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Dependence of Argon K-Shell Ionization on the Charge of Bare Nuclei at 1 to 2 MeV/amu*

J. R. Macdonald, L. M. Winters, M. D. Brown, L. D. Ellsworth, T. Chiao, and E. W. Pettus
Physics Department and Nuclear Science Laboratory, Kansas State University, Manhattan, Kansas 66506
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Argon K-shell ionization cross sections have been determined from x-ray yields measured in single collisions with beams of the bare nuclei C^{+6}, N^{+7}, O^{+8}, and F^{+9} at energies of 1.05, 1.50, and 1.88 MeV/amu. The data deviate by as much as a factor of 2.6 from the Z_1^2 dependence predicted for ionization cross sections. This deviation monotonically increases with Z_1 and increases somewhat with velocity.

By restricting atomic collisions to single collisions of fully stripped nuclei in thin gas targets, it is possible to remove the effect of the initial electron configuration from the ionization process even at relatively low velocities. In this Letter, we report the projectile nuclear charge dependence of argon K-shell ionization cross sections produced by the bare nuclei C^{+6}, N^{+7}, O^{+8}, and F^{+9} at energies 1.05, 1.50, and 1.88 MeV/amu. Although the ionization cross sections that were determined from the measured x-ray yields depend somewhat on uncertain fluorescence yields, the results show a large deviation from a Z_1^2 charge dependence.

Although the general trends of inner-shell ionization induced by heavy ions at energies greater than 0.5 MeV/amu are accounted for by scaling existing Coulomb-Born[1] and semiclassical binary-encounter[2] calculations for ionization by protons, either model must be modified to account for the following results. (1) Deviations of up to 30% from the predicted Z_1^2 dependence of inner-shell ionization on projectile atomic number have been reported[3,4] and a model with a velocity-dependent Z_1^3 term has been proposed[4] to account for this discrepancy. (2) Multiple K- and L-shell ionization resulting in satellite and hypersatellite lines has been observed for projectiles heavier than α particles.[5,6] An impact-parameter model[7,8] based on independent ionization probabilities has been proposed to explain the relative intensities of some of these lines. (3) Large variations have been observed[9,10] in target x-ray cross sections in single collisions with heavy ions of different initial charge states but identical energies. One can speculate that target outer-shell ionization (and hence inner-shell fluorescence yield[11]) may depend upon projectile configuration, but this cannot account for the factor-of-5 variation in argon K x-ray yield produced by different charge states of fluorine at 36 MeV.[9] No quantitative model for this effect has been proposed.

It is clear that these three phenomena are related. For example, the target configuration formed in multiple ionization by heavy ions may have dramatically different fluorescence yields[11,12] (and hence reported ionization cross sections) from configurations induced by protons. Also, the projectile electron configuration may effectively screen the target from the projectile nuclear charge or introduce electron promotion[13] making both the multiple ionization distributions and nuclear charge dependence strongly coupled to the state of the projectile entering the collision. In this work, we have removed the complication of projectile initial configuration from the interpretation of the nuclear charge dependence of inner-shell ionization. However, our results include only estimates of final-state configurations, but high-resolution electron studies of these collisions may improve these estimates.

In this experiment, 3- to 30-nA beams of fully stripped nuclei were typically available at the entrance to the differentially pumped gas cell. Approximately 30% of these beams could be focused through the four gas cell apertures $s_1=1.0$ mm, $s_2=1.5$ mm, $s_3=2.5$ mm, and $s_4=3.0$ mm. Movable Faraday cups were used to ensure 100% transmission from the interaction region through the gas cell and this important criterion was monitored for each run. In addition, a charge spectrometer[14] was mounted behind the gas cell and was used to ensure that the charge purity of the incident beam was better than 99% fully stripped nuclei. Projectile final–charge-state distributions were measured in all cases, and an upper limit on the argon target thickness was chosen so that less than 5% of the beam had undergone charge exchange.

A Si(Li) detector was mounted inside the gas cell. X-ray energy calibration was determined from characteristic lines excited by protons in suitable gas and solid targets or produced in an ^{55}Fe source. The detector resolution was 175 eV full width at half-maximum at 3 keV and the argon $K\alpha$ and $K\beta$ x rays, shifted to higher than characteristic energy when produced by the heavy-ion collisions, were resolved.

The energy of the argon $K\alpha$ line was measured with an accuracy of about 5 eV and an energy shift was determined by subtracting the energy of the line when excited by protons. Estimates of the L-shell configuration of the target were made by comparing our measured energy shifts with values calculated by House.[15] Although M-shell configurations cannot be estimated in this way, we have assumed that this shell is empty because this is the configuration used by House to calculate $K\alpha$ x-ray energies. Corresponding fluorescence yields have been calculated by McGuire,[11] and with four or less holes in the $2p$ shell, the M-shell configuration introduces only a small uncertainty in the fluorescence yield. In Table I we have listed our measured $K\alpha$ and $K\beta$ energy shifts, the vacancy configuration we have assumed, and the fluorescence yield.

