Projectile Z dependence of Al K-shell vacancy production in 10-MeV/amu ion-solid collisions

R. L. Watson, V. Horvat, J. M. Blackadar, and K. E. Zaharakis

In a continuing effort to explore the properties of highly asymmetric collision systems for which $Z_1 >> Z_2$ (where Z_1 and Z_2 are respectively the projectile and target atomic numbers), the Z_1 dependence of K-vacancy production in Al targets ($Z_2 = 13$) is examined in the present report. Using 10-MeV/amu projectiles of Ne, Ar, Cr, Kr, Xe, and Bi, these measurements provide cross sections at a considerably higher velocity ratio ($v_1/v_{2K} = 1.87$) than in our previous study [1] and for collision asymmetries Z_1/Z_2 up to 6.38. The primary objectives of this work are to provide a body of K-vacancy production cross section data of sufficient accuracy and extent to encourage further development of more reliable theoretical methods, and to use this database as a means of establishing an empirical scaling law capable of systematizing cross sections for a wide variety of collision systems.

As in the previous study [1], the K-vacancy production cross sections have been determined from K x-ray yields measured with a Si(Li) detector. The effect on the cross sections of projectile charge state variation during passage through the target was assessed by performing measurements for targets ranging in thickness from 10 μg/cm² to 3.6 mg/cm². In addition, high resolution x-ray spectra were taken with a curved crystal spectrometer for the purpose of determining the x-ray yield contributions associated with secondary processes and examining the extent of multiple ionization produced in K-shell ionizing collisions by the various heavy-ion projectiles. This latter information was used to calculate the appropriate fluorescence yields for converting the K x-ray production cross sections to K-vacancy production cross sections.

The spectra of Al Kα x rays obtained with the curved crystal spectrometer using beams of 10 MeV/amu Ne and Bi ions are compared in Fig. 1. The Kα satellites (KL^1 through KL^7) originating from Kα x-ray transitions in atoms having one to seven L-shell vacancies (1490 to 1600 eV) are prominent features in both of these spectra. The peaks appearing in the energy region above 1600 eV are identified as the Kα hypersatellites (K^2L^0 through K^2L^7) originating from Kα x-ray transitions in atoms having two K-vacancies and zero to seven L-vacancies. The brackets above the Kα satellite and hypersatellite peaks in the spectrum obtained with Bi ions display the theoretical energies calculated with the Dirac-Fock

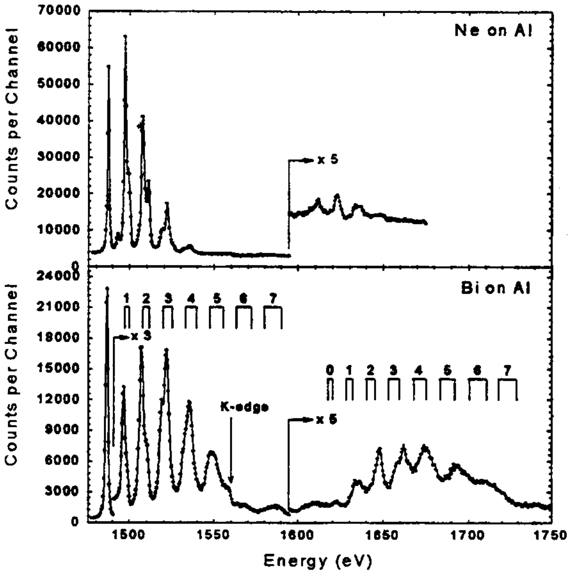

Figure 1. High resolution Al Kα x-ray spectra measured with a curved crystal spectrometer using 10-MeV/amu Ne (top) and Bi (bottom) projectiles. The brackets in the spectrum for Bi ions indicate the calculated energy positions of the seven Kα satellite and eight hypersatellite peaks for Al atoms having three M electrons (lower energy line) and zero M electrons (higher energy line).

code of Desclaux [2] for Al atoms in the ground state M-shell electron configuration $3s^23p^1$ (lower energy line) and for Al atoms having an empty M-shell (higher energy line). Another noteworthy feature in the spectrum obtained with Bi ions is the large enhancement of the Kα diagram line (KL^0 peak) relative to the Kα satellite peaks. This enhancement is attributed to Al K x-ray production by secondary processes [1]. Secondary x-ray production may occur as a result of photoionization of target atoms by both projectile x rays and target KL^6, KL^7, and Kα hypersatellite x rays, whose energies are just above the Al K-absorption edge. Bombardment of target atoms by electrons generated in ion-atom collisions (primarily cusp electrons and binary encounter electrons) also contributes substantially to the secondary x-ray yield [3].

