Proc. of 12th International Workshop on Positron and Positronium Chemistry, August 28–September 1, 2017, Lublin, Poland

A Method to Produce Linearly Polarized Positrons and Positronium Atoms with the J-PET Detector

Muhsin Mohammed[a,b,*], P. Białas[a], C. Curceanu[c], E. Czerwiński[a], K. Dulski[a], A. Gajos[a], B. Głowacz[a], M. Gorgol[d], B.C. Hiesmayr[e], B. Jasińska[d], D. Kisielewska[a], G. Korcyl[a], P. Kowalski[f], T. Kozik[a], N. Krawczyk[a], W. Krzemień[g], E. Kubicz[a], M. Pawlik-Niedźwiecka[a], S. Niedźwiecki[a], M. Pałka[a], L. Raczyński[f], J. Raj[a], Z. Rudy[a], N.G. Sharma[a], S. Sharma[a], Shivani[a], M. Skurzok[a], M. Silarski[a], A. Wieczorek[a,h], W. Wiślicki[f], B. Zgardzińska[d], M. Zieliński[a] and P. Moskal[a]

[a]Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University, 30-348 Kraków, Poland

[b]Department of Physics, College of Education for Pure Sciences, University of Mosul, Mosul, Iraq

[c]INFN, Laboratori Nazionali di Frascati, 00044 Frascati, Italy

[d]Institute of Physics, M. Curie-Skłodowska University, 20-031 Lublin, Poland

[e]Faculty of Physics, University of Vienna, 1090 Vienna, Austria

[f]Department of Complex System, National Centre for Nuclear Research, 05-400 Otwock-Świerk, Poland

[g]High Energy Physics Division, National Centre for Nuclear Research, 05-400 Otwock-Świerk, Poland

[h]Institute of Metallurgy and Materials Science, Polish Academy of Sciences, 30-059 Kraków, Poland

A method for creating linearly polarized positrons and *ortho*-positronium (*o*-Ps) atoms with the J-PET detector is presented. The unique geometry and properties of the J-PET tomography enable one to design a positron source such that the quantization axis for the estimation of the linear polarization of produced *o*-Ps can be determined on the event by event basis in a direction of the positron motion. We intend to use ^{22}Na or other β^+ decay isotopes as a source of polarized positrons. Due to the parity violation in the beta decay, the emitted positrons are longitudinally polarized. The choice of the quantization axis is based on the known position of the positron emitter and the reconstructed position of the positronium annihilation. We show that the J-PET tomography is equipped with all needed components.

DOI: 10.12693/APhysPolA.132.1486

PACS/topics: 41.75.Fr, 41.75.Ht, 77.22.Ej, 36.10.Dr, 85.75.Mm, 87.57.uk

1. Introduction

The J-PET is a novel tomography device using plastic scintillators as detectors for annihilation photons [1–8]. The tomograph is designed also for tests of discrete symmetries in the decays of positronium atoms [9] and for studies of multi-partite quantum entanglement of photons originating from the decays of positronium [10]. The discrete symmetries may be tested via measurements of the expectation values of the symmetry odd operators which are constructed from the spin of an *ortho*-positronium (*o*-Ps) atom and the momentum vectors of the photons [9]. Here we present in detail a method applied in the J-PET detector for the determination of the linear polarization of *o*-Ps atoms produced in the unpolarized porous material [9].

Positronium is the lightest purely leptonic system decaying into photons. As an atom bound by a central potential, it is a parity eigenstate, and as an atom built out of an electron and an anti-electron, it is an eigenstate of the charge conjugation operator. Therefore, this makes the positronium atom an interesting system for testing the discrete symmetries such as C, P, and T either alone or in combination [11]. In the previous experiments studying the decays of positronium atoms, the CP and CPT symmetries were tested with the accuracy of about 0.3% [12, 13], which is many orders of magnitude less precise than the accuracies achieved in the quark sector [14].

2. The detection system and the annihilation chamber

The Jagiellonian positron emission tomograph (J-PET) is the first positron emission tomography scanner based on organic scintillators and a prototype of a cost-effective scanner for the simultaneous metabolic imaging of the whole human body [15]. The J-PET prototype consists of 192 detection modules, each equipped with photomultipliers (PMTs) on both ends and arranged axially in three layers forming a cylindrical diagnostic chamber with the inner diameter of 85 cm. This results in 384 analog channels that have to be processed by the data acquisition system (DAQ). The main part of the J-PET DAQ system is the collection of TRBv3 modules [16, 17].

