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Argon and krypton x-ray production by fluorine projectiles of different charge states*

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Kr K, Kr L, and Ar K x-ray yields have been measured for excitation by 36- and 48-MeV fluorine ions in $+6$ to $+9$ charge states. The significant decrease in the dependence of the target x-ray yields on the projectile charge state, which is observed as the parameter Z_1/Z_2 is decreased, is in agreement with theoretical expectations.

I. INTRODUCTION

It is now well established[1-6] that target K-shell x-ray cross sections can exhibit a strong dependence on the electronic charge state of the projectile ion—a result which is not predicted by existing theories of direct Coulomb ionization,[7,8] but which might be obtained by the inclusion of screening of the projectile nucleus. In some cases the large variation of x-ray yield with charge state can be attributed to variations in the mean fluorescence yield of the states excited by the different charge states of the projectile[9]; but in other cases only small variations of fluorescence yield occur, and the change in x-ray yields is attributed to variations in the ionization cross sections with the different projectile configurations.[3] Although the magnitude of this effect has been systematically investigated for argon targets excited by carbon, nitrogen, oxygen, and fluorine ions,[3] the mechanism responsible for the charge-state dependence is not yet fully understood. At low velocities the projectile is expected to approximate a structureless point-charge in its interaction with the target when $Z_1/Z_2 \ll 1$.[10] (Z_1 and Z_2 are the atomic numbers of the projectile and the target.) Thus, because the ratio Z_1/Z_2 provides a measure of the influence of the projectile's electronic structure on the target ionization process, we have studied the magnitude of the charge-state effect as a function of this parameter.

In the present work we have measured Kr K and L x-ray yields produced by incident 36- and 48-MeV F ions with charge states from $+6$ to $+9$. Additional data have also been acquired for Ar K x-ray yields obtained with 36- and 48-MeV F ions. As the Z_1/Z_2 ratio is decreased from $\frac{1}{2}$ (F^{q+} on Ar) to $\frac{1}{4}$ (F^{q+} on Kr), we observe a significant *decrease* in the dependence of the target x-ray yield on the projectile charge state. In addition, although the direct Coulomb-ionization theory[7,8] does not correctly predict the absolute magnitudes of the cross sections for the fully stripped ions, we note that the observed projectile energy dependence of these cross sections is in general agreement with the theoretical predictions.

II. EXPERIMENT

The apparatus and experimental method have been described in detail elsewhere,[3,11] and consequently only a brief description will be provided here. Fluorine ions were accelerated to an energy of 36 or 48 MeV, passed through a stripping foil to obtain the desired charge state, and then directed by a switching magnet into the apparatus shown in Fig. 1. The ion beam traversed a differentially pumped target cell and was collected in a suppressed Faraday cup. Careful collimation of the beam assured that all incident ions were collected. The pressure of the target was monitored by an accurately calibrated capacitance manometer. X rays were counted by a Si(Li) detector which was positioned at 90° to the beam and which has a resolution of ~200 eV at 5.9 keV.

The target gas pressure was kept low enough ($\leqslant$30 mTorr for Kr and $\leqslant$10 mTorr for Ar) to ensure that only single collision events were observed. Estimates employing the measured cross sections indicate that the probability of observing double collision events in which inner-shell vacancies were produced was less than 0.1%. Single collision conditions were further confirmed by the strict linearity between x-ray yield and target gas pressure which was observed in all cases. The fluorine ions did undergo some charge exchange at the higher target pressures; however, this could produce no more than a 5% change in the measured cross sections, and was thus neglected.

Absolute cross sections were determined in the following manner. Two Si(Li) detectors were mounted on opposite sides of the interaction region, approximately 10 cm from the beam. For this geometry the effective solid angle factor ($\frac{1}{4}\pi \int \Omega \, dl$), which is defined as the fraction of 4π sr subtended by the detector integrated over the interaction length of the target, could be calculated for each detector to an accuracy of 5% ($\frac{1}{4}\pi \int \Omega \, dl$

$=8.14\times10^{-4}$ cm). The Kr K, Kr L, and Ar K x-ray yields produced by 3.0-MeV protons incident on Kr and Ar targets were then measured (Table I). The absolute yields obtained with the two detectors agreed to within 10%. The detectors were next positioned about 2.5 cm from the beam and the proton measurements were repeated. By comparing the new x-ray yields to the absolute cross sections obtained with the detectors at the 10-cm position, an effective solid angle factor ($\frac{1}{4}\pi\int\Omega\,dl$ $=6.9\times10^{-3}$ cm) was determined for the new geometry. The heavy-ion data in Table I were taken with the detectors in the 2.5-cm position. The efficiencies of the detectors which are listed in Table II were obtained from the transmission curve presented in Ref. 3.

