Review of physics program at J-PET

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Abstract. The Jagiellonian - Positron Emission Tomograph (J-PET) is a multi-purpose detector for tests of discrete symmetries and quantum entanglement of photons originating from the decay of positronium atoms. The research is performed by measurement of angular correlations between photons from the annihilations of the lightest leptonic bound system. The J-PET detector is the only device which enables determination of polarisation of photons from positronium annihilation together with estimation of positronium spin axis on the event-by-event basis. The novelty of the system is based on a usage of plastic scintillators as active detection material and trigger-less data acquisition system. The aim of two independent detection setups currently in use together with different annihilation chambers is to improve limits on C, CP and CPT symmetries and to search for the entanglement of photons originating from electron-positron annihilation. Additionally a precise measurement of ortho-positronium life time would allow to test of non-relativistic quantum electrodynamics and search for Mirror Matter.

1 Introduction

J-PET is a detection system based on plastic scintillators [1]. It was designed for medical imaging as a cost effective tomograph [2], while it is also a precise and unique setup for basic research in several areas of physic [3]. J-PET is capable of simultaneous detection of multiple photons. It takes an advantage of Compton scattering and fast, trigger-less detection system [4]. The work based on the J-PET data is focused on test of discrete symmetries, search for the annihilation photons entanglement, test of non-relativistic quantum electrodynamics (NRQED), and search for Mirror Matter as a Dark Matter candidate. For basic research a positronium (Ps) is the main object of interest [5]. 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} [6–8].

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2 Jagiellonian - Positron Emission Tomograph

J-PET is a multipurpose system for detection of photons originating from electron-positron annihilation. It is used for medical imaging and morphological studies [9–12], while for physic research a vacuum chamber with β^+ radioactive source is placed in the centre of the detector.

The first, fully operative detector consists of three layers of plastic scintillator strips forming a cylindrical chamber [13]. Each of such strip is based on EJ-230 material and its dimensions are $500 \times 19 \times 7$ mm^3. Optical signals are read out by the R9800 Hamamatsu photomultiplier at each 19×7 mm^2 side of a strip. 48 strips are placed on 425 mm radius and another 48 strips - on 467.5 mm radius, forming two inner layers, respectively. Strips in the second layer are rotated by 3.75° with respect to modules of first layer to improve geometrical acceptance. 96 strips compose the third layer with 575 mm radius. The second working system is modular. Scintillators of $500 \times 24 \times 6$ mm^3 are read out by Hamamatsu 1x4 S13 SiPM matrix at each 24×6 mm^2 side of a strip. 13 of axially arranged strips form a rectangular module and 24 of such modules are placed on 740 mm diameter forming a chamber as 24-sided prism.

Position of photon interaction with scintillator strip (hit) is approximated on a XY plane to the centre of the strip itself. The Z coordinate, along the strip, is calculated from a time difference of signals registered at both ends of this strip [1]. Time of such interaction is calculated from a sum of times of these signals [14, 15]. Signals from photomultipliers are probed in time domain at different amplitude thresholds [16, 17], which allows to derive the signal start time and Time-Over-Threshold (TOT) measurement [18]. This TOT value is equivalent to the energy deposited by photon within the strip.

Polymer scintillators for both detection setups are used [19]. Therefore a Compton scattering is a process for deposition of energy by photons. Measurement of momenta of primary ($\vec{k_i}$) and scattered ($\vec{k_i'}$) photon pairs allows for estimation of linear polarisation $\vec{\epsilon_i} = \vec{k_i} \times \vec{k_i'}$ of primary photon, since the highest probability of Compton scattering is in the plane perpendicular to the electric vector of the photon [20, 21]. Determination of photon polarisation without the usage of external magnetic field is a unique feature of the J-PET system [3, 22]. Figure 1 presents a sketch of J-PET detector with an exemplary annihilation event where a single scattering of photon takes place.

Positronium atoms are used for basic research at J-PET. Para-positronium (p-Ps) is created in a sodium source, while ortho-positronium (o-Ps) is created in a porous material surrounding a source [23]. Detection of neon deexcitation photon is a start signal for a measurement of positronium lifetime. The place and time of annihilation of p-Ps $\rightarrow 2\gamma$ is calculated from a difference and a sum of hit times, respectively, of both γ. For reconstruction of position and time of o-Ps $\rightarrow 3\gamma$ annihilation a dedicated trilateration method [24] is used. As already mentioned, the deposition of energy is determined by means of TOT measurement, however, for o-Ps $\rightarrow 3\gamma$ the energy of annihilation photons is calculated from their angular correlation [25].

