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Towards Charge Conjugation Symmetry Test in Electromagnetic Interaction Using J-PET

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Charge conjugation symmetry (C-symmetry) is well-known to be maximally violated in weak interactions. However, its conservation is yet to be tested in electromagnetic and strong interactions. With the aim to test this symmetry in electromagnetic interactions, the forbidden decay channel of the triplet positronium state — the ortho-positronium — shall be explored. The C-symmetry forbids this state from decaying into anything other than an odd number of photons; henceforth, a search for four-photon decay extends the feasibility of testing the C-symmetry in electromagnetic interaction using the J-PET detector. Furthermore, the bosonic nature of photons hints at a distinct configuration in the event of a C-symmetry violation. Known for its outstanding timing and angular resolution, J-PET offers a viable and substantial platform to perform this symmetry test. In this article, the motivation behind the study, the theoretical assumptions, and recent advancements in testing C-symmetry using J-PET shall be discussed.

topics: Jagiellonian positron emission tomography (J-PET) detector, charge conjugation symmetry (C-symmetry), forbidden decays, Bose–Einstein statistics

1. Introduction

Under the charge conjugation symmetry (C-symmetry), the laws of physics shall remain invariant for matter and anti-matter. However, the evidence of an abundance of matter over anti-matter implies otherwise. While C-symmetry is found to be maximally violated within the weak interaction, it remains conserved in electromagnetic interactions (EM) as described by quantum electrodynamics (QED). Although QED theoretically preserves C-symmetry, experimental verification of this invariance in purely electromagnetic processes is still limited, motivating its in-depth investigation [1–3].

As for the exploration, the systems that are the eigenstates of C-symmetry are scarce [4]. One such promising system is positronium (Ps), the bound system of an electron and a positron (a composite of matter and anti-matter) [2, 5]. Ps exists in two states, i.e., para-positronium (p-Ps, singlet, C = +1) and ortho-positronium (o-Ps, triplet, C = −1). Consequently, p-Ps decays into an even number of photons (predominantly 2γ), while o-Ps decays into an odd number of photons (predominantly 3γ). Thus, observing the forbidden number of photons in the final state of o-Ps decay is a direct test of C-symmetry, violation of which could hint toward physics beyond the Standard Model [6, 7] — this is because QED is precisely verified with experimental data. This search could be subjected to an additional test of the spin statistics of the bosons. Mani and Rich [8] in 1971 hypothesized that due to the bosonic nature of photons, the decay channel of p-Ps to 4 photons emitted towards the vertices of a tetrahedral configuration is not allowed. This particular constraint could be used in the search for C-symmetry-violating decay of o-Ps, as the competing background (p-Ps $\to 4\gamma$) will be absent. Following the same hypothesis, this article reports the preliminary feasibility test for this forbidden decay channel using the 24-module J-PET detector [1, 9–11]. The primary aim of the experiment is to estimate the ratio of the branching ratio of this forbidden decay (o-Ps $\to 4\gamma$) channel with respect to the branching ratio of the allowed decay (o-Ps $\to 3\gamma$) channel. In this article, we have explored the signal and the control sample for the aforementioned study.

2. Detector

The experiment was conducted using the modular J-PET detector housed at the Jagiellonian University [9, 12]. The 24-module ring consists of plastic scintillator strips arranged axially. Each module contains 13 strips, read out at both ends using silicon photomultipliers (SiPMs), enabling precise timing information. Additionally, the triggerless data acquisition [13] allows for continuous data collection, suitable for multi-photon registration. These features make the J-PET detector well-suited for quantum entanglement studies [14] and tests of discrete symmetries, including C, CP, and CPT [15–18] (where C, P, and T denote charge, parity, and time reversal, respectively).

During data acquisition, each hit is recorded as time stamps in the SiPMs when signals from the scintillators cross a particular threshold, namely 30 and 70 mV. Accumulated time stamps are further utilized to reconstruct hit parameters such as hit time, hit position, and the energy deposition proxy, time over threshold (TOT) [19]. The high granularity of the detector results in a high spatial resolution in the XY coordinate (X as the vertical and Y as the horizontal axis, perpendicular to the detector's axial (Z) direction), which corresponds to an angular resolution of $\sim 1^{\circ}$–2° [1]. This feature of modular J-PET is exploited in signal selection to identify the tetrahedral configuration in Ps decay. Ps is formed through the natural decay of the radioactive source sodium 22 (^{22}Na) encapsulated in porous XAD4 material inside a small plastic chamber [20, 21]. In the decay, ^{22}Na emits a positron (e^+) and an excited neon (Ne*) nucleus. In the de-excitation, the Ne* nucleus emits an energetic 1274 keV photon within a few picoseconds, coinciding with the Ps formation. Meanwhile, the emitted e^+ captures an e^- from the surrounding medium, forming Ps, and subsequently undergoes multi-photon decay.

