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COMMISSIONING OF THE J-PET DETECTOR FOR STUDIES OF DECAYS OF POSITRONIUM ATOMS*

E. Czerwiński[a], K. Dulski[a], P. Białas[a], C. Curceanu[b], A. Gajos[a]
B. Głowacz[a], M. Gorgol[c], B.C. Hiesmayr[d], B. Jasińska[c]
D. Kisielewska[a], G. Korcyl[a], P. Kowalski[e], T. Kozik[a]
N. Krawczyk[a], W. Krzemień[f], E. Kubicz[a], M. Mohammed[a,g]
Sz. Niedźwiecki[a], M. Pałka[a], M. Pawlik-Niedźwiecka[a]
L. Raczyński[e], Z. Rudy[a], N.G. Sharma[a], S. Sharma[a], R.Y. Shopa[e]
M. Silarski[a], M. Skurzok[a], A. Wieczorek[a], W. Wiślicki[e]
B. Zgardzińska[c], M. Zieliński[a] P. Moskal[a]

[a]Faculty of Physics, Astronomy and Applied Computer Science
Jagiellonian University, Łojasiewicza 11, 30-348 Kraków, Poland
[b]INFN, Laboratori Nazionali di Frascati
CP 13, Via E. Fermi 40, 00044, Frascati, Italy
[c]Department of Nuclear Methods, Institute of Physics
Maria Curie-Skłodowska University
pl. Marii Curie-Skłodowskiej 1, 20-031 Lublin, Poland
[d]Faculty of Physics, University of Vienna
Boltzmanngasse 5, 1090 Vienna, Austria
[e]Świerk Computing Center, National Centre for Nuclear Research
05-400 Otwock-Świerk, Poland
[f]High Energy Physics Division, National Center for Nuclear Research
05-400 Otwock-Świerk, Poland
[g]Department of Physics, College of Education for Pure Sciences
University of Mosul, Mosul, Iraq

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The Jagiellonian Positron Emission Tomograph (J-PET) is a detector for medical imaging of the whole human body as well as for physics studies involving detection of electron–positron annihilation into photons. J-PET has high angular and time resolution, and allows for measurement 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 the background rejection in the decays of positronium atoms.

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1. Introduction

Discrete symmetries C (charge conjugation), P (parity) and T (time reversal) and their combinations are subject of vigorous investigation in various systems, such as nuclei [1] or mesons [2]. This interest is motivated among others by matter and anti-matter abundance asymmetry in the Universe (CP symmetry), Lorenz invariance, unitarity and locality of quantum field theory (CPT symmetry), and uniqueness of time itself (T symmetry). Tests of these symmetries are also performed in lepton systems. At present, the hypothesis of CP symmetry conservation is excluded at 90% confidence level in the accelerator neutrino oscillations and should reach sensitivity greater than 3σ by 2026 [3]. Decays of positronium (a bound state of electron and positron) were investigated in search of CP and CPT violation [4, 5] resulting in upper limits at the level of 10^{-3}.

The Jagiellonian Positron Emission Tomograph (J-PET) system will, apart from medical applications, contribute to studies of discrete symmetries in decays of positronium [6]. Search of forbidden decays of the positronium triplet state, so-called ortho-positronium o-Ps $\rightarrow 4\gamma$ and singlet state, so-called para-positronium p-Ps $\rightarrow 3\gamma$ will test the C symmetry. Tests of the other fundamental symmetries and their combinations will be performed by the measurement of the expectation values of symmetry-odd operators constructed using o-Ps spin ($\vec{S}$), momentum of annihilation quantum ($\vec{k}_i$) and its polarization ($\vec{\epsilon}_i$). Table I contains a list of such operators. It is worth to mention that operators constructed with photons polarization vectors are also available at J-PET system.

TABLE I

Discrete symmetries test operators for the o-Ps $\rightarrow 3\gamma$ process [6]. The odd-symmetric operators are marked with "$-$" and are available for studies at the J-PET system.

