B. Kim,[1] M. Charlton,[2] J. Choi,[1] M. Chung,[3] P. Clad,[4] P. Comini,[5] P. Crivelli,[6] P-P. Crpin,[4] O. Dalkarov,[7] P. Debu,[5] L. Dodd,[2] A. Douillet,[4] S. Guellati,[4] J. Heinrich,[4] P-A. Hervieux,[8] L. Hilico,[4] A. Husson,[9] P. Indelicato,[4] G. Janka,[6] S. Jonsell,[10] J-P. Karr,[4] K. Khabarova,[7] E-S. Kim,[11] S. Kim,[1] Y. Ko,[12] N. Kolachevski,[7] T. Kosinsky,[13] N. Kuroda,[14] B. Latacz,[5] H. Lee,[1] J. Lee,[12] A. Leite,[5] E. Lim,[11] L. Liszkay,[5] T. Louvradoux,[4] D. Lunney,[9] K. Lvque,[8] G. Manfredi,[8] B. Mansouli,[5] M. Matusiak,[13] G. Mornacchi,[15] V.V. Nesvizhevsky,[16] F. Nez,[4] S. Niang,[5] R. Nishi,[14] S. Nourbaksh,[15] K. Park,[1] P. Prez,[5] B. Radics,[6] C. Regenfus ,[6] S. Reynaud,[4] J-Y. Rouss,[5] A. Rubbia,[6] J. Rzadkiewicz,[13] Y. Sacquin,[5] F. Schmidt-Kaler,[17] N. Sillitoe,[4] M. Staszczak,[13] B. Vallage,[5] D. van der Werf,[2] A. Voronin,[7] A. Welker,[15] S. Wolf,[17] D. Won,[1] S. Wronka,[13] Y. Yamazaki,[18] K-H. Yoo[3]

(GBAR Collaboration)

[1] *Department of Physics and Astronomy, Seoul National University, 599 Gwanak-Ro, Gwanak-gu, Seoul 08826, Korea*

[2] *Department of Physics, Swansea University, Swansea SA2 8PP, United Kingdom*

[3] *Department of Physics, Ulsan National Institute of Science and Technology (UNIST), 50, UNIST-gil, Ulsan 44919, Republic of Korea*

[4] *Laboratoire Kastler Brossel, Universit Pierre et Marie Curie, 4 pl. Jussieu, F-75252 Paris Cedex 05, France*

[5] *IRFU, CEA, Saclay, F-91191 Gif-sur-Yvette Cedex, France*

[6] *IPP, ETHZ, CH-8093 Zrich, Switzerland*

[7] *P. N. Lebedev Physical Institute, 53 Leninsky Prospect, 117991 Moscow, Russia*

[8] *Universit de Strasbourg, CNRS, Institut de Physique et Chimie des Matriaux de Strasbourg, UMR 7504, F-67000 Strasbourg, France*

[9] *CSNSM, Btiments 104 et 108, F-91405 Orsay Campus, France*

[10] *Department of Physics, Stockholm University, SE-10691 Stockholm, Sweden*

[11] *Department of Accelerator Science, Korea University Sejong Campus, Sejong-ro 2511, 0019 Sejong, Republic of Korea*

[12] *Center for Underground Physics, Institute for Basic Science, 70 Yuseong-daero 1689-gil, Yuseong-gu, Daejeon 34047, Korea*

[13] *Narodowe Centrum Badan Jadrowych, ul. Andrzeja Sotana 7, 05-400 Otwock, Swierk, Poland*

[14] *Institute of Physics, University of Tokyo, 3-8-1 Komaba, Meguro, Tokyo 153-8902, Japan*

[15] *CERN, 1211 Geneva 23, Switzerland*

[16] *Institut Max von Laue - Paul Langevin (ILL), 71 avenue des Martyrs, Grenoble, France, F-38042*

[17] *QUANTUM, Institut fr Physik, Johannes Gutenberg Universitt, D-55128 Mainz, Germany*

