Charge-changing collisions of argon ions on argon gas. One-electron capture

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(Received 27 June 1980)

Single-electron-capture cross sections have been measured for argon ions with initial charges $2 \leq q \leq 12$ incident on an argon-gas target. The cross sections show little dependence on the incident ion energy in the range $1q-10q$ keV. A remarkable oscillating feature is seen for cross sections $\sigma_{q,q-1}$ when $q \geq 7$. Particularly, $\sigma_{8,7}$ is smaller than $\sigma_{7,6}$ and $\sigma_{9,8}$, the Ar^{8+} electronic structure being Ne-like. Variation of the cross section is shown as function of the initial charge at constant energy.

I. INTRODUCTION

The study of charge changes of multiply charged ions during collisions with atoms has grown rapidly during these last few years. In such collisions—electron capture and stripping—the ions are most likely left in an excited state[1-4] which decay via photon emission. Since electron-capture cross sections are quite large, it is evident that it plays an important role in energy-loss mechanisms of high-temperature[5-7] and astrophysical plasmas.[8]

Electron capture may be an important mechanism governing the loss of certain multiply charged ions in the interstellar medium.[9] Ion stripping may be an efficient mechanism for slowing down particles of the solar wind.[10,11] It may also be a drawback in the acceleration of heavy ions as envisioned in heavy-ion fusion projects.[12] In 1964, Hasted and Hussain[13] reported the first experimental determination of cross sections for electron capture by doubly charged slow argon ions on argon ($v < v_0$ the atomic unit of velocity). Since then, Mc Gowan and Kerwin[14] carried on additional work limited to argon ions with $q \leq 3$ and kinetic energies comparable to those of Hasted ($E < 4$ keV). Very recently a renewed interest in the collisional system $Ar^{q+} + Ar$ was observed. Klinger *et al.*[15-17] published results for initial charge $2 \leq q \leq 7$ at energies $10 < E \leq 90$ keV. Crandall *et al.*[18] studied the $Ar^{5+} + Ar$ system which gives Ar^{4+} at energies $E > 25$ keV. More recently, in the low-energy range where few measurements where available some results were published for collisions with $q \leq 4$.[19-21]

The purpose of this paper is to report experimental values for the single-electron-capture cross sections for Ar^{q+} ions incident on Ar ($2 \leq q \leq 12$) at laboratory kinetic energies in the range $1q-10q$ keV. With the exception of Ar^{2+} up to $Ar^{6+} + Ar$,[13-21] most of these collision systems had not been studied previously. In Sec. II, a description of the experimental device is presented and the main features of the ion source are underlined. In Sec. III, the cross sections for the capture of one electron are given, their accuracies discussed.

A comparison to previously published data when they cover our actual energy-charge-state range and to theoretical predictions is proposed.

II. EXPERIMENTAL AND DATA-EVALUATION PROCEDURES

The experimental setup has been described elsewhere.[10] Briefly, a well collimated beam of argon ions Ar^{q+} ($2 \leq q \leq 12$) is directed into a collision cell containing the target gas at an adjustable pressure in the range 5×10^{-7}–5×10^{-5} torr. Beam energies range from $1q-10q$ keV. To analyze the collision products, a 167° magnet is used:

$$Ar^{q+} + Ar \rightarrow Ar^{(q-1)+} + Ar^{+}$$

is considered here.

These experiments were possible when the "Micromafios" E.C.R. ion source[22,23] has been assembled. Table I summarizes typical currents (in μA) and ion charge q for different gases as obtained at 7-kV extraction voltage. The ion source is pulsed, the typical pulse length is one second, and the duty cycle is set at 0.5.

