Positronium negative ion experiments—formation, photodetachment and production of an energy tunable positronium beam—

Yasuyuki Nagashima, Koji Michishio, Takayuki Tachibana, Hiroki Terabe and Ryohei Suzuki

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

Abstract. Recent developments in the efficient production of positronium negative ions open the door to a new era of experimental investigations of these ions. In the present paper, experimental studies so far are reviewed.

1. Introduction
More than fifty years ago, J. A. Wheeler [1] proposed the existence of several kinds of exotic systems composed of three particles with equal masses and bound through Coulomb interaction. The positronium negative ion (Ps\(^-\)), a bound state of a positron and two electrons, is the only system that has been observed thus far [2]. Since the prediction by Wheeler, many theoretical studies have been performed to explore the nature of Ps\(^-\). For example, the ground-state energy and the annihilation rate have been calculated [3]–[10] and the photodetachment process has been studied [11]–[13]. However, measurements of the decay rate have been the only experiments performed for many years [14]–[16] because of extremely low Ps\(^-\) intensities.

In 2006, a new method of generating Ps\(^-\) was developed [17]. Some of the slow positrons injected into a clean tungsten sample are emitted as Ps\(^-\). Although the formation efficiency observed was less than 0.01%, a dramatic enhancement of the efficiency up to 1.25% has been achieved by coating Cs atoms onto the tungsten surface [18, 19]. Furthermore, coating with Na has been found to be as effective for Ps\(^-\) production and the effect appears to remain for longer [20]. This technique has enabled us to perform the first observation of the photodetachment of Ps\(^-\) [21].

This paper will give a brief review of the experimental studies performed so far.

2. Ps\(^-\) Formation using carbon thin film
The first observation of Ps\(^-\) was made by Mills [2] in 1981 using the beam-foil method. A beam of 400 eV positrons was guided onto a 4nm carbon foil, supported by a Ni mesh, and the \(\gamma\)-ray spectra were monitored with a Ge (Li) detector placed downstream. The grid located behind the carbon film was biased positively so as to accelerate the Ps\(^-\) but return any transmitted positrons to the foil. The \(\gamma\)-rays from two photon annihilation of the accelerated Ps\(^-\) monitored...
by the detector were blue shifted and hence separated from the $\gamma$-rays from any other two photon annihilation processes. The Ps$^-$ formation efficiency, the fraction of positrons yielding Ps$^-$, was 0.028%.

Mills also investigated the decay rate of the Ps$^-$. The bias for the grid in front of the target and the distance between the target and the foil were changed and the Ps$^-$ formation efficiencies measured were fitted to obtain the decay rate. The value determined was $2.09 (9) \text{ ns}^{-1}$, which is consistent with the theoretical value calculated by Ho [5].

In order to obtain a more precise value, Mills developed a tandem acceleration method [15]. Instead of detecting the $\gamma$-rays, positrons generated by stripping the accelerated Ps$^-$ with another carbon foil were detected. Although Mills did not obtain the final result, Fleischer et al. [16] determined the decay rate using the same method in 2006. Their value was $2.089(15) \text{ ns}^{-1}$, which is consistent with recent theoretical results [8, 10].

3. Efficient emission of Ps$^-$ from alkali metal coated tungsten surfaces
When positrons with a few keV energy are incident upon metal surfaces, they lose their energy and are thermalized. Some of them diffuse back to the surface and contribute to the positron re-emission or Ps emission if energetically allowed. The energy required to emit Ps$^-$ from the surface, $\phi_{Ps^-}$, can be written as [22, 17]

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

(1)

where $\phi_+$ and $\phi_-$ are the positron and electron work functions, respectively, $E_B$ is the electron binding energy to Ps (0.33eV) and $E_{Ps^-}$ is the Ps binding energy (6.80eV). The values of $\phi_{Ps^-}$, which are estimated to be negative for polycrystalline tungsten and W(100), show that the Ps$^-$ emission is energetically allowed.

Figure 1 shows our experimental setup to observe Ps$^-$ emission [17]. Slow positrons with an energy of 0.1keV are incident onto the target, biased at $-W$, through an earthed grid. The positron incident energy at the target was $eW + 0.1\text{keV}$, where $e$ is the charge of the positron. The emitted Ps$^-$ ions were accelerated and annihilated in a narrow region a few cm from the grid. The blue-shifted $\gamma$-rays were detected by a Ge detector. The energy of the $\gamma$-rays emitted at an angle $\theta$ from the direction of the Ps$^-$ momentum is

$$E = \frac{1}{1 + \lambda - \sqrt{2\lambda + \lambda^2 \cos^2 \theta}} mc^2,$$

(2)

where $\lambda = \frac{eW}{3mc^2}$, $m$ is the positron mass and $c$ is the speed of light. The vacuum in the target chamber was about $2 \times 10^{-8}\text{Pa}$.

Figure 2 shows the obtained $\gamma$-ray spectra for W(100) [18]. The value of $W$ was set at 3kV. No significant peak of blue-shifted $\gamma$-rays was observed for the unannealed target. After annealing, a small peak due to Ps$^-$ formation appeared for both polycrystalline tungsten and W(100). The Ps$^-$ emission efficiencies were lower than 0.01%.

