Enhancement of the Cu Kα x-ray Diagram Lines in Fast Heavy Ion Collisions

R. L. Watson, V. Horvat, and J. M. Blackadar

High resolution x-ray spectral measurements were performed, in conjunction with the cross section study described in the preceding report, to establish the average numbers of L- and M-shell vacancies produced in K-shell ionizing collisions by heavy ions. This information was required in order to calculate the fluorescence yields for converting the measured K x-ray yields to K-vacancy production cross sections. In the course of these experiments, it was observed that the intensity of the $K\alpha_{1,2}$ diagram line doublet became increasingly enhanced over that expected from ion-atom collisions as the projectile atomic number increased. This report discusses our analysis of this effect.

A 12.7 cm Johansson-type curved crystal spectrometer was mounted on a specially designed vacuum chamber with its focal circle oriented perpendicular to the beam axis. It viewed the target, which was tilted at a 45° angle relative to both the beam axis and the spectrometer axis, from above. The spectrometer was equipped with a LiF diffraction crystal and a flow proportional counter (10% methane and 90% argon at 1 atm). Scans of the Cu K x-ray region were performed in second order for all of the self- supporting foil targets. Unfortunately, the beam intensities required for the high resolution measurements were too high to use on the evaporated targets with mylar backings. The resolution obtained for the Cu $K\alpha_1$ line was 12 eV (FWHM).

Typical spectra are shown in Fig. 1. The first two peaks in each spectrum contain the $K\alpha_2$ and $K\alpha_1$ (diagram) lines originating from initial states having one K vacancy and zero L vacancies, while the other peaks in the fitted portion of each spectrum contain the Kα satellite lines originating from initial states having one K vacancy and one to seven L vacancies. The broad peak above the Kα satellite region contains the Kα hypersatellites (double K-vacancy initial states). It is readily seen from the changes in the Kα satellite intensity distribution that the degree of multiple ionization increases considerably in going from Ne projectiles to Bi projectiles. Another noteworthy feature of the spectra shown in Fig. 1 is the rapid increase in the intensity of the $K\alpha_{1,2}$ peaks relative to the Kα satellite peaks as the projectile atomic number increases.

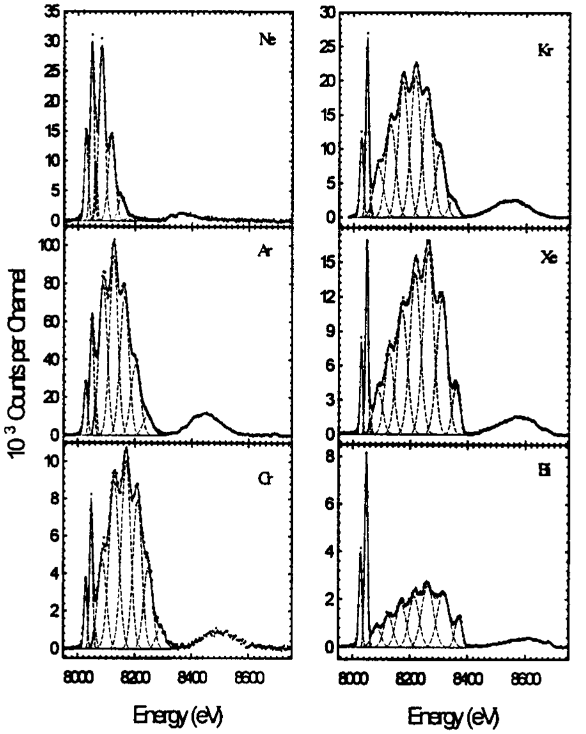

Figure 1. Cu Kα x-ray spectra excited by 10 MeV/amu projectiles passing through a 2.57 mg/cm² thick Cu foil, measured in second order with a curved crystal spectrometer. The fitted portions of the spectra contain the $K\alpha_{1,2}$ diagram line doublet and the $K\alpha L^n$ satellites. The broad peaks to the right of the satellites contain unresolved Kα hypersatellites.

