Test for Non-Relativistic QED in decays of positronium atoms

Sushil Sharma[1,2,3,*], *Kamil* Dulski[1,2,3,**], and *Pawel* Moskal[1,2,3]
on behalf of the J-PET collaboration

[1]Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University, Kraków, Poland
[2]Total-Body Jagiellonian-PET Laboratory, Jagiellonian University, Kraków, Poland
[3]Center for Theranostics, Jagiellonian University, Kraków, Poland

Abstract. Positronium (Ps) is a bound state of electron and positron governed by electromagnetic interactions. Precise measurement of its decay rate is an important observational parameter to test theoretical predictions derived from Non-Relativistic Quantum Electrodynamics (NRQED). In this work, we present a new method for measuring the decay rate of Ps atoms, which has the potential to improve the precision and thus the description of the behavior of particles in bound states and to provide insight into the non-relativistic regime of QED.

1 Introduction

The study of a bound system of two particles is the most appropriate tool to understand the nature of forces. In the high energy regime, quantum chromodynamics (QCD) is commonly used to understand the forces between quarks carrying a color charge [1]. Moreover, the bound system of heavy quarks (charm - **c**, bottom - **b**) and their anti-quarks ($\overline{c}$, $\overline{b}$), forming a family of heavy mesons called quarkonium (charmonium $(c,\overline{c})$, bottomonium $(b,\overline{b})$, is a solid basis for the study of Non-Relativistic QCD (NRQCD) [2]. In the low-energy regime, there is a structural analogus to the bound state of the quarkonium and to the simplest two-body system consisting only of leptonic objects, the positronium atom (Ps). It consists of an electron (e^-) bound to its antiparticle positron (e^+), describes the interactions of electrically charged particles, and is a sensitive probe of quantum electrodynamics (QED). Prior to annihilation, e^+ and e^- can also form in one of two states, depending on the total spin number (S) - para-positronium (p-Ps, S=0) and ortho-positronium (o-Ps, S=1). The analogy between positronium and quarkonium can be extended to other phenomena, such as the energy levels and decay rates of Ps atoms, which can be accurately calculated using the formalism of Non-Relativistic QED (NRQED) [3, 4]. However, the best experimental estimate of the o-Ps decay rate [5] reported by producing o-Ps in SiO_2 powder and using YEP (yttrium-aluminium perovskite) is still two orders of magnitude less precise than the theoretically predicted values [6]. In this work, we present a method for estimating the o-Ps decay rate using XAD4 as the medium for o-Ps production and employing the Jagiellonian Positron Emission Tomograph (J-PET), which is based on plastic scintillators and offers advantages over YEP in terms of excellent time performance and with no pile-up feature allows the use of sources with higher activities (up to 5 MBq).

*e-mail: sushil.sharma@uj.edu.pl
**e-mail: k.dulski@uj.edu.pl

2 Jageillonian Positron Emission Tomograph : J-PET

J-PET is a plastic scintillator-based multiphoton detector [7]. The current study is carried out with 3-layer prototype consisting of 192 detection modules arranged in 3 concentric layers [8]. Each detector module consists of a plastic scintillator of dimension 50x2.5x0.7 cm^3, connected to vacuum tube photomultipliers at both axial ends. Data is measured using FPGA-based acquisition in triggerless mode [9]. To take advantage of the excellent fast timing properties of plastic scintillators (rise time 0.5 ns, fall time $\approx$ 1.8 ns), the time above threshold (TOT) is used as the criterion for the energy deposition [10]. One of the main criteria for

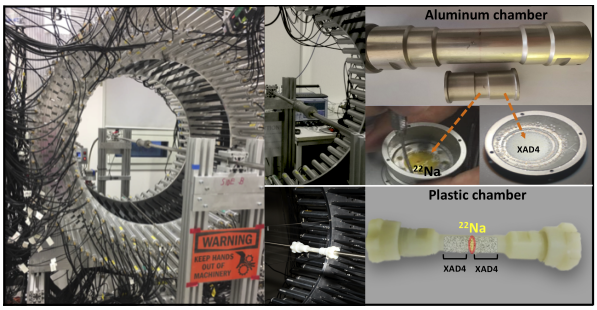

Figure 1. (a) A picture of the experimental setup with the source chamber aligned in the center of the geometry of the 3-layer prototype of J-PET. This study is performed with two different source chambers. The first chamber is made of aluminum, while the second chamber is made of polyamide (PA6) [11]. To increase the probability of Ps atom formation, a ^{22}Na source surrounded by XAD4 material was placed in the center of the chambers in both experiments.

distinguishing the decay channels of Ps atoms is based on the study of the angular correlation of annihilation photons [12]. J-PET provides an angular resolution of 1° [13], which makes it favourable to study the decays of Ps by simultaneously registering several photons that follow a different angular correlation depending on their origin. Detailed information about the electronics and the signal readout chain can be found in article [9]. The measured data is analysed using dedicated framework developed by the collaboration [14].

