Journal of Physics: Conference Series **1586** (2020) 012010 doi:10.1088/1742-6596/1586/1/012010

Influence of Cosmic Radiation while Testing the Time Reversal Symmetry in the Decay of Ortho-Positronium Atoms using the J-PET detector

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Abstract. This article reports the influence of cosmic radiation interaction while testing the T-symmetry in metastable triplet states of positronium with the Jagiellonian-Positron Emission Tomograph (J-PET) detector. The J-PET detector developed at Jagiellonian University in Krakow, Poland is one of its kind being based on organic scintillators. J-PET is an axially symmetric and high acceptance scanner that can be used as a multi-purpose detector system. It is well suited to pursue tests of discrete symmetries in decays of positronium in addition to medical imaging. Cosmic rays have been considered as a well known source of background while performing test measurements with the J-PET detector. It is important to estimate and reject the significant contribution of the cosmic ray interactions within the J-PET detector in order to improve the sensitivity while testing T-symmetry violation. Therefore, the results of cosmic radiation uniquely being separated due to their large energy deposits in plastic scintillator detectors are shown in this article.

1. Introduction

Cosmic rays were discovered by an Austrian physicist Victor Hess in the early 1900's when he found that a charged electroscope discharged rapidly as it ascended in a balloon [1]. Elementary particles and light nuclei originating mainly from solar flares and from outside the solar system reach the Earth's atmosphere and a small fraction of primary cosmic protons and electrons with high energy reach the surface. Most of these incoming cosmic rays are absorbed in the Earth's atmosphere producing secondary particles that reach the Earth's surface [2]. The galactic cosmic rays are known to have higher energies [3] when compared to the photons emitted from the decay of positronium atoms which leaves us with the possibility to separate them from the favourable set of events for the experiment.

This article gives a brief description of the J-PET detector and details of the setup used for a test measurement in the next section. Section 3 explains the method used to produce positronium atoms and record the annihilation photons in the J-PET detector. Furthermore, the approach used to study Time reversal symmetry using one of the symmetry-odd-operator is briefly illustrated. Influence of cosmic radiation interaction with the J-PET detector during the experimental test run is shown in Section 4. Future endeavours with respect to the studies of T-symmetry using the J-PET detector in positronium systems are discussed in Section 5.

2. Jagiellonian - Positron Emission Tomograph

Positron emission tomography (PET) is a nuclear medicine functional imaging technique that is used to observe metabolic processes in the body as an aid to the diagnosis of tumours at the cellular level [4]. All commercially available PET scanners utilize relatively expensive crystal detectors for the detection of annihilation photons [5, 6]. The Jagiellonian - Positron Emission Tomograph (J-PET) is the first PET scanner constructed using plastic scintillator strips to make the tomograph cost effective and portable [8, 9, 11, 13]. One of the unique features of the J-PET detector is its ability to measure polarization of the annihilation photons [16, 17]. The J-PET detector consists of 192 plastic scintillator strips (EJ-230) of dimensions $500 \times 19 \times 7\ mm^3$ each, forming three concentric layers (48 modules on radius 425 mm, 48 modules on radius 467.5 mm and 96 modules on radius 575 mm) (Fig. 1 - Left Panel)[11].

