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Role of residual K-shell vacancies in solid target x-ray cross sections*

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Thin solid Cu targets were bombarded with Cl ions at incident energies of 40, 50, and 60 MeV. The target K x-ray yields were measured as a function of target thickness. The yield of the Cu target K x rays per scattered projectile increases exponentially with target thickness for all incident Cl charge states from 7+ to 15+ and decreases exponentially with target thickness for the incident Cl charge state 16+. A model calculation which contains the probability for a K vacancy in the projectile as a function of its depth in the target describes the observed behavior. A factor of 8 variation in the Cu K x-ray yield per scattered projectile was observed depending on how the beam was prepared and on what thickness target was used.

I. INTRODUCTION

The results of a study of target K x-ray production for ^{16}O ions incident on thin solid Al targets have been previously reported by Brandt *et al.*[1] In that work variations in the x-ray production rate were studied for charge states of 3+ to 8+ over a target thickness range of ~1–25 $\mu g/cm^2$. A model was proposed to account for the measured variations in the Al K x-ray production rates; it is based upon the dynamic screening of the projectile charge by the target electrons. The central feature of this model is the assignment of the variations in target x-ray production to changes in direct Coulomb ionization. Modifications in the effective charge of the projectile were assumed to be associated with the interaction between the target electron gas and the projectile. Other work by Betz *et al.*[2] has utilized a model in which individual processes that may affect the projectile are included. Specifically, the rates for vacancy production, charge exchange, and quenching processes for the projectile moving in a target medium are a central feature of these authors' report of a new lifetime measurement technique for heavy ions.

Hopkins[3] has recently extended the ideas of Betz *et al.* to describe Cu K x-ray production which occurs after the beam has passed through a carbon backing upon which a thin layer of Cu is evaporated. Hopkins[3] suggests that the variation in Cu K x-ray yield as a function of the thickness of the thin carbon backing is due to the enhancement of the Cu ionization cross section for projectiles with K vacancies. Groeneveld *et al.*[4] have reported studies of projectile and target x rays for 10-MeV Ne^{2+} ions on various thickness Al targets. In that work the variation in target x-ray yield was assigned to a $2p\sigma$-$1s\sigma$ vacancy transfer mechanism. Feldman, Silverman, and Fortner[5] have reported studies of Ar^{+}-Al collisions using Al foils of varying thickness, with the result that a double collision mechanism is important to the target x-ray production.

In this work we report the measurement of the production of Cu target K x rays by Cl projectiles in thin solid targets. The enhancement in the target ionization cross section for projectiles with a K vacancy compared to projectiles without K vacancies makes this system particularly suitable for studying this target thickness effect. This large variation results in an enhancement by a factor of ~8 in the Cu K x-ray production rate for Cl^{16+} ions compared to Cl ions having charge states less than 16+ for the thinnest targets investigated. We observe a factor-of-2 *decrease* in the effective target K x-ray cross section for 60-MeV Cl^{16+} in going from 2.1- to 183-$\mu g/cm^2$ Cu targets. Over the same target thickness range, Cl^{9+} projectiles show a factor-of-2 *increase* in effective target cross section. Both sets of data can be fitted simultaneously using the model of Betz *et al.*[2] to obtain the fraction of the beam with K-shell vacancies as it travels through the solid.

II. EXPERIMENTAL

The measurements of Cu K x-ray yields were made for incident Cl ions on a series of thin solid Cu targets. The targets were prepared by vacuum evaporation of Cu on transmission-mounted carbon backings. The absolute Cu K x-ray production rates were measured as a function of Cu target thickness and incident charge state for beam energies of 40, 50, and 60 MeV. Ion beams of H and Cl were obtained from the model EN tandem Van de Graaff accelerator at Kansas State University.