3. Signal and control sample selection and discussion

Investigating the specific configuration of the forbidden decay of o-Ps provides a direct and stringent test of the C-symmetry, as it effectively eliminates the background contamination from other decay channels. To search for the forbidden decays (o-Ps $\rightarrow 4\gamma$) of the o-Ps, we used the allowed decay channel (o-Ps $\rightarrow 3\gamma$) as a control sample, since o-Ps decays, whether allowed or forbidden, must satisfy energy–momentum conservation, and using the same dataset for both event selections ensures that the resulting analysis is influenced by the same sources of systematic uncertainty. Assuming that the systematic uncertainties affect the signal and the control sample in the same manner, the use of the control sample facilitates the reduction of systematic uncertainties and validation of the methodology used in the analysis. Photons from the decay of o-Ps can be identified based on the decay kinematics. However, the presence of the de-excitation photons could contaminate the selection parameters [22]. This issue is mitigated by removing the high TOT photons (characteristic of de-excitation photons). Figure 1a shows an exemplary plot of the sum versus the difference of the two smallest relative angles from 3-photons events. The distribution reflects the presence of various decay channels, such as direct annihilation into two photons,

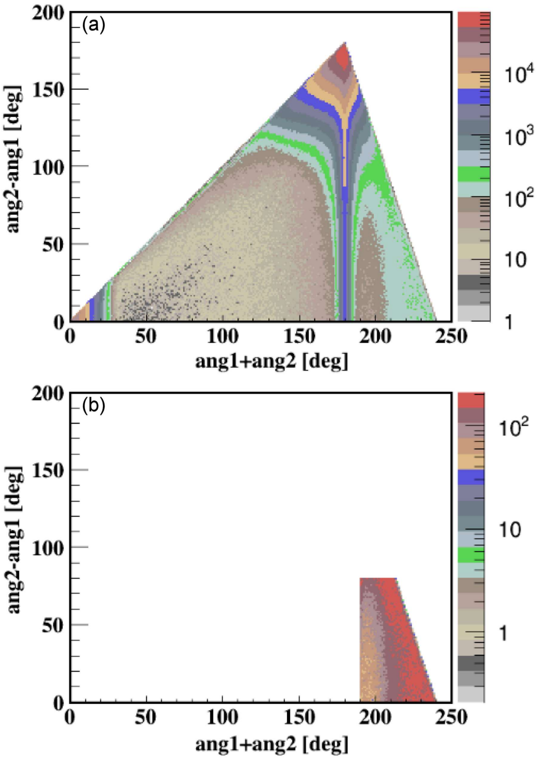

Fig. 1. (a) The plot illustrates the sum (ang1 + ang2) vs difference (ang2 - ang1) of the two smallest opening angles formed between photons in a 3-hit event. The distribution is composed of contributions from different processes, such as direct annihilation into two photons, para-positronium annihilation or pick-off annihilations and ortho-para spin conversion. These processes predominantly lead to back-to-back 2γ annihilations, which can scatter and mimic the 3-photon decay of ortho-positronium (o-Ps). The straight band around 180° on the X-axis arises from these back-to-back photons in the events. The region with ang1 + ang2 $> 200^{\circ}$ contains possible candidates for genuine 3-photon events from o-Ps decay. (b) The 3-photon decay signal from o-Ps, clearly visible after selection cuts. Background events are rejected by applying kinematic constraints consistent with allowed 3-photon decays.

