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Résumé. — Les sections efficaces d'échange de charge ont été mesurées pour les ions Arq+ de charge initiale 2 ≤ q ≤ 12 incidents sur des gaz rares : hélium, néon et argon. Les sections efficaces mesurées dans le domaine d'énergie 2 q-10 q keV sont indépendantes de l'énergie. On observe que les valeurs des sections efficaces oscillent autour d'une variation moyenne linéaire en charge. Les sections efficaces présentent une dépendance par rapport au potentiel d'ionisation de la cible.

Abstract. — Single electron capture cross sections have been measured for argon ions with initial charge 2 ≤ q ≤ 12 incident on rare gas targets of helium, neon and argon. The cross sections measured in the energy range 2 q-10 q keV are quasi energy independent. It is observed that the cross sections show oscillations about a mean linear variation in charge. The cross sections show a dependence on the target ionization potential.

1. Introduction. — Electron capture by low energy multiply charged ions colliding on neutral atoms has become a subject of considerable interest in connection with fusion research [1, 2] and astrophysical problems [3-6]. A great number of calculations have resulted, which are based on different models [7-9]. Even though the interest of experimentalists has been focussed on the studies of charge exchange on atomic hydrogen [10-12] in the low and high energy range and on molecular deuterium [13, 14], a great number of measurements have been performed utilizing various gaseous targets [15, 16]. From these results, a scaling law has been deduced for practical purposes [17].

The object of this paper is to report experimental values for the single electron capture cross sections for Arq+ ions (2 ≤ q ≤ 12), incident on He, Ne and Ar at laboratory kinetic energies in the range 2 q-10 q keV. In section 2, the experimental and data evaluation procedures are presented; the main features of the ion source have been presented elsewhere [18]. In section 3, the cross sections for the capture of one electron are given for the collision of Ar ions on the different gas targets He, Ne and Ar; their accuracies are discussed. A comparison with previously published data and theoretical predictions is made.

2. Experimental and data evaluation procedures. — The experimental set up has been described elsewhere [19]. Briefly, a well collimated beam of argon ions with initial charge 2 ≤ q ≤ 12 is directed into a collision cell containing the target gas (He, Ne or Ar).

The pressure in the collision cell is adjusted, utilizing an automatic pressure regulated admission valve in the range 5 x 10^-7-5 x 10^-5 torr. The ion energy range extends from 2 q to 10 q keV where q is the incident ion charge. The cross sections are measured utilizing a standard beam target method. In the single collision approximation, the slope of the linear part of the curve:

\[ \frac{dI_q}{d\pi} = I_q(0) \sigma_{el} \]

gives the charge exchange cross section of electrons from the target to the incident ion of initial charge i and final charge f. The associated currents I_q(0) and I_q(0) are measured in the limit of zero target thickness \( \pi = n_0 \cdot l \) (\( n_0 \) is the target number density, \( l \) its length.)

Hereafter we consider only single electron charge exchange; \( q \) being the initial charge of the projectile, the cross section may be written as:

\[ \sigma_{q \rightarrow q-1} \simeq \frac{1}{q} \frac{I_q}{n_0} \cdot l \]

The estimate of the errors in a cross section value is typically of the order of ± 20% as in previously obtained results [20].
3. Results and discussion. — 3.1 RESULTS. —
As is usually observed in charge exchange collisions of multiply charged ions on atomic or molecular targets at velocities \( v < v_p \) for a given incident ion charge, the cross sections for one or many electron exchange are weakly energy dependent [16, 20, 21]. The incident charge dependences of the cross section for argon ions colliding with He, Ne and Ar are shown in figures 1, 2 and 3 respectively.

An interesting feature is seen on these figures: the mean cross section variation is satisfactorily described by \( \sigma_{q,q-1} \approx \text{const.} \times q \). In this proposed fit, as may be seen from comparison of \( \sigma_{q,q-1} \) in figures 1, 2 and 3 the target is different: from He to Ne and to Ar, the ionization potential decreases.

In figure 4 are given for comparison the measured cross sections for single electron exchange in the collision of ions on He: triangles designate argon ions up to charge 7 [15], crosses Xe ions up to charge 8 [15]. Our values for argon ions are slightly smaller than those of Salzborn and Müller. In figure 5 are given for comparison, the measured cross sections for single electron exchange in the collision of different ions on Ne: Xe ions [15] (closed circles) up to charge 8; Ar ions up to charge 7 (open triangles) [15] and present data. The agreement between measured values for

Fig. 1. — One electron charge exchange cross sections of argon ions \( (2 \leq q \leq 12) \) colliding He atoms as a function of projectile charge (open circles O). Comparison to theoretical results. Open square : □ Ref. [7]; closed points : ● Ref. [8]; crosses : × Ref. [9]; open triangles : △ Ref. [15].

