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# Charge multiplication via Auger decay of $L$ vacancies in the production of highly charged Ar ions by collisions with 1-MeV/amu $O^{q+}$ and $F^{q+}$

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Cross sections for the production of Ar recoil ions in collisions with 1-MeV/amu $O^{q+}$ and $F^{q+}$ ($q=2$ to bare nuclei) were measured by the time-of-flight technique. The cross sections for the production, by pure ionization, of recoil ions having charges greater than 6 display an unexpected behavior as a function of $q$. They rise at low $q$, reach a maximum in the vicinity of $q=5$–7, and then decrease at high $q$. Cross sections calculated using the independent-electron approximation rise continuously in this region and are lower than the experimental cross sections by as much as 4 orders of magnitude for high recoil-ion charge and low $q$. The observed turnover in the cross sections, as well as the large discrepancies in absolute magnitude between experiment and calculation, are accounted for by vacancy multiplication resulting from $L$-shell ionization followed by Auger decay.

Total cross sections for direct ionization[1–4] (DI) and transfer ionization[5–7] (TI), in which ionization of the target is accompanied by capture to the projectile, have been measured for a number of collision systems. Theoretical efforts to describe these multielectron processes have, for the most part, been limited to applications of the independent-electron approximation[8] (IEA). These treatments have employed a variety of prescriptions, such as the classical trajectory Monte Carlo method[1,9] (CTMC), to calculate the single-electron ionization probability as a function of impact parameter $p(b)$ and have utilized binomial or multinomial statistics to compute the total probabilities for ionizing specific numbers of electrons.[4,9–11] It has generally been assumed for medium-$Z$ targets like Ar that ionization is predominately from the $M$ shell while capture is mainly from the $L$ shell.[6,9] The results of such calculations for light ions on an Ar target give fair agreement with experiment for low-recoil ion charges, but theory and experiment quickly diverge as the recoil-ion charge state increases and the projectile charge state decreases.[1,4,5]

In the present experiments, cross sections for direct ionization and ionization accompanied by one-electron capture and one-electron loss were measured for a wide range of oxygen and fluorine projectile charge states ($q=2+$ to fully stripped) incident on Ar at 1 MeV/amu. The cross sections for the direct ionization of six or more electrons display an unusual dependence on $q$ which has not been observed or predicted previously. We shall show that the behavior in question reflects the importance of charge multiplication by Auger decay following $L$-shell ionization, and when this effect is accounted for, the IEA provides cross sections that are in good agreement with experiment.

The oxygen ion measurements were performed at the Texas A&M University Cyclotron Institute, and the fluorine ion measurements were performed at the Kansas State University J. R. Macdonald Laboratory. Similar systems were used in both sets of measurement.[12,13] The desired charge state of the incident beam was selected by means of an analyzing magnet positioned a short distance upstream from a differentially pumped gas cell. The Ar pressure in the gas cell was maintained around 1 mTorr, while the pressure outside was kept lower than this by at least 3 orders of magnitude. Pressure-dependence measurements were performed to verify that single-collision conditions were satisfied for both projectiles and recoil ions. The recoil ions were extracted from the gas cell by an electric field directed perpendicular to the beam and al-

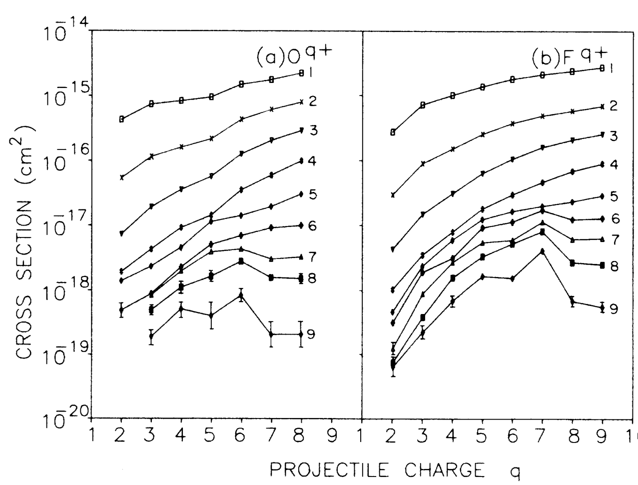


Fig. 1. Experimental cross sections for Ar recoil-ion production by pure ionization as a function of the projectile charge; (a) oxygen projectiles; (b) fluorine projectiles. The numbers along the right-hand side label the recoil-ion charge.

