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Systematics of Target and Projectile K X-ray Production and REC for

20-80 MeV Cl^{19+} Ions Incident on 25-200 $\mu\text{g}/\text{cm}^2$ Cu Targets*

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ABSTRACT

A systematic investigation of K x-ray production for 20-80 MeV Cl ions in collision with thin self-supporting Cu targets has been conducted. Target and projectile characteristic x rays and radiative electron capture (REC) have been measured as a function of target thickness for incident charge states $q < Z_1 - 2$. At 80 MeV data were also obtained for $q = Z_1 - 1$. Large enhancements in both characteristic x-ray production and REC were observed for $q = Z_1 - 1$. Measured x-ray yields were parametrized vs. target thickness using the model of Betz et al. and least squares fits to the data were performed. Target K x-ray production for $q < Z_1 - 2$ is described reasonably well by the CPSSR + ECR theory. For $q = Z_1 - 1$ the enhancement in the x-ray yield is predicted quite well by the method of Gray et al. The mean fluorescence yield for the highly stripped Cl ions is determined and found to increase by a factor of about six over the range 20-80 MeV, having a value (~ 0.1) nearly equal to the single K-vacancy value at 20 MeV. The radiative lifetime for the projectile ions is found to be $\sim 3 \times 10^{-14}$ sec which is about three times longer than the single K-vacancy radiative lifetime calculated by Scofield. Parametrization of the REC yields vs. target thickness is used to normalize the measured REC intensity to the fraction of ions with K vacancies. Resulting REC cross sections are compared with the free-electron theory of Bethe and Salpeter and good agreement is obtained if it is assumed that each of the "loosely" bound electrons in Cu contributes equally to the REC process. By combining the results obtained for the characteristic x rays and REC, the fluorescence yield for K-shell capture events may be estimated, giving values in the range $(2-4) \times 10^{-3}$ for the beam energies studied.

I. INTRODUCTION

The dependence of heavy-ion induced x-ray production on foil thickness has been demonstrated in several recent experiments.¹⁻⁶ This dependence has been attributed to the changing fraction of ions with K vacancies at a depth x in the foil, since it is found that a projectile with a K vacancy produces a large enhancement in the probability for K-vacancy production in the target^{2,4}. Hence, measured x-ray yields are strongly dependent upon whether or not the incoming beam has a K vacancy. Experimentally it is found that target x-ray yields increase with foil thickness for incident charge states $q \leq Z_1 - 2$ and decrease for charge states $q > Z_1 - 2$. The increase in x-ray production for $q \leq Z_1 - 2$ can be understood qualitatively from the fact that, as the foil thickness is increased, a larger fraction of ions possesses K vacancies, and these ions are more effective at producing K vacancies in the target atoms. Similarly, the decrease in the target yields for incident charge states $q > Z_1 - 2$ can be understood from the fact that, initially after entry into the foil, projectile K-vacancy loss by electron capture outweighs K-vacancy production in the projectile by ionization, thereby reducing the fraction of ions with K vacancies for larger foil thicknesses.

These results imply that K-vacancy equilibrium is not reached until the ion travels many atomic layers through the foil. Indeed, the works of Scharfer et al.⁷ and Gray et al.⁸ with sulphur ions show directly that the K-vacancy bearing fraction of the beam is dependent on foil thickness. In addition, Gray et al. found that all charge state fractions of an ion beam moving in a solid depend on target thickness, and that this dependence could be quantitatively understood in terms of the changing fraction of ions with K vacancies. On the other hand,

charge equilibrium for shells higher than the K shell is reached very rapidly (in the first few atomic layers) after entry into the foil as shown by the work of Cocke *et al.*⁹ Thus it is important to distinguish between charge distribution equilibrium and charge state equilibrium.

In order to describe these results quantitatively a "two-component" model proposed by Betz *et al.*¹, based on the formulation by Allison,¹⁰ has been applied²⁻⁵ in which the beam is considered to consist of two fractions of ions, those with a K vacancy and those without a K vacancy. For collision systems in which a significant fraction of the beam develops two K vacancies in passage through the foil, Gardner *et al.*⁶ have shown that it is necessary to consider a "three-component" model¹⁰ where the projectile may have zero, one, or two K vacancies. In this case target K-vacancy production is enhanced even more due to the presence of the two projectile vacancies. Gray *et al.*^{4,6} have found that the enhancement in target K-vacancy production due to projectile K vacancies can be described quite well in terms of a semi-empirical formula based on the works of Meyerhof¹¹ and Taulbjerg *et al.*¹²

In order to compare heavy-ion induced x-ray production cross sections with theoretical calculations, it is essential that target thickness effects be taken into account. It has been shown⁴ that measured target yields can vary by factors of eight or more depending on the foil thickness and the incident charge state of the beam. Thus the cross sections must be determined for vanishing target thickness. The energy dependence of target x-ray production cross sections determined in this manner have been reported¹³⁻¹⁶ and the results have been compared with theoretical predictions of ionization and electron capture.

Measurements of target thickness effects have been reported for both target and projectile x rays although most studies have concentrated on target x rays. These effects, however, have not been measured for both target and projectile x rays in the same experiment nor has the systematic beam energy dependence of the projectile collision parameters been investigated. Complicating the measurement of projectile x-ray yields for solid targets is the fact that it is necessary to use self-supporting foils to accurately determine projectile x-ray production due to a single species of target atom.

