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Tests of discrete symmetries in positronium decays with the J-PET detector

E Czerwiński for the J-PET collaboration
Institute of Physics, Jagiellonian University, Cracow, Poland
E-mail: `eryk.czerwinski@uj.edu.pl`

Abstract. The newly constructed Jagiellonian Positron Emission Tomograph (J-PET) is the first tomograph built from plastic scintillators. As a detector optimized for the registration of photons from the electron-positron annihilations, it also capable to tests discrete symmetries in decays of positronium atoms via the determination of the expectation values of the discrete-symmetries-odd operators, which may be constructed from the spin of ortho-positronium atom and the momenta and polarization vectors of photons originating from its annihilation.

1. Positronium system

Positronium is a bound state of an electron and a positron. It is an eigenstate of the charge conjugation operator as being a system of an electron and an anti-electron. It is also a parity eigenstate since binding is provided by a central potential.

There are two possible ground states of positronium: $^1S_0$ para-positronium (p-Ps) and $^3S_1$ ortho-positronium (o-Ps). First one has a mean lifetime of 125 ps, while second one - 142 ns. In general, positronium is the lightest purely leptonic object decaying into photons. Therefore final state interactions are expected at the level of 10^{-9} to 10^{-10} [1, 2]. This makes positronium an unique laboratory to study discrete symmetries [3, 4, 5]. Recently such studies were commenced by the J-PET experiment [6].

2. J-PET detector

Although designed for medical imaging and morphological studies [7, 8] the Jagiellonian Positron Emission Tomograph is a multipurpose detector. Three layers of plastic scintillator strips form a cylindrical chamber. Single strip is EJ-230 material of $500 \times 19 \times 7$ mm^3 dimensions read out at each 19×7 mm^2 side by the R9800 Hamamatsu photomultiplier. Two inner layers consist of 48 such modules each, placed on 425 mm and 467.5 mm radius, respectively, with modules in the second layer rotated by 3.75° with respect to modules of first layer. Third layer is composed by 96 modules on radius 575 mm. Position of photon interaction along scintillator strip is derived from a time difference of signals from both photomultipliers attached to this strip [9], whereas time of interaction is calculated from a sum of times of these signals [10, 11]. Signals from 192 photomultipliers are probed in time domain at 4 different amplitude thresholds. In total up to 8 time measurements (leading and trailing edges) are performed [12, 13] allowing for precise signal start time derivation and Time-Over-Threshold measurement equivalent to photon deposited energy determination. All Time-to-Digital Converter (TDC) channels are distributed on the 8 Trigger Readout Boards (TRBs) in the trigger-less manner, while the gathered data are processed with a developed analysis framework [14].

Since EJ-230 is a polymer scintillator, a deposition of energy by photons goes via Compton scattering. The highest probability of this scattering is in the plane perpendicular to the electric vector of the photon [15, 16]. Therefore registration of primary ($\vec{k_i}$) and scattered ($\vec{k_i'}$) quanta pairs allows for estimation of its linear polarization $\vec{\epsilon_i} = \vec{k_i} \times \vec{k_i'}$. Registration of polarization of gamma quanta is a unique feature of the J-PET system [6, 17], which allows to study the multi-partite entanglement of photons originating from the decays of positronium atoms [18].

In J-PET, ortho-positronium atoms are created in a porous material surrounding a sodium source [19]. The emitted positron is stopped producing o-Ps which may annihilate into 3γ. Detection of neon deexcitation γ is a start signal for possible positronium lifetime measurement. The annihilation place and time is calculated with a dedicated trilateration method [20], since annihilation gamma quanta momentum vectors are coplanar. Additionally, reconstructed directions of annihilation photons are used for calculation of energy of these photons [21]. Reconstructed annihilation place and time together with a start signal from prompt gamma and known source position allow for e^+ velocity direction determination. This determines spin direction of positron, due to the parity violation in β-decay. Since the polarization of positron is to large extent preserved during the thermalization process [22, 23], the spin of o-Ps is determined as well [24].

Details about J-PET characteristics are presented in Ref. [25, 26, 27]. Here, a short presentation of data taking capabilities of J-PET system is given.

So far J-PET performed seven data taking campaigns. These measurements were conducted with different target materials and shapes to investigate positronium formation rates. In parallel a throughput of data acquisition and storage systems was successfully tested with source activities up to 10 MBq. Additionally, detector performance and stability were confirmed in a continuous data collection period reaching 4 months.