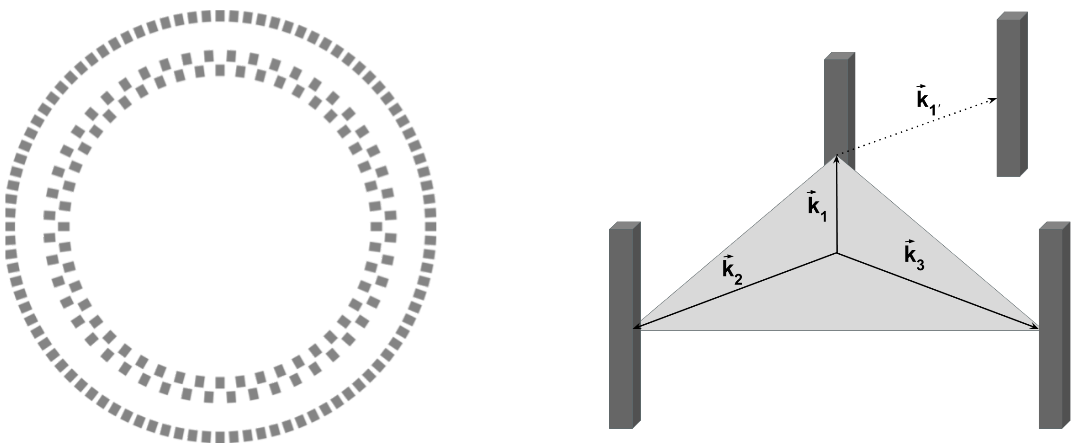

Figure 1. (Left) 2-Dimensional schematic of the J-PET detector. (Right) Schematic representation of the decay of *o-Ps* $\rightarrow 3\gamma$ (bold arrows) and one of them to have scattered into a secondary photon (dotted arrow). The primary photons interact with the plastic scintillators (dark grey strips) to have corresponding momentum directions: $\vec{k}_1$, $\vec{k}_2$ and $\vec{k}_3$, and the secondary photon with momentum direction: $\vec{k}'_1$.

Each scintillator in the J-PET scanner is optically connected at two ends to Hamamatsu R9800 vacuum tube photomultipliers [12]. This results in 384 analog channels that are processed by a fully equipped trigger-less Data Acquisition System (DAQ) together with the readout mechanism [14, 15]. The readout chain consists of Front-End Electronics (FEE) such as Time-to-Digital or Analog-to-Digital Converters (TDCs or ADCs) [14, 15]. The J-PET collaboration has developed a dedicated J-PET analysis framework which is a highly flexible, ROOT-based software package which aids the reconstruction and calibration procedures for the tomograph [10]. The results presented in this article were produced using the J-PET analysis framework to collect data and perform off-line analysis [10, 16]. The J-PET detector, together with the trigger-less DAQ system constitutes an efficient photon detector with fast timing properties [14]. This allows us to investigate the fundamental discrete symmetries in the purely leptonic sector [7].

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3. Producing meta-stable ortho-Positronium to test T-symmetry recorded by the J-PET detector

Time reversal symmetry violation has not been observed in purely leptonic systems, so far [21]. The Standard Model predicts photon-photon interaction or weak interaction to mimic the symmetry violation in the order of 10^{-9} (photon-photon interaction) and 10^{-13} (weak interactions), respectively [22, 23, 24, 25, 26]. There is about 6 orders of magnitude difference between the present experimental upper limit and the standard model predictions [18, 19, 20]. Discrete symmetries were proposed to be tested with the ortho-positronium (o-Ps) system by determining the non-zero expectation value of the operator constructed the polarization ($\vec{\epsilon_i}$) direction and momentum direction ($\vec{k_2}$) of the annihilation photons originating from the decay of o-Ps atoms, as listed in Table 1 [7]. The observation of a non-zero expectation value of this operator would imply non-invariance of these symmetries. Symmetries for which the given operator is odd (marked " − " in Table 1) can be tested at the J-PET system, namely P, T and CP.

Table 1. Discrete symmetry odd-operator polarization and momentum directions of the annihilation photons from the decay of o-Ps

Operator	C	P	T	CP	CPT
$\vec{\epsilon_1} \cdot \vec{k_2}$	+	−	−	−	+

The J-PET detector enables the test of T-symmetry in ortho-Positronium atoms by placing a point-like ^{22}Na source in the center of the detector geometry [8, 29, 30, 31]. The ^{22}Na is surrounded with XAD-4 porous polymer to enhance the production of positronium atoms [27]. The positron emitted from the source ($^{22}Na \rightarrow {}^{22}Ne^{*} + e^{+} + v_e$), interacts with the electrons in the XAD-4 porous polymer producing a meta-stable triplet state, ortho-Positronium (o-Ps) which predominantly decays into three photons: $e^{+} + e^{-} \rightarrow o\text{-}Ps \rightarrow 3\gamma$. Furthermore, the expectation value of the T-symmetry-odd operator: $\vec{\epsilon_1} \cdot \vec{k_2}$ [7], is evaluated as the direction of polarization, $\vec{\epsilon_1}$, which is measured as the cross-product of the momentum directions of the primary and corresponding secondary photons ($\vec{k_1} \times \vec{k_1'}$) and $\vec{k_2}$ as the momentum direction of the second most energetic annihilation photon (Fig. 1 Right Panel).