In the present work we present the results of a study examining both target and projectile K x-ray production as a function of target thickness for 20-80 MeV Cl ions incident on thin self-supporting Cu targets. Radiative electron capture (REC) by the incident Cl ions is also examined. Preliminary reports of our results have previously been published.¹⁷ Target and projectile x-ray yields are parametrized as a function of target thickness using the model of Betz et al.¹ Measurement of both target and projectile x rays enables us to obtain a single set of self-consistent fitting parameters to characterize all of the data simultaneously. Values obtained for the fitting parameters are compared with theoretical results where possible.

II. EXPERIMENTAL

A. Procedure

The work described here was conducted at Triangle Universities Nuclear Laboratory using the FN tandem Van de Graaff accelerator. A schematic of the experimental apparatus is shown in Fig. 1. The incident ions struck thin Cu targets of varying thickness which were positioned inside a hexagonal scattering chamber as shown. The incident beam was collimated by means of graphite apertures of diameter 3.2 mm

Absolute normalization of the incident beam intensity was accomplished by detecting elastically scattered Cl ions in a silicon surface barrier detector mounted inside the chamber at 60° to the incident beam. Scattered ions were collimated with a mylar aperture of 3.2 mm diameter placed in front of the particle detector. The incident beam intensity was also integrated by means of a Faraday cup as indicated in the Figure. X rays were detected from below in air at 90° to the incident beam with a Kevex Si(Li) detector having a $25.4\text{-}\mu\text{m}$ Be window. The detector viewed the target through a $25.4\text{-}\mu\text{m}$ Mylar window. An aluminum mask of thickness 3.2 mm with a 3.2 mm diameter hole was placed over the x-ray detector to preclude detection of x rays near the edge of the detector, thereby improving detector resolution. In order to minimize pileup and dead time effects a $12.7\text{-}\mu\text{m}$ aluminum absorber was used to attenuate the x-ray intensity so that counting rates were ≤ 400 counts/sec.

X-ray production for both target and projectile x rays was measured using self-supporting Cu foils with a range of thicknesses $60\text{--}220\text{ }\mu\text{g}/\text{cm}^2$. The targets were prepared by vacuum evaporation. Target x-ray production for thicknesses $< 60\text{ }\mu\text{g}/\text{cm}^2$ was measured using Cu films evaporated onto $20\text{ }\mu\text{g}/\text{cm}^2$ C backings. For target x-ray production it is, of course, not necessary to use self-supporting foils so long as the beam passes through the actual target material first. For a given target the effective target thickness was changed by rotating the target rod about a horizontal axis. Absolute target thicknesses were determined to about $\pm 5\%$ by measuring Coulomb-scattered 10 MeV oxygen ions. In addition, these thicknesses were checked in some cases using Coulomb-scattered protons with 3 MeV incident energy. For the range of target thicknesses used the targets

can be considered "thin" since the beam does not lose appreciable energy in passing through the foil and since the self-absorption of the measured x rays is negligible.

Since the Cl projectile x rays were attenuated to a large degree (~99%) due to the various absorbers, it was necessary to determine accurately the absolute detector efficiency as a function of x-ray energy. Detector efficiency was determined in two ways: (1) calculated by using tabulated photon absorption cross sections¹⁸ for the known absorbers in the path between target and detector and (2) experimentally by measuring proton-induced x-ray production at 3 MeV and comparing with tabulated values of proton-induced x-ray production cross sections such as those found in Ref. 19. The results of these detector efficiency measurements are shown in Figure 2. The efficiencies obtained from the two methods agreed to within 10% and so the calculated efficiency was used to correct all of the measured x-ray intensities.

B. Results

Target and projectile K x-ray production was measured for Cl ions with energies 20, 40, 60 and 80 MeV. Data were obtained at each energy for incident charge states $q < Z_1 - 2$. At 80 MeV data were obtained for charge state $q = Z_1 - 1$ as well. A typical x-ray spectrum for 40 MeV Cl on Cu is shown in Fig. 3. Measured x-ray intensities were corrected for detection efficiency (Fig. 2) and experimental x-ray production cross sections were determined for characteristic K x rays and REC.

The resulting x-ray production cross sections are shown in Figs. 4-9 plotted as a function of target thickness. The smooth curves are the results of least squares fits to the data which will be discussed below. Figs. 4, 6 and 8 show the target x-ray production, projectile x-ray pro-

duction and REC, respectively, for the four beam energies studied for incident charge states $q < Z_1 - 2$. The incident charge states ranged from 3+ at 20 MeV to 10+ at 80 MeV. For incident charge states $q < Z_1 - 2$, K x-ray production has been shown to be nearly insensitive to the precise charge state^{2,4}. For $q = Z_1 - 2$ the beam has a metastable component, namely, $1s2s$ (3S), which results in slightly higher x-ray production due to the K-to-K electron transfer made possible by this component of the beam. In this work, we took no measurements with this He-like beam, and so we need not be concerned with this effect. The increase in target x-ray production and REC as a function of target thickness reflects the fact that the increasing fraction of ions with K vacancies enhances the probabilities for these processes. Similarly, the decrease in the projectile x-ray cross sections can be understood from the fact that K-vacancy loss (by electron capture or vacancy decay) outweighs K-vacancy production (by ionization) for the thicker foils.

Figs. 5, 7, and 9 show the experimental cross sections for target x-ray production, projectile x-ray production and REC, respectively, obtained from 80 MeV Cl ions with incident charge state $q = Z_1 - 1$ ($A = 1$), as well as the respective cross sections (from Figs. 4, 6 and 8) for $q < Z_1 - 2$ ($A = 0$). X-ray production by 80 MeV Cl ions with $q = Z_1 - 1$ is seen to be greatly enhanced in each case over that for $q < Z_1 - 2$. The enhancement in target x-ray production is in qualitative agreement with that of other investigators^{2,4} and is expected on the basis of the model of Betz *et al.*¹ It will be shown below that the corresponding enhancements in the projectile x rays and REC are also expected on the basis of this same model and, in fact, the magnitude of the cross sections for $A = 1$ can be predicted quite accurately using the results for $A = 0$.

