Single and multiple *L*-shell ionization by fast heavy ions

V. Horvat, R. L. Watson, Y. Peng, J. M. Blackadar

Spectra of *L* x rays emitted from a variety of solid targets (atomic number Z_2 = 49-67) under bombardment by fast heavy ions (atomic number Z_1 = 10-54) at 6-15 MeV/amu were measured in high resolution using a curved crystal spectrometer equipped with a LiF crystal. The spectra were measured in the first order of reflection and then analyzed in order to examine the systematics of *L* x-ray satellite structure [1]. In this report the focus is on multiple *L*-shell ionization.

The measured spectra were described in terms of a background function (a straight line) and peaks having Voigt profiles. The method of analysis was similar to the one used previously for spectra of Ho *L* x rays measured in the second order of reflection [2]. The procedure was somewhat simplified due to the fact that the distributions of *L* x-ray satellite peaks for a given transition type showed no evidence of underlying structure in all but a few of the measured spectra. On the other hand, the fitting function was amended in order to take into account the effects of the absorption edges.

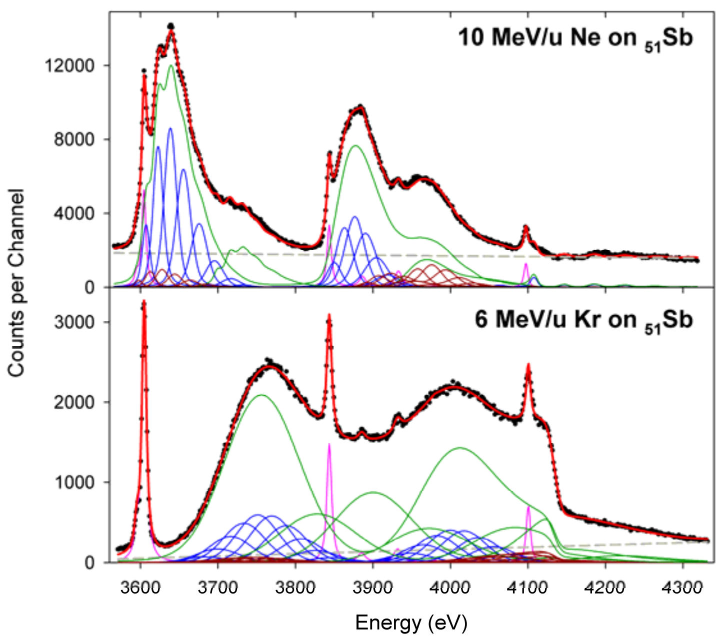

Figure 1. Solid circles: Measured spectra of Sb *L* x rays obtained under bombardment of a thick solid Sb target by 10 MeV/amu Ne (top) and 6 MeV/amu Kr ions (bottom). Lines: Overall fitting function (red) and its components (blue, brown, green, and gray).

Two examples of the fitted spectra (those obtained with 10 MeV/amu Ne on Sb and 6 MeV/amu Kr on Sb) are shown in Figure 1. Measured numbers of counts are shown as solid black circles, while the red line represents the overall fit. The background is shown as a dashed gray line, while the pink lines outline the combined contributions from the diagram x rays. $L\alpha_1$, $L\beta_1$, $L\beta_6$, and $L\beta_2$ x-ray satellites are shown in blue, $L\alpha_2$, $L\beta_{15}$, $L\eta$, $L\beta_3$ and $L\beta_4$ x-ray satellites are shown in and brown, while the green lines represent the combined contributions from all the *L* x-ray transitions involving *n* *L* vacancies in the initial state (i.e., the L^n components, where n = 1, 2, 3, …).

The spectrum of Sb *L* x rays induced by 10 MeV/amu Ne projectiles shows L^n components for n = 1 and 2, but there is no evidence of contributions from components having $n > 2$. In contrast, the spectrum obtained with 6 MeV/amu Kr projectiles clearly exhibits L^n components with n ranging from 1 to 4.

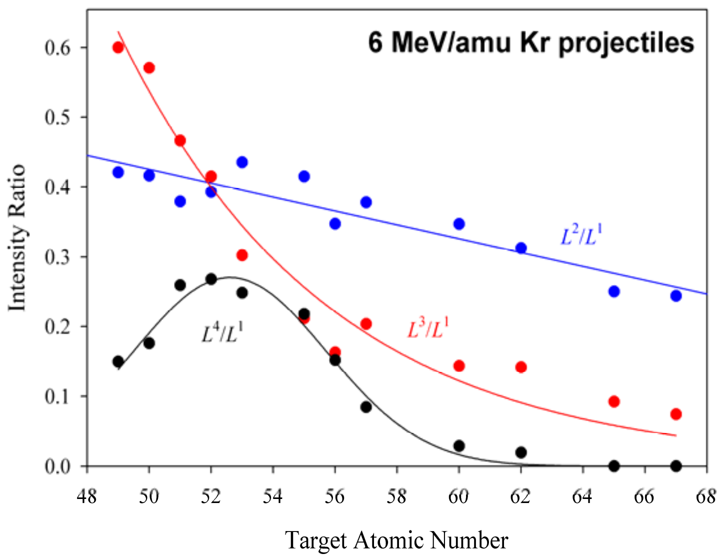

Figure 2. Relative intensities of L^n x-ray components as a function of target atomic number for 6 MeV/au Kr projectiles.