Figure 1 shows a distribution of annihilation points reconstructed using Time-of-Flight in a transverse plane. Data collected in March 2019 for less than 3 h are shown for hit multiplicity equal to 2. Position of detection modules of two inner layers are clearly visible ($\sim$ 40 cm distance from the center), together with modules of third layer ($\sim$ 60 cm radius). At $\sim$ 10 cm radius an annihilation chamber is visible. It is a cylinder with inner wall covered with porous material to increase probability of o-Ps formation. Sodium source is localized in vacuum in the center of the chamber. The aim of measurement with a chamber is to separate in space the positronium formation and annihilation (cylinder wall) from positron emission (source) for determination of positronium polarization. It is worth to notice, that the 3 h period of trigger-less data taking of J-PET results in $\sim$90 GB of compressed data on disk.

In case of reconstruction of o-Ps decay into 3γ an event with at least 3 hits is required. A hit multiplicity distribution is presented in Figure 2. As mentioned in Ref. [28], in case of 4 hits events, a $\sim$80% of data reduction is expected due to rejection of cosmic radiation.

3. Charge conjugation

Quantum electrodynamics (QED) is invariant under charge conjugation symmetry (C). Therefore in the case of pure QED description of positronium decays, annihilation into an even number of photons is allowed for p-Ps, whereas o-Ps can decay into an odd number of photons. Since weak interactions within the Standard Model must be included for positronium properties, additional photonic decay modes are available. Due to the Landau-Yang theorem [29, 30] the o-Ps $\to 2\gamma$ one is forbidden, therefore the simplest possible is p-Ps $\to 3\gamma$. Since this decay violates charge conjugation, it must also violate parity to conserve CP symmetry.

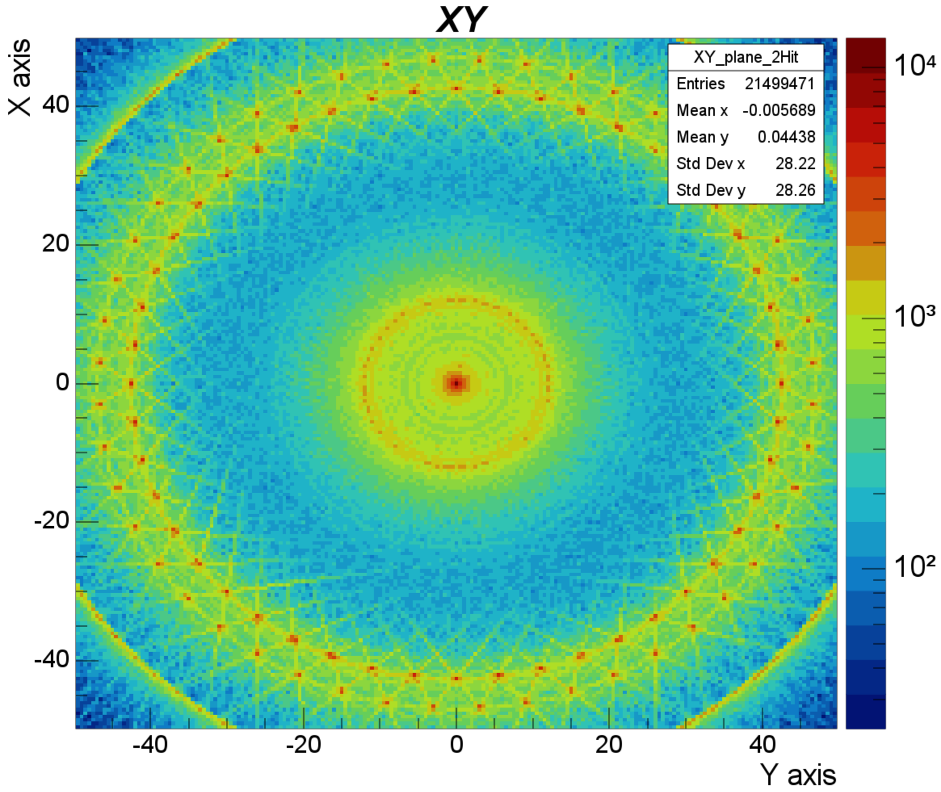

Figure 1. Distribution of reconstructed annihilation positions in a transverse plane derived from a simple Time-of-Flight calculation with one selection criterion: hit multiplicity equal to 2.

Best experimental limits for C violation in positronium decays are:

$$BR(\text{p-Ps} \to 3\gamma/\text{p-Ps} \to 2\gamma) < 2.8 \times 10^{-6} \text{ at } 68\%\text{C.L.} \quad [31] \tag{1}$$

$$BR(\text{o-Ps} \to 4\gamma/\text{o-Ps} \to 3\gamma) < 2.6 \times 10^{-6} \text{ at } 90\%\text{C.L.} \quad [32] \tag{2}$$

$$BR(\text{p-Ps} \to 5\gamma/\text{p-Ps} \to 2\gamma) < 2.7 \times 10^{-7} \text{ at } 90\%\text{C.L.} \quad [33] \tag{3}$$

Data taking capabilities of J-PET supersede the above mentioned measurements for source activity (100 kBq [33] vs 10 MBq) and time of the measurement (116 days [32] vs 120 days of continuous data taking so far).