Vacancy-production cross sections are obtained by dividing the measured x-ray cross sections by the fluorescence yields appropriate to the vacancy configurations of the radiating atoms. The choice of fluorescence yields has been discussed in Refs. 3 and 11; the values adopted here are given in Table II. For the Kr K and Ar K x rays it is believed that these values are known to approximately 10%.

The relative uncertainty in the cross sections is estimated as 10%, attributable to statistics, data analysis, beam current integration, and fluctuations in the target pressure during a given run. The sources contributing to the uncertainty in the absolute value of the cross sections are the uncertainties in the solid angle (10%), fluorescence yield (10% for Kr K and Ar K), absolute-pressure calibration (10%), and detector efficiency (10%). Thus, the uncertainty in the absolute Kr K and Ar K vacancy-production cross sections is approximately 22%.

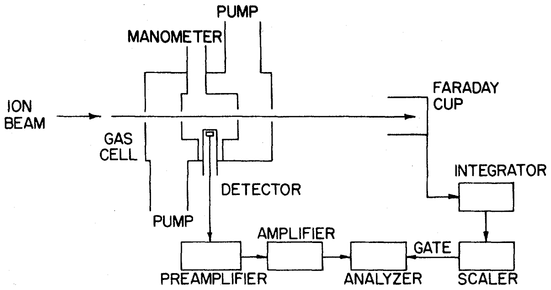

FIG. 1. Schematic diagram of the apparatus for determination of x-ray yields. The entrance apertures (1.0 and 1.5 mm) to the gas cell are smaller than the exit apertures (2.5 and 3.0 mm) to ensure complete collection of the ion beam.

III. RESULTS AND DISCUSSION

The x-ray yield and vacancy-production cross sections obtained in the present experiment are listed in Table I. Most of these values are an average of several independent data runs taken at different times with the two Si(Li) detectors located at various distances from the target. Results of the individual runs agreed to within experimental uncertainties. Our 3-MeV-proton cross sections are in good agreement with those published in Ref. 11 (present Kr cross sections are 15% smaller than those in Ref. 11, while our Ar results are 10% larger). The cross sections for Kr L x rays produced by 36-MeV F ions are also in good agreement with those given in Ref. 1

TABLE I. Krypton and argon x-ray (σ_x) and vacancy-production (σ_v) cross sections are given as a function of the number of electrons (n) carried by the incident projectile ion (Z_1) with a kinetic energy E. The absolute uncertainty in σ_x is less than 20% and in σ_v is less than 22%. Relative uncertainties are 10%.

		E		σ_x (10^{-21} cm^2)			σ_v (10^{-20} cm^2)	
Z_1	n	(MeV)	Kr K	Kr L	Ar K	Kr K	Kr L	Ar K
1	0	1.89[a]	0.0101	1.59	0.472	0.001 52	6.6	0.387
		2.53[a]	0.0201	1.81	0.615	0.003 02	7.5	0.504
		3.00	0.0315	1.93	0.703	0.004 73	8.0	0.576
9	0	36	0.178	428	110	0.0267	1780	75
	1		0.154	265	71	0.0231	1100	47.6
	2		0.135	176	37	0.0203	730	24.9
	3		0.115	134	25	0.0173	556	16.6
9	0	48	0.562	430	168	0.084	1780	113
	1		0.476	275	95	0.072	1140	64
	2		0.429	194	52	0.064	804	35

[a] Cross sections for 1.89- and 2.53-MeV protons were taken from Ref. 11 and scaled by factors which bring the 3-MeV cross sections of Ref. 11 into agreement with those obtained in the present work. In all cases, this resulted in an adjustment of less than 15% in the published cross sections.

