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L x-ray production in $_{57}$La, $_{58}$Ce, $_{60}$Nd and $_{62}$Sm by 35–60 MeV carbon and oxygen ions

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Abstract

L x-ray production cross sections have been measured for thin solid targets (~50 μg/cm^2) of $_{57}$La, $_{58}$Ce, $_{60}$Nd and $_{62}$Sm for 35–60 MeV C^{4+} and O^{5+} ions. There is an increase in these cross sections with the increasing projectile energy and the ratio of its atomic number to the atomic number of the target nucleus (Z_1/Z_2). The measured L x-ray production cross sections have been compared with the predicted values of the first Born approximation (FBA) and of the ECPSSR theory that accounts for the projectile energy loss and Coulomb deflection and the perturbed stationary-state and relativistic nature of the L-shell. For C^{4+} ions, there is a reasonable agreement with the ECPSSR predicted values for the higher Z elements (Nd and Sm), while for the lower Z elements (La and Ce), the FBA is in a better accord with the data. For O^{5+} ions, the FBA gives a better agreement for all the elements than the ECPSSR theory.

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Keywords: L-shell; Cross section; HPGe; Lanthanum; Cerium; Neodymium; Samarium; Carbon ions; Oxygen ions; First Born approximation; ECPSSR; MeV; Ion-atom collisions

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1. Introduction

In heavy-ion-atom collisions, an inner shell vacancy is produced due to the direct ionization (DI) as well as from the electron capture (EC) by an

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Table 1
A survey of L-shell x-ray production measurements for C and O ions

Projectile	Target	Energy range	Type of x-ray measurements	Reference (year)
O	Ag, Au	12–50 MeV	L_{total}, L_α/L_β, and L_α/L_γ ratios	Bissinger et al. [7] (1974)
O	Ce, Pr, Sm, Eu, Dy, Ho	8–36 MeV	L_{total}, L_l, L_α, $L_{\beta1}$, $L_{\beta2}$, $L_{\gamma1}$, $L_{\gamma2,3}$	Pepper et al. [8] (1975)
C,N,O	Au	0.4–3.4 MeV	$L_{subshells}$, L_{total}	Sarkadi and Mukoyama [9] (1980)
C,O	Nd, Gd, Ho, Yb, Au, Pb	25 MeV C ($q = 4,5,6$), 32 MeV O ($q = 5,7,8$)	L_{total}	Andrews et al. [10] (1987)
Li, Be, C, N, F, Si	Yb, Au	0.5–3.0 MeV/u for Li, Be, C, F; and 0.5–2.6 MeV/u for N, Si	$L_{\alpha1,2}$, $L_{\gamma1}$, $L_{\gamma2,3,(6)}$	Malhi and Gray [11] (1991)
C	Cu, Ga, Ge, Br, Y, Nd, Gd, Ho, Yb, Au, Pb	2–25 MeV	L_{total}	Mehta et al. [12] (1993)
C,O	Au, Bi	3.6–9.5 MeV for C, 4.0–7.2 MeV for O	L_1, L_2, L_3, L_η, L_l, L_α, L_β, $L_{\gamma5}$, $L_{\gamma1}$, $L_{\gamma2,36}$, $L_{\gamma44'}$ L_{total}	Bhattacharya et al. [13] (1994)
C	La, Ce, Pr, Nd, Sm, Eu, Dy, Er	0.4–2.8 MeV/amu	L_1, L_2, L_3	Braziewicz et al. [14] (1994)
O, Ni	Au	60–72 MeV for O, 58–87 MeV for Ni	L_η, L_l, L_α, $L_{\beta1}$, $L_{\beta4}$, $L_{\beta2,15,3}$, $L_{\beta5,7}$, $L_{\gamma1}$, $L_{\gamma2,36}$	Goyal et al. [15] (1995)
C,N	Hf, Ta, W, Os, Ir, Pt, Au, Bi, Th	0.4–1.8 MeV/amu	L_1, L_2, L_3	Semaniak et al. [16] (1995)
O	Ni, Cu, Zn, Ga, Ge	12 MeV	L_{total}	Yu et al. [17] (1999)
O	Au, Bi, Th, U	6.4–70 MeV	L_1, L_2, L_3, $L_{\alpha1,2}$, $L_{\gamma1}$, $L_{\gamma23}$	Pajek et al. [18] (2003)
C	Re, Pt, Au	4–8 MeV	L_1, L_2, L_3, L_α, L_β, L_γ, $L_{\gamma2,3}$, $L_{\gamma44'}$	Lapicki et al. [19] (2004)
C	Ce, Nd, Lu	4–10 MeV	L_1, L_2, L_3, L_1, L_α, L_β, $L_{\gamma15}$, $L_{\gamma2,3}$, $L_{\gamma44'}$	Lapicki et al. [20] (2005)

ionic projectile. The DI mechanism is dominant when $Z_1 \ll Z_2$ and $v_1 \gg v_{2S}$, while the EC process dominates if $Z_1 \leqslant Z_2$ and $v_1 \leqslant v_{2S}$, where Z_1 and Z_2 are the atomic numbers of the projectile and the target atom, and v_1 and v_{2S} are the velocities of the projectile and the target inner-shell (S = K-, L-shell) electrons. The first-order Born approximation (FBA) describes the process using the plane wave Born approximation (PWBA) [1] for DI and the Oppenheimer–Brinkman–Kramers approximation of Nikolaev (OBKN) [2] for EC, whereas the ECPSSR theory for DI [3] and EC [4] accounts for the energy loss (E), Coulomb deflection (C) of the incident ion as well as for the perturbed stationery states (PSS) and the relativistic (R) nature of inner shell electrons.

A large database for the L-shell ionization by protons and light ions exists in the literature [5,6], whereas it is scarce for heavy-ion projectiles. Only a few measurements are available in the literature on the study of the L-shell ionization by carbon and oxygen ion beams for energies $E_1 \geqslant 30$ MeV. Table 1 surveys the published data on L-shell x-ray production by heavy-ion beams [7–20]. At energies above 30 MeV, the reports [7,8,10–12,15,18] of experimental x-ray production cross-sections are indeed rare. In the present work, L-shell x-ray production cross sections have been measured with thin (47–59 μg/cm^2) solid targets of $_{57}$La, $_{58}$Ce, $_{60}$Nd and $_{62}$Sm for 35–60 MeV C^{4+} and O^{5+} ions. For this range of projectile-target systems, the 36 MeV O^{5+}on $_{58}$Ce and $_{62}$Sm cross sections are the only other data [8]. The measured x-ray production cross sections are compared with the predictions of the FBA [1,2] and ECPSSR [3,4] theories, and the data of Pepper et al. [8] from three decades ago.

2. Experimental details and data evaluation

The experiment was performed with 15 UD pelletron at Nuclear Science Centre (NSC), New Delhi, India. The carbon and oxygen beam having