

Total Electron Transfer Cross Sections for Highly Charged Ion - Alkali Metal Atom Collisions

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Abstract

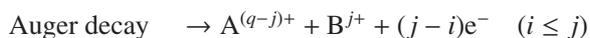
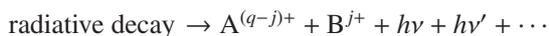
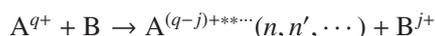
The cross sections for highly charged iodine ion (I^{q+} , $q = 6 \sim 30$, $E = 1.5q$ keV) - alkali metal atom (Na, K, Rb, Cs) collisions have been measured on the basis of the initial growth-rate method. It is shown that the cross sections increase as the charge of the projectile ion increases. We compare our data with the calculations by the extended classical over-barrier model and the classical-trajectory Monte Carlo method. The cross sections are represented by $\sigma_q^{exp} = 1.05 \times 10^{-13} \cdot q/IP^2$ (cm²), reasonably well, where IP (eV) is the ionization energy of the target atom.

Keywords:

highly charged ion, charge exchange, electron transfer, electron capture, cross section

1. Introduction

The investigation of the electron transfer processes in collisions of highly charged ions (HCIs) with neutral atoms and molecules is of great importance not only in basic atomic collision physics, *e.g.* for understanding the interactions between charged particles, but also in such diverse fields as controlled-thermonuclear-fusion research, development of x-ray laser devices and astrophysics. In such processes, several electrons could be simultaneously transferred to excited states of HCIs with significantly large cross sections, and finally the product ions are stabilized by emission of photon(s) or electron(s) or both,



where j and i are, respectively, the number of electrons initially transferred from the target and the number of electrons eventually captured by the projectile ion after stabilization, and n, n' are principal quantum numbers

of the transferred electron states. To date, multiple electron transfer processes have been widely studied [1]. The electron transfer cross sections in HCIs-atom collisions have been expressed by the classical over-barrier model (ECBM) [2-6] reasonably well. The energy deposition model has been successfully applied to the observed Auger decay processes and multiple ionization processes [7-9]. Recent activities in those studies are reviewed by Cederquist *et al.* [10].

Previously, we measured the absolute cross sections ($\sigma_{q,q-i}^j$) for i -electron capture (to the projectile) and j -electron removal (from the target) in collisions of HCIs with rare gas atoms [11,12] at collision energy of $1.5q$ keV by the coincidence measurement method, and studied the decay processes from the excited states produced by electron transfer processes [13]. We deduced a simple scaling relation for the partial and total multiple-electron transfer cross sections in HCIs ($q = 6 \sim 30$) - rare gas atom collisions from ECBM

[14]. Furthermore, we have shown that this scaling law deduced for rare gas atoms can also reproduce our measured data for molecular targets [15], as well. For alkali metal atoms, since the ionization energies are fairly small in comparison with those of rare gas atoms, it is expected that electrons are transferred to HCIs with quite large cross sections.

2. Experiments

Figure 1 shows the experimental apparatus, this is basically the same as that of Tawara *et al.* [16]. In the present study, an electron beam ion source (EBIS) is used for the purpose of producing low energy (1.5q keV) HCIs. After the charge and mass selection by the magnet, the ions are directed into the collision chamber and enter into the target cell, which is 28 mm long with the entrance aperture of 0.5 mm and the exit aperture of 2 mm in diameter. The target cell is connected to the oven, in which an alkali metal vapor is generated, and its temperature is measured by thermocouples and controlled by a programmable controller to within $\pm 0.1^\circ\text{C}$. The temperature of the collision cell is kept higher than that of the oven so as to prevent the alkali metal atoms in the target cell from sticking on the wall. In order to judge whether the density of alkali atoms is sufficiently stable, we employ a surface ionization type ion gauge which is located above the target cell and monitor the flux of alkali atoms passing through a small hole on this target cell wall. The target density is estimated from the measured oven temperature on the basis of the vapor pressure data [17]. The primary ions and charge-changed ions exiting the target cell pass through four mesh electrodes. The retarding positive voltage V_r is applied to the second and third meshes which are connected together. The

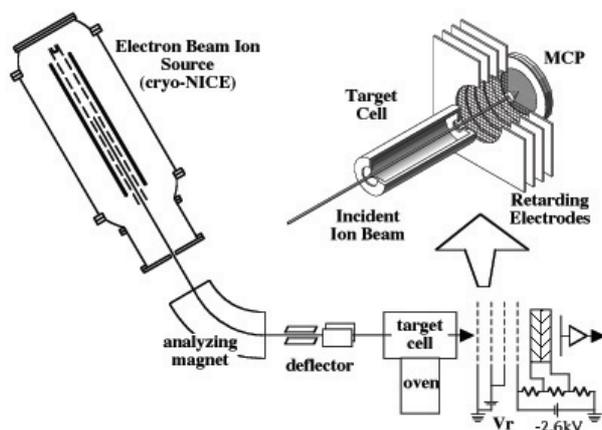


Fig. 1 A schematic experimental apparatus in which the retarding technique is combined with the growth rate method.

ions, retarded between the first and second meshes and yet pass through the third mesh, are accelerated toward the fourth mesh at -2.6 kV and finally detected with a micro-channel plate (MCP). At a voltage slightly higher than 1.5 kV applied to the retarding meshes, the incident A^{q+} ions whose energy is $1.5q\text{ keV}$ are reflected and the scattered ions having lower charges are detected by the MCP. By further increasing the retarding voltage to about $1.5q/(q-1)\text{ kV}$, both the incident Aq^+ and scattered $A^{(q-1)+}$ ions are reflected and only the ions which captured two or more electrons are detected.