(discrepancy is –13%). However, the present Ar *K* results for 36-MeV F ions are consistently about 37% higher than those in Ref. 3. This discrepancy results primarily from a 26% downward readjustment of earlier cross sections (i.e., those in Refs. 1, 2, and 11) which was performed in Ref. 3. In light of our careful redetermination of the absolute cross sections, made possible by the accurate calculation of the solid-angle factors with the detectors positioned 10 cm from the beam (Sec. II), the readjustment carried out in Ref. 3 now appears to have been in error, and, consequently, *all* cross sections presented in that paper are systematically low by 37%.[12] Nevertheless, it should be noted that the present *relative* Ar *K* cross sections for 36-MeV F are in good agreement (13%) with those given in Ref. 3 and that the conclusions of that work are not altered because of the error in the absolute cross sections.

Recent recalculations of theoretical Ar *L* fluorescence yields[13] reveal a strong influence of multiplet splittings on the values obtained for some configurations, and consequently there is considerable uncertainty in the average fluorescence yield when multiple vacancies exist. Since we anticipate a comparable uncertainty in the Kr *L* fluorescence yield, we will not attempt a detailed analysis of the ionization cross sections from the Kr *L* x-ray data. Ar and Kr *K*-shell vacancy-production cross sections for excitation by 36- and 48-MeV F ions are plotted in Fig. 2 as a function of the charge state of the incident ion. As has been noted previously[3-5] the cross sections show an exponential dependence on the projectile charge state. The Kr cross sections exhibit a smaller dependence on the projectile charge state but a larger dependence on projectile energy than do the Ar cross sections. To indicate the variation of the size of the charge-state effect with the parameter Z_1/Z_2, the ratios $\sigma(n)/\sigma(0)$ are plotted in Fig. 3 as a function of n, where n is the number of electrons carried by the incident projectile, and $\sigma(n)/\sigma(0)$ is the cross section for a projectile in charge state n divided by the cross section for the fully stripped ion. The ratio $\sigma(3)/\sigma(0)$ equals ~65% for F on Kr, whereas for F on Ar it is equal to only ~20%. Clearly, the magnitude of the charge-state dependence decreases significantly as Z_1/Z_2 decreases, approaching conditions under which we expect that the influence of the projectile electrons should be small and that the direct-Coulomb-ionization theory will apply. It would be of interest to extend this work to other systems with smaller values of the Z_1/Z_2 parameter to learn if the charge-state effect continues to decrease systematically.

In the remainder of this section we shall concentrate on the data from the fully stripped F^{9+} projectiles, comparing these results with those predicted by the Coulomb ionization theory. In Table III the observed vacancy-production cross sections for F^{9+} ions are listed together with scaled values obtained by multiplying the proton cross sections by Z_1^2. For F^{9+} on Ar, measured cross sections are a factor of 3 larger than theory. This observation is in agreement with the results of previous

TABLE II. Detector transmission efficiencies (ϵ) for the observed x rays, and the fluorescence yields for excitation by protons (ω_p) and by fluorine ions (ω_F).

X Ray	ϵ [a]	ω_p	ω_F
Kr *L*	0.52	0.0241 [b]	0.0241 [c]
Ar *K*	0.85	0.122 [d]	0.148 [e]
Kr *K*	1.00	0.660 [d]	0.660 [f]

[a] Reference 11.

[b] E. J. McGuire, Phys. Rev. A 3, 587 (1971). This theoretical value is now subject to a large uncertainty (Ref. 13).

[c] The value of ω_F for an atom with the multiple *M*-shell vacancies produced by F-ion impact is unknown. Therefore, ω_p has been used.

[d] W. Bambynek *et al.*, Rev. Mod. Phys. 44, 716 (1972).

[e] C. P. Bhalla, Phys. Rev. A 8, 2877 (1973); also, see Ref. 3.

[f] Although ω_F is not known exactly, it is expected not to differ greatly from ω_p since the latter is relatively large.

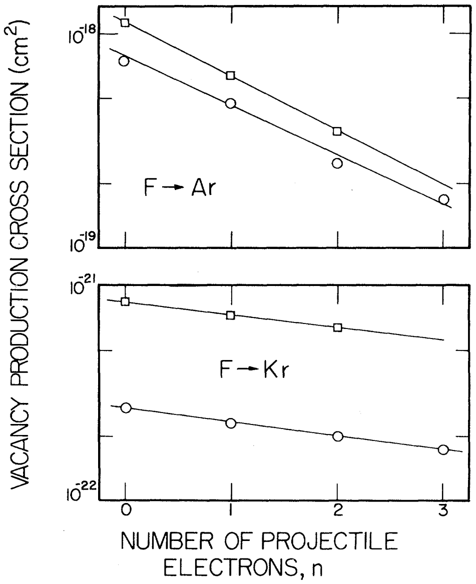

FIG. 2. *K*-shell vacancy-production cross sections vs the number of electrons carried by the incident F ion. Circles denote 36 MeV, and squares, 48-MeV F ions. Uncertainty in the cross sections is ~22% and the size of the data points is comparable to the relative uncertainty.