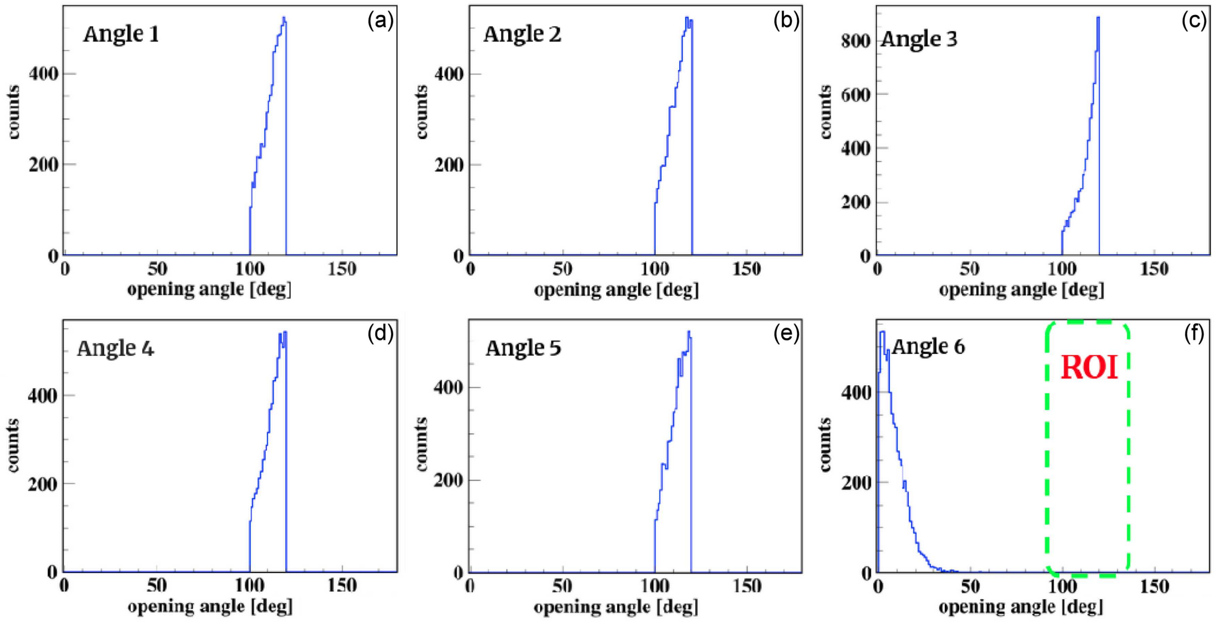

Fig. 2. Experimental distribution (based on 0.15% of collected data) of six opening angles between the momentum vectors of photons from 4-photon annihilation events: $(\gamma_1\gamma_2), (\gamma_1\gamma_3), (\gamma_1\gamma_4), (\gamma_2\gamma_3), (\gamma_2\gamma_4)$, and $(\gamma_3\gamma_4)$. A broad angular region of 100°–120° is considered to search for the opening angles corresponding to 109.5°, taking into account the detector's angular resolution. Five of the angles satisfy this flexible condition of 100°–120°, while the sixth angle is plotted under the constraint that the other five angles are within this range. The sixth angle in panel (f) does not fall into the region of interest (green dashed box).

para-positronium annihilation or pick-off annihilations and ortho-para spin conversion, and residual background, after removing high TOT photons. Figure 1b shows the o-Ps 3-photon signal after applying the selection criteria. The selection relies on kinematic features of a 3-body decay, such as the coplanarity and simultaneity, which are well established in the J-PET group for CP symmetry test [18]. However, the efficiency and refinement of these criteria are under evaluation using dedicated Monte Carlo (MC) simulations.

For the 4γ search, we focus on identifying tetrahedral photon emission configurations as proposed by Mani and Rich [8]. In particular, we search for four-photon events with mutual opening angles close to 109.5°. Assuming the modular J-PET to be capable of detecting such a special configuration, a preliminary analysis of an 8-h dataset was conducted. The objective was to identify six opening angles between 100° and 120°. Figure 2 shows the six opening angles obtained for the 4-photon event. Five out of six angles fall within the region of interest (ROI). However, the absence of the sixth angle from the ROI rejects the presence of any regular tetrahedral configuration. Nonetheless, the sixth angle also shows the prevalent background from scattering processes, visible as concentration near 0°. These observations require further investigation and support from the ongoing MC simulations, including estimation of detection efficiencies.

4. Conclusions

In this paper, we present preliminary studies on testing C-symmetry in EM interactions using the J-PET detector. By searching for the forbidden decay of o-Ps into four photons, we aim to probe potential violations of fundamental discrete symmetries. A preliminary analysis of an 8-h dataset revealed no signal in the ROI, consistent with Standard Model expectations. The ongoing work includes evaluating detection efficiencies, validating the selection criteria with MC simulations, and analyzing extended datasets to improve sensitivity. Ultimately, this study aims to establish an upper limit on the ratio of the branching ratio of o-Ps $\to 4\gamma$ with respect to the branching ratio of o-Ps $\to 3\gamma$ decays using the modular J-PET detector.

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