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Single and double electron capture associated with target K-shell ionization for $F^{7+,8+,9+}$+Ar

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Ratios for target Ar K-shell ionization associated with single and double electron capture, as well as the ratios corresponding to total capture and the projectile K x rays, were determined for 1.8- to 2.2-MeV/u $F^{7+,8+,9+}$ projectiles. This work was performed at Western Michigan University with the tandem Van de Graaff accelerator. Coincidences between emitted K-shell X-rays (both target and projectile) and the corresponding charge-changed particles were observed. The F^{9+} Ar K X-ray coincidence ratios for double to single capture are found to well exceed unity over the limited energy range of the measurements. Possible explanations for this anomalous behavior are discussed.

INTRODUCTION

Ion–atom collisions have been of fundamental interest in the fields of atomic physics and astrophysics for decades and are valuable for testing the validity of theoretical models and predictions. Of particular importance are charge-changing cross sections and K-shell ionization. Theoretical studies of collisions often deal with the calculation of electron capture and K-shell ionization cross sections,[1–3] whereas the corresponding experimental studies deal with the measurement of these cross sections.[4–6]

Motivation for the present investigation is based on previous work for fully stripped fluorine[7] and oxygen projectiles[8] on Ar targets. Coincidence techniques employed in the present work allow the emitted X-rays to be assigned to their respective charge-changed particles and vice versa. This permits the emission of a K-shell X-ray to be associated with single or double electron capture. The measurement of only double and single total electron capture does not accomplish this and the following results would not be observable.

The collision of energetic projectile fluorine ions with target Ar atoms can result in the loss of one or more electrons from the target. One or two of these electrons may come from the K shell, after which an electron from an outer shell of the Ar atom can then fall to the K shell with the simultaneous emission of an X-ray. The projectile may capture no electrons, one, or more electrons in the collision process. The captured electron(s) may come from any shell of the target atom, not necessarily from the Ar K shell.

EXPERIMENTAL PROCEDURE

This work was performed using the tandem Van de Graaff accelerator facility at Western Michigan University. A 90° analyzing magnet was used to select F^{7+} ions with the desired energy. When required, the ions were post-stripped to F^{8+} or F^{9+} by a thin carbon foil. The ion beam was then deflected into the target beamline by a dipole switching magnet and collimated by adjustable apertures before entering the interaction region (Figure 1).

The collision chamber is a differentially pumped gas cell where the target gas pressure (∼ 8 mTorr) was set to remain in the single-collision regime, with total charge exchange less than 5%. An Si(Li) X-ray detector with a 0.4-μm polymer entrance window was placed at 90° to the beamline, providing a detection efficiency of nearly 100% in the energy region of characteristic Ar X-ray emission and ∼85% in the F K X-ray region, having an effective

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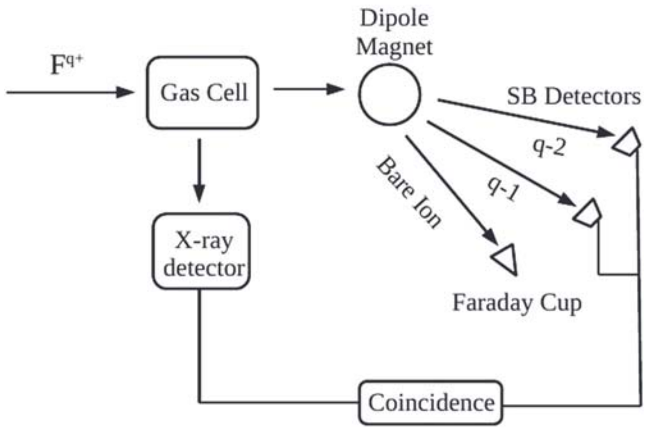

FIGURE 1 Experimental schematic for the detection of coincidences between emitted X-rays and the charge-changed ions

area of 60 mm^2 and a beamline-to-crystal distance of ~17 mm.

After passing through the collision chamber, the ion beam was charge-state analyzed using a dipole magnet. The primary ion beam was collected by a Faraday cup negatively biased to suppress ejected electrons, and the resulting current was measured with a Keithley electrometer. The singly and doubly charge-changed ion beam components were measured using separate silicon surface-barrier particle detectors. The X-ray and particle detector data were collected with an event-mode data acquisition system, and standard coincidence techniques were used to assign the measured X-rays to their respective charge-changed particles or vice versa.