III. ANALYSIS

In order to interpret the above results, the dependence of the respective x-ray yields on foil thickness must be determined. To do this we use the two-component model of Betz et al.¹ in which the beam is considered to consist of two fractions of ions---those with a K vacancy and those without a K vacancy. In this model the fraction of ions Y with a K vacancy at a depth x in the foil is given by

$$Y(x) = \frac{\sigma_v}{\sigma} (1 - e^{-\sigma x}) + A e^{-\sigma x} . \quad (1)$$

In this equation A is the fraction of incident ions with one K vacancy, and $\sigma = \sigma_v + \sigma_c + \sigma_t$ where σ_v is the K-vacancy production cross section for the projectile, σ_c the cross section for capture to the K shell, and σ_t the cross section for radiative or Auger decay. In principle, the possibility of projectiles having two K vacancies should also be considered, but for the collision system studied here the two-component model has been shown to be adequate⁴.

A. Target X-Ray Yields

It is observed experimentally^{2,4} that a projectile with a K vacancy produces a large increase in the measured target K x-ray yield. Therefore, the measured target x-ray yield, written in units of a cross section, for a foil of thickness T is given by

$$\bar{\sigma}_x^t(T) = \frac{1}{T} \int_0^T [\sigma_{x0}^t (1-Y) + \sigma_{x1}^t Y] dx \quad (2)$$

where σ_{x0}^t is the target K x-ray production cross section due to a projectile without a K vacancy and σ_{x1}^t that due to a projectile with a K vacancy. (The superscript t denotes target x-ray cross sections.) Letting $\sigma_{x1}^t = \alpha \sigma_{x0}^t$ where $\alpha > 1$ (α is a function of energy), eqs. (1) and (2) give⁴

$$\bar{\sigma}_x^t(T) = \sigma_{x0}^t \left[1 + (\alpha - 1) \frac{\sigma_v}{\sigma} - \frac{(\alpha - 1)}{\sigma T} \left(\frac{\sigma_v}{\sigma} - A \right) (1 - e^{-\sigma T}) \right]. \quad (3)$$

This equation parametrizes the target x-ray production as a function of target thickness subject to the validity of the assumptions inherent in eq. (1).

B. Projectile X-Ray Yields

For the characteristic projectile x rays, contributions to the measured intensity from decays inside the foil and outside the foil must be considered separately. In this analysis we assume that the contribution to the x-ray intensity from long-lived metastable states is small so that essentially all x-ray events occur within a distance small enough to be viewed by the detector. Inside the foil the x-ray intensity dN_x^1 resulting from an elemental thickness dx of the foil is given by

$$dN_x^1(x) = I_0 Y(x) \lambda_x dx \epsilon \quad (4)$$

where I_0 is the total number of incident ions, λ_x is the radiative decay probability per unit path length (in units of cm^{-2}) and ϵ is the detection efficiency. This equation may be integrated using the expression for $Y(x)$ from eq. (1). Outside the foil the x-ray intensity is

$$N_x^0(T) = I_0 Y(T) \omega_K \epsilon \quad (5)$$

where T is the foil thickness and ω_K is the mean K-shell fluorescence yield for the highly ionized projectiles. Eqs. (4) and (5) are used to obtain an expression for the measured projectile K x-ray yield $\bar{\sigma}_x^p(T)$ (in units of a cross section) as a function of target thickness

$$\bar{\sigma}_x^p(T) = \lambda_x \frac{\sigma_v}{\sigma} + [\sigma_{xo}^p - \lambda_x (\frac{\sigma_v}{\sigma} - A)] \left(\frac{1 - e^{-\sigma T}}{\sigma T} \right) + A \frac{\sigma_{xo}^p}{\sigma_v T} e^{-\sigma T} \quad (6)$$

where $\bar{\sigma}_x^p \equiv (N_x^i + N_x^o)/I_0 T \epsilon$ and $\sigma_{xo}^p = \omega_K \sigma_v$. (The superscript p denotes projectile x-ray cross sections.)

In this equation it is assumed that σ_{xo}^p does not depend on the incident charge state for $q < Z_1 - 2$, thereby requiring that electrons in shells higher than the K shell reach charge state equilibrium very rapidly (in the first few atomic layers) after entry into the foil. The recent work of Cocke et al.⁹ shows this to be a reasonable assumption. Thus σ_{xo}^p is interpreted as the K x-ray production cross section for a projectile with no initial K vacancies and an equilibrium charge distribution in the higher shells. The same equilibrium condition for electrons in shells higher than the K shell is necessary so that λ_x and ω_K will be constant and not dependent upon the incident charge state.

From eq. (6) it is seen that $\bar{\sigma}_x^p$ decreases with target thickness for both $A = 0$ and $A = 1$ and that for $A = 1$ the cross section is greatly enhanced. Hence, this equation is in qualitative agreement with the measured cross sections shown in Figs. 6 and 7.