4. Cosmic ray interaction in the J-PET detector

Cosmic rays have been considered as a well known source of background while performing test measurements with the J-PET detector. It is important to estimate and reject the significant contribution of the cosmic ray interactions within the J-PET detector in order to improve the sensitivity while testing T-symmetry violation. Cosmic radiation are uniquely segregated from the data sample due to their large energy deposits in the detector. The energy deposits from the interaction of particles in the J-PET detector are measured using the time-over-threshold (TOT) technique [28]. In the beginning of 2018, we conducted two experimental test runs: one without the placement of any radioactive source in the vicinity of the J-PET detector in order to study the cosmic radiation contribution to the experiment, and the other experimental run was conducted by placing a point-like ^{22}Na source in the center of the detector geometry.

Fig. 2 shows the sum of energy deposition of four-interactions in an event time window: 200 ns, as a function of TOT. Cutting out events above 100 ns reduces the registered cosmic radiation by 97.5%.

5. Conclusion

The J-PET collaboration aims to search for the violation of T-symmetry in the decay of positronium atoms. The J-PET detector enables the test of T-symmetry-odd operator

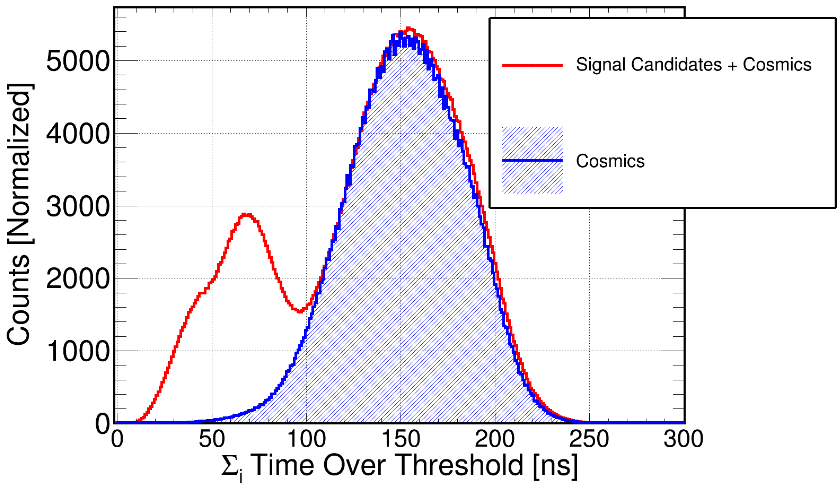

Figure 2. Experimental distribution of time-over-threshold (TOT) for measurement with (red) and without (blue) positronium source. The spectra were normalized to the same measurement time.

constructed using the momenta and polarization directions of photons from annihilation of o-Ps. The test measurements with and without a positronium source was conducted in order to study the cosmic radiation interaction influence within the J-PET detector. It was observed that after rejecting the four-interaction events with total TOT sum greater than 100 ns as shown in Fig. 2 and by using additional analysis criteria, the cosmic background is reduced to the level of 0.0025% in the final data sample used to test the T-symmetry. In order to improve the present experimental upper limit of T-symmetry violation in purely leptonic systems by one order of magnitude, J-PET collaboration aims to conduct an experimental run in the following year.

6. Acknowledgement

This work was supported by The Polish National Center for Research and Development through grant INNOTECH-K1/IN1/64/ 159174/NCBR/12, the Foundation for Polish Science through the MPD and TEAM/2017-4/39 programmes, the National Science Centre of Poland through grants no. 2016/21/B/ST2/01222, 2017/25/N/NZ1/00861, the Ministry for Science and Higher Education through grants no. 6673/IA/SP/2016, 7150/E-338/SPUB/2017/1 and 7150/E-338/M/2017.

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