Test of CP symmetry in positronium decay with the J-PET detector

Shivani on the behalf of the J-PET collaboration

Motivation

The Jagiellonian Positron Emission Tomograph (J-PET) detector enables to perform tests of discrete symmetries via the determination of the expectation values of the odd symmetry operators, which can be constructed by investigating the spin of ortho-positronium atom and the momenta and polarization vectors of photons originating from its annihilation.

Moreover, the ability of the J-PET detector to determine the angle between the decay and scattering planes of photons, opens possibilities for experimental definition of orthogonal states of high energy photon and, hence, enables studies of the multipartite entanglement of gamma quanta originating from the positronium decay[1].

Trilateration Methods

In J-PET, due to its relatively high angular acceptance and timing resolution, a reconstruction of the o-Ps→ 3γ process is possible by means of a new trilateration-based reconstruction method.[7]

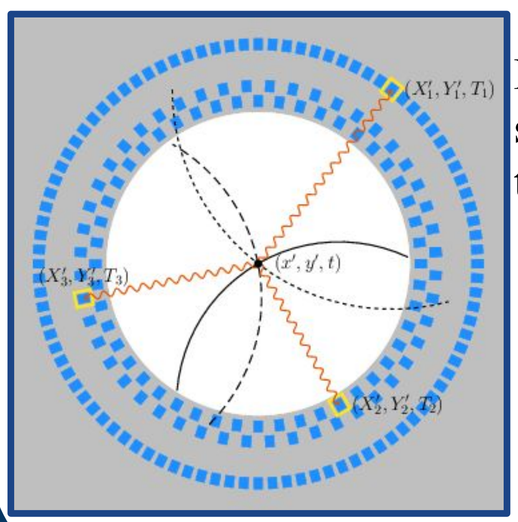


Fig.5. Scheme of a possible o-Ps spin direction determination with the J-PET detector[5].

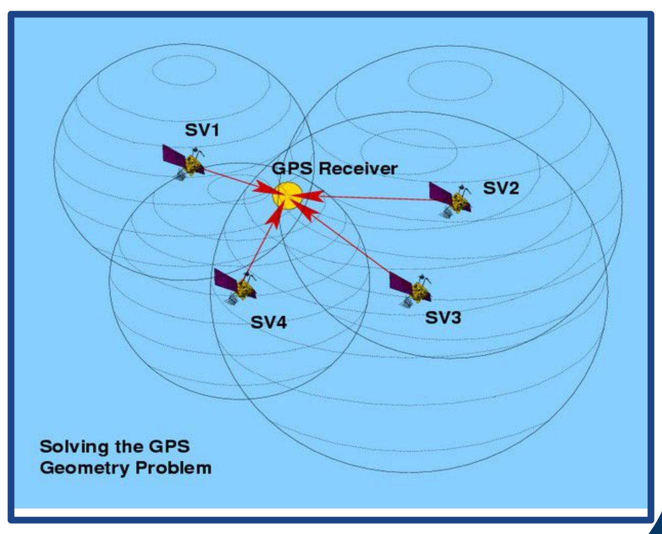


Fig.6.Global Positioning System (GPS), a trilaterations based on measurements of time and position of signals by four satellites[5 ,6].

The J-PET detector

The Jagiellonian Positron Emission Tomograph (J-PET) was constructed as a prototype of a cost-effective scanner for the simultaneous metabolic imaging of the whole human body [6,7,10.11].

1st Layer - 48 modules - radius 425 mm.
2nd Layer - 48 modules - radius 467.5 mm.
3rd Layer - 96 modules - radius 575 mm.

