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Development of a PbWO₄ Detector for Single-Shot Positron Annihilation Lifetime Spectroscopy at the GBAR Experiment

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We have developed a PbWO₄ (PWO) detector with a large dynamic range to measure the intensity of a positron beam and the absolute density of the ortho-positronium (o-Ps) cloud it creates. A simulation study shows that a setup based on such detectors may be used to determine the angular distribution of the emission and reflection of o-Ps to reduce part of the uncertainties of the measurement. These will allow to improve the precision in the measurement of the cross-section for the (anti)hydrogen formation by (anti)proton–positronium charge exchange and to optimize the yield of antihydrogen ion which is an essential parameter in the GBAR experiment.

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1. Introduction

The GBAR (gravitational behaviour of antihydrogen at rest) experiment [1, 2] aims to measure the acceleration of antihydrogen atoms in the terrestrial gravitational field. A first milestone of the experiment, is to produce (anti)hydrogen atoms and (anti)hydrogen ions (antihydrogen ion is formed by an antiproton and two positrons) with keV or less kinetic energy. First, an antihydrogen atom is produced in the collision between an antiproton and an ortho-positronium (o-Ps). Then, an antihydrogen ion is produced in the collision between the antihydrogen atom and a second o-Ps. These two collisions occur in a dense o-Ps cloud (up to 10^4 Ps/cm³) created inside a small cavity (typically $1 \times 1 \times 10$ mm³). These processes are equivalent to the production of hydrogen atoms and ions by proton-positronium and hydrogen-positronium charge exchange.

A PWO detector has been developed to measure the density of o-Ps in the target region using the method of single shot positron annihilation lifetime spectroscopy (SSPALS) [3]. PWO is a dense crystal scintillator that can absorb all the energy of a γ ray from the decay of o-Ps without the Compton edge made by the γ ray escaping with partial energy loss in the crystal. The assembly of a PWO crystal and a photomultiplier tube (PMT) generates only a few photo-electrons per γ ray. This allows a large dynamic range by changing the PMT gain. The PWO detector can measure the quantity of o-Ps and the intensity of the positron beam at the same time due to its short decay time. To understand the systematic uncertainties of the measurement, a simulation based on Geant4 with the Penelope library (Geant v4.10.03) [4, 5] and a positronium library [6] has been performed. Experimental methods to reduce the systematic uncertainties have been developed to achieve less uncertainty than in a previous cross-section measurement of the hydrogen atom production [7].

In this report, the development of the PWO detector system is described.

2. Experimental details

A positron beam is generated by an electron linac. The particles are cooled and accumulated in the Penning-Malmberg traps [8]. After extraction from the trap, the positron pulse is accelerated by a switched drift tube and focused by the Einzel lenses to hit a positron/positronium converter made of mesoporous silica [9, 10] as shown in the schematic view in Fig. 1. The target region of the collision between the o-Ps cloud and the antiproton beam is located at the center of the reaction chamber. For the first tests, performed at relatively low beam intensity compared with the required intensity for antihydrogen ion production, a flat positronium converter with size 2×2 cm² is used. An assembly of a microchannel plate (MCP) and a phosphor screen of 1 cm diameter is used for the measurement of the positron beam profile at the target position.

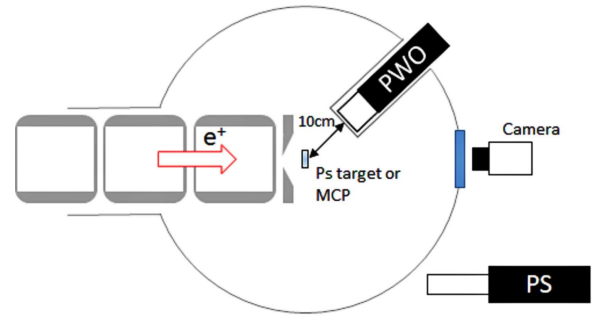


Fig. 1. Schematic view of the target area. The tubes with gray color show the Einzel lenses for the positron beam focusing. The circular line outlines the reaction chamber. The positronium converter and the MCP assembly are translated by a linear drive to place them at the center of the chamber. A camera is placed downstream of the MCP assembly to image the positron beam profile. The PWO detector and a plastic scintillator (PS) are installed at the backside of the target region for the γ ray measurement.