At a known acceleration potential V_{acc}, a first magnet analyzes the extracted current delivered by the source and separates a given charge-to-mass argon-ion ratio. The incident current is collimated and transmitted into the collision cell (entrance diameter: 3 mm, exit hole diameter: 10 mm) where it is measured. The total transmission through the second analyzing magnet to the collector is checked. Then gas is fed to the target using an automatic pressure-regulated leak valve. Two identical ionization gauges are used to measure pressures in the collision chamber and in the volume surrounding the collision chamber. When argon gas is fed to the collision chamber, the surrounding pressure rises. Although differential turbomolecular pumping is provided, a pressure

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TABLE I. Typical currents (in μA) and ion charge q for different gases as obtained at 7-kV extraction voltage.

9	1	2	3	4	5	6	7	8	9	10	11	12	13
$^{12}_{6}C$	>30	>30	>30	>30	5	0.2							
$^{15}_{7}N$	>30	>30	>30	>30	20	3	0.1						
$^{18}_{8}O$	>30	>30	>30	>30	25	15	3	0.1					
$^{20}_{10}Ne$	>30	>30	>30	>30	>30	20	10	2	<0.1				
$^{40}_{18}Ar$	>30	>30	>30	>30	>30	>30	>30	>30	10	3	1	0.3	<0.1

increase is, however, observed and measured. The surrounding pressure is always at least one order of magnitude lower than in the collision chamber. The magnetic field is then adjusted to collect the proper formed ion; here $Ar^{(q-1)+}$. The associated total current is measured using a Faraday cup connected to a vibrating reed electrometer. The total current I_t is the sum of two components—I_{q-1} formed within the collision cell, I_{ss} due to the incident ion beam interacting with gas leaking out the collision cell to the surrounding space. In order to evaluate the contribution of formed ion current due to the presence of target gas in the volume surrounding the collision chamber, the gas flow is directed outside the cell. The current is then measured and simply substracted from the total current. Under these conditions, the gas flowing into the collision cell is very limited. A schematic diagram of the data measurement and handling device is shown in Fig. 1. The system is placed under control of an HP desktop calculator which performs both acquisition and delayed calculation of the cross sections and error bar attached to each cross-section value. The gas used both as projectile and target is spectroscopically pure argon.

A typical cross section $\sigma_{q,q-1}$ for argon ions with initial charge q incident on argon atoms is determined by means of the single-collision regime formula

$$\sigma^{\mathrm{Ar}}_{q,q-1}(\mathrm{Ar}) = \frac{q}{q-1}\frac{I_{q-1}}{I_q}\frac{1}{n_0 l},$$

where q and $q-1$ refer to incident and produced charge, I_{q-1} and I_q refer to the intensities of ions of charge $q-1$ and of incident ions of charge q. $n_0 l$ is the target thickness.

From the measurement procedure an estimate of the relative error on the cross section is made. The relative error is the sum of errors on projectile and electron captured ion currents to which relative errors on pressure and target length are added. The uncertainty of pressure is of order ±10% for the type of ionization gauges used. Owing to entrance and exit holes on the collision chamber, pressure gradients exist at both ends. They may extend over lengths on the order of the hole diameters, giving to the interaction length an additional ±8%. Adding the errors on currents (±2%), the total error on the cross sections is then ±20%. To make sure that the cross-section values are not influenced by the presence of ions in metastable states,[24] two ion source parameters are varied: neutral gas pressure and HF power level fed to the plasma electrons. Charge-exchange collisions are considered effective to leave ions in metastable states.[24] In the ion source, the charge-exchange collision frequency $N_0\langle\sigma_{q,q-1}v_i\rangle$, where N_0 is the neutral gas pressure number density, $\sigma_{q,q-1}$ the charge-exchange cross section for ion of charge q, v_i the ion velocity in the source plasma, is for ion temperature of 1 eV in the source on the order of $10^3\ s^{-1}$. The probability that ions are left in metastable states in the source is then small. Considering HF power level, it influences directly electron temperature in the source. Considering the ionization rate coefficients[25] which are larger than the excitation rate coefficients, the collision frequency for ion excitation is estimated to be of order $10^3\ s^{-1}$. The probability of collisional excitation is then small. Finally, considering the time

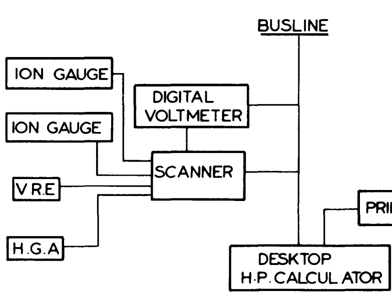

FIG. 1. Schematic diagram of the data acquisition and treatment device. VRE: Vibrating Reed Electrometer; HGA: High Gain Amplifier.

