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Test of discrete symmetries with J-PET

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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. Positronium being a bound state of electron and positron, is the lightest matter-antimatter system and at the same time eingenstate of the C and P operators, which makes it a unique probe in such endeavour. The experimental method consists of the measurement of angular correlations constructed based on the momenta and/or polarization of photons originating from the positronium annihilation, and the positronium spin orientation. The J-PET detector is the only device which enables determination of polarization of photons from positronium annihilation together with estimation of positronium spin axis on the event-by-event basis. This allows exploration of a new class of discrete symmetry-odd operators that has not been investigated before. With first measurements demonstrating such capabilities, we are able to reach the precision of CP and CPT tests at permill level. In this contribution we describe experimental techniques and new results of discrete symmetry tests in the decays of positronium.

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1. Introduction

The original aim of the Jagiellonian Positron Emission Tomography (J-PET) project was to construct a low-cost, high-acceptance, multi-purpose medical scanner for novel medical imaging technique based on photons originating from electron-positron annihilation [1–3]. However, unique properties of the experimental setup allowing the measurement of the the polarization of annihilation photons, and determination of the positronium spin on the event-by-event basis made the J-PET detector a perfect experimental tool for various fundamental studies such as: tests of discrete symmetries in the positronium system [4], studies of photon quantum correlations [5, 6], search for rare and forbidden decays [4], or Mirror Matter searches [7]. In this contribution, we present the experimental methods and summarize recent results obtained by the J-PET collaboration.

2. Positronium properties

The positronium (Ps) is a meta-stable exotic atom consisting of a bound system of an electron and a positron. The Ps atom model is described in an analogical way to the hydrogen atom, in which one replaces the proton by the positron particle. Consequently, its overall energy spectrum is, in the first approximation, similar to the hydrogen one, up to the mass difference between the positron and proton, which makes the transition frequencies roughly two times smaller. Because Ps atom is a purely leptonic system its theoretical description is relatively simple and not limited by the hadronic uncertainties. Its properties, such as energy spectrum and lifetimes, are precisely described by Quantum Electrodynamics (QED) with very small radiative corrections from Quantum Chromodynamics (QCD) and weak interaction effects in the SM [8].

The ground state of the Ps has two possible configurations, a singlet state ${}^1S_0$ para-positronium, $\mathrm{p-Ps}$, and the ${}^3S_1$ triplet, ortho-positronium, $\mathrm{o-Ps}$. The lifetimes of the two ground states in the vacuum are approximately 125 picosecond and 142 nanoseconds for the $\mathrm{p-Ps}$ and $\mathrm{o-Ps}$, respectively. The $\mathrm{o-Ps}$ decay has been evaluated to two-loop level using the non-relativistic QED [9]. As a system formed of particle and its antiparticle, Ps state is an eigenstate of the charge conjugation parity C. It is also an eigenstate of the spatial parity $\mathcal{P}$ and its eigenvalue is given by the product of the orbital wavefunction $(-1)^L$ and the intrinsic parities of electron and positron, which by convention are of opposite signs. Therefore in the ground state the parity of Ps is equal to $\lambda_P = -1$, while the Ps charge conjugation eigenvalue is dependent on the total spin S of the system, $\lambda_C = (-1)^S$. It implies that the $\mathrm{p-Ps}$ is a $C\mathcal{P}$-odd state while the $\mathrm{o-Ps}$ is even with respect to this operator. In the frame of the Standard Model (SM), the symmetries C, $\mathcal{P}$ and $\mathcal{T}$ and its combinations are conserved by the electromagnetic interactions, therefore observation of any symmetry breaking in the Ps system would be a sign of New Physics phenomena. According to the SM predictions, photon-photon interaction or weak interaction can mimic the symmetry violation at the level of 10^{-9} and 10^{-13}, respectively [10–12]. Thus, there is a range of about 6 orders of magnitude for possible observation of $C\mathcal{P}$ and/or $C\mathcal{P}\mathcal{T}$ symmetry violation with respect to the estimated experimental upper limits [13, 14].

A proposed test of Ps invariance under a certain symmetry operation consists of the measurement of non-vanishing expectation value of an operator odd under a given transformation [15]. The convenient angular correlation operators can be constructed based on the momenta and/or polarization of photons originating from the o − Ps annihilation, and the spin of the Ps [4]. The correlation operators are presented in Table 1. The $\vec{k}_1$, $\vec{k}_2$, and $\vec{k}_3$ denote the momenta of the three photons in ascending order ($|\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3|$), and $\vec{\epsilon}_1$, $\vec{\epsilon}_2$, and $\vec{\epsilon}_3$ are their corresponding polarization vectors. The $\vec{S}$ operator denotes a o − Ps spin vector.

Table 1: Operators constructed based on spin orientation of the o − Ps, polarization and momentum directions of the annihilation photons related to discrete symmetry. +/− signs correspond to even and odd operators under the given transformation [4].