The count rates of the scattered ions at the retarding voltage between 1.5 kV and $1.5q/(q-1)\text{ kV}$ were confirmed to be almost constant. To determine the growth rate of the scattered ions $A^{(q-i)+}$, the retarding voltage was fixed at the middle in this constant region. The linear growth curve of the count rate of the scattered ions was obtained as a function of the target gas pressure, which is still sufficiently low. From this growth curve, the total electron transfer cross sections σ_q were determined in the usual way.

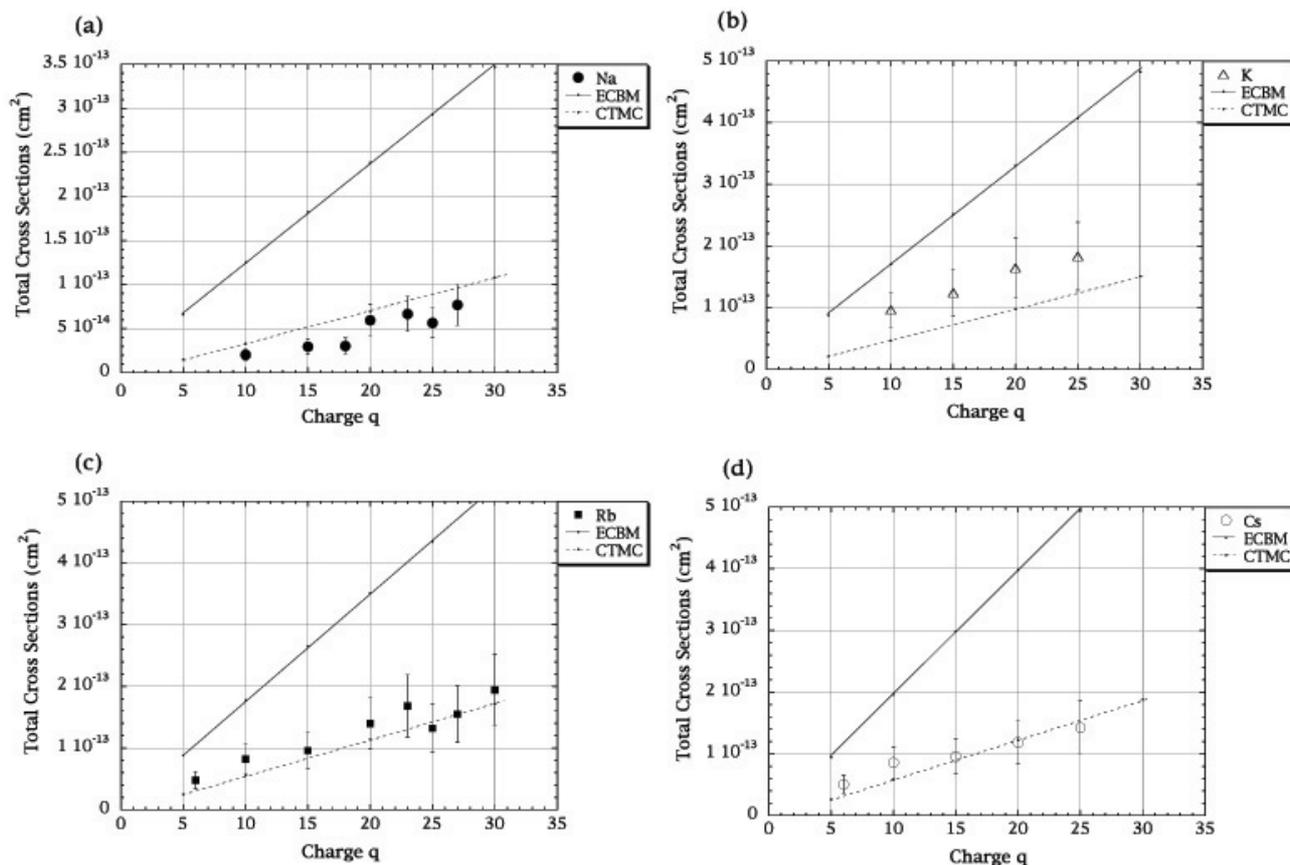
3. Results and discussion

In this paper, we consider the electron transfer cross section $\sigma_{q,q-i}^j$ of highly charged iodine ion collisions with alkali metal atoms B (B = Na, K, Rb or Cs). Here the j -electron transfer cross section is expressed as $\sigma_q^j = \sum_i \sigma_{q,q-i}^j$, the i -electron capture cross section is $\sigma_{q,q-i} = \sum_j \sigma_{q,q-i}^j$ and the total electron transfer cross section is $\sigma_q = \sum_{i,j} \sigma_{q,q-i}^j = \sum_j \sigma_q^j = \sum_i \sigma_{q,q-i}$.

