Ps$^-$ emission from Cs coated surfaces

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Abstract. Recently, we have observed the efficient emission of positronium negative ions from Cs coated W(100) and polycrystalline Mo and Ta surfaces. The efficient emission enables us to perform new experimental studies on these ions. The investigations of the efficient production of positronium negative ions are reviewed and a measurement of the binding energy of the ions and a photodetachment experiment are proposed.

1. Introduction
The positronium negative ion (Ps$^-$), a bound state of a positron and two electrons, is the simplest three-body system which provides a good sample for testing QED corrections. Therefore, a number of theoretical investigations have been carried out since the first prediction of the stability of this ion by Wheeler in 1946 [1]. For example, the binding energy $E_B$ has been calculated by several authors [2]–[6] and resonances in the electron-positronium (Ps) continuum have been studied [7][8]. The photodetachment cross sections have also been calculated [9][10]. However, after the first observation of Ps$^-$ by Mills [11] in 1981, no experimental investigations have been performed on this system except for a few measurements of the decay rate [12]–[15]. In order to accomplish more extensive investigations into the fundamental processes, new methods of generating more efficient Ps$^-$ production had to be developed.

When slow positrons impinge on a metal surface, they lose their kinetic energy via processes such as phonon excitation or electron-hole pair creation and are thermalized. Some of these diffuse back to the surface and if energetically allowed, they contribute to the positron re-emission or Ps emission. In 2006, we observed the spontaneous emission of Ps$^-$ from a polycrystalline tungsten surface as another channel [16]. The Ps$^-$ emission efficiency (the fraction of incident slow positrons yielding Ps$^-$) was only 0.007%. In 2008, we succeeded in significantly increasing this value by obtaining Ps$^-$ from a W(100) surface coated with Cs [17].

In the present paper, the efficient emission of Ps$^-$ from alkali metal-coated surfaces will be reviewed and future experimental investigations will be proposed.

2. Efficient emission of Ps$^-$ from a Cs coated W(100) surface
The effect of Cs coating on the Ps$^-$ emission from metal surfaces has been discussed by Mills [11] and Laricchia [18][19]. Mills suggested that it becomes energetically favorable to form Ps$^-$ if the electron work function of a surface is lowered by coating it with Cs. Laricchia suggested that good yields of Ps$^-$ might be obtained at positron incident energies of a few eV at grazing angles.
The formation method of Ps$^-$ in our experiments is based on the spontaneous emission of these ions from a Cs coated surface. The Ps$^-$ is emitted from a tungsten surface spontaneously because the Ps$^-$ work function, expressed as

$$\phi_{Ps^-} = \phi_+ + 2\phi_- - E_B$$

is negative, where $\phi_+$ and $\phi_-$ are the positron and electron work functions, respectively. Here, using the chemical potential for the electron and positron, $\mu_+$, $\mu_-$, the values of $\phi_+$ and $\phi_-$ can be written as

$$\phi_+ = -D - \mu_+, \ \phi_- = D - \mu_-$$

respectively, where $D$ is the effect of the adsorbate dipole. Therefore, the Ps$^-$ work function is expressed as

$$\phi_{Ps^-} = -\mu_+ - 2\mu_- - E_B + D.$$  

Equation (3) shows that the Ps$^-$ work function depends on the surface state. It is well known that alkali metal adsorption on a tungsten surface reduces the electron work function due to the depolarization of the surface dipole. As a result, the Ps$^-$ work function can be decreased and hence the Ps$^-$ emission efficiency will be increased.

The experimental system used was a magnetically guided slow positron beam apparatus with a trochoidal $E \times B$ filter. The beam intensity at the target was $1 \times 10^5$ $e^+$/$s$ and the beam diameter was about 5mm.

![Schematic diagram of the target chamber](image)

**Figure 1.** Schematic diagram of the target chamber [17].

Figure 1 shows the schematic diagram of the target chamber. The target was biased at -3kV so that the positrons were incident onto the target with an energy of 3.1keV. The Ps$^-$ emitted from the target were accelerated by the electric field between the target and the grounded grid. A pure Ge detector was used to detect the blue-shifted annihilation $\gamma$-rays which were emitted on self-annihilation by the oncoming Ps$^-$\,. In order to detect the low count rate events of Ps$^-$, the background was reduced by using the Ge detector signal in coincidence with that from a NaI scintillation detector placed behind the target. The target was a W(100) film of thickness 2$\mu$m. It was annealed at 1800K in situ for 30 min and then coated with Cs using an alkali metal dispenser. The coverage of the Cs layer was set to be $2 \times 10^{14}$ atoms cm$^{-2}$.