4. CP, T and CPT symmetries

Time invariance and combination of discrete symmetries for the o-Ps → 3γ decay are investigated by determination of expectation values of operators presented in Table 1. There are only upper limits on CP [34, 35] and CPT [2, 36] symmetry violation in the decays of positronium:

$$\begin{aligned} C_{CP} &= 0.0013 \pm 0.0022, \quad [34] \text{ for } \langle(\vec{S}\cdot\vec{k}_1)(\vec{S}\cdot(\vec{k}_1\times\vec{k}_2))\rangle \\ C_{CPT} &= 0.0071 \pm 0.0062, \quad [36] \text{ for } \langle\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)\rangle. \end{aligned} \tag{4}$$

Therefore there is at least 6 orders of magnitude level for possible discovery of CP or CPT symmetry violation taking into account an expected level of final state interactions. It is worth

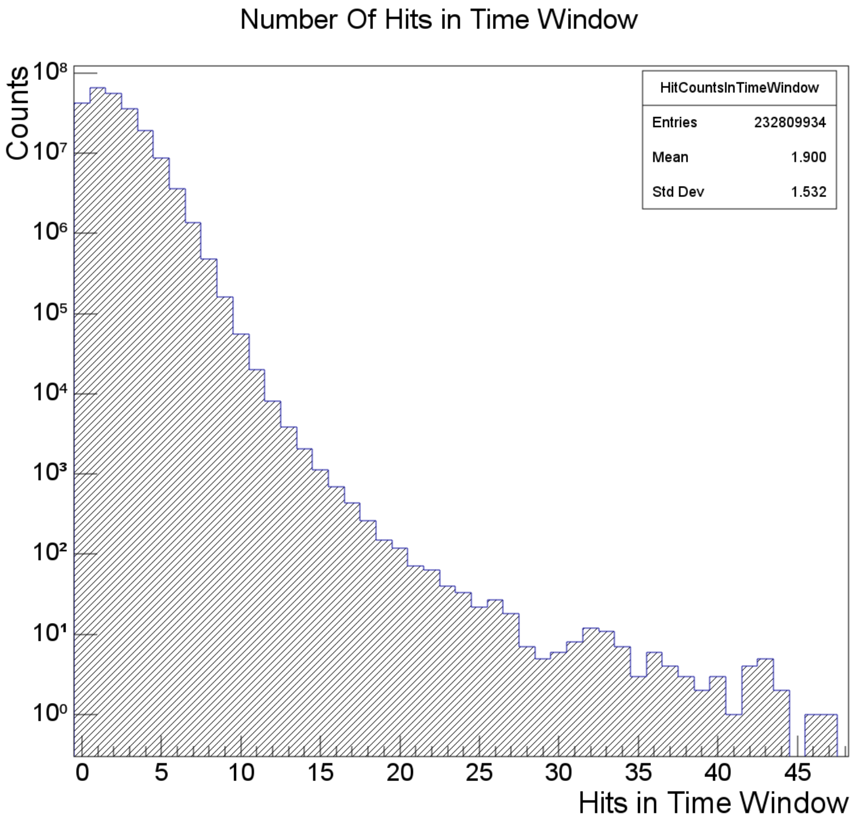

Figure 2. Hit multiplicity for data collected for less than 3 h. Events with no hits are obtained for signals of low amplitude - not crossing all four thresholds. User defined time window for event creation was set to 5 ns.

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

Table 1. Properties of operators for the o-Ps → 3γ decay for given symmetries. $\vec{k_i}$ denotes the momentum of the i^{th} photon ($k_1 \geq k_2$), $\vec{S}$ is the spin of the o-Ps and a polarization of i^{th} photon is marked as $\vec{\epsilon_i}$ [6]. The odd-symmetric operators available for studies at the J-PET system are marked with ”-”.

to stress, that for a purely leptonic system there is no measurement of violation of T or CP invariance. Any observation of CP violation in positronium decays in the next generation of experiments would point to existence of effects preventing observation of CPT violation in the EDM [37].

Apart of a capability for a long measurement with a source of high activity, the J-PET system will be upgraded with additional detection layer soon. This fourth detection layer is read out by silicon photomultipliers and will provide almost full acceptance coverage in azimuthal angle. Additionally, new CP and CPT operators can be investigated at J-PET uniquely taking an advantage of measurement of polarization of photons [6] together with studies the entanglement of photons originating from positronium annihilations [18]. An expected accuracy for measurements with J-PET system are $\mathcal{O}(10^{-5})$ for CP and CPT expectation values [6, 25].

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