3 Measuring the lifetime of Ps atoms to estimate the o-Ps decay rate

In this paper, we report the method for estimating the decay rate by measuring the lifetime of o-Ps atoms with J-PET[15, 16]. The study is based on the production of o-Ps atoms using a β^+ emitter source surrounded by porous material characterised mainly by different pore structures and densities, which increase the probability of formation and trapping of o-Ps in the pores (interatomic voids with sizes ranging from nanometers to micrometers). It was found that the thermalization process of o-Ps in porous material is slower than its lifetime. During the thermalization, the lifetime of o-Ps may shorten due to their interaction with atomic electrons from the environment, annihilating them into 2 photons triggered by the pick-off process, so the decay rate of o-Ps in a material can be expressed as follows [17]:

$$\lambda_{o-Ps}^{medium} = \lambda_{o-Ps} + \lambda_{pick-off}(t), \tag{1}$$

where λ_{o-Ps}^{medium} is the o-Ps decay rate in the medium, ($\lambda_{pick-off}(t)$) is the decay rate in vacuum, and ($\lambda_{pick-off}(t)$) is the time-dependent contribution of the pick-off annihilations. To compare the value of the o-Ps decay rate predicted in NRQED theory with the experimentally determined value, the contribution of the pick-off process must be estimated. In previous

studies [5], two decay channels were investigated in which the energy spectra of photons originating from the decays of o-Ps into two (2G) or three annihilation photons (3G) were measured with inorganic or semiconductor-based detectors. To estimate the actual contribution of the pick-off in experimentally measured o-Ps→3γ, Monte Carlo simulations were performed in which the same event was generated without considering material effects. Since the time information is also recorded, the ratio $\lambda_{pick-off}(t)/\lambda_{o-Ps}$ can be estimated as a function of time, allowing precise determination of the o-Ps decay rate in vacuum [5, 17].
Here we report about a new approach that was developed based directly on the measurement of the lifetime spectra of o-Ps atoms. For this purpose, two different types of events have been studied. The first type of events allows the measurement of the lifetime spectrum of o-Ps when it decays into three (3G, see Fig. 2(a)), while the second type of events measures the lifetime spectrum when it decays into two (2G, see Fig. 2(b)). The advantage of the ^{22}Na source is that it emits the characteristic 1275 keV gamma (prompt photon) in addition to the emission of e^+. In the context of J-PET, the registration of the prompt gamma (dashed-magenta line in Fig. 2(a,b)) is used as a trigger for the formation, while the registration of the annihilation photons indicates the decay of the o-Ps atoms. Finally, the lifetime is defined as the average registration time of the annihilation photons minus the registration time of the prompt photon. The lifetime is estimated event by event for both events simultaneously. The

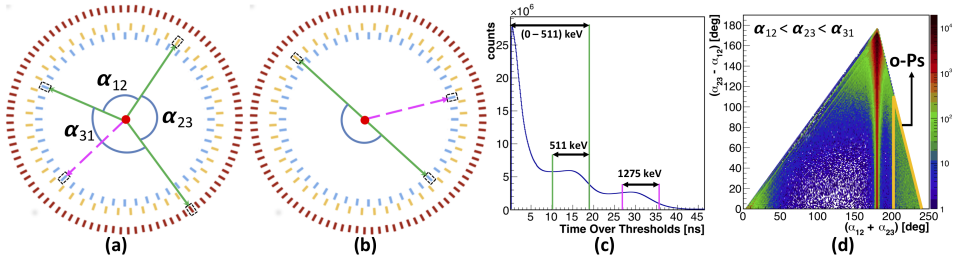

Figure 2. (a) Shows the definition of the events analysed to measure the lifetime of o-Ps when decaying into 3 photons and (b) when decaying into 2 photons. The annihilation photons are shown by green lines, while the prompt gamma is shown in magenta. The angle between the annihilation photons is represented by α_{ij}. (c) selection criteria based on the TOT values for prompt gamma (1275 keV), annihilation photons from decays in 3 (energy of photons varies between 0-511 keV) and from decays in 2 (energy of photons is 511 keV each). (d) shows the sum of the two smallest angles versus their difference, as shown in (a), a selection criterion for marking events in the decay of o-Ps in 3 (represented by the area marked with yellow lines), while for the selection of decays in 2, the range around the sum of the two smallest angles is between 178°-182°.