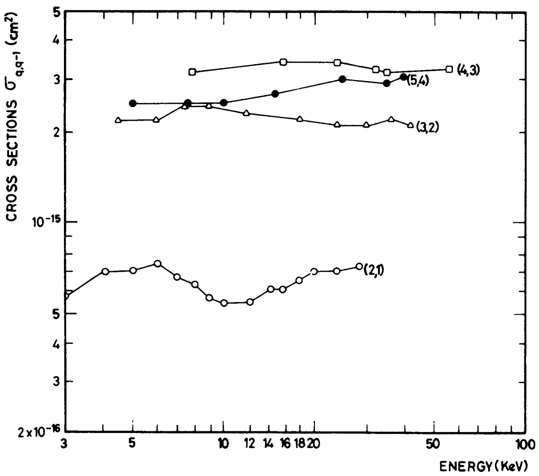

FIG. 2. One-electron-capture cross section for the collision of Ar ions on argon as function of energy. ○ $\sigma_{2,1}$; △ $\sigma_{3,2}$; □ $\sigma_{4,3}$; ● $\sigma_{5,4}$.

of flight for any of the argon ions, it is seen that it exceeds by at least two to three orders of magnitude the excited-level lifetimes.[26] Finally, utilizing different diaphragms on the target exit side, the solid angle through which scattered particles penetrate into the analyzing magnet is varied. For a diameter of 10 mm, the angle is the full magnet acceptance angle (±3° with respect to incident beam direction), with a smaller diaphragm the interception angle has been reduced to ±1°30′. Under these conditions, no collected-current variation is noted. This is in agreement with the recent observations of Stevens *et al.*[27] and Anderson *et al.*[28]

III. RESULTS AND DISCUSSION

The cross sections for argon ions incident on argon are shown in Figs. 2, 3, and 4. Except for $Ar^{2+}+Ar$, the data show little dependence on the collision energy in this range. To simplify data comparison, Table II gives the cross-section values $\sigma_{2,1}$ as measured by Mc Gowan *et al.*,[14]

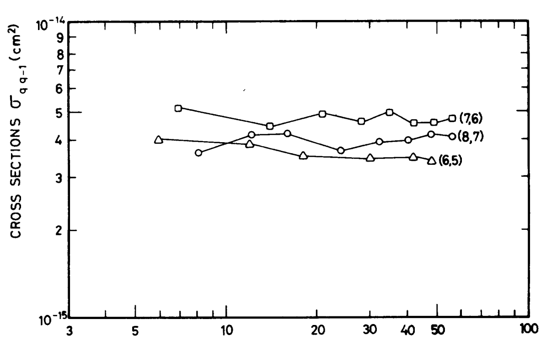

FIG. 3. Electron-capture cross sections for argon ions in argon. △ $\sigma_{6,5}$; □ $\sigma_{7,6}$; ○ $\sigma_{8,7}$.

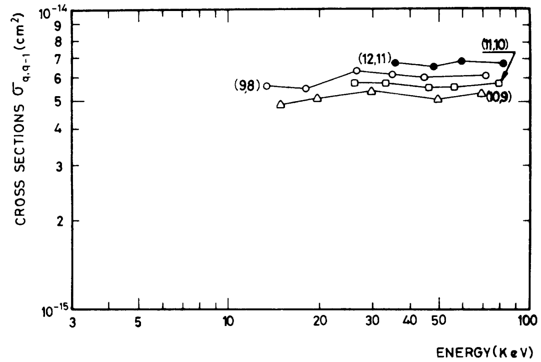

FIG. 4. Electron-capture cross sections for argon ions in argon. ○ $\sigma_{9,8}$; △ $\sigma_{10,9}$; □ $\sigma_{11,10}$; ● $\sigma_{12,11}$.

