Z_1^3 Dependence of K-Shell Ionization Cross Sections at 7.1 MeV/amu*

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Relative K-shell ionization cross sections were measured for 7.1-MeV/amu projectiles of He^{2+}, B^{5+}, C^{6+}, N^{7+}, O^{8+}, F^{9+}, and Ne^{10+} on targets of Ca, Fe, Y, and Cd. The scaled cross section ratios $R = [4\sigma(Z_1)]/[Z_1^2\sigma(2)]$ exhibit linear Z_1 dependence characteristic of the effects of increased binding of target electrons and polarization. The absence of higher-order Z_1 dependence suggests that the contributions to the ionization σ by charge exchange to the empty orbitals of the projectile are relatively small.

The recent demonstrations[1,2] of the existence of Z_1^3 (projectile) dependence in the K-shell ionization cross sections attributable to the effects of increased binding of target electrons and polarization[1-5] have been limited to $Z_1 \geq 3$ and to only a few projectile-target combinations. We report here the observation of such a characteristic Z_1^3 dependence over a wide range of projectile-target combinations at 7.1 MeV/amu, namely with bare-nuclei projectiles of He, B, C, N, O, F, and Ne on thin foil targets of Ca, Fe, Y, and Cd. These results are to be contrasted with the observation of MacDonald *et al.*[6] of higher-order Z_1 dependence in the 1-2-MeV/amu positive-ion impact on Ar. The Ar results have been interpreted[7,8] in terms of the contributions from the charge exchange between the target K shell and the empty orbitals of the projectile (CEBS for brevity). Since the fully stripped nature of the projectiles is expected to be largely preserved for the present cases ($\gtrsim 75\%$ of the equilibrium charge distribution[9]), the absence of higher-order Z_1 dependence suggests that the CEBS contributions are relatively small. Estimates of these CEBS cross sections, based on the Brinkman-Kramers expression,[7] are consistent with this deduction.

The various fully stripped 7.1-MeV/amu ion beams were obtained by degrading with Al foils the full-energy beams accelerated from the Yale heavy-ion accelerator. The degraded beams were magnetically analyzed and focused through a $\frac{5}{32}$-in.-diam collimator and a suppressor ring (−300 V bias) before impinging on the target. Charge normalization was accomplished by integrating the charge collected in the insulated target chamber. An Ortec Ge(Li) semiconductor x-ray detector was used for x-ray detection. The consistencies of the relative yields for the various targets were monitored by the use of multielement targets (vacuum deposited onto ~40-μg/cm^2 carbon foils). Corrections due to the attenuations of the $K\alpha$ and $K\beta$ intensities in the various media between the target and detector have been incorporated in the extracted total K x-ray yields.

The conversion to ionization cross sections for multiply ionized atoms is generally hampered by the lack of accurate fluorescence yield information, ω_K. For the present cases, the prescription of Larkins[10] can be used without gross errors since (1) we are concerned only with the changes in ω_K of a given atom and (2) the number of multiple vacancies as deduced from the energy shifts of the K x-ray lines is not too large. The calculated ω_K are tabulated in Table I. In each case, the average L vacancies were deduced by comparing the change in the $K\beta$-$K\alpha$ separation energy $\Delta K_{\alpha\beta}$ to the results of Hartree-Fock-Slater calculations.[11] This $\Delta K_{\alpha\beta}$ was measured more accurately than the shift in either the $K\alpha$ or the $K\beta$ line. Figure 1 displays the final results in the form of ionization cross section ratios $R = [4\sigma(Z_1)]/[Z_1^2\sigma(2)]$, where $\sigma(2)$ and $\sigma(Z_1)$ correspond to the K-shell ionization cross sections, respectively, for α-particle and bare-Z_1-projectile impact. The experimental errors as deduced from repeated runs are typically $\lesssim 10\%$.

For a given target, Coulomb ionization theories[12,13] predict $R = 1$ for all projectiles of the same velocity. Except for Y, the results in Fig. 1 show deviations which are linear with Z_1 within the experimental uncertainties. Such deviations are attributable to binding and polarization effects. Indeed the change in the slope in going from Cd to Ca can be qualitatively understood in terms of the finite-charge effects which were elucidated by Basbas *et al.*[1] Namely for Cd, where the velocity demarcation parameter $\xi_K v_1/\frac{1}{2}\theta_K v_{2K} = 0.85 < 1$, a negative slope is expected because of increasing target K-shell binding with increasing Z_1. For both Fe and Ca where $\xi_K > 1$ ($\xi_K = 1.66$

TABLE I. The shift in the $K\beta$-$K\alpha$ separation energy $\Delta K_{\alpha\beta}$, the average number of L vacancies, and the calculated fluorescence yield ω_K are listed for each projectile-target combination. All entries are relative to those for α-particle impact.

	Cd			Y			Fe			Ca		
Proj.	$\Delta K_{\alpha\beta}$ (eV)	L vacancies	Rel. ω_K	$\Delta K_{\alpha\beta}$ (eV)	L vacancies	Rel. ω_K	$\Delta K_{\alpha\beta}$ (eV)	L vacancies	Rel. ω_K	$\Delta K_{\alpha\beta}$ (eV)	L vacancies	Rel. ω_K
He^{+} [a]	0	0.0	1.00	0	0.0	1.00	0	0.0	1.00	0	0.0	1.00
B^{5+}	24	0.3	1.00	21	0.3	1.01	19	0.6	1.05	25	1.2	1.12
C^{6+}	52	0.6	1.01	36	0.5	1.01	46	1.3	1.10	28	1.2	1.12
N^{7+}	72	0.8	1.01	62	1.0	1.03	65	1.7	1.14	48	1.7	1.19
O^{8+}	97	1.1	1.01	83	1.3	1.03	75	1.9	1.15	49	1.7	1.19
F^{9+}	120	1.4	1.02	95	1.5	1.04	91	2.3	1.19	82	2.5	1.30
Ne^{10+}	148	2.0	1.03	126	2.0	1.05	109	2.7	1.22	69	2.5	1.30