 

lowed to drift to a chevron microchannel-plate (MCP) detector assembly. Charge-state identification of the recoil ions was provided by time-of-flight spectrometry. The projectile detector was located downstream from the exit port of the gas cell behind another analyzing magnet used to select the post-collision projectile charge state. In the oxygen ion experiments, a silicon surface-barrier detector was used as the projectile detector. In the fluorine ion experiments, a position-sensitive parallel-plate avalanche detector was used, and this system provided the ability to detect up to three different projectile charges at a single analyzing magnet setting in an event-by-event data-acquisition mode.

The measured cross sections for direct ionization of Ar by $O^{q+}$ and $F^{q+}$ are shown in Figs. 1(a) and 1(b). The features of interest here are displayed by the cross sections for recoil charge states 6 through 9. In particular, these cross sections rise at low $q$, reach a maximum in the vicinity of $q=5$–7, and then decrease at high $q$.

The IEA model was employed in an effort to understand the systematics of the direct-ionization cross sections. The first attempt utilized the CTMC to estimate the one-electron ionization probability as a function of impact parameter. The multielectron ionization cross sections resulting from this calculation rose continuously as a function of $q$, however, and gave no indication of the turnover observed in the experimental data. Because the CTMC predictions underestimated the one-electron ionization cross sections by over a factor of 2, another calculation was carried out using a simple exponential dependence of the one-electron ionization probability on impact parameter,[4]

$$p(b)=p(0)\exp(-b/r), \tag{1}$$

where $p(0)$ is the CTMC one-electron ionization probability at impact parameter $b=0$ and $r$ is a constant. The one-electron ionization cross sections are then given by

$$\sigma(1)=2\pi\begin{bmatrix}8\\1\end{bmatrix}\int_0^\infty p(0)\exp(-b/r)[1-p(0)\exp(-b/r)]^7 b\,db\,. \tag{2}$$

Solving this equation for $r$ using the experimental one-electron ionization cross sections for $\sigma(1)$ normalizes the calculated one-electron ionization cross sections to the experimental results, which in turn provides more reliable estimates of the theoretical cross sections for multielectron ionization. The calculated ionization cross sections obtained by this method are shown for $O^{q+}$ and $F^{q+}$ in Figs. 2(a) and 2(b). Again it is found that the cross sections rise continuously and give no indication of the experimentally observed turnover for high-recoil charges. Moreover, the calculated cross sections for low-$q$ and high-recoil-ion charges are lower than the experimental values by up to 4 orders of magnitude.

Recently, DuBois and Manson[14] showed that $L$-shell ionization followed by Auger decay is a major contributor to the production of multiply charged Ar recoil ions by proton impact. This finding, which has also been verified by the calculations of Sergeev, Nikolaev, and Novozhilova,[15] suggests the possibility that $L$-shell ionization might also play an important role in recoil-ion charge multiplication for collisions of low-$q$ heavy ions. Experimental evidence of the effect of this charge multiplication process on recoil-ion charge-state distributions has recently been reported by Levin *et al.*[16]

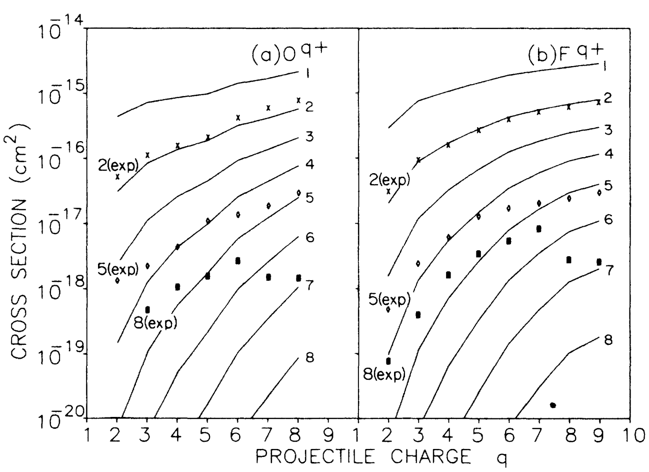


Fig. 2. Ionization cross sections calculated using the IEA with exponential-ionization probability functions and experimental cross sections for one-electron ionization (see explanation in the text); (a) oxygen projectiles; (b) fluorine projectiles. The numbers along the right-hand side label the recoil-ion charge. Experimental data points for $q=2$, 5, and 8 are shown for comparison.