C. REC Yields

In the case of REC, contributions to the measured REC intensity can only come from inside the foil. Since a K vacancy must be present for REC to occur, the REC intensity dN_{REC} resulting from an elemental thickness dx of the foil in the solid angle $\Delta\Omega_x$ is given by

$$dN_{\text{REC}}(x) = I_0 Y(x) \frac{d\sigma_{\text{REC}}^0}{d\Omega} \Delta\Omega_x \epsilon dx \quad (7)$$

where $\frac{d\sigma_{\text{REC}}^0}{d\Omega}$ is the REC cross section per K vacancy. Integrating eq. (7) over target thickness we get an expression for the measured REC yield per incident projectile

$$\frac{d\bar{\sigma}_{\text{REC}}}{d\Omega}(T) = \frac{d\sigma_{\text{REC}}^0}{d\Omega} \left\{ \frac{\sigma_v}{\sigma} \left[1 - \frac{1}{\sigma T} (1 - e^{-\sigma T}) \right] + \frac{A}{\sigma T} (1 - e^{-\sigma T}) \right\} \quad (8)$$

where $d\bar{\sigma}_{\text{REC}}/d\Omega \equiv N_{\text{REC}}/I_0 T \Delta\Omega_x \epsilon$ and N_{REC} is the measured REC intensity (at 90°).

From eq. (8) it is seen that $d\bar{\sigma}_{\text{REC}}/d\Omega$ increases with target thickness for $A = 0$. This is due to the fact that the fraction of ions with K vacancies increases as the target thickness increases. In contrast, for $A = 1$, $d\bar{\sigma}_{\text{REC}}/d\Omega$ decreases with target thickness since a smaller fraction of the ions possess K vacancies for larger foil thicknesses. These features are in qualitative agreement with the measured REC cross sections shown in Figs. 8 and 9.

D. Least-Squares Analysis

Equation (3) can be used to perform a least squares fit to the measured target x-ray production cross sections shown in Figs. 4 and 5 giving values for the parameters σ_{xo}^t , α , σ_v and σ . If, however, x-ray production is measured only for $A = 0$ ($q < Z_1 - 2$), then only σ_{xo}^t , σ and the product $(\alpha-1)\sigma_v$ can be determined independently. In the present work $A = 0$ for the 20, 40

and 60 MeV data while, for 80 MeV, data were obtained for both $A = 0$ and $A = 1$. For the 80 MeV data a simultaneous least squares fit was performed to the data for $A = 0$ and $A = 1$ allowing the extraction of all four parameters. The solid curves shown in Figs. 4 and 5 are the results of these fits to the data.

Similarly, eq. (6) can be used to perform a least squares fit to the measured projectile cross sections, shown in Figs. 6 and 7, giving values for the parameters σ_{x0}^p , λ_x , σ_v and σ . For $A = 0$ only σ_{x0}^p , σ and the product $\lambda_x \sigma_v$ are determined. Eq. (8) is used to fit the REC cross sections (Figs. 8 and 9) giving values for $d\sigma_{\text{REC}}^0/d\Omega$, σ_v and σ . For $A = 0$ only σ and the product $(d\sigma_{\text{REC}}^0/d\Omega) \sigma_v$ are determined, while for $A = 1$ the intercept at $T = 0$ gives the value of $d\sigma_{\text{REC}}^0/d\Omega$ directly.

It is noted that the parameters σ_v and σ are common to each of the three cross section formulations, i.e. eqs. (3), (6) and (8), and hence their value should be the same for each case. In the least squares analysis of the projectile x rays and REC, these parameters were constrained to have values equal to those found for the target x rays. There are three reasons for constraining σ_v and σ in this way: (i) Data were obtained for smaller values of the target thickness (down to $25 \mu\text{g}/\text{cm}^2$) for the target x rays, providing measurements over the region where the cross section changes most rapidly. Target x-ray production can, of course, be measured for arbitrarily thin target thicknesses by using a backing foil. ii) Target x-ray intensities are easier to determine accurately since there is no interference in the spectrum from REC in the region of the Cu x rays as is the case for the Cl projectile x rays. iii) When the target and projectile x-ray production were fit separately (with eqs. (3) and (6)), allowing σ to vary freely, the values of σ obtained were the same to within $\sim 15\%$.

The solid curves shown in Figs. 6-9 are the results of the fits to the data using eqs. (6) and (8) under the constraint that σ (and σ_v for 80 MeV and $A = 1$) be equal to the values obtained from the analysis of the target x rays using eq. (3). In this way a single self-consistent set of parameters was obtained for all of the data.

IV. DISCUSSION

A. Target X Rays

The results of the above least squares analysis of the target x-ray production are summarized in Table I. Quoted errors include the fitting error only. The large decrease in σ over the range of energies studied is due to decreases in the capture cross section σ_c and the decay cross section σ_T with increasing velocity. The decrease in the product $(\alpha-1)\sigma_v$ is due to the large decrease in α with increasing energy which outweighs the increase in σ_v . The decrease in α reflects the fact that the probability of electron transfer from the target K shell to the K shell of the projectile decreases with increasing projectile velocity. More will be said about this later. The increase in σ_{xo}^t (the cross section for vanishing target thickness for $A = 0$) is due primarily to the increase in target K-vacancy production with increasing projectile energy. A small contribution may exist due to an increase in the fluorescence yield with increasing multiple ionization for the higher beam energies.

Our results for 60 MeV projectiles can be compared with the work of Gray et al.⁴ These authors find values for σ_{xo}^t , σ and $(\alpha-1)\sigma_v$ of 1180 b, 1890 kb, and 2485 kb, respectively. From Table I it is seen that these values are all within 10% of the values obtained in the present work.

