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From tests of discrete symmetries to medical imaging with J-PET detector

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We present results on CPT symmetry tests in decays of positronium performed with the precision at the level of 10^{-4}, and *positronium images* determined with the prototype of the J-PET tomograph. The first full scale prototype apparatus consists of 192 plastic scintillator strips read out from both ends with vacuum tube photomultipliers. Signals produced by photomultipliers are probed in the amplitude domain and are digitized by FPGA based readout boards in triggerless mode. In this contribution we report on the first two- and three-photon positronium images and tests of CPT symmetry in positronium decays.

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1. Introduction

The Jagiellonian Positron Emission Tomograph (J-PET) is the first PET scanner built from plastic scintillators [1–6] capable to determine polarization of annihilation photons [7, 8]. J-PET is designed to serve as multipurpose detector for (i) tests of discrete symmetries in decays of positronium and search for physics beyond the Standard Model [7, 9–13], (ii) development of multi-photon and positronium imaging [10, 14–20], (iii) test of quantum entanglement of photons originating from the decay of positronium [7, 8, 21–24], and (iv) the development of proton beam range monitoring in proton radiotherapy [25, 26].

Here we report on the first CPT symmetry tests with the J-PET detector [10] and first 2-photon in-vitro positronium image [15] of the mean lifetime in the tumor cardiac myxoma and healthy adipose tissue that has been determined using a 192-strip J-PET tomography prototype described in the following section.

2. J-PET tomography

The Jagiellonian PET (J-PET) detector [3, 27, 28], shown in Fig. 1, is a modern tomographic apparatus based on long polymer (plastic) scintillation strips. It consists of three concentric layers (radii equal to 42.5 cm, 46.75 cm, and 57.5 cm) of 50 cm long EJ-230 scintillating strips, with a total number of 192 strips. Cross section of each scintillator is equal to 19 mm x 7 mm. Detection of radiation (with energy of ~ 1 MeV) in the J-PET detector is via the Compton scatterings in plastic scintillators. Each scintillating strip is read out from both ends using vacuum photomultipliers. The collected signals are processed by dedicated data acquisition system (DAQ) consisting of front-end-electronics [29] and field programmable gate array (FPGA) platform [30], all working in trigger-less mode. Signals are probed on four selected thresholds. The energy of each signal is calculated as a Time-over-Threshold (TOT) value, which is an equivalent of the energy deposited in the scintillator by photons [31]. Data analysis is carried out in the dedicated Framework software [32] that allows the reconstruction of both individual signals and complete events. The times of the reconstructed signals were measured with the resolution of 150 ps [3].

A cylinder-shaped chamber was placed inside the J-PET detector, as shown in Fig. 1. The source ^{22}Na with an activity of about 10 MBq was localized in the centre of the chamber and was used as a source of positrons. The source was sandwiched between two thin layers of Kapton foil ($\approx 7\ \mu$m) to reduce the positron scatterings in the source material. The walls of the chamber, which served as a shield for the emitted positrons, were covered with a layer of porous medium (mesoporous silica with gypsum) to obtain a high fraction of ortho-poitronium (o-Ps) annihilation into three photons (mean o-Ps lifetime $\tau^{\mathrm{target}}_{\mathrm{o\text{-}Ps}} \approx 100$ ns). A vacuum inside the chamber was maintained at 10^{-3} Pa to minimize the effect of positron scattering before reaching the walls of the chamber. Measurement with cylindrical chamber lasted for 26 days. An exemplary event from the annihilation of a positron with an electron from the chamber wall, resulting in the emission of two photons, is shown schematically in Fig. 1 a).

To test the tomographic capabilities of the J-PET detector two imaging modes were performed - from two-photon and three-photon positron-electron annihilation. Examples of events for which images were reconstructed are shown in Fig. 1 b) and c), for two- and three-photon annihilation,

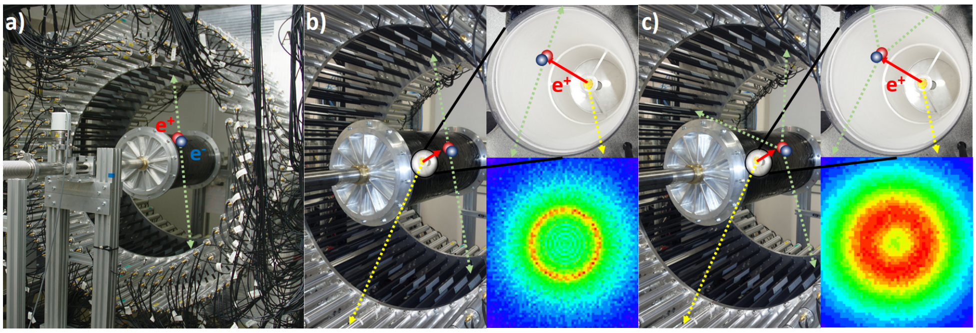

Figure 1: a) Photograph of the J-PET detector with the cylindrical chamber inside. A positron (e^+) with an electron (e^-) annihilates on the walls of the chamber into two photons (green arrows) which are detected by the scintillators (black strips). Positron from the ^{22}Na source (yellow circle) is emitted into the walls of the chamber, where it can annihilate with an electron into b) two or c) three photons (green arrows). In addition, after the emission of positron, ^{22}Na goes to the excited state of ^{22}Ne*, which deexcites by emission of an additional photon (yellow arrow). Reconstructed distribution of the annihilation photons for b) two- and c) three-gamma positronium annihilation.

respectively. The selection of events for a proper imaging mode was conducted based on the multiplicity and TOT of signals in an event, as well as geometric and timing correlations of the reconstructed signals. Distribution of the annihilation photons from the measurement with the cylindrical chamber is shown in Fig. 1 b) and c), for two- and three-photon annihilation, respectively.

