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Development of Energy-Tunable Positronium Beams Employing the Photodetachment of Positronium Negative Ions

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Recent progress on the development of an energy-tunable positronium beam is reviewed. We describe experimental results for the efficient emission of positronium negative ions from alkali-metal coated tungsten surfaces. The ions generated using this technique have been accelerated by an electric field and photodetached in order to produce positronium beams with a hitherto unrealized energy range up to 1.9 keV.

1. Introduction

When positrons impinge on liquids, insulators, or powders, bound states of a positron and an electron, positronium, can be formed during the energy-loss processes in these materials. Positronium can also be formed on metal surfaces when positrons leave the surface and travel through the low-density electron gas at the outermost surface. The kinetic energy of the emitted positronium is a few eV.

Formation of fast positronium with kinetic energies from 10 eV to 500 eV was realized by passing slow positrons through a 40 Å thick carbon film (beam-foil method) [1]. Neutralization of slow positrons by grazing incidence onto Al (100) and Cu (100) surfaces was also performed, resulting in formation of positronium with the energies below 150 eV [2]. The first mono-energetic energy-tunable positronium, Ps, beam was produced using the charge-exchange reactions between slow positrons, e^+, and gas atoms/molecules, A, as $e^+ + A \rightarrow Ps + A^+$ [3, 4]. A beam with energy in the range 10 eV–100 eV has been developed employing this technique [5, 6] and applied to research on specular reflection of positronium from LiF surface [7] and positronium–atom/molecule collisions [8, 9].

Recently, an energy-tunable positronium beam has been developed employing the photodetachment of the positronium negative ion, a bound state of a positron and two electrons. The beam has been realized by laser irradiation after acceleration of the ions using an electric field. The beam energy is in the range above 300 eV, which is complementary to that of the beam produced using the charge-exchange technique. In the present paper, we outline recent progress in efficient formation of positronium negative ions [10, 11], production of the positronium beam [12], and the outlook for a new production scheme employing a trap-based pulsed positron beam.

2. Efficient production of positronium negative ions

Positronium negative ions were first observed in the laboratory by passing slow positrons through an ultra-thin carbon film [13]. The emission efficiency of the ions was 0.03 %. Another formation process was observed using a clean polycrystalline tungsten (W) surface, which has a negative affinity for the ions [14]. When slow positrons were injected, the ions were spontaneously emitted from the surface via a two electron capture process at the surface. However, the efficiency was as low as 0.007 %.

Recently, we have observed efficient emission of positronium negative ions from a Cs-coated

W (100) surface. The emission efficiency was estimated to be 1.25 %, which is 200 times larger than that before Cs deposition [10]. When alkali-metal is adsorbed on the surface, the electron work function is decreased due to the reduction of the surface dipole barrier by the adsorbate atoms at the outermost surface. For example, the reduction of the work function is about 3 eV for a Cs-coverage of 2.2×10^{14} cm^{-2} on W (100) [15]. This implies an increase in the fraction of conduction electrons contributing to the formation of the ions.

However the efficiency decreases to one-tenth in half a day even at UHV conditions (2×10^{-8} Pa). This is attributed to the effect of residual gas molecules on the adsorbed Cs. We have also investigated the effect for other alkali-metals, Na and K, which are chemically less-reactive than Cs due to their lower ionization energies. The efficiencies for Na- and K-coated W surfaces were found to be as high as 1.5 % and the effect lasts longer than that for the Cs-coated surface. The efficiency for the Na-coated surface decreases gradually and is still as high as 0.5 % even three days after the deposition [11].