*corresponding author; e-mail: muhsin.m@doctoral.uj.edu.pl

A dedicated solution for the continuous data recording (trigger-less) is a novel approach in such detector systems and assures that most of the information is preserved on the storage for further, high-level processing [17]. Signal discrimination applies a unique method of using LVDS buffers located in the FPGA board which probes signals in the voltage domain at four thresholds with the accuracy of about 30 ps [7]. The computing model for the remote data processing is being developed [18].

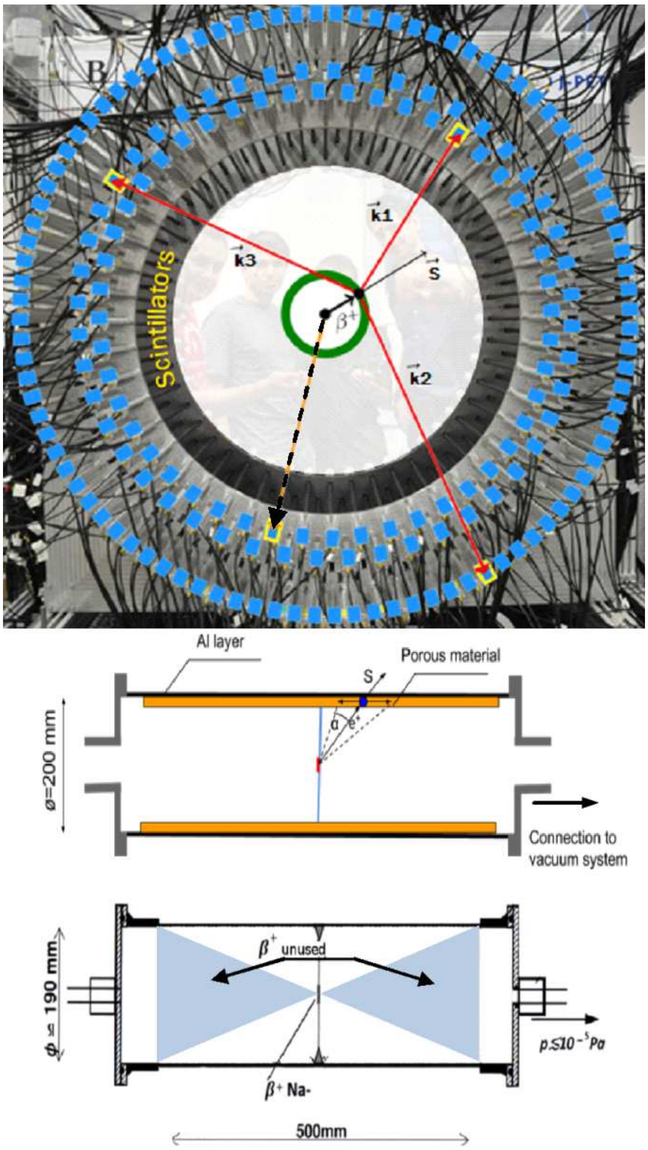

Fig. 1. (top) Photo of the J-PET. J-PET is made of 3 cylindrical layers of EJ-230 plastic scintillator strips (black) with a dimension of $7\times19\times500$ mm^3 and Hamamatsu R9800 photomultipliers (gray). The superimposed rectangles indicate positions of photomultipliers. (below) Schemes of large annihilation chamber.