RESULTS AND DISCUSSION

The scattered beam fraction (F) for a given process is given as the ratio of the number of events (X-rays or charge-changed particles) to the number of total incident ions.

$$F = \frac{\# \quad \text{of events}}{\# \quad \text{of incident ions}}$$

A higher density of target particles will necessarily create more projectile–target interaction events; thus, the fraction F is a function of the gas pressure and under single-collision conditions it is a linear function. The denominator of the fraction F was determined by ntegrating the beam current and adding to it the respective charge-changed projectile events. The numerator of the fraction F was determined by measuring the number of charge-changed particles with electronic counters referenced to the particle detectors or the number of K X-rays (Ar or F) registered in coincidence with a singly or doubly charge-changed projectile.

X-rays detected in coincidence with singly and doubly charge-changed particles were recorded, with examples of such spectra shown in Figure 2. The Ar K X-ray peaks can be clearly seen in the F^{9+} spectra for single and double capture. The energy calibration for all spectra was performed using the Mn K_α and K_β lines from a standard ^{55}Fe source, as well as the hydrogen-like 1s-2p transition of fluorine.[10]

The ratios of total double to single electron capture are shown in Figure 3a. The F^{9+} total double to single electron capture ratios are about 0.25, whereas those for F^{8+} are about 0.10. This ratio for F^{7+} varies from about 0.10 to 0.05 over the projectile energy range. The F^{9+} ratios are nearly constant but may rise slightly over the energy range, whereas the F^{8+} ratios remain relatively constant, and the F^{7+} ratios decrease by about a factor of 2 as the projectile velocity increases in the range studied. These total yields for double to single capture ratios are consistent with those from an earlier F^{q+}+Ar experiment,[9] also shown in Figure 3a.

The present charge-state results are expected, as the total capture yields should increase with the projectile ionization state with those for F^{9+} being the largest. The ratios obtained for $F^{8+,9+}$+Ar are consistent with the $O^{7+,8+}$+Ar measurements performed over a similar energy range,[8] also shown in Figure 3. The fully stripped fluorine double to single capture ratio is higher than that for oxygen at the same energy due to the higher charge state for fluorine. The ratios for the fully stripped and H-like oxygen over the energy range are different by about the same amount as the fully stripped and H-like fluorine ratios, respectively. The reason for the difference in the fluorine ratios for incident 7+, 8+, and 9+ ions lies also in the number of K-shell vacancies for each projectile. For single capture, both F^{8+} (one K-shell vacancy) and F^{9+} (two K-shell vacancies) can capture an electron to its K shell, whereas F^{7+} must capture to the L or a higher shell. For double electron capture, only F^{9+} can capture both electrons to its K shell. One electron can be captured to the K shell for F^{8+}, but the second electron must be captured to the L or higher shell. These results demonstrate that the number of projectile K-shell vacancies is a significant contributing factor to the total capture yields.

The ratios of double to single electron capture Q-2/Q-1 associated with target Ar K-shell ionization are shown in Figure 3b. It can be seen that the F^{7+} Q-2/Q-1 ratios for K-shell ionization are significantly less than unity, with the values remaining relatively constant with projectile energy. The F^{8+} Q-2/Q-1 ratios are larger than those for F^{7+} and are close to, but never exceed, unity and also remain relatively constant with energy. However, unexpectedly, the F^{9+} Q-2/Q-1 ratios for Ar K-shell X-ray emission well

