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Searches for discrete symmetries violation in *ortho*-positronium decay using the J-PET detector

Daria Kamińska, Aleksander Gajos, Eryk Czerwiński, Tomasz Bednarski, Piotr Białas, Marek Gorgol, Bożena Jasińska, Łukasz Kapłon, Grzegorz Korcyl, Paweł Kowalski, Tomasz Kozik, Wojciech Krzemień, Ewelina Kubicz, Szymon Niedźwiecki, Marek Pałka, Lech Raczyński, Zbigniew Rudy, Oleksandr Rundel, Neha Gupta Sharma, Michał Silarski, Adam Słomski, Adam Strzelecki, Anna Wieczorek, Wojciech Wiślicki, Marcin Zieliński, Bożena Zgardzińska, Paweł Moskal

Abstract. In this paper, we present prospects for using the Jagiellonian positron emission tomograph (J-PET) detector to search for discrete symmetries violations in a purely leptonic system of the positronium atom. We discuss tests of CP and CPT symmetries by means of *ortho*-positronium decays into three photons. No zero expectation values for chosen correlations between *ortho*-positronium spin and momentum vectors of photons would imply the existence of physics phenomena beyond the standard model. Previous measurements resulted in violation amplitude parameters for CP and CPT symmetries consistent with zero, with an uncertainty of about 10^{-3}. The J-PET detector allows to determine those values with better precision, thanks to the unique time and angular resolution combined with a high geometrical acceptance. Achieving the aforementioned is possible because of the application of polymer scintillators instead of crystals as detectors of annihilation quanta.

Key words: discrete symmetries • J-PET • *ortho*-positronium

D. Kamińska✉, T. Bednarski, P. Białas, E. Czerwiński, A. Gajos, G. Korcyl, T. Kozik, E. Kubicz, P. Moskal, Sz. Niedźwiecki, M. Pałka, Z. Rudy, O. Rundel, N. G. Sharma, M. Silarski, A. Słomski, A. Strzelecki, M. Zieliński
Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University,
11 S. Łojasiewicza Str., 30-348 Kraków, Poland,
E-mail: daria.kaminska@doctoral.uj.edu.pl

M. Gorgol, B. Jasińska, B. Zgardzińska
Department of Nuclear Methods, Institute of Physics, Maria Curie-Sklodowska University,
1 M. Curie-Skłodowskiej Sq., 20-031 Lublin, Poland

Ł. Kapłon, A. Wieczorek
Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University,
11 S. Łojasiewicza Str., 30-348 Kraków, Poland
and Institute of Metallurgy and Materials Science of the Polish Academy of Sciences,
25 W. Reymonta Str., 30-059 Kraków, Poland

P. Kowalski, L. Raczyński, W. Wiślicki
Świerk Computing Centre,
National Centre for Nuclear Research,
7 Andrzeja Soltana Str., 05-400 Otwock/Świerk, Poland

W. Krzemień
High Energy Physics Division,
National Centre for Nuclear Research,
7 Andrzeja Soltana Str., 05-400 Otwock/Świerk, Poland

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Introduction

One of the important issues of physics nowadays is validation of discrete symmetries: charge conjugation (C), space reflection (P), time reversal (T), and combinations of them. These problems, extensively studied since decades in elementary processes governed by electroweak forces, still need to be measured with higher accuracy in order to explain fundamental questions such as predominance of matter over antimatter in the Universe or validity of the Lorentz invariance.

In those studies, the lightest strange meson sector occurs specially fruitful. The violation of CP and T symmetries were observed by Cronin and Fitch [1] and the BABAR Collaboration [2]. Surprisingly, in lepton sector, there is no indication of the discrete symmetries violation. It is important to emphasize that the presently known sources of the CP symmetry violations are still too small to account for the observed excess of matter over antimatter [3], and this remains one of the greatest puzzles in physics and cosmology.

In this paper, we focus on CP and CPT symmetry tests in decays of positronium and perspectives of their investigation by means of the Jagiellonian positron emission tomograph (J-PET) detector.

Violation of discrete symmetries in *ortho*-positronium decays

A special role in discrete symmetry violation searches is played by a positronium atom, which, because of its sensitivity [4] to a variety of symmetry violation effects, is one of the best candidates for such kind of studies.