The Kα satellite intensities were obtained from least squares fits employing Gaussians to represent each of the satellite peaks and the Kα diagram lines. The extracted intensities were then corrected for proportional counter efficiency and absorption in the target. Variation of the crystal reflectivity was assumed to be negligible over the range of energy involved. Based on numerous previous studies of K x-ray spectra excited by ion impact, the relative intensities of the Kα satellites are expected to approximate binomial distributions. Therefore, the observation that the intensities of the KL^0 peaks are greatly enhanced over those predicted by a binomial fit to the satellite peaks in the spectra obtained with Cr, Kr, Xe, and Bi projectiles (see Fig. 1) is strong evidence that other mechanisms besides those associated with direct interactions between the projectile nucleus and target electrons contribute to the production of K x rays from singly ionized target atoms. As has been pointed out in several previous investigations [1-3], photoionization of target atoms by projectile x rays and by ion-excited target Kβ x rays that are shifted above the K binding energy due to multiple ionization is a plausible mechanism for KL^0 enhancement. Another possible source of KL^0 x rays is electron impact ionization caused by secondary electrons produced in the ion-atom collisions.

It was necessary to correct the x-ray yields measured with the Si(Li) detector system for contributions from these other mechanisms in order to obtain reliable cross sections for vacancy production by direct ion-atom interactions. Therefore, the thickness dependence of this effect was investigated and compared with predictions of the calculated KL^0 enhancements expected from photoionization. The ion-induced contribution to the KL^0 peak of each high resolution spectrum was estimated by first fitting a binomial distribution to the satellite intensities to obtain the best value of the average L-vacancy probability p_L. The binomial intensity $I_{bin}(n)$ of a KL^n peak, is given by

$$I_{bin}(n) = P(n)\, I_{K\alpha} ,$$

where $I_{K\alpha}$ is the total Kα x-ray intensity corrected for KL^0 enhancement (i.e., $I_{K\alpha} = I_{tot} - I_E$), and

$$P(n) = \binom{8}{n} p_L^{\,n} (1 - p_L)^{8-n} .$$

The binomial intensity for n = 0 [$I_{bin}(0)$] was taken to be the KL^0 peak intensity associated with the ion-induced contribution. It is given by the following expression:

$$I_{bin}(0) = \frac{P(0)}{1 - P(0)} [I_{tot} - I_{obs}(0)] ,$$

in which $I_{obs}(0)$ is the observed intensity of the KL^0 peak. Finally, the relative enhancement of the KL^0 peak, defined as

$$R_E = \frac{I_{obs}(0) - I_{bin}(0)}{I_{tot}} ,$$

was calculated and used to examine the dependence of the enhancement effect on projectile atomic number and target thickness.

In considering the possible sources of the observed KL^0 enhancements, photoionization by Kβ x rays shifted above the K binding energy by multiple ionization is expected to be a prime candidate. Additionally, x rays emitted by some of the projectiles (specifically Kr K x rays and Bi L x rays) have significant cross sections for photoionizing Cu K electrons. The role of photoionization was investigated by performing calculations of the expected KL^0 relative enhancement based on the observed intensities of Cu Kβ x rays emitted above the absorption edge and (in the pertinent cases) the observed intensities of projectile x rays. The results are shown in Figs.

2 and 3. In Fig. 2, the measured and calculated KL^0 relative enhancements for a target thickness of 2.57 mg/cm^2 are plotted as a function of projectile atomic number. The apparent dip in the data at $Z_1 = 54$ is caused by the additional contributions to R_E from projectile x rays at the two neighboring points $Z_1 = 36$ (Kr) and 83 (Bi). Within experimental errors, the relative enhancements observed for Ne, Ar, and Cr projectiles are fully accounted for by Kβ photoionization. However, the relative enhancements observed for the Kr, Xe, and Bi projectiles are considerably larger than those predicted for photoionization alone. Since the reliability of the calculations is expected to be of the order of ±10%, it must be concluded that another mechanism produces substantial additional contributions to the KL^0 x-ray intensity. As mentioned above, the most likely candidate is K-shell ionization by secondary electrons. It is well known, for example, that binary encounter electrons are produced with energies peaking around 4mE/M at zero degrees, where m is the mass of the electron, and M and E are the mass and energy of the projectile, respectively. For 10 MeV/amu projectiles, the peak energy is 22 keV, which is 2.5 times larger than the Cu K binding energy. Moreover, cross sections for ionization by electron impact are comparable to those for photoionization. A method for estimating the expected contribution from secondary electrons is discussed in the following report.

