Towards the production of an energy-tunable positronium beam using Ps⁻ photodetachment technique

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Abstract. The production of an energy-tunable positronium beam by photodetachment of positronium negative ions, which was proposed many years ago, has become feasible by the recent development of efficient formation of the ions and successful photodetachment. Here we shall describe our current efforts directed towards the production of a positronium beam using this technique.

1. Introduction
It is well known that positronium (Ps) atoms can be formed and emitted with a maximum energy of a few eV when keV-energy positrons strike a solid target in vacuum. Ps can also be formed in gases, liquids and powders. However, once Ps atoms are formed, it is impossible to accelerate them to the required energy using an electric field.

Energy-tunable Ps beams have been developed using charge exchange of positrons with a low-density gas and thin foils. Ps formation by the reaction,

\[ e^+ + M \rightarrow Ps + M^+ , \]

of a positron with a molecule, M, is a significant channel at intermediate energies [1,2]. The Ps kinetic energy, \( T_{Ps} \), is related to that of the \( e^+ \) kinetic energy, \( T_{e^+} \), by

\[ T_{Ps} = T_{e^+} - E_I + E_{Ps} \]

where \( E_I \) is the ionization energy of the target gas. \( E_{Ps} \) is the Ps binding energy, i.e.,

\[ E_{Ps} = 6.8 \text{eV}/n^2 \]

and \( n \) is the principal quantum number of the Ps. This technique has been used for the observation of Ps specular reflection from the surface of LiF [3] and the measurement of Ps-gas scattering cross sections in the energy range below 100eV [2,4].

Ps atoms with kinetic energies from 10 to 500 eV have also been formed by the partial transmission of keV-energy positrons through a 50-Å carbon film in vacuum [5]. The Ps energy distribution

\[ dN = (10^{-3} \text{eV})^{1/2} E^{-3/2} dE d\Omega \]

has been obtained.

It has been proposed that the production of an energy-tunable monoenergetic Ps beam might be feasible by the photodetachment of accelerated positronium negative ions (Ps⁻) [2,6,7]. Recently, we observed the efficient emission of Ps⁻ formed from thermalized positrons impinging on tungsten, molybdenum, tantalum and iron surfaces coated with alkali metals [8-12]. Furthermore, we have
succeeded in the photodetachment of Ps\(^+\) for the first time [13]. We now aim to realise the production of energy-tunable Ps beams using these techniques.

2. **Efficient production of Ps\(^+\)**

It is well known that electronic surface states are sensitive to adsorbates on the surfaces. The lowering of electron work functions by the deposition of an overlayer of alkali metal on a metal surface enables efficient emission of Ps\(^+\) from the surfaces.

The Ps\(^+\) work function, the energy required to emit Ps\(^+\) from a metal surface, is

\[
\phi_{Ps^+} = \phi_+ + 2\phi_- - E_{Ps^+},
\]

where \(\phi_+\) and \(\phi_-\) are the positron and electron work functions, respectively, and \(E_{Ps^+}\) is the Ps\(^+\) binding energy, which has been calculated theoretically to be 7.13eV [14, 15]. When the surface is coated with an alkali metal, the Ps\(^+\) work function depends on the effect of the adsorbate dipole, \(D\), as

\[
\phi_{Ps^+}' = \phi_{Ps^+} - D.
\]

The value of \(D\) for Cs on a tungsten surface is reported to be about 3eV for \(2.2 \times 10^{14}\) atoms/cm\(^2\) [16]. This indicates that Ps\(^+\) emission is more feasible in this case than from the uncoated surfaces.

In 2008, we observed the efficient emission of Ps\(^+\) from a Cs coated W(100) surface [8]. The mean emission efficiency (the fraction of incident slow positrons yielding Ps\(^+\)) over a 3000s interval following Cs deposition was 1.25\%, which is two orders of magnitude higher than that obtained using carbon thin films [6] and clean tungsten surfaces [17]. However, the efficiency decreased and was almost constant at about 0.1\% after 60000s. The decrease may have been due to the accumulation of residual molecules in the target chamber onto the target surface or the structural change of the Cs layer. Recently, we observed that the Ps\(^+\) emission efficiency from Na coated tungsten is higher than that from the Cs coated surface, even though the effect of the adsorbate dipole for Na is smaller than that for Cs. Furthermore, the decrease of the emission efficiency was slower than that for the Cs coated surface and the efficiency was still higher than 0.5\% after 3 days [12].

3. **Photodetachment of Ps\(^+\)**

The Ps\(^+\) photodetachment process has been studied theoretically and cross sections have been calculated [18,19]. Recently, we have succeeded in the first observation of the photodetachment of Ps\(^+\) in the slow positron beam facility in KEK, Tsukuba, Japan [13].

The positrons generated at the beam dump of an electron Linac with a repetition rate of 50Hz were collected and transported to the Na coated polycrystalline tungsten target [20]. The width of the positron pulse at the target position was 12ns. The Ps\(^+\) ions emitted from the target were accelerated and the Doppler shifted \(\gamma\)-rays were detected using Ge detectors. In order to lower the background due to the pile-up of the \(\gamma\)-rays produced in a short period of time, excess counts were reduced by surrounding the detectors in lead shielding with a slit to allow the passage of the \(\gamma\)-rays. Two detectors were used to obtain high statistics.

In order to photodetach the Ps\(^+\), a Q-switched Nd: YAG pulsed laser of 12ns width was used. The wave length was 1064nm and the power was 1J/pulse. The repetition frequency was half of that for the slow positron beam and the data was acquired for laser on/off repeatedly.

Figure 1 shows the obtained \(\gamma\)-ray spectra. The peak attributed to Ps\(^+\) annihilation decreased upon laser irradiation. This shows that Ps\(^+\) ions were converted to ortho-Ps atoms, which self-annihilate into 3\(\gamma\)-rays, by the photodetachment.
4. Production of an energy-tunable Ps beam by the photodetachment of Ps

The success of the Ps photodetachment technique opens the door to a new era of the production of energy-tunable Ps beams. Figure 2 shows the conceptual design of such a beam. The pulsed slow positron beam is transported along the curved magnetic field on to the Na coated tungsten surface. The emitted Ps ions are accelerated and photodetached using a high power Q-switched Nd: YAG pulsed laser. Irradiation with a 230nm laser, where Feshbach resonance is predicted theoretically [18,19], might enable us to perform the photodetachment more efficiently. However, using a 1064nm laser will result in a beam with smaller angular divergence. The Ps beam is transported through the biased grids to eliminate charged particles such as electrons and positrons, and impinges onto the target.

Using the Ps beam, the investigation of Ps passing through thin foils suggested by Mills in 1989 [21] may be possible. Observation of coherent resonance excitation [22] of Ps may also be feasible if we can prepare a spatially periodic field with optimum conditions.

Figure 2. Schematic diagram of the proposed energy-tunable Ps beam apparatus.
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