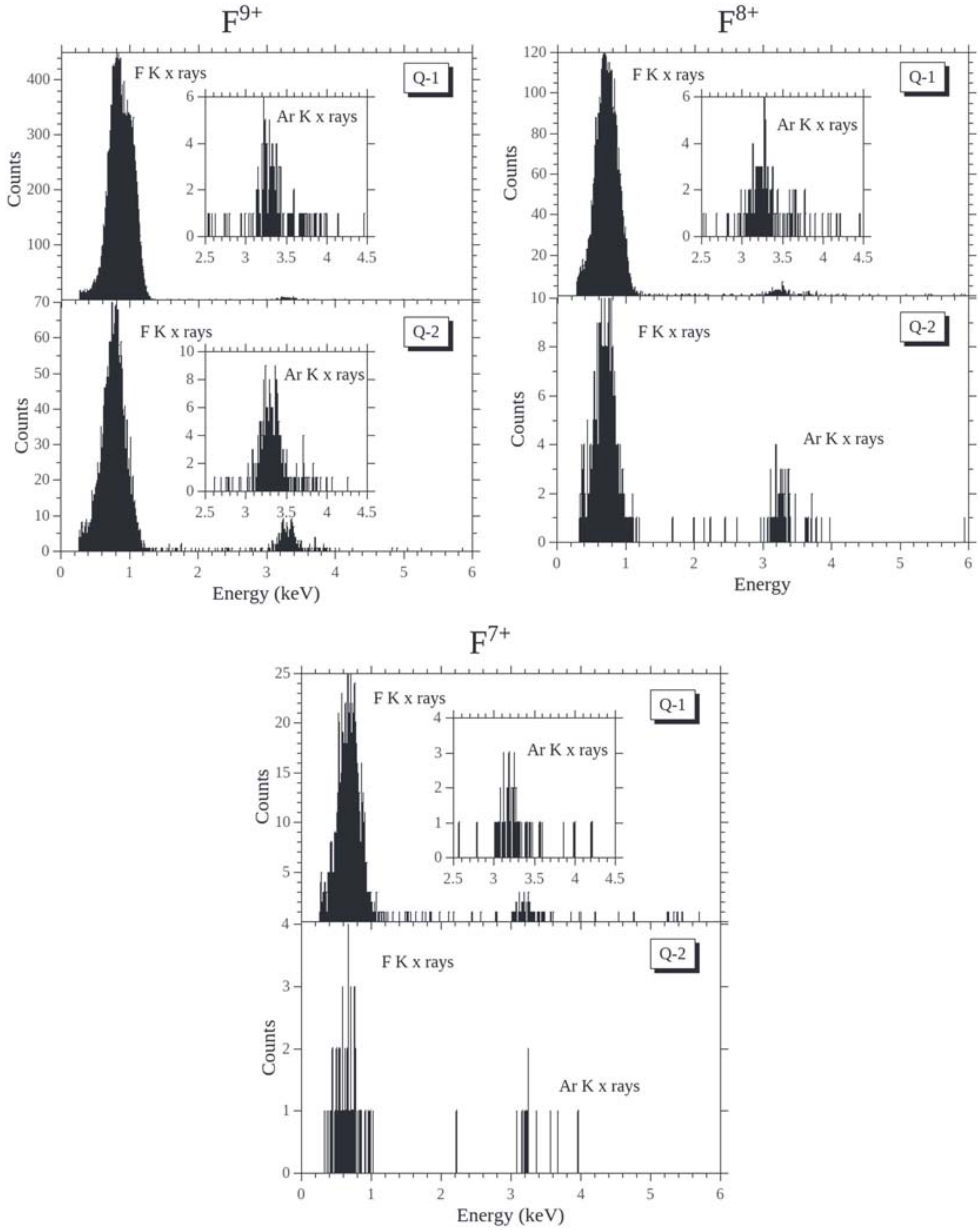

FIGURE 2 Coincidence X-ray spectra for single (Q-1) and double (Q-2) electron capture for 2.1-MeV/u F^{9+}, F^{8+}, and F^{7+} + Ar (at 8 mTorr gas pressure)

exceed unity and are about 2.5 times larger than the ratios for F^{8+} ions over the range investigated.

For highly stripped fast ion projectiles in the present energy range, the bulk of target ionization comes primarily from the L and M shells,[11] and the impact-induced ionization dominates the electron removal process over electron capture.[12] This fact makes the results for F^{9+} producing Ar X-rays unexpected. The total yield ratios also do not decrease and are nearly constant with the projectile energy. This may be due to the projectile average electron velocity lying between the target bound K- and L-shell electron velocities (the projectile velocity is about 60% of the Ar K-shell velocity), making capture from the K shell per electron quite probable.

The ratios of double to single electron capture associated with projectile F K-shell ionization are shown in Figure 3c. It can be seen that the characteristic K X-ray Q-2/Q-1 ratios for F^{7+} and F^{8+} are nearly constant, just decreasing slightly, for the energies measured, and the F^{9+} ratios may increase slightly with projectile energy, much the same as

