Nuclear Instruments and Methods in Physics Research A 819 (2016) 54–59

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Trilateration-based reconstruction of *ortho*-positronium decays into three photons with the J-PET detector

A. Gajos [a], D. Kamińska [a], E. Czerwiński [a,*], D. Alfs [a], T. Bednarski [a], P. Białas [a], B. Głowacz [a], M. Gorgol [b], B. Jasińska [b], Ł. Kapłon [a,c], G. Korcyl [a], P. Kowalski [d], T. Kozik [a], W. Krzemień [e], E. Kubicz [a], M. Mohammed [a], Sz. Niedźwiecki [a], M. Pałka [a], M. Pawlik-Niedźwiecka [a], L. Raczyński [d], Z. Rudy [a], O. Rundel [a], N.G. Sharma [a], M. Silarski [a], A. Słomski [a], A. Strzelecki [a], A. Wieczorek [a,c], W. Wiślicki [d], B. Zgardzińska [b], M. Zieliński [a], P. Moskal [a]

[a] Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University, 30-348 Cracow, Poland
[b] Department of Nuclear Methods, Institute of Physics, Maria Curie-Skłodowska University, 20-031 Lublin, Poland
[c] Institute of Metallurgy and Materials Science of Polish Academy of Sciences, Cracow, Poland
[d] Świerk Computing Centre, National Centre for Nuclear Research, 05-400 Otwock-Świerk, Poland
[e] High Energy Department, National Centre for Nuclear Research, 05-400 Otwock-Świerk, Poland

ARTICLE INFO

Article history:
Received 3 November 2015
Received in revised form
19 February 2016
Accepted 22 February 2016
Available online 26 February 2016

Keywords:
Reconstruction
Positronium
Discrete symmetry
J-PET

ABSTRACT

This work reports on a new reconstruction algorithm allowing us to reconstruct the decays of ortho-positronium atoms into three photons using the places and times of photons recorded in the detector. The method is based on trilateration and allows for a simultaneous reconstruction of both location and time of the decay. Results of resolution tests of the new reconstruction in the J-PET detector based on Monte Carlo simulations are presented, which yield a spatial resolution at the level of 2 cm (FWHM) for *X* and *Y* and at the level of 1 cm (FWHM) for *Z* available with the present resolution of J-PET after application of a kinematic fit. Prospects of employment of this method for studying angular correlations of photons in decays of polarized *ortho*-positronia for the needs of tests of CP and CPT discrete symmetries are also discussed. The new reconstruction method allows for discrimination of background from random three-photon coincidences as well as for application of a novel method for determination of the linear polarization of *ortho*-positronium atoms, which is also introduced in this work.

1. Introduction

Trilateration 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. In a two-dimensional space, knowledge of three intersecting and non-identical circles is required in order to find a unique solution for the aforementioned point. Similarly, in a three-dimensional case, information about three spheres narrows the set of possible solutions to at maximum two points. In practical trilateration applications, additional requirements on the sought point location usually exist which allow us to identify the correct solution of the possible two.

Applications of trilateration-based localization usually determine the radii of the spheres by measuring the times of propagation of certain types of signals exchanged between the object being localized and several reference objects whose positions are well-defined and correspond to centers of the spheres. The propagation time measurement requires both the object being localized and the reference ones to determine the moment of signal emission or arrival with respect to the same starting point. This, however, is not possible in many practical realizations where the signal arrival or emission time cannot be measured for the localized object. The classical trilateration problem has then to be extended to involve an additional unknown time and the radii of the spheres become parametrized by this variable rather than being constant. As the problem of finding an intersection of three spheres with radii defined up to variable value is under-determined, one additional constraint is required in order to limit the set of solutions to two as in classical trilateration. The additional information can be provided by a fourth reference object, as is the case in the most widely known application, the Global Positioning System (GPS). A similar approach, however, was

* Corresponding author.
E-mail address: eryk.czerwinski@uj.edu.pl (E. Czerwiński).

http://dx.doi.org/10.1016/j.nima.2016.02.069
0168-9002/

recently applied in particle physics for reconstruction of the K_L neutral meson decays into two and three neutral pions at the KLOE experiment [1,2]. In these cases photons act as the exchanged signal and the reference points are provided by the recording places of the 4 and 6 photons, respectively coming from the decays $K_L \rightarrow 2\pi^0 \rightarrow 4\gamma$ and $K_L \rightarrow 3\pi^0 \rightarrow 6\gamma$.

Decays with three secondary particles only, however, can be reconstructed as well in a similar manner when the additional constraint is based on the geometry of the event rather than on a fourth particle. In this paper, we present a reconstruction method based on trilateration, intended for reconstructing decays of *ortho*-positronium into three gamma quanta ($o-\mathrm{Ps} \rightarrow 3\gamma$) for the needs of discrete symmetry tests in *ortho*-positronium decays.

2. Prospects of discrete symmetry studies with the J-PET detector

Although the CP and CPT discrete symmetries are thoroughly tested in a large variety of phenomena (see e.g. [3]), there have been only a few experiments investigating their conservation in the leptonic sector [4–8]. *Ortho*-positronium ($o-\mathrm{Ps}$), the triplet bound state of electron and positron, was pointed out as a purely leptonic system sensitive to symmetry violation effects [9] and several angular correlations observable in the *ortho*-positronium decays into three photons have been defined [10]. These correlations use momenta of the photons produced in the decay ordered by energy $|\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3|$ and the spin $\vec{S}$ of the positronium. The two latest experiments following this scheme searched for non-zero expectation values of the CP-odd correlation $(\hat{S} \cdot \hat{k}_1)(\hat{S} \cdot \hat{k}_1 \times \hat{k}_2)$ [8] and $(\hat{S} \cdot \hat{k}_1 \times \hat{k}_2)$ sensitive to CPT violation [7] in decays of spin-polarized *ortho*-positronia and both have limited the symmetry violation with a precision between 10^{-2} and 10^{-3}.

