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Development of a High-brightness, Energy-tunable Positronium Beam for Surface Scattering Experiments

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We have developed an apparatus, which can output a high-quality, energy-tunable positronium (Ps) beam, for fundamental studies on Ps interactions with surfaces. The beam was produced through a two-step process, in which Ps negative ions were efficiently generated by the impact of slow positrons onto a Na-coated W thin-film and were then photodetached by an infrared laser beam. An experimental system for surface scattering experiments was also constructed and tested. The Ps beam was incident on a LiF (100) crystal surface in a grazing-angle geometry and the scattered components were projected onto a position sensitive detector. We show the current status of the Ps beam apparatus and some of the test results of the surface scattering experiment.

1. Introduction

Positronium (Ps) is a system composed of an electron and a positron, bound through Coulomb attraction. It can be formed when positrons strike through materials such as gases, powders and insulators. If slow positrons with an energy below a few keV are implanted onto metal surfaces, Ps atoms can also be formed on those surfaces and spontaneously emitted into vacuum. Once Ps is generated, its interactions with materials are of great interest in the research fields of atomic collision physics, material science and radiation chemistry. The thermalization process in SiO_2 powder and aerogel grains [1], and spin-exchange reaction with powder surfaces [2–4] and gas molecules [5] were investigated by positron annihilation spectroscopy. Using a low-energy beam of Ps atoms (1 eV–400 eV) formed via the charge-exchange reaction [6], scattering cross-sections for various gases have been measured and allowed us to clarify the dynamics of Ps-atom/molecule collisions in the gas phase [7]. Furthermore, a scattering experiment with a Ps beam incident on a LiF(100) surface was successfully achieved and specular reflection from the surface was observed [8]. According to Ref. [9], Ps reflection and diffraction from surfaces, which originates from the interference of elastically-scattered Ps atoms, can become a unique probe of the structure of ordered surfaces or adsorbed layers because of its neutrality, sensitivity to the outermost atomic layers and the absence of complex multiple scattering. However, in order to realize this type of experiment, a coherent (mono-energetic and collimated) beam is required. This is technically challenging owing to the neutrality and the short-lived nature of Ps.

In the last decade, we have studied the efficient generation of Ps negative ions, a bound state of two electrons and one positron, on alkali-metal coated W surfaces, upon slow positron impact [10]. With the development of this efficient source, we have succeeded in the observation of

Ps-photodetachment at an IR wavelength [11] and shape resonance in the UV region [12]. The subsequent generation of an energy-tunable Ps beam was also accomplished in the high energy domain (0.3 keV–2 keV) [13]. The Ps beam obtained in this fashion is available in a wide energy range, under ultra-high vacuum conditions and is applicable to the investigation of Ps-surface scattering.

In the present work, we have developed a new Ps beam apparatus, which provides a high-quality Ps beam. We show the current status of the apparatus and the test results of Ps scattering from a LiF(100) surface.

2. Experimental system

The experimental system will be described in detail elsewhere [14], but the conceptual design and the operating principle are briefly explained here. The apparatus was constructed at the Tokyo University of Science. It is composed of a slow positron generator, a two-stage buffer-gas trap [15], a Ps production system and a surface scattering system (Fig. 1(a)). The generator and trap are commercially available systems purchased from First Point Scientific Inc. Slow positrons are generated from a ^{22}Na radioactive source (0.37 GBq) combined with a solid Ne moderator. The buffer-gas trap consists mainly of a Penning trap, a combination of axially symmetric magnetic and electric fields, where some cooling gases (mixture of N_2 and CF_4) are introduced. The slow positrons introduced into the trap lose their kinetic energy via inelastic collisions with the cooling molecules and are accumulated at the bottom of the potential well formed by the electromagnetic field. They are then extracted from the exit of the trap as nano-second positron bursts (repetition rate 50 Hz, width ~10 ns), a temporal structure which is suitable for synchronization with a pulsed laser source (repetition rate 50 Hz, width 12 ns). Since the annihilation lifetime of the Ps negative ion is as short as 479 ps, a pulsed laser, which provides a sufficient photon flux density, is required for high effciency photodetachment (~60 %) [11]. In order to ensure better temporal matching between the laser beam and the generated Ps ions (see below), the temporal width of the positron burst is further compressed to about 2 ns using a potential buncher placed after the exit of the trap.

