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Studies of discrete symmetries in decays of positronium atoms

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Abstract. A positronium - a bound state of electron and positron - is an eigenstate of parity and charge conjugation operators which decays into photons. It is a unique laboratory to study discrete symmetries whose precision is limited, in principle, by the effects due to the weak interactions expected at the level of 10^{-14} and photon-photon interactions expected at the level of 10^{-9}.
The Jagiellonian Positron Emission Tomograph (J-PET) is a detector for medical imaging as well as for physics studies involving detection of electron-positron annihilation into photons. The physics case covers the areas of discrete symmetries studies and genuine multipartite entanglement. The J-PET detector has high angular and time resolution and allows for determination of spin of the positronium and the momenta and polarization vectors of annihilation quanta. In this article, we present the potential of the J-PET system for studies of discrete symmetries in decays of positronium atoms.

1 Introduction

Various systems, like the accelerator neutrinos [1], mesons [2] or nuclei [3], can be used as probes for investigations of charge conjugation (C), parity (P) and time reversal (T) discrete symmetries. The CP symmetry violation plays a key role in explanation of the matter and anti-matter abundance asymmetry in the Universe, the CPT symmetry is conserved in all quantum field theories preserving Lorentz invariance, unitarity and locality, while uniqueness

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of time itself motivates the T symmetry studies. The search for CP and CPT violation was also performed in the decays of a bound state of electron and positron (positronium) [4, 5]. This bound state is also considered for observation of the gravitational quantum states [6]. All of these systems, among others, are used in the Standard Model Extension framework for Lorentz and CPT tests [7–9].

A recent development of the Jagiellonian Positron Emission Tomograph (J-PET) [10–12] provides a new tool for medical applications as well as for discrete symmetries studies in decays of positronium [13]. Test of the C symmetry will be performed as a search for forbidden decays: o-Ps $\rightarrow 4\gamma$ of the positronium triplet state (ortho-positronium) and p-Ps $\rightarrow 3\gamma$ of singlet state (para-positronium). Measurement of the expectation values of symmetry-odd operators for the o-Ps $\rightarrow 3\gamma$ process will test the other fundamental symmetries and their combinations. Such operators can be constructed from o-Ps spin ($\vec{S}$) and momentum of annihilation quantum ($\vec{k}_i$). Additionally, the operators with annihilation quantum polarization ($\vec{\epsilon}_i$) are uniquely available at the J-PET system [13].

2 The J-PET detector

The Jagiellonian Positron Emission Tomograph consists of three cylindrical layers constructed with plastic scintillator strips. Each of such strip made of EJ-230 material is $500 \times 19 \times 7$ mm^3. Single detection module consists of one scintillator strip and the R9800 Hamamatsu photomultiplier connected at each 19×7 mm^2 side. 48 modules placed on radius 425 mm compose 1st layer of the J-PET detector, 48 modules on radius 467.5 mm - 2nd layer and 96 modules on radius 575 mm - 3rd layer. An interaction place and time of γ quantum with scintillator can be determined from the difference and the sum of times of signals from both photomultipliers attached to a given strip [10]. Therefore there are in total 384 analog signals to process. Each of them is probed in time domain at 4 different amplitude thresholds resulting in up to 8 time measurements (leading and trailing edge of the signal at each threshold) [14, 15]. The 1536 Time-to-Digital Converter (TDC) channels are trigger-lessly distributed on the 8 Trigger Readout Boards (TRBs). Apart of interaction place and time [16–18], the energy deposited by gamma quantum is also determined from the measurement of the Time-Over-Threshold (TOT) value, which depends on the amount of light registered by a photomultiplier. The gathered data are offline processed with a dedicated analysis framework [19].

3 The experimental technique

The measurements with a point-like ^{22}Na source placed inside the J-PET system were already performed for the preliminary determination of the detector time and spatial resolution [20, 21]. For physics studies a point-like source covered by the XAD-4 porous polymer [22, 23] was placed in the center of the detector. The XAD-4 material is used to increase the probability of positronium formation. In addition, a test experiment with a source surrounded by aluminum cylinder was also performed [24], while the future measurements will be performed with a cylinder with the inner wall covered by the porous material currently developed at the Maria Curie-Sklodowska University in Lublin. The aim of measurement with a cylinder is to separate in space the positronium formation and annihilation (cylinder wall) from positron emission (source).

The following reactions chain is considered:

$$
\begin{aligned}
{}^{22}\mathrm{Na} &\rightarrow {}^{22}\mathrm{Ne}^* + e^+ + \nu_e \\
{}^{22}\mathrm{Ne}^* &\rightarrow {}^{22}\mathrm{Ne} + \gamma \\
e^+ + e^- &\rightarrow \text{o-Ps} \rightarrow 3\gamma
\end{aligned}
\tag{1}
$$

The detection of 1274 keV prompt γ from ${}^{22}\mathrm{Ne}^*$ deexcitation is a start signal for the positronium lifetime measurement. The emitted positrons are stopped in the cylinder wall producing o-Ps which may undergo annihilation to 3γ. Due to the coplanarity of annihilation gamma quanta momentum vectors ($\vec{k}_i$) the annihilation point and time is reconstructed with a dedicated method based on the trilateration [25]. Known directions of photons from annihilation of positronium into 3γ enables to calculate the energy of each photon as described in Ref. [26].

The location of positron emission is known since the point-like source is placed in the center of the detection system. Therefore the reconstructed annihilation place and time together with a start signal from prompt gamma allow for e^+ velocity ($\vec{v}$) direction determination. Due to the parity violation in β-decay the positrons are longitudinally polarized along their direction of motion. The determined spin direction of positron provides the spin of o-Ps as well [27], since the polarization of positron is to large extent preserved during the thermalization process [28, 29].

At J-PET the polymer scintillators are used, therefore the gamma quanta are registered by means of Compton scattering. This scattering is most likely to occur in the plane perpendicular to the electric vector of the photon [30, 31]. Therefore registration of annihilation ($\vec{k}_i$) and scattered ($\vec{k}_i'$) quanta pairs allows to determine its linear polarization $\vec{\epsilon}_i = \vec{k}_i \times \vec{k}_i'$, and hence enables to study the multi-partite entanglement of photons originating from the decays of positronium atoms [32].

The potential of the J-PET detector for studies of discrete symmetries in decays of positronium atoms is described in Ref. [13], while the commissioning of J-PET for such studies is presented Ref. [24].

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