Durable emission of positronium negative ions from Na- and K-coated W(100) surfaces

Hiroki Terabe¹, Koji Michishio, Takayuki Tachibana and Yasuyuki Nagashima¹

Department of Physics, Tokyo University of Science, 1-3 Kagurazaka, Shinjuku, Tokyo 162-8601, Japan
E-mail: j1211706@ed.kagu.tus.ac.jp and ynaga@rs.kagu.tus.ac.jp

New Journal of Physics 14 (2012) 015003 (6pp)
Received 28 October 2011
Published 20 January 2012
Online at http://www.njp.org/
doi:10.1088/1367-2630/14/1/015003

Abstract. The emission of positronium negative ions from Na- and K-coated W(100) surfaces has been studied. The emission efficiencies (the fractions of incident slow positrons yielding the ions) for both samples were found to be as high as 1.5%. Although the efficiencies decreased with time after coating, the effects were more durable than that for Cs coating. In particular, the efficiency after Na coating was still higher than 0.5% after three days. The successful development of a durable Ps⁻ source opens the door to a new era of experimental investigations on the Ps⁻ ion.

Contents

1. Introduction 1
2. Experimental procedure 2
3. Results and discussion 3
4. Conclusions 5
Acknowledgments 6
References 6

1. Introduction

In 2008, efficient emission of the positronium negative ion (Ps⁻), a bound state of one positron and two electrons, from a Cs-coated W(100) sample bombarded with slow positrons was

¹ Authors to whom any correspondence should be addressed.
Table 1. First ionization energy and maximum reduction of $\Delta$ by alkali-metal coating on W(100).

| Element | First ionization energy (eV) [6] | Maximum reduction of $\Delta$ by alkali-metal coating on W(100) (eV) [7] |
|---------|---------------------------------|-------------------------------------------------|
| Na      | 5.139 076                       | −2.4                                            |
| K       | 4.340 663                       | −2.7                                            |
| Cs      | 3.893 905                       | −3.0                                            |

observed [1–4]. The energy required for Ps$^-$ emission from a metal surface, $\phi_{Ps^-}$, is given by [1]

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

where $\mu_+$ and $\mu_-$ are the positron and electron chemical potentials, respectively, and $\Delta$ is the effect of the surface dipole barrier. $E_B$ is the total binding energy of Ps$^-$, a energy required to break up Ps$^-$ into its constituent particles. It is equal to the sum of the positronium binding energy (6.80 eV) and the electron binding energy to positronium (0.33 eV). The value of $\phi_{Ps^-}$ is negative for W(100) and tungsten polycrystalline surfaces, and thus the Ps$^-$ ions are emitted spontaneously.

Although the emission efficiency, the fraction of slow positrons yielding Ps$^-$, was less than 0.01% [5], a dramatic enhancement to 1.25% was achieved by coating the W(100) sample with a monolayer of Cs. The enhancement was attributed to a reduction in the surface dipole barrier, which resulted in an increase in the number of conduction electrons contributing to the Ps$^-$ formation. However, the efficiency decreased with time and was almost constant at about 0.1% after $6 \times 10^4$ s. This may be because the Cs layer on the sample surface reacted with residual molecules in the sample chamber. In order to perform new experiments with Ps$^-$, a higher-efficiency and more stable Ps$^-$ source is required.

The first ionization energies and the maximum reductions of $\Delta$ by alkali metal coating on W(100) are listed in table 1. For Cs, the ionization energy is the lowest and reaction with residual molecules in the chamber is the greatest. On the other hand, K and Na are chemically less reactive than Cs and thus the coating may be effective for longer, although the efficiency is not expected to be as high as that of the Cs coating [8]. In this work, we have studied the effects of Na and K coating on W(100) samples on Ps$^-$ emission.

2. Experimental procedure

Figure 1 shows, schematically, the sample chamber used in the present experiment. The apparatus was the same as that used in previous work, where the Ps$^-$ emission efficiencies for Cs-coated surfaces were measured [1–4], with the exception of the addition of Na and K deposition systems and a quartz crystal deposition monitor system. The base pressure was $2–6 \times 10^{-8}$ Pa, which was comparable with that in previous works.

