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

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Abstract

In this paper we present prospects for using the 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 a unique time and angular resolution combined with a high geometrical acceptance. Achieving the aforementioned is possible due to application of polymer scintillators instead of crystals as detectors of annihilation quanta.

Keywords: discrete symmetries, J-PET, ortho-positronium
1. Introduction

One of the important issues of physics nowadays is validation of discrete symmetries: charge conjugation ($C$), space reflection ($P$) and 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 such fundamental questions 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 J. Cronin and V. Fitch [1] and by the BABAR Collaboration [2]. Surprisingly, in lepton sector there is no indication of the $T$, $CP$ and $CPT$ 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 J-PET detector.

2. Violation of discrete symmetries in ortho-positronium decays

A special role in discrete symmetry violation searches plays a positronium atom, which due to 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 for p-Ps state (120 ps [5]).

Studies of discrete symmetries violation in ortho-positronium state were proposed by Bernreuther et al. in 1988 [4]. The signals for discrete symmetries vi-
olation 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 non-vanishing value of one of forbidden correlations (e.g. $\vec{S} \cdot \vec{k}_1 \times \vec{k}_2$ for $CPT$ symmetry).

The measured observable is the asymmetry:

$$A = \frac{N_+ - N_-}{N_+ + N_-},$$  \hspace{1cm} (1)

where $N_+$ and $N_-$ denotes 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 equations:

$$A = C_{CP} \cdot S^{CP},$$  \hspace{1cm} (2)

$$A = C_{CPT} \cdot S^{CPT},$$  \hspace{1cm} (3)

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

3. Experimental verification

3.1. $CP$ symmetry

The most recent measurement was presented at 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 oPs decay were registered by LYSO crystals. The measured value of $CP$ violating parameter is equal to [6]:

$$C_{CP} = 0.0013 \pm 0.0012_{\text{stat}} \pm 0.0006_{\text{syst}}.$$  \hspace{1cm} (4)

Precision of obtained result is limited by available statistics, which cannot be increased by higher intensities of radioactive sources due to pile-ups in detector system [6].
3.2. \( CPT \) symmetry

The \( CPT \) violation coefficient was measured by Vetter and Freedman using the Gammasphere detector \cite{7} - a \cite{pic} spectrometer for nuclear structure research built by 110 high-purity germanium detectors. During the experiment the \( ^{68}\text{Ge} \) and \( ^{22}\text{Na} \) positron sources were used, with quite low intensities 0.04MBq 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 \cite{pic}ortho-positronium decays allows to determine the following \( CPT \) violation coefficient \cite{7}:

\[
C_{CPT} = 0.0071 \pm 0.0062. \tag{5}
\]

Obtained result is the most precise measurement till now.

4. Prospects for J-PET

Jagiellonian Positron Emission Tomograph (J-PET) is a detector based on plastic scintillators characterized by shorter signals (about 5ns) than commonly used crystal scintillators (e.g. 50 ns for GSO crystal) \cite{8, 9}. This allows to use high intensity sources and fast digital electronics readout \cite{10, 11, 12}. Compton scattering spectrum instead of photopeak can be used by applying a dedicated analysis \cite{13, 14, 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 orthopositronium in different materials, momentum distributions due to quantum electrodynamic (QED) effects as well as efficiency for the gamma quanta detection. Detailed description of these effects can be found e.g. in \cite{16, 17, 18}.

Main source of background contains events from direct annihilation or para-positronium decay where one of gamma scattered and was registered by the detector. However, those events can be rejected by requiring small time differences between registration of gamma quanta, because scattered events need
Figure 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 $\alpha$-Ps $\rightarrow 3\gamma$ (region 1) and two kinds of background events (regions 2 and 3 from $2\gamma$ events with the secondary scattering in the detector) is indicated.