The H beam at an energy of 3 MeV was used to determine the target thickness for each target by measuring the Cu(p, p)Cu elastic scattering yield at a laboratory angle of 45°. The target thicknesses used in this work ranged from 2.1 to 183 $\mu g/cm^2$, with uncertainties in the measured target thicknesses of $\lesssim 5\%$. The Cu K x rays were detected at a laboratory angle of 90° to the incident beam direction, and the scattered Cl ions were detected at a laboratory angle of 30°. The ratio of the K x-ray yield $\mathcal{Y}_{Kx}$ to the scattered-particle yield, $\mathcal{Y}_P$ was measured for each target thickness. The effective integrated cross section $\bar{\sigma}_{Kx}$ for target K x-ray production was determined by normalizing ($\mathcal{Y}_{Kx}/\mathcal{Y}_P$) for the relative detector efficiencies and Rutherford scattering cross section.

A target was positioned with the Cl beam incident on the Cu at an angle of 15° with the normal. X-ray and scattered-particle spectra were recorded simultaneously. The target thickness for each target was varied by adjusting the angle to 30°, then to 45°, with the measurement repeated for each angle setting. Pure charge states of 7+ to 16+ for the Cl beam were used in the measurements. The higher charge states were produced by passing the primary beam through a carbon stripping foil between the 90° analyzing magnet and the switching magnet. The switching magnet was then utilized to select the charge state of interest.

III. DISCUSSION

Shown in Fig. 1 are the measurements of the Cu K x-ray yield per scattered ion ($\mathcal{Y}_{Kx}/\mathcal{Y}_P$) for Cl charge states from 9+ to 16+. The measurements were made for 60-MeV Cl ions on solid

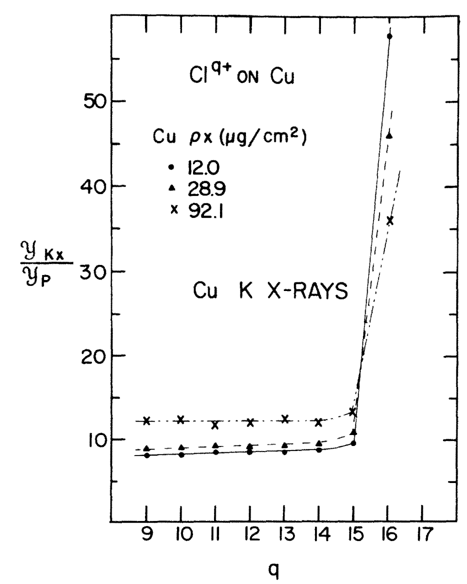

FIG. 1. Charge and target thickness dependence for 60-MeV Cl ions on thin solid Cu targets.

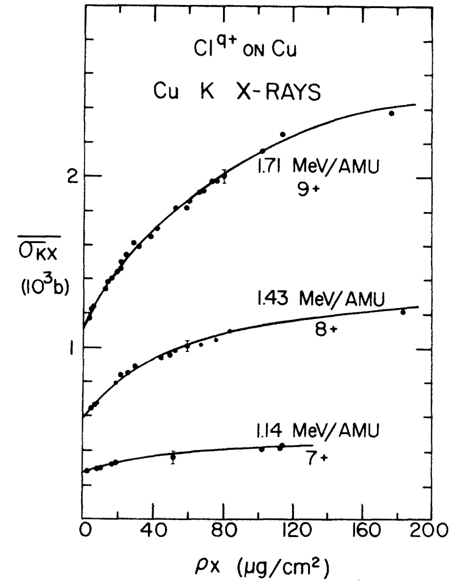

FIG. 2. Large variaion in σ_{Kx} with target thickness for three beam energies. The target thickness dependence can be fitted with the model of residual K-shell excitation of the projectile.

Cu targets having thicknesses of 12.0, 28.9, and 92.1 $\mu g/cm^2$. For incident charge states up to 14+ the ratio $\mathcal{Y}_{Kx}/\mathcal{Y}_P$ is essentially constant. The data for the 15+ charge state is increased by ~8% over that for the lower charge states. There is a large enhancement in $\mathcal{Y}_{Kx}/\mathcal{Y}_P$ for the single-K-vacancy Cl^{16+} charge state in comparison to the data for the charge states < 16+.