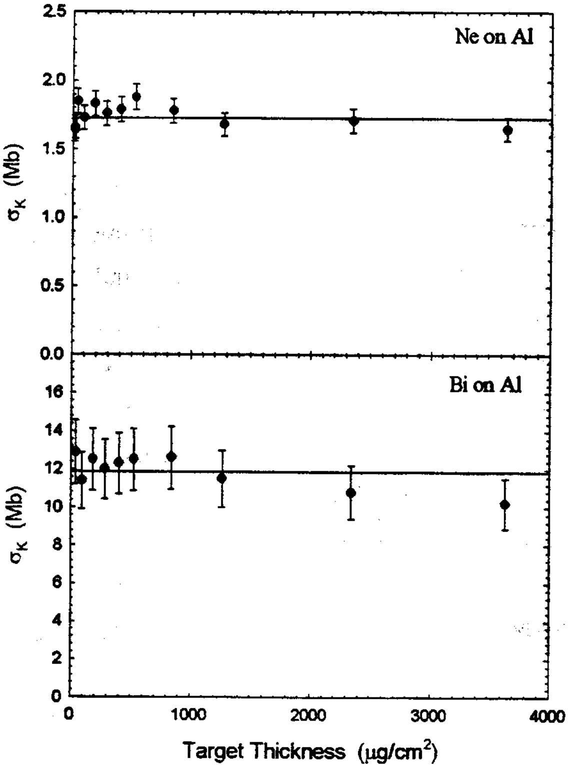

Figure 2. Experimental Al K-vacancy production cross sections for Ne (top) and Bi (bottom) projectiles as a function of target thickness. The solid lines show the average values of the cross sections.

The K-vacancy production cross sections obtained for Ne and Bi projectiles are shown plotted as a function of target thickness in Fig. 2. Judging from a comparison of the individual data points with the average values of the cross sections (shown by the solid lines) there is no evidence of a thickness dependence similar to that observed previously for Cu. This same conclusion applies to the data obtained with the other projectiles. The reason for the absence of a target thickness dependence of the K-vacancy production cross sections for low Z_1 projectiles (e.g., Ne and Ar) on Al is that the total K-capture cross section is much smaller than the direct ionization cross section. In the case of the higher Z_1 projectiles, Al K-electrons are preferentially captured to the outer-shells of the projectiles. Since the incident projectile ions have already been stripped of outer-shell electrons, the subsequent charge equilibration process that opens inner-shell capture channels as the projectile passes through the target does not substantially increase the K-vacancy production cross section.

Theoretical cross sections for Al K-vacancy production by charge equilibrated 10-MeV/amu projectiles are presented in Fig. 3a. The direct ionization cross sections were calculated using the plane wave Born approximation (PWBA) [4] and the K-electron capture cross sections were obtained using the prescription of Lapicki and McDaniel [5]. In Fig. 3b, the measured K-vacancy production cross sections for Al are compared with the total theoretical cross sections. It is evident that the theoretical cross sections increase much faster than the experimental cross sections beyond $Z_1 = 10$ and overestimate the experimental cross sections by about a factor of 15 at $Z_1 = 83$.