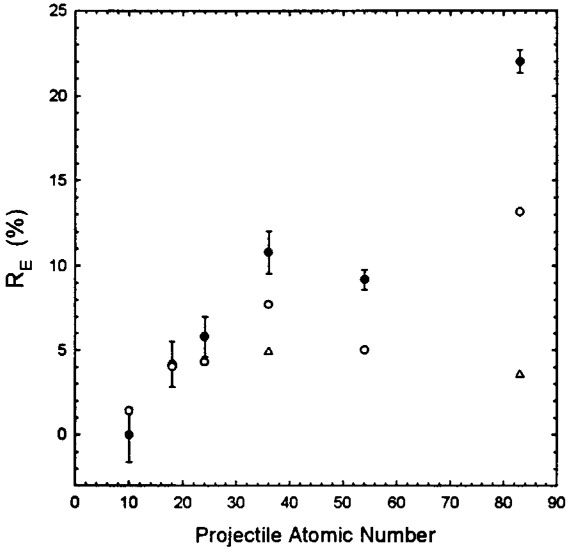

Figure 2. Comparison of the experimental (filled circles) and calculated (open circles) relative enhancements for a 2.57 mg/cm^2 thick Cu foil. The calculated contributions to the relative enhancements for $Z_1 = 36$ and 83 from fluorescence by projectile (Kr K and Bi L) x rays are shown by the open triangles.

The target thickness dependence of the KL^0 relative enhancement is shown in Fig. 3 for Kr, Xe,and Bi projectiles. In the cases of Kr and Bi, the predicted photoionization relative enhancement does not go to zero at zero target thickness because of contributions from projectile x rays produced in the target backing. It was found that the measured relative enhancements were well represented by the empirical fitting function

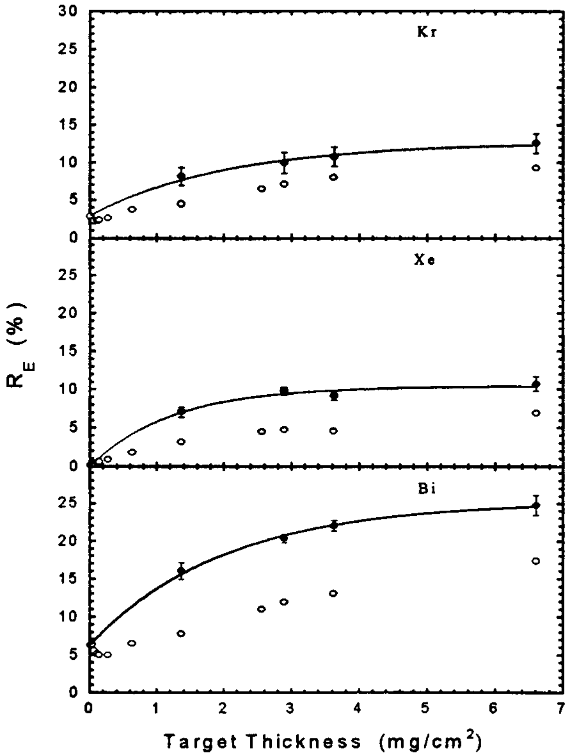

Figure 3. Target thickness dependence of the relative enhancement for Kr, Xe, and Bi projectiles. (Filled circles are experimental and open circles are calculated). The curves show the results of least squares fits to the experimental points.

$$R_E = a + b(1 - e^{-ct})$$

where a, b, and c are fitting parameters and t is the target thickness. The results of fits with this function, shown by the solid lines in Fig. 3, were used to correct the measured Kα x-ray yields in the cross section determinations for Kr, Xe, and Bi projectiles. The relative enhancements used to correct the x-ray yields for Ne, Ar, and Cr were the ones calculated for photoionization.

References

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