Efficient formation of positronium negative ions

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Abstract. The emission of positronium negative ions from W(100) and Mo and Ta polycrystalline surfaces has been investigated. A dramatic change in the emission efficiency upto 1.5% was observed upon coating Ta with Cs. The efficiency obtained in the present work may be sufficient to enable thorough investigations of the ions.

1. Introduction

It is well known that an electron can bind to a positron to form positronium (Ps). It is hydrogen-like, but because the reduced mass is \( m_e/2 \), where \( m_e \) is the rest mass of the electron, the binding energy of the ground state is half that of the hydrogen atom, 6.80eV. In vacuum, the Ps in a singlet spin state self-annihilates into 2\( \gamma \)-rays with a mean lifetime of 125ps, whilst the Ps in a triplet state self-annihilates into 3\( \gamma \)-rays with a lifetime of 142ns.

Another electron can also bind to Ps to form a positronium negative ion (Ps\(^-\)), provided the two electrons are in a singlet spin state. The mean lifetime is 479ps and the binding energy, the energy required to break-up the ion into an isolated positron and two electrons, is 7.13eV. The existence of this system was proposed by Wheeler [1] in 1946 and confirmed experimentally in the pioneering work of Mills [2] in 1981 using the beam-foil method, where a conversion efficiency (the fraction of incident slow positrons yielding Ps\(^-\)) of 0.028 % was obtained. After this observation, no experimental investigations have been performed on this system except for a few measurements of the decay rate [3]–[5]. A number of theoretical investigations have been performed [6]–[26]. For more extensive experimental studies, formation methods producing the ions with a higher efficiency must be developed.

When low-energy positrons impinge on metal surfaces, some of them penetrate into the bulk, lose their energy until thermalized, and then diffuse back to the surface where there are several channels for the fate of the positrons. The positrons may be trapped in the surface potential well and annihilate there. If the positron work function, \( \phi_+ \), is negative, positrons may be emitted. The positrons may also be emitted as Ps when the potential for Ps "just outside" the surface, \( \phi_{Ps} = \phi_+ + \phi_- - 6.8eV \), is negative, where \( \phi_- \) is the electron work function. Researchers of positron physics often refer to \( \phi_{Ps} \) as the "Ps work function" although there can be no Ps inside solids. Ps\(^-\) may also be produced from thermalized positrons at metal surfaces and emitted if the "Ps\(^-\) work function",

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

(1)
is negative, where $E_B$ is the binding energy of $\text{Ps}^−$. The values of $\phi_{\text{Ps}^-}$ in Table 1, estimated using Equation (1) with experimental values of $\phi_+$ and $\phi_-$, show the process of $\text{Ps}^−$ emission is energetically allowed from $(100)$ and from polycrystalline W and Mo surfaces. In 2006, we detected $\text{Ps}^−$ emission to confirm the existence of this channel for a W polycrystalline surface [32]. However, the obtained conversion efficiency was only 0.006 %.

The value of $\phi_{\text{Ps}^-}$ is dependent on the surface dipole barrier; an alkali-metal coverage decreases $\phi_{\text{Ps}^-}$ and thus the $\text{Ps}^−$ emission efficiency is likely to increase. Formation of $\text{Ps}^−$ by bombarding surfaces with a Cs coverage has been suggested by Mills [2] and Laricchia [33][34]. In the present study, we have successfully observed the emission of $\text{Ps}^−$ from a Cs coated $(100)$ surface with an efficiency of 1.25 %, which is two orders of magnitude higher than that obtained for the clean, uncoated $(100)$ surface and 45 times greater than the highest efficiency reported thus far [35]. We have also observed the emission of $\text{Ps}^−$ from an uncoated Mo polycrystalline surface and Cs coated Mo and Ta polycrystalline surfaces.

### 2. Experimental Setup

The experimental system employed was a magnetically guided slow positron beam apparatus at the Tokyo University of Science shown in Figure 1. It was similar to that used for the study of inner-shell ionization by low-energy positron impact [36].

Positrons from a $^{22}\text{Na}$ positron source of activity 740 MBq were moderated in an electro-polished tungsten mesh moderator. The slow positrons emitted from the moderator followed helical paths down the line of travel of the beam in the magnetic field of 0.01T and entered the $E \times B$ filter, where unmoderated positrons were removed from the beam. After leaving the filter, the beam was transported with an energy of 100 eV to the target. The beam intensity at the target position was $1 \times 10^5 e^+/s$ and the beam diameter was about 5 mm. The base pressure of the target chamber was $2.4 \times 10^{-8}$ Pa.