preliminary selection of the prompt and annihilation photons is based on the measured TOT values. Fig. 2(c) shows the typical TOT spectra obtained with the ^{22}Na source. Since Compton scattering is the dominant process in the interaction of photons with plastic scintillators, the maximum measured TOT values for 511 keV (from e^+e^- annihilations in 2) and 1275 keV (prompt photon) are visible as bumps around 16 ns and 30 ns, maximum energy deposits corresponding to Compton edges. The enhancement at lower TOT values is due to the contribution of annihilation photons originating from o-Ps→3G (the energies of the individual photons can vary between 0-511 keV), as well as some contribution from scattered photons. In Fig 2(c), three regions for selecting prompt photon (magenta) and annihilation photons (green lines) are shown. By applying cuts to individual hits whose TOT values lie between the selected region, annihilation and prompt photons can be marked in the respective events. Later, the events can be further cleaned based on the criterion of angular correlation between

annihilation photons. In the case of o-Ps→3G, the sum of the two smallest angles should be larger than 180° (for purer selection, more than 200° can be chosen), as shown by the yellow lines in Fig. 2(d). For events with hits by 511 keV photons, the range for the two smallest angles ($\alpha_{12}+\alpha_{23}$) is chosen between 178°-182°. To measure the decay rate of o-Ps in vacuum, the lifetime of o-Ps decaying into 2G and 3G was measured. Geant4 simulations generating both types of events were also performed, including detector geometry, physics models, and source chamber specifications. To estimate the contribution of the pick-off (t), the lifetime spectra of the 2G/3G ratio of the simulated (without assuming the pick-off process) were compared with the experimentally obtained spectra. Finally, the decay rate was determined by fitting the lifetime spectra (2G) as a function of time with an exponential model corrected for the contribution of the pick-off.

4 Summary and conclusion

We have presented a new method for precise determination of the o-Ps decay rate using the J-PET detector. The approach is based on measuring the lifetime spectra of o-Ps atoms decaying into 3G (in vacuum) and into 2G (due to pick-off process). The preliminary results are promising and show that the new method has the potential to improve the accuracy of the decay rate measurement by several factors and to be a good test for NRQED. We will report on the detailed analysis of the data elsewhere.

5 Acknowledgement

The authors acknowledge the support 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, OPUS no. 2019/35/B/ST2/03562, Miniatura 6 no.2022/06/X/ST2/01444, 2021/41/N/ST2/03950, the Ministry of Education and Science through grant no. SPUB/SP/490528/2021, 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] M. Kramer, H. Pagels, Phys. Rep. **36**, 137-276 (1978)
[2] W. Marciano, Prog. in Part. and Nucl. Phys. **47**, 141-201 (2001)
[3] W.E. Caswell and G.P. Lepage, Phys. Letters **167B**, 437-442 (1985)
[4] S.D. Bass, S. Mariazzi, P. Moskal and E. Stepien, Rev. Mod. Phys. **95**, 021002 (2023)
[5] Y. Kataoka, S. Asai, T. Kobayashi, Phys. Lett. B **671**, 219-223 (2009)
[6] G.S. Adkins, Ann. Phys. (New York) **146**, 78-128 (1983)
[7] P. Moskal et al., Acta Phys. Pol. B **47**, 509-535 (2016)
[8] S. Niedźwiecki et al., Acta Phys. Pol. B **48**, 1567-1576 (2017)
[9] G. Korcyl et al., IEEE Trans. Med. Imaging **37**, 2526-2535 (2018)
[10] S. Sharma et al., EJNMMI Phys. **7**, 1-15 (2020)
[11] M. Gorgol et al., Acta Phys. Pol. B **51**, 293-300 (2020)
[12] P. Moskal et al., Nat. commun. **12**, 5658 (2021)
[13] P. Moskal et al., Eur. Phys. J. C **78**, 1-9 (2018)
[14] W. Krzemień et al., SoftwareX **11**, 100487 (2020)
[15] K. Dulski et al., Nucl. Instr. Meth. A **1008**, 165452 (2021)
[16] P. Moskal et al. Science adv. **7**, eabh4394 (2021)
[17] S. Asai, S. Orito, N. Shinohara, Phys. Lett. B **357**, 475-480 (1995)