experiments, in which the measured cross sections for heavy ions on gas targets (at scaled energies[7] in excess of ~0.2) have consistently been larger than the Coulomb ionization values.[1-3,5] However, for F^{9+} on Kr (at a scaled energy of ~0.1) we find that the K-shell vacancy-production cross sections are a factor of 4 smaller than the theoretical predictions. A further comment on this observation will be made below.

The theory of direct Coulomb ionization, evaluated in the plane-wave Born approximation (PWBA), predicts that the inner-shell ionization cross sections for a wide variety of projectile-target configurations will fall on a universal curve when scaled appropriately and plotted against a reduced-energy parameter.[7,14] While recognizing the limitations of extending the theory to large values of Z_1, we have placed the present results into perspective by plotting the vacancy-production cross sections for the fully stripped projectiles on such a universal curve (the solid points in Fig. 4). Although the theoretical calculation is rigorously valid only in the limit of zero-charge projectiles with large velocities, Brandt *et al.* have suggested how the theory may be extended to include projectiles of finite charge and low velocity.[15-18] Although the foundation for a perturbed stationary-state theory to include binding, polarization, and deflection effects has been published,[17,18] the evaluation of theoretical cross sections in this general formulation is not readily accomplished. Therefore, we follow the lead of these authors[15,16] who have also introduced these effects as compensating modifications to the experimental data points so that all the data can be compared to the single universal curve obtained in the PWBA.[7] The open data points in Fig. 4 include these corrections for the increased binding of the target K shell and the

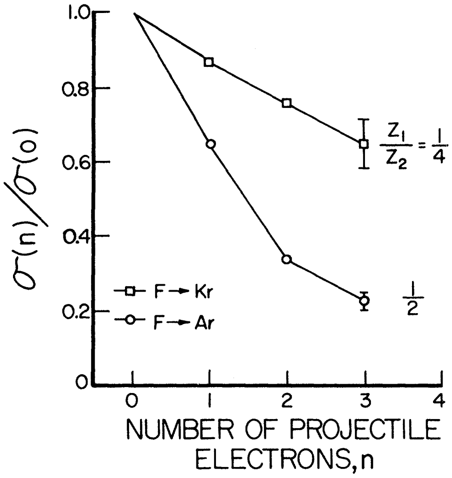

FIG. 3. Cross-section ratios $\sigma(n)/\sigma(0)$ vs n, the number of projectile electrons, as a function of the parameter Z_1/Z_2. Relative uncertainty in the data points as shown by the error bars is ~10%. The data are for 36-MeV F projectiles.

TABLE III. Experimental vacancy-production cross sections $[\sigma_v]$ for 36- and 48-MeV fully stripped F^{9+} projectiles are compared with theoretical values obtained by scaling experimental cross sections obtained with 1.89- and 2.53-MeV protons $[Z_1^2\sigma_v(p)]$, as given in Table I. The last column gives the ratio of the experimental to theoretical values.

E (MeV)	X ray	σ_v (10^{-20} cm^2)	$Z_1^2\sigma_v(p)$ (10^{-20} cm^2)	Ratio
36	Kr K	0.0267	0.123	0.22
	Kr L	1780	535	3.3
	Ar K	75	31.3	2.4
48	Kr K	0.084	0.245	0.34
	Kr L	1780	608	2.9
	Ar K	113	40.8	2.8

