State-selective differential cross section measurements for the one-electron capture processes in the \( F^{4+} - \) He, Ne, Ar systems at \( E_{\text{lab}} = 45 \) eV

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Abstract. Using a crossed-beam apparatus, we measured systematically the relative state-selective differential cross sections for the charge-transfer processes at very low collision energy. The cross section obtained in \( F^{4+} + \) He system shows a peak around 0° angle, while those in \( F^{4+} + \) Ne and Ar collisions at the same collision energy show clear angular thresholds. The strong peak observed in \( F^{4+} + \) He system is interpreted as due to the glory scattering, and the cross section maximum in \( F^{4+} + \) Ne and Ar collisions at non-zero angles is due to the rainbow scattering.

1. Introduction
There exists various state-selective measurements for the charge-transfer reactions involving multiply-charged ions performed at a few hundred eV or higher energy region \([1]\). The purpose of the study is to obtain information on the selection rules and the transition probabilities as well as to obtain the absolute value of the integral cross sections for each reaction channel.

The deflection angle of the scattered ions is small in such energy regions, hence it is almost impossible to determine the angular dependence of the cross sections unless an apparatus with an extremely high angular-resolution is used \([2]\). When the collision energy is lowered, the angular scattering becomes more prominent. The angular differential cross sections are very sensitive to the shape of the potential curves concerning the process. Therefore, experimental results can be analyzed in detail in comparison with the theoretical ones based on \textit{ab initio} potentials. However, only few experimental results have so far been reported at very low energy region, because it is still not an easy task to produce highly-charged ions and to decelerate them \([3 - 6]\). We introduced a compact electron-beam ion-source to a conventional crossed-beam apparatus to measure state-selective differential cross sections below 100 eV region. In this paper, present status of the measurements and the analysis based on the theoretical potentials is reported.

2. Experimental
Details of the crossed-beam apparatus used were described previously \([7]\). It consists of a small electron-beam ion-source, a Wien-filter as a mass selector, an energy selector and a one-dimensional position-sensitive ion-detector. The energy- and mass-selected primary ion beam was crossed at a right
Figure 1. Energy spectra obtained in F^{4+} - He system. (a) A two dimensional graph. Calculated energy-positions are shown by dots. (b) A spectrum obtained at $\theta_{\text{lab}} = 3.0^\circ$, and (c) at $\theta_{\text{lab}} = 6.0^\circ$.

angle with a supersonic nozzle beam. An in-plane geometry was used to detect the product ions. The base pressure of the scattering chamber was about $4 \times 10^{-6}$ Pa, and the background pressure was about $1 \times 10^{-4}$ Pa with the target beam running.

The intensity of the ion beam after the mass selection was on the order of $10^{-11}$ A, and the energy spread of the ion beam was about $1.5 \times q$ eV (FWHM), where $q$ indicates the charge number of the ions. After the mass selection, the ions were decelerated to the transmission energy of the double hemispherical energy selector. The transmission energy was 42 eV, and the energy width of the primary beam was reduced to about $0.25 \times q$ eV. The overall angular resolution of the detector system was determined to be better than $\pm 1^\circ$ (FWHM) by measuring the angular distribution of the primary beam.

State-selective differential cross sections were obtained by measuring the kinetic energy of the product ions. The energy spectra of the scattered ions at different scattering angles were recorded by rotating the energy analyzer.

Accurate determination of the collision energy is important for the assignment of reaction channels from the energy spectrum of the product ions. For this purpose, we measured the elastically scattered ions simultaneously, because the energy and angular dependence of the elastic scattering are uniquely determined by the scattering geometry. The target beam energy in the isentropic limit was estimated to be $E = (5/2)kT$ ($T$ = nozzle temperature: 300K), and this value was used in the calculation of the kinematics.

In figure 1(b) and 1(c), the energy spectra of the scattered ions obtained in F^{4+} + He system are shown. In figure 1(a), all the measured spectra are shown in a 2-dimention plot. In figure 1(b) and 1(c), two peaks are clearly observed. The left side peak corresponds to the elastically scattered signals, and the right side one is due to the charge transfer reactions. Changing the value of the impact energy, we calculated the angular and energy dependence of the elastic scattering so as to reproduce the measurements, and determined the initial energy to be $44 \pm 1$ eV. The calculated positions for the elastic scattering and the following charge transfer reactions are shown by dots in figure 1(a):

$$F^{4+}(2s^22p\,{}^2P) + \text{He} \rightarrow F^{3+}\, (2s^22p3s\,{}^1P) + \text{He}^+ + 10.0\, \text{eV},$$

$$\rightarrow F^{3+}\, (2s^22p3s\, {}^3P) + \text{He}^+ + 10.9\, \text{eV}. \quad (1)$$

$$F^{3+}\, (2s^22p\,{}^2P)$.

$$\rightarrow F^{3+}\, (2s^22p3s\,{}^3P) + \text{He}^+ + 10.9\, \text{eV}. \quad (2)$$
We observed the F$^{3+}$ ions around 0° angle even when the target beam was stopped. Therefore, special care had to be taken to ensure a correct background subtraction. We have carefully determined the amount of background counts using the method reported previously [7].