Figure 1 presents a photo of the J-PET prototype. Superimposed arrows indicate momentum and spin vectors involved in the typical event of *ortho*-positronium production with spin S. A black dot in the center indicates a sodium ^{22}Na radioactive source emitting longitudinally polarized positron (β^+) from a parity-violating beta decay and prompt gamma quantum (dashed arrow) from the de-excitation of daughter nucleus ^{22}Ne. *Ortho*-positronium (dot marked on the cylinder) may decay into three photons ($\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3$). Each photon may interact via the Compton effect in the scintillator strips (marked by rectangular rims). In the first test measurements a large annihilation chamber and a sodium source with an activity of about 9 MBq were used. The source was closed in the Kapton foil inside the cylindrical aluminum chamber (see Fig. 1, bottom). In the first tests, positrons were annihilating in the aluminum wall. In the next experiments, the annihilation chamber will be realized as the positron's source with a porous material cylinder around it (see Fig. 1, middle), where we have the plan to use porous target materials like LA-1000 or polymer XAD-4 on the internal surfaces of the large chamber or a dedicated material presently developed at the Maria Curie-Skłodowska University in Lublin. XAD-4 polymer gives a very high fraction of 3γ annihilation [19].

In order to determine a polarization axis on an event-by-event basis, we can use the trilateration method which is a widely known technique used for the determination of a position of a point known to lie simultaneously on surfaces of several spheres with given radii and centers [20]. In the case of this study, the three photons travel from the *o*-Ps decay point (which needs to be localized) to the detector where the 3D positions and times of their interaction with the detector are recorded as reference points.

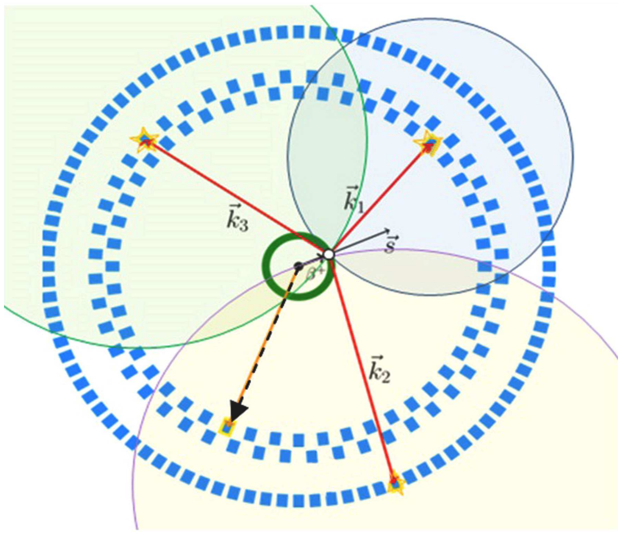

Fig. 2. Scheme of the trilateration-based reconstruction used to determine the ortho-positronim annihilation point.

Figure 2 shows a reconstruction method based on trilateration which can be used to reconstruct the $o-\mathrm{Ps}\to 3-\gamma$ decay vertex which, in turn, allows us to estimate the positron momentum direction and hence to choose the spin quantization axis along which the *o*-Ps atoms are linearly polarized.

3. The degree of the *ortho*-positronium polarization

The positrons emitted from ^{22}Na are longitudinally spin-polarized due to the parity nonconservation in the weak interaction. This gift of nature means that slow positron derived from a radioactive source are always spin polarized to some extent [21]. The average polarization can be estimated from the average velocity of the positrons emitted in the beta$^+$ decays. The mean polarization of the positron is equal to $p = v/c$, where v denotes to the positron velocity, c is the speed of light. The average polarization of ^{22}Na source is equal to about 0.67, while for ^{68}Ge it is 0.90 [22, 13]. This polarization is too large extent preserved during the thermalization process [23]. Its losses in the material are estimated to be about 8% for positrons from ^{22}Na and 17% for positrons from ^{68}Ge [24]. Moreover, the *ortho*-positronium polarization is by a factor of 2/3 smaller with respect to the positron polarization because the spin of electrons in the target is not polarized [25]. The factor 2/3 may be explained as follows. The electrons and positrons both have spin 1/2. The two spins can be added to give a total spin of $S = 0$ or 1. Thus Ps possesses four ground states indexed with S and S_z, where S is the total spin and S_z is the z-projection of S. The triplet $|1,1\rangle, |1,0\rangle, |1,-1\rangle$ and singlet $|0,0\rangle$ states can be expressed as: $|S=1, S_z=1\rangle = |\uparrow\rangle|\uparrow\rangle$, $|S=1, S_z=0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle|\downarrow\rangle + |\downarrow\rangle|\uparrow\rangle)$, $|S=1, S_z=-1\rangle = |\downarrow\rangle|\downarrow\rangle$, $|S=0, S_z=0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle|\downarrow\rangle - |\downarrow\rangle|\uparrow\rangle)$, where arrows denotes the spin projections of positron and electron.