The PWO detector measures the γ rays from the annihilation of positrons and the decay of o-Ps at the same time. The PWO detector is placed 10 cm behind the positronium converter. It is assembled from a PWO crystal of $4 \times 4 \times 3.8$ cm³ size segmented to 4 pieces and a PMT (H7195, Hamamatsu). A plastic scintillator is installed at the backside of the reaction chamber as a reference detector.

3. Beam test and Compton background measurement

The raw signal from the PWO detector is shown in Fig. 2 when the positron beam hits the positronium converter (solid line) or the MCP (diagonal filled). The FWHM of the positron annihilation signal is less than 20 ns which is sharp enough to distinguish it from the o-Ps decay signal that appears as an exponential decay curve with 142 ns lifetime. The two lines show a clear indication of o-Ps production and decay. The small peak near $0.8 \mu\text{s}$ is expected due to the after pulse from PMT [3]. The switching noise from the switched drift tube appears near $0.1 \mu\text{s}$.

The simulation shows that the most important uncertainty comes from the Compton scattered γ rays. A Compton background fraction about 16–21% of the total signal is expected when the distance between the positronium converter and the PWO detector is 15–25 cm. In the SSPALS method, the deposited energy of single γ rays is not measured. Thus, the Compton background must be subtracted properly from the measured intensity. The simulation shows that the measured beam intensity with the current setup is over-estimated by up to 21%. To understand the Compton background, a tungsten block of $4 \times 4 \times 4$ cm³ is installed in front of the PWO detector at a distance of 11 cm from the

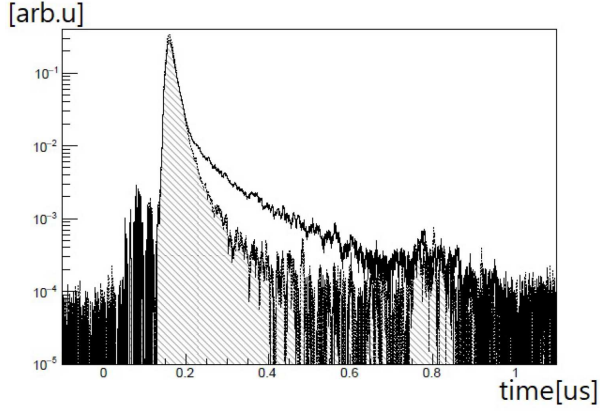


Fig. 2. The raw signal distribution from the PWO detector (averaged data sample). The diagonal filled histogram shows the signal from the PWO detector when the e^+ beam hits the MCP and the solid line histogram shows the signal when the e^+ beam hits the positronium converter.

positronium converter. The γ rays originating from the annihilation of positrons and the decay of o-Ps at the target position cannot reach the PWO detector other than by the Compton scattering on obstacles such as the chamber itself which is made of stainless-steel. The measured γ intensity is reduced by 21% when the tungsten block is mounted and the distances between the positronium converter and the PWO detector is 20 and 25 cm, as compared in the absence of the tungsten block, while the simulation gives 19% for the same distances.

4. Detection system development

When the cavity shaped target is used instead of a flat target, another source of uncertainty comes from the amount of o-Ps that decays outside the target cavity. The present simulation is based on a $20 \times 2 \times 2 \text{ mm}^3$ inner hole size. It has a $10 \times 2 \text{ mm}^2$ entrance window made of 30 nm thick Si_3N_4 . The top and bottom walls are made of SiO_2 . The wall opposite the entrance window is coated with a mesoporous silica film [9, 10]. The two other $2 \times 2 \text{ mm}^2$ sides are free, allowing o-Ps to escape. The o-Ps is generated inside the target cavity at about 50 meV kinetic energy [9] and moves during its lifetime with several reflections at the cavity surface. The angular spread of o-Ps emission [9] and reflection is not very well known. The angle with regard to the normal to the emission/reflection plane is generated with an isotropic or cosine distribution, resulting in different amounts of o-Ps escaping.