Two identical samples, A and B, were used. They were W(100) foils of 2 $\mu$m thickness, manufactured at Aarhus University, and were supported on a backing of polycrystalline tungsten foils of 25 $\mu$m thickness. First, they were annealed in situ at 1800 K for 30 min by the passage of electric currents. Layers of Na and K were produced using alkali-metal dispensers.
Figure 1. Schematic diagram of the sample chamber.

The sample was biased at a voltage $V_s$ so that the positrons impinged on the sample with an energy of $-eV_s + 0.1\text{ keV}$, where $e$ is the charge of the positron. The value of $V_s$ was set at $-1\text{ kV}$ for sample A and $-3\text{ kV}$ for sample B. A grounded mesh with 89% transmission was placed at a distance $d$ in front of the sample. The distance $d$, which could be changed using a linear transfer, was set at 2 mm for sample A and 3 mm for sample B, respectively. The Ps$^-$ ions emitted from the samples were accelerated by the electric field between the sample and the mesh, and hence the $\gamma$-rays arising from the Ps$^-$ self-annihilation were blue-shifted. The $\gamma$-rays were monitored using the Ge detector in coincidence with signals from the NaI scintillation detector placed behind the sample.

3. Results and discussion

Figure 2(a) shows the annihilation photon energy spectra for sample A. The thicknesses of the K and Na layers were $3.3 \times 10^{14}\text{ atoms cm}^{-2}$ (2.4 Å) and $6.2 \times 10^{14}\text{ atoms cm}^{-2}$ (2.5 Å), respectively, where the electron work functions become the lowest. Figure 2(b) shows the spectra for sample B with a Na coating of $3.4 \times 10^{14}\text{ atoms cm}^{-2}$ (1.3 Å). The spectra for the samples without coating were accumulated for $1.0 \times 10^{5}\text{ s}$ after annealing. Those with coating were taken for $1.0 \times 10^{5}\text{ s}$ after deposition. The energies of the Ps$^-$ self-annihilation $\gamma$-rays are indicated by the vertical arrows. Small peaks due to the Ps$^-$ self-annihilation were observed for the samples without coating. After coating, a dramatic increase in the peak intensity was observed for both alkali metals.
Figure 2. Annihilation photon energy spectra for (a) sample A ($V_s = -1$ kV, $d = 2$ mm) and (b) sample B ($V_s = -3$ kV, $d = 3$ mm). The vertical arrows indicate the energies of Ps$^-$ self-annihilation $\gamma$-rays.

The data on time dependence of Ps$^-$ emission efficiency for samples A and B are shown in figure 3, together with those for Cs-coated W(100) in the previous work [1]. The Ps$^-$ emission efficiency for sample A increased after K coating and reached a maximum value of 1.5%, which is higher than that for the Cs-coated sample. Then the value decreased and was almost constant at about 0.1% after $1.2 \times 10^5$ s. The change after K coating was more gradual than that after Cs coating.

The efficiency for sample A increased slightly after Na coating and reached the maximum value 1.5%, which is almost the same as that for K coating, after $4 \times 10^4$ s. For sample B, the efficiency increased slowly after Na coating and reached the maximum value 1.4% after $6 \times 10^4$ s. The efficiencies for sample B with Na coating are slightly lower on average than those for sample A with Na coating. This might be due to the difference in the thickness of the Na layers and the positron incident energies [9]. Also, the vacuum conditions, i.e. residual molecules in the chamber which could not be detected using our experimental system, might be different. However, the efficiencies for both samples were higher than 1.0% even after $1.2 \times 10^5$ s, when the efficiency for the K-coated sample dropped to 0.1%. This means that
Figure 3. \(\text{Ps}^-\) emission efficiencies from the samples with alkali metal coating plotted against time after deposition. The data for Na-coated sample A \((3.4 \times 10^{14} \text{ atoms cm}^{-2}, V_s = -1 \text{ kV})\) were not obtained in the region between \(1.9 \times 10^5\) and \(2.1 \times 10^5\) s.

