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Nuclear Instruments and Methods in Physics Research B 205 (2003) 417–420

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The measurement of the electron impact ionization cross-sections of hydrogen-like ions

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Abstract

We have measured electron impact ionization cross-sections of hydrogen-like iron and hydrogen-like molybdenum with an electron beam ion trap. The measurements were performed in the electron energy range between 13.5 and 40 keV for hydrogen-like iron and between 50 and 80 keV for hydrogen-like molybdenum.

PACS: 34.80.Kw; 32.30.Rj
Keywords: Electron impact ionization; Hydrogen-like ion; Iron; Molybdenum; Electron beam ion trap

1. Introduction

We have measured electron impact ionization cross-sections of hydrogen-like ions with an electron beam ion trap (EBIT). The electron impact ionization cross-sections of hydrogen-like ions have been measured due to their importance for modeling of high temperature plasmas and for testing of theoretical predictions. For low Z elements up to $Z = 8$ the crossed beam method has been used to obtain the cross-sections [1–3]. On the other hand, for high Z elements measurements have been performed using a trap based method with EBITs [4,5].

In the trap based method, assigning the subscripts B and H for bare and hydrogen-like ions respectively, the electron impact ionization cross-section can be written as [4,5]

$$\sigma_{\mathrm{H}}^{\mathrm{EI}} = \frac{1}{\left(\frac{N_{h\nu_{\mathrm{H}}}}{N_{h\nu_{\mathrm{B}}}}\right)} \frac{\sigma_{\mathrm{B}}^{\sum RR} \frac{\mathrm{d}\sigma_{\mathrm{H}}^{RR=1}}{\mathrm{d}\Omega}}{\frac{\mathrm{d}\sigma_{\mathrm{B}}^{RR=1}}{\mathrm{d}\Omega}} = \delta R_{\mathrm{H}} \frac{R_{\mathrm{B}}}{\delta R_{\mathrm{B}}} \bigg/ \frac{N_{h\nu_{\mathrm{H}}}}{N_{h\nu_{\mathrm{B}}}}, \qquad (1)$$

where σ^{EI} is the electron impact ionization cross-section, $N_{h\nu}$ the intensity of the radiative recombination X-rays observed at right angles with respect to the electron beam axis in the limit of zero charge exchange in the trap, $R = \sigma^{\sum RR}$ the total radiative recombination cross-section and

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0168-583X/03/$ - see front matter
doi:10.1016/S0168-583X(02)02053-0

$\delta R = \mathrm{d}\sigma^{RR=1}/\mathrm{d}\Omega$ the differential radiative recombination cross-section in the direction of the observation. The intensity ratio $N_{h\nu_\mathrm{H}}/N_{h\nu_\mathrm{B}}$ is obtained experimentally in the limit of zero charge exchange. The theoretical total and differential radiative recombination cross-sections are used to get the ionization cross-sections.

We will report the measurements for the electron impact ionization cross-sections of hydrogen-like iron and hydrogen-like molybdenum with the trap based method. It is well known that impurity ions of the wall materials exist in fusion plasmas and heavy elements such as iron are observed in the solar plasma. The electron impact ionization cross-sections of such elements are essential to model and to understand these plasmas.

2. Experiment

We used the Tokyo-EBIT for the measurements [7,8]. The source ions were injected from the top of the EBIT with a metal vapor vacuum arc ion source. The injected ions were trapped and ionized to highly charged ions in the trap constituted by a series of coaxial cylindrical electrodes called drift tubes. The X-rays emitted from the ions were observed at right angles with respect to the electron beam axis and detected with a Ge detector. The X-ray signals were stored in a computer with a multi-parameter data acquisition system [9], simultaneously with the time information of X-ray detection. The time information was used to check the X-ray intensity variation with time to confirm the equilibrium condition. During the measurements neon gas was introduced to the trap for evaporative cooling and, thus, escape of the highly charged ions was negligible. The trapped ions were dumped every 4 s for iron and every 20 s for molybdenum to avoid accumulation of unwanted ions such as barium originating from the cathode of the electron gun.

The measurements were performed at 13.3, 14.8, 17.3, 19.8, 24.8, 29.8 and 39.6 keV electron energies for iron and at 49.4, 64.4 and 79.6 keV for molybdenum. The obtained X-ray spectra were binned in 0.1 s intervals for iron and 1 s intervals for molybdenum from the start of the trapping. The binned spectra were fitted by a combination of Gaussian functions and the peak heights of the radiative recombination X-ray lines were obtained. After checking the equilibrium condition, we summed over the spectra measured during the time when the system satisfied the condition, fitted the Gaussian functions to the summed spectrum and obtained the peak heights.

3. Results and discussion

In the trap based method the intensities of the radiative recombination X-rays are measured at several neutral densities or electron currents to extrapolate away the charge exchange contribution [4,5].

For iron both the neutral density and the electron current were scanned at 15 keV. The ionization cross-section and the charge exchange correction were obtained at the energy. For other electron energies from 12.5 to 40 keV a single measurement was performed without scanning of the neutral density and the electron current. The charge exchange contribution was corrected with the value obtained at 15 keV. The results are shown in Fig. 1. The error bars shown are statistical. Our own theoretical result calculated with the relativistic distorted wave method is also presented for comparison. In our calculation the Di-

