A semiempirical scaling law for target K x-ray production in heavy ion collisions

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In view of the fact that reliable theoretical methods for predicting cross sections for K x ray production in heavy ion-atom collisions have yet to be developed, and because these cross sections are of practical use in analytical applications and for beam monitoring in experiments with heavy ions, it is desirable to examine scaling relations that might provide a means for their estimation. First-order descriptions of inner-shell ionization based on the PWBA as well as the classical binary encounter approximation (BEA) predict that target K-shell ionization cross sections are proportional to the square of the projectile effective charge (Z_{eff}^2) divided by the square of the target electron binding energy (B_K^2) times a function that defines the V dependence of the collision process (where V is the projectile speed divided by the K-electron average speed). Therefore, a plot of the K-shell ionization cross section multiplied by B_K^2/Z_{eff}^2 versus V should define a universal function that depends only on V. This type of scaling has been found to work reasonably well for proton and alpha particle projectiles with Z_{eff} taken to equal the projectile atomic number (Z_1) [1].

In order to develop a scaling method applicable to heavy ions, cross sections were measured for K x-ray production in targets of Al, Ti, Cu, Zr, Ag, Sm, and Ta by Ar, Kr, and Xe ions ranging in energy from 2.5 to 25 MeV/amu. In addition, the degree of simultaneous L-shell ionization and the enhancement of the Kα diagram lines due to secondary ionization processes were assessed by performing high-resolution spectral measurements on Al, Ti, V, Co, and Cu targets. This information was used to correct for the Kα x-ray yield produced by secondary electron bombardment and photoionization, and to calculate the fluorescence yields needed to convert the Kα x-ray production cross sections into K vacancy production cross sections. The results of these measurements are described in Ref. [2].

In the case of heavy ion projectiles, the goal of providing a convenient scaling method for estimating K x-ray production cross sections is obscured by the fluorescence yield factor (which depends on the degree of multiple ionization) since its calculation is difficult and relies on a number of untested approximations and assumptions. Therefore, in the present treatment, it was decided to replace the calculated fluorescence yield $\omega_{K\alpha}$ with the single vacancy fluorescence yield ω_0 and, in effect, consider it to be part of the overall scaling factor. It was found that the B_K^2/ω_0 scaling factor is quite effective in accounting for the target dependence of the cross sections.

In seeking to account for the projectile dependence of the Kα x-ray production cross sections, the following procedure was found to provide values for Z_{eff} that gave reasonably good projectile scaling. Because the Al data points sampled the highest V region, where the V dependence is nearly constant, the four cross sections measured at 10, 15, 20, and 25 MeV/amu were chosen to establish the average Z_{eff} normalization factors, which were defined as

$$Z_{eff} = \{\sigma_{K\alpha}(Z_1)/[\omega_0\sigma_K(1)]\}^{1/2}, \qquad (1)$$

where $\sigma_{K\alpha}(Z_1)$ is the measured Al Kα x-ray production cross section for a projectile with atomic number Z_1 and $\sigma_K(1)$ is the Al K-shell ionization cross section predicted by the ECPSSR theory for protons. The fully scaled cross sections are shown in Fig. 1 as a function of V. It is found that multiplying the

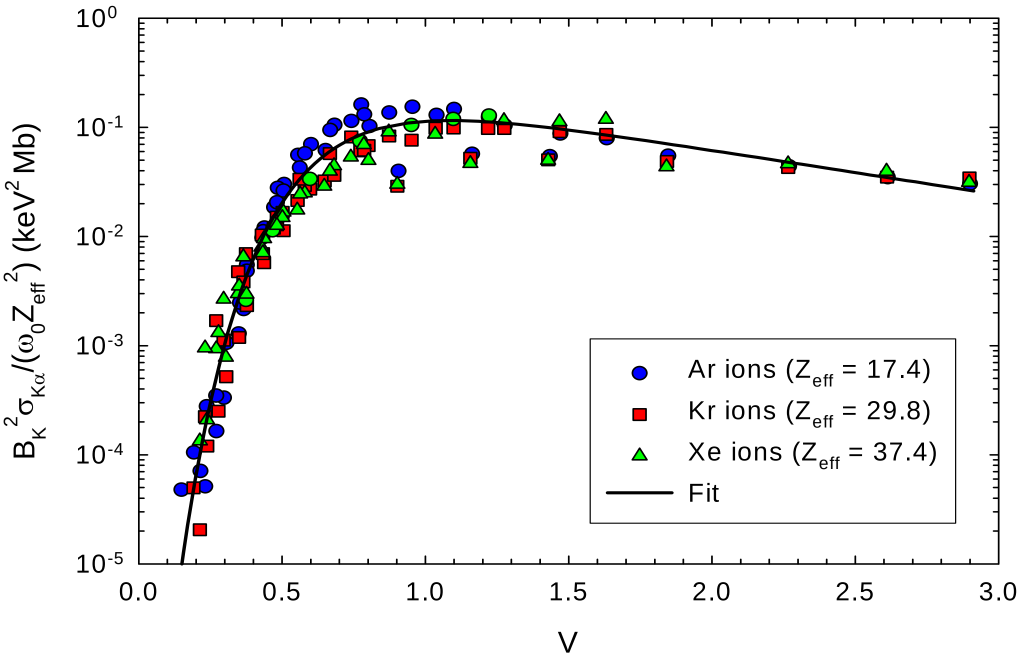

Figure 1. The fully scaled Kα x-ray production cross sections as a function of speed ratio. A semiempirical "universal" curve has been fit to the data points.