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

3. The J-PET detector setup

The J-PET detector is the first Positron Emission Tomography scanner built from plastic scintillators [1, 2, 16, 17]. The first, full-scale prototype consists of three cylindrical layers including in total 192 plastic scintillators strips with dimensions of $7 \times 19 \times 500$ mm^3. Light signals from each strip are converted to electrical signals by photomultipliers placed at opposite ends of the strip [18]. The position and time of the photons interacting in the detector material are determined based on the arrival time of light signals at both ends of the scintillator strips. The signals are probed in the voltage domain with the accuracy of about 30 ps by a dedicated, fully digital front-end electronics and the data are collected by the trigger-less and re-configurable data acquisition system [19, 20]. A dedicated software framework was developed for the data processing and simulations [21]. The hit-position and hit-time are reconstructed by the reconstruction methods based on the compressing sensing theory and the library of synchronized model signals [18, 22, 23]. For the experimental studies a point-like ^{22}Na source, emitting positrons via β decay, is placed in the center of the detector and is surrounded with XAD-4 porous polymer [24]. The porous polymer enhances the o − Ps formation probability.

4. Symmetry tests with CPT-odd operator

The combined CPT operation is one of the last fundamental symmetries conserved by Nature. CPT invariance is also assumed by most of the modern quantum field theories, including QED. Any confirmed CPT symmetry breaking would be sign of New Physics.

The J-PET collaboration has performed a search for a CPT-violating angular correlation in the three-photon annihilation of o − Ps atoms [25]. Using a β emitting sodium source of 10 MBq, the J-PET collected a sample of a total of 7.3×10^6 event candidates from the o − Ps $\to 3\gamma$ annihilation process. One of the consequences of the parity violation in the β decay process is the

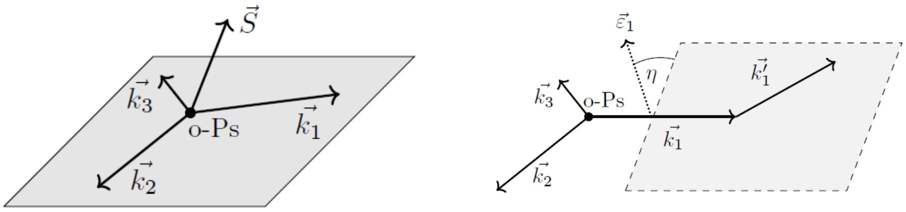

Figure 1: Left: scheme of the $o - Ps$ decay plane defined by the $\vec{k}_i$ momenta of the photons. $\vec{S}$ denotes the Ps spin vector (adapted from [25]). Right: estimation of polarization vector for a photon produced in $o - Ps \rightarrow 3\gamma$ at J-PET (adapted from [15]).

longitudinal polarization along the velocity direction of the emitted positrons. This polarization is preserved to high extent during the Ps formation [4, 26] and can be estimated, without usage of the magnetic field, by combining the information about the positron emission point with the position of the reconstructed Ps annihilation vertex. The newly image reconstruction technique described in the publication [25], and later in [27, 28], enables the determination of the Ps annihilation vertex and consequently the the $o - Ps$ spin axis. The total effective polarisation was estimated to be $P \sim 37.4\%$. The scheme of the measurement is presented in Fig. 1, left panel.

The expectation value of the angular correlation $O_{CPT} = \frac{\vec{S}\cdot(\vec{k}_1 \times \vec{k}_2)}{|\vec{k}_1 \times \vec{k}_2|} = \cos\theta$ has been estimated, achieving a sensitivity three times better than the previous result [13]. No significant asymmetry has been observed. The measurement error is dominated by the statistical uncertainty Future measurements with the upgraded detector setup and higher statistics will improve the sensitivity [29].

5. New CP and T operators using photon polarization

The experimental upper limit for the CP-violation in Ps decays has a sensitivity of 2.2×10^{-3} [14], by measuring the angular correlation of $(\vec{S} \cdot \vec{k}_1)\vec{S} \cdot \vec{k}_1 \times \vec{k}_2$. In J-PET a novel spin-independent operator is constructed for the $o - Ps \rightarrow 3\gamma$ annihilations by including the polarization vector of one of the final state photons [4, 30]:

$$C_{T\prime} = \vec{k}_2 \cdot \vec{\epsilon}_1, \tag{1}$$

where ϵ_1 denotes the polarization vector of the most energetic photon and $\vec{k}_2$ is the momentum of the second most energetic one. Such angular correlations using photon electric polarization have been never explored in the $o - Ps$ decays. In the J-PET, the ability of recording secondary interactions of scattered photons, as shown in Fig. 1 right panel, allows the measurement of the expectation value $\langle C_{T\prime} \rangle$. A preliminary result with a precision of 10^{-4} has been established with J-PET. Further data and the upgraded setup can increase the sensitivity at the level of 10^{-5}.

6. Conclusions

Precision measurement of positronium decays provides a way to test fundamental symmetries. The J-PET detector is the only device which enables determination of photon polarization together with estimation of positronium spin axis on the event-by-event basis. With first measurements demonstrating such capabilities we are able to reach the precision of CP and CPT tests at permill level. The current results are dominated by the statical errors. Apart from the discrete symmetry tests, J-PET can be also used in the studies of photon quantum correlations, search for rare and forbidden decays, or Mirror Matter searches. The upgraded detector, with an additional layer of read out by matrices of silicon photomultipliers (SiPM) is currently fully operational. It is is expected to triple the efficiency for the single photon detection and improve the time resolution by about a factor of 1.5 [31].

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