The positronium atom structure is analogous to the Bohr atom. The *ortho*-positronium triplet (*o*-Ps) and *para*-positronium singlet (*p*-Ps) states can be distinguished and their spin alignment determines their properties. Due to the charge conjugation conservation, the *o*-Ps can decay only into odd number of photons, while the *p*-Ps decays into even number of photons, and the mean lifetime of *o*-Ps state in vacuum is longer (140 ns [5]) than that for *p*-Ps state (120 ps [5]).

Studies on discrete symmetries violation in *ortho*-positronium state were proposed by Bernreuther *et al.* in 1988 [4]. The signals for discrete symmetries violation in a spin-polarized *ortho*-positronium will be visible in selected set of angular correlations build on *i*-th photon momentum $\vec{k}_i$ (photons are numbered in order of decreasing energy) and *ortho*-positronium spin $\vec{S}$. The evidence for discrete symmetry violations will be observed in nonvanishing value of one of the forbidden correlations (e.g., $\vec{S}\cdot\hat{k}_1\times\hat{k}_2$ for CPT symmetry). For details see Table 1.

The measured observable is the asymmetry:

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

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

Asymmetry value can be associated to the CP (C_{CP}) and CPT (C_{CPT}) violation parameters by the following equations:

$$A = C_{CP} \cdot S^{CP} \qquad (1)$$
$$A = C_{CPT} \cdot S^{CPT}$$

where S^{CP} and S^{CPT} are the analyzing powers build on operators $(\hat{S}\cdot\hat{k}_1)$ $(\hat{S}\cdot\hat{k}_1\times\hat{k}_2)$ and $\vec{S}\cdot\hat{k}_1\times\hat{k}_2$, respectively.

Experimental verification

CP symmetry

The most recent measurement was presented at the Tokyo University in 2010 [6]. Positrons emitted from the 1 MBq ^{22}Na source at the center of experimental setup were passing through plastic scintillators and bound with electrons in silica aerogel inserted in the external 5-kG magnetic field. The gamma rays emitted from *o*-Ps decay were registered by LYSO crystals.

The measured value of CP violating parameter is equal to [6]:

$$C_{CP} = 0.0013 \pm 0.0012_{stat} \pm 0.0006_{syst}. \qquad (2)$$

Precision of obtained result is limited by available statistics, which cannot be increased by higher intensities of radioactive sources because of pile-ups in detector system [6].

CPT symmetry

The CPT violation coefficient was measured by Vetter and Freedman using the Gammasphere detector [7] – a 4π spectrometer for nuclear structure research built by 110 high-purity germanium (HPGe) detectors. During the experiment, the ^{68}Ge and ^{22}Na positron sources were used, with quite low intensities 0.04 MBq to avoid pile-ups in detector. *Ortho*-positronium was formed in silicon dioxide aerogel and decays into three gammas that were registered by detector. Reconstruction of 2.65×10^7 *ortho*-positronium decays allows to determine the following CPT violation coefficient [7]:

$$C_{CPT} = 0.0071 \pm 0.0062. \qquad (3)$$

Obtained result is the most precise measurement till now.

Prospects for J-PET

J-PET is a detector based on plastic scintillators characterized by shorter signals (about 5 ns) than commonly used crystal scintillators (e.g., 50 ns for GSO crystal) [8, 9]. This allows to use high-intensity sources and fast digital electronics readout [10–12]. Compton scattering spectrum instead of photopeak can be used by applying a dedicated analysis [13–15].

As a preparation for this project, a series of simulations have been carried out in order to estimate physical and instrumental background for studies of discrete symmetries. They account for the accidental coincidences and secondary scatterings in the detector material as well as positron thermalization process in matter, different lifetimes of *ortho*-positronium in different materials, momentum distributions because of quantum electrodynamic

Table 1. Dependency between angular correlation operators and discrete symmetries. Minus sign denotes forbidden correlations and observing their nonvanishing value will be evidence for symmetry violation

Operator	Discrete symmetry				
	C	P	T	CP	CPT
$\vec{S}\cdot\hat{k}_1\times\hat{k}_2$	+	+	−	+	−
$(\hat{S}\cdot\hat{k}_1)\cdot(\hat{S}\cdot\hat{k}_1\times\hat{k}_2)$	+	−	−	−	+

