PROCEEDINGS OF SCIENCE

CP symmetry test at J-PET

Eryk Czerwiński[a,*] **on behalf of the J-PET Collaboration**

[a] *Marian Smoluchowski Institute of Physics, Jagiellonian University, ul. prof. St. Łojasiewicza 11, 30-348 Kraków, Poland*

E-mail: eryk.czerwinski@uj.edu.pl

The Jagiellonian Positron Emission Tomograph (J-PET) is a detector for tests of discrete symmetries as well as for biomedical imaging. The novelty of the system is based on usage of plastic scintillators for active detection material and trigger-less data acquisition system. The apparatus consists of 192 plastic scintillators read out from both ends with vacuum tube photomultipliers. Positronium being an eigenstate of both the C and P operators is an unique probe to test the CP symmetry. This test performed at J-PET is based on determination of polarisation of photons from positronium annihilation. This allows exploration of a new class of discrete symmetry odd operator that was not investigated before.

8th Symposium on Prospects in the Physics of Discrete Symmetries (DISCRETE 2022)
7-11 November, 2022
Baden-Baden, Germany

*Speaker

https://pos.sissa.it/

PoS(DISCRETE2022)063

1. Introduction

The amount of CP violation contained in the Standard Model appears to be insufficient for a convincing explanation of the observed prevalence of matter over antimatter in the Universe [1, 2]. For these reasons, discrete symmetry tests remain an interesting experimental research area in fundamental physics. One possible way to study the discrete symmetry violation is to investigate the expectation values for the symmetry odd-operators of the non-degenerate stationary states. Such tests performed with positronium, a bound state of an electron and a positron, are based on the determination of an expectation values of symmetry odd operators for specific symmetries [3, 4]. The previously performed investigations of angular correlations for CPT [5] and CP [6] symmetries are based on the momenta of gamma rays and spin of ortho-positronium. The J-PET group extends the study to other operators, taking advantages of properties of the J-PET tomography scanner, which enables to determine the momentum direction of the secondary scattered photons [7].

2. Experimental techniques

The Jagiellonian Positron Annihilation Tomograph (J-PET) is optimised for detection of annihilation gamma originating from electron-positron annihilation [8]. It is the first PET scanner which uses plastic scintillator strips, making it more cost efficient and portable [9–11]. The usage of plastic scintillators as detection elements with very good timing properties and high granularity of these strips allow for identification of gamma scatterings. Combination of the above mentioned properties translates directly into unique feature of determination of polarisation direction of annihilation gamma on the event by event basis with the J-PET system [7, 12, 13]. The detector is made up of 192 plastic scintillator strips (EJ-230) with dimensions of $500 \times 19 \times 7\text{mm}^3$ eac. They are arranged in three concentric layers (48 modules on radius 425 mm, 48 modules on radius 467.5 mm, and 96 modules on radius 575 mm). Each scintillator of the J-PET scanner is optically coupled to Hamamatsu R9800 vacuum tube photomultipliers on both ends [14–16]. This yields 384 analog channels, which are processed by a fully equipped trigger-less Data Acquisition System (DAQ) and readout mechanism [17–19]. The experiments were conducted with a point-like ^{22}Na source placed in the center of the detector and surrounded by a porous polymer [20, 21]. The positrons emitted from the source ($^{22}Na \rightarrow {}^{22}Ne^{*} + e^{+} + \nu_e$) combine with the electrons in the porous polymer to produce ortho-Positronium (o-Ps), a meta-stable triplet state that primarily decays into three photons due to charge conjugation symmetry conservation.

Data acquisition system of J-PET operates in trigger-less mode [17, 19]. Therefore multiple offline analysis dedicated to specific studies can be performed without being affected by trigger requirements. So far the J-PET group conducted several continuous data-taking campaigns. The periods devoted to measurements for CPT symmetry studies last from 26 days [5] up to 9 months, being 16 months in total, while measurements for CP symmetry last from 6 days up to 8 months (12 months in total). It is worth to mention that new data-taking campaigns using modular version of J-PET detector are in progress now, with the aim to improve the already published result [22].

Data collected during 122 days of four independent data taking campaigns are used to measure the expectation value of the CP sensitive operator: $O_{CP} = \frac{\vec{k}_i \cdot (\vec{k}_j \times \vec{k}'_j)}{|\vec{k}_j \times \vec{k}'_j|}$. where $\vec{k}_i$ and $\vec{k}_j$ denote momentum of the i-th and j-th annihilation photons, while $\vec{k}'_j$ is the momentum of the scattered photon [7]. Identification of momentum direction of annihilation photon is based on the known annihilation point (source position) and reconstructed point of interaction with scintillator strips, due to good timing resolution. These annihilation photons are identified based on their common emission time and coplanarity of momenta. The scattered photon is identified by comparison the measured time of flight between consecutive interaction between different strips and expected time of flight based on the measured interaction points and speed of light. From kinematics we infer that the sum of the two smallest relative azimuthal angles between the registered annihilation photons for *o-Ps*$\rightarrow 3\gamma$ must be greater than 180° [7]. This condition allows for suppression of a large sample of background from e+e- $\rightarrow 2\gamma$ events. With the available statistics of 7×10^5 events we are able to reach an accuracy of 10^{-4} without contribution from systematical uncertainties [23, 24]. The previous test of CP symmetry with o-Ps reached the level of 10^{-3} [6]. It is worth to stress, that reported here the study of angular correlations performed at J-PET show full angular coverage in terms of both, geometrical acceptance as well as analysis efficiency.

