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# Total Cross Sections for Charge Transfer and Stripping of Al, Cr, and Er Ions in He and $N_2$[†]

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Absolute measurements are reported of the total cross sections for charge transfer and stripping of $Er^+$, $Er^{2+}$, $Al^+$, and $Cr^+$ ions incident on He and $N_2$ in the energy range from 15 to 100 keV. These measurements include $\sigma_{10}$, $\sigma_{12}$, and $\sigma_{21}$. The $\sigma_{12}$ cross sections are greater than those of the $\sigma_{10}$ at the same velocity for all ions except $Cr^+$. Charge-transfer cross sections $\sigma_{10}$ have a velocity dependence which is not predicted by the simple adiabatic criterion.

## I. INTRODUCTION

Cross sections for charge transfer and stripping of various ions in noble and atmospheric gases have been the subject of much research. However, most of the work has been carried out with ions of the noble and atmospheric gases and the alkali metals. Recently, this work has been expanded to ions of various metals. This report furthers this work in that it examines in detail the unexpected energy dependence, as reported by Layton *et al.*[1] of the total cross section for charge transfer $\sigma_{10}$ for $Al^+$ in $N_2$ below 100 keV. In addition, it presents total cross sections involving ions of Al, Cr, and Er not previously reported. Cross sections which have been measured are listed in Table I.

These cross sections were measured as a function of energy from 15 to 100 keV with the exception of $Er^+$ which was limited to 70 keV by the accelerator analyzing magnet.

## II. APPARATUS AND EXPERIMENTAL PROCEDURES

The Sandia Laboratories 100-kV ion accelerator was used in this study. The $Al^+$ and $Cr^+$ ions were obtained from thermionic sources. The Al source was made by flame spraying $Al_2O_3$ onto a tantalum filament; the Cr source was made by coating a tungsten filament with $Cr_2O_3$ which had been mixed with distilled water. When the filaments were heated in a vacuum, singly charged ions of the metal were emitted. This type of source gives ions in the ground state only. The $Er^+$ and $Er^{2+}$ ions were from a modified electron impact source in which a second filament containing Er metal was used. A discharge was maintained with Ar gas and the Er-coated filament heated to supply Er vapor. Since this source was energetic enough to supply both $Er^+$ and $Er^{2+}$, the ion beams could have contained long-lived excited states as well as ground-state ions, provided that such states exist and have lifetimes greater than $10^{-5}$ sec. This time is based on time of flight of the ions from source to experimental chamber at maximum energy. The accelerator delivers a beam of magnetically analyzed ions having small energy spread to the experimental chamber. Figure 1 shows the magnetically analyzed, singly ionized outputs of these

TABLE I. Measured cross sections.

| Ion | Helium target | Nitrogen target |
|---|---|---|
| $Al^+$ | $\sigma_{10}$ $\sigma_{12}$ | $\sigma_{10}$ |
| $Cr^+$ | $\sigma_{10}$ $\sigma_{12}$ | $\sigma_{10}$ |
| $Er^+$ | $\sigma_{10}$ $\sigma_{12}$ | $\sigma_{10}$ $\sigma_{12}$ |
| $Er^{2+}$ | $\sigma_{21}$ | $\sigma_{21}$ |