Shown in Fig. 2 are the measurements of $\bar{\sigma}_{Kx}$ for ^{35}Cl at 40, 50, and 60 MeV. A strong dependence of $\bar{\sigma}_{Kx}$ on target thickness is observed in all cases. The thickness dependence follows an exponential form for the Cl^{7+}–Cl^{9+} data. Figure 3 illustrates the measurements of $\bar{\sigma}_{Kx}$ for Cl ions on Cu at an incident energy of 60 MeV (1.71 MeV/amu). A large increase in $\bar{\sigma}_{Kx}$ is observed for incident Cl^{16+}, which contains a single K vacancy, as in the case of thin gas targets. The extrapolated ratio of the $\bar{\sigma}_{Kx}$ values for Cl^{16+} and Cl^{9+} is ~8.

We have utilized a two-component model for target x-ray cross sections based on the previous work of Betz *et al.*[2] and Hopkins.[3] The model which is used is similar to the work of Groenveld *et al.*[4] and Feldman *et al.*[5] in that it describes the production of target x rays by a heavy ion moving through a given thickness T of the solid target. The formulation of the model is based upon a set of observations and assumptions:

(i) Experimentally, a strong enhancement in the target x-ray yield is observed for the $q = Z_1 - 1$ charge state of the incident ion in comparison to charge states having $q \leq Z_1 - 2$. This feature is

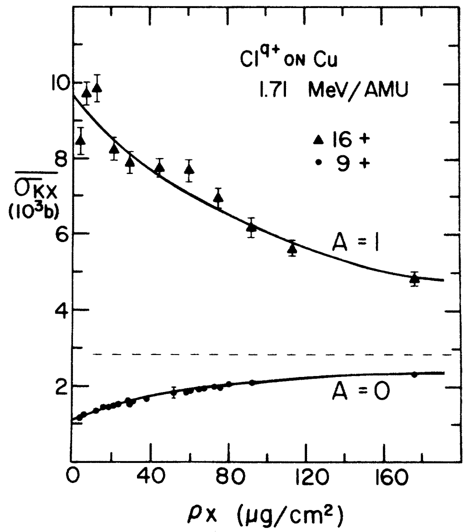

FIG. 3. Experimental values of $\bar{\sigma}_{Kx}$ for incident 1.71-MeV/amu Cl ions on thin solid Cu targets in the 9+ ($A=0$) and 16+ ($A=1$) incident charge states. The solid curves are model calculations resulting from a least-squares fit to both experimental curves, simultaneously, with a single set of parameters.

observed for both gas and solid targets.[3,6] It is therefore assumed that $\sigma_{K1} = \alpha\sigma_{K0}$, where σ_{K1} and σ_{K0} are the target K x-ray production cross sections for the projectile, with a K vacancy, and without a K vacancy, respectively. Existing data require $\alpha > 1$. The quantities σ_{K0} and σ_{K1} are determined for vanishing target thickness.

(ii) A two-component model is assumed in which $Y_0(x) = 1 - Y_1(x)$, where $Y_0(x)$ is the fraction of ions with a full K shell, and $Y_1(x)$ is the fraction with one K-shell vacancy. The inclusion of other components is handled in a similar manner under the restriction that $\sum_i Y_i(T) = 1$, where $Y_i(T)$ is associated with the ith charge state component. The present data for Cl ions on Cu are not dependent upon charge state for $q \leq Z_1 - 2$. Double K-vacancy production of the projectile for similar systems is small, in comparison to single K ionization. Hence the two-component assumption seems appropriate for the system investigated in this work.