X-ray yields were measured for four target thicknesses (from 0 to 5 μm of argon gas) and x-ray production cross sections were extracted using techniques reported elsewhere.[16] These cross sections have an absolute uncertainty of approximately 30% and a relative uncertainty of less than 15%. In Table II are listed the x-ray production cross sections and K-shell ionization cross sections determined using the fluorescence yields in Table I. The major uncertainty in the ionization cross sections is the validity of the fluorescence yields that have been used. This estimate may be improved when a more sophisticated model is used to do the fluorescence yield calculations for the states of highly ionized argon. However, definitive values of these ionization cross sections will be obtained only when electron and x-ray yields in similar collisions have been measured.

TABLE I. Ar K x-ray energy shifts observed in single collisions of heavy nuclei with argon atoms. Vacancy configurations consistent with these energy shifts (Ref. 15) and a fluorescence yield for each configuration (Ref. 11) are given.

	Energy shifts (eV)			
Ion	$K\alpha$	$K\beta$	Vacancy configuration	ω_K
H^+	0	0	$[1s]$	0.130
C^{+6}	53	156	$[1s, 2p^2, 3s^2, 3p^6]$	0.162
N^{+7}	70	181	$[1s, 2p^3, 3s^2, 3p^6]$	0.177
O^{+8}	78	233	$[1s, 2p^3, 3s^2, 3p^6]$	0.177
F^{+9}	94	242	$[1s, 2p^4, 3s^2, 3p^6]$	0.184

TABLE II. Column 3, experimental cross sections for Ar K x-ray production by fully stripped nuclei. Column 4, ionization cross sections calculated using fluorescence yields from Table I. Column 5, relative intensities of the $K\alpha$ and $K\beta$ transitions.

		Ar K cross sections		
Ion	Energy (MeV/amu)	X-ray (10^{-21} cm^2)	Ionization (10^{-20} cm^2)	$K\beta/K\alpha$ ratio
H^+	1.05	0.20	0.16	···
	1.50	0.32	0.25	···
	1.88	0.42	0.33	···
C^{+6}	1.05	8.0	4.9	0.13
	1.50	22	13	0.12
	1.88	28	17	0.12
N^{+7}	1.05	12	6.5	0.13
	1.50	33	18	0.14
	1.88	50	29	0.15
O^{+8}	1.05	22	12	0.12
	1.50	54	31	0.13
	1.88	78	44	0.13
F^{+9}	1.05	46	25	0.14
	1.50	95	51	0.14
	1.88	130	70	0.13

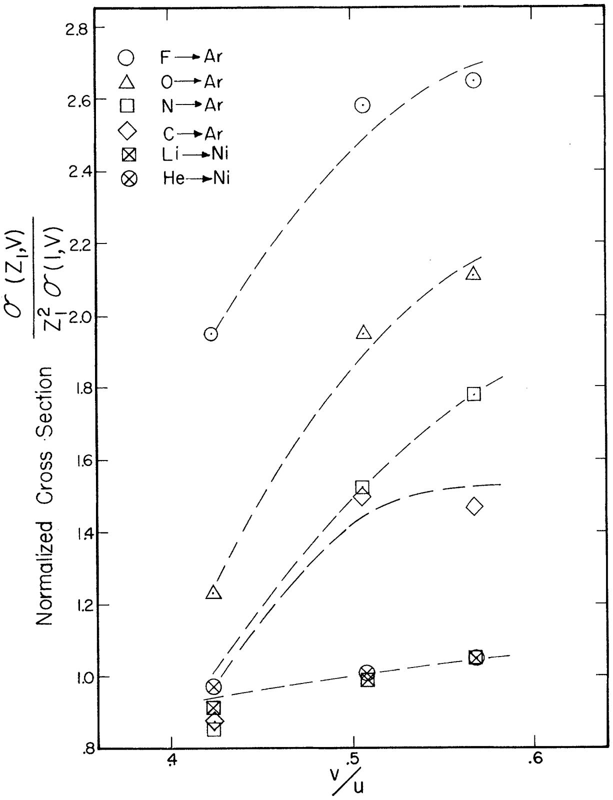

FIG. 1. Velocity dependence of Ar K-shell ionization cross sections $\sigma(Z_1,v)$ for bare nuclei C^{+6}, N^{+7}, O^{+8}, and F^{+9}, and Ni K-shell cross sections (Ref. 4) produced by He and Li. Cross sections are normalized to proton cross sections $\sigma(1,v)$. The projectile velocity v is scaled by the electron orbital velocity $u=(2I/m_e)^{1/2}$.

