Testing time reversal symmetry in the decay of ortho-Positronium atoms using the J-PET detector

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Introduction

Testing time reversal symmetry has been one of the most curious problems in particle physics. The best experimental upper limits for CP and CPT (C-Charge Conjugation, P-Parity and T-Time) symmetries violation in positronium decay are set to about 0.3×10^{-3} [1–3]. According to the Standard Model predictions, photon-photon interaction or weak interaction can mimic the symmetry violation at the level of 10^{-9} and 10^{-13}, respectively [4–7]. Thus, there is a range of about 7 orders of magnitude for possible observation of CP and/or CPT symmetry violation. So far, discrete symmetries were proposed to be tested with the ortho-Positronium (o-Ps) system by determining the non-zero expectation values of the operators constructed from the spin ($\vec{S}$) of the o-Ps and the momentum vectors of the annihilation photons $\vec{k}_1$, $\vec{k}_2$ and $\vec{k}_3$, where, $\vec{k}_1 > \vec{k}_2 > \vec{k}_3$ as presented in TABLE I. The observation of non-zero expectation values of these operators would imply non-invariance of these symmetries for which the given operator is odd (marked " − " in TABLE I)

TABLE I: Discrete symmetry odd-operators using spin orientation of the o-Ps, polarization and momentum directions of the annihilation photons.

Operator	C	P	T	CP	CPT
$\vec{S}\cdot\vec{k}_1$	+	−	+	−	−
$\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)$	+	+	−	+	−
$(\vec{S}\cdot\vec{k}_1)\cdot(\vec{S}\cdot(\vec{k}_1\times\vec{k}_2))$	+	−	−	−	+
$\vec{\epsilon}_1\cdot\vec{k}_2$	+	−	−	−	+
$\vec{S}\cdot\vec{\epsilon}_1$	+	+	−	+	−
$\vec{S}\cdot(\vec{k}_2\times\vec{\epsilon}_2)$	+	−	+	−	−

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Jagiellonian Positron Emission Tomograph

Positron emission tomography (PET) is a non-invasive technique used in the diagnostics of various types of tumors at the cellular level. All commercially available PET scanners utilize relatively expensive crystal detectors for the detection of annihilation photons [8, 9]. 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 [11, 12, 15, 18, 19]. The J-PET detector consists of 192 plastic scintillator strips of dimensions $500 \times 19 \times 7\ mm^3$ each, forming three concentric layers (48 modules at radius 425 mm, 48 modules at radius 467.5 mm and 96 modules at radius 575 mm). The J-PET detector, together with the trigger-less DAQ system constitutes an efficient photon detector with high timing properties [15, 20, 21]. One of the unique features of the J-PET detector is its ability to measure polarization of the annihilation photons. Polarization is determined as a vector product of the momenta of the photon before and after the scattering in the detector. This allows us to investigate the fundamental discrete symmetries in the purely leptonic sector [10]. In order to produce positronium atoms, a point-like ^{22}Na source is placed in the center of the detector and is surrounded with XAD-4 porous polymer [23]. The porous polymer enhances the ortho-positronium formation probability. For the present studies of the time reversal symmetry, we measure the expectation value of $\vec{\epsilon}_1 \cdot \vec{k}_2$ operator. Thus, we are interested in events with three reconstructed gamma quanta originating from the $oPs \rightarrow 3\gamma$ annihilation, where, one of them is scattered enabling us to determine it's polarization.

Conclusion

Positronium is an excellent laboratory enabling studies of many interesting phenomena [25] such as e.g. gravitation of antimatter [25], search for mirror photons [26, 27], studies of quantum entanglement [28, 29] and tests of discrete symmetries in the leptonic sector [10]. So far, T-violation effects were not discovered in a purely leptonic system e.g in the positronium system. The J-PET detector offers a measurement of the direction of polarization ($\vec{\epsilon}$) of photons simultaneously with their momentum direction ($\vec{k}$). High accuracy of time measurement together with an effective reduction of the background based on the event geometry should allow to increase the sensitivity by one order of magnitude with respect to the current experimental limits [10].

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