3. Conclusions

First measurement of expectation value of symmetry-odd operator reported by J-PET group, together with prospects of upcoming results, confirms the potential of the detector for tests of discrete symmetries [5, 25]. This device has unique property of combining determination of photon polarisation together with estimation of positronium spin axis on the event-by-event basis.

Acknowledgements

This work was supported 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 and 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.

References

[1] P.A. Vetter and S.J. Freedman, Phys. Rev. Lett. **91**, 263401 (2003).

[2] A. Pokraka and A. Czarnecki, Phys. Rev. D **96** (2017) no.9, 093002 doi:10.1103/PhysRevD.96.093002 [arXiv:1707.09466 [hep-ph]].

[3] G.S. Adkins, *Proceedings, 5th Meeting on CPT and Lorentz Symmetry*, Bloomington, 254–257 (2010), URL https://doi.org/10.1142/9789814327688_0050, [arXiv:1007.3909 [hep-ph]].

[4] G. S. Adkins, R. N. Fell, and J. Sapirstein. Ann. Phys., **295** (2002) 136 doi:10.1006/aphy.2001.6219

[5] P. Moskal *et al.*, Nature Commun. **12**, (2021) no.1, 5658 (2021), [arXiv:2112.04235 [nucl-ex]].

[6] T. Yamazaki, T. Namba, S. Asai and T. Kobayashi, Phys. Rev. Lett. **104**, 083401 (2010), [erratum: Phys. Rev. Lett. **120** no.23, 239902 (2018)], URL https://doi.org/10.1103/PhysRevLett.104.083401, [arXiv:0912.0843 [hep-ex]].

[7] P. Moskal *et al.*, Acta Phys. Polon. B **47**, 509 (2016), URL https://doi.org/10.5506/APhysPolB.47.509, [arXiv:1602.05226 [nucl-ex]].

[8] K. Dulski *et al.*, Nucl. Instrum. Meth. A **1008**, 165452 (2021). URL https://doi.org/10.1016/j.nima.2021.165452, [arXiv:2006.07467 [physics.ins-det]].

[9] P. Moskal *et al.*, IEEE Trans. Instrum. Measur. **70** (2020), 2000810 doi:10.1109/TIM.2020.3018515 [arXiv:2008.10868 [physics.ins-det]].

[10] Ł. Kapłon *et al.*, Bio-Algorithms and Med-Systems **10** (2014) no.1, 27-31 doi:10.1515/bams-2013-0108 [arXiv:1504.06886 [physics.ins-det]].

[11] S. Niedźwiecki *et al.*, Acta Phys. Polon. B **48** (2017), 1567 doi:10.5506/APhysPolB.48.1567 [arXiv:1710.11369 [physics.ins-det]].

[12] B. C. Hiesmayr and P. Moskal, Sci. Rep. **9** (2019) no.1, 8166 doi:10.1038/s41598-019-44570-z [arXiv:1807.04934 [quant-ph]].

[13] P. Moskal *et al.*, Eur. Phys. J. C **78** (2018) no.11, 970 doi:10.1140/epjc/s10052-018-6461-1 [arXiv:1809.10397 [physics.ins-det]].

[14] L. Raczyński *et al.*, Phys. Med. Biol. **62** (2017) no.12, 5076-5097 doi:10.1088/1361-6560/aa7005 [arXiv:1706.00924 [physics.ins-det]].

[15] L. Raczyński *et al.*, Nucl. Instrum. Meth. A **786** (2015), 105-112 doi:10.1016/j.nima.2015.03.032 [arXiv:1503.05188 [physics.ins-det]].

[16] P. Moskal *et al.*, Nucl. Instrum. Meth. A **775** (2015), 54-62 doi:10.1016/j.nima.2014.12.005 [arXiv:1412.6963 [physics.ins-det]].

[17] G. Korcyl *et al.*, Acta Phys. Polon. B **47**, 491 (2016), URL https://doi.org/10.5506/APhysPolB.47.491, [arXiv:1602.05251 [physics.ins-det]].

[18] W. Krzemien, A. Gajos, K. Kacprzak, K. Rakoczy and G. Korcyl, SoftwareX **11** (2020), 100487 doi:10.1016/j.softx.2020.100487 [arXiv:2002.10183 [physics.ins-det]].

[19] G. Korcyl *et al.*, IEEE Transactions on Medical Imaging **37**, 2526–2535 (2018), URL https://doi.org/10.1109/TMI.2018.2837741, [arXiv:1807.10754 [physics.ins-det]].

[20] M. Gorgol *et al.*, Acta Phys. Polon. B **51**, 293 (2020).

[21] B. Jasińska *et al.*, Acta Phys. Polon. B **47** (2016), 453 doi:10.5506/APhysPolB.47.453 [arXiv:1602.05376 [nucl-ex]].

[22] N. Chug and A. Gajos, these proceedings.

[23] J. Raj *et al.*, Acta Phys. Polon. B **51** (2020), 149 doi:10.5506/APhysPolB.51.149 [arXiv:1912.01694 [physics.ins-det]].

[24] E. Czerwiński and J. Raj, EPJ Web Conf. **262**, 01009 (2022), URL https://doi.org/10.1051/epjconf/202226201009.

[25] A. Gajos *et al.*, Adv. High Energy Phys. **2018** (2018), 8271280 doi:10.1155/2018/8271280 [arXiv:1804.07148 [physics.ins-det]].