Hertel *et al.*,[21] H. Klinger *et al.*[15] and our data. The smooth maximum observed on the $\sigma_{2,1}$ value around 6 keV could probably be attributed to a mixing of different exit channels

$$Ar^{2+}(^3P)+Ar(^1S)\rightarrow Ar^{+}(^2P)+Ar^{+}(^2P)$$

and

$$Ar^{2+}(^3P)+Ar(^1S)\rightarrow Ar^{+}(^2S)+Ar^{+}(^2P)$$

(See Refs. 13, 14, and 27). It is seen that in the low-energy limit the agreement is good with Mc Gowan's values and in the high-energy limit with those of Salzborn *et al.*[15] Table III presents the data obtained by McGowan,[14] Salzborn,[15] and us for the collision

$$Ar^{3+}+Ar\rightarrow Ar^{2+}+Ar^{+}.$$

In the energy overlap range, it is seen that the

TABLE II. Cross section values ($\times 10^{-16}$) cm², ($\sigma_{2,1}$).

Ionic energy (keV)	M.K.[a]	H.K.[b]	Present results	Ionic energy (keV)	S.[c]	Present results
0.8	2.7			7.0		6.6
1.0		0.3		8.0		6.1
1.2	3.3		2.6	9.0		5.6
1.4	3.1		3.2	10.0	5.1	5.4
1.6	3.6		3.4	11.0		5.5
1.8	3.6		3.8	12.0	5.3	5.5
2.0	4.0	0.37	4.2	13.0		6.2
2.4	4.1			14.0	5.5	6.1
2.8	4.0			15.0		6.2
3.0		0.57	5.9	16.0	5.7	6.1
3.2	4.4			18.0		6.5
3.6	4.8			20.0	5.9	7.0
4.0		0.70	6.9	24.0	6.0	7.0
5.0		0.90	6.8	28.0	6.3	7.2
6.0		1.2	7.3	32.0	6.6	

[a] Reference 14.
[b] Reference 21.
[c] Reference 15.

TABLE III. Cross section values ($\times 10^{-15}$)cm^2 ($\sigma_{3,2}$).

Ionic energy (keV)	M.K.[a]	S.[b]	Present results
1.8	1.8		
2.1	2.0		
2.7	2.0		
4.5			2.2
6.0			2.2
7.5			2.5
9.0			2.5
12.0			2.3
15.0		2.5	
18.0			2.2
24.0		2.6	2.1
30.0			2.1
36.0			2.2
42.0			2.1
54.0		2.7	

[a] Reference 14.
[b] Reference 15.

agreement is good. Table IV summarizes the cross-section values for $\sigma_{4,3}$ as measured by Salzborn *et al.*[15] and ourselves; within the error uncertainty, the data are in fair agreement. For $\sigma_{5,4}$ there is just one series of values[15] to compare with. Our values are slightly smaller. In many collision experiments, the target pressure is measured indirectly since the chamber dimension is too small to allow pressure measurement. Furthermore, the correction for gas leaking out and contributing to charge-exchanged current is not performed, thus giving a larger cross-section value. These arguments could cause Salzborn's values to be larger than ours. From our measurements a mean cross-section value is deduced $\sigma_{5,4} \simeq 2.8 \times 10^{-15}$ cm^2 to compare with Salzborn's value $\sigma_{5,4} \simeq 4.5 \times 10^{-15}$ cm^2. The same observation applies to the collision