The extracted values of σ_{x0}^t may be compared with theoretical predictions of ionization as shown in Fig. 10. Single vacancy fluorescence²⁰ yields were used to calculate theoretical x-ray cross sections from the vacancy production cross sections. It is seen that the plane-wave-Born approximation (PWBA)²¹ and the binary encounter approximation (BEA)²² overestimate the measured cross sections by as much as an order of magnitude. The solid curve²³ labeled CPSSR + ECR(K $\rightarrow$ L, M, ...) includes contributions from (1) direct ionization (CPSSR) given by the theory of Basbas et al.²⁴ with the relativistic treatment as developed by Brandt and Lapicki²⁵ and (2) electron capture (ECR) to the L and higher shells based on the theory of Lapicki and Losonsky²⁶ modified for radial cutoffs²⁷ and including the relativistic corrections of Lapicki and McDaniel²⁸. Although Refs. 26-28 deal only with electron capture by fully stripped ions, it is possible to estimate capture by a projectile with electrons by assuming that their only role is to occupy otherwise available states on the projectile.²⁹ This, of course, neglects the screening of the projectile nuclear charge which may be important. The ECR contribution to the solid curve in Fig. 10 is about 15% of the total ionization cross section for all energies investigated. Agreement with the CPSSR + ECR theory is seen to be fair with the agreement improving for higher incident beam energies.

These results indicate that target K-vacancy production for the collision system studied here ($Z_1/Z_2 \sim 0.6$) may be predicted reasonably well within the framework of the CPSSR + ECR theory. However, the present results tend to disagree with those of McDaniel et al.²⁷ in which it is concluded that direct ionization alone accounts for σ_{x0}^t for $0.44 \leq Z_1/Z_2 \leq 0.67$. We find that the CPSSR + ECR theory underestimates

the data even with the 15% contribution to the cross section due to electron capture. This fact may support the contention by Gardner *et al.*¹⁶ that electron capture, to the L and higher shells of the projectile, plays a considerably larger role relative to direct ionization for Cl + Cu collisions. However, the discrepancy could also be due to inadequacies of the direct ionization theory for this collision system. These questions clearly need further study.

We have also measured cross sections σ_{xo}^t for vanishing target thickness for Cl bombardment of other targets in the range $19 \leq Z_2 \leq 35$.³⁰ We find that agreement with the CPSSR + ECR becomes considerably worse as $Z_1/Z_2 \rightarrow 1$. This result is, of course, expected for more symmetric collisions. The importance of obtaining the cross section for vanishing target thickness in comparisons with theory should be stressed, however, since there can be sizeable differences between the zero thickness cross section σ_{xo}^t and the equilibrium cross section $\bar{\sigma}_x^t(\infty)$ (from Fig. 4 $\sigma_{xo}^t \approx \frac{1}{2}\bar{\sigma}_x^t(\infty)$).

It is of considerable importance to be able to determine the value of σ_v , the K-vacancy production cross section for the projectile, since knowledge of this parameter allows determination of several quantities of interest concerning the highly stripped projectile. In the present work σ_v is determined directly from the 80 MeV data by fitting eq. (3) to the data for $A = 0$ and $A = 1$ shown in Fig. 5. For 60 MeV we can use the value of α (≈ 8.1) found by Gray *et al.*⁴ to determine σ_v , giving a value of 360 kb which is consistent with the value found by those authors. Since α is simply the ratio $\sigma_{x1}^t/\sigma_{xo}^t$, its value can be determined quite accurately when data is obtained for both $A = 0$ and $A = 1$. Furthermore, Gray *et al.*⁴ find that the factor α can be calculated quite accurately according to the formula (see also Gardner *et al.*⁶)

$$\alpha-1 = \frac{\sigma_R^w \omega_{Cu}}{\sigma_{xo}^t}, \quad (9)$$

where $\sigma_R = \pi R^2$ and R is the radius corresponding to the peak in the dynamic coupling elements as given by Taulbjerg *et al.*¹², w is the Meyerhof¹¹ vacancy transfer probability, and ω_{Cu} is the fluorescence yield²⁰ for Cu. The He-like binding energy³¹ for the Cl K-shell was used in the calculation of w . Values of $\sigma_R = 7.07 \times 10^{-19} \text{ cm}^2$ and $\omega_{Cu} = 0.445$ were used.

If the value of $(\alpha-1)$ given by Eq. (9) is calculated for the present 80 MeV data, we find a value of 3.9 which is about 15% lower than our measured value of 4.6, giving further evidence that eq. (9) provides rather reliable estimates of α . If we use this calculated value of α along with the values of σ_{xo}^t , $(\alpha-1) \sigma_v$, and σ found from an analysis of the $A = 0$ data only, eq. (3) can be used to predict the measured cross sections $\bar{\sigma}_x^t(T)$ for $A = 1$. The result is shown by the dashed curve in Fig. 5. It is seen that the target K x-ray production for $A = 1$ can be predicted quite well using results obtained for $A = 0$ in conjunction with Eq. (9).

For 20 and 40 MeV Cl projectiles α was calculated from Eq. (9), allowing a determination of σ_v . The values obtained for α and σ_v are listed in Table I. The large decrease in α with increasing energy reflects the fact that K-to-K electron transfer becomes less probable for higher projectile velocities.

The present results cannot be compared in a meaningful way with the vacancy sharing theory of Meyerhof¹¹ since the conditions required for application of this theory are not satisfied in the present work.³² There are basically two reasons for this: (1) vacancy sharing is applicable only in the case where K vacancies in the heavier collision partner result from transfer from the $2p\sigma$ molecular orbital, i.e., direct K -vacancy production must be negligible. If the contribution due to direct excitation is large, its effect must be subtracted before comparing with the vacancy sharing model. In our case the vacancy production giving rise to σ_{x0}^t is accounted for almost totally (except possibly at 20 MeV) by the direct ionization theory including electron capture²¹⁻²⁹. Hence σ_{x0}^t cannot be used to determine a meaningful value for the experimental vacancy sharing probability w . (2) Vacancy sharing applies to the outgoing part of the collision.¹¹ Hence the cross section σ_{x1}^t cannot be used to determine w since it contains a large contribution due to direct electron capture and this contribution cannot be separated experimentally from the part due to transfer from the $2p\sigma$ orbital. Furthermore, Winters et al.³³ observed that Cl K -vacancy production as a function of target Z_2 becomes monotonic for energies $E \gtrsim 30$ MeV, indicating that direct excitation dominates over vacancy transfer from $2p\sigma$ for the energy range investigated here.

