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L x-ray production cross sections in high-Z atoms by 3–5 MeV/u silicon ions

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A B S T R A C T

Total L x-ray production cross sections have been measured in $_{74}W$, $_{79}Au$, $_{82}Pb$, and $_{83}Bi$ by impact of 3–5 MeV/u ^{28}Si ions, with different charge states q = 8^+ up to 12^+. We find that the measured cross sections do not differ with the charge state of the projectile ions, but they vary with the beam energies. The experimental data has been compared with three theoretical results, ECUSAR, ECPSSR and SLPA by using the multiple-hole fluorescence and Coster-Kronig yields. The comparison has showed the best agreement with the ECUSAR. The SLPA results also describe the experiments quite well for $_{74}W$, $_{79}Au$ and $_{83}Bi$, but certain differences are observed for $_{82}Pb$, while the ECPSSR values underestimate by up to a factor two. Surprisingly, the theoretical-experimental agreement is better at low beam energies than in the high beam energy side.

1. Introduction

The measurement of inner-shell ionization of heavy targets by ion impact has led to advances in radiation [1], plasma [2], atomic and nuclear physics [3], and in particle induced x-ray emission (PIXE) technique [4,5]. Since the inception, PIXE mostly has made use of the light ions such as protons and alphas [6–16], nevertheless the use of heavy ions for the PIXE analysis is increasing due to advantage of higher cross sections and hence the scope of achieving the better sensitivity [17]. Discrepancies observed between the theories and experiments have often been ascribed to the multiple ionization even experiments done with the protons [18]. Though the multiple-ionization effect has been known for a long while in L-shell ionization by the heavy ion impacts [19–35], however, this effect is still rarely used in the analysis for the x-ray emission in view of the elemental analysis.

The inner shell ionization of a target (atomic number Z_T) by a projectile (atomic number Z_P) is the effect of two contributions: the direct ionization (DI) (a target bound electron ends in the continuum) and the electron capture (EC) (electron transfer from the target to a bound state of the projectile). In asymmetric collisions, $Z_P/Z_T \ll 1$, the DI is the main contribution, while for symmetric collisions, $Z_P/Z_T \sim 1$, the EC is also important. In this contribution we have the double aim of contributing to the experimental knowledge of the L-shell ionization of very heavy targets (W, Au, Pb and Bi) by a heavy ion (^{28}Si); and for a meaningful comparison with existing ionization theories. We selected two completely different formalisms for the theoretical comparison, the well-known ECPSSR [36] and ECUSAR [37] theories, within the binary collisional formalism, and the shellwise local plasma approximation (SLPA) [38,39], which is a many electron model within the dielectric formalism. The collisional systems measured here correspond to asymmetric collisions, i.e. $0.15 \le Z_P/Z_T \le 0.18$, but less asymmetric than that used for a previous work [35].

In Section 2, we present the experimental description for the L x-ray production cross-sections in thin solid targets ionized by the swift ^{28}Si ions. The impact velocities are much lower than the orbital velocity of the L-shell electrons in the target atom, $v_T = (Z_T–4.15)/2$ and the velocity ratio v_P/v_T remains in the bound $0.026 \le v_P/v_T \le 0.043$. In Section 3, we briefly describe and comment on the theoretical models considered in the present work. Section 4 gives the effects of the single- and multiple-hole atomic parameters required for conversion of the ionization cross sections to the x-ray production cross sections, and Section 5 summarizes the results.