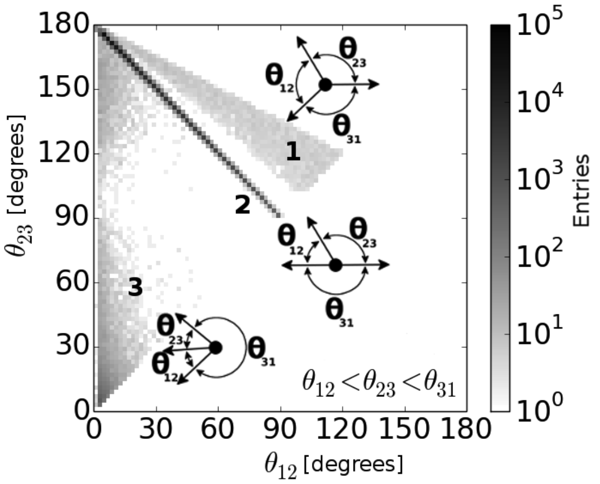

Fig. 1. Distribution of relative angles between reconstructed directions of gamma quanta. The numbering of quanta was assigned such that $\theta_{12} < \theta_{23} < \theta_{31}$. Shown distributions were obtained requiring three hits each with energy deposition larger than 50 keV. Typical topology of *o*-Ps → 3γ (region 1) and two kinds of background events (regions 2 and 3 from 2γ events with the secondary scattering in the detector) is indicted.

(QED) effects, as well as efficiency for the gamma quanta detection. Detailed description of these effects can be found, for example, in [16–18].

Main source of background contains events from direct annihilation of *para*-positronium decay where one of the gamma scattered and was registered by the detector. However, these events can be rejected by requiring small time differences between registration of gamma quanta, because scattered events need extra time to travel to the other part of the detector. Similarly, after ordering the relative angles ($\theta_{12} < \theta_{23} < \theta_{31}$), the true and false events have very small overlap region at the θ_{23} vs. θ_{12} correlation plot (Fig. 1).

For selected events, a novel reconstruction algorithm (analogous to the one described in Refs. [19, 20]) allows to obtain the time and spatial coordinates of the *ortho*-positronium decay point by using information about time of interaction of gamma quanta in the detector. The information available for *i*-th hit includes its spatial location and recording time. The problem of localizing the vertex is, in its principle, similar to GPS positioning and can be solved in a similar manner.

We expect that J-PET should allow to improve the accuracy because of the following reasons: about 10 times better timing resolution with respect to [6] and about 40 times better than [7], more than 10 times smaller pile-ups, and about 4 times better angular resolution. These features allow to improve sensitivity for the studies on discrete symmetries with respect to previous measurements. Violation of CP or CPT invariance in purely leptonic systems has never been seen so far.