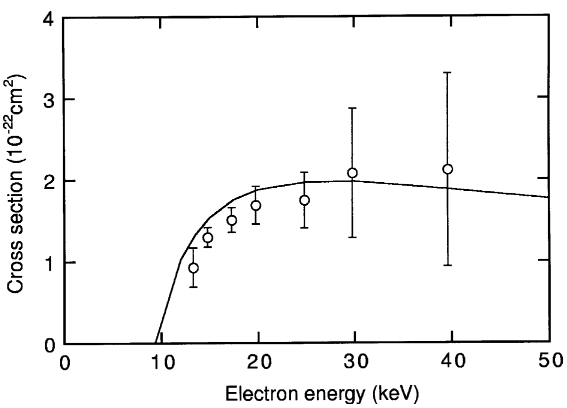

Fig. 1. The electron impact ionization cross-sections of hydrogen-like iron ions. The line is our theoretical result calculated with the relativistic distorted wave method.

rac–Fock potential of average configuration obtained from GRASP calculation [10] was used as the distorted potential in the calculation of continuum wave functions. The amplitude of continuum wave functions [11,12] were obtained in numerical way starting from large enough radius, using the WKB method. This is significant for low energy states. The transition matrix elements for the energy of ionized electrons lower than 1 eV were obtained from extrapolation. The calculated values reproduce well the experiment except for the low energy region.

For molybdenum only the beam current was scanned for extrapolation to get the intensities in the limit of zero charge exchange. This was performed for all the energies studied. From the intensity ratios in the limit the cross-sections were obtained. The results are shown in Fig. 2. The error bars on this figure are also statistical. These are compared with the experimental results measured previously [4]. The agreement between both the results is quite good. The result calculated with Fontes et al. [6], which is based on the relativistic distorted wave method with the generalized Breit interaction, is shown on the figure as a reference. The relativistic effects and the Breit interaction become more important with increase in the electron energy and the nuclear charge [6,13].

We summarize the electron impact ionization cross-sections obtained in this study in Table 1.

Table 1
The ionization cross-sections of hydrogen-like iron and hydrogen-like molybdenum

	E_e (keV)	σ_H^{EI} (10^{-22} cm^2)
Fe ($Z = 26$)	13.3	0.93 ± 0.24
	14.8	1.30 ± 0.12
	17.3	1.51 ± 0.15
	19.8	1.69 ± 0.23
	24.8	1.75 ± 0.34
	29.8	2.08 ± 0.79
	39.6	2.12 ± 1.18
Mo ($Z = 42$)	49.4	0.282 ± 0.022
	64.4	0.313 ± 0.029
	79.6	0.323 ± 0.051

As the electron energy increases the errors increase, as shown in Figs. 1 and 2. The error of the electron impact ionization cross-section ϵ_H^{EI}, propagated from that of the intensity ratio in the limit of zero charge exchange $\epsilon^{N_{h\nu_H}/N_{h\nu_B}}$, can be written $\epsilon_H^{EI} = \alpha \times \epsilon^{N_{h\nu_H}/N_{h\nu_B}}$ with the coefficient α given by

$$\alpha = \sigma_H^{EI^2} \frac{\delta R_B}{R_B} \frac{1}{\delta R_H}. \quad (2)$$

Fig. 3 shows the electron energy dependence of α for iron and molybdenum, which are calculated with the values used and obtained in this study. One can see that α grows rapidly as the electron energy increases. Measurements with much higher accuracy are required with increase in the electron

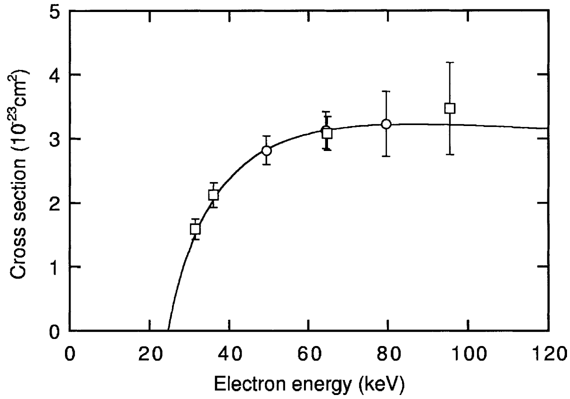

Fig. 2. The electron impact ionization cross-sections of hydrogen-like molybdenum ions. The circles are our results and the squares are those obtained by Marrs et al. [4]. The line is calculated with the formula proposed by Fontes et al. [6].

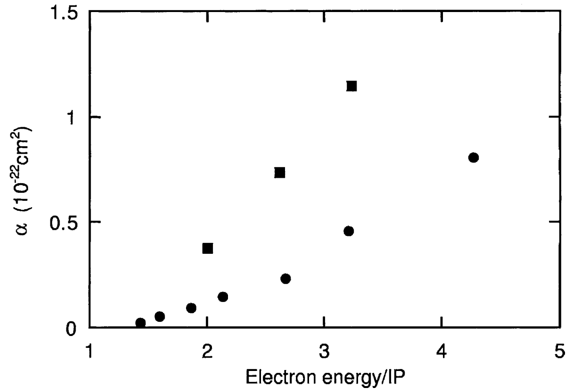

Fig. 3. α in Eq. (2) for iron (●) and molybdenum (■). The abscissa is the electron energy in ionization threshold units.

energy to obtain the cross-sections with high accuracy.

4. Conclusion

We have measured the electron impact ionization cross-sections of hydrogen-like iron between 13.5 and 40 keV and hydrogen-like molybdenum between 50 and 80 keV. The results are compared with theoretical results and, for molybdenum, also with the experimental results measured previously. Accumulation of the cross-sections with high accuracy are needed to get good understanding of this process and also to verify theoretical results used for plasma modeling.

Acknowledgements

This work was performed under the auspices of the International Cooperative Research Project (ICORP) of the Japan Science and Technology Corporation. We are grateful to the Royal Society and Great Britain Sasakawa Foundation for additional funding for the travel to perform this collaboration. H.W. thanks Japan Society for the Promotion of Science for the support of the JSPS overseas research fellowship.

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