In Fig. 2 (a), (b), (c) and (d), we show the charge dependence of the absolute total electron transfer cross section $\sigma_q = \sum_{i,j} \sigma_{q,q-i}^j$ for Na, K, Rb and Cs targets, respectively, and we list them in table. We find that σ_q increases in proportion to q for all the targets. A similar tendency had been observed in our previous experiment for HCI-rare gas atom or molecule collisions [11,12,18-20]. The present cross sections are very large up to 10^{-13} cm^2 . This may be ascribed to the reason mentioned in Introduction. The calculated values by ECBM are also shown in Fig. 2. We note the obvious difference between the experimental and calculated values. The calculated σ_q by ECBM are 2 ~ 3 times as large as our experimental ones. This is in contrast to the good agreement in the case of the rare gas atom targets. We also compare in Fig. 2 our experimental values with the calculated ones by the classical-trajectory Monte Carlo (CTMC) simulations. I. Yamada [21] have calculated the one electron capture cross sections ($\sigma_{q,q-1}$) in HCI-atomic hydrogen collision at the collision energy ($1.5q\text{ keV}$) by CTMC. In addition the

Table 1 The absolute total electron transfer cross sections σ_q (10^{-14} cm 2). The experimental uncertainties are estimated to be about $\pm 30\%$.

	q									
	6	10	15	18	20	23	25	27	30	
Na	2.0	3.5	3.0	5.8	6.7	5.7	7.7			
K	9.6	12.0		16.0		18.0				
Rb	4.8	8.2	9.6		14.0	17.0	13.0	16.0	19.0	
Cs	5.0	8.6	9.6		12.0		14.0			

Fig. 2 Absolute total electron transfer cross sections for Na, K, Rb and Cs as a function of the projectile ions charge q . The calculated values by the ECBM and CTMC are represented by the full line and the dotted line, respectively.

calculations for alkali metal targets (Na, K, Rb and Cs), which can be regarded as quasihydrogenic at the collision energy of $1.5q$ keV, have been carried out, and the ionization energy dependence of the cross sections is studied. In HCI-alkali metal atom collisions, the one electron capture processes are dominant in comparison with the two or more electron capture processes. Actually, we confirmed experimentally that the ratio of the one electron capture cross section ($\sigma_{q,q-1}$) and the two electron capture one ($\sigma_{q,q-2}$) is larger than 10. Therefore σ_q is virtually equal to $\sigma_{q,q-1}$ and the total electron capture cross section is virtually equal to the total electron transfer cross sections ($\sum_i \sigma_{q,q-i} = \sum_j \sigma_q^j = \sigma_q$). As Figure 2 shows our experimental total electron transfer cross sections agree with the CTMC calculations within

the experimental uncertainties.

In Fig. 3, the total electron transfer cross sections for alkali metal atoms are plotted over the scaling parameter, q/IP^2 , where q is the initial charge of the projectile and IP (eV) is the ionization potential energy of the target atom. It is found that the experimental cross sections are approximately proportional to the scaling parameter, q/IP^2 . Thus, a scaling formula for alkali metal atom targets is obtained;

$$\sigma_q^{exp} = 1.05 \times 10^{-13} \cdot q/IP^2 \text{ (cm}^2\text{)}.$$

The scaling law for the rare gas targets [14] is also shown in Fig. 3. The gradient of the rare gas scaling is about 2.5 times as large as the gradient of the alkali metal one.

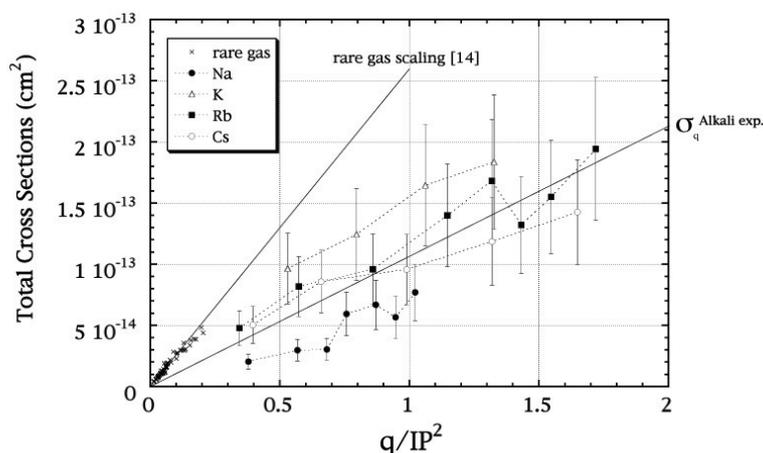


Fig. 3 Comparison of the observed total electron transfer cross sections with the scaling law for the rare gas atom targets. The scaling law for rare gas atom targets and fitted line to our data for the alkali metal atom targets are represented by the full lines.

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