If the positron and electron from which the Ps is formed are unpolarized, then the four lowest energy levels, a singlet and three triplet states will each be generated with equal likelihood. If some degree of polarization does exist in the incident positron (for example if the incident positron has spins aligned up(+) along the quantization axis), so the Ps will be formed more copiously with $S_z = +1$ than with $S_z = -1$. Figure 3 indicates in the pictorial way that 75% of produced Ps will be formed with spin $S = 1$ and only 25% with spin $S = 0$. Moreover, 1/3 of *ortho*-positronia ($S = 1$) will possess $S_z = 0$.

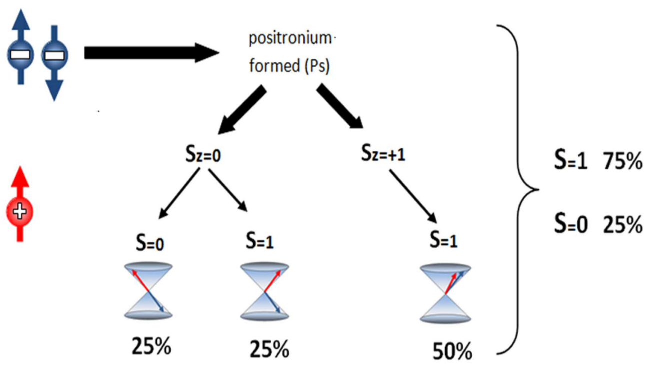

Fig. 3. Schematic diagram of combined spin states probabilities of positronium formation in an unpolarized porous material by spin polarized positrons.

The polarization of positrons along the quantization axis may be expressed as $P_{e^+} = (N^{e^+}_{+1/2} - N^{e^+}_{-1/2})/(N^{e^+}_{+1/2} + N^{e^+}_{-1/2})$, where $N^{e^+}_{+1/2}$ and $N^{e^+}_{-1/2}$ denote number of positrons with spin projection upstream and downstream their direction of motion, respectively.

In order to derive the linear spin polarization of *ortho*-positronia produced by positrons polarized with the degree of P_{e^+} and unpolarized electrons we first estimate that (as indicated in Fig. 3) the number of *ortho*-positronia produced with spin projection +1, 0 and −1 is equal respectively to: $N_{+1} = 0.5N^{e^+}_{+1/2}$; $N_{-1} = 0.5N^{e^+}_{-1/2}$; $N_0 = 0.25(N^{e^+}_{+1/2} + N^{e^+}_{-1/2})$.

Thus, linear polarization of *ortho*-positronium, defined as an expectation value of the spin projection onto quantization axis, reads

$$\begin{aligned} P^{(\text{linear})}_{o-\text{Ps}} &= +1\left(N_{+1}/(N_{+1}+N_0+N_{-1})\right) \\ &\quad +0\left(N_0/(N_{+1}+N_0+N_{-1})\right) \\ &\quad -1\left(N_{-1}/(N_{+1}+N_0+N_{-1})\right), \end{aligned}$$

leading to the following relation for the linear polarization of *ortho*-positronium atoms produced in the unpolarized material by positrons with linear polarization of P_{e^+}:

$$\begin{aligned} P^{(\text{linear})}_{o-\text{Ps}} &= 0.5(N^{e^+}_{+1/2} - N^{e^+}_{-1/2}) \\ &\quad /0.75(N^{e^+}_{+1/2} + N^{e^+}_{-1/2}) = 2/3P_{e^+}. \end{aligned}$$

The linear *ortho*-positronium polarization $P_{o-\text{Ps}}$ achieved in the previous experiments was equal to 0.43 for the ^{22}Na source and 0.61 for the ^{68}Ge source [26].