Figure 2 shows, schematically, the target and the detectors used in the present experiments. The target was biased at a voltage $−3.0\text{kV}$, so that the positrons were incident on the target with an energy of 3.1keV. The $\text{Ps}^−$ emitted would be accelerated by the electric field between the target and the grounded grid placed at a distance $d$ in front of the target. The distance $d$ was set at 3 mm. The self-annihilation of the $\text{Ps}^−$ produced blue-shifted $\gamma$-rays in the region of a few cm from the target. The energy of the $\text{Ps}^−$ annihilation $\gamma$-rays for the present experimental condition was 542keV [32]. The $\gamma$-rays were detected using the Ge detector in coincidence with the signals from the NaI scintillation detector placed behind the target.

### 3. Results and Discussion

#### 3.1. $\text{Ps}^−$ emission from Cs deposited W(100) surfaces

The target was a W($100$) foil, purchased from Aarhus University, of dimensions 10mm × 10mm × 2 μm supported on a backing of polycrystalline W foil 25μm thick. It was annealed in situ at 1500°C for 30min by passing an electric current in order to reduce bulk defects, which act as
Figure 1. Schematic diagram of the slow positron beam apparatus at the Tokyo University of Science.

Figure 2. The target and the detectors used in the present experiments.

positron traps, and to clean the target surface. The Cs layer of $2 \times 10^{14}$ atoms cm$^{-2}$ coverage was produced using a Cs dispenser.

Figure 3 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 the deposition.

The conversion efficiency, $f$, for the uncoated W(100) after annealing was 0.005%. After the deposition, $f$ 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 about 0.1% after 17h, which is still higher than that obtained using the beam foil method [35].
3.2. $\text{Ps}^-$ emission from Mo and Ta polycrystalline surfaces

The Mo and Ta targets were commercially obtained polycrystalline foils 20 $\mu$m thick. They were annealed \textit{in situ} at 1500°C for 30min. Figure 4 shows the annihilation photon energy spectra. The spectra for the unanneled and annealed targets were taken for a period of about 35–115h. For the annealed Mo target, a low-intensity peak attributed to the $\text{Ps}^-$ emission was seen at 542keV. The value of $f$ was 0.002%. For the Mo target with $2 \times 10^{14}$ atoms cm$^{-2}$ Cs coverage, the value of $f$ for a spectrum accumulated for 3000s after deposition was 0.8%.

For the annealed Ta target, no significant peak was seen at 542keV. This is consistent with the fact that the estimated value of $\phi_{\text{Ps}^-}$ for Ta is positive, as shown in Table 1. After Cs coating with a $2 \times 10^{14}$ atoms cm$^{-2}$ coverage, a peak due to the $\text{Ps}^-$ emission appeared in the spectrum accumulated for 3000s. Similar phenomena were also observed for a Fe polycrystalline target [37]. The value of $f$ was 1.5%, which was higher than that for the Cs coated W(100) surface.

The change of $f$ by Cs coating might due to the electron and positron work function changes as discussed elsewhere [35][37]. However, the effect observed was too large to explain using a simple model based on the changes of the electron and positron energy levels in the target. The
structures of the adsorbate islands on the surface might be a contributory factor to the increased \( \text{Ps}^- \) emission. The contamination of the surfaces by residual molecules in the chamber might also affect the emission.

4. Conclusions
We have found that the \( \text{Ps}^- \) emission has been greatly improved by the Cs deposition onto a W(100) surface. The emission efficiency measured over a time interval of 3000s immediately after the coating was found to be 1.25% for the target with a \( 2 \times 10^{14} \) atoms cm\(^{-2} \) Cs layer. The efficiencies for Mo and Ta polycrystalline surfaces have also been improved. In particular, the efficiency for Ta polycrystalline surface, which did not emit \( \text{Ps}^- \) before Cs coating, over a time interval of 3000s immediately after the coating was 1.5% for a target with a \( 2 \times 10^{14} \) atoms cm\(^{-2} \) Cs layer, which is even higher than that obtained for the Cs coated W(100) surface.

The efficiency obtained in the present work might be sufficient to enable thorough investigations of, for example, precision measurements of the \( \text{Ps}^- \) decay rates and the \( \text{Ps}^- \) binding energy.

5. Acknowledgment
We thank Professors A. P. Mills, Jr., G. Laricchia, K. G. Lynn, A. H. Weiss and T. Hyodo and Dr. T. Tachibana for valuable discussions and their encouragement. This work was supported
by the Reimei Research Promotion project (Japan Atomic Energy Agency).

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