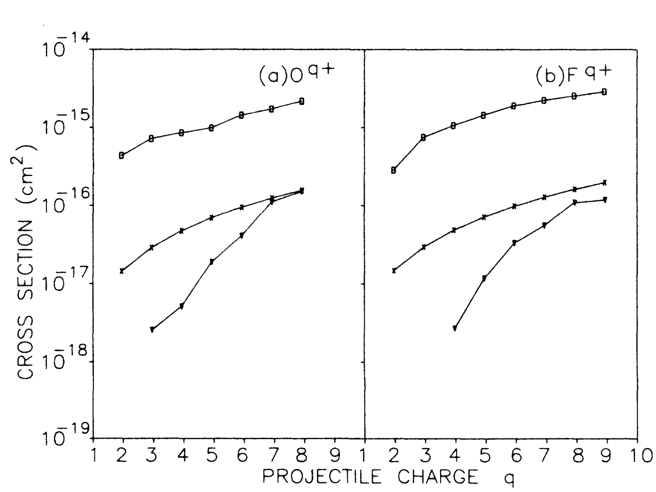


Fig. 3. Experimental cross sections for Ar recoil-ion production by one-electron ionization (□), one electron capture (▽), and calculated cross sections for Ar $L$-shell one-vacancy production (×), as a function of the projectile charge; (a) oxygen projectiles; (b) fluorine projectiles.

Total single $L$-vacancy production cross sections (the sum of ionization and capture) for the present cases were estimated by scaling the proton cross sections using a power law determined by Be *et al.*[17] They are shown in Figs. 3(a) and 3(b) along with the one-electron ionization cross sections and the total one-electron-capture cross sections obtained in the present measurements. The fact that the one-electron-capture cross sections converge with the total single $L$-vacancy production cross sections as $q$ increases indicates that (a) capture is almost entirely from the $L$ shell and (b) the cross section for $L$-shell one-electron ionization (which is given by the difference between the total single $L$-vacancy production cross section and the one-electron-capture cross section) is much larger than the $L$-capture cross section for low $q$. Therefore, corrections to the direct-ionization cross sections for charge multiplication by Auger decay will be much larger at low $q$ than at high $q$, where very little $L$-shell ionization occurs. Furthermore, because there are more ways of producing high-recoil-ion charges than low-recoil-ion charges by combinations of ionization plus Auger decay, the corrections will be much larger for high-recoil-ion charges than for low-recoil-ion charges.

In order to estimate the contribution of charge multiplication resulting from $L$-shell ionization to the experimental ionization cross sections, the $L$-shell one-electron vacancy production and one-electron-capture probabilities were each represented by Eq. (1) with $p_L(0)$ set to the CTMC value of 0.6 for fully stripped projectiles. [The same value of $p_L(0)$ was used for all projectile charge states since the cross sections were found to be fairly insensitive to this parameter.] The radius parameters $r_L$ and $r_{Lc}$ were determined by fitting the expressions for the one-electron vacancy production and capture cross sections [analogous to Eq. (2)] to the cross section data shown in Fig. 2 in the same manner as described above for the $M$-shell ionization probability. The $M$-shell plus $L$-shell multielectron ionization cross sections ($m$ and $l$ are the number of $M$-shell and $L$-shell vacancies, respectively) were then calculated by means of the equation[6,8]

$$\sigma(ml)=2\pi\int_0^\infty \binom{8}{m} P_M^m(1-P_M)^{8-m}\binom{8}{l}P_{Li}^l(1-P_{Li}-P_{Lc})^{8-l}b\,db$$
$$\simeq 2\pi\binom{8}{m}P_M^m(0)[1-P_M(0)]^{8-m}\binom{8}{l}\int_0^\infty P_{Li}^l(1-P_{Li}-P_{Lc})^{8-l}b\,db\,, \tag{3}$$

where

$$P_M=p_M(0)\exp(-b/r_M)\,,$$
$$P_L=p_L(0)\exp(-b/r_L)\,,$$
$$P_{Lc}=P_{Lc}(0)\exp(-b/r_{Lc})\,,$$

and

$$P_{Li}=p_L(0)\exp(-b/r_L)-p_{Lc}(0)\exp(-b/r_{Lc})\,.$$

Finally, the recoil-ion production cross sections were obtained by summing all the $\sigma(ml)$ that contribute to the same recoil-ion charge, as summarized in Table I, assuming one additional $M$-shell vacancy per $L$-shell vacancy due to Auger decay. This procedure is strictly valid only when the $L$-shell fluorescence yields are zero and multiple Auger and shake-off processes are negligible. These assumptions are adequate for the level of accuracy needed in