In Fig. 1 is shown the velocity dependence of the argon K-shell ionization cross sections measured with bare nuclei. The results are normalized to the cross sections for proton ionization with $\sigma(Z_1,v)/Z_1^2\sigma(1,v)$ plotted as a function of v/u, where v is the projectile velocity, $u=(2I/m_e)^{1/2}$ is representative of the velocity of an electron bound with a binding energy I, Z_1 is the projectile atomic number, and $\sigma(Z_1,v)$ is the target ionization cross section at velocity v. Smooth curves guide the eye between data points for the same projectile. Also displayed in Fig. 1 are the normalized Ni K-shell ionization cross sections induced by helium and lithium.[4] Similar cross sections for oxygen projectiles[17] were not included because they are not fully stripped in this energy range. It is evident in Fig. 1 that these heavy-ion data deviate by up to a factor of 2.6 from Z_1^2 scaling of proton cross sections. The deviation monotonically increases with Z_1 and increases with velocity.

To account for the deviation from Z_1^2 scaling observed with the lighter projectiles, Basbas *et al.*[4] have introduced increased binding energy of the orbiting electron and initial-state polarization effects to produce a term proportional to $(Z_1-1)/Z_2$ in cross sections normalized to proton cross sections. To compare with this model we have plotted in Fig. 2 the cross sections at three velocities as a function of $(Z_1-1)/Z_2$. The data sets labeled E, F, G, and H for Ar K-shell ion-

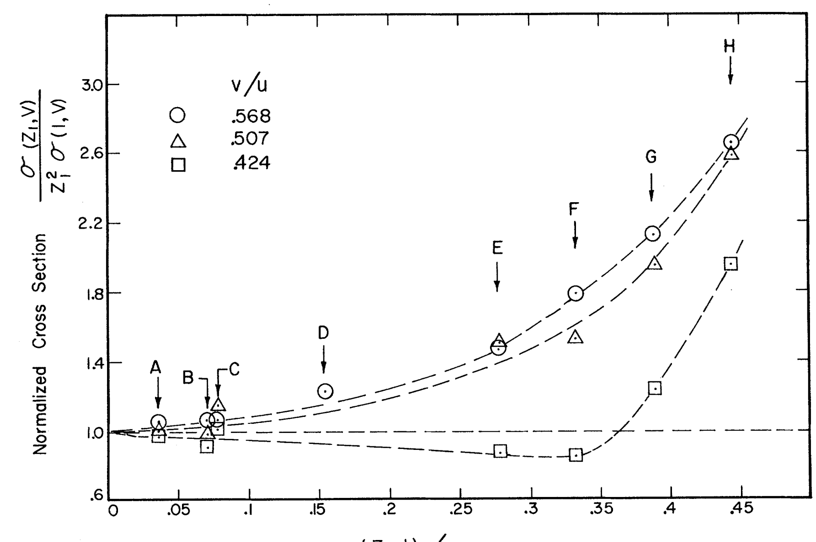

FIG. 2. Charge dependence of K-shell ionization cross sections at three different projectile velocities. The cross sections $\sigma(Z_1,v)$ are normalized to proton cross sections $\sigma(1,v)$ scaled by Z_1^2. The data sets E, F, G, and H are the results of the present work for Ar K-shell ionization by C^{+6}, N^{+7}, O^{+8}, and F^{+9}, respectively. The data sets A and B are for Ni K-shell ionization and C and D are for Al K-shell ionization by He and Li, respectively (Ref. 4).

ization by C^{+6}, N^{+7}, O^{+8}, and F^{+9}, respectively, are the results of the present investigation. The data sets A and B for Ni K-shell ionization and the sets C and D for Al K-shell ionization by helium and lithium, respectively, are reported by Basbas *et al.*[4] Particularly at the lowest velocity, a term linear in $(Z_1-1)/Z_2$ cannot account for the observed deviation of the normalized cross section from unity. For the two higher-velocity data sets the deviation of the normalized cross sections from unity is positive and monotonically increases with projectile charge state. The positive linear dependence on $(Z_1-1)/Z_2$ of the deviation that has been proposed[4] cannot account fully for the cross sections although the addition of a small quadratic contribution qualitatively describes the data. McGuire[8] has proposed including a term proportional to $Z_1^{\,4}$ in the ionization cross section to account for charge exchange to the continuum of the projectile during the collision. This term gives an approximate quadratic dependence of scaled cross section on $(Z_1-1)/Z_2$. At the lowest velocity, inclusion of such a term along with a negative linear term as proposed[4] in this velocity region also can qualitatively describe the charge dependence shown in Fig. 2.

Although a fit to the deviation of the data from $Z_1^{\,2}$ scaling can be made by some combination of these two terms, their combined magnitude must be larger than the results of Born-approximation calculations. Hence, there is no compelling reason to make such a fit since other phenomena may complicate the picture. No explanation at present fully describes inner-shell ionization by swift heavy ions.

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