W(100) with Na coating has a higher durability than W(100) with Cs or K coating. Although the change in \(\Delta\) is smaller for Na coating, the efficiencies for Na-coated W(100) are as high as those for K-coated surfaces.

In summary, the change in efficiency for the both samples coated with alkali metals of higher ionization energies was more gradual as expected. Surprisingly, the maximum values for K and Na coating were higher than those for Cs coating. We speculate that the maximum value for the Cs-coated surface might be even higher but the decrease was too rapid to observe under the experimental conditions. Although the reason for the unexpectedly high efficiencies for \(\text{Ps}^-\) emission from alkali-metal-coated surfaces has been discussed in previous papers [1, 2], the details are not known. Further investigations are necessary, both experimentally and theoretically.

The durability of \(\text{Ps}^-\) emission from a Na-coated surface enables us to realize new experiments for the \(\text{Ps}^-\) ion. Recently, we succeeded in the first observation of the photodetachment of \(\text{Ps}^-\) produced using the present method [10]. An energy-tunable positronium beam has also been achieved by the \(\text{Ps}^-\) photodetachment technique [11].

4. Conclusions

We found that the \(\text{Ps}^-\) emission from Na-coated W(100) is as effective as and the decrease is more gradual than those for Cs- and K-coated surfaces. The present technique has been applied for the first observation of \(\text{Ps}^-\) photodetachment [10]. It can be used for other \(\text{Ps}^-\) experimental investigations, e.g. the observation of Feshbach resonances of \(\text{Ps}^-\) photodetachment [12–14] and the measurement of the \(\text{Ps}^-\) decay rate with higher precision than in previous measurements [15, 16].

New Journal of Physics 14 (2012) 015003 (http://www.njp.org/)
Acknowledgments

We thank Mr Ryohei Suzuki for his assistance with the experiment. This work was supported by a Grant-in-Aid for Scientific Research (grant no. 23654093) from the Ministry of Education, Science and Culture of Japan.

References

[1] Nagashima Y, Hakodate T, Miyamoto A and Michishio K 2008 New J. Phys. 10 123029
[2] Nagashima Y, Hakodate T, Miyamoto A, Michishio K and Terabe H 2009 Phys. Status Solidi c 6 2291
[3] Nagashima Y, Hakodate T, Miyamoto A, Michishio K and Terabe H 2009 J. Phys.: Conf. Ser. 194 012039
[4] Michishio K, Tachibana T, Terabe H, Miyamoto A and Nagashima Y 2010 J. Phys.: Conf. Ser. 199 012003
[5] Nagashima Y and Sakai T 2006 New J. Phys. 8 319
[6] David R L (ed) 2008 CRC Handbook of Chemistry and Physics 89th edn (Boca Raton, FL: CRC Press)
[7] Kiejna A and Wojciechowski K F 1981 Prog. Surf. Sci. 11 293
[8] Terabe H, Michishio K, Tachibana T and Nagashima Y 2011 J. Phys.: Conf. Ser. 262 012058
[9] Schultz P J and Lynn K G 1988 Rev. Mod. Phys. 60 701
[10] Michishio K, Tachibana T, Terabe H, Igarashi A, Wada K, Kuga T, Yagishita A, Hyodo T and Nagashima Y 2011 Phys. Rev. Lett. 106 153401
[11] Michishio K et al in preparation
[12] Bhatia A K and Drachman R J 1985 Phys. Rev. A 32 3745
[13] Ward S J, Humberston J W and McDowell M R C 1987 J. Phys. B: At. Mol. Phys. 20 127
[14] Igarashi A, Shimamura I and Toshima N 2000 New J. Phys. 2 17
[15] Mills A P Jr 1983 Phys. Rev. Lett. 50 671
[16] Fleischer F, Degreif K, Gwinner G, Lestinsky M, Liechtenstein V, Plenge F and Schwalm D 2006 Phys. Rev. Lett. 96 063401