It is, however, important to note that the tensor polarization of *ortho*-positronium produced in the unpolarized material which is defined as

$$\begin{aligned} P^{(\text{tensor})}_{o-\text{Ps}} &= +1\left(N_{+1}/(N_{+1}+N_0+N_{-1})\right) \\ &\quad +1\left(N_{-1}/(N_{+1}+N_0+N_{-1})\right) \\ &\quad -2\left(N_0/(N_{+1}+N_0+N_{-1})\right), \end{aligned}$$

will be equal to zero independent of the degree of the positron spin polarization:

$$\begin{aligned} P^{(\text{tensor})}_{o-\text{Ps}} &= \left[0.5(N^{e^+}_{+1/2} + N^{e^+}_{-1/2}) \right. \\ &\quad \left. -0.5(N^{e^+}_{+1/2} + N^{e^+}_{-1/2})\right]/0.75(N^{e^+}_{+1/2} + N^{e^+}_{-1/2}) = 0. \end{aligned}$$

4. Summary

The J-PET is optimized for the detection of photons from the electron–positron annihilation with high time and angular-resolutions, thus providing new opportunities for research with photons originating from the decays of positronium atoms in fundamental physics. In this article, a method to create the *ortho*-positronium spin polarization with the J-PET detector without the usage of the external magnetic field was described.

Acknowledgments

The authors acknowledge the administrative and technical support by A. Heczko, W. Migdał. We appreciate valuable discussions with Dr. Jan Wawryszczuk and the financial support by the Polish National Center for Development and Research through grant INNOTECH-K1/IN1/64/159174/NCBR/12, the EU and MSHE grant no. POIG.02.03.00-16100-013/09, National Science Center through the grant No. 2016/21/B/ST2/01222. B.C. Hiesmayr gratefully acknowledges the Austrian Science Fund FWF-P26783.

References

[1] P. Moskal et al., *Phys. Med. Biol.* **61**, 2025 (2016).

[2] P. Moskal et al., *Nucl. Instrum. Methods Phys. Res. A* **775**, 54 (2015).

[3] L. Raczyński et al., *Nucl. Instrum. Methods Phys. Res. A* **764**, 186 (2014).

[4] L. Raczyński et al., *Nucl. Instrum. Methods Phys. Res. A* **786**, 105 (2015).

[5] P. Moskal et al., *Nucl. Instrum. Methods Phys. Res. A* **764**, 317 (2014).

[6] J. Smyrski et al., *Nucl. Instrum. Methods Phys. Res. A* **851**, 39 (2017).

[7] M. Pałka et al., *JINST* **12**, P08001 (2017).

[8] L. Raczyński et al., *Phys. Med. Biol.* **62**, 5076 (2017).

[9] P. Moskal et al., *Acta Phys. Pol. B* **47**, 509 (2016).

[10] B.C. Hiesmayr, P. Moskal, *Sci. Rep.* **7**, 15349 (2017).

[11] J. McDonough et al., *Phys. Rev. D* **38**, 2121 (1988).

[12] T. Yamazaki et al., *Phys. Rev. Lett.* **104**, 083401 (2010).

[13] P. Coleman, *Positron Beams and Their Applications*, World Sci. Pub., Singapore 2000.

[14] K.A. Olive et al., *Chin. Phys. C* **38**, 090001 (2014).

[15] S. Niedźwiecki et al., *Acta Phys. Pol. B* **48**, 1567 (2017).

[16] W. Krzemień et al., *Acta Phys. Pol. A* **127**, 1491 (2015).

[17] G. Korcyl et al., *Acta Phys. Pol. B* **47**, 491 (2016).

[18] W. Krzemień et al., *Acta Phys. Pol. B* **47**, 561 (2016).

[19] B. Jasińska et al., *Acta Phys. Pol. B* **47**, 453 (2016).

[20] A. Gajos et al., *Nucl. Instrum. Methods Phys. Res. A* **819**, 54 (2016).

[21] K.F. Canter, P.G. Coleman, T.C. Griffith, G.R. Heyland, *J. Phys. B* **5**, L167 (1972).

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

[23] J. Van House, P.W. Zitzewitz, *Phys. Rev. A* **29**, 96 (1984).

[24] J. Yang, M. Chiba, R. Hamatsu, T. Hirose, M. Irako, T. Kumita, *Jpn. J. Appl. Phys.* **36**, 3764 (1997).

[25] B.K. Arbic, S. Hatamian, M. Skalsey, J. Van House, W. Zheng, *Phys. Rev. A* **37**, 3189 (1988).

[26] P. Vetter, *Int. J. Mod. Phys. A* **19**, 3865 (2004).