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

2. Measurement technique

The J-PET detector consists of 192 plastic scintillator strips ($500 \times 19 \times 7$ mm^3 each) made of EJ-230 organized in layers forming three cylinders (48 modules on radius 425 mm, 48 modules on radius 467.5 mm and 96 modules on radius 575 mm) [7]. Each scintillator at both of its ends is equipped with a R9800 Hamamatsu photomultiplier. In the first test, a point-like ^{22}Na source was placed in the center and was covered by the XAD-4 porous polymer [8]. A test with the aluminum cylinder surrounding the source was also performed[1]. The positrons emitted from $^{22}\mathrm{Na} \rightarrow ^{22}\mathrm{Ne}^* + e^+ + \bar{\nu}_e$ and $^{22}\mathrm{Ne}^* \rightarrow ^{22}\mathrm{Ne} + \gamma$ reaction chain with the γ carrying 1274 keV of energy are stopped in the cylinder wall producing o-Ps which may annihilate emitting 3γ. Detection of prompt photons with 1274 keV energy from Ne deexcitation can be used as a start signal for the positronium lifetime measurement. Gamma quanta from o-Ps annihilation are registered by means of the Compton scattering inside the scintillator strips. Two coordinates of the interaction point are determined from the known strip position, while the position along the module is reconstructed from the time difference of signals registered by two photomultipliers connected to the ends of that scintillator [9–13]. Annihilation point and time of o-Ps is then reconstructed using the trilateration technique [14] taking advantage of the coplanarity of $\vec{k}_i$. The known location of positron emission with reconstructed annihilation place allows for straightforward velocity ($\vec{v}$) direction determination. The emitted positrons are longitudinally polarized ($\vec{P} = \frac{\vec{v}}{c}$) due to the parity violation in the β-decay. Since the polarization of positron is to a large extent preserved during the thermalization process [15, 16], the known spin direction of positron provides the determination of o-Ps spin. Gamma quanta undergo Compton scattering at J-PET plastic scintillators. Since the Compton scattering is most likely to occur in the plane perpendicular to the electric vector of the photon [17, 18], registration of annihilation and scattered quanta pairs allows to reconstruction of its linear polarization $\vec{\epsilon_i} = \vec{k_i} \times \vec{k'_i}$, where $\vec{k_i}$ and $\vec{k'_i}$ denote momentum vectors of i^{th} gamma quantum before and after the Compton scattering, respectively [6]. For annihilation into 3γ with a known $\vec{k}_i$, it is possible to calculate the energy loss of each γ as described in Ref. [19]. The energies of gamma quanta can be also estimated using independent method. At the J-PET system, the electric signals from photomultipliers are 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) [20, 21]. Measured Time-Over-Threshold (TOT)

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[1] For the future experiments, the inner wall of the cylinder will be covered by the porous material presently under development at the Maria Curie-Skłodowska University in Lublin.

value depends on the amount of light registered by photomultiplier, while number of photons in the scintillator depends on the energy deposited by gamma quantum. This method is especially useful to distinguish between prompt ($E_\gamma = 1274$ keV) and annihilation quanta ($E_\gamma \leq 511$ keV).

3. Selection of data

Three data-taking campaigns are already concluded with the J-PET experiment for commissioning and physics studies which is equivalent to approx. 700 h of data taking with different configuration and settings of detection system[2]. Apart of threshold synchronization and calibration measurements, the data were collected also for performance studies according to NEMA standards which were so far evaluated based on the simulations only [22, 23]. Measurements were performed also with XAD-4 polymer target and 6 different polymer samples. Data is acquired in the triggerless mode, therefore, an offline reconstruction and signal selection is required for background rejection [20, 21, 24]. For o-Ps data sample, the main background contribution is the detector-based scattering when 2 annihilation gamma quanta from p-Ps are registered together with a single scattering or 1 annihilation γ from p-Ps undergoing 2 scatterings are registered, as schematically presented in Fig. 1.

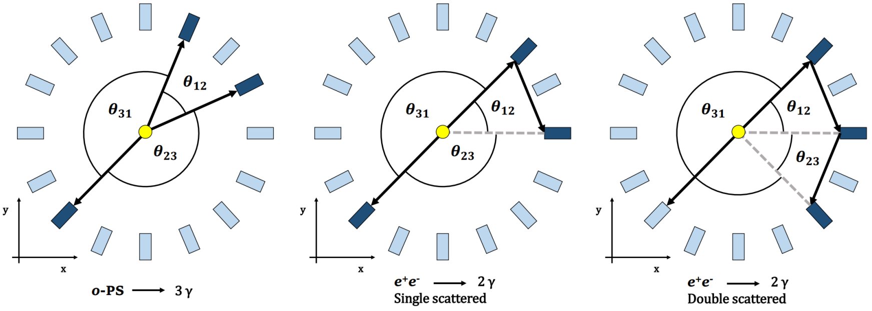

Fig. 1. Colour on-line) Definition of angles in XY view between registered gamma quanta with indexing fulfilling the condition $\theta_{12} \leq \theta_{23} \leq \theta_{13}$. Light rectangles represent scintillators, dark rectangles — scintillators with registered hit and yellow circle in the middle — annihilation region.

These scattered events can be rejected in the process of the offline data reconstruction [24]. Here, we present the preliminary results obtained from the second J-PET data-taking campaign for a 1 h 40 min measurement with the XAD-4 target of radius $R \approx 1$ cm with only two following criteria applied offline:

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[2] The fourth campaign is ongoing.

1. Number of registered hits in 200 ns time window equals 3.
2. TOT values for 2 hits correspond to annihilation quantum energy loss and TOT value for the 3$^{\rm rd}$ hit corresponds to prompt energy loss.