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 $\theta_{23}$ vs $\theta_{12}$ correlation plot (Figure 1). For selected events, a novel reconstruction algorithm (analogous to the one described in Ref. [19, 20]) allows to obtain the time and spatial coordinates of the orthopositronium decay point by using information about time of interaction of gamma quanta in the detector [19]. 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 detector should allow for a significant improvement in sensitivity for $\mathcal{C}\mathcal{P}$ and $\mathcal{C}\mathcal{T}$ tests with respect to the best previous experiments [6, 7]. The appraisal is based on preliminary simulations which will be described in details in the forthcoming publications. The improvement is expected mainly because of about two orders of magnitude larger statistics, which
can be achieved due to the possibility of longer runs (within next three years in total about one year of data taking is planned) and due to the usage of the higher activity of positron source (10 MBq at J-PET vs. 1 MBq at [6] or 0.04 MBq at [7]). The rate limitations of previous experiments are overcome by J-PET detector due to its much higher granularity and about one to two orders of magnitude shorter duration of signals (plastic scintillators at J-PET [8, 9] vs. LYSO [6] or HPGe/BGO [7]) leading to the significant reduction of pile-ups. In addition, it is also important to stress that the J-PET detector is characterized by about 3 times higher angular resolution and most importantly that the J-PET time resolution (∼0.1ns) [8, 9] is improved by about a factor of ten with respect to experiment [6], and by about a factor of fifty with respect to the Gammasphere detector [7].

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References

[1] J. H. Christenson, J. W. Cronin, V. L. Fitch and R. Turlay, Phys. Rev. Lett. 13 (1964) 138.

[2] B. Aubert et al. [BaBar Collaboration], Phys. Rev. Lett. 86 (2001) 2515 [hep-ex/0102030].

[3] A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. 5 (1967) 32 [JETP Lett. 5 (1967) 24] [Sov. Phys. Usp. 34 (1991) 392] [Usp. Fiz. Nauk 161 (1991) 61].
[4] W. Bernreuther, U. Low, J. P. Ma and O. Nachtmann, Z. Phys. C 41 (1988) 143.

[5] M. D. Harpen, Med. Phys. 31 (2004) 57.

[6] T. Yamazaki, T. Namba, S. Asai and T. Kobayashi, Phys. Rev. Lett. 104 (2010) 083401 [arXiv:0912.0843 [hep-ex]].

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

[8] P. Moskal et al., Nucl. Instrum. Meth. A 775 (2015) 54 [arXiv:1412.6963 [physics.ins-det]].

[9] P. Moskal et al., Nucl. Instrum. Meth. A 764 (2014) 317 [arXiv:1407.395 [physics.ins-det]].

[10] G. Korcyl et al., Bio-Algorithms and Med-Systems 10(1) (2014) 37

[11] M. Pałka M. et al. Bio-Algorithms and Med-Systems 10(1), 41

[12] W. Krzemien et al., Acta Phys. Polon. A 127 (2015) 1491 [arXiv:1503.00465 [physics.ins-det]].

[13] L. Raczyński et al., Nucl. Instrum. Meth. A 764 (2014) 186 [arXiv:1407.8293 [physics.ins-det]].

[14] L. Raczyński et al., Nucl. Instrum. Meth. A 786 (2015) 105 [arXiv:1503.05188 [physics.ins-det]].

[15] P. Moskal et al., Acta Phys. Polon. A 127 (2015) 1495 [arXiv:1502.07886 [physics.ins-det]].

[16] P. Kowalski et al., Acta Phys. Polon. A 127 (2015) 1505 [arXiv:1502.04532 [physics.ins-det]].

[17] J. Cal-González et al., Phys. Med. Biol. 58 5127

[18] V. B. Berestetskii, E. M. Lifshitz and L. P. Pitaevskii, Relativistic Quantum Theory, Headington Hill Hall, Oxford. Pergamon Press, 1971
[19] A. Gajos, Diploma Thesis (2013), Jagiellonian University, Kraków, Poland

[20] A. Gajos [KLOE-2 Collaboration], Acta Phys. Polon. B 46 (2015) 1, 13 [arXiv:1501.04801 [hep-ex]].

[21] A. Gajos Presentation at the Jagiellonian Symposium, Retrieved September 27, 2015, from http://koza.if.uj.edu.pl/jagiellonian-symposium-2015/file/talks/s3_gajos.pdf Acta Phys. Pol. B (in preparation)