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References

1. Christenson, J. H., Cronin, J. W., Fitch, V. L., & Turlay, R. (1964). Evidence for the 2π decay of the K_2^0 meson. *Phys. Rev. Lett.*, *13*, 138–140. DOI: 10.1103/PhysRevLett.13.138.
2. BABAR Collaboration: Aubert, B. *et al.* (2001). Measurement of CP-violating asymmetries in B^0 decays to CP eigenstates. *Phys. Rev. Lett.,* 86, 2515–2522. DOI: 10.1103/PhysRevLett.86.2515.
3. Sakharov, A. D. (1967). Violation of CP invariance, C asymmetry and Baryon asymmetry of the Universe. *Pisma Zh. Eksp. Teor. Fiz.*, *5*, 32–35. DOI: 10.1070/PU1991v034n05ABEH002497.
4. Bernreuther, W., Low, U., Ma, J. P., & Nachtmann, O. (1988). How to test CP, T, and CPT invariance in the three photon decay of polarized $^3S1$ positronium. *Z. Phys. C*, *41*(1), 143–158. DOI: 10.1007/BF01412589.
5. Harpen, M. D. (2004) Positronium: Review of symmetry, conserved quantities and decay for the radiological physicist. *Med. Phys.*, *31*(1), 57–61. DOI: 10.1118/1.1630494.
6. Yamazaki, T., Namba, T., Asai, A., & Kobayashi, T. (2010). Search for CP violation in positronium decay. *Phys. Rev. Lett.*, *104*, 08340–08344. DOI: 10.1103/PhysRevLett.104.083401.
7. Vetter, P. A., & Freedman, S. J. (2003). Search for CPT-odd decays of positronium. *Phys. Rev. Lett.*, *91*, 263401–263405. DOI: 10.1103/PhysRevLett.91.263401.
8. Moskal, P., Zoń, N., Bednarski, T., Białas, P., Czerwiński, E., Gajos, A., Kamińska, D., Kapłon, Ł., Kochanowski, A., Korcyl, G., Kowal, J., Kowalski, P., Kozik, T., Krzemień, W., Kubicz, E., Niedźwiecki, Sz., Pałka, M., Raczyński, L., Rudy, Z., Rundel, O., Salabura, P., Sharma, N. G., Silarski, M., Słomski, A., Smyrski, J., Strzelecki, A., Wieczorek, A., Wiślicki, W., & Zieliński, M. (2015). A novel method for the line-of-response and time-of-flight reconstruction in TOF-PET detectors based on a library of synchronized model signals. *Nucl. Instrum. Methods Phys. Res. Sect. A-Accel. Spectrom. Dect. Assoc. Equip.*, *775*, 54–62. DOI: 10.1016/j.nima.2014.12.005. [arXiv:1412.6963].
9. Moskal, P., Niedźwiecki, Sz., Bednarski, T., Czerwiński, E., Kapłon, Ł., Kubicz, E., Moskal, I., Pawlik-Niedźwiecka, M., Sharma, N. G., Silarski, M., Zieliński, M., Zoń, N., Białas, P., Gajos, A., Kochanowski, A., Korcyl, G., Kowal, J., Kowalski, P., Kozik, T., Krzemień, W., Molenda, M., Pałka, M., Raczyński, L., Rudy, Z., Salabura, P., Słomski, A., Smyrski, J., Strzelecki, A., Wieczorek, A., & Wiślicki, W. (2014). Test of a single module of the J-PET scanner based on plastic scintillators. *Nucl. Instrum. Methods Phys. Res. Sect. A-Accel. Spectrom. Dect. Assoc. Equip.*, *764*, 317–321. DOI: 10.1016/j.nima.2014.07.052. [arXiv:1407.7395].
10. Korcyl, G., Moskal, P., Bednarski, T., Białas, P., Czerwiński, E., Kapłon, Ł., Kochanowski, A., Kowal, J., Kowalski, P., Kozik, T., Krzemień, W., Molenda, M.,

Niedźwiecki, Sz., Pałka, M., Pawlik, M., Raczyński, L., Rudy, Z., Salabura, P., Gupta-Sharma, N., Silarski, M., Słomski, A., Smyrski, J., Strzelecki, A., Wiślicki, W., Zieliński, M., & Zoń, N. (2014). Trigger-less and reconfigurable data acquisition system for positron emission tomography. *Bio-Algorithms and Med-Systems*, *10*(1), 37–40. DOI: 10.1515/bams-2013-0115.