3. Production of an energy-tunable positronium beam

When positronium negative ions, Ps^-, are irradiated with photons, the photodetachment process $Ps^- + h\nu \rightarrow Ps(n) + e^-$ occurs (n is the principal quantum number of formed positronium). This process has a threshold at $B_{Ps^-} + B_{Ps}(1 - 1/n^2)$, where B_{Ps^-} and B_{Ps} are the one-electron binding energies of the positronium negative ion (0.33 eV) and the ground-state positronium (6.80 eV), respectively. The relative yield of *ortho*-positronium ($S = 0$) to *para*-positronium ($S = 1$) formed in this process is 3:1 in accordance with the spin-statistics. This process can be used for the production of energy-tunable positronium beams. We have produced a beam using a pulsed slow positron beam and a high power pulsed laser [12]. The advantage of using a pulsed positron beam is that it can be synchronized with a pulsed laser which has a sufficiently high photon density for the photodetachment. Figure 1 shows a schematic of the positronium beam apparatus. A LINAC-based slow positron beam (intensity 5×10^6 $e^+ \cdot s^{-1}$, width 12 ns FWHM, repetition 50 Hz) supplied by the KEK IMSS Slow Positron Facility [16] was used. The positron beam was magnetically guided to the experimental chamber passing through a 5 mm diameter aperture (not shown in Fig. 1) and deflected by 45 degrees along a curved magnetic field. Then the beam was incident onto a target passing through grids B and A. The intensity and the diameter at the target were 4×10^5 $e^+ \cdot s^{-1}$ and 7 mm, respectively.

The target was a poly-crystalline W foil with the size of 10 mm × 10 mm × 25 μm (99.95 % purity). The W foil was annealed in-situ at 1800 K for 30 min by resistive heating. A Na layer was formed on the surface using an alkali-metal dispenser purchased from SAES Getters S.p.A. after cool-

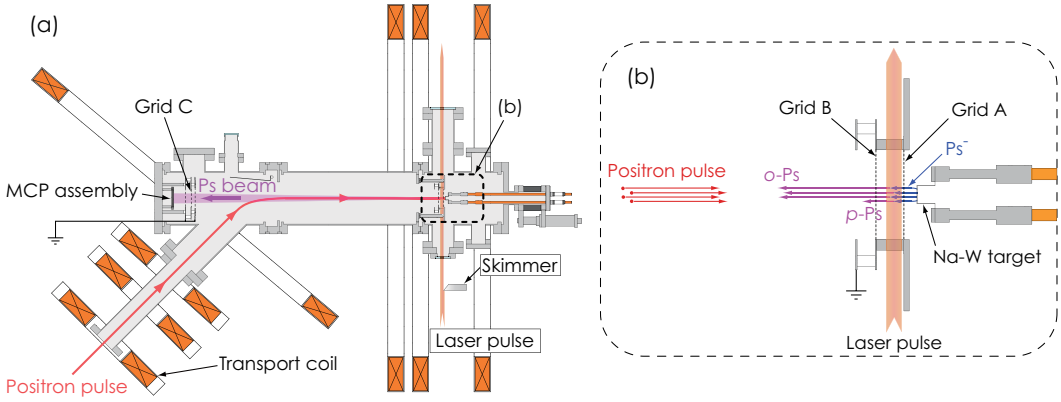

Fig. 1. (a) Apparatus for the positronium beam production, (b) schematic view of the photodetachment region (not to scale) [12].

