$L_i(\alpha, \beta, \gamma, \ell)$ subshell X-ray production cross-sections and theirs emission ratio in Pb and Au for proton energy 1-2.5 MeV

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Abstract The $L_i(\alpha, \beta, \gamma, \ell)$ subshell X-ray production cross-sections for Pb and Au were measured at incident proton energy between 1 to 2.5 MeV. The obtained data are compared to available data given in Sokhi and Crumpton [1] and Orlic and al.[2] compilations. The given data are also compared with the predictions of ECPSSR model [3]. The comparison shows a good agreement.

Key words: $L_\alpha$, $L_\beta$, $L_\gamma$ and $L_\ell$ X-ray cross-section, emission ratio.

1. Introduction

L-Outer shell ionisation of atoms by protons was studied extensively in the last few years. The knowledge of proton induced X-ray production cross-sections is very important for a considerable number of experimental and theoretical applications like inner shell ionisation process by proton impact. For theoretical predictions of L- subshell X-ray production cross sections, we have used ECPSSR model [3] which is based on PWBA Model [4] corrected by Coulomb deflection effect (C) [5], loss Energy effect (E) [6], Relativistic effect (R) [7] and Perturbed Stationary State (PSS) effect [8].

In this paper, we give new measurements of $L_i(i=\alpha, \beta, \gamma$ and $\ell)$ X-ray emission cross sections for Au and Pb under proton impact in the energy range 1 to 2.8 MeV. We report also the X-emission ratios $L_\alpha/L_\beta$, $L_\alpha/L_\gamma$, $L_\beta/L_\gamma$ and $L_\alpha/L_\ell$. Comparison of the present work with the available experimental data [1,9,10] and with the theoretical calculations by ECPSSR model is done.

2. Experimental set-up

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The measurements were performed at a 4 MV Van de Graaff Accelerator, with an incident beams of 2 mm diameter. A current of 12 nA was used to avoid the damage of the target. Au and Pb samples of 100 μg/cm² thickness were prepared by evaporation on 30 μg/cm² carbon substrates. The experiment was carried out using PIXE and RBS techniques simultaneously in order to eliminate the integrated charge and target thickness and to reduce experimental uncertainties which can become part from these two factors. Targets were positioned at 45° to the incident beam direction and to the Si(Li) detector used for collecting the X-rays. A Si surface barrier detector for the backscattered protons was placed at 170° to the beam direction. X-rays emitted from target pass through a Mylar window an air gap and beryllium window before reaching the Si(Li) detector placed outside the reaction chamber. The L_i (α, β, γ and ℓ) subshell X-ray production cross-sections for individual X-ray lines at an incident proton energy, E_p, is given by

\[ \sigma_{L_i}^X = 4\pi \sigma_R \frac{N_x^i \Omega_R}{N_R^i \Omega_x \varepsilon_x F} \]

where \( N_x^i \) and \( N_R^i \) are the measured X-ray counts in the characteristic i (i = α, β, γ, •) peak and protons backscattered by the target, respectively. \( \varepsilon_x \) is the X-ray detector efficiency. \( \sigma_R \) is the Rutherford scattering cross section. \( \Omega_x \) and \( \Omega_R \) are the solid angles of the X-ray and the surface barrier detectors, respectively. \( F \) is the factor for the X-ray absorption in the windows and air between the target and the Si(Li) detector. \( N_x^i \) values were determined from the experimental spectrum using AXIL program. The number of backscattered protons, \( N_R^i \), was obtained by summing the counts in the RBS peak.

3. Results and discussion

The measurements were performed at selected energies ranging from 1 to 2.5 MeV. The final results for L_α, L_β, L_γ and L_l X-ray production cross section for Au and Pb are given in table 1. Theoretical calculation of L_i-subshell X-ray ionisation cross sections [6], \( \sigma_{L_i} \), are converted to X-ray production cross-sections, \( \sigma_{L_i}^X \), using the Coster-Kroning transition probabilities (f_{12}, f_{13}, f_{23}) [11], the fluorescence yields (\( \omega_1, \omega_2 \) and \( \omega_3 \)) [11] and the radiative widths, \( F_{\text{ni}} \) [12], as in the following expressions:

\[ \sigma_{L_\alpha}^X = \left[ \sigma_{L_1} (f_{13} + f_{12} f_{23}) + \sigma_{L_2} f_{23} + \sigma_{L_3} \right] \omega_3 F_{3\alpha} \]
\[ \sigma_{L_\beta}^X = \left[ \sigma_{L_1} (f_{13} + f_{12} f_{23}) + \sigma_{L_2} f_{23} + \sigma_{L_3} \right] \omega_3 F_{3\beta} \]
\[ \sigma_{L_\gamma}^X = \sigma_{L_1} \omega_1 F_{1\gamma} + (f_{12} \sigma_{L_1} + \sigma_{L_2}) \omega_2 F_{2\gamma} \]