In the spectrum shown at the bottom of Figure 1, the L^3 component is more intense than the L^2 component. This is somewhat surprising, since it is expected that the cross section for n-fold L-shell ionization monotonically decreases as n increases. A tentative explanation for the observed effect might involve the effects of vacancy rearrangement between the time of L-shell ionization and L x-ray emission, combined with the n-dependence of the L x-ray fluorescence yield.

For 6 MeV/amu Kr projectiles, the dependence of L^n component relative intensities on the target atomic number is shown in Figure 2. Relative to the L^1 component, the L^2 component decreases in intensity as the target atomic number increases. This dependence appears to be linear. In contrast, the intensity ratio of L^3 to L^1 component decreases much faster as a function of Z_2 and exceeds the intensity ratio of L^2 to L^1 at $Z_2 < 52$. The intensity ratio of the L^4 to L^1 component, on the other hand, seems to peak around the value of $Z_2 = 52$, where the intensity ratios L^3 / L^1 and L^2 / L^1 are equal.

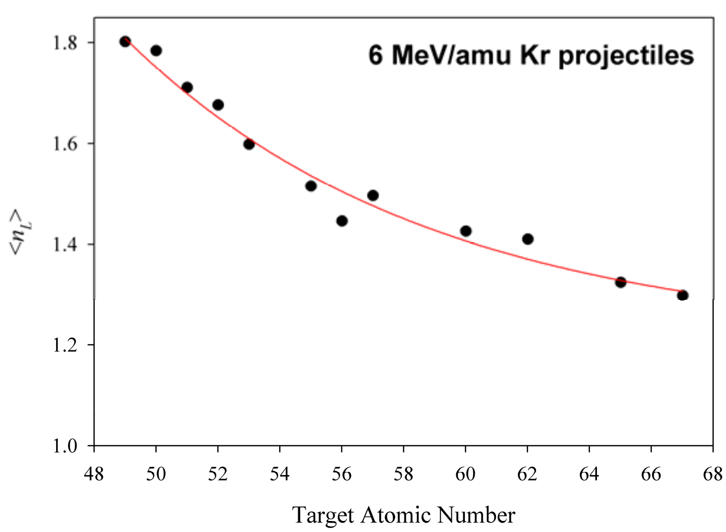

Figure 3. Apparent average number of L vacancies at the time of L x-ray emission as a function of target atomic number for 6 MeV/amu Kr projectiles.

The dependence on target atomic number of the apparent average number of L vacancies at the time of L x-ray emission ($<n_L>$) for 6 MeV/amu Kr projectiles is shown in Figure 3. This average value was calculated from the raw intensities of the L^n components. The red line in

Figure 3 represents the best-fit exponential decay curve.

The dependence on projectile atomic number of the apparent average number of *spectator L* vacancies at the time of *L* x-ray emission ($<n_L>$ - 1) for Sb target is shown in Figure 4. The blue and red circles represent the results of measurements with 10 MeV/amu and 6 MeV/amu beams, respectively. The lines represent best fits of logistic curves. More measurements are needed to establish whether logistic curves adequately represent the data points over a wider range of projectile atomic numbers and energies.

[1] V. Horvat *et al.*, *Progress in Research*, Cyclotron Institute, Texas A&M University (2006-2007), p.

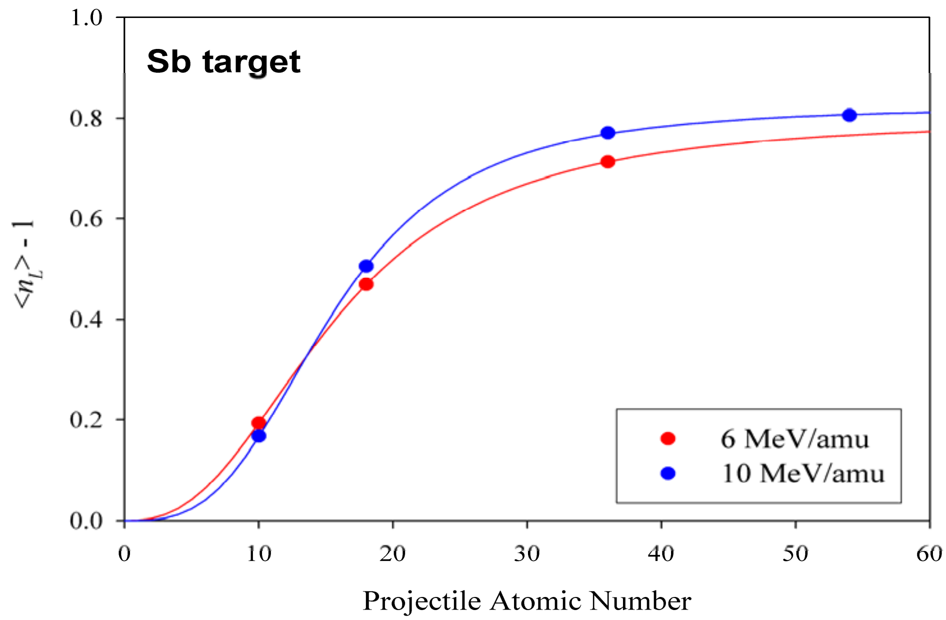

Figure 4. Projectile atomic number dependence of the apparent number of spectator *L* vacancies at the time of *L* x-ray emission.

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[2] V. Horvat, R. L. Watson, J. M. Blackadar, A. N. Perumal, and Yong Peng, Phys. Rev. A **71**, 062709 (2005).