[18] *Ulmer Fundamental Symmetries Laboratory, RIKEN, 2-1 Hirosawa, Wako, 351-0198, Saitama, Japan*

Development of a $PbWO_4$ detector for single-shot positron annihilation lifetime spectroscopy at the GBAR experiment

Abstract

To understand the antihydrogen ion production by the collision between antiproton beam and ortho-positronium (o-Ps), the measurement of the o-Ps density in the target area of the antihydrogen ion production is one of the important topic for the GBAR experiment. The $PbWO_4$ (PWO) detector which is possible to have large dynamic range of intensity measurement has been developed to measure the absolute density of o-Ps and the intensity of e^+ beam precisely with the uncertainty below 20% as the minimum requirement. Also, the simulation has been studied to understand the possible uncertainties of the measurement.

1. Introduction

The GBAR (Gravitational Behaviour of Antihydrogen at Rest) experiment [1] aims to measure the antimatter's gravitational acceleration in the terrestrial gravitational field. As the first milestone of the experiment, it is planed to produce antihydrogen ions with keV or less kinetic energy and to measure the cross section of the antihydrogen ion production from two steps of procedure. Firstly, antihydrogen atom is produced by the collision between antiproton and o-Ps and secondly, antihydrogen ion is produced by the collision between the antihydrogen atom and o-Ps. It is aimed to make these two collisions in one target region by enough density of o-Ps up to 10^{12}Ps/cm^3 inside the cavity shaped target (1×1×10 mm^3). So, the measurement of the density of o-Ps in the target area is one of the most important issue to understand the antihydrogen ion production for the GBAR experiment.

The PWO crystal has relatively dense scintillator which can absorb the full energy of the γ ray from the o-Ps decay without the compton edge. The assembly of the PWO crystal and the photomultiplier tube (PMT) generates only few photo-electron and this allows large dynamic range to measure from single γ ray to intense γ rays by changing the PMT gain. The PWO detector can measure the density of the o-Ps gas and the intensity of the e^+ beam at the same time from the single pulsed beam with faster decay time than the lifetime of o-Ps (142ns). With all the requirements, the PWO detector for the single shot positron annihilation lifetime spectroscopy (SSPALS) [3] has been developed. To understand the systematic unceratainties of the measurement, the simulation based on Geant4 library [5, 6] and positronium library [7] has been developed and the experimental methods to reduce the systematic uncertainties have been developed. In this report, the current status of the positronium production test and the development of the PWO detection system are described.

2. beam line detail and detector specification

The e^+ beam based on the electron linac is accumulated and trapped in the high field trap. After the exaction from the high field trap, the e^+ beam which is focused by the couple of Einzel lenses and tuned by correction coils hits the positron/positronium converter made by the mesoporous silica target [4] as shown in the schematic view in Fig. 1. The target area of the collision between o-Ps and antiproton beam is in the center of the reaction chamber. Currently, the positronium target (converter) with size 2×2 cm^2 is used for the test of the positronium production and the detection system and the microchannel plate (MCP) with the effective area of 1cm diameter is used for the measurement of the e^+ beam size at the target position. All the beam tuning and the beam test have been performed with relatively low beam intensity compared with the final intensity for the antihydrogen production. The beam is tuned with the size smaller than the MCP effective range.

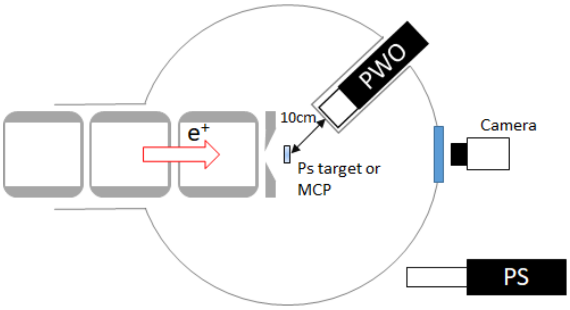

Figure 1: The schematic view of the target area with the Einzel lenses for the e$^+$ beam tuning and the detection system as the PWO detector and the plastic scintillator(PS) for the γ ray measurement and MCP with the camera for the positron beam shape measurement. The tubes with gray color show the Einzel lenses and the circular line shows the reaction chamber.