Fig. 2. — One electron capture cross section in the charge exchange collision of \( \text{Ar}^{q+} \) ions \( (2 \leq q \leq 12) \) on Ne as function of projectile charge (symbols are as in Fig. 1).

Fig. 3. — One electron capture cross section in the charge exchange collision of \( \text{Ar}^{q+} \) ions \( (2 \leq q \leq 12) \) on Ar as function of projectile charge (symbols as in Fig. 1).
Fig. 4. — Comparison of measured one electron capture cross sections of different ions on He. Open circles: present data Ar\(^{+}\) (2 ≤ q ≤ 12); triangles: Ar\(^{+}\), Ref. [21]; crosses: Xe\(^{+}\), Ref. [15].

Fig. 5. — Comparison of measured one electron capture cross sections of different ions on Ne: Open circles: present data Ar\(^{+}\) (2 ≤ q ≤ 12); triangles: Ar\(^{+}\), Ref. [21]; closed circles: Xe\(^{+}\), Ref. [15]; star, Ref. [22].

Fig. 6. — Comparison of measured one electron capture cross sections of different ions on Ar: Open circles: present data Ar\(^{+}\) (2 ≤ q ≤ 12); closed points: Xe\(^{+}\), Ref. [15]; triangle: O\(^{+}\), Ref. [15]; square: N\(^{+}\), Ref. [15]; circle: C\(^{+}\), Ref. [15]; X = Ar (present results).

Charges up to 8 is good. Recently in the energy range 7-45 eV, the total electron capture of Ne\(^{10+}\) on Ne has been measured by Vane et al. [22]. They have shown that the total cross section (of order 2.4 × 10\(^{-15}\) cm\(^2\) ± 30 %) is velocity independent. It is interesting to notice that Ne\(^{10+}\), undergoing charge exchange with Ne behaves as Ar\(^{10+}\) colliding on Ne, giving a cross section of the same order of magnitude. Considering the present data and estimated uncertainty, since \(\sigma_{q,q-1}\) is always less the total exchange cross section (\(\sigma_{q,k}\) for \(k > 1\) have to be added to \(\sigma_{q,q-1}\)), it is observed that the agreement is good (on Fig. 5, Ne\(^{10+}\) exchange cross section is represented by a star).

Figure 6 summarizes the measured cross section values \(\sigma_{q,q-1}\) for different ions impinging on Ar. Gardner et al. [23] have used C, N and O ions up to charge \(Z = 2\) (Z atomic number). For higher charges Salzborn et al. [15] have utilized Ar ions up to charge +7 and Xe up to charge +8; it has been noticed...
that these values have been overestimated (for charges $> 4$) by as much as 40\% [23, 20]. Correcting gives values in agreement with the present data.

3.2 Discussion. — On figures 1, 2 and 3 the results of different theoretical calculations are represented for comparison with the present data.

The cross sections, calculated by Presnyakov et al. [7], show a $q^2$ dependence. In the limiting case where $v < v_0$, the single electron capture cross section is expressed as:

$$\sigma_{q=1} \approx \pi a_0^2 \left( I.P. (eV)/13.6 \right)^2 (cm^2)$$

with $a_0 = 0.53$ Å and I.P. (eV) ionization potential of the target ($q$ is at least $\geq 3$). On the aforementioned figures open squares are associated with this formula. It is recognized that, for interpretation, this model is of limited use.

The open triangles represent the experimental fitting law for single electron transfer as proposed by Salzborn et al. [15, 17]; the cross section is written as:

$$\sigma_{q=1} \approx 1.43 \times 10^{-12} q^{1.17} [I.P. (eV)]^{-2.76} (cm^2).$$

For targets with high ionization potentials (He, Ne) this fit is satisfactory but we would prefer a linear variation in $q$ as represented (dot dashed line).

The crosses on figures 1, 2 and 3 represent the results of Grozdanov et al. [9] calculations. Their cross section variation is linear in $q$ and parallel to our dot slash line.

The filled circles are the results of the theoretical evaluation of Olson et al. [8]: they are closer to the present values for Ar than those of Grozdanov et al.

