PHYSICAL REVIEW A VOLUME 22, NUMBER 4 OCTOBER 1980

Energy dependence of $L\alpha$-to-Ll x-ray intensity ratios for Yb and Pb produced by heavy-ion bombardment

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(Received 27 February 1980)

Measurements of the incident-ion energy dependence of $L\alpha$-to-Ll x-ray intensity ratios are reported for protons incident at 0.40 to 2.20 MeV/amu on thin targets of Pb and for ^{4}He and C ions incident upon Yb. The data are compared to calculations of the $L\alpha$-to-Ll ratio which include the effects of alignment of the $2p_{3/2}$ state of the target.

Recent measurements of alignment effects associated with the emission of L-shell x-rays or L-shell Auger processes following high-velocity heavy-ion impact have been reported.[1-5] The work of Kamiya *et al.*[1] has addressed the energy dependence on the $L\alpha$-to-Ll x-ray intensity ratios for ^{1}H and ^{3}He impact. These authors report the following expressions for the $L\alpha$-to-Ll ratio which include the effects of alignment:

$$\frac{L\alpha}{Ll}=\frac{\Gamma^{\alpha_1}+\Gamma^{\alpha_2}}{\Gamma^{l}}\left[1+\left(1-\frac{5\Gamma^{\alpha_1}}{4(\Gamma^{\alpha_1}+\Gamma^{\alpha_2})}\frac{A_2}{5}\right)\right]\Big/\left(1-\frac{A_2}{4}\right) \tag{1}$$

and

$$\frac{L\alpha}{Ll}\simeq\frac{\Gamma^{\alpha_1}+\Gamma^{\alpha_2}}{\Gamma^{l}}(1+0.225\,A_2), \tag{2}$$

where Γ^{L_i} are the radiative widths and A_2 is the alignment parameter. The angular distributions of the Ll and $L\alpha$ radiation are given by

$$W_{L_i}(\theta)=[W_{L_i}(90°)/4\pi][1+\gamma_i A_2 P_2(\cos\theta)], \tag{3}$$

where $W_{L\alpha}(\theta)=W_{L\alpha_1}(\theta)+W_{L\alpha_2}(\theta)$, and L_i specifies a particular transition. The quantities γ_i are defined in Ref. 1 and $W_{L_i}(90°)$ is the x-ray intensity measured at $\theta=90°$, where θ is the angle between the beam and the direction of x-ray emission for the line of interest.

We have measured the absolute L-shell x-ray intensities per incident projectile for ^{1}H ions incident on Pb targets over an incident energy range of 0.40 to 2.20 MeV (a scaled velocity range of $0.13\lesssim v_1/\langle v_{L\,III}\rangle\lesssim 0.33$). This phase of the work was performed using the 2 Mv Van de Graaff accelerator of the Regional Nuclear Physics Laboratory at North Texas State University. The data for ^{4}He on Yb is from Gray *et al.*[6] and the data for ^{12}C on Yb was acquired[7] using the model EN tandem at Oak Ridge National Laboratory. All targets were transmission-mounted thin foils and the x-ray intensities were measured using Si(Li) detectors. All x-ray energy spectra were fitted using the computer code SAMPO[8] to extract the intensities of the Ll and $L\alpha$ x-ray transitions. Corrections were made to the measured x-ray intensities to account for the x-ray energy dependence of the overall detector efficiency. The relative error in the measured x-ray intensities was typically $\lesssim 3\%$.