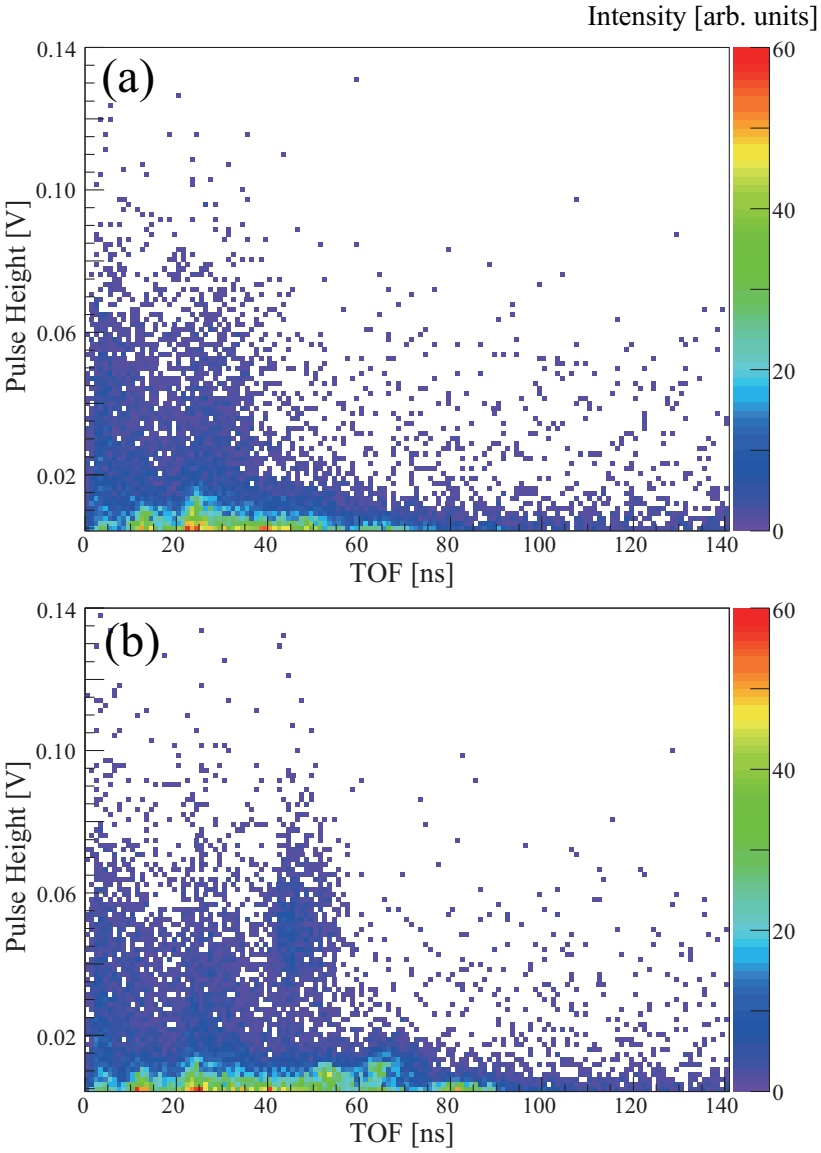

Fig. 2. Two-dimensional TOF-pulse height spectra for (a) laser off and (b) laser on.

ing down to room temperature. The surface density was estimated to be about 2×10^{14} atoms $\cdot$ cm^{-2} using a quartz crystal oscillator (INFICON, BK-A0F).

The target bias, V_{target}, was varied from 0 to 2.3 kV. Grids A and B were equally biased at V_{grid}. Positronium negative ions emitted from the target were accelerated by the potential difference between V_{target} and V_{grid}. Vgrid was fixed at 2.8 kV. The positronium negative ion beam was then crossed with the pulsed laser light in the field free region formed between the two grids and photodetached. The light was the fundamental wave from a Q-Switched Nd:YAG laser (width 12 ns FWHM, repetition 25 Hz). The wavelength was 1064 nm (1.165 eV), so that only ground-state positronium was formed by the photodetachment of the positronium negative ion according to the threshold values. The diameter of the laser light was 8 mm. The power was measured to be 9 W using a thermal sensor (OPHIR, 10A-P) and varied using an attenuator (Leysop, HPLA).

If we ignore the emission energy of the ions from the surface, the energy of the positronium

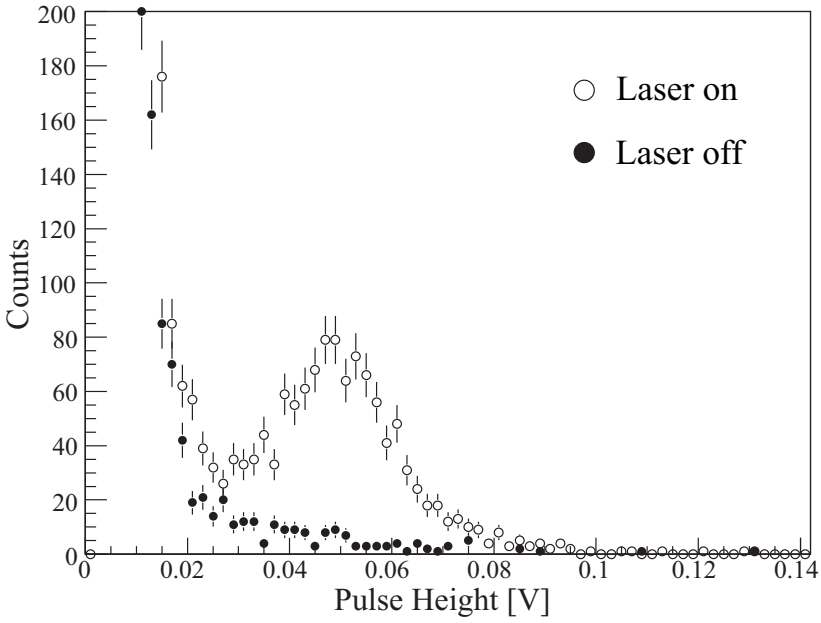

Fig. 3. Pulse height distributions in the timing window between 40 ns and 65 ns of the two dimensional spectra shown in Fig. 2.