$$Ar^{6+} + Ar \rightarrow Ar^{5+} + Ar^{+},$$

where our mean measured cross-section value is 3.5×10^{-15} cm^2 to compare with Salzborn's mean value $\sigma_{6,5} \simeq 6.5 \times 10^{-15}$ cm^2. For $q \geq 7$ there are no other measured points to compare with but an isolated value[15] at 70 keV $\sigma_{7,6} \simeq 8.7 \times 10^{-15}$ cm^2 to compare with the present mean value $\sigma_{7,8} \simeq 4.7 \times 10^{-15}$ cm^2. It is observed that for $q = 8$ which is associated to a Ne-like ion, the mean single-electron-capture cross section is lower than that associated with $q = 7$. The $q = 9$ cross section is associated with a fluorinelike incident ion and shows a large increase with respect to $q = 8$. From $q = 10$ up to $q = 12$, it is observed that the cross section increases continuously.

Figure V represents the single-electron-capture

TABLE IV. Cross section values ($\times 10^{-15}$)cm^2 ($\sigma_{4,3}$).

Ionic energy (keV)	S.[a]	Present results
10		3.2
16.0		3.4
24.0		3.4
32.0	4.2	3.2
40.0		3.1
48.0	4.1	
56.0		3.2
60.0	4.2	

[a] Reference 15.

cross section as a function of the initial charge at constant projectile energy. This is compared with the predictions of Presnyakov *et al.*,[29] Olson *et al.*,[30] Grozdanov *et al.*,[31] and Müller *et al.*[32] A general trend may be noted. The experimental points are situated between two extreme values those of Presnyakov, which show a q^2 dependence and are lower than measured, and those of Grozdanov *et al.*, which show a q dependence and are much greater than measured. At constant energy and for impact velocity of order 5×10^7 cm/s (~60 keV) all these theories show smooth cross-section variation as a function of incident charge. The structure which appears on our experimental

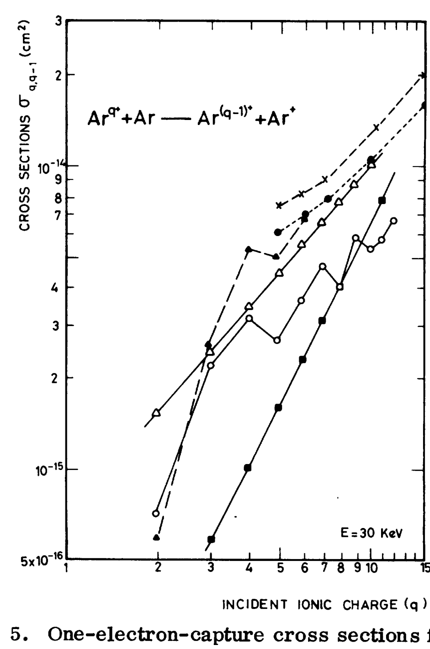

FIG. 5. One-electron-capture cross sections for argon ions on argon as a function of incident-ion charge q at constant energy (30 keV). ○: present data, ■: theoretical values (Ref. 29), △: theoretical values (Ref. 17,32), ●: theoretical values (Ref. 30), ×: theoretical values (Ref. 31), ▲: experimental values (Ref. 15).

curve could be attributed to specific incident-ion electronic structure. When comparison with experimental values is possible, it is seen that even though some discrepancies exist, the behavior is alike: $\sigma_{6,5} > \sigma_{4,3} > \sigma_{5,4}$. Since the individual cross sections are quasi-energy independent, they may be interpreted as electron transition taking place in the ionic energy spectrum where the density of states is sufficiently high.

IV. SUMMARY

Cross sections for single-electron capture by multiply charged argon ions incident on argon have been determined experimentally. The cross sections may be understood qualitatively by means of molecular potential-energy curve-crossing model of the collisions.

A tendency toward larger cross sections for larger incident-ion charge is found but the cross sections do not depend monotonically on the incident charge. When $q \geq 4$, the cross sections $\sigma_{q,q-1}$ seem to fit a mean curve $\sigma_{q,q-1} \simeq 6 \times 10^{-16} q$ cm^2 with oscillations around this line. The multiple-electron capture exists but has not been considered here. It is the object of a future publication.

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