measured K x-ray production cross sections by $B_K^2/(\omega_0 Z_{eff}^2)$ has the remarkable effect of grouping most of the data points for all three projectiles along a "universal" curve. A fit to the data points (which excluded the Al points for the measurements at 2.5, 4, and 6 MeV/amu) using an extreme value four parameter tailed function [3] is shown by the solid curve in Fig. 1. The equation of this curve is

$$F(V) = a_0 \exp(B) \quad (2)$$

where $B = (1/a_2a_3)\{-V + a_1 + a_2 - a_2a_3 \exp[-(V + a_2 \ln a_3 - a_1)/a_2]\}$

with $a_0 = 0.113262$, $a_1 = 1.069489$, $a_2 = 0.233611$, and $a_3 = 4.485867$. The average absolute deviation of the Kα x-ray production cross sections calculated using Eq. (2) from the experimental cross sections is $(26\pm9)\%$.

A graph of Z_{eff} versus Z_1 is shown in Fig. 2. The error bars on the data points for Ar, Kr, and Xe represent the standard deviations from the average values of Z_{eff} determined using the four Al cross sections. The other data points in Fig. 2 were calculated using Al cross sections from a previous study [4] at 10 MeV/amu that were re-evaluated to include the double K-vacancy production contributions. The equation of the fitted solid curve in this figure is

$$Z_{eff} = 46.29[1 - \exp(-0.0256Z_1)]. \quad (3)$$

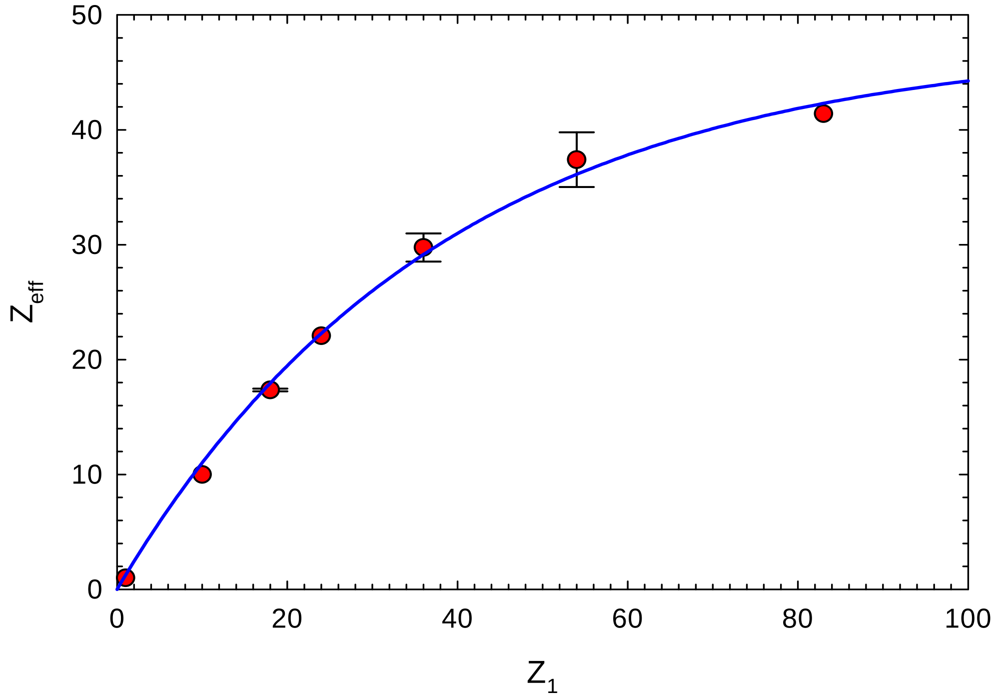

Figure 2. A graph showing the dependence of the projectile effective charge on the projectile atomic number. The solid curve has been fit to the data points.

[1] P. Richard, *Atomic Inner-shell processes* (edited by B. Crasemann), Academic Press, New York, Vol. I, p. 73 (1975).

[2] R. L. Watson, Y. Peng, V. Horvat, and A. N. Perumal, Phys. Rev. A **74**, 062709 (2006).

[3] R. L. Watson, V. Horvat, J. M. Blackadar, and K. E. Zaharakis, Phys. Rev. A **62**, 052709 (2000).

[4] *Peakfit peak separation and analysis software*, version 4.0, AISN Software Inc., Jandel Scientific, 2591 Kerner Blvd., San Rafael, CA 94901 (1995).