The lack of a reliable theoretical method for estimating K-vacancy production cross sections in heavy ion collisions with $Z_1/Z_2 > 0.6$ motivates one to seek empirical scaling laws that are capable

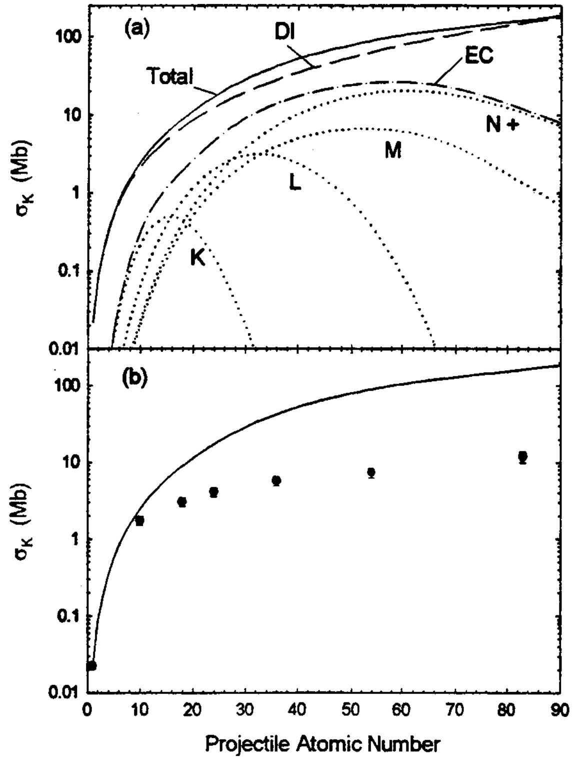

Figure 3. (a) Theoretical total Al K-vacancy production cross sections for charge equilibrated projectiles (solid curve), PWBA direct ionization cross sections (dashed curve), and total K-electron capture cross sections [5] for charge equilibrated projectiles (dot-dashed curve) as a function of projectile atomic number. The dotted curves show the cross sections for K-electron capture to various shells of the projectile. (b) Comparison of the experimental Al K-vacancy production cross sections for charge equilibrated projectiles (solid curve) with the experimental cross sections (data points).

of at least providing rough estimates of these quantities. In this regard, a very simple scaling law has been found that gives a reasonable representation of the cross sections for K-vacancy production in both Al and Cu targets by 10 MeV/amu projectiles. The K-vacancy production cross section for a projectile with atomic number Z_1, $\sigma(Z_1)$, is approximately given by

$$\sigma(Z_1) = \sigma(1)\, Z_R^{2.4},$$

where $\sigma(1)$ is the cross section for K-vacancy production in the same target by protons and Z_R is the reduced atomic number defined as

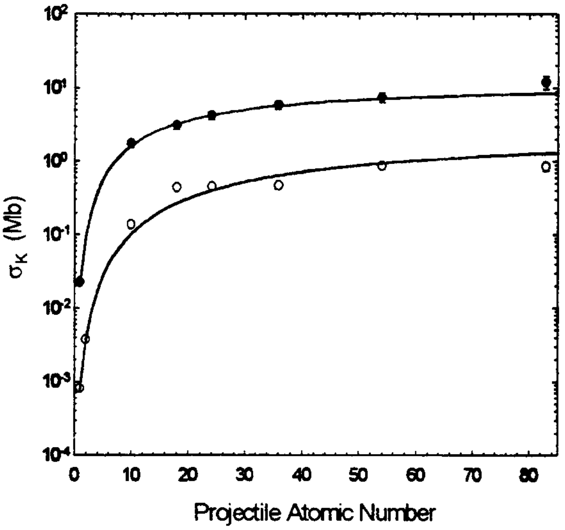

Figure 4. Comparison of the experimental K-vacancy production cross sections for 10-MeV/amu projectiles on Al (filled circles) and Cu (open circles; from Ref. 1) with the predictions of the empirical scaling law (solid curves).

$$Z_R = \frac{Z_1 Z_2}{Z_1 + Z_2}.$$

The predictions of this scaling law are compared with the experimental K-vacancy production cross sections for Al and Cu in Fig. 4. Although some of the data points deviate rather significantly from the curves defined by the scaling law, overall agreement is (on average) ±26% for Cu and ±8.6% for Al. Measurements aimed at examining the general applicability of this scaling law are currently in progress.

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