3. Results

In figure 2(a), relative differential cross section in the laboratory frame for the reaction channels (1) and (2) are shown. In the present measurements, energy resolution was not sufficient to separate these channels, so the obtained cross sections are the sum of the channel (1) and (2). Note that the definition of the differential cross section is $d\sigma/d\Omega$, not $d\sigma/d\theta = 2\pi \sin \theta d\sigma/d\Omega$. The cross section shows a peak around 0° and decreases monotonically with the increase of the scattering angle.

Results obtained in F$^{4+}$ + Ne system are shown in figure 2(b). The open circle corresponds to the following reactions:

\[ \text{F}^{4+}(2s^22p^2 \, ^2P) + \text{Ne} \rightarrow \text{F}^{3+}(2s^22p3p \, ^3D) + \text{Ne}^+ + 9.6 \text{ eV}, \]

\[ \rightarrow \text{F}^{3+}(2s^22p3p \, ^1P) + \text{Ne}^+ + 10.0 \text{ eV}. \]

The cross section increases steeply with the increase of the scattering angle, shows peak at around 3°, and decreases monotonically. We noticed that another peak starts to appear in the energy spectra at around 8°. This process could be uniquely assigned as,

\[ \text{F}^{4+}(2s^22p^2 \, ^2P) + \text{Ne} \rightarrow \text{F}^{3+}(2s^22p3s \, ^1P) + \text{Ne}^+ + 13.1 \text{ eV}. \]

Due to poor statistics for this channel, a fitting program was used to derive the cross section value. The cross section for channel (5), displayed in filled circle in figure 2(b), shows two maxima at around 9.5° and 13.5°.

The F$^{3+}$ signal observed in F$^{4+}$ + Ar collision is assigned to the charge transfer to the excited state: F$^{3+}(2s^22p3d)$ with the exothemicity of about 9 eV:

\[ \text{F}^{4+}(2s^22p^2 \, ^2P) + \text{Ar} \rightarrow \text{F}^{3+}(2s^22p3d \, ^1P) + \text{Ar}^+ + 9 \text{ eV}. \]

As this electronic configuration results in the closely lying terms of $^1F$, $^3F$, $^1D$ and $^3D$, the cross section shown in figure 2(c) is considered to be the sum to all these states. The cross section shows a peak at 0° angle and has maximum at around 5°.

4. Discussion

In a separate measurement for N$^{2+}$ + He collision, which is the isoelectronic system of the F$^{4+}$ + He, a similar angular dependence was observed in the reaction N$^{2+}(2s^22p \, ^2P) + \text{He} \rightarrow \text{N}^+(2s^22p \, ^2P) + \text{He}^+ + 5.0 \text{ eV}$. The interaction potentials for NH$^{2+}$ system have been reported by Lafyatis et al [8]; we also calculated them again and fitted the results to an appropriate analytical function to obtain classical
deflection function within a two-state model. Results are shown in figure 3(a), and 3(b).

When the charge transfer reaction occurs in the incoming part of the trajectory, the trajectory will be determined mainly by the repulsive Coulomb force.

While if the reaction occurs in the outgoing part of the trajectory, the ion trajectory before the reaction will be determined by the attractive or repulsive force depending on the collision systems, then the trajectory will be controlled by the repulsive Coulomb force. The NHe$^2+$ system has a deep well of about 2 eV, therefore the ion trajectory is determined by the strong attractive force before the reaction. When the deflection angle comes to 0 at a certain impact parameter, the classical differential cross section, $d\sigma/d\Omega = b / [\sin \theta (d\theta/db)]$, diverges due to the factor $1/\sin\theta$. This is known as the glory scattering.

We temporarily assigned the strong forward peak observed in the charge transfer reaction to the glory scattering both for N$^{2+}$ + He and F$^{4+}$ + He systems.

The minimum in the lower-half of the deflection function, $d\theta/db = 0$, gives another singularity to the classical differential cross section, known as the rainbow scattering. When the interaction potentials have not strong attractive part or have only repulsive character, the glory scattering will not occur, and the rainbow scattering will come to be seen clearly. The observed structure in O$^{2+}$ (2$s^2$2$p^3$ $^3$P) + He $\rightarrow$ O$^+$ (2$s^2$2$p$ $^3$P) + He$^+$ + 5.5 eV collisions [7], which appears at the same reduced collision angle, was tentatively assigned to the rainbow scattering.

We again consider that the maximum observed in F$^{4+}$ + Ne and Ar collisions at a certain angle may be due to the rainbow effect. Detailed theoretical analysis is in progress concerning these assignments.

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