formed by the photodetachment, E_{Ps}, is expressed as

$$E_{\mathrm{Ps}} = 2e(V_{\mathrm{grid}} - V_{\mathrm{target}})/3, \tag{1}$$

where e is the elementary charge. The *ortho*-positronium atoms formed with an energy of 1 keV can fly a long distance (~2 m) during their lifetime (142 ns) while the *para*-positronium atoms, which have a shorter lifetime (125 ps), self-annihilate almost immediately after formation. The positronium atoms were detected by a micro-channel plate (MCP) and a metal anode assembly with an effective diameter of 40 mm (Photonics, 3040MA). The distance between the MCP and the photodetachment region L was 80 cm. A retarding bias, V_{c}, was applied to gird C, which was mounted in front of the MCP to discriminate charged particles.

The output signals were accumulated by a digital oscilloscope (LeCroy, WaveRunner 64Xi-A) with reference to the LINAC trigger. The data were transferred to a personal computer after accumulation and the time of flight (TOF) of the *ortho*-positronium and the pulse height of the signals were determined by a waveform analysis.

Figure 2 shows two-dimensional TOF-pulse height spectra for laser off and laser on. The potentials V_{target} and V_{c} were set at 0 and 4.5 kV, respectively. The component at 5 ns is attributed to annihilation γ-rays from positrons in the target and the self-annihilation of *para*-positronium emitted from the surface. The second component at 25 ns originates from the γ-rays emitted from pair annihilation of back-scattered positrons at the chamber wall. In addition to these components, another component is observed at 45 ns with the laser. The pulse height spectra are shown in Fig. 3, obtained by the projection of the plots in the TOF window between 40 ns and 65 ns. A peak with the laser in Fig. 3 has a characteristic distribution and is separated from background. A discrimination level of the pulse height was set at 0.025 V, which corresponds to 2σ value of the pulse height distribution determined by fitting a Gaussian function. The levels are the same for the values of V_{target} in the range of the present experimental setup.

Figure 4 shows the TOF spectra. Two peaks which appear for laser off correspond to the two components shown in Fig. 2(a). Another peak shown for laser on corresponds to the third component