The momentum vectors of all three gamma quanta, generated from o-Ps annihilation, lie in one plane. Although the direction of prompt γ emission is not correlated with such an annihilation plane, in the XY view an o-Ps event fulfilling the two above-mentioned criteria would have the same topology as the left scheme in Fig. 1 and, therefore, will occupy the region of $\theta_{12}+\theta_{23} > 180^\circ$ in Fig. 2. The registered annihilation of p-Ps with single scattering occurs as a line around $\theta_{12}+\theta_{23} \approx 180^\circ$, while double scattered events are visible close to $(0^\circ, 0^\circ)$. The enhanced number of events close to $(100^\circ, 100^\circ)$ corresponds to scatterings by close to 90°. Registration of such scatterings is at most probable due to the geometry of the J-PET detector. The conclusion from the distribution presented in Fig. 2 is that a significant part of the background can be rejected based on the angular correlations. Another constraint to reject single scattered events is based on the plane constructed with three interaction points of gamma quanta with scintillators as shown in Fig. 3. For registered 3 annihilation γ from o-Ps, such a plane should be close to annihilation place. However, for a selection of events with two annihilation and one prompt photon, such a plane would not be close to detector center, while p-Ps events with single scatterings would create a plane crossing the center. Distribution of such a distance is presented in

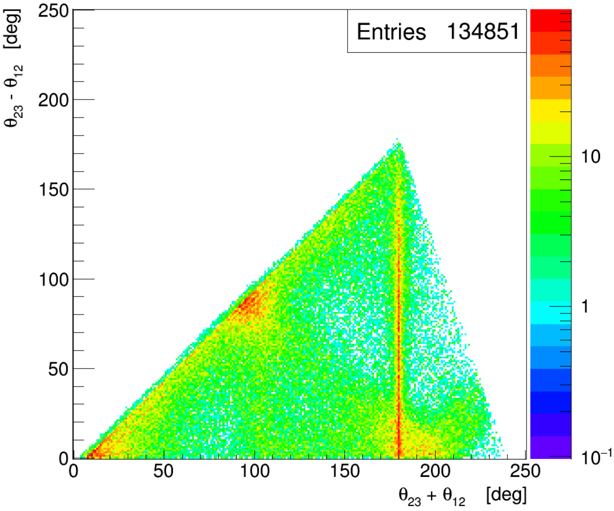

Fig. 2. Distribution of registered events for $\theta_{23}+\theta_{12}$ and $\theta_{23}-\theta_{12}$ angles as defined in Fig. 1. Statistics collected during 1 h 40 min of measurement.

Fig. 4 with visible maximum at distances below about 5 cm. The enhanced number of events for few bins of higher distance is due to the geometry of the detector.

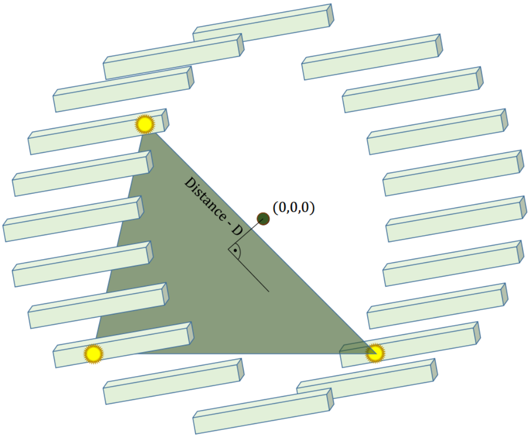

Fig. 3. Distance between plane constructed with 3 hits and the source placed at the center of the detector.

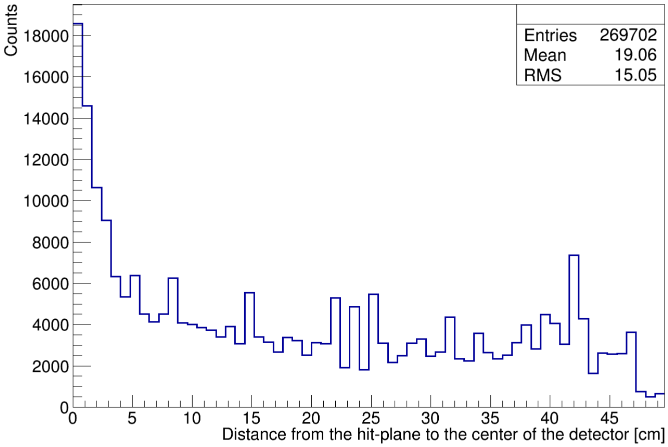

Fig. 4. Distribution of the hit-plane distance from detector center. Statistics collected during 1 h 40 min of measurement.

4. Summary

The investigation of discrete symmetries is continuously performed in many systems. So far, no CP-violation effects were discovered for the purely leptonic bound state such as positronium. The Jagiellonian PET, presently in commissioning stage, will contribute to these studies. The unique properties of the J-PET system are the usage of plastic scintillators for gamma quanta detection and capability of positronium spin determination together with measurement of γ polarization. High accuracy of time measurement together with rejection of background based on the event geometry should allow for reaching a sensitivity of 10^{-5} for CP symmetry violation with the J-PET detector [6].

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