

# Kinetic energy of Ps formed by Ore mechanism in Ar gas

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**Abstract.** In order to investigate kinetic energy of positronium (Ps) formed by Ore mechanism, we performed positron annihilation age-momentum correlation (AMOC) measurements in Ar gas for 5.0 MPa and 7.5 MPa at room temperature. From the time dependence of Doppler broadening of *para*-Ps (*p*-Ps) self-annihilation gamma-ray component, we observed Ps slowing down process. Using a simple slowing down model, we obtained the initial kinetic energy of Ps formed by Ore mechanism and Ps-Ar momentum transfer cross section. The initial kinetic energy was 3.9 eV which was higher than the kinetic energy of Ps formed at the upper limit of Ore gap. The momentum transfer cross section was  $0.019 \pm 0.010 \text{ nm}^2$  in between 1 eV and 3.9 eV, and was close to the theoretical calculation.

## 1. Introduction

A positron injected into dense gases has been studied to investigate a correlation between positronium (Ps) and gas molecules [1, 2]. In this case, a Ps is formed during the slowing down of a positron. However, pick-off annihilation of the Ps with gas should depend on the kinetic energy of the Ps. The kinetic energy of Ps was measured to investigate the Ps slowing down in rare gases [3, 4, 5].

In a gas phase, Ps formation is explained by Ore mechanism. An energetic positron picks up one of electrons in an atom (A) and forms a Ps.



A suitable positron energy for a Ps formation is proposed as follows [6]. The kinetic energy of positrons must exceed the Ps formation threshold energy  $E_0 = E_I - E_{\text{Ps}}$ , where  $E_I$  is the ionization potential of the gas atom and  $E_{\text{Ps}} = 6.8 \text{ eV}$  is the bounding energy of Ps. If  $E_{\text{ex}}$  is the lowest significant excitation energy for the atom, then for positrons of energy in the range  $E_0 < E < E_{\text{ex}}$  the only possible inelastic process is Ps formation. This energy range is so-called Ore gap [2], and the initial kinetic energy of Ps can be estimated. Rare gas are suitable to observe the kinetic energy of Ps formed by Ore mechanism because the Ps loses its kinetic energy very slowly only by elastic collisions below 5.1 eV which is the lowest Ps excitation energy. In the case of an Ar gas, Ore gap ranges from 9 eV (Ps formation threshold) to 11.7 eV (1st electronic excitation threshold of Ar). The kinetic energy of Ps formed by Ore mechanism supposed to range from 0 to 2.7 eV.

In this study, we determined the time dependence of the kinetic energy of the Ps and discuss Ore mechanism.



## 2. Experimental

We performed a positron annihilation age-momentum correlation (AMOC) measurement in Ar gas for 5.0 MPa and 7.5 MPa at room temperature, to observe the initial kinetic energy of Ps and to reveal the Ps slowing down process below 6.8 eV. Time resolution of this system was 300 ps at the full width at half maximum (FWHM). Energy resolution of this system was 1.23 keV at 511 keV at FWHM. The positron source ( $^{22}\text{Na}$ , 0.5 MBq) was sandwiched between two sheets of 5  $\mu\text{m}$  of the Ni foil (purity > 99 %). The positron source was placed in the center of a cylindrical high-pressure vessel with a diameter of 2.8 cm and a height of 5.0 cm. Detail of the experimental set up of this work was described elsewhere [7, 8].

## 3. Results and discussion

Since the Doppler broadening of  $p$ -Ps (intrinsic lifetime = 0.125 ns) annihilation gamma-ray is narrower than those of any other annihilation gamma-rays [9], we resolved the time dependent Doppler broadening spectrum into two components by using two Gaussian functions. Intensities of the  $p$ -Ps and other annihilation components were estimated by the positron annihilation lifetime spectrum. We, therefore, obtained the  $p$ -Ps component as a function of positron annihilation time by subtracting the broad component from the Doppler Broadening spectrum. The  $p$ -Ps component whose lifetime was 0.125 ns observed from 0 ns to 1 ns. From the Doppler broadening of the  $p$ -Ps component, the kinetic energies of Ps were obtained and listed in Table 1 as a function of an annihilation time. Resolution of the annihilation time was 0.2 ns.

In order to determine a momentum transfer cross section, we adopted a Ps slowing down model [3, 10] which was described as,

$$\frac{dE_{\text{Ps}}(t)}{dt} = -\frac{2n_{\text{Ar}}\sigma_m M_{\text{Ar}}}{(M_{\text{Ar}} + m_{\text{Ps}})^2} \sqrt{2m_{\text{Ps}}E_{\text{Ps}}(t)} \left( E_{\text{Ps}}(t) - \frac{3}{2}k_{\text{B}}T \right), \quad (2)$$

where  $\sigma_m$  is the Ps-Ar momentum transfer cross-section,  $M_{\text{Ar}}$  the Ar mass,  $m_{\text{Ps}}$  the Ps mass,  $n_{\text{Ar}}$  the number density of Ar,  $k_{\text{B}}$  the Boltzmann constant, and  $T$  the temperature. Since theoretical calculation indicates that the momentum transfer cross section weakly depends on the Ps kinetic energy below the Ps break-up threshold, we assumed the cross section to be a constant value and solved the differential equation of (2). Time-averaged kinetic energy of Ps is given as