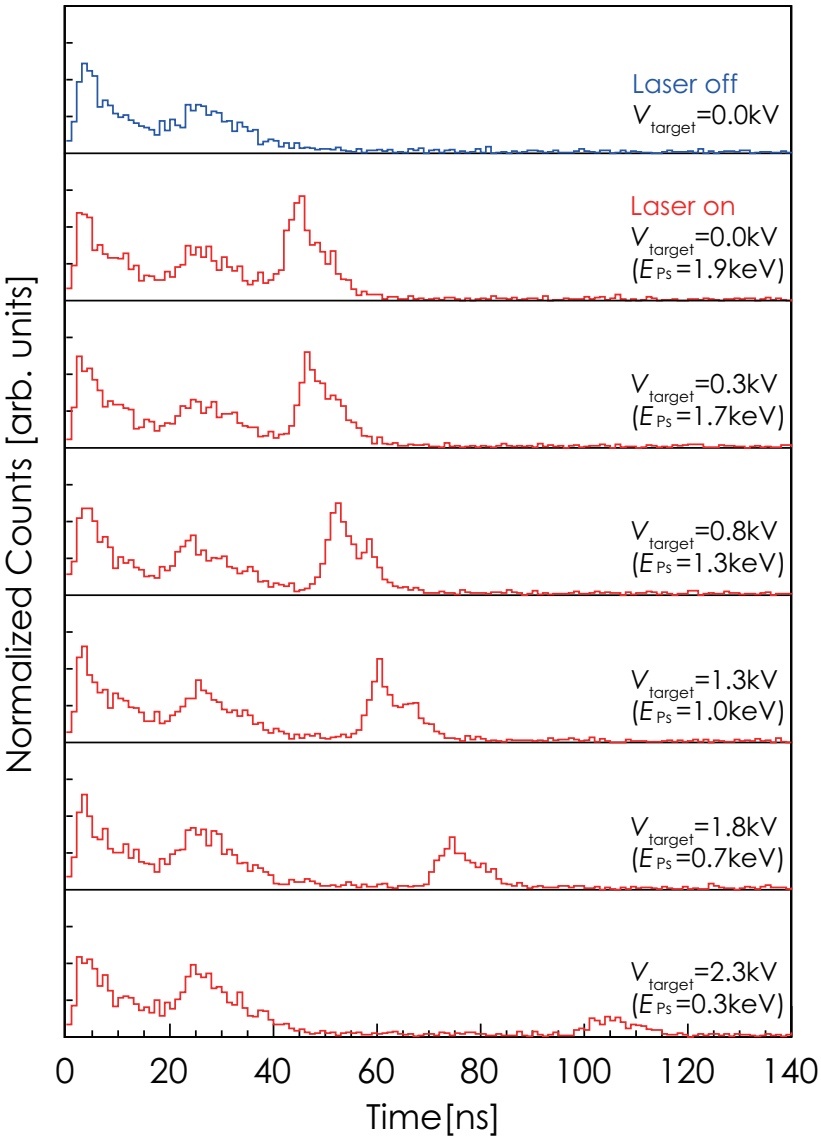

Fig. 4. TOF spectra [12].

shown in Fig. 2(b). The peaks have double peak structures. This is attributed to timing structure of the positron beam. TOFs of the each peak were determined from the first peak. Figure 5 shows the TOF obtained from Fig. 4 plotted against the values of V_{target}. The solid curve shows the TOF of positronium given by

$$t = L/\sqrt{E_{Ps}/m_e}, \tag{2}$$

where m_e is the electron mass. The good agreement indicates the formation of an energy-tunable positronium beam via photodetachment. The energy range obtained in this experiment was from 0.3 keV to 1.9 keV.

Figure 6 shows the normalized positronium beam intensities as a function of the positronium energy. The values have been corrected for the inflight annihilation of the *ortho*-positronium atoms and the positronium negative ions. The intensity increases with the positronium kinetic energy and levels off. This behavior may be due to the energy dependence of the MCP detection efficiency and/or beam divergence of the beam.

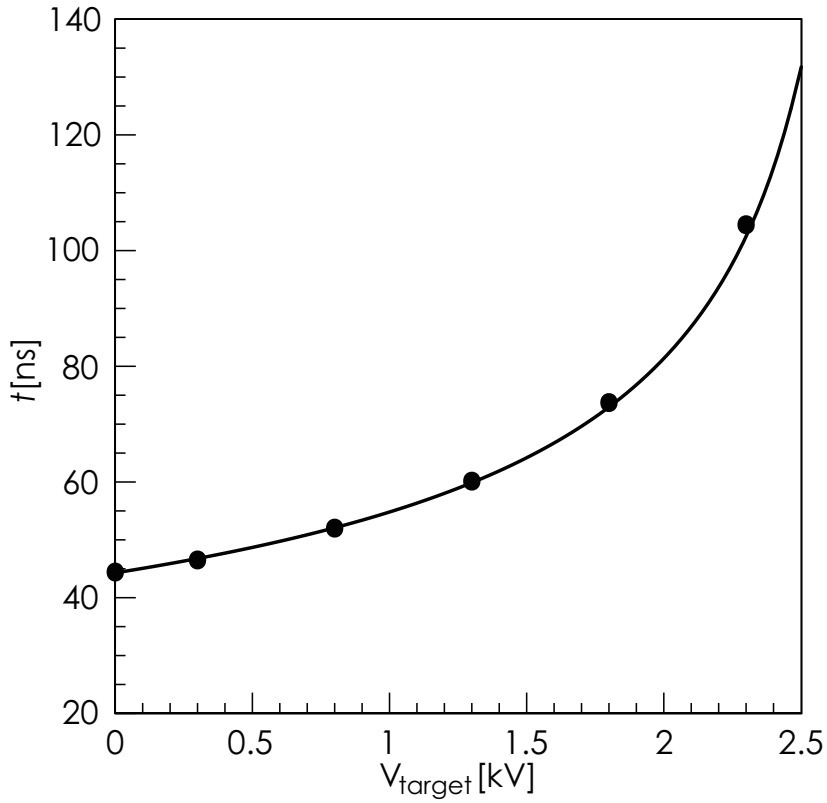

Fig. 5. TOF obtained from Fig. 4 as a function of the target bias, V_{target} [12]. Solid curve shows the TOF of the positronium calculated using Eq. (2).