TABLE I. Cross sections $\sigma(ml)$ that contribute to the production of Ar recoil ions by direct ionization plus Auger decay, where $m$ is the number of $M$-shell vacancies and $l$ is the number of $L$-shell vacancies.

| Recoil-ion charge | Contributing cross sections | | | | |
|---|---|---|---|---|---|
| 1 | $\sigma(10)$ | | | | |
| 2 | $\sigma(20)$, | $\sigma(01)$ | | | |
| 3 | $\sigma(30)$, | $\sigma(11)$ | | | |
| 4 | $\sigma(40)$, | $\sigma(21)$, | $\sigma(02)$ | | |
| 5 | $\sigma(50)$, | $\sigma(31)$, | $\sigma(12)$ | | |
| 6 | $\sigma(60)$, | $\sigma(41)$, | $\sigma(22)$, | $\sigma(03)$ | |
| 7 | $\sigma(70)$, | $\sigma(51)$, | $\sigma(32)$, | $\sigma(13)$ | |
| 8 | $\sigma(80)$, | $\sigma(61)$, | $\sigma(42)$, | $\sigma(23)$, | $\sigma(04)$, |
| | | $\sigma(71)$, | $\sigma(52)$, | $\sigma(33)$, | $\sigma(14)$ |
| 9 | | $\sigma(81)$, | $\sigma(62)$, | $\sigma(43)$, | $\sigma(24)$, $\sigma(05)$ |
| | | | $\sigma(72)$, | $\sigma(53)$, | $\sigma(34)$, $\sigma(15)$ |

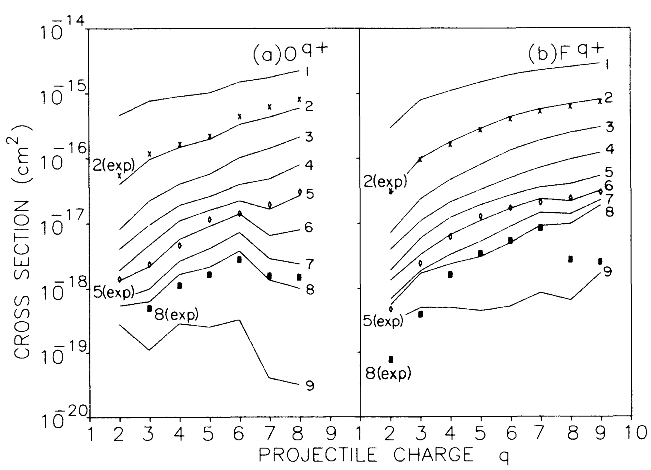


Fig. 4. Total-vacancy production cross sections for pure ionization calculated by summing all the $\sigma(ml)$ that contribute to the same recoil-ion charge state; (a) oxygen projectiles; (b) fluorine projectiles. The numbers along the right-hand side label the recoil-ion charge. Experimental data points for $q=2$, 5, and 8 are shown for comparison.

the present analysis.

The calculated recoil-ion production cross sections for $O^{q+}$ and $F^{q+}$ are shown in Figs. 4(a) and 4(b). As expected, the effect of adding charge multiplication via the Auger decay of *L*-shell vacancies has been to raise the cross sections for high-recoil-ion charge and low *q*.

In the case of a Ne target, Auger decay of *L* vacancies cannot occur, and since the cross sections for *K* capture or ionization are too small to contribute significantly,[18,19] the effects of charge multiplication should be negligible. This prediction was verified experimentally by performing similar measurements on Ne under the same conditions as in the Ar experiments. The results of the neon measurements were in good agreement with previous results.[5]

In summary, the importance of charge multiplication resulting from the Auger decay of inner-shell vacancies on the cross sections for the production of highly charge recoil ions by low-*q* projectiles has been demonstrated. In the cases of $O^{q+}$ and $F^{q+}$ on Ar, *L*-vacancy production is primarily by direct ionization at low *q* and by electron capture at high *q*. This difference in the energy and *q* dependence of the inner-shell ionization and capture processes leads to a *q*-dependent correction for charge multiplication in the pure ionization channel which accounts for the large (up to 4 orders of magnitude) differences between the experimental findings and the predictions of the IEA for pure *M*-shell ionization. The effects of charge multiplication on the electron-capture channel, however, do not vary with *q*, and therefore do not produce a turnover similar to that observed in the direct-ionization data.

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