1. Each of such strip made of EJ-230 material is 500 × 19 × 7 mm^3

2. Total 384 analog signals to process.

3. The 1536 Time-to-Digital Converter channels are trigger-lessly distributed on the 8 Trigger Readout Boards. [3,4]

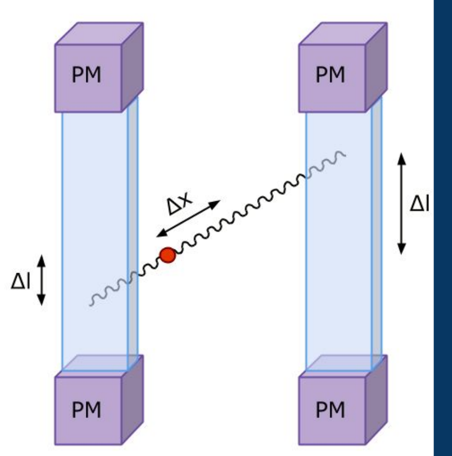
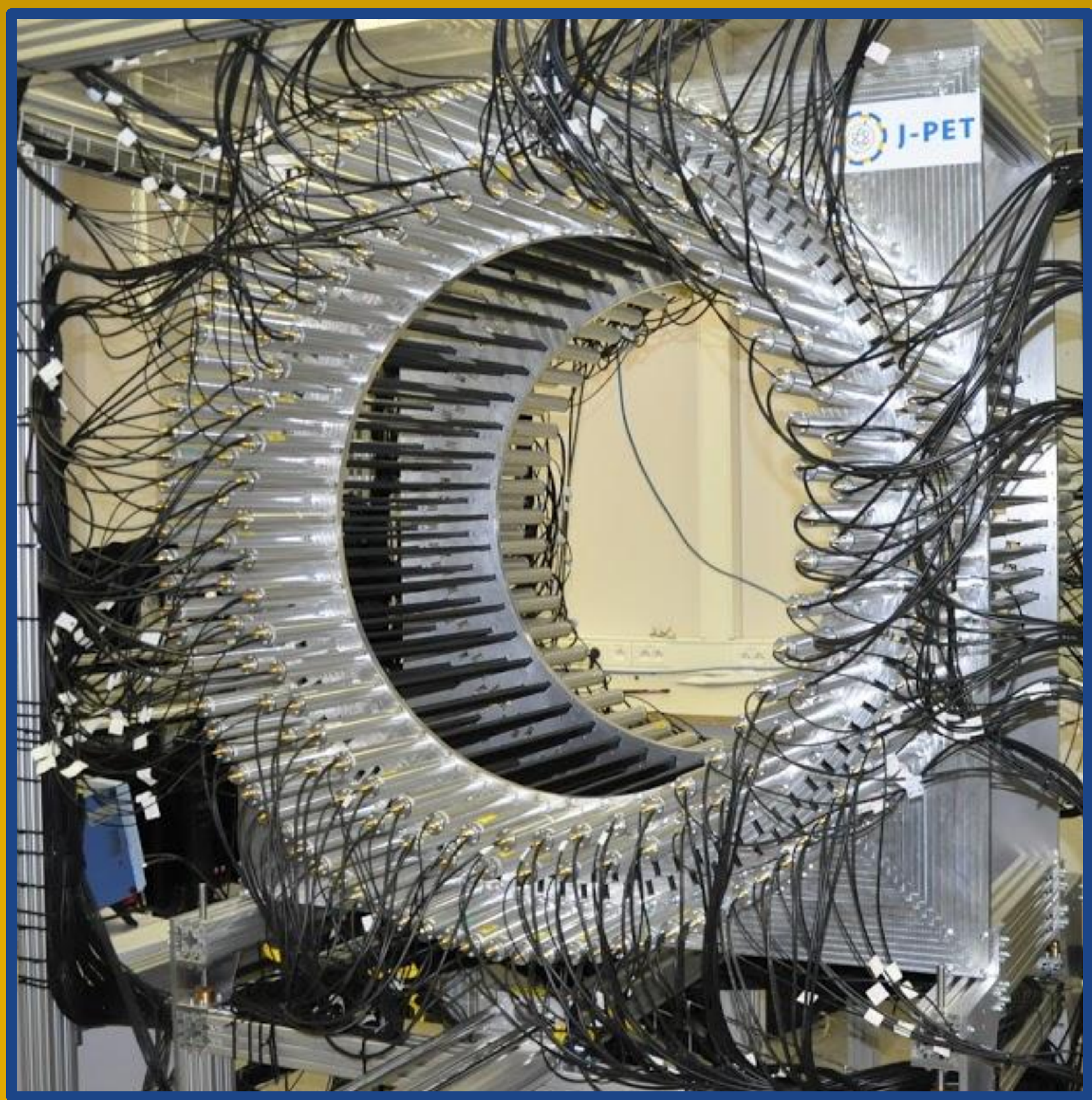


Fig. 1. Light signals from each strip are converted to electrical signals by photomultipliers placed at opposite ends of the strip.



Discrete Symmetry Test

The J-PET enables to perform test of discrete symmetries via the determination the expectation values of odd symmetry operator, which may be constructed from spin of o-Ps atom and momenta and polarization vector of its annihilation photons. Moreover, J-PET is the first experiment able to reconstruct the o-Ps - 3γ annihilation point in an extensive medium[1].

Table 1 :Operators for the o−Ps→3γ process and their properties with respect to the C, P, T, CP and CPT symmetries. New operators not explored before are shown in the last three rows.

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

Positronium Production

Using an extensive cylindrical annihilation chamber with porous material for o-Ps production allows for determination of spin direction of positron forming the o-Ps atom, thus providing an estimate of positronium spin vector[6].

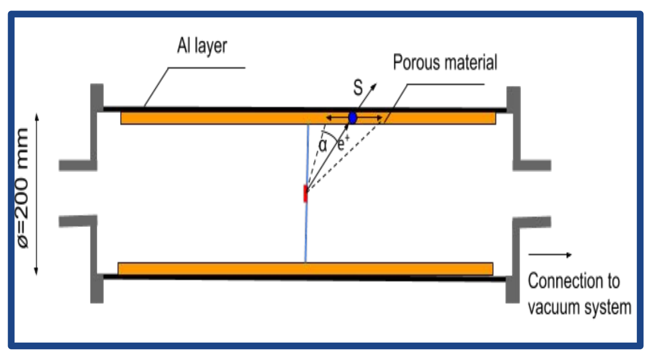


Fig.2 Pictorial representation of Annihilation chamber.