11. Pałka, M., Bednarski, T., Białas, P., Czerwiński, E., Kapłon, Ł., Kochanowski, A., Korcyl, G., Kowal, J., Kowalski, P., Kozik, T., Krzemień, W., Molenda, M., Moskal, P., Niedźwiecki, Sz., Pawlik, M., Raczyński, L., Rudy, Z., Salabura, P., Sharma, N. G., Silarski, M., Słomski, A., Smyrski, J., Strzelecki, A., Wiślicki, W., Zieliński, M., & Zoń, N. (2014). A novel method based solely on FPGA units enabling measurement of time and charge of analog signals in Positron Emission Tomography. *Bio-Algorithms and Med-Systems*, *10*(1), 41–45. DOI: 10.1515/bams-2013-0104. [arXiv:1311.6127].
12. Krzemień, W., Gajos, A., Gruntowski, A., Stoła, K., Trybek, D., Bednarski, T., Bialas, P., Czerwiński, E., Kaminska, D., Kapłon, Ł., Kochanowski, A., Korcyl, G., Kowal, J., Kowalski, P., Kozik, T., Kubicz, E., Moskal, P., Niedźwiecki, Sz., Pałka, M., Raczyński, L., Rudy, Z., Salabura, P., Sharma, N. G., Silarski, M., Słomski, A., Smyrski, J., Strzelecki, A., Wieczorek, A., Wiślicki, W., Zieliński, M., & Zon, N. (2015). Analysis framework for the J-PET scanner. *Acta Phys. Pol. A*, *127*(5), 1491–1494. DOI: 10.12693/APhysPolA.127.1491. [arXiv:1503.00465].
13. Raczyński, L., Moskal, P., Kowalski, P., Wiślicki, W., Bednarski, T., Białas, P., Czerwiński, E., Kapłon, Ł., Kochanowski, A., Korcyl, G., Kowal, J., Kozik, T., Krzemień, W., Kubicz, E., Molenda, M., Moskal, I., Niedźwiecki, Sz., Pałka, M., Pawlik-Niedźwiecka, M., Rudy, Z., Salabura, P., Sharma, N. G., Silarski, M., Słomski, A., Smyrski, J., Strzelecki, A., Wieczorek, A., Zieliński, M., & Zoń, N. (2014). Novel method for hit-position reconstruction using voltage signals in plastic scintillators and its application to Positron Emission Tomography. *Nucl. Instrum. Methods Phys. Res. Sect. A-Accel. Spectrom. Dect. Assoc. Equip.*, *764*, 186–192. DOI: 10.1016/j.nima.2014.07.032. [arXiv:1311.6127].
14. Raczyński, L., Moskal, P., Kowalski, P., Wiślicki, W., Bednarski, T., Białas, P., Czerwiński, E., Gajos, A., Kapłon, Ł., Kochanowski, A., Korcyl, G., Kowal, J., Kozik, T., Krzemień, W., Kubicz, E., Niedźwiecki Sz., Pałka, M., Rudy, Z., Rundel, O., Salabura, P., Sharma, N. G., Silarski, M., Słomski, A., Smyrski, J., Strzelecki, A., Wieczorek, A., Zieliński, M., & Zoń, N. (2015). Compressive sensing of signals generated in plastic scintillators in a novel J-PET instrument. *Nucl. Instrum. Methods Phys. Res. Sect. A-Accel. Spectrom. Dect. Assoc. Equip.*, *786*, 105–112. DOI: 10.1016/j.nima.2015.03.032. [arXiv:1503.05188].
15. Moskal, P., Sharma, N. G., Silarski, M., Bednarski T., Białas, P., Bulka, J., Czerwiński, E., Gajos, A., Kamińska, D., Kapłon, Ł., Kochanowski, A., Korcyl G., Kowal, J., Kowalski, P., Kozik, T., Krzemień, W., Kubicz, E., Niedźwiecki, Sz., Pałka, M., Raczyński, L., Rudy, Z., Rundel, O, Salabura, P., Słomski, A., Smyrski, J., Strzelecki, A., Wieczorek, A., Wiślicki, W., Wochlik, I., Zieliński, M., & Zoń, N. (2015). Hit time and hit position reconstruction in the J-PET detector based on a library of averaged model signals. *Acta Phys. Pol. A*, *127*(5), 1495–1499. DOI: 10.12693/APhysPolA.127.149. [arXiv:1502.07886].
16. Kowalski, P., Moskal, P., Wiślicki, W., Raczyński, L., Bednarski, T., Białas, P., Bułka, J., Czerwiński, E., Gajos, A., Gruntowski, A., Kamińska, D., Kapłon, Ł., Kochanowski, A., Korcyl, G., Kowal, J., Kozik, T., Krzemień, W., Kubicz, E., Niedźwiecki, Sz., Pałka, M., Rudy, Z., Salabura, P., Sharma, N. G., Silarski, M., Słomski, A., Smyrski, J., Strzelecki, A., Wieczorek, A., Wochlik, I., Zieliński, M., & Zoń, N. (2015). Multiple scattering and accidental coincidences in the J-PET detector simulated using GATE package. *Acta Phys. Pol. A*, *127*(5), 1505–1512. DOI: 10.12693/APhysPolA.127.1505. [arXiv:1502.04532].
17. Cal-González, J., Herraiz, J. L., España, S., Corzo, P. M. G., Vaquero, J. J., Desco, M., & Udias, J. M. (2013). Positron range estimations with PeneloPET. *Phys. Med. Biol.*, *58*, 5127–5152. DOI: 10.1088/0031-9155/58/15/5127.
18. Berestetskii, V. B., Lifshitz, E. M., & Pitaevskii, L. P. (1971). Relativistic quantum theory. Oxford, New York: Pergamon Press.
19. Gajos, A. (2013). *A novel algorithm for the* $K \to \pi^0 \pi^0 \to \gamma\gamma\gamma\gamma$ *decay vertex reconstruction for the KLOE-2 experiment.* Diploma Thesis, Jagiellonian University, Krakow, Poland.
20. Gajos, A. (2015). Study of the $K_S K_L \to \pi l \nu 3\pi 0$ process for time reversal symmetry test at KLOE-2. *Acta Phys. Pol. B*, *46*, 13–18. DOI: 5506/AphysPolB.46.13.