The $L\alpha$-to-Ll ratios for ^{1}H ions incident upon Pb are given in Fig. 1. The data are compared to the results of Eq. (2) using radiative widths calculated by Scofield.[9] The values of A_2 were taken from Ref. 1. The data and calculations are in good agreement. The present measurements of $L\alpha$-to-Ll do not increase at the lower proton energies as reported by Busch *et al.*[10]

Shown in Fig. 2 are the measurements of $\lesssim L\alpha$-to-Ll for ^{4}He ions (0.3 to 4.2 MeV/amu and ^{12}C ions (0.5 to 2.67 MeV/amu) incident on thin Yb targets. The solid line is the calculation from Eq. (2) using the value of A_2 from Ref. 1 and radiative widths from Scofield.[9] In the case of

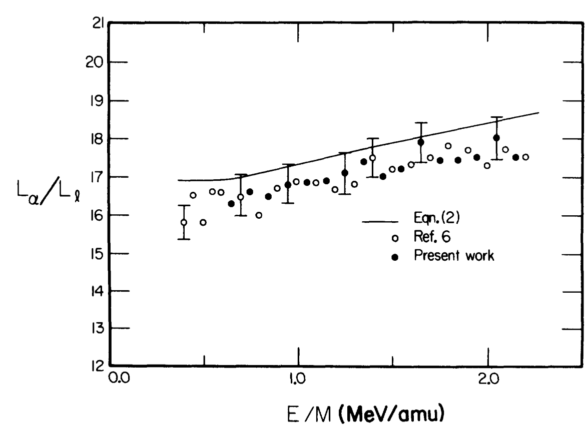

FIG. 1. The ratio of the $L\alpha$ and Ll x-ray production cross sections for Pb as a function of the incident proton energy. The errors indicated are the typical relative errors only.

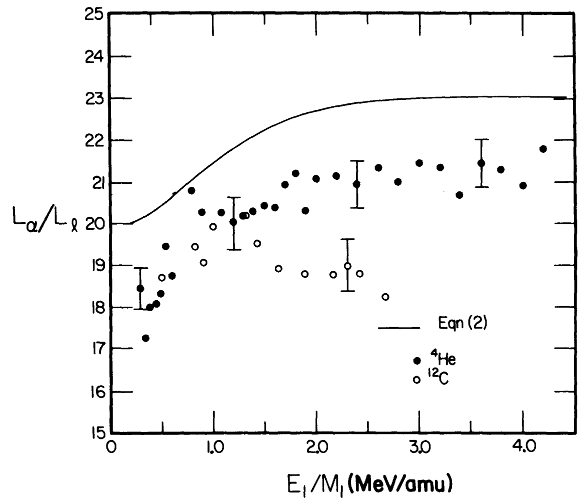

FIG. 2. The ratios of $L\alpha$ and Ll x-ray production cross sections for Yb as functions of incident energy for ^{4}He and ^{12}C ions. The errors indicated are the typical relative errors only.

^{4}He ions the energy dependence of the data and the calculations are in reasonable agreement. There is a slight increase in the differences between theory and experiment ranging from ~7% for the high-energy data to ~10% for the low-energy data. Similar behavior of the energy dependence in the comparisons of data and theory are reported by Kamiya *et al.*[1] The data for ^{12}C ions do not follow the predicted energy dependence at all. The ^{12}C data for $L\alpha$-to-Ll are essentially constant over the measured energy range. This feature of the $L\alpha$-to-Ll data for ^{12}C ions on Yb suggests that the angular distributions for the $L\alpha$ and Ll radiations may be isotropic. The effects of multiple ionization[11] may destroy the angular momentum coupling requirements which are invoked to establish alignment for transitions to $j=\frac{3}{2}$ states, i.e., the transitions may not be to a state with a well-defined angular momentum. Work is in progress to make direct measurements of the $L\alpha$ and Ll angular distributions for heavy-ion bombardment using Eq. (3) to extract alignment parameters directly in order to study the behavior observed for the $L\alpha$-to-Ll ratios observed in the present work.

ACKNOWLEDGMENTS

The partial support by the Faculty Research Fund (North Texas State University) of this work was appreciated. The assistance of B. Payne, G. H. Pepper, F. D. McDaniel, and P. D. Miller in the experimental phases of the work is acknowledged. This work was supported in part by the Division of Chemical Sciences, U. S. Department of Energy.

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