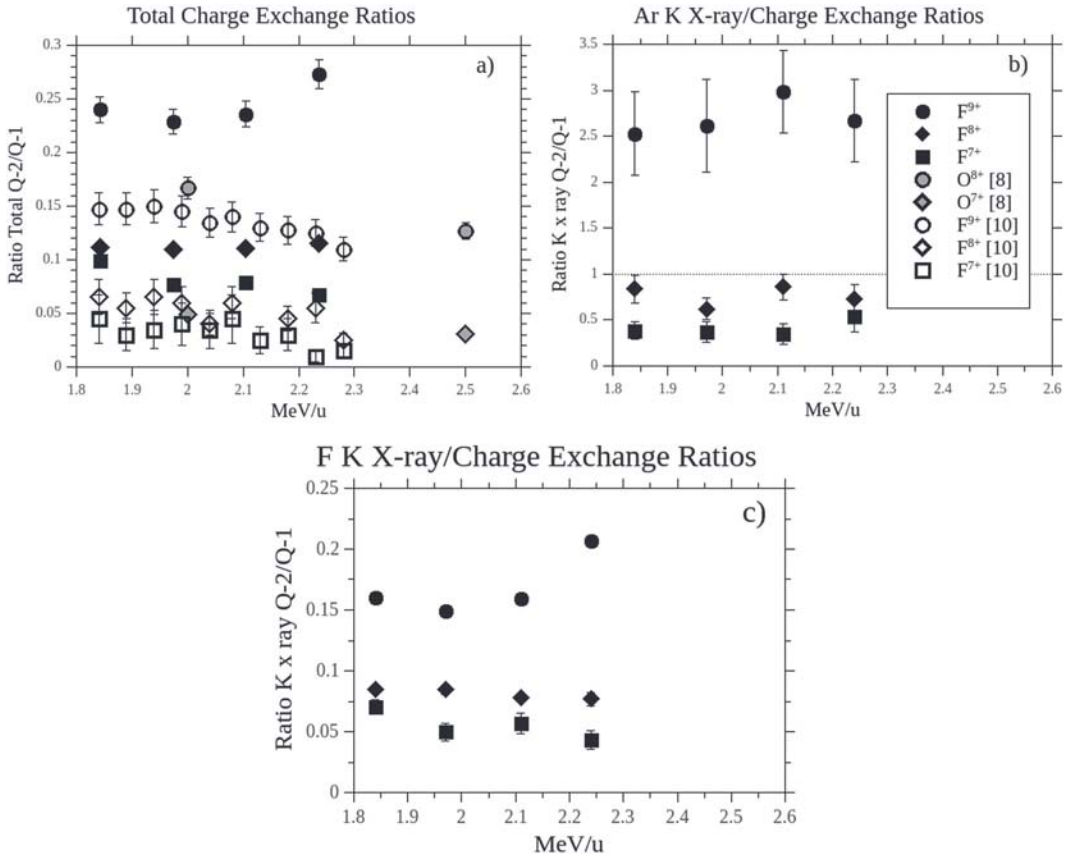

FIGURE 3 (a) Total single and double electron capture ratios (Q-2/Q-1) for $F^{7+,8+,9+}$+Ar in the present work, as well as earlier results for $O^{7+,8+}$+Ar[8] and $F^{7+,8+,9+}$+Ar.[9] The relative uncertainty for the ratios of the present work is about 5%. Ratios of double (Q-2) to single (Q-1) electron capture associated with characteristic Ar K (b) and F K (c) X-ray emission for F^{q+} projectiles. The average relative uncertainties for the F^{7+}, F^{8+}, and F^{9+} capture ratios for the Ar K X-rays shown in (b) are 30%, 20%, and 20%, respectively. The average relative uncertainties for the F^{7+}, F^{8+}, and F^{9+} capture ratios for the F K X-rays shown in (c) are 5%, 5%, and 15%, respectively

the total Q-2/Q-1 ratios shown in Figure 3a. Furthermore, the values of the F ratios are about the same as those found for the total yield ratios, with the F ratios being a little lower.

The Q-2/Q-1 ratios of fluorine K X-ray production for F^{7+} and F^{8+} are both about an order of magnitude smaller than the corresponding ratios for argon over the entire energy range. The F^{9+} ratios for F K X-ray production are about a factor of 20 smaller than those for Ar over the energy range. The F K X-ray charge exchange ratios have essentially the same behavior as the corresponding total capture ratios over the projectile energy range for all incident ions, with F^{7+} decreasing slightly over the energy range, F^{8+} remaining essentially constant, and F^{9+} possibly increasing slightly at the highest energy.

CONCLUSION

The ratios of total double to single electron capture, as well as the same ratios for Ar K X-rays and F K X-rays, for $F^{7+,8+,9+}$+Ar were determined in the projectile energy range 1.8–2.2 MeV. All of the F^{7+}, F^{8+}, and F^{9+} ratios were found to remain relatively constant with incident ion energy, with the F^{7+} and F^{8+} ratios being less than unity. The unexpected result of this work is that the F^{9+} Ar K X-ray ratios well exceeded unity by a factor of about 2.5.

The target Ar K X-ray production results for F^{9+} give insight into the importance of projectile K-shell vacancies in electron capture events and in the subsequent characteristic target X-ray production. Two projectile K-shell vacancies greatly increase the likelihood of single or double electron capture, with one K-shell vacancy increasing the likelihood considerably less so. The emission of characteristic target Ar K-shell X-rays is also related to the number of projectile K-shell vacancies, with the presence of two vacancies increasing the K-shell X-ray yield. This is manifested by the fact that the Ar K ratio for F^{9+} is the only one greater than unity. The actual cross sections for all the processes studied here will shed more light on the results. The data for these cross sections were also obtained, and the cross sections are being analyzed. These cross sections will be reported in a future publication.

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