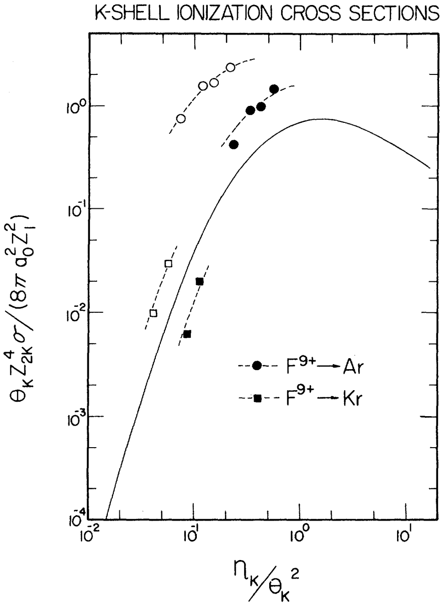

FIG. 4. Scaled cross sections vs reduced energy. For definitions of the various parameters, see Ref. 14. The solid points are the uncorrected cross sections, while the open points include the corrections suggested by Brandt *et al.* (Ref. 15) for the increased binding of the target electrons and the deflection of the projectile caused by its finite charge. The two lowest-energy data points for F^{9+} on Ar are taken from Ref. 3. The solid curve represents the universal K-shell Coulomb ionization cross sections derived from the calculations of G. S. Khandelwal, B. H. Choi, and E. Merzbacher [At. Data 1, 103 (1969)]. The size of the data points are commensurate with the ~22% absolute uncertainty of the experimental data.

Coulomb deflection of the projectile which occur for a slow projectile of finite charge. For the argon data, it is seen that the corrections further increase the discrepancy with the theoretical curve, while for the krypton data the corrections have overcompensated the deviation of the uncorrected data points from the universal curve. However, Brandt *et al.* have indicated that in this velocity region the polarization of the K-shell orbit must also be considered in comparing ionization cross sections with theory. Because the details of this effect have not yet been published, this correction has not been included in the data of Fig. 4. Nevertheless, this effect should reduce the scaled cross sections,[15,17] thus moving the corrected krypton data points into better agreement with the universal curve. It is not expected that the discrepancy in the argon data can be fully compensated in this manner.

Additional qualitative information may also be obtained from Fig. 4. It is seen that the energy dependence of the ionization cross sections for the F^{9+} on Ar and F^{9+} on Kr systems follows the general shape of the universal curve. Thus, the stronger energy dependence of the F on Kr cross sections compared to that of the F on Ar system (Fig. 2) is explained in terms of their relative positions on the universal curve. The disagreements between the theoretical and experimental values of the cross sections for the fully stripped ions, as listed in Table III might also reflect the location of the data points on the universal curve and the magnitudes of the correction terms in each case.

IV. CONCLUSION

The projectile charge-state dependence of K-shell vacancy-production cross sections has been examined as a function of the Z_1/Z_2 ratio of the target-projectile system. It is found that, as Z_1/Z_2 decreases, the effect of the projectile electrons on the target ionization process decreases significantly, in agreement with theoretical expectations.

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[9] D. Burch, N. Stolterfoht, D. Schneider, H. Wieman, and J. S. Risley, Phys. Rev. Lett. 32, 1151 (1974).

[10] At low projectile velocities (i.e., for $v_1 << \frac{1}{2}\theta_K v_{2K}$, where v_1 is the projectile velocity, and v_{2K} is the velocity of the target K-shell electron), K-shell ionization occurs only on deep penetration by the projectile to internuclear distances much less than the target K-shell radius a_{2K}. Thus, if $Z_1 << Z_2$, implying that $a_{1K} >> a_{2K}$, the projectile electrons will be found mainly outside the interaction region, leaving the projectile nucleus to excite the target K shell as a *bare* charged particle (Ref. 15).

[11] L. M. Winters, J. R. Macdonald, M. D. Brown, L. D. Ellsworth, and T. Chiao, Phys. Rev. A 7, 1276 (1973).

[12] An updating and revision of the earlier cross-section measurements (Refs. 1–3 and 11) is currently in progress.

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[14] To obtain a "universal" cross-section curve which is valid at low projectile velocities, a scaled cross section is plotted as a function of a reduced energy parameter. The scaled cross section takes the form $\theta_K Z_{2K}^4 \sigma/(8\pi a_0 Z_1^2)$, where σ is the experimental ionization cross section, Z_{2K} is the screened nuclear charge seen by a K-shell target electron, and a_0 is the radius of the hydrogen Bohr orbit. The energy parameter is η_K/θ_K^2, where $\eta_K \equiv v_1^2/v_{2K}^2$ and $\theta_K \equiv I_{2K}/(Z_{2K}^2 \mathrm{Ry})$. v_1 is the velocity of the projectile; v_{2K} is the velocity of a target K-shell electron; I_{2K} is the binding energy of a target K-shell electron; and Ry is the rydberg constant (see Refs. 7 and 15).

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