For similar reasons, our results cannot be compared with the universal scaling model of Lennard et al.³⁴ Furthermore, these authors investigated collisions involving gas targets whereas our work deals with thin foils. In addition, they used projectiles in which there were no initial $2p$ vacancies, a condition not necessarily satisfied in the work described here.

B. Projectile X Rays and REC

The results of the least squares analyses of the projectile x rays and the REC are summarized in Table II. As in Table I, quoted errors include only the fitting error. Since the values of σ and σ_v were constrained to be the same as for the target x-ray production their values are not repeated in Table II.

The dashed curve in Fig. 7 was calculated from eq. (6) using the values of $\sigma_{xo}^p (= \omega_K \sigma_v)$, $\lambda_x \sigma_v$ and σ found from the analysis of $A = 0$ data and the value of σ_v determined from the product $(\alpha - 1) \sigma_v$ given in Table I after calculating $\alpha - 1$ from eq. (9). As for target x-ray production, it is seen that the projectile x-ray production for $A = 1$ can be predicted quite well from the results obtained for $A = 0$.

The increase in σ_{xo}^p (the zero thickness cross section for $A = 0$) is due in part to the increase in vacancy production but is also due to an increase in the fluorescence yield of the highly stripped Cl ions. Values of the mean fluorescence yield may be calculated from the relation $\omega_K = \sigma_{xo}^p / \sigma_v$. The results are listed in the table. (For 80 MeV, ω_K was determined directly from the fitting.) These values are plotted in Fig. 11 as a function of the incident beam energy. The single vacancy fluorescence yield²⁰ is shown for reference. It is observed that ω_K has a value (~ 0.1) nearly equal to the single K-vacancy value for 20 MeV Cl and increases by a factor of about six over the range 20-80 MeV. The scale along the top of the figure gives the average number of L vacancies, $\bar{n}_L$, corresponding to the energy range investigated here. Values of $\bar{n}_L$ were deduced by comparing observed Cl K α energy shifts with computed shifts obtained from Hartree-Fock-Slater³⁵ calculations assuming a fully stripped M shell.

The scaled theoretical estimate for ω_K shown in Fig. 11 was calculated using the scaling procedure of Larkins.³⁶ The actual values for ω_K were

computed from the formula of Greenberg et al.³⁷, namely,

$$\omega_K(\bar{n}_L) = \frac{\omega_o}{1 - \frac{\bar{n}_L}{7} (1 - \omega_o)} \quad (10)$$

where ω_o is the single vacancy fluorescence yield.²⁰ This formula assumes that both the x-ray and Auger transition rates scale in proportion to the total number of remaining electrons. Qualitative agreement with the trend of the experimental data is obtained but the theoretical curve differs systematically in magnitude from the experimental values, especially at the higher energies. This is not unexpected and is probably due to intrinsic inaccuracies in the scaling procedure used to calculate ω_K .

The values of $\lambda_x \sigma_v$ given in Table II are seen to go through a maximum. This is due to the fact λ_x decreases monotonically with increasing projectile velocity while σ_v increases. Using the values of σ_v from Table I to calculate λ_x , the radiative lifetime τ_x for K-shell decay for the projectile ions may then be deduced from $\tau_x = 1/nv\lambda_x$, where n is the atomic density (atoms/cm³) and v is the incident velocity. The resulting values of τ_x are listed in Table II. Uncertainties in τ_x are such that no systematic beam-energy dependence can be discerned. However, since the average equilibrium charge³⁸ for 20-80 MeV Cl ions does not change appreciably ($\bar{q} \approx 10 - 12.5$), it might be expected that τ_x would not vary greatly over this energy range. The average of the values shown in the table is $\bar{\tau}_x = 2.8 \times 10^{-14}$ sec which is about three times longer than the theoretical single K vacancy radiative lifetime³⁹ of 1.1×10^{-14} sec. Qualitatively such an increase in lifetime is expected for a highly stripped ion. These results are in substantial agreement with the work of Betz et al.¹ in which the radiative lifetime for ~100 MeV sulphur ions in collisions with thin solid targets is determined to be about 1.5×10^{-14} sec.

Finally we consider the REC cross sections given in Table II. The peaked behavior of the product $\sigma_v(d\sigma_{\text{REC}}^0/d\Omega)$ is due to the fact that $d\sigma_{\text{REC}}^0/d\Omega$ decreases with increasing beam energy while σ_v increases. In a manner similar to that used for Figs. 5 and 7, the results of the $A = 0$ analysis can be used to predict the measured cross sections $d\bar{\sigma}_{\text{REC}}/d\Omega$ for $A = 1$ using eq. (8). The dashed curve in Fig. 9 shows the predicted cross sections for 80 MeV which are seen to agree quite well with the measured cross sections as was the case for the target and projectile x-ray production.

Using the values of σ_v from Table 1, the REC cross section per K vacancy $d\sigma_{\text{REC}}^0/d\Omega$ may be determined. Within the limits of validity of the expression used for $Y(x)^1$, the values shown for $d\sigma_{\text{REC}}^0/d\Omega$ in Table II are properly normalized to the fraction of ions which develop K vacancies. This normalization is essential if REC cross sections are to be compared with theoretical calculations.