For o-Ps measurement the cylindrical or spherical annihilation chamber is used. Since the sodium source is separated from the chamber wall covered with porous material, the β^+ decay is spatially separated from o-Ps annihilation. Therefore a direction of e^+ velocity is determined from known source position and reconstructed position of annihilation. Due to the parity violation in β-decay, the direction of e^+ velocity corresponds to the spin direction of positron. Determination of positron spin is another unique feature of the J-PET system, since the polarisation of positron is to large extent preserved during the thermalization process [26, 27].

More details of characteristics of J-PET detector can be found in Refs. [13, 28–30].

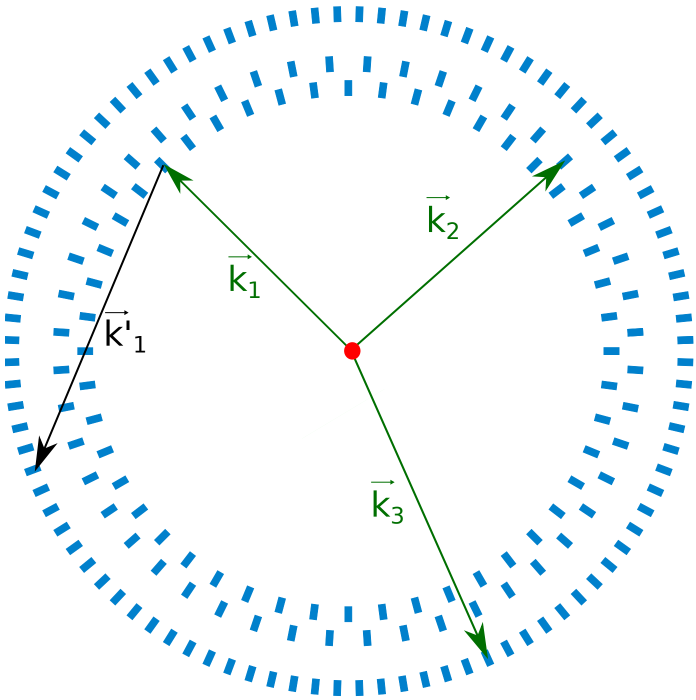

Figure 1. An exemplary event of ortho-positronium self annihilation at J-PET. A schematic transverse cross-section of the tomograph. Blue rectangles indicate scintillator strips and the red dot represents the sodium source. Annihilation photons with momenta $\vec{k_i}$ for i=1,2,3 are depicted as green arrows, while black arrow shows the scattered photon with momentum $\vec{k_1'}$.

3 Discrete symmetries

There are multiple motivations to study CP or CPT invariance [31–33]. The CPT theorem merges unitarity, locality and Lorentz invariance of quantum field theory. Therefore test of CPT invariance probes fundamentals of physics [34]. The observed prevalence of matter over antimatter in the Universe is not explained by the amount of CP violation contained in the Standard Model [35, 36]. Therefore search for a violation of discrete symmetries is still an interesting experimental endeavour in the area of fundamental physics.

Investigation of expectation values for symmetry odd-operators of a non-degenerate stationary state is a possible way to search for a violation of discrete symmetry. Preparation in a fully controlled way of the initial and final state is the main challenge for the experimental study of the time reversal invariance, due to the anti-unitary character of the symmetry operator [37]. There is no experimental report on the limit for the T-symmetry violation in the decay of positronium and all the previous investigations of CP and CPT symmetry odd operators with positronium were based on the products of photons momenta and positronium spin vectors [38].

The unique properties of the J-PET system allow to extend such studies to other operators, namely the symmetry-odd operators constructed with polarisation of photons originating from the decays of the o-Ps atoms [37].

In 2021 the first measurement of the expectation value of the angular correlation $O_{CPT} = \vec{S} \cdot (\vec{k_1} \times \vec{k_2})/(|\vec{k_1} \times \vec{k_2}|)$ with the first detector and cylindrical annihilation chamber was reported by the J-PET collaboration [39]. This result based on the determination of the polarisation vector of o-Ps $\vec{S}$ and the momentum of the i-th annihilation photon $\vec{k_i}$ is three times more precise than the previous result. For the first time the investigated operator was measured in the whole available phase-space. The result shows no CPT symmetry violation at the level of 10^{-4}.

