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Testing CPT symmetry in ortho-positronium decays with J-PET detector

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Search for possible violation of combined charge, parity, and time-reversal symmetries is yet another approach for a test of New Physics, therefore a bound state of electron and positron (positronium) as the lightest matter-antimatter system and at the same time an eigenstate of the C and P operators is an unique probe in such endeavour. The test is performed by measurement of angular correlations in the annihilations of the lightest leptonic bound system. With the Jagiellonian Positron Emission Tomograph (J-PET) we have collected an unprecedented range of kinematical configurations of exclusively-recorded annihilations of the positronium triplet state (ortho-positronium) into three photons. Employing a novel technique for estimation of positronium spin axis on the basis of a single event, we determined the complete distribution of an angular correlation between spin and annihilation plane of ortho-positronium. We present recently published result of determined expectation value of this correlation at the precision level of 10^{-4}, with an over three-fold improvement on the previous measurement. We discuss also the prospects for reaching the precision level of 10^{-5} with the CPT symmetry test at the J-PET detector.

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1. Introduction

The symmetry under a combination of charge conjugation, parity transformation and reversal in time, also known as the CPT symmetry is the last of discrete symmetries not found to be violated in Nature. Although extensive tests of this invariance are performed, it is relatively scarcely tested in bound leptonic systems. The lightest of such systems if positronium, the bound state of an electron and a positron. Positronium physics is largely governed by QED [1], a theory tested to precision level of 10^{-12} in measurements of electron magnetic moment and the fine structure constant [2, 3], which does not forsee CPT noninvariance. However, effects beyond standard QED cannot be excluded and recently measured discrepancies from QED expectations in the fine structure of positronium [4] call for further investigation.

One of the means to test the CPT invariance in bound leptonic systems is based on searching for certain CPT-asymmetric angular correlations in annihilations of ortho-positronium (o-Ps), the triplet positronium state, into three photons. A correlation between orientation of the decay plane, determined by momenta of the two most energetic annihilation photons $\mathbf{k}_1$ and $\mathbf{k}_2$, and the spin of the ortho-positronium atom $\mathbf{S}$, is described by the following operator:

$$O_{CPT} = \frac{S}{|S|} \cdot \frac{\mathbf{k}_1 \times \mathbf{k}_2}{|\mathbf{k}_1 \times \mathbf{k}_2|}, \tag{1}$$

constructed so as to transform oddly under the combined CPT operation. Observation of a non-vanishing mean value of this operator in three-photon ortho-positronium annihilations would be an indication of CPT violation in the process [5, 6].

The recent realization of such a CPT test was performed using the Gammasphere array of germanium detectors in order to record a broad range of kinematical configurations of the o-Ps $\to 3\gamma$ annihilations resulting in a zero-compatible measurement of a CPT-violation coefficient at the precision level of 10^{-3} [7]. In the J-PET experiment, we expand on the ideas from this measurement by introducing positronium spin estimation on a single event basis as well as profit from an improved resolution of the experimental setup in order to enhance the test sensitivity to the 10^{-4} level and beyond.

2. The experimental setup

The J-PET detection setup was originally created as a prototype of a first Positron Emission Tomograph (PET) based on plastic scintillators and recording photon interactions through the Compton scattering process. Besides being used in medical imaging research towards construction of a cost-effective total body PET scanner [8] and imaging with positronium properties [9, 10], it constitutes a general-purpose detector of sub-MeV energy photons well suited for fundamental studies [6].

The detector comprises 192 strips of plastic scintillators with dimensions of $7\times19\times500$ mm^3 organized into thee concentric layers of 48, 48 and 192 strips and radii of 42.5 cm, 46.75 cm and 57.5 cm respectively [11]. Each of the strips is read out at both ends by vacuum photomultiplier tubes (PMT-s) and electric signals from the PMT-s deliver information on the amount of scintillation light and time of light arrival to each of the strips ends. Subsequently, axial position of a γ interaction along a strip is determined from time difference of PMT signals [12]. Energy deposited in Compton scattering is estimated using time-over-threshold (TOT) of electric pulses from the PMT-s [13]. The dimensions of the scintillator strips provide angular resolution of the momentum direction of recorded photons at the level of 1^o. The time resolution of γ interactions is about 250 ps.