Figure 1(b) shows a schematic diagram of the Ps beam production system and the setup for the surface scattering experiment. The positron bursts are accelerated to an energy of 5 keV by a potential gap (not shown in Fig. 1) and then focused onto an efficient converter of Ps negative ions, i.e. a Na-coated W(100) film with a thickness of 100 nm, using a magnetic lens [16]. According to previous studies [10], positrons reaching the surface are converted to Ps negative ions with an efficiency as high as a few percent. Ps negative ions emitted from the opposite side of the film are accelerated by a potential gap, W, between the converter and a grid passing through a two-aperture lens. A voltage

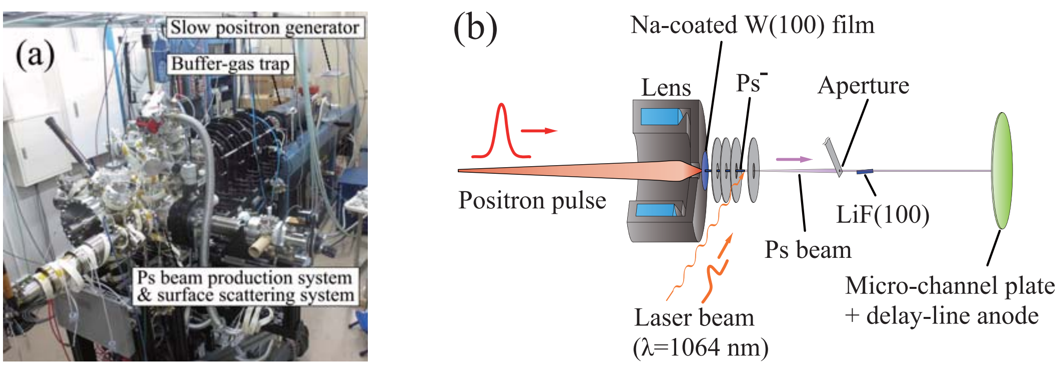

Fig. 1 (a) Photograph of the Ps beam apparatus at the Tokyo University of Science, (b) schematic diagram of the Ps beam production system and the setup for the surface scattering experiment.

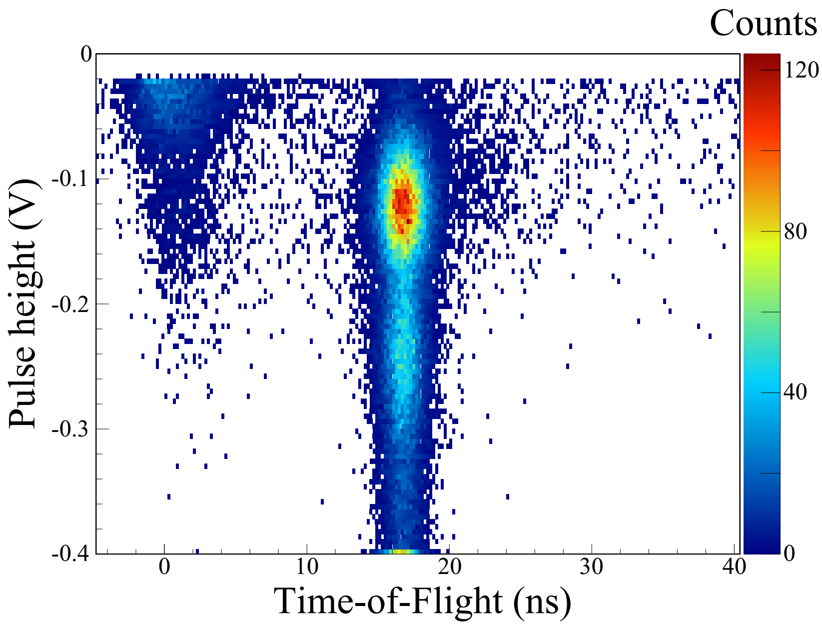

Fig. 2 2-dimensional Time-of-Flight and pulse-height distribution of the detected signals, accumulated over 1800 s.

of 5 kV was applied across the gap W in this measurement. Ps-ions are photodetached by an IR laser beam (fluence 0.2 J cm^{-2}, wavelength 1064 nm) from a commercial Q-switched Nd:YAG laser. The resultant Ps atoms fly a long distance, $L = 0.419$ m, and are detected by an assembly of a micro-channel plate (MCP) with an effective diameter of 83 mm and delay-line anodes (RoentDek, DLD80). Signal waveforms from the MCP and the anodes are stored in a digitizer and analyzed online. To identify the mass of the particles detected, Time-of-Flight spectra from the photodetachment point to the detector are measured simultaneously with the spatial profiles.

In the surface scattering experiment, an aperture with a diameter of 2 mm was installed in the Ps beamline for collimation purposes. In order to observe the specular reflection of Ps atoms [8], an air-cleaved LiF(100) was selected as the sample and placed just after the aperture. It was annealed at a temperature of about 300 °C in vacuum and cooled down to room temperature.