The electron and positron work functions for the surface with coating can be written as

$$\phi_{c^-} = \phi_- + D, \quad \phi_{c^+} = \phi_+ - D,$$

(3)

where $D$ is the effect of the dipole layer of the coating. Hence, the energy required to emit Ps$^-$ is given by

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

(4)

Since the value of $D$ for an alkali metal coating is negative [23], $\phi_{c^-}$ is still negative and $|\phi_{c^-}|$ increases by coating with such metals. Thus the Ps$^-$ emission efficiency will increase.
Figure 1. Experimental setup for observing the Ps\textsuperscript{−} emission from tungsten surfaces [18]

Figure 2 (c) shows the γ-ray spectrum for a W(100) surface with a 0.8 monolayer of Cs coating. The Ps\textsuperscript{−} emission efficiency is 1.25%, which is two orders of magnitude higher than that for the uncoated surface. However, the efficiency decreased with time and was almost constant at 0.1% 17h after coating. The decrease may be due to the effect of residual gas molecules in the UHV target chamber.

We have also tested coating with Na, which is less active chemically, in order to obtain longer stability at the cost of the maximum value of the efficiency. The effect of D is reported to be smaller than that for Cs. Surprisingly, we found that the efficiency immediately after the deposition was higher than that for Cs coating (figure 2 (d)) and also the efficiency remained above 0.5% for more than 3 days [20].

4. Ps\textsuperscript{−} photodetachment
The development of an efficient method of Ps\textsuperscript{−} formation enables us to investigate the Ps\textsuperscript{−} photodetachment, which has been investigated theoretically by several authors, as shown in figure 1 in [13]. Several resonance structures were predicted.

Recently, we have succeeded in the observation of Ps\textsuperscript{−} photodetachment with the crossed beam method using a Ps\textsuperscript{−} beam and a high power pulsed Nd: YAG laser [21]. A pulsed slow positron beam at the KEK-IMSS slow positron facility [24] was used. The Ps\textsuperscript{−} ions were produced by bombarding a Na coated polycrystalline tungsten surface with the beam. The laser pulses were synchronized to the positron pulses. The wave length of the laser was 1064nm, corresponding to a photon energy of 1.165eV, which is higher than the photodetachment threshold energy (0.33eV). The γ-rays produced by the self-annihilation of the accelerated positron beam were detected with a NaI(Tl) scintillation detector and a Ge detector. The positron beam intensity was monitored with a NaI(Tl) detector. The positron beam intensity was about 5×10\textsuperscript{8} s\textsuperscript{-1}

The results are shown in figure 3. The positron beam intensity is suppressed by an order of magnitude when the laser is on. This indicates that the positron beam is photodetached by the laser. The suppression is not observed when the laser is off. This indicates that the Ps\textsuperscript{−} ions are not produced by the laser.

The suppression of the positron beam intensity is due to the photodetachment of Ps\textsuperscript{−} ions. The Ps\textsuperscript{−} ions are not produced by the laser. This indicates that the Ps\textsuperscript{−} ions are not produced by the laser.
Figure 2. Annihilation γ-ray energy spectra for (a) unannealed, (b) annealed, (c) Cs coated and (d) Na coated W(100) surfaces. The arrows indicate the γ-ray energy predicted by Eq.(2).

Ps− were monitored using Ge detectors. The relative amount of para-positronium and ortho-positronium formed from Ps− photodetachment is 1:3. Therefore, the Ps− Doper-shifted peak in the γ-ray energy spectrum will be decreased by 3/4 if the laser intensity is high enough.

Figure 3 shows the annihilation γ-ray energy spectra observed with laser off and on. The peak at 529 keV is attributed to the blue-shifted annihilation γ-rays from accelerated Ps−. The peak intensity decreased by 57 % upon laser irradiation. The decrease was less than 3/4 because some of the Ps− ions self-annihilated before crossing the laser beam in the field free region and the laser power was not sufficient to photodetach all the Ps− crossing the laser. The lower limit of the photodetachment cross section was obtained to be 2.1×10^{−17} cm², which is consistent with the values calculated by Bhatia and Drachman [11], Ward and Humberston [12] and Igarashi et al [13].
5. Towards the production of an energy-tunable positronium beam

Energy-tunable Ps beams have been developed using charge exchange of positrons with a low density gas by the reaction
\[ e^+ + M \rightarrow Ps + M^+ \] (5)
of a positron with a molecule, M [25]. The Ps kinetic energy, \( T_{Ps} \), is related to that of the positron kinetic energy, \( T_{e^+} \), as
\[ T_{Ps} = T_{e^+} - E_I + E_{Ps}, \] (6)
where \( E_I \) is the ionization energy of the target gas molecules. This technique has been used for the observation of Ps specular reflection from a LiF surface [26] and the measurement of Ps-gas scattering cross sections in the energy range below 100eV [27]. Formation of Ps beams with a kinetic energy from 10 to 500eV have also been tried by partial transmission of keV-energy positrons through 5nm carbon film [28].