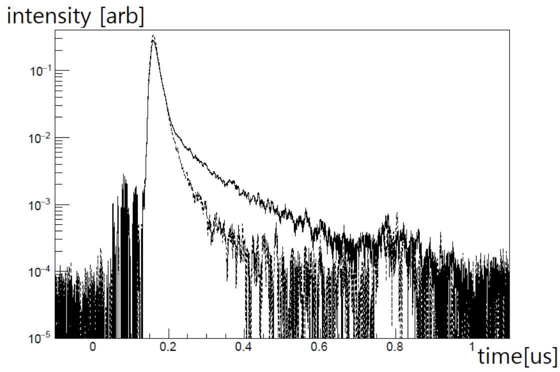

Figure 2: The raw signal distribution from the PWO detector (averaged data sample). The dashed line shows the detected signal from the PWO detector when the e$^+$ beam hits the MCP and the solid line shows the signal when the e$^+$ beam hits the positronium target (solid line).

With collision of the focused e$^+$ beam and the positronium target, the PWO detector measures the γ rays from the annihilation of e$^+$ and the decay of o-Ps at same time. The PWO detector is mounted at the flange which is concaved to the inside of the chamber at the backside of the target with minimum 10cm distance. The PWO detector is composed of assembly of 4 pieces of $PbWO_4$ crystals with 4×4×3.8 cm^3 (2×2×3.8 cm^3 per each crystal) size and a photomultiplier tube (H7195, Hamamatsu). The DAQ system is the oscilloscope (Waverunner 44Xi-A, Lecroy) and the data analysis is done by the offline anaysis after the data taking. One plastic scintillator is installed at the backside of the reaction chamber as a reference detector.

3. beam test and detection system developement

The raw signal from the PWO detector when the e$^+$ beam hits the MCP is shown in the Fig. 2 as dashed line with some switching noise near 0.1μs range. The FWHM of the signal is less than 20ns and the width is sharp enough to distinguish from the o-Ps curve based on the o-Ps life time. The solid line in the figure shows the raw signal distribution when the e$^+$ beam hits the positronium target and the two lines show clear difference by o-Ps production and decay. The small peak near the 0.8μs is expected as the after pulse from PMT [3].

The simulation based on Geant4 with penelope library (Geant v4.10.03) and positronium library [7] has been developed to estimate the possible uncertainties from the density measurement of o-Ps at the target region. The most important uncertainty is come from the compton scattering background from the simulation study. With including all the installed equipments in the simulation geometry not only the chamber itself but also the equipments for the e$^+$ beam and for the antiproton beam, the compton background about 16% $\sim$ 21% for total signal amount is expected at the distance between target and the PWO detector as 15cm to 25cm. For the SSPAL method which doesn't measure the deposit energy of the single γ ray, the measured intensity is the biased intensity if the compton background is not subtracted from the measured value. With respect of the simulation result, the measured beam intensity with the current setup gives the beam intensity as overestimated value up to 21%. To get the correct beam intensity with understanding of the compton background, the tunsten (W) block with 4×4×4cm^3 is installed in front of the PWO detector. By adding the W block between the target and the PWO detector, the γ rays can't reach to the PWO detector from the target. Only γ rays scattered at the other obstacles like reaction chamber by the compton scattering can reach to the PWO detector. The simulated compton scattering background amount can be checked by real measurement with the W block setup and the deviation between the simulation and the measurement can be the correction factor for the compton scattering fraction at the o-Ps density measurement. The fraction between the beam intensity with (dashed line) and without (solid line) W block is measured as 21% and the simulation shows the fraction as 19%.

By the comparision between measurement and simulation results, the simulation has small deviation with measured data about 3% for the total beam intensity.

