gamma_{scat.} + \gamma_{prompt}$$
- $$oPs \longrightarrow 2\gamma_{pickoff} + 2\gamma_{scat.} + \gamma_{prompt}$$
- Random coincidental photons - photons from uncorrelated events detected on time.

In analyzing the data collected during the measurement, a time-over-threshold (TOT) method [22] is employed to differentiate between annihilation photons and prompt photons. The TOT allows to separate the annihilation and prompt photons, by identifying the corresponding compton edges. As shown in Figure 1, the annihilation photons are selected asking for a TOT measured below 60 ns. At this level of the selection the background sources described before are indistinguishable from the signal events, expected in the very low TOT region. The task of this study is to apply the usage of Machine Learning methods to improve the separation while keeping a high purity for the scarce signal events. Due to the nature of these processes, classification classes are highly imbalanced; for instance, signals from rare decays are expected to have very low statistics, whereas background processes are abundant.

4. Input Feature selection

In previous analysis [9] various features like the Scatter test value (expected time (distance / c) - registered time difference calculated for 2 hits) and TOT distributions were successfully used to differentiate between the hits from annihilations of Ps and the scattered hits. However, for this intended study due to the overlap between the signal and the scattered hits, we aim to utilize Machine learning algorithmns. For this purpose, a full Monte Carlo model using J-PET official Geant4 simulations was generated. As a first step we have listed down few features based on the previous generic analysis which could be tested to classify the events. The features for machine learning (ML) training are considered based on the kinematics of the background processes(scatter test, total deposited energy or Energy of each hit), while others are added to investigate the correlations(opening angle(Theta), time of flight, total deposited energy - largest deposited energy, Total deposited energy - smallest deposited energy). These input features are shown in figure 2. With the help of the MC simulations for background processes and signal, which is currently ongoing, diverse Machine Learning algorithms will be tested, with special focus in Boosted Decision Trees (BDT), already implemented in the ROOT framework [24]. The key idea behind using these features is to understand the background arising from low energy scattered photons and the correlation between different features for a particular decay channel.

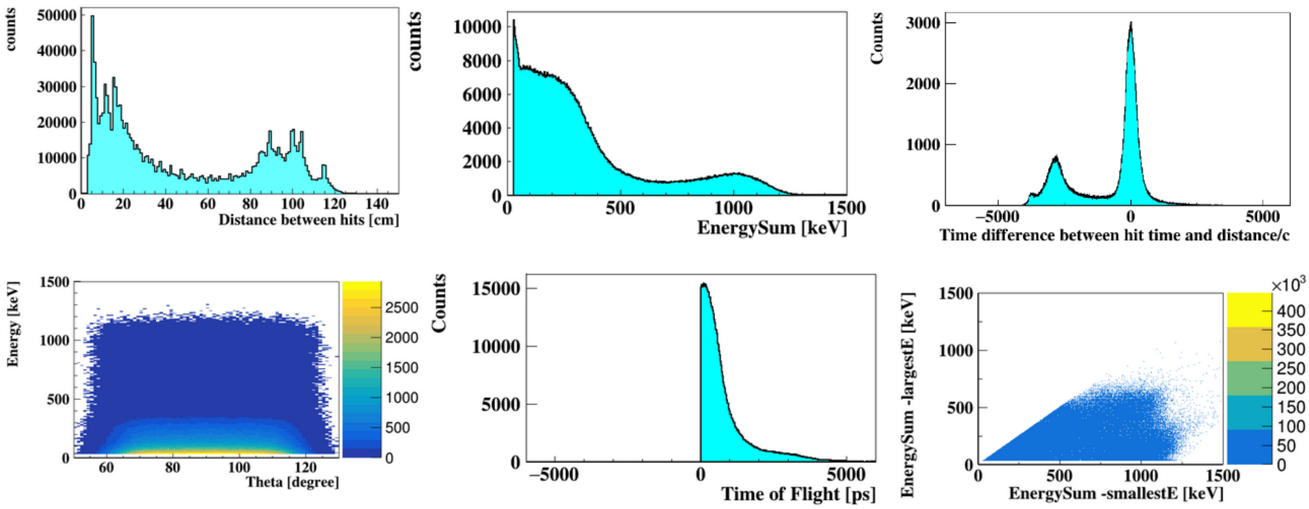

Figure 2: Input features for machine learning training, simulated using the official J-PET Monte Carlo package for background events. The top row shows (from left to right): distance between hits, sum of hit energies in an event, and the scatter test value. The bottom row includes: time of flight (center), correlation between the opening angle and the energy of hits (left), and the influence of the highest and lowest energy deposits on the total energy sum (right).

5. Summary

To address the challenge of signal-like background events, we intend to leverage Machine Learning (ML) techniques to discriminate between signal and background events. By reframing the signal selection task as an ML classification problem, we aim to train a classifier capable of identifying signal events with high accuracy while minimizing false positives from background noise. Currently, a very preliminary study of such a method was implemented in [23], showing a great improvement in separating background from the oPs to 3 gamma events. The plan is to extend that study to the 5 gamma events to achieve the needed sensitivity. We are in the process of generating higher statistics of Monte Carlo data signal events for 5 gamma decays, to enhance the training of our ML models.

Future work will focus on refining the ML models, optimizing the feature selection, and evaluating the classifier's performance on both simulated and experimental data. Additionally, we will explore advanced ML algorithms and techniques to further improve classification accuracy and efficiency. The successful implementation of these methods has the potential to significantly enhance the sensitivity and precision of the J-PET detector in studying rare and forbidden decays, contributing valuable insights to the field of particle physics.

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