3. Results and Discussion

Figure 2 shows the Time-of-Flight (TOF) and pulse-height distribution of the MCP signals. A prompt component in the TOF at around 1 ns originates from the annihilation gamma-rays generated in the converter. A delayed component with a characteristic peak structure on the pulse-height axis was clearly observed at a TOF of around 17 ns. It is consistent with the TOF of Ps atoms formed by the photodetachment of the accelerated Ps negative ions, given by $t = L/\sqrt{(2eW/3m)}$, where e and m are the elementary charge and electron mass, respectively, confirming the successful production of an energy-tunable Ps beam. The kinetic energy of the beam is expressed as $K = 2W/3$, if we neglect the effect of the photoelectron recoil and the emission energies of Ps ions. K is 3.3 keV in the present setup when $W = 5.0$ kV. The temporal width of the beam was about 2 ns which is comparable to that of the positron pulse. The collection of events corresponding to the Ps atoms is ensured by selecting the appropriate windows on the TOF and pulse-height axes. The signal to background ratio was as high as 1000.

To confirm the suitability of the Ps beam for the surface scattering experiment, we carried out a

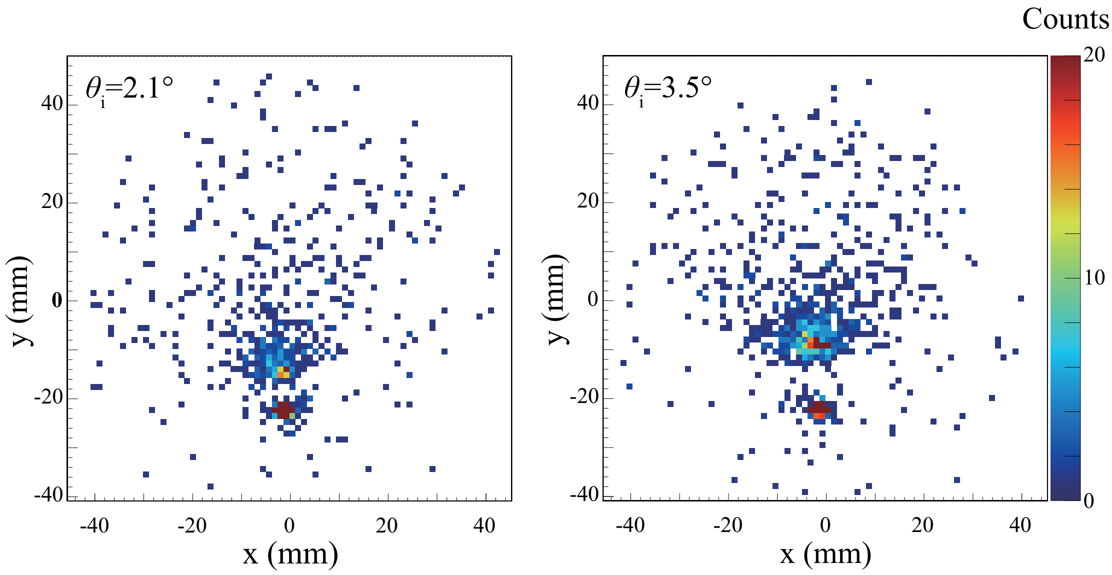

Fig. 3 Spatial profiles of the Ps atoms scattered at the incident angle of 2.1° (left) and 3.5° (right).

trial measurement where the beam collimated by the aperture was incident on the LiF(100) sample with a grazing angle and the scattered components are projected onto the detector. Fig. 3 shows the spatial profiles of Ps atoms scattered with an energy of 3.3 keV, at incident angles θ_i of 2.1° and 3.5°, respectively. Some of the Ps atoms that did not hit the sample were observed as direct-beam spots at the y-position of −23 mm. Scattered components were clearly observed above the direct spots at both incident angles. The y-position of each component shifts in accordance with the incident angle and corresponds to the position of specular reflection, i.e. when the incident angle is equal to the exit angle. Even though the incident energy of 3.3 keV is much higher than that of the previous measurement [8], the reflection was observed without loss or severe breaking-up owing to the grazing incidence geometry. This shows that the performance of the newly developed Ps beam apparatus is appropriate for the future investigations of surface scattering. More detailed studies and subsequent Ps diffraction measurements are possible in the future.

4. Summary

We have developed a new Ps beam apparatus for the investigation of Ps interactions with atoms/molecules at surfaces. The apparatus was constructed at the Tokyo University of Science and is now in operation. We confirmed the production of an energy-tunable beam of Ps atoms formed by the photodetachment of Ps negative ions. The obtained beam was used to perform a surface scattering experiment in grazing-incidence geometry and the specular reflection of Ps atoms from a LiF(100) surface was observed. This experimental technique opens up a new era in the experimental field of Ps scattering with atoms/molecules in the solid phase.

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