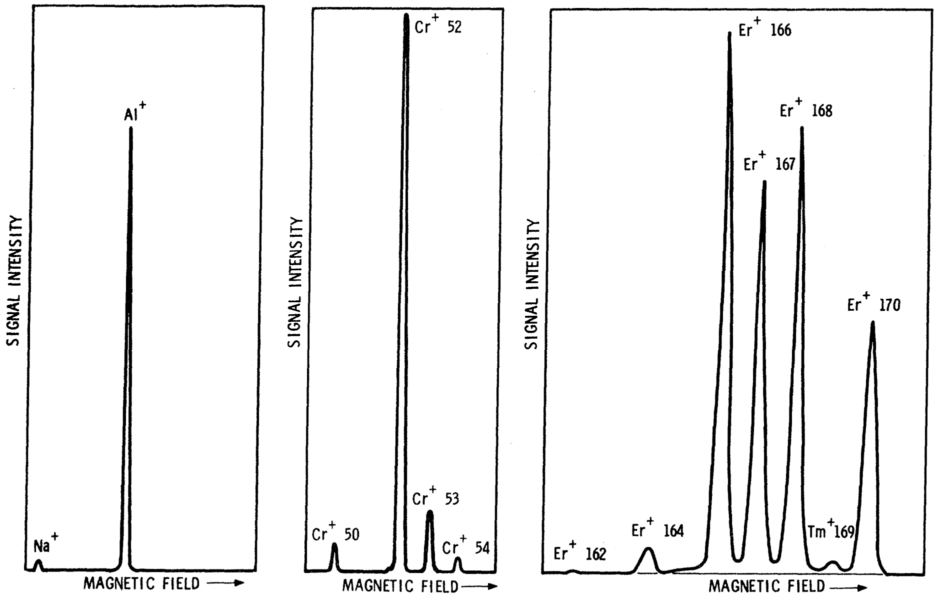

FIG. 1. Magnetically analyzed, singly ionized outputs of the $Al^+$, $Cr^+$, and $Er^+$ sources.

sources. In the case of Er, the energy spread cannot be more than 1 eV to provide this sort of resolution. The beam energy is determined to 2% by measuring the terminal potential with a voltage divider and correcting for ion-source potentials.

The experimental apparatus (Fig. 2) used in this study has been described in detail in earlier papers.[2,3] The only changes to the apparatus were the removal of the monitor, which was located between apertures B and C, and the replacement of the secondary electron detector with a secondary electron multiplier (SEM). Use of the SEM in this study was necessary because of the low ion output of the sources used. The first dynode of the SEM was maintained at ground potential so that all particles impacted with the accelerator energy only (less any small inelastic energy losses). Thus $\gamma$, the number of secondary electrons ejected from the first dynode per incident particle, is, to a good approximation, independent of particle charge for a fixed particle energy.[4–6] This approximation holds for all energies used in the present study.

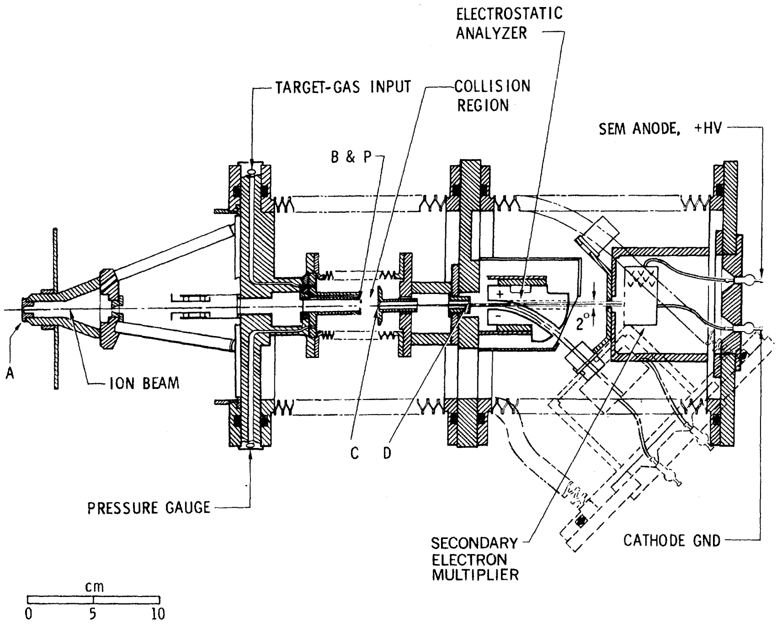

FIG. 2. Experimental apparatus.