We have compared our results for $d\sigma_{\text{REC}}^0/d\Omega$ with predictions of the free-electron theory of Bethe and Salpeter⁴⁰. Other investigators have compared REC cross sections with calculations based on the Born approximation^{41,42}. The relevant parameter in determining the applicability of each theory is the Sommerfeld parameter, $\eta = Ze^2/\hbar v$, which is the ratio of the Cl K-shell velocity to the incident projectile velocity. If $\eta \gtrsim 1$ the disturbance of the atomic orbitals during the collision is large and the Bethe-Salpeter theory is applicable. For $\eta \lesssim 1$ the disturbance is small and the Born approximation should be more appropriate. In our case $\eta > 1.7$ for all beam energies investigated, so we consider only the Bethe-Salpeter theory. Furthermore, predictions based on the Born approximation⁴¹ have been shown to be in qualitative disagreement with the trend of the experimental cross sections⁴² for collision systems similar to those investigated here.

Since the Bethe-Salpeter theory gives only the total REC cross section, theoretical differential cross sections at 90° were calculated assuming a $\sin^2\theta$ dependence^{43,44} for the REC intensity. The results are shown in Fig. 12. Two theoretical curves are shown. The lower dashed curve is calculated directly from the theory assuming that each target atom has a single electron which can be captured. This curve underestimates the experimental values by more than an order of magnitude. However, a copper atom has several electrons which can be captured radiatively, and these electrons should be included in the theoretical calculations. The criterion to be used in determining how many target electrons to include is that the captured electron be essentially "free" with respect to the incident projectile. This condition may be expressed by

$$\left[\frac{E/M}{U/m_e} \right]^{1/2} \gg 1$$

where E is the incident energy, M the projectile mass, U the target electron binding energy, and m_e the electron mass. This expression is, of course, just the ratio of the incident projectile and orbital electron velocities. A simple calculation for 20-80 MeV Cl using the binding energies listed by Bearden and Burr⁴⁵ shows that this condition is satisfied only for the ten $M_{4,5}$ and one N_1 electrons in Cu. If it is assumed that each of these electrons contributes equally to radiative capture, then the upper solid curve is obtained which is seen to be in excellent agreement with the measured REC cross sections.

Finally, by combining the results obtained for the projectile x rays and the REC, the radiative probability for K-shell capture events may be estimated. Using the values obtained for ω_K and λ_x , the decay cross section $\sigma_T = \lambda_x/\omega_K$ is calculated which, in turn, allows the total capture cross section $\sigma_c = \sigma - \sigma_v - \sigma_T$ to be determined. Then, using the experi-

mentally determined REC cross sections $d\sigma_{\text{REC}}^0/d\Omega$, the fluorescence yield for K-shell capture events is given by $\omega_{\text{REC}} = \sigma_{\text{REC}}/\sigma_{\text{c}}^{46}$. We find values in the range $(2-4) \times 10^{-3}$ as shown in Table II. Due to the errors propagated from the subtraction of large numbers (in the calculation of σ_{c}), uncertainties in ω_{REC} are such that no systematic beam energy dependence can be discerned. The average of the values shown is 3×10^{-3} . To our knowledge this is the first experimental determination of the radiative probability for K-shell capture events.

V. CONCLUSION

We have presented a quantitative description of target and projectile (including REC) x-ray production for Cl ions in collisions with thin Cu targets. By parametrizing the measured x-ray yields as a function of target thickness we obtained values for certain fundamental parameters which describe the collision dynamics. Simultaneous measurement of both target and projectile yields gives a single self-consistent set of fitting parameters which describe all of the data. X-ray production was found to be greatly enhanced for incident charge states $q = Z_1 - 1$ and it was shown that this enhancement could be predicted quite reliably based on results obtained for $q < Z_1 - 2$.

In summary we have obtained the following results: (1) Target K-vacancy production by projectile ions without a K vacancy is reasonably described within the framework of direct (Coulomb) ionization, plus electron capture, for the collision system studied here. The enhancement in target K-vacancy production by projectile ions with a K vacancy is in quantitative agreement with the prediction of Gray *et al.*⁴ (2) The mean fluorescence yield for the highly stripped Cl ions is determined and found to increase by a factor of six over the energy range investigated. (3) The radiative lifetime τ_x for

the highly ionized projectile is about three times longer than the theoretical single K-vacancy radiative lifetime³⁹. (4) The REC cross section, when properly normalized to the fraction of ions with K vacancies, is in good agreement with the free-electron theory of Bethe and Salpeter.⁴⁰ The fluorescence yield for K-shell capture events is determined and found to have a value of $\sim 3 \times 10^{-3}$. We know of no theoretical calculation with which to compare this result.

In conclusion, measurements such as those presented here provide information on the state of highly stripped ions moving in solids and also provide an understanding of the systematics of vacancy production in heavy ion-atom collisions.

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Table I. Results of least squares analysis, using eq. (3), of Cu target K x-ray yields shown in Figs. 4 and 5.

E	^a A	^b σ_{xo}^t	^b $(\alpha-1)\sigma_v$	^b σ	$\alpha-1$	σ_v
(MeV)		(b)	(kb)	(kb)		(kb)
20	0	7.0 ± 0.2	8200 ± 3000	12200 ± 4400	95 ^c	86
40	0	190 ± 10	6300 ± 600	5700 ± 500	21 ^c	300
60	0	1100 ± 20	2600 ± 200	2100 ± 100	7.1 ^d	360
80	0,1	3500 ± 100	1600 ± 100	1800 ± 200	4.6 ± .20 ^b	350 ± 20 ^b

a) A is the fraction of incident ions with one K vacancy.

b) Values obtained from least squares fits to the data.

c) Calculated from eq. (9).

d) From Ref. 4.