3. Positronium imaging and test of the CPT symmetry in positronium decays

Positronium is copiously produced in the human body during the positron emission tomography [16, 18]. Positronium imaging is a method enabling to determine image of positronium properties in the living organisms [15, 17, 19, 20, 33]. One of the positronium properties which may appear useful in the cancer diagnosis is the mean-lifetime which depends on the size of intra-molecular voids and concentration in them of bio-active molecules as e.g. oxygen [15, 16, 18, 34–37]. Imaging of positronium lifetime requires applications of isotopes emitting prompt gamma as e.g. ^{44}Sc or ^{22}Na [38]. Registration of the prompt gamma is used to determine the time of the emission of the positron (which is within tens of picoseconds equal to the time of the formation of the positronium atom) and the registration of annihilation photons is used for the determination of the position and time of the positronium annihilation. The most effective way of the positronium mean lifetime image reconstruction is based on the registration of annihilations of ortho-positronium into two photons, which may occur in the tissue due to the pick-off and conversion processes and which is about 70 times more frequent than annihilation into three photons [15, 19]. The experimental setup used to determine the first positronium image of phantom constructed from tumor and healthy tissues is shown in the left panel of Fig. 2. In the first demonstration of positronium image the resolution of 20 ps was obtained [15] and it is sufficient to distinguish between the healthy and cancer tissues for which differences larger than 50 ps (in the range of 50ps - 200ps) [39] or even 700 ps [15] are observed.

Positronium imaging based on three-photon decays is shown in Fig. 1c. The technique was applied in the studies of CPT symmetry. The CPT symmetry combines transformations of charge conjugation (C), parity (P) and reversal in time (T), and it has been tested in relatively few leptonic systems compared e.g. to hadronic matter. The J-PET detector was used to conduct a CPT test in three-photon annihilations of the triplet state of positronium atoms (ortho-positronium) through searching for non-zero CPT-asymmetric angular correlations in this process. The CPT-odd operator defined as $\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$ reflects a correlation between the spin of annihilating positronium atom ($\vec{S}$) and the orientation of the annihilation plane spanned by the momenta of the final state photons ordered by their magnitude ($|\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3|$). Its expectation value must amount to zero if the system is CPT invariant [40].

While previous studies were limited in sensitivity by the uncertainty on determination of the positronium spin direction [41, 42], this factor was minimized in J-PET by reconstruction of three-photon annihilation events in an extensive-size medium using trilateration [43]. A cylindrical vacuum chamber was used where positrons from a ^{22}Na β^{+} source, located in its center, were allowed to thermalize and form positronium in a porous medium on the chamber inner surface as shown in Fig. 2 (right). Reconstructed annihilation points provided an estimate of the direction of emission of the positron, and, through its longitudinal polarization in a β^{+} decay, also of positronium spin orientation allowing for spin estimation on a single event basis. Moreover, due

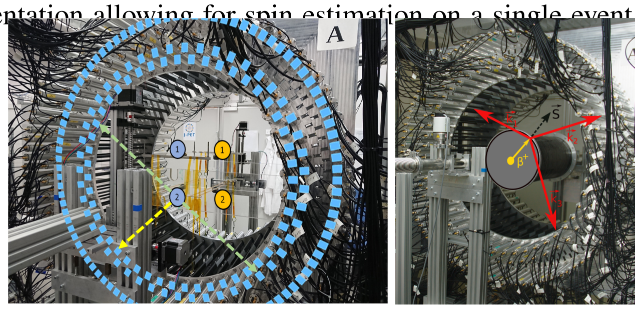

Figure 2: (Left) Photograph of the J-PET detector with superimposed cross-section of the detection modules (blue rectangles). Cardiac Myxoma (blue circles) and adipose tissue (yellow circles) samples from two patients, marked by 1 and 2, were inserted inside the J-PET detector. During the measurement two annihilation photons (green arrows) and one deexcitation photon (yellow arrow) were registered by the J-PET detector for positronium imaging. **(Right)** The cylindrical positronium production and annihilation chamber used with J-PET to estimate the spin of the ortho-positronium on a single event basis.

to the large geometrical acceptance angular resolution of about 1°, J-PET records a broad range of kinematical configurations of ortho-positronium annihilation events and is the first experiment capable of determination of the distribution of this operator in the entire range of its definition, thus providing additional information for the searches of a CPT-violating asymmetry. While the obtained value of a CPT-violation parameter $C_{CPT} = 0.00067 \pm 0.00095$ is consistent with CPT invariance [10], this test reached precision improved over previous best measurement by a factor of over three and further improvement is possible as the sensitivity is predominantly statistical.

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