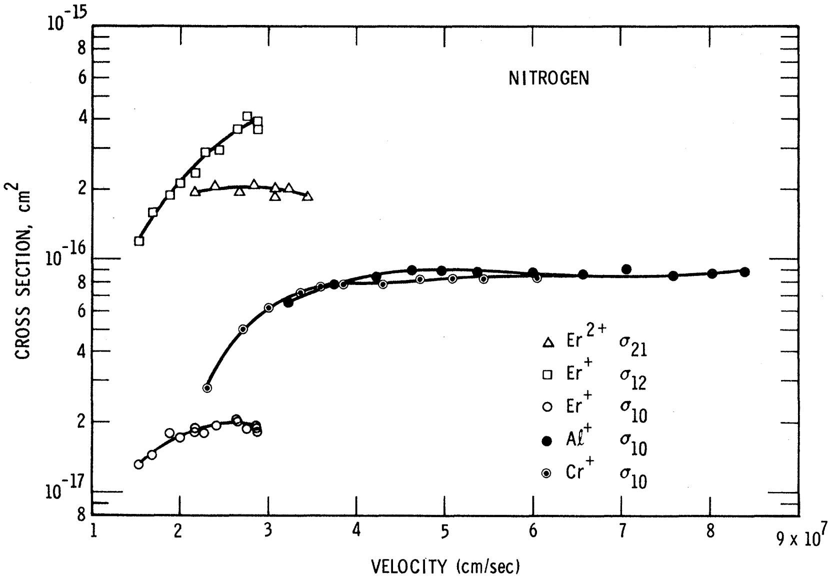

FIG. 3. Total cross sections for charge transfer and stripping of $Er^+$, $Er^{2+}$, $Al^+$, and $Cr^+$ on $N_2$ vs velocity of the incident ions.

The SEM voltage was selected to be within a range of voltages where measurements showed that the ratio of current associated with the final charge state to the current associated with the incident ion beam was constant.

Experimental procedures and data reduction methods described in detail in the earlier studies[2,3] were followed here. However, for the $\sigma_{12}$ and $\sigma_{21}$ cross sections, the SEM was positioned as shown by the dotted lines in Fig. 2. Voltage on the analyzer plates was adjusted to deflect particles of the desired initial and final ionic states to the SEM.

As in the earlier work, small-angle scattering of the ions in the final charge state was of concern here. Because of the small signals, however, only the scattering of Al, Cr, and Er on $N_2$ could be checked experimentally. In all cases, less than 1% was found to scatter outside the ±1 ° acceptance angle of the detector at the lowest energy.

The experimental uncertainty in $\sigma_{if}$ is ± 9% and was arrived at by considering the sources and estimated uncertainties listed in Table II. Other potential sources of error, i.e., state of ion beam, residual gas scattering, capture in accelerator tube, and target gas impurities have been reduced to less than 1% by either experimental arrangement or data acquisition and reduction procedures.

## III. DATA

Data from the present study are shown in Figs. 3 – 5. Data for He and $N_2$ target gases are listed in Tables III and IV, respectively. For charge transfer between unlike particles, theory and

TABLE II. Cross sections for charge transfer and stripping of $Er^+$, $Er^{2+}$, $Al^+$, and $Cr^+$ on He.[a–c]