The other source of the uncertainty from the o-Ps density measurement is come from the amount of o-Ps which is annihilated outside of the target cavity. The o-Ps is reflected in the surface of the target cavity and the reflected angle is not well studied parameter. The cosine angle distribution and isotropic angle distribution have been tested and the escaped amount is different depends on the distribution. To know the escaped amount of o-Ps, the assembly of 4 PWO detectors has been designed which has cross shape. The PWO detector is composed of 2x2x3.8cm^3 PWO crystal and small PMT and 4 detectors are mounted at each side of W block with size as 2x2x4cm^3. In front of the PWO detector assembly, W block with 2x4x4cm^3 is attached to make a different sensitivity for aniihilation point of the o-Ps.

By the blocking of γ ray from the center of target by W block, the PWO detector at the left and right side has more sensitivity to the γ rays from the decaying point at the escaped position although the PWO detectors at the top and bottom side has same sensitivity independent of the decaying position. The Fig. 3 shows the time distribution of signal in the simulation for the PWO detectors in the top and bottom side of the W block (top) and for the PWO detectors in the left and right side of the W block (bottom). The life distribution is different depends on the position of detector and the fitted life time is 152±2 ns for the left and right side and 263±12 ns for the top and bottom side when o-Ps is reflected by isotropic distribution. For the cosine distribution for the reflected angle, the fitted life time is 150±2 ns for the left and right side and 195±10 ns for the top and bottom side. For the both case of angle distribution, there's a deviation between the detector position and this will give us approach to reduce the uncertainty.

4. Conclusion

The PWO detector has been developed to measure the e$^+$ beam intensity and o-Ps detensity as SSPAL method for the GBAR experiment. Current, the e$^+$ beam tuning to the positronium target, positronium target test and detection system test has been performed. We confrimed that the system for the positronium production and measurement properly operates and has tested to improve the detection precision.

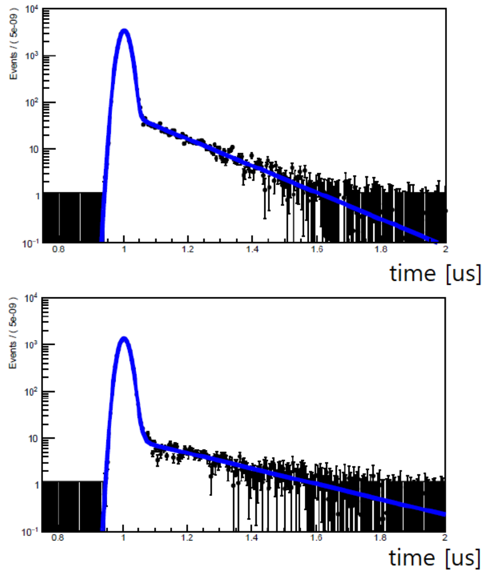

Figure 3: the detected signal by PWO detector with positronium target (solid line) and MCP (dashed line)

5. Acknowledgement

This work is supported by the Ministy of Education of the Republic of Korea and the National Research Foundation of Korea NRF-2016R1A6A3A11932936, NRF-2016R1A2B3008343 and French National Research Agency grant ANR-14-CE33-0008.

[1] P. Perez, *et al.*, Hyperfine interactions, 233, 21-27 (2015)
[2] J. P. Merrison,*et al.*, Phys.Rev.Lett. 78, 14 (1997)
[3] D.B. Cassidy, S.H.M. Deng, H.K.M. Tanaka, and A. P. Mills Jr., Appl.Phys.Lett. 88, 194105 (2006)
[4] P.Crivelli, *et al.*, Phys.Rev.A 81,052703 (2010)
[5] S. Agostinelli, *et al.*, Nuc. Inst. and Meth. A, 506,250-303 (2003)
[6] J. Allison *et al.*, IEEE Trans. Nucl. Sci, 53, 270-278 (2006)
[7] P. Crivelli *et al.*, JINST 5 08001 (2010)