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Contribution of CK Transfer to Proton induced L Subshell X-Ray Production Cross-Sections for Direct and Indirect Vacancies

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The contribution of CK transfer to the proton induced L subshell X-ray production cross-sections due to both direct and indirect vacancies has been determined for the elements Pb & Th at incident proton energies ranging from 1 MeV to 10 MeV. The contribution for direct vacancies (without K to L transfer) was estimated by calculating the X-ray production cross-sections in absence of CK transfer, while for indirect vacancies, it was assumed that the L subshell X-rays were emitted only due to vacancies transferred from K to Li subshells. It has been observed that for X-rays resulting from direct vacancies, the contribution of CK transfer initially decreases with increase in energy and thereafter increases in both the cases. This contribution has been found to be up to 20% & 17% in Pb and Th respectively for Ll & Lα X-ray groups. In case of X-rays from indirect vacancies, there was no regular trend at lower energies and thereafter the contribution becomes almost constant.

Key Words: Coster-Kronig transfer, Proton ionization cross sections, Inner shell X-rays, Inner shell vacancies

INTRODUCTION

When vacancies are created in the inner shells, the X-rays resulting from these vacancies contain information on the concerned process responsible for creation of vacancy. However, it is seen that in all shells above K shell, some processes faster in time alter the initial primary vacancy distribution in different sub-shells of a shell before these vacancies are filled either through X-ray emission or Auger process. Due to these alterations, the emitted X-ray line / group may not directly reveal the information about the primary interaction process. The processes initiated after the primary vacancy creation, which result in alteration of the primary vacancy distribution in L and higher sub-shells, include the following.

- The direct vacancies in L, M and higher shells may be altered by the non-radiative Coster-Kronig and super-Coster-Kronig transitions which are much faster in time in comparison to the time involved in normal inter shell

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transitions.

- Similarly, if the energy of incident radiation or the transition energy of the vacancy creating radioactive process is higher than the lower shell / subshell (say K shell) and the X-ray line / group being measured is of higher shell (say L shell), then the lower to higher sub shell transitions (say K to L_i) being faster in time will alter the primary sub-shell vacancy status of the higher shell (say L shell).

Thus, it is seen that in measurements involving inner shells, the X-ray energies and intensities may not reveal true characteristics of the primary vacancies and the contribution of processes initiated after the primary interactions have to be properly taken care of.

In case of L subshell X-ray emission, the X-rays originate either due to the direct vacancies resulting from interaction of incident projectile with L subshell electrons or due to indirect vacancies resulting from the filling lower vacant levels. Very little work has been done for a detailed insight into the contribution of the vacancies initiated after the primary interaction processes leading to the X-ray emission. Rani *et al*[1] have investigated the effect of CK transitions on L_3 subshell X-ray fluorescence cross sections for some elements in the range $41 \le Z \le 92$. Allawadhi *et al*[2] have investigated the effect of Coster-Kronig transitions on average L shell fluorescence yields. Oz *et al*[3,4] and Ertugrul[5] have reported the measurements of Coster-Kronig enhancement factors of some elements in the range $66 \le Z \le 92$. Sogut[6] has reported the variation of enhancement effect of Coster Kronig transitions on L_3 X-rays of Ba, La & Ce compounds. Rohit Thakkar *et al*[7] have investigated the Coster Kronig transfer dependence of the L subshell X-ray Intensity ratios using protons as projectiles. In another work[8], the enhancement produced by the Coster–Kronig transitions for deuterons induced L subshell X-rays and the variation of the enhancement factors (namely k_l, k_α, k_β & $k\gamma$) with incident deuteron energy and the atomic number has been studied.

In the present work, the contribution of CK transfer to the proton induced L subshell X-ray production cross-sections due to both direct and indirect vacancies has been determined for the elements Th & Pb at incident proton energies ranging from 1 MeV to 10 MeV.

DETERMINATION OF THE COSTER KRONIG CONTRIBUTION

In the present investigation, the direct vacancies in the L subshells will result from the ionization of L subshells by the incident protons only (without the K to L transfer of vacancies). The cross-sections for the emitted L X-rays induced by protons can be determined by following relations

$$\sigma L_l = \left[\sigma L_1 \left(f_{12} f_{23} + f_{13}\right) + \sigma L_2 f_{23} + \sigma L_3\right] w_3 F_{3l} \quad \text{---------(1)}$$

$$\sigma L_\alpha = \left[\sigma L_1 \left(f_{12} f_{23} + f_{13}\right) + \sigma L_2 f_{23} + \sigma L_3\right] w_3 F_{3\alpha} \quad \text{---------(2)}$$

$$\sigma L_\beta = \sigma L_1 w_1 F_{1\beta} + \left[\sigma L_1 f_{12} + \sigma L_2\right] w_2 F_{2\beta} + \left[\sigma L_1 \left(f_{12} f_{23} + f_{13}\right) + \sigma L_2 f_{23} + \sigma L_3\right] w_3 F_{3\beta} \quad \text{---------(3)}$$

$$\sigma L_\gamma = \sigma L_1 w_1 F_{1\gamma} + \left[\sigma L_1 f_{12} + \sigma L_2\right] w_2 F_{2\gamma} \quad \text{---------(4)}$$

Here, σL_i (where i=1-3) represent the proton ionization cross-sections for the L_i subshells. The w_i's represent the L_i subshell fluorescence yields and f_{12}, f_{13} & f_{23} are the Coster Kronig transition probabilities for the L subshells. The F_{ij}, in these equations (1-4), are the fractional radiative decay rates for different L X-ray groups namely L_l, L_α, L_β and L_γ keeping in view the resolution of the presently available X-ray detectors.