The J-PET device is a novel detector based on long (50 cm) strips of fast plastic scintillator arranged axially in a multi-layer barrel [11–13]. While J-PET was developed with Positron Emission Tomography in mind, it is capable of recording photons from *ortho*-positronium decays, thus allowing for tests of both CP and CPT symmetries with the aforementioned angular photon correlations. Detailed description of potential of the J-PET detector for studies of discrete symmetries in decays of positronium atom can be found in Ref. [14]. The design of J-PET system results in large acceptance allowing us to record all three photons from a single event and fast signals from plastic scintillators together with dedicated readout electronics provide a resolution of the time of photon interaction in the detector of about 80 ps [15,16], superior to the setups of previously conducted experiments [8,7]. We expect to significantly improve sensitivity for the CPT test by at least an order of magnitude with respect to the experiment performed using the Gammasphere [7] by collecting about two orders of magnitude larger statistics due to the possibility of longer runs and due to the usage of the higher rate of the positronium production (10 MBq at J-PET vs. 0.4 MBq at Gammasphere) which was limited by pile-ups and 1 μs coincidence window. This limitation is overcome by J-PET detector due to its much higher granularity and about two orders of magnitudes shorter duration of signals leading to the significant reduction of pile-ups and due to the triggerless DAQ [17] with no hardware coincidence window. Additional factor is due to angular resolution, which at J-PET is 0.5° and ~1° for polar and azimuthal angles, respectively, while at Gammasphere both are about 4°.

With the J-PET detector we expect to improve the sensitivity for measuring expectation values of CP odd operator by more than an order of magnitude with respect to the measurement performed at Tokyo University [8] because of more than two orders of magnitude larger statistics and about 3 times better angular resolution. In addition, it is possible with J-PET to register any orientation of the decay plane with respect to the spin direction and any relative angle between the gamma quanta, while it was fixed in the previous experiment [8]. Moreover since any of the scintillator strips may detect any of the three gamma quanta, the J-PET is less sensitive to geometric asymmetries of the relative detector arrangement and asymmetries due to the uncertainties in the detection efficiency determination.

It is also important to stress that the J-PET detector time resolution is a few times higher than at the experiment at Tokyo University [8] and by more than an order of magnitude better with respect to the Gammasphere. This will allow us to reduce the background significantly and hence to improve the sensitivity for the studies of the C violating $p-\mathrm{Ps} \rightarrow 3\gamma$ process.

The J-PET system is a multipurpose detector, which allows for positronium polarization determination, as it is described in Section 5. Other experiments, like described in reference [18], aiming at search of the phenomena beyond the Standard Model description of $o-\mathrm{Ps}$ decays were optimized for the acceptance, efficiency end energy resolution for registration of gamma quanta compromising both timing and angular resolutions. The latter is one of the most important characteristics in the case of the correlations studies. The usage of BGO crystals in previous experiments gives and advantage of higher detection efficiency with respect to the organic scintillators used by J-PET, however this could be compensated by the application of additional layers to J-PET system. On the other hand, the granularity of the scintillators at J-PET results in the high angular resolution for gamma registration as mentioned before, while fast timing of the organic scintillators allows for the usage of high activity sources (10 MBq at J-PET vs. 3.6×10^{-3} MBq [18]) without pile-up contribution.

In the experiments performed so far, the $o-\mathrm{Ps}$ decay place was assumed to lie within positronium aerogel targets (e.g. a hemisphere [7]) and no attempt was made to reconstruct the exact point nor the time of its decay. In J-PET, however, due to its relatively high angular acceptance and timing resolution, a reconstruction of the $o-\mathrm{Ps} \rightarrow 3\gamma$ process is possible by means of a new trilateration-based reconstruction method presented in the next section. Advantages of such full reconstruction of the $o-\mathrm{Ps}$ decay for its polarization determination and the CP and CPT symmetry tests with J-PET are discussed in Section 5.

3. Principle of the $o-\mathrm{Ps} \rightarrow 3\gamma$ decay reconstruction

In the $o-\mathrm{Ps} \rightarrow 3\gamma$ decay, photons travel from the decay point (which needs to be localized) to a particle detector where the places and times of their interaction with the detector are recorded and serve as reference points, further on referred to as photon hits. The lack of a fourth reference is compensated by the fact that all three photons are produced in a three-body decay and thus their momenta as well as the $o-\mathrm{Ps}$ decay point are contained within a single plane in the frame of reference of the decaying positronium atom.[1] Hence, an additional constraint needed for the trilateration problem to be determined in this case can be introduced as a requirement that the decay point lies on a plane spanned by the tree photon recording points.

Fig. 1a shows a scheme of an $o-\mathrm{Ps} \rightarrow 3\gamma$ decay taking place inside the J-PET detector. For clarity, only a single layer of the detector is shown and the inter-strip spacing is increased. For each

[1] As the momentum of decaying positronium is not zero, the three photons slightly deviate from coplanarity in the detector frame of reference. This effect was studied using MC simulations and its contribution was found negligible with respect to the $\mathcal{O}$ (1 cm) resolution achieved so far (Section 4).