Recent results on the positronium decay studies with the J-PET detector

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Abstract. Positronium, as a bound state of electron and positron and the lightest matter-antimatter system and at the same time an eigenstate of the C and P operators is a unique probe to search for possible violation of combined charge, parity, and time-reversal symmetries (CPT). The test is performed by a measurement of angular correlations in the annihilations of the lightest leptonic bound system. The J-PET detector is the only device which enables the determination of the polarization of photons from positronium annihilation together with the positronium spin axis on an event-by-event basis. This allows to explore a new class of discrete symmetry odd operators that were not investigated before. The first test of CPT symmetry at J-PET is presented together with preliminary results of CP, P and T symmetry test.

1 Introduction

Motivations to study CP and CPT invariance are manifold [1–3]. One of them being that the CPT theorem reveals foundational character of CPT symmetry conservation requirement, which is equivalent to usage of unitary, local and Lorentz-invariant quantum field theory. As such, tests of CPT invariance probe fundamentals of physics [4]. Moreover, CPT contains charge conjugation, and therefore represents a symmetry between matter and antimatter. The amount of CP violation contained in the Standard Model appears to be insufficient for a convincing explanation of the observed prevalence of matter over antimatter in the Universe [5, 6]. For these reasons, discrete symmetry tests remain an interesting experimental research area in fundamental physics. One possible way to study the discrete symmetry violation is to investigate the expectation values for the symmetry odd-operators of the non-degenerate stationary states. The anti-unitary character of the discrete-symmetry operator makes the experimental studies of the time reversal invariance more challenging than other symmetries, since it requires abilities of preparing the initial and final states of the process in a fully controlled way [7]. So far, none of the experiments reported limits on the T-symmetry violations in the decays of positronium. The known final state interactions of photons are expected to mimic the T-symmetry violation at the level of 10^{-9} [8, 9]. All of the previous investigations with positronium, which tested the discrete symmetries odd operators, were based on the products of photons momenta and positronium spin vectors [10]. The J-PET group extends the study to other operators, taking advantages of properties of the J-PET tomography scanner, which enables to determine the momentum direction of the secondary

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scattered photons [7]. Using the J-PET detector, the discrete-symmetries can be investigated by searching for the possible non-zero expectation values of the symmetry-odd operators which are constructed from the momentum vectors of the primary and secondary scattered photons originating from the decays of the o-Ps atoms [7].

2 Jagiellonian - Positron Emission Tomograph

PET (positron emission tomography) is a nuclear medicine functional imaging technology for observing metabolic processes in the body as a tool for tumor diagnostics at the cellular level [11–14]. For the detection of annihilation photons, all commercially available PET scanners use relatively expensive crystal detectors. The Jagiellonian-Positron Emission Tomograph (J-PET) is the first PET scanner to use plastic scintillator strips, making it more cost efficient and portable [15–18]. The J-PET detector's ability to measure the polarization of annihilation photons is one of its distinguishing properties [7, 19, 20]. The detector is made up of 192 plastic scintillator strips (EJ-230) with dimensions of $500 \times 19 \times 7\text{mm}^3$ each that are arranged in three concentric layers (48 modules on radius 425 mm, 48 modules on radius 467.5 mm, and 96 modules on radius 575 mm). Each scintillator of the J-PET scanner is optically coupled to Hamamatsu R9800 vacuum tube photomultipliers on both ends [21–23]. This yields 384 analog channels, which are processed by a fully equipped trigger-less Data Acquisition System (DAQ) and readout mechanism [24–26].

The experiments were conducted with a point-like ^{22}Na source placed in the center of the detector and surrounded by XAD-4 porous polymer to produce positronium atoms [27]. The positrons emitted from the source ($^{22}Na \rightarrow {}^{22}Ne^{*} + e^{+} + \nu_e$) combine with the electrons in the XAD-4 porous polymer to produce ortho-Positronium (o-Ps), a meta-stable triplet state that primarily decays into three photons due to charge conjugation symmetry conservation.

The key feature of the J-PET detector is its fast timing properties from plastic scintillators which allows the calculation of the relative azimuthal angles between the interacting photons. From kinematics we infer that the sum of the two smallest relative azimuthal angles between the registered annihilation photons for *o-Ps*$\rightarrow 3\gamma$ must be greater than 180° [7]. Using this feature of the detector we are capable of suppressing a large sample of background of e+e- $\rightarrow 2\gamma$.

3 Results

Recently the J-PET collaboration reported a measurement of the expectation value of the angular correlation $O_{CPT} = \frac{\vec{S}\cdot(\vec{k_1}\times\vec{k_2})}{|\vec{k_1}\times\vec{k_2}|}$, where $\vec{S}$ denotes the polarization vector of o-Ps and $\vec{k_i}$ is the momentum of the i-th annihilation photon [28]. With a 10 MBq sodium source a sample of almost 10^7 event candidates from the o-Ps$\rightarrow 3\gamma$ was collected. Since parity is violated in the β decay, the emitted positrons are polarized longitudinally along the momentum direction [7]. In the production of Ps this polarization is preserved to a large degree [29]. Therefore, the polarization of the o-Ps can be estimated from the emission point of the positron and annihilation point of o-Ps. The sensitivity of O_{CPT} reached by J-PET is three times better than the previous result [28]. The error has a negligible systematical contribution and the result of measurement shows no CPT symmetry violation.

Based on 122 days of data taking with 1 MBq source we report preliminary accuracy of the measurement of the expectation value of the following operator: $O_{CP,P,T} = \frac{\vec{k_i}\cdot(\vec{k_j}\times\vec{k_j'})}{|\vec{k_j}\times\vec{k_j'}|}$. Here $\vec{k_k}$ denotes the momentum of the k-th annihilation photon and $\vec{k_k'}$ is the momentum of the scattered photon [7, 30]. With the available statistics of 7×10^5 events we are able to reach an accuracy of 10^{-4} without contribution from systematical uncertainties. It is worth to mention that the previous test of CP symmetry with o-Ps reached the level of 10^{-3} [10].

4 Conclusion

First measurement of expectation value of symmetry-odd operator reported by J-PET group, together with prospects of upcoming results, confirms the potential of the detector for tests of discrete symmetries [28, 31]. This device has unique property of combining determination of photon polarization together with estimation of positronium spin axis on the event-by-event basis. Although the accuracy of CPT and CP, P, T tests are statistically dominated, the J-PET detector undergoes an upgrade for an additional layer of scintillators read out by silicon photomultipliers (SiPMs), which would allow to triple the efficiency for the single photon detection and improve the time resolution by about a factor of 1.5.

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