First Laser Spectroscopic Study of the Positronium Negative Ion

The positronium negative ion, a bound state of two electrons and a positron, is one of the simplest three-body systems. Since this system is composed of leptonic particles with the same mass, it provides a good testing ground for the many-body problem in quantum mechanics and quantum electrodynamics. However, experiments have been hampered by difficulties in achieving adequate intensities and its short annihilation lifetime. In the present work, we performed the first laser spectroscopic study of Ps^-, where Ps^- ions were efficiently generated by a novel method using a Na-coated W surface. The shape resonance of the $^1P^o$ symmetry was observed in the photodetachment of Ps^-.

An electron can bind to its antiparticle, the positron, to form a hydrogen-like bound state called a positronium (Ps). Another electron can bind to a Ps atom to form the positronium negative ion (Ps^-). Its unique property, consisting of particles and an antiparticle with the same mass, provides a stringent testing ground for the many-body problem in quantum mechanics. Since the prediction of its existence in 1946, a wide variety of theoretical work on such aspects as energy level structure and annihilation properties has been reported [1]. Experimental verifications, however, have been hampered due to the extremely low intensity of the ion and its short annihilation lifetime (479 ps), and so only a few measurements of its lifetime have been made. In the last decade, an efficient method of generating Ps^- ions has been developed by injecting slow positrons into alkali-metal coated surfaces [2], offering a new path for research on this exotic ion. In the present work, we performed a laser spectroscopic study of the Ps^- ions employing the efficient Ps^- source in conjunction with a linac-based pulsed positron beam.

Ps^- ions were generated using a pulsed positron beam at the KEK IMSS Slow Positron Facility [3] synchronized with a nanosecond pulsed laser source, which provides sufficient photon flux density for the photodetachment of the short-lived Ps^-. The electron linac was operated in a short pulse mode with a repetition rate of 50 pps. The slow positron beam with a pulse width of 12 ns (FWHM) was magnetically guided into the experimental chamber with a transport energy of 4.2 keV. It was deflected by a magnetic field (deflection angle of 45 degrees) and then made incident onto a target after passing through two grids biased at 3400 V (**Fig. 1**). The target voltage was varied to control the acceleration voltage of the Ps^- ions.

The target was Na-coated W from which Ps^- ions are efficiently emitted (conversion efficiency of ~2%) [2]. The substrate was a polycrystalline W film with a thickness of 50 μm (purity 99.95%). In order to remove vacancy-type defects and clean the surface, it was annealed *in-situ* by resistive heating at a temperature of 1800 K for 30 min. After cooling down to room temperature, sub-monolayer Na was deposited using a commercial alkali-metal dispenser. The Ps^- ions emitted from the target were accelerated by a potential gap, W, between the target and the forward grid, and were photodetached by laser irradiation in a field-free region formed between the two grids. The light source was a tunable dye laser (dye solution; Coumarin460) pumped by the third harmonic wave of a Q-switched Nd:YAG laser with a repetition of 10 Hz. By using a type 1 BBO crystal, the output light was converted to the second harmonic with a wavelength range of 225–230 nm. In the photodetachment of Ps^-, *o*-Ps (S = 1) and *p*-Ps (S = 0) are formed. Although the short-lived *p*-Ps atoms immediately annihilate into photons after the formation, even for the excited states, the long-lived *o*-Ps atoms can fly a long distance and be detected by a micro-channel plate (MCP) detector placed at 0.88 m away from the target.

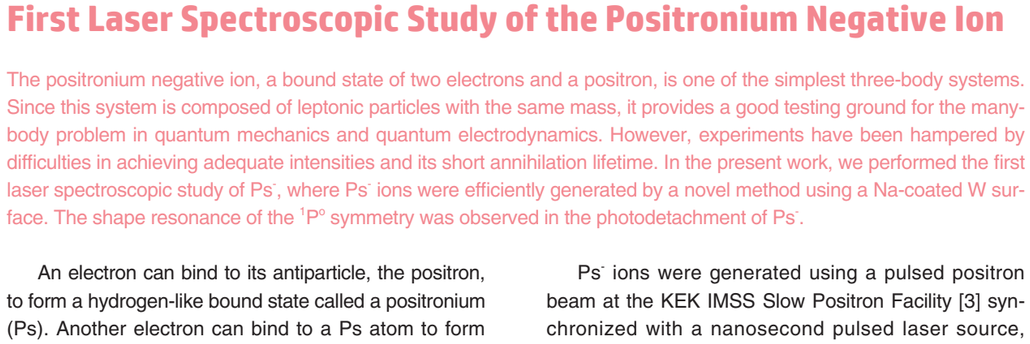

Figure 1: Schematic view of the experimental setup for the laser spectroscopy of positronium negative ions [4].