These theoretical evaluations [8, 9] give values generally too large compared to present and other experimental values (Figs. 4, 5 and 6).

More recently, using the Bohr Lindhard cross sections for the capture of one classical [24] electron combined with the statistical Bohr atom electron distribution, Knudsen et al. [25] have derived a simple estimate of the single electron capture cross section: in their calculation they show that in the limit of low ion velocity, the cross section is linear in projectile charge $q$ (with $q > 4$) and independent of projectile velocity according to

$$\sigma_{\text{capture}} = \pi a_0^2 \frac{1}{2} z^{2/3} \left( \left( \frac{I.P.}{I_0} \right)^{1/2} \alpha \right)^{-2} (cm^2)$$

with $z$: target atomic number, $I.P.$ target ionization potential, $I_0$ atomic hydrogen ionization potential and

$$\beta = z^{-1/3} + \frac{\pi}{z} \left( \frac{I.P.}{I_0} \right)^{1/2}.$$ 

With $\alpha$ parameter to be adjusted, they obtain in the case of He ($\alpha = 0.40$) $\sigma_{\text{capture}}/q \approx 2.5 \times 10^{-16}$ to be compared with our value of $3.37 \times 10^{-16}$. In the case of argon ($\alpha = 0.46$) they obtain $\sigma_{\text{capture}}/q \approx 10^{-15}$, our value being $6 \times 10^{-16}$. It should be noted that the parameter $\alpha$ is found by fitting for each target atom the calculated cross sections to low velocity high charge ion data. In the case of argon atom target, the data have been taken from Salzborn et al. [15] (their values are overestimated) and Zwally et al. [26] (their data had been obtained with C$^4+$ and were a factor of $\sim 3$ too high due to experimental difficulties); these arguments considered would thus lead to a larger value for $\alpha (\sim 0.6)$ which thus give a lower $\sigma_{\text{capture}}/q$ value.

We consider now specifically the case of Ar$^{6+}$ colliding He for which theoretical estimate of the cross sections have been made utilizing a molecular model [27]; it appears that summing the cross sections for capture of one electron into 3d, 4s and 4p states of Ar$^{5+}$ gives a total-cross section of order $2.1 \times 10^{-15}$ cm$^2$

at 12 keV decreasing to $1.9 \times 10^{-15}$ cm$^2$ at 24 keV. The present results are in excellent agreement with these theoretical predictions: the mean value of $2 \times 10^{-15}$ cm$^2$ shown in figures 1 and 4 is in fact associated with a slight decrease over the experimental energy range: the extent of the cross section variation is of order $\pm 10\%$ about the mean value; being about maximum at the lower limit of the energy explored. This has also been observed by Müller et al. [28].

In the case of a Ne target a fit of the present data to the simplified theory [25] cited above is possible for $\alpha = 0.5$, in the projectile low energy limit.

Double electron capture on autoionization levels can also occur [15, 20]; but since the double capture cross sections are one order of magnitude smaller than the single capture cross section, the values obtained for single capture are only perturbed to a small extent. Furthermore after a single electron capture, the $(q - 1) +$ ion may be excited and if this excitation is large enough, autoionization may lead to ionization of other electrons. If this process were to take place prior to post collision charge analysis, a lower capture cross section would be observed.

These two effects cannot definitely be ruled out but it is reasonable to assume that the cross sections are not largely influenced by them.

4. Conclusion. — The evolution of charge exchange cross sections of argon ions ($2 \leq q \leq 12$) on different target atoms has been measured in the low energy limit. It has been shown to be ion velocity independent and varying as $q$ for $q \geq 4$. As suggested by Knudsen et al. [25], the present data can be shown to fit with

$$\sigma_{q=1} \approx K q [I.P. (eV)]^3$$
for \( q \geq 4 \). This leads to

\[
\begin{align*}
K &= 4.94 \times 10^{-12} \text{ for He } ; \\
K &= 4.94 \times 10^{-12} \text{ for Ne } ; \\
K &= 2.37 \times 10^{-12} \text{ for Ar } .
\end{align*}
\]

The oscillations around the mean variation line as function of \( q \) are probably attributable to specific electronic configurations in the colliding pair. They have been predicted for multiply charged ions colliding on atomic hydrogen [27]. For the case of \( \text{Ar}^{8+} \), a relative minimum is observed which is associated with a Ne like ion structure.

References