It has been proposed that the production of an energy-tunable monoenergetic Ps beam might be feasible by the photodetachment of Ps\(^-\) produced using Cs coated carbon film or tungsten surface [2, 29, 30]. The photodetachment technique developed using a Na coated tungsten surface [31] has realized the production of such a Ps beam [32].

Recently, grazing incidence fast atom diffraction has been discovered [33, 34]. Using the Ps beam produced by the Ps\(^-\) photodetachment, grazing incidence fast Ps diffraction may also be feasible.

Acknowledgment

The authors would like to gratefully acknowledge the collaborations with T. Sakai, T. Hakodate, A. Miyamoto, T. Hyodo, K. Wada, A. Yagishita, T. Kurihara, A. Igarashi and T. Kuga.

References
[1] Wheeler J A 1946 Ann. N. Y. Acad. Sci. 48 219
[2] Mills Jr. A P 1981, Phys. Rev. Lett. 46 717
[3] Kolos W, Roothaan C C J and Sack R A, 1960 Rev. Mod. Phys. 32 178
[4] Frost A A, Inokuti M and Lowe J P 1964 J. Phys. Chem. 41 482
[5] Ho Y K 1983 J. Phys. B: At. Mol. Phys. 16 1503
[6] Frolov A M and Yeremin A Y 1989 J. Phys. B: At. Mol. Opt. Phys. 38 1263
[7] Ho Y K 1993 Phys. Rev. A 48 4780
[8] Frolov A M 1999 Phys. Rev. A 60 2834
[9] Drake G W F and Grigorescu M 2005 J. Phys. B: At. Mol. Opt. Phys. 38 3377
[10] Puchalski M and Czarnecki A 2007 Phys. Rev. Lett. 99 203401
[11] Bhata A K and Drachman R J 1985 Phys. Rev. A 32 3745
[12] Ward S J, Humberston J W and McDowell M R C, J. Phys. B: At. Mol. Phys. 20 127
[13] Igarashi A, Shimamura I and Toshima 2000 N, New J. Phys. 2 17
[14] Mills Jr A P 1983 Phys. Rev. Lett. 50 671
[15] Mills Jr A P, Friedman P G and Zuckerman D M 1989 Annihilation in Gases and Galaxies (NASA Conference Publication No. 3058) ed R J Drachman pp 213
[16] Fleischer F, Degreif K, Gwinner G, Liechtenstein V, Plenge F, Swalm D 2006 Phys. Rev. Lett. 96 063401
[17] Nagashima Y and Sakai T 2006 New J. Phys. 8 319
[18] Nagashima Y, Hakodate T, Miyamoto A and Michishio K 2008 New J. Phys. 10 123029
[19] Nagashima Y, Hakodate T, Miyamoto A, Michishio K and Terabe H 2009 J. Phys. Conf. Ser. 194 012039
[20] Terabe H, Michishio K, Tachibana T and Nagashima Y 2011 J. Phys. Conf. Ser. 262 012058
[21] Michishio K, Tachibana T, Terabe H, Igarashi A, Wada K, Yagishita A, Hyodo T and Nagashima Y 2011 Phys. Rev. Lett. 106 153401
[22] Wilson R J and Mills Jr A P 1983 Phys. Rev. B 27 3949
[23] Kiejna A and Wojciechowski K F 1981 Prog. Surf. Sci. 11 293
[24] Hyodo T, Wada K, Yagishita A, Kosuge Y, Saito Y, Kurihara T, Kikuchi T, Shirakawa A, Sanami T, Ikeda M, Ohsawa S, Kakihara K, Shidara T 2011 J. Phys. Conf. Ser. 262 012026
[25] Brown B L 1985 Positron Annihilation R M Singru and P C Jain ed (World Scientific, Singapore) pp 328
[26] Weber M H, Tang S, Berko S, Brown B L, Canter K F, Lynn K G, Mills Jr A P, Roellig L O, Viescas A 1988 Phys. Rev. Lett. 81 2542
[27] Brawley S J, Armitage S, Beale J, Leslie D E, Williams A I, Laricchia G 2010 Science 330 789
[28] Mills A P and Crane W 1985 Phys. Rev. A 31 593
[29] Laricchia G 1995 Positron Spectroscopy of Solids A Dupasquier and A P Mills Jr ed (IOS, Amsterdam) pp 401
[30] Laricchia G, Armitage S, Kovář Á and Murtagh D J 2008 Atomic, Molecular, and Optical Physics 56 E Arimondo, P R Berman and C C Lin ed (Elsevier, Amsterdam) pp 1
[31] Nagashima Y, Michishio M, Tachibana T, Terabe H 2011 J. Phys. Conf. Ser. 262 012041
[32] Michishio K, Suzuki R, Tachibana T, Terabe H, Wada K, Hyodo T, Yagishita A and Nagashima Y, in preparation.
[33] Schüller A, Wethekam S, Winter H 2007 Phys. Rev. Lett. 98 016103
[34] Rousseau P, Khemliche H, Borisov A G, Roncin P 2007 Phys. Rev. Lett. 98 016104