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2. Experimental details and data analysis

The L x-ray production cross sections were measured in the $_{74}$W, $_{79}$Au, $_{82}$Pb, and $_{83}$Bi elements by the ^{28}Si ions (charge states = 8+ and 12+) in the energy range 84–140 MeV. The measurements were performed using the 15 UD Pelletron accelerator at Inter-University Accelerator Centre (IUAC), New Delhi. Pure (99.99%) targets of $_{79}$Au, $_{82}$Pb, and $_{83}$Bi (thickness 120 μg/cm^2) were prepared on the 20 μg/cm^2 carbon backing using the vacuum deposition technique [40]. Thin and spectroscopically pure (99.999%) targets of $_{74}$W with 193 μg/cm^2 on Mylar backing (3 μm), procured from Micromatter, Deer Harbor, Washington, USA was also used in the present work. The energy loss for the incident beam within the target was negligibly small for the target thickness and beam energies used in the present work. Estimated the energy loss by projectile ion in the target material was < 0.5% in most cases except ~1% for $_{74}$W at 84 MeV only. A Si(Li) solid state detector (thickness = 5 mm, diameter = 10 mm, 25 μm Be window from ORTEC, Oak Ridge, Tennessee, USA) was placed in the horizontal ion beam plane configuration outside the vacuum chamber at an angle of 125° to the beam direction and a distance of 170 mm from the target. In the energy range of the measured L x-ray spectra, the energy resolution of the detector was ~200 eV for the Mn Kα x rays. The energy calibration of the detector was performed before and after the measurements using the radioactive ^{55}Fe, ^{57}Co and ^{241}Am sources. The chamber was maintained with a pressure about 10^{-6} Torr. Details of the experimental setup are given in Kumar et al. [35].

A typical L x-ray spectrum from the elemental target of $_{82}$Pb ionized by the 140 MeV ^{28}Si ions is shown in Fig. 1. The spectrum exhibits peaks corresponding to the ionized Li (i = 1–3) subshells. The intense components of the x rays for the elements, viz., Lℓ, Lα1,2, and Lβ2,15 from the L3 subshell, the Lη, Lβ1 and Lγ1,5 from the L2 subshell, and the Lβ3,4 and Lγ2,3 from the L1 subshell, are labeled in the spectrum. The spectrum in semi-log plot shows the weak appearance of Lη and Lγ5. The ratios of net counts for all the lines to the background counts as subtracted by the exponential background (dashed curve) from the spectrum are 0.443, 0.038, 0.096, and 0.215 for Lℓ, Lα, Lβ, and Lγ, respectively. Fig. 2 shows L x-ray spectra of $_{74}$W, $_{79}$Au, $_{82}$Pb, and $_{83}$Bi target excited by the ^{28}Si ion beam at 107 MeV energies. The fluorescence transitions from the Li subshells along with the x-ray energies for various elements are given in Table 1.

The L x-ray production cross section is calculated using the

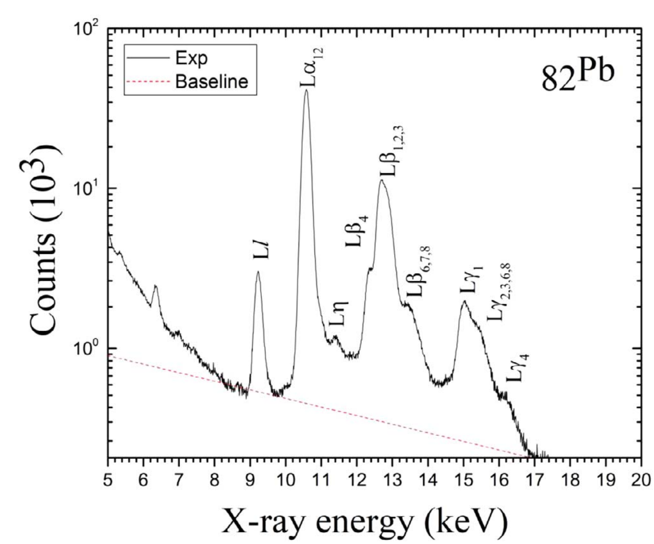

Fig. 1. L x-ray spectra of $_{82}$Pb bombarded with the 140 MeV ^{28}Si ions. The dashed curve exhibits the background due to Compton scattering in the relatively thick (5 mm) detector. As discussed in Section 2, the background amount to < 9% of extracted net x-ray counts except the Lℓ and Lγ line.