We use a cross-shaped assembly of the four small PWO detectors to determine the amount of escaped o-Ps as shown in Fig. 3. The four small PWO detectors are mounted along the four sides of a tungsten block ($2 \times 2 \times 4 \text{ cm}^3$). In front of the detector assembly, another tungsten block of $2 \times 4 \times 4 \text{ cm}^3$ is attached in such

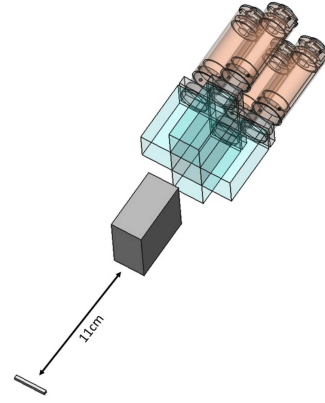


Fig. 3. The drawing of the cross-shaped detector assembly is shown in the top of the figure. The four PWO crystals are mounted along the four sides of a tungsten block. Each PWO crystal is assembled with cylindrical PMT. The target cavity drawn as a thin box is at the bottom of figure. The tungsten block is installed between the detector assembly and the target cavity.

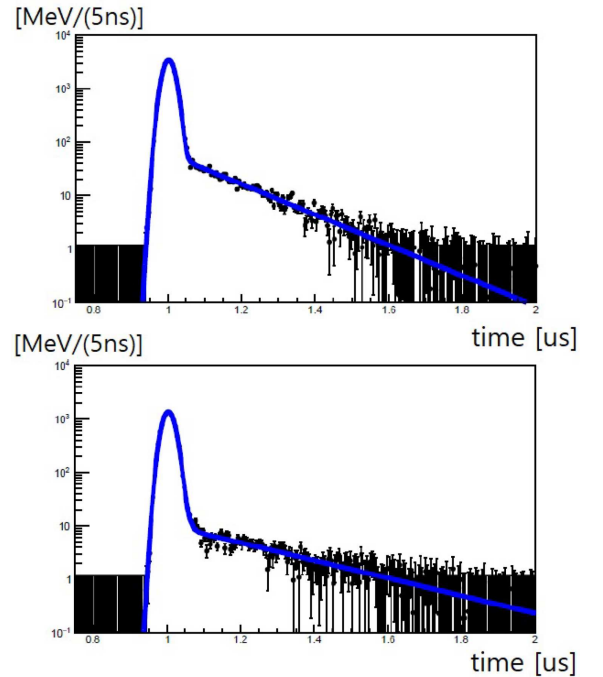


Fig. 4. The simulated raw signal distribution of the detector assembly. The positron pulse is simulated by a Gaussian distribution and the angular distribution at emission or reflection of o-Ps is isotropic. The raw signal distributions at the left and right PWO detectors (top part) and the top and bottom PWO detectors (bottom part) are shown. The solid line shows the fitted PDF.

a way that the detectors at the top and bottom have higher acceptance to γ rays originating from a decay position outside of the cavity. Detectors at the left and right sides have less dependent sensitivity on the decay position.

Figure 4 shows the time distributions of the signal in the simulation for the detectors at the top/bottom sides of the tungsten block (top part) and at the left/right sides (bottom part). This time distribution is fitted using a likelihood method with a Gaussian probability density function (PDF) for positron annihilation and a Gaussian convoluted with an exponential decay PDF for o-Ps decay. The fitted lifetime is 152 ± 2 ns for the left and right detectors and 263 ± 12 ns for the top and bottom side detectors when the angular spread of both emission and reflection is the isotropic distribution. For the cosine distribution of both emission and reflection, the fitted lifetime is 150 ± 2 ns for the left and right side detectors and 195 ± 10 ns for the top and bottom detectors. Thus, for both angular distribution models, the observed lifetime is different for the two detector positions. We can then use the relation between the two apparent lifetime values to reduce the uncertainty of the positronium density measurement.

5. Conclusion

A PWO detector has been developed and tested to measure the positron beam intensity and the o-Ps density using SSPALS method for the GBAR experiment. We optimized the design in order to measure the positronium density in a cavity. We confirmed that the system for the positronium production and measurement operates properly. An accurate knowledge of the o-Ps density will allow one to extract a precise measurement of the anti-hydrogen and antihydrogen ion formation by antiproton-positronium, antihydrogen-positronium charge exchange cross-sections.

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