Figure 2 shows the annihilation photon energy spectra. The spectra for the unannealed and annealed targets were taken over a period of about 40h. The spectrum for the Cs coated
surface was accumulated for 3000s immediately after deposition. The conversion efficiency for the uncoated W(100) after annealing was 0.005%. Figure 2 (c) shows the efficient emission of Ps\(^-\) from a Cs coated tungsten surface. After the coating, the emission efficiency, \(f\), increased to 1.25\%, which is 250 times higher than for the uncoated surface. The value decreased with time after deposition and was almost constant at 0.1\% after 17h, which is still greater than that obtained using the beam-foil method.

![Graphs showing annihilation photon energy spectra for (a) unannealed, (b) annealed and (c) Cs coated W(100) surfaces. The arrows indicate the photon energy of the self-annihilation of the accelerated Ps\(^-\).](image)

**Figure 2.** The annihilation photon energy spectra for (a) unannealed, (b) annealed and (c) Cs coated W(100) surfaces. The arrows indicate the photon energy of the self-annihilation of the accelerated Ps\(^-\).

We have also tested coating with Na, which is less active chemically, in order to obtain long term stability. The coverage of the Na layer was estimated to be about 2 \(\times\) 10\(^{14}\) atoms cm\(^{-2}\). Surprisingly, immediately after the deposition, \(f\) was greater than that for the Cs coating and remained higher than 1\% for more than one day.

### 3. Measurement of the Ps\(^-\) binding energy

In this work, we have made an estimate of the value of \(E_B\), which has not been measured thus far, by observing the Ps\(^-\) emission from polycrystalline Mo and Ta surfaces. The targets were commercially obtained polycrystalline foils of 20\(\mu\)m thickness. They were annealed in situ at 1500\(^\circ\)C for 30min. For the annealed Mo target, a low-intensity peak attributed to Ps\(^-\) emission was seen at 542 keV. For the Mo target with a 2 \(\times\) 10\(^{14}\) atoms cm\(^{-2}\) Cs coverage, the value of \(f\) was 0.8\%. This observation sets a lower limit to the Ps\(^-\) binding energy. The result indicates that the positron in the Mo target can leave the uncoated surface as Ps\(^-\), i.e.,

\[\phi_+ + 2\phi_- - E_B < 0,\]

to therefore,

\[E_B > \phi_+ + 2\phi_-\]
Figure 3. The annihilation photon energy spectra for (a) unannealed, (b) annealed and (c) Cs coated polycrystalline Mo surfaces and (d) unannealed, (e) annealed and (f) Cs coated polycrystalline Ta surfaces.

The right-hand term can be obtained from previous measurements of $\phi_+ [20]$ and $\phi_- [21]$ to be $7.1 \text{eV}$.

For the annealed Ta target, no significant peak was seen at 542 keV though a peak due to Ps$^-$ emission appeared in the spectrum after Cs coating. This indicates that the positrons in the target which diffuse back to the surface cannot leave the uncoated surface as Ps$^-$, i.e.,

$$\phi_+ + 2\phi_- - E_B > 0,$$

therefore,

$$E_B < \phi_+ + 2\phi_-,$$

which was determined to be obtained to be $7.3 \text{eV}$ using previous measurements of $\phi_+ [22]$ and $\phi_- [21]$. Therefore, $E_B$ has been estimated to be

$$7.0 \text{eV} < E_B < 7.3 \text{eV}, \quad (4)$$

which is consistent with theoretical values that have been calculated [2][3][6]. This is the first experimental approach to estimate the binding energy of Ps$^-$. However, an accurate value is necessary to compare with the theoretical results.

In order to obtain such a value, we are planning to measure the dependence of the Ps$^-$ yield on alkali metal coverage for the Ta target. We will search for the coverage corresponding to $\phi_{Ps^-} = 0$, and determine the binding energy as

$$E_B = \phi_0^+ + 2\phi_0^-,$$

where $\phi_0^+$ and $\phi_0^-$ are the positron and electron work functions measured for the coverage corresponding to $\phi_{Ps^-} = 0$, respectively [23].
4. Ps− photodetachment experiment
The significant increase obtained in the emission efficiency opens up the possibility of performing Ps− photodetachment experiments. An experiment using the pulsed positron beam at KEK [24] together with a Nd: YAG laser synchronized to the positron beam is being planned [25]. Using the Ps− photodetachment technique, the production of a variable energy Ps beam will be feasible [13][18].

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