[a] Assumed L vacancy to be negligibly small.

and 2.24, respectively), positive slopes are expected because the increasing polarization of the target K orbital induced by the passing projectile shortens the effect interaction distance. The zero slope in Y ($\xi_K = 1.04$) may be interpreted as the cancelation of the two competing effects. Two other mechanisms which can give rise to polarization effect have been reported.[3-5] However, the competing role of the increased binding effect, as evidenced here and elsewhere,[1,2] must be explicitly accounted for if meaningful comparisons are to be made between the various theoretical predictions and the present results.

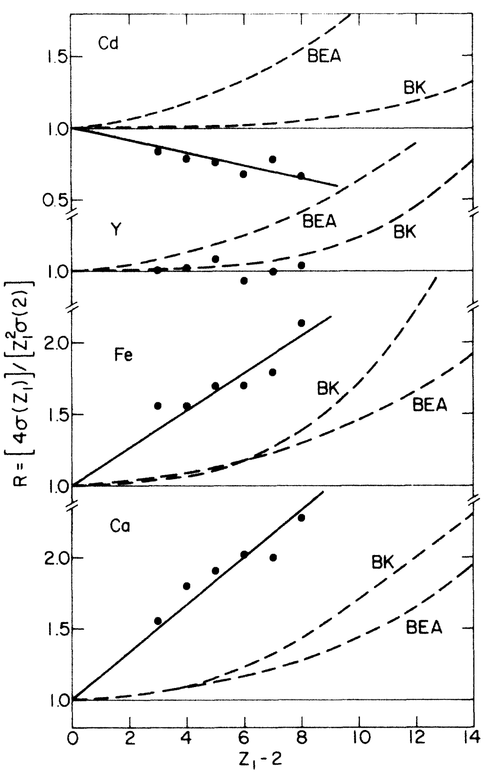

FIG. 1. The scaled K-shell ionization cross sections relative to those of α-particle impact, R, are displayed versus $Z_1 - 2$. The solid lines are drawn for visual aid. The dashed curves are the theoretical ratios formed by adding the calculated CEBS cross sections σ^{EX} to the direct Coulomb ionization cross sections σ^D (see text).

As noted earlier, the Ar data of MacDonald *et al.*[6] exhibited higher-order additive Z_1 terms which where attributed[7,8] to the CEBS effects. The Ar data and the present results taken together clearly indicate that the binding, polarization, and CEBS effects can be significant in the K-shell ionization depending on the projectile-target combination and the impact velocity. The interpretations[7,8] of the Ar data without regard to the polarization effects may be erroneous since the impact velocities used correspond to $\xi_K \geq 1$. The fact that an increasing scaling factor for the CEBS contributions was required[7] to fit the Ar data with increasing impact velocity may be a consequence of this omission.[14] Conversely, the role of the CEBS mechanism in the present cases must be investigated since the fully stripped state of the projectiles still comprised $\gtrsim 75\%$ of the equilibrium charge-state distribution.[9]

Calculations of the CEBS cross sections σ^{EX} were performed using both the Brinkman-Kramers (BK) expression[7] and the binary-encounter approximation[15] (BEA). The BEA theory[14] was also used to estimate the direct Coulomb ionization cross sections σ^D. The theoretical ratios with no binding and polarization corrections,

$$R = \frac{4\sigma(Z_1)}{Z_1^2\sigma(2)} = \frac{[1.0 + \sigma^{EX}(Z_1)/\sigma^D(Z_1)]}{[1.0 + \sigma^{EX}(2)/\sigma^D(2)]}, \quad (1)$$

are represented in Fig. 1 by the dashed curves. Following previous practices,[7] we have scaled down the BK estimates by a factor of 0.3 for all cases. The relative accuracies of our computations have been verified by the essential agreement of our computed results for the case of $F^{9+} + Ar$ with those of Refs. 7 and 8. For the purpose of discussion note that $\sigma^{EX}(2)/\sigma^{D}(2) < 10^{-2}$ for the present cases, and that the denominator in Eq. (1) is essentially unity. In the case of Y, for which the binding and polarization effects presumably cancel out, the BK estimates are seen to be consistent with observations whereas the BEA predictions overestimate σ^{EX}. This feature of the BEA is known[15] to occur at the lower scaled velocities. The BK and BEA predictions for Fe and Ca do not differ significantly except for $Z_1 > 10$. From the comparisons of predictions and observations in Fig. 1, we can conclude that (1) the BK theory provides a more consistent representation of σ^{EX} than the BEA theory and (2) the binding and polarization effects account for a substantial fraction of the observed Z_1 dependence.

In summary, the present study is seen to provide some clarification of the domains in which the various mechanisms may be expected to significantly affect K-shell ionization. The effects of increased binding and polarization which contribute terms in the cross section proportional to $\pm(Z_1/Z_2)^3$ are seen to dominate in the present cases. The CEBS mechanism which contributes terms of the order $\sim(Z_1/Z_2)^5$ (based on the scaled BK theory) is seen to account for the differences between the present observations and those of MacDonald *et al.*[6] Finally, the observed Z_1^2 dependence at $\xi_K \simeq 1$ reiterates the need to treat the various Z_1^3 effects on a unified theoretical framework.

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