Table II. Results of least squares analyses, using eqs. (6) and (8),
of Cl projectile K x-ray and REC yields shown in Figs. 6-9.

E	^a A	^b σ_{xo}^p	^b $\lambda_x \sigma_v$	^c ω_K	^d τ_x	^b $\sigma_v \frac{d\sigma_{REC}^o}{d\Omega}$	$\frac{d\sigma_{REC}^o}{d\Omega}$	^e ω_{REC}
(MeV)		(kb)	(kb ²)		(10 ⁻¹⁴ sec)	(kb ² /sr)	(kb/sr)	(10 ⁻³)
20	0	11 ± 1	40,300 ± 800	0.13	2.4	220 ± 10	2.6	2.5
40	0	89 ± 3	120,000 ± 3,400	0.30	2.0	280 ± 10	0.93	2.0
60	0	151 ± 3	86,600 ± 4,200	0.42	2.7	230 ± 10	0.64	4.5
80	0,1	224 ± 10	49,400 ± 9,500	0.64 ± 0.03 ^b	4.0	160 ± 10	0.47 ± 0.03 ^b	3.2

^a) A is the fraction of incident ions with one K vacancy.

^b) Values obtained from least squares fits to the data.

^c) Calculated from $\omega_K = \sigma_{xo}^p / \sigma_v$. (For 80 MeV ω_K is determined directly.)

^d) Calculated from $\tau_x = 1/nv\lambda_x$ where n = atomic density (atoms/cm³) and v = incident velocity.

^e) Calculated from $\omega_{REC} = \sigma_{REC} / \sigma_c$ where $\sigma_{REC} = \frac{8\pi}{3} d\sigma_{REC}^o(90^\circ)/d\Omega$ and $\sigma_c = \sigma - \sigma_v - \sigma_\tau$ (see text).

FIGURE CAPTIONS

- Fig. 1. Schematic diagram of the experimental arrangement.
- Fig. 2. Absolute detection efficiency, equal to the product of detector solid angle and intrinsic detector efficiency, for the geometry of Fig. 1. The solid angle was equal to 6.7×10^{-4} sr.
- Fig. 3. Typical x-ray spectrum resulting from 40 MeV Cl ions incident on a thin solid Cu target.
- Fig. 4. Target K x-ray cross section vs. target thickness for 20, 40, 60 and 80 MeV Cl ions with initial charge states $q < Z_1 - 2$ incident on thin Cu foils. The solid curves are least squares fits to the data using eq. (3) with $A = 0$.
- Fig. 5. Target K x-ray cross section vs. target thickness for 80 MeV Cl^{10+} ($A = 0$) and Cl^{16+} ($A = 1$) ions incident on thin Cu foils. The solid curves are the result of a simultaneous least squares fit to the data for $A = 0$ and $A = 1$ using eq. (3). The dashed curve was calculated from eq. (3) for $A = 1$ using results obtained for $A = 0$ (see text).
- Fig. 6. Projectile K x-ray cross section vs. target thickness for 20-80 MeV Cl ions with initial charge states $q < Z_1 - 2$ incident on thin Cu foils. The solid curves are least squares fits to the data using eq. (6) with $A = 0$.
- Fig. 7. Projectile K x-ray cross section vs. target thickness for 80 MeV Cl^{10+} ($A = 0$) and Cl^{16+} ($A = 1$) ions incident on thin Cu foils. The solid curves are the results of a simultaneous least squares fit to the data for $A = 0$ and $A = 1$ using eq. (6). The dashed curve was calculated from eq. (6) for $A = 1$ using results obtained for $A = 0$ (see text).

- Fig. 8. Differential REC cross section (at 90°) vs. target thickness for 20-80 MeV Cl ions with initial charge states $q < Z_1 - 2$ incident on thin Cu foils. The solid curves are least squares fits to the data using eq. (8) with $A = 0$.
- Fig. 9. Differential REC cross section (at 90°) vs. target thickness for 80 MeV Cl^{10+} ($A = 0$) and Cl^{16+} ($A = 1$) ions incident on thin Cu foils. The solid curves are least squares fit to the data using eq. (8) with $A = 0$ and $A = 1$, respectively. The dashed curve was calculated from eq. (8) for $A = 1$ using results obtained for $A = 0$ (see text).
- Fig. 10. Target K x-ray production cross section $\sigma_{\text{xo}}^{\text{t}}$ for vanishing target thickness as a function of incident beam energy. Comparison is made with theoretical predictions of direct ionization (refs. 21-29).
- Fig. 11. Mean fluorescence yield for Cl projectile ions as a function of beam energy. The solid line through the data is drawn to guide the eye. The single vacancy fluorescence yield is from Ref. 20. The dashed curve is a scaled theoretical estimate of the fluorescence yield (refs. 36 and 37). The scale along the top gives the average number of L vacancies at x-ray emission assuming a fully stripped M shell (ref. 35).
- Fig. 12. Differential REC cross section (at 90°) per K vacancy vs. Cl ion energy. The dashed curve was calculated from the Bethe-Salpeter (ref. 40) free-electron capture theory, corrected for the $\sin^2\theta$ angular distribution of REC (refs. 43 and 44). The solid curve was obtained by multiplying the dashed curve by the number (11) of "free" (i.e. loosely bound) electrons in Cu (see text).

TOP VIEW

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SIDE VIEW

Fig. 1

Fig. 2

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 10

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Fig. 11

Fig. 12

Fig. 13