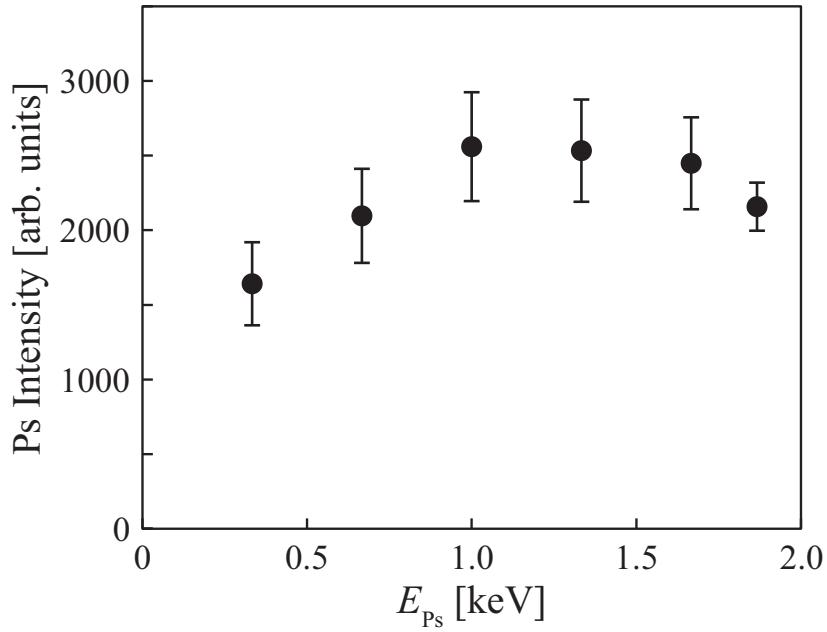

Fig. 6. Normalized positronium intensity against E_{Ps}.

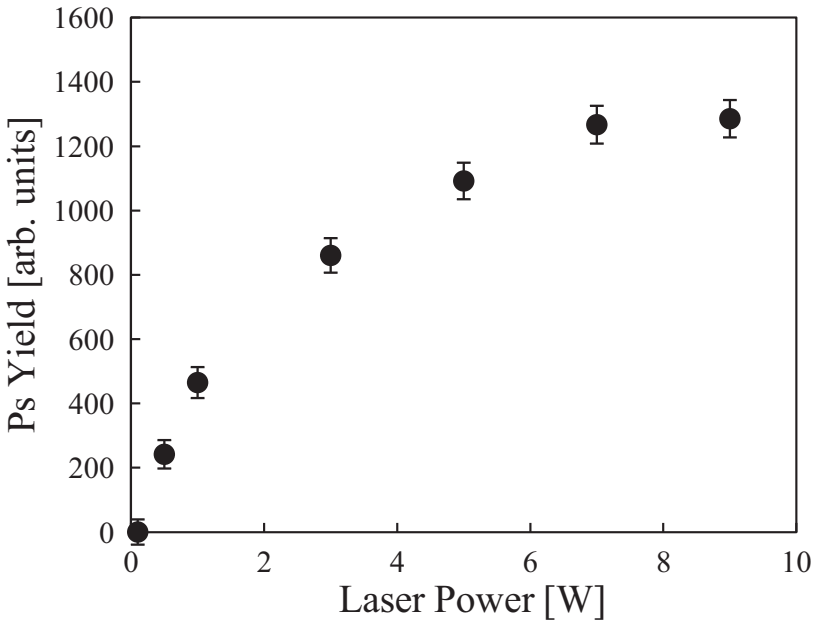

Fig. 7. Positronium yield as a function of the laser power, with V_{target} = 1.3 kV.