(iii) The rate equation for processes which govern the single K-vacancy state of the projectile in the target at a distance x measured in target particles per cm² is (see Ref. 2)

$$\frac{dY_1}{dx} = \sigma_V Y_0 - (\sigma_Q + \sigma_T) Y_1,$$

where σ_V is the K-shell vacancy production cross section for the projectile, σ_Q is the K-shell capture cross section of the projectile, and $\sigma_T = (n\tau V)^{-1}$ is the quenching cross section due to the decay of the projectile K vacancy. Integration of the rate equation gives

$$Y_1 = (\sigma_V/\sigma)(1 - e^{-\sigma x}) + A e^{-\sigma x},$$

where $\sigma = \sigma_V + \sigma_T + \sigma_Q$, and A is the fraction of incident ions with a K vacancy.

Using these assumptions and averaging the weighted target K x-ray production cross sections over the target thickness gives

$$\bar{\sigma}_K(T) = \left(\frac{\sigma_{K0}}{T}\right) \int_0^T [1 + (\alpha - 1) Y_1(x)]\, dx,$$

and hence

$$\bar{\sigma}_{Kx}(T) = \sigma_{K0} \left[1 + (\alpha - 1)\frac{\sigma_V}{\sigma} - \frac{\alpha - 1}{\sigma T}\left(\frac{\sigma_V}{\sigma} - A\right)(1 - e^{-\sigma T}) \right].$$

A least-squares analysis was performed on the data for 60-MeV (1.71-MeV/amu) Cl on Cu using the expression given for $\bar{\sigma}_{Kx}$. In this case, the target x-ray yields were measured for incident charge states of 9+ to 16+. A slight increase in target x-ray production was measured for the 15+ data. However, the measured increase is small in comparison to that observed for incident Cl ions in the 16+ charge state. The ratio of $\bar{\sigma}_{Kx}$ for 15+ to σ_{Kx} for q (= 9+, 10+, 11+, . . . , 14+) is 1.08, while the same ratio for 16+ to q is 8.1. The results of the model predictions are shown in Fig. 3.

Both the 16+ ($A=1$) and 9+ ($A=0$) values of σ_{Kx} were fitted simultaneously with a single set of parameters. The quantities σ_{K0}, σ_V, α, and σ' were treated as fitting parameters. The symbol σ' specifies the sum of σ_Q and σ_T. The values of the parameters obtained from this procedure are given in Table I. A comparison of the parameters obtained in this work is given for values of σ_V and σ', obtained from other sources. The magnitude of σ_V from the model calculations is in agreement with the experimental result $\sigma_V \simeq 6 \times 10^{-19}$ cm² ob-

TABLE I. Values of the parameters for 60-MeV Cl on Cu.

	Present work	Other sources
σ_V	3.5×10^{-19} cm²	~6×10^{-19} cm² [a]
σ'	15.4×10^{-19} cm²	~15.7×10^{-19} cm² [b]
α	8.1	8.4 [b]
σ_{K0}	1.18×10^{-21} cm²	
w		2.80×10^{-2} [b]
σ_R		7.07×10^{-19} cm² [b]
ω_{Cu}		0.443 [c]

[a] Reference 6.
[b] See text.
[c] Atomic value for ω_K has been taken from Ref. 11.

tained from the systematics of Cl K x-ray production of Winters *et al.*[6] A comparison of the value of σ' obtained in the present work to other findings is based upon a value of $\sigma_\tau = 6.7\times10^{-19}$ cm^2, which is calculated for $\tau = 0.97\times10^{-14}$ sec (see Ref. 3), and a scaled value of $\sigma_Q = 9.0\times10^{-19}$ cm^2 from the modified Brinkman-Kramers (BK) calculation based upon the work of Nikolaev.[7]

Comparison of the BK calculations to experimental data for electron capture for C, N, O, and F ions on Ar and Kr have been reported by Guffey.[8] Extrapolation of the systematics given by Guffey for the ratio of BK calculations to available charge-exchange data in these systems has been performed to yield a scaling factor for Cl on Cu. The scaling factor arrived at by this procedure is 32, which gives a scaled charge capture cross section of $\sigma_Q = 9\times10^{-19}$ cm^2.