A level of 10^{-5} can be reached for a new measurement with the modular J-PET detector and the spherical annihilation chamber.

A simultaneous search for violation of CP, P and T symmetries in positronium decay can be performed at J-PET with the measurement of the expectation value of the $O_{CP,P,T} = \vec{\epsilon_i} \cdot \hat{k}_j$ operator. Here the momentum of the i-th annihilation photon $\vec{k_i}$ and the momentum of the scattered photon $\vec{k_i'}$ are reconstructed for $\vec{\epsilon_i}$ determination and the unit vector of the j-th ($j \neq i$) annihilation photon $\hat{k}_j$ is also reconstructed [37, 40]. The collected statistics of 7×10^5 events allows to reach an accuracy of 10^{-4}, while the previous test of CP symmetry with o-Ps is at the level of 10^{-3} [38].

A new test with the modular J-PET detector and increased source activity and measurement duration would allow to achieve 10^{-5} sensitivity.

Angular correlation of just annihilation photons from a similar measurement can be also studied in the form of Dalitz plot. Since a correlation for a forbidden p-Ps→ 3γ decay is expected to be different than for o-Ps→ 3γ, a study of Dalitz plot for three annihilation photons would allow to search for the C symmetry violation.

4 Search for the entanglement of photons from annihilation of e^+e^-

Understanding of the entanglement of photons originating from e^+e^- annihilation is improved over the last century from the theory point of view [20, 41–43]. However, the most recent results of measurements are contradicted [44, 45]. As mentioned in Section 2, detection of photons at J-PET is entirely based on the Compton scattering, and the polarisation of photons is used for the test of CP symmetry. However, in contrast to tests of discrete symmetries, where data samples are based on the o-Ps→ 3γ annihilation, for a study of the entanglement a measurement focused on the p-Ps→ 2γ is performed. For registration of such back-to-back event both annihilation photons have to undergo double scattering. The first interaction of photon with the scintillator strip allows for para-positronium identification, while the second interaction is used for determination of the polarisation direction. Registration of polarisation of gamma quanta is a unique feature of the J-PET system [3, 22], which allows to study the multi-partite entanglement of photons originating from the decays of positronium atoms [46]. The result on the entanglement of annihilation photons at J-PET may allow to solve the existing discrepancy concerning correlations investigated so far [47].

5 Test of non-relativistic quantum electrodynamics and search for Mirror Matter

The decay rate of o-Ps into 3γ or 5γ is precisely predicted on the ground of non-relativistic quantum electrodynamics (NRQED) with small radiative corrections from quantum chromodynamics (QCD) and effects of weak interaction [33]. However, the current experimental results are 100 times less precise. The same data samples as for the studies of discrete symmetries can be used to measure decay rates of o-Ps. For the determination of the o-Ps lifetime, the identification of a photon from neon deexcitation is required. Emission time of this photon can be identified as a positronium creation time. Data sample collected so far by J-PET should be sufficient to reach the same accuracy as NRQED for o-Ps decay rate.

If a discrepancy between experimental and theoretical results would be observed, it may be explained in terms of the so-called invisible decays of o-Ps via annihilation into a virtual photon [48]. This virtual photon would oscillate into a mirror photon, as was proposed by Glashow [49], and would connect the o-Ps with its own mirror partner. This Mirror Matter was suggested in order to restore parity violation in weak interactions. The parity violation in the new hidden mirror sector is performed in the opposite way [50].

6 Conclusion

The cost effective positron electron tomograph based on the plastic scintillators opens a broad range of basic research area [3]: from the improved accuracy for the test of CPT symmetry, via the new operator based on the polarisation of photon for test of CP symmetry, to search for entanglement of annihilation photons and Mirror Matter candidates. The modular version of the J-PET system is already used to collect data in a more effective way than its predecessor aiming at reaching next level of accuracy.

7 Acknowledgements

The J-PET collaboration acknowledges the support provided by the Foundation for Polish Science through the TEAM POIR.04.04.00-00-4204/17 program, the National Science Centre of Poland through grants MAESTRO no. 2021/42/A/ST2/00423, OPUS no. 2019/35/B/ST2/03562, the Ministry of Education and Science through grant no. SPUB/SP/490528/2021, the EU Horizon 2020 research and innovation programme, STRONG-2020 project, under grant agreement No 824093, and the SciMat and qLife Priority Research Areas budget under the program *Excellence Initiative - Research University* at the Jagiellonian University, and Jagiellonian University project no. CRP/0641.221.2020.

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