| $Er^+$ | | $Er^+$ | | $Al^+$ | | $Al^+$ | | $Cr^+$ | | $Cr^+$ | | $Er^{2+}$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Velocity | $\sigma_{10}$ | Velocity | $\sigma_{12}$ | Velocity | $\sigma_{10}$ | Velocity | $\sigma_{12}$ | Velocity | $\sigma_{10}$ | Velocity | $\sigma_{12}$ | Velocity | $\sigma_{21}$ |
| 1.55 | 0.42 | 1.54 | 1.18 | 3.25 | 0.30 | 3.79 | 0.55 | 2.34 | 0.17 | 3.36 | 0.43 | 2.18 | 3.44 |
| 1.72 | 0.65 | 1.88 | 3.57 | 3.78 | 0.73 | 4.62 | 1.24 | 2.72 | 0.38 | 3.85 | 0.70 | 2.66 | 5.49 |
| 1.89 | 0.85 | 2.17 | 5.53 | 4.24 | 1.25 | 5.34 | 1.95 | 3.02 | 0.70 | 4.32 | 1.20 | 3.07 | 5.92 |
| 2.02 | 1.00 | 2.42 | 7.93 | 4.63 | 1.40 | 5.98 | 2.78 | 3.32 | 1.03 | 4.74 | 1.93 | 3.43 | 6.57 |
| 2.17 | 1.14 | 2.65 | 9.64 | 5.01 | 1.58 | 6.58 | 3.50 | 3.58 | 1.44 | 5.12 | 2.05 | | |
| 2.30 | 1.12 | 2.86 | 10.1 | 5.35 | 1.58 | 7.10 | 3.90 | 3.84 | 1.76 | 5.45 | 2.94 | | |
| 2.30 | 1.09 | | | 5.96 | 1.44 | 7.58 | 4.60 | 4.33 | 2.58 | 6.08 | 4.25 | | |
| 2.42 | 1.13 | | | 6.57 | 1.33 | | | 4.73 | 3.40 | | | | |
| 2.54 | 0.97 | | | 7.10 | 1.42 | | | 5.09 | 3.80 | | | | |
| 2.65 | 0.99 | | | 7.57 | 1.41 | | | 5.47 | 4.32 | | | | |
| 2.76 | 1.01 | | | 8.03 | 1.54 | | | 6.05 | 4.58 | | | | |
| 2.86 | 1.03 | | | 8.39 | 1.52 | | | | | | | | |
| 2.86 | 0.91 | | | | | | | | | | | | |

[a] Units of $\sigma_{if}$ are $10^{-17}$ cm$^2$.

[b] Units of velocity are $10^7$ cm/sec.

[c] Experimental uncertainty in $\sigma_{if}$ is 9%.

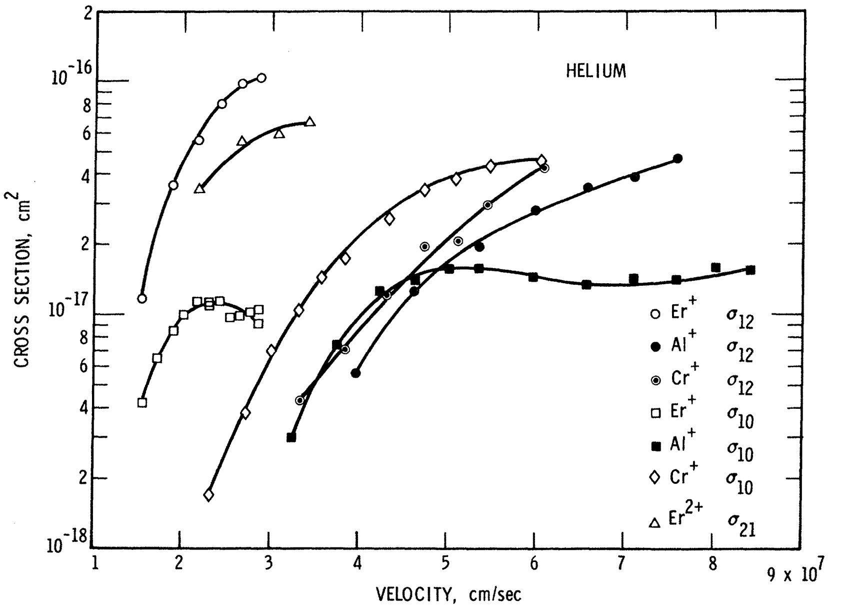

FIG. 4. Total cross sections for charge transfer and stripping of Er$^+$, Er$^{2+}$, Al$^+$, and Cr$^+$ on He vs velocity of the incident ions.