Combining σ_τ and σ_Q from the above estimates gives a value of $\sigma' = 15.7\times10^{-19}$ cm^2. The value of the parameter α suggests that the difference between the 16+ and 9+ to 15+ data for Cl on Cu is not due to a simple charge screening interaction, as given by Brandt *et al.*[1] Taking the limit of the dynamic screening model for a vanishingly thin target gives the prediction that the ratio of the target x-ray production cross sections for different charge states q_1 and q_1' should go as $(q_1/q_1')^2$. In the present case, the dynamic screening model predicts a value of ~1.14 for the ratio of the target cross sections for 16+ and 15+ Cl ions. This is in contrast to a measured ratio of 8.1.

It may be appropriate to associate α primarily with the effects of charge transfer, which creates a target K-shell vacancy by the transfer of the target K electron to the projectile. This type of interaction is plausible in view of the observation that $\bar{\sigma}_{KX}$ for a vanishingly thin target is approximately independent of the incident charge state up to the point where there is a K-shell vacancy in the incident projectile. The value of α is estimated using the works of Meyerhof[9] and Taulbjerg, Vaaben, and Fastrup.[10] This procedure gives

$$\alpha = (\sigma_{K0} + \omega_{\rm Cu} w \sigma_R)/\sigma_{K0},$$

where $\sigma_{K0} = 1.18\times10^{-21}$ cm^2 for the 60-MeV Cl data, $w = 1/(1+e^{2|x|})$(from Ref. 9), $\omega_{\rm Cu}$ is the Cu K fluorescence yield,[11] and $\sigma_R = \pi R^2$. The value of $R = 2.6/Z_2$ a.u. is taken from Ref. 10, using the radius corresponding to the peak in the dynamic coupling elements for $Q = 0.60$. The values of w, $\omega_{\rm Cu}$, R, and σ_R are given in Table I. The He-like Cl K-shell binding energy obtained from the ionization potential[12] for Cl XVI is used in calculating w.

The saturation value for $\bar{\sigma}_{KX}$ shown as the dashed line in Fig. 3 is evaluated for $\sigma T \gg 1$. For 60-MeV Cl on Cu $\sigma_{KX}^{\rm sat} = 2730$ b. The significance of the saturation σ_{KX} is found in the requirement that the target thickness dependence be removed from the equation for $\bar{\sigma}_{KX}$, yielding the value of $Y_1 = 0.19$ for thick layers of the target. This result requires a target thickness $T > 10^3$ μg/cm^2. While it has been generally accepted that a high-velocity heavy ion would equilibrate after traversing only a few μg/cm^2 of the target material, the present work suggests that inner-shell equilibration occurs deep within the target, and not in the first few atomic layers.

IV. CONCLUSION

In summary, the experimental results presented in this work establish the need to give direct consideration to the effects of target thickness on the projectile, and its relation to measured target x-ray production cross-section data. Measurements of solid target x-ray production cross sections with heavy ions that do not take target thickness effects into consideration can vary by a factor of 2 or more, depending upon the thickness of the targets employed. Comparisons of x-ray cross-section data for heavy ions to direct Coulomb ionization theories, such as the plane-wave Born approximation (PWBA), cannot be justified when the $\bar{\sigma}_{KX}$ data are strong functions of the target thickness. Additional processes such as inner-shell charge transfer may, necessarily, have to be considered. The applicability of corrections to the PWBA for heavy ions may need to be examined in view of the results of the present work. Dynamic screening of the projectile charge, and the assignment of the K x-ray production rates to a pure direct Coulomb ionization formulation are in need of careful study, in view of the qualitative agreement of the data of this work for Cl on Cu with the model which is developed using the premise found in the work of Betz *et al.*[2]

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