The L subshell X-ray production cross-sections σL_l, σL_α, σL_β and σL_γ for direct vacancies were evaluated from the L subshell ionization cross sections[9] (σL_i), L subshell fluorescence yields & Coster-Kronig transition probabilities[10] (f_{ij}) and radiative decay rates (F_{ij})[11] using above equations (1-4) at incident proton energies ranging from 1 MeV to 10 MeV. The contribution of
CK transfer for direct vacancies (without K to L transfer) was estimated by calculating the X-ray production cross-sections in absence of CK transfer. The CK contribution was estimated as the percentage deviation between the X-ray production cross-sections in the presence and in absence of CK transitions.

The X-ray production cross-sections for the indirect vacancies only have been estimated by assuming the L subshell X-rays emitted only due to vacancies transferred from K to L_i subshells using following relations (5-8)

$$\sigma L_l = \left[\left(\sigma K\, n_{KL_1}\right)\left(f_{12} f_{23} + f_{13}\right) + \left(\sigma K\, n_{KL_2}\right) f_{23} + \left(\sigma K\, n_{KL_3}\right)\right] w_3 F_{3l} \quad \text{-------(5)}$$

$$\sigma L_\alpha = \left[\left(\sigma K\, n_{KL_1}\right)\left(f_{12} f_{23} + f_{13}\right) + \left(\sigma K\, n_{KL_2}\right) f_{23} + \left(\sigma K\, n_{KL_3}\right)\right] w_3 F_{3\alpha} \quad \text{-------(6)}$$

$$\sigma L_\beta = \left(\sigma K\, n_{KL_1}\right) w_1 F_{1\beta} + \left[\left(\sigma K\, n_{KL_1}\right) f_{12} + \left(\sigma K\, n_{KL_2}\right)\right] w_2 F_{2\beta} + \left[\left(\sigma K\, n_{KL_1}\right)\left(f_{12} f_{23} + f_{13}\right) + \left(\sigma K\, n_{KL_2}\right) f_{23} + \left(\sigma K\, n_{KL_3}\right)\right] w_3 F_{3\beta} \quad \text{------(7)}$$

$$\sigma L_\gamma = \left(\sigma K\, n_{KL_1}\right) w_{1 F_{1\gamma}} + \left[\left(\sigma K\, n_{KL_1}\right) f_{12} + \left(\sigma K\, n_{KL_2}\right)\right] w_2 F_{2\gamma} \quad \text{------(8)}$$

Where, all the terms have the same meaning as explained above for equations 1-4. The K to L_i vacancy transfer probabilities, n_{KLi}, used in the above calculations have been take from the tables of Rao *et al*[12]. The CK transfer contribution was estimated as above by calculating the percentage deviation between two sets of subshell production cross sections obtained by taking the CK transfer probabilities as zero.

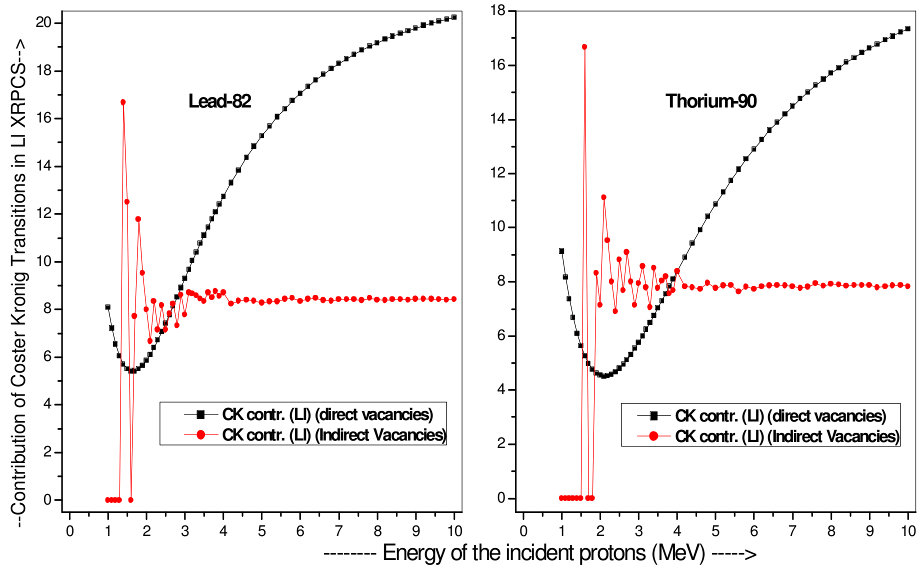

Fig. 1 : Plots of the contribution of Coster Kronig Vacancy transfer in Ll X-ray production cross-sections due to direct & indirect vacancies for Pb & Th against incident proton energies ranging from 1 MeV to 10 MeV.

RESULTS AND DISCUSSION

The CK transfer contribution to both direct and indirect proton induced L subshell vacancies in Thorium and Lead obtained by the procedure as explained above were plotted against the incident proton energies. The typical plots of CK transfer contribution to the L_l X-ray production cross sections due to direct and indirect vacancies in Th & Pb are shown in Fig.1.

From the results, it has been observed that for X-rays resulting from direct vacancies, the contribution of CK transfer initially decreases with increase in energy and thereafter increases in both the cases. This contribution has been found to be up to 17% & 20% in Th and Pb respectively for $L_{l\ \&}$ L_α X-ray groups. However, it was interesting to note that in case of X-rays from indirect vacancies, there was no regular trend at lower energies i.e. up to 4-5 MeV, but, thereafter, the contribution becomes almost constant and does not depend much on incident proton energy.

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