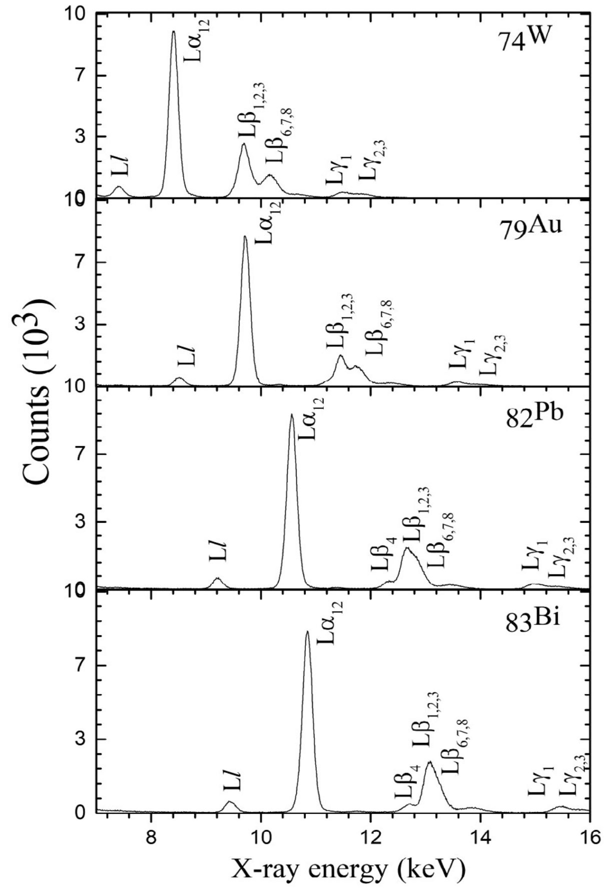

Fig. 2. L x-ray spectra from $_{74}$W, $_{79}$Au, $_{82}$Pb, and $_{83}$Bi bombarded with 107 MeV ^{28}Si ions.

Table 1
L x-ray fluorescence transition along with the energies for various elements used in the present work.

Fluorescence transition (subshell)	x-ray Energy (keV)			
	$_{74}$W	$_{79}$Au	$_{82}$Pb	$_{83}$Bi
Lℓ (L_3)	7.387	8.494	9.184	9.420
$L\alpha_{1,2}$ (L_3)	8.367	9.671	10.501	10.786
$L\eta$ (L_2)	8.724	10.309	11.349	11.712
$L\beta_1$ (L_2)				
$L\beta_3$ (L_1)	9.674	11.431	12.593	12.999
$L\beta_4$ (L_1)	9.524	11.024	12.306	12.69
$L\beta_{2,15}$ (L_3)	9.956	11.576	12.612	12.968
$L\gamma_{1,5}$ (L_2)	11.286	13.382	14.765	15.248
$L\gamma_{2,3,4}$ (L_1)	11.784	13.939	15.365	15.863

following relation:

$$\sigma_i^x = \frac{Y_i^x A \sin\theta}{N_A \varepsilon_p n_p t\beta} \quad (1)$$

where Y_i^x is the intensity of the *i*th x-ray peak, A is the atomic weight of the target, θ is the angle between the ion beam and the target, N_A is the Avogadro's number, $\sigma_i^x(E)$ (in cm^2) is the x-ray production cross section of *i*th x-ray line at the incident projectile energy (E), ε_p is the absolute detector efficiency, including the absorbing component of Mylar foil used at the window as shown in Fig. 3, and n_p is the number of incident projectiles. Since the inner-shell ionization also depends on the charge state (q) of the projectile ion because for the bare projectiles with no K shell electron or projectile ions with one K shell vacancy, the electron capture contributes considerably to the ionization, whereas, capture is not much while low positive charge states are used for the incident ions;