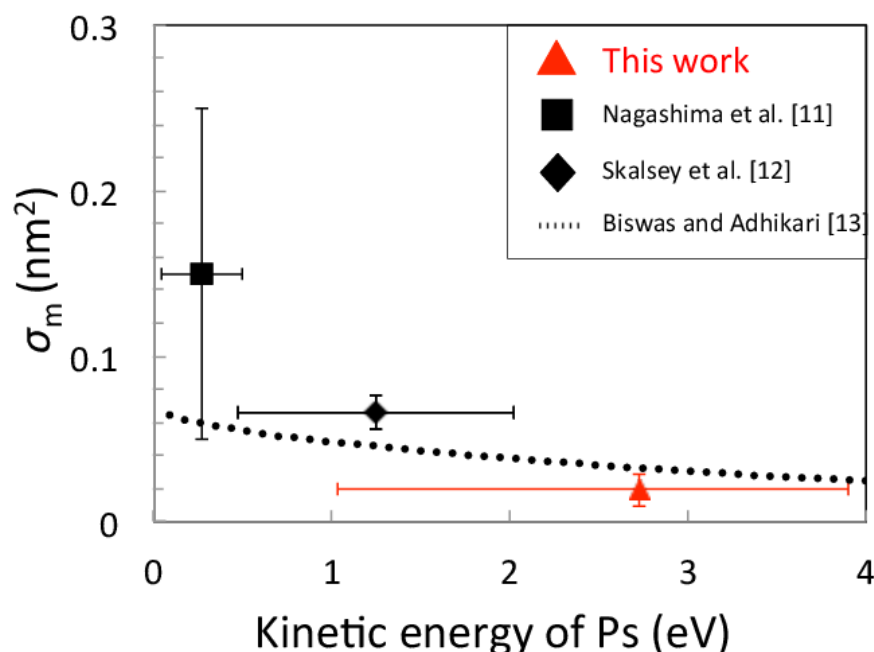
$$\overline{E_{\text{Ps}}}(t_1, t_2) = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} E_{\text{Ps}}(t) dt, \quad (3)$$

where  $t_1$  and  $t_2$  are lower and upper limit of the annihilation time range.

The momentum transfer cross section was determined so that the difference between the observed time-averaged kinetic energy of Ps and the calculated one was minimum value. The

**Table 1.** Observed and calculated time-averaged kinetic energies of Ps,  $\overline{E_{\text{Ps}}^{\text{obs}}}(t_1, t_2)$  and  $E_{\text{Ps}}(t_1, t_2)$ , in Ar gas.

Pressure (MPa)	5.0		7.5	
Number density ( $\text{nm}^{-3}$ )	1.3		2.0	
Time range $t_1 \sim t_2$ (ns)	$\overline{E_{\text{Ps}}^{\text{obs}}} \text{ (eV)}$	$\overline{E_{\text{Ps}}} \text{ (eV)}$	$\overline{E_{\text{Ps}}^{\text{obs}}} \text{ (eV)}$	$\overline{E_{\text{Ps}}} \text{ (eV)}$
0.0 $\sim$ 0.2	3.7	3.7	3.7	3.5
0.2 $\sim$ 0.6	2.5	3.1	2.0	2.3
0.6 $\sim$ 1.0	1.8	2.0	1.4	1.0



**Figure 1.** Momentum transfer cross section  $\sigma_m$  of Ps-Ar elastic scattering as a function of the kinetic energy of Ps. Symbols ( $\blacktriangle$  This work,  $\blacksquare$  [11],  $\blacklozenge$  [12]) show experimental values. The horizontal and vertical error bars show observed energy range and statistical error, respectively. Dotted line shows theoretical calculation [13]

calculated time-averaged kinetic energies of Ps obtained are shown in Table 1 together with the observed ones. The momentum transfer cross section was determined to be  $0.019 \pm 0.010$  nm<sup>2</sup>, and is shown together with literature values in Fig.1. For the experimental values, the horizontal error bars represent the energy range used for the determination of the cross section. The theoretical calculation [13] was closer to our result than other experimental results [11, 12].

Calculated initial kinetic energy of Ps,  $E_{Ps}(0)$ , was 3.9 eV which was higher than the upper limit of the Ore gap energy (2.7 eV). The Ps formation cross section in a positron-Ar collision has a peak around 20 eV which is higher than the Ore gap [14, 15]. During the slowing down of positrons, the Ps can be formed and its kinetic energy would be around 13 eV. The Ps with a kinetic energy more than 6.8 eV would immediately break-up into a positron and an electron by a collision with Ar atoms [16]. In this experimental condition, the density of the gas was high enough to slow Ps down to 6.8 eV within several ps. The Ps whose energy was lower than 6.8 eV would survive and slow down until the annihilation took place in the Ar gas. Thus, the initial distribution of the kinetic energy of Ps would range below 6.8 eV. The value of  $E_{Ps}(0)$  would be an expectation value of the distribution. This results suggested that the initial distribution of the Ps formed by Ore mechanism should change according to the break-up process of the energetic Ps.

#### 4. Summary

Time dependence of Doppler broadening of *p*-Ps self-annihilation gamma-ray was observed by the AMOC measurement. Initial kinetic energy of Ps formed by Ore mechanism in Ar gas was

determined from the Doppler broadening, and was 3.9 eV which was higher than the kinetic energy of Ps formed at the upper limit of the Ore gap. This suggests that the break-up process of the energetic Ps should be considered for the energy distribution of the Ps formed by Ore mechanism which proposed effective range of the initial energy of the Ps formed in gases. From the Ps slowing down model, we obtained momentum transfer cross sections as well as the time dependence of the kinetic energy. The cross section was  $0.019 \pm 0.010 \text{ nm}^2$  in between 1 eV and 3.9 eV, and was close to the theoretical calculation [13].

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