Fig.3 Scheme of large annihilation chambe.

Experimental Technique

1. In J-PET detector positrons are emitted from the source ($^{22}Na \rightarrow {}^{22}Ne^* + e^+ + \nu_e$) placed in the center(Red), covered with XAD-4 porous material (Blue).As in Fig. 2[5]

2. The red arrow indicate gamma photon originating from the de-excitation of $^{22}Ne^*$(γ), annihilation photons from ortho positronium decay (k_1,k_2 and k_3) and one of the scatter photon(k_1').

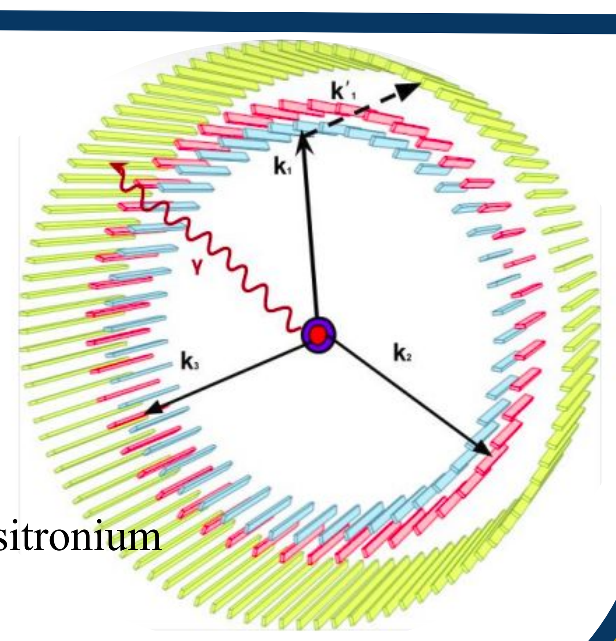


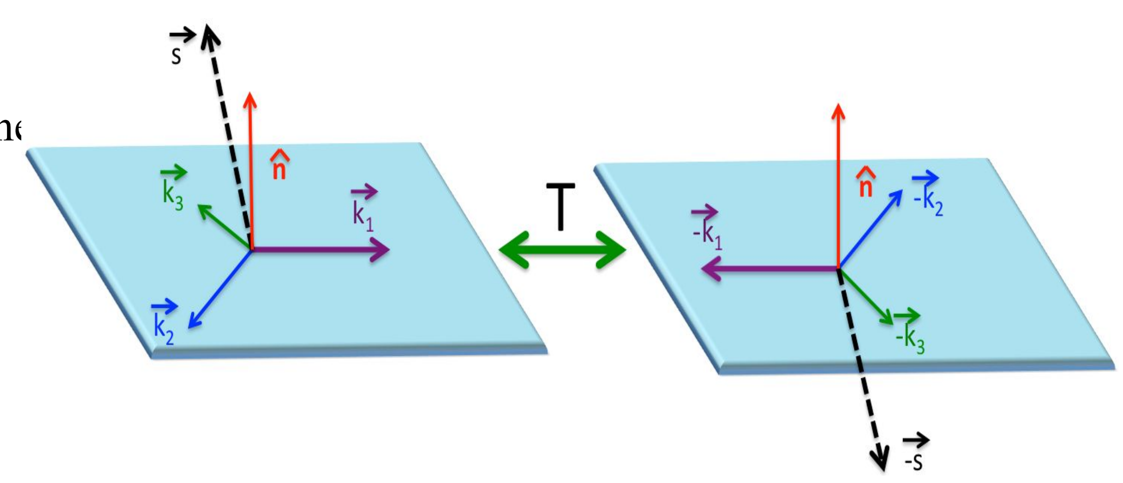
Fig.4.

Time Reversal symmetry in o-Ps

In order to test the time reversal violation, we investigate the expectation values for the T-odd-symmetry-operators. So far, T-violation effects were not discovered in a purely leptonic system such as positronium. The Jagiellonian-PET scanner offers high acceptance to measure the direction of polarization of the annihilation photons together with its momentum direction (k)[1,9].

The decay plane is oriented by the ordering of photons according to the descending momentum:

$|k_1| > |k_2| > |k_3|$



$\vec{S}\cdot\vec{k}_1 \times \vec{k}_2 \rightarrow$ for CPT symmetry

The measured observable is the asymmetry:[7,8]

$$A = \frac{N_+ - N_-}{N_+ + N_-}$$

N+ and N– denote the number of decays with the normal to the decay plane parallel (+) and antiparallel (−) to the spin direction, respectively.

$$N_{0<\Theta<90} \neq N_{90<\Theta<180} \Rightarrow \text{T is violated}$$

Asymmetry value can be associated to the CP(C^{CP}) and CPT (C^{CPT}) violation parameters by:

$$A = C_{CP} \cdot S^{CP} \rightarrow (S.k_1)(S.k_1 \times k_2)$$
$$A = C_{CPT} \cdot S^{CPT} \rightarrow S.k_1 \times k_2$$

Reference

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Acknowledgement

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