Positronium atoms are produced by positrons emitted by a ^{22}Na β^+ source located in the center of a cylindrical vacuum chamber of 12 cm radius with its inner walls coated with a 3 mm thick layer of porous silica enhancing positronium formation. Such production system combined with trilaterative reconstruction of the o-Ps $\to 3\gamma$ decay positions [14] allows for estimation of the direction of positron emission separately for each event. Subsequently, most likely direction of o-Ps spin polarization is obtained using the statistical longitudinal polarization of positrons from β^+ decay and chances of e^+ spin polarization propagating to the formed positronium atom. This method of per-event spin estimation largely enhances the analyzing power for searching for asymmetries in the distribution of the O_{CPT} defined in Eq. 1 with respect to the previous experiment [15].

3. Data analysis and results

J-PET allows for an exclusive selection of o-Ps $\to 3\gamma$ events which starts with identification of coincidences of three and more photon interactions recorded within a time window of 2.5 ns, each characterized by TOT in the range below the expected location of the Compton edge for 511 keV photons from direct e^+e^- annihilations. One of the major background components originates from events contaminated with a secondary Compton-scattered photon recorded in the detector. Such events are recognized by considering a hypothetitcal photon propagating directly between all pairs of recorded interaction points in the event. In case a pair is found with spatial distance and time between the recorded interactions consistent up to the speed of light factor, later of the two interactions is rejected from the event candidate.

For events with exactly three photon interactions remaining, analytical reconstruction of the o-Ps annihilation point is performed using a trilateration-based algorithm [14]. The reconstructed vertex is used to infer the photon momentum directions and energies are reconstructed from angular event topology and momentum conservation thus reproducing the complete photons' momentum vectors.

At this stage, dominant background comes from direct $e^+e^- \to 2\gamma$ annihilations. It is discriminated by reconstructing a hypothetical 2γ annihilation point using each pair of recorded photon interactions and rejecting events where a likely $e^+e^- \to 2\gamma$ annihilation is identified to originate in the porous material in the positronium formation chamber.

Around 2 million of thus identified o-Ps $\to 3\gamma$ event candidates constitute an unprecedented sample of ortho-positronium annihilations recorded with a broad range of their allowed kinematical configurations. These events are used to obtain the full spectrum of the O_{CPT} operator, probing the entire range of its definition for the first time. No asymmetries in the distribution are found, as quantified by the operator mean value of $(2.5 \pm 3.6) \times 10^{-4}$ which — accounting for the experiment's analyzing power dominated by spin polarization uncertainty — translates to the CPT-violation amplitude of $C_{CPT} = (6.7 \pm 9.5) \times 10^{-4}$ [15].

4. Prospects for future experiments with J-PET

The first CPT symmetry test in positronium annihilations performed with J-PET has improved the precision over the previous best result by over a factor of three. Presently, the positronium production setup has been improved to use a spherical rather than cylindrical geometry which enhances utilization of positrons from the isotroipc source by a factor of 1.5 and minimizes spurious asymmetries possibly originating from geometry of the annihilation medium [16]. A data sample amounting to about 4.5 times the statistics of the measurement discussed in the previous Section was already collected and is presently being analyzed.

Simultaneously, a new detector based on the J-PET technology was constructed and commissioned. This detector comprises 24 modules of 13 densely-packed plastic scintillator strips equipped with silicon photomultiplier readout and fully digital front-end electronics and data acquisition provinding improved time resolution for γ interactions. The modules can be arranged into multiple configurations including multi- and single layer [17]. Monte Carlo simulations of the entire experiment using different detector arrangements were conducted in order to select the best tradeoff between single photon recording probability (enhanced in multi-layer setups) and amount of background from secondary Compton-scattered photons which is more likely recorded between multiple detector layers. On the basis of these studies, a single layer setup was selected which is expected to enhance the geometrical acceptance for three-photon anhihiltions of o-Ps by a factor of about 11 with respect to the first J-PET detector [18].

A combination of the factors described above are expected to allow J-PET to collect a saple of o-Ps $\rightarrow 3\gamma$ events two orders of magnitude greater than that used in the first CPT test within 4 months of continuous measurement which is being prepared as of writing of this contribution and scheduled to start by the end of 2022 with a view to reaching the sensitivity of the CPT test at the level of 10^{-5}.

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