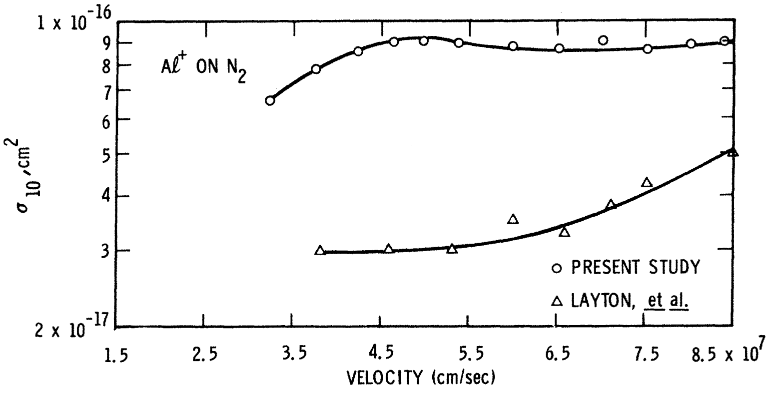

FIG. 5. Comparison of the present total cross section for charge transfer $\sigma_{10}$ of Al$^+$ in N$_2$ with that published by Layton *et al.* (Ref. 1).

TABLE III. Cross sections for charge transfer and stripping of Er$^+$, Er$^{2+}$, Al$^+$, and Cr$^+$ on N$_2$.$^{a-c}$

| Er$^+$ |  | Er$^+$ |  | Al$^+$ |  | Cr$^+$ |  | Er$^{2+}$ |  |
|---|---|---|---|---|---|---|---|---|---|
| Velocity | $\sigma_{10}$ | Velocity | $\sigma_{12}$ | Velocity | $\sigma_{10}$ | Velocity | $\sigma_{10}$ | Velocity | $\sigma_{21}$ |
| 1.54 | 1.31 | 1.54 | 12.1 | 3.24 | 6.56 | 2.32 | 2.81 | 2.18 | 19.2 |
| 1.68 | 1.44 | 1.69 | 16.2 | 3.76 | 7.77 | 2.72 | 4.99 | 2.38 | 20.4 |
| 1.88 | 1.79 | 1.88 | 18.8 | 4.23 | 8.51 | 3.02 | 6.26 | 2.67 | 19.5 |
| 2.00 | 1.73 | 2.00 | 21.2 | 4.67 | 8.96 | 3.35 | 7.20 | 2.84 | 20.7 |
| 2.16 | 1.89 | 2.17 | 23.6 | 4.97 | 8.99 | 3.59 | 7.62 | 3.07 | 18.3 |
| 2.17 | 1.85 | 2.27 | 28.7 | 5.37 | 8.92 | 3.85 | 7.82 | 3.07 | 20.1 |
| 2.27 | 1.80 | 2.42 | 29.9 | 5.99 | 8.79 | 4.31 | 7.79 | 3.23 | 20.1 |
| 2.42 | 1.94 | 2.65 | 36.3 | 6.57 | 8.66 | 4.72 | 8.31 | 3.43 | 18.7 |
| 2.64 | 2.07 | 2.75 | 41.4 | 7.06 | 9.02 | 5.09 | 8.33 |  |  |
| 2.65 | 2.02 | 2.87 | 36.1 | 7.58 | 8.63 | 5.43 | 8.37 |  |  |
| 2.74 | 1.86 | 2.87 | 39.2 | 8.03 | 8.87 | 6.06 | 8.43 |  |  |
| 2.86 | 1.92 |  |  | 8.40 | 8.97 |  |  |  |  |
| 2.86 | 1.94 |  |  |  |  |  |  |  |  |
| 2.86 | 1.88 |  |  |  |  |  |  |  |  |
| 2.87 | 1.81 |  |  |  |  |  |  |  |  |

[a] Units of $\sigma_{if}$ are $10^{-17}$ cm$^2$/molecule. [b] Units of velocity are $10^7$ cm/sec. [c] Experimental uncertainty in $\sigma_{if}$ is 9%.