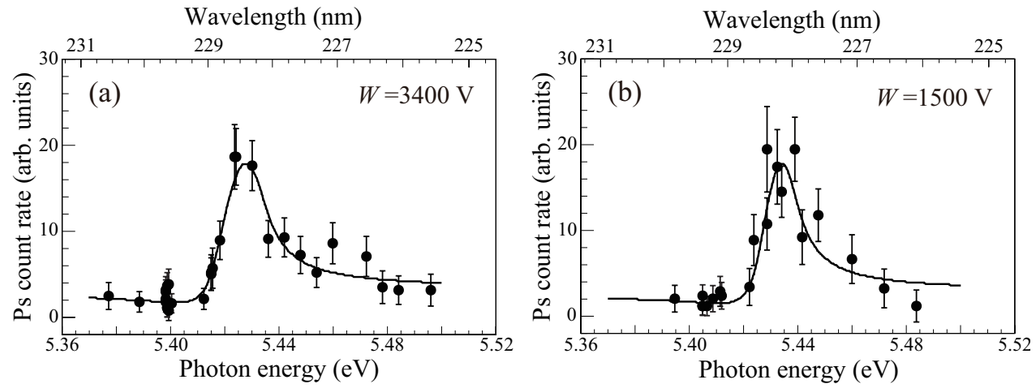

Figure 2: Resonance profiles in the photodetachment of Ps^- ions, measured at the acceleration voltages of 3400 V **(a)** and 1500 V **(b)**. The solid lines show the results fitted to the data using the Fano profile convoluted with the Doppler width due to the Ps^- velocity distribution [4].

Figure 2 shows the resonance profiles, which show the count rate of Ps atoms formed by photodetachment as a function of photon energy (wavelength), for the acceleration voltages W = 3400 V and W = 1500 V [4]. Peaks with asymmetric tails were clearly observed above the formation threshold of Ps (n = 2). The data were fitted using the Fano function convoluted with the Doppler width due to the Ps^- velocity distribution. A shift in the resonance position was observed in accordance with the acceleration voltages, indicating the longitudinal Doppler shift. The resonance position in the rest frame of the Ps^- ions was derived by the weighted arithmetic mean of each zero-velocity position. The resonance position and width are in good agreement with three-body calculations of the shape resonance in the $^1P^o$ symmetry.

With the combination of the two-photon adsorption technique, various resonances with narrow widths will be accessible for future research. Moreover, the present method enables the production of a mono-energetic tunable beam of excited-state Ps atoms, which can be used for novel research on collision dynamics with atoms, molecules and solids.

REFERENCES

[1] Y. Nagashima, *Phys. Rep.* **545**, 95 (2014) and references therein.
[2] H. Terabe, K. Michishio, T. Tachibana and Y. Nagashima, *New J. Phys.* **14**, 015003 (2012).
[3] K. Wada, T. Hyodo, T.Kosuge, Y. Saito, M. Ikeda, S. Ohsawa,T. Shidara, K. Michishio, T. Tachibana, H. Terabe, R. H. Suzuki, Y.Nagashima, Y. Fukaya, M. Maekawa, I. Mochizuki and A. Kawasuso, *J. Phys. Conf. Ser.* **443**, 012082 (2013).
[4] K. Michishio, T. Kanai, S. Kuma, T. Azuma, K. Wada, I. Mochizuki, T. Hyodo, A. Yagishita and Y. Nagashima, *Nat. Commun.* **7**, 11060 (2016).

BEAMLINE

SPF-B1

K. Michishio and Y. Nagashima (Tokyo Univ. of Science)