Figure 7 shows the positronium yield against the laser power for V_{target} = 1.3 kV. The yield increases with increasing laser power and is almost saturated above 7 W. The saturation indicates that most positronium ions crossed with laser light are photodetached.

The maximum count rate of the positronium atoms was 0.1 count per pulse (cpp) for V_{target} = 2.8 kV. In contrast, the rate estimated from the formation efficiency of positronium negative ions (1.5 %) [11], photodetachment fraction (58 %) [17], and the transport efficiencies of the ions and the positronium (16 %) is 7 cpp. Even if we assume that the MCP detection efficiency for positronium is 10 % [2], the discrepancy remains. It may be attributed to a low detection efficiency of the MCP and/or the loss of positronium due to beam divergence.

The positronium beam employing the photodetachment method has advantages over the charge-exchange method such as high energy capability in the range of keV and utility in UHV condition. The beam may be used for studies on positronium collisions with atoms/molecules or solid surfaces in the high energy region. Furthermore the positronium beam may be applied as an outermost-surface analysis tool.

4. Plan for a positronium beam utilizing a trap-based positron beam

In order to produce the positronium beam, a pulsed slow positron beam based on a LINAC has been utilized. Pulsed positron beams have also been developed employing a magnetic bottle RF trap [18]. Although a sub-nanosecond pulsed beam can be obtained by this system, the beam intensity is too low for the production of a positronium beam. The nitrogen buffer-gas trap developed by Surko *et al.* [19] is the most efficient positron trap system (trapping efficiency ~30 %) reported so far. It can be operated efficiently with a repetition rate of tens-Hz and is suitable for the production of positronium beams.

We are developing a positronium beam system utilizing the buffer-gas trap as shown in Fig. 8. The trap system has been purchased from First Point Scientific [20]. It consists of a slow positron beam generator based on an encapsulated ^{22}Na source and a solid Ne moderator, a two stage buffer-gas trap, and a buncher. A sub-nanosecond positron pulse can be generated with a repetition rate of more than a few Hz [21, 22].

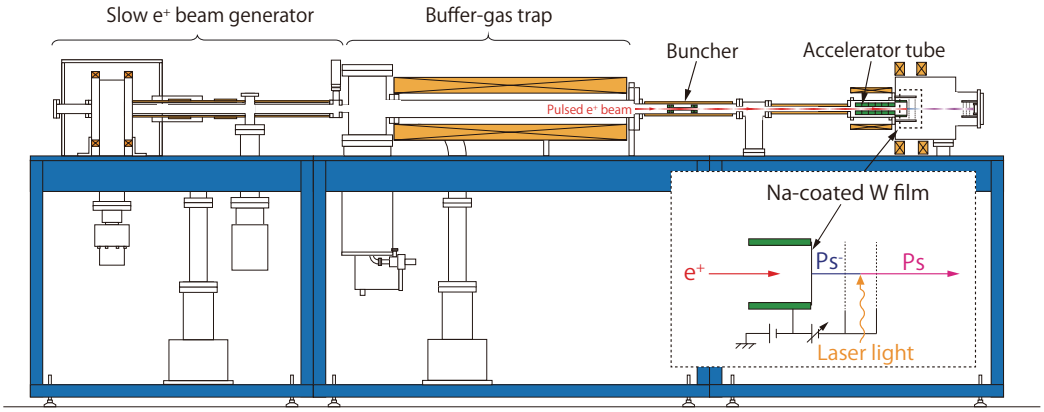

Fig. 8. Conceptual design of the positronium beam utilizing the trap-based positron beam.

A transmission geometry to form positronium negative ions will be adopted instead of the current back-reflection geometry. The advantage is to increase the acceleration energy to over tens of keV. Furthermore, the path length of the positronium beam to the detector can be shorter than that in the back-reflection geometry and thus the beam divergence can be suppressed. This compact system can be operated in a university scale laboratory.

5. Conclusion

We have reviewed the development to an energy-tunable positronium beam employing the photodetachment method. We found efficient emission of the ions from a Na-coated W surface. Using this ion source, an energy-tunable positronium beam with an energy range from 0.3 keV to 1.9 keV has been realized. The beam may be applied for studies on positronium interactions with atoms/molecules in gases or surfaces.

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