TABLE IV. Sources and estimated uncertainties.[a]

| Source | Uncertainty (%) | Remarks |
|---|---|---|
| Target thickness $l$ | 1 | See discussion, Sec. II of Ref. 2 |
| Incident current reading $I_i$ | 3 | Electrometer limitation |
| Final current reading $I_f$ | 3 | Electrometer limitation |
| $\gamma$ cancellation in ratio $I_f/I_i$ | 5 | Based on laboratory studies |
| Pressure $P$ | 2 | Maximum estimated error due to scale factor<br>This is conservative, based on manufacturer's specifications |
| Small angle scattering | 5 | Based on laboratory measurements |

[a] Symbols used here are from discussion of experimental procedure, Sec. II of Ref. 2.

experiment[7] show the cross section to be small at low velocity, to rise to a maximum, and to fall as the velocity is increased. It was expected that data from the present study should be consistent with the adiabatic criterion. The velocity at which the maximum occurs is found to be proportional to the internal energy defect $\Delta E$. In the cases studied here, the internal energy defects are 9.6, 8.8, and 9.5 eV for ground-state-to-ground-state transfer of $Al^+$, $Cr^+$, and $Er^+$, respectively, in $N_2$. From the adiabatic criterion,[7] the cross sections for charge transfer, $\sigma_{10}$, should reach a maximum at a velocity of about $1.6\times10^8$ cm/sec. This is in good agreement with the high-energy data of Layton *et al.*[1] for $Al^+$ on $N_2$ which show a maximum at $1.7\times10^8$ cm/sec. However, in all three cases in the present study, the charge-transfer cross sections $\sigma_{10}$ peak at a velocity, or at least remain constant at velocities, low compared to the maxima predicted by the adiabatic criterion. This unexpected velocity dependence in the $\sigma_{10}$ cross-section data cannot be accounted for by leaving the $N_2^+$ in an excited state, since this would result in a larger $\Delta E$. Since the $Al^+$ and $Cr^+$ are created in the ground state, the $\Delta E$'s stated above are the minimum values. In the case of $Er^+$, there is a possibility that an excited state of $Er^+$ could account for the low-velocity peak seen in the $\sigma_{10}$ cross section. However, this state would have to be metastable and lie at about 8.2 eV above the ground state of $Er^+$, and this does not seem likely because of the multitude of excited states of $Er^+$ below 8.2 eV. The velocity dependence of $\sigma_{10}$ for $Al^+$ on $N_2$ is shown in Fig. 5 together with the low-velocity data of Layton *et al.*[1] The difference in magnitude and shape between these data and those of the present study is not understood. However, the important feature of the present data is the small maximum at about $4.7\times10^8$ cm/sec (where the data of Layton *et al.* are constant with velocity) which is well below the adiabatic maximum predicted at about $1.6\times10^7$ cm/sec. This same type of velocity dependence in $\sigma_{10}$ is seen for $Al^+$, $Cr^+$, and $Er^+$ in He, and for these cases the adiabatic maximum is predicted at about $3\times10^8$ cm/sec.

The cross sections for capture by $Er^{2+}$, $\sigma_{21}$, in both He and $N_2$ are larger than the corresponding cross sections for capture by $Er^+$, $\sigma_{10}$. This is expected since the energy defect is smaller when $Er^{2+}$ is used, and there is less competition from the stripping channel.

The larger cross section for $Er^+$ in He and $N_2$ is the stripping cross section $\sigma_{12}$ and is the larger for $Al^+$ in He over most of the velocity range. Unlike $Er^+$ and $Al^+$, $\sigma_{12}$ for $Cr^+$ in He is smaller than $\sigma_{10}$ except at the largest velocity. The stripping cross sections $\sigma_{12}$ for $Al^+$ and $Cr^+$ in He are nearly the same, whereas $\sigma_{10}$ cross sections for $Al^+$ and $Cr^+$ in He show a large difference in both magnitude and shape.

## IV. CONCLUSIONS

General features of the data indicate that, for metal ions incident on He and $N_2$, the stripping cross sections $\sigma_{12}$ are greater than the charge-transfer cross sections $\sigma_{10}$. The exception is for $Cr^+$ on He where the two are equal at high velocity. Also, the charge-transfer cross sections $\sigma_{10}$ have a velocity dependence which is not predicted by the simple adiabatic criterion. However, more work is needed with metal ions before any general empirical conclusions can be drawn.

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