Figure 1 shows experimental L_i (i = α, β, γ and ℓ) X-ray emission cross sections for Au together with the theoretical values of ECPSSR model, data of Sokhi and Crumpton [1] and data of Jesus and al. ref.[9,10]. The experimental predictions of ECPSSR model are close to the present data as well as with the data in [1, 9] for L_α and L_γ. The experimental measurements for L_β agree with those given in [1] but they are over the theoretical data of about 30%. For L_γ line, the obtained data are below the data in [1, 9] and slightly below the theoretical values. The experimental uncertainties of the present data are estimated to be between ±5% to ±6% for L_α, L_β and ±7% to ±8% for L_γ and L_l. The uncertainties in the determined cross-sections became from the contribution of \( N_x^i \) for about ±4% to 6%, detector solid angles for ±2%.
Figure 2 indicates a good agreement between the present data and those in ref [1, 9] for L_α, L_β and L_γ lines, only for L_γ our data are below the data in [1] of about 50%. Comparison with ECPSSR theory gives an overall agreement for L_α and L_γ over the energy range and underestimation for L_β X-ray cross sections. The figure shows that for L_γ line, our data are below the theoretical data as well as the data in ref [1,9]. Our measurements are given with uncertainties of ± 6% for L_α and L_β lines and between ± 7% to ± 9% for L_γ and L_δ.

Table 1: L_α, L_β, L_γ and L_δ X-ray production cross-sections (in b) for protons on Au and Pb in the energy range 1 to 2.5 MeV. The uncertainties on L_α, L_β, are estimated to be about 6% and less than 9%. For L_γ and L_δ lines.

| E_p (MeV) | L_α  | L_β  | L_γ  | L_δ  |
|-----------|------|------|------|------|
| Au        |      |      |      |      |
| 1.0       |      |      |      |      |
| 1.5       | 8.56 | 5.95 | 0.44 | 0.49 |
| 1.8       | 16.24| 9.64 | 0.70 | 0.76 |
| 2.0       | 20.44| 12.05| 0.88 | 0.98 |
| 2.2       | 25.94| 15.46| 1.3  | 1.24 |
| 2.4       |      |      |      |      |
| 2.5       |      |      |      |      |

Pb

| E_p (MeV) | L_α  | L_β  | L_γ  | L_δ  |
|-----------|------|------|------|------|
| 1.0       | 1.93 | 1.40 | 0.12 | 0.15 |
| 1.5       | 6.02 | 4.37 | 0.39 | 0.44 |
| 1.8       | 12.23| 6.80 | 0.59 | 0.63 |
| 2.0       | 15.40| 8.59 | 0.76 | 0.82 |
| 2.2       | 19.69| 11   | 0.98 | 1.05 |
| 2.4       | 23.30| 12.49| 1.13 | 1.19 |
| 2.5       | 25.58| 14.25| 1.44 | 1.25 |

The X-ray emission relative rate for the following fraction is given in table 2.

Table 2: X-ray emission rate for Au and Pb using proton beam of 1-2.5 MeV. The ratios are with error less than 1%.

|      | L / L | L / L | L / L | L_δ / L |
|------|-------|-------|-------|---------|
| Au   | 0.79  | 0.17  | 0.25  | 0.05    |
| Pb   | 0.92  | 0.17  | 0.19  | 0.50    |
Figure 1: L\(_\alpha\), L\(\beta\), L\(\gamma\) and l X-ray production cross-sections for protons on Au. (■) Present work, (●) data of Sokhi (1), (—) ECPSSR predictions ref (3), (▲) data of Jesus ref. (9)

Figure 2: L\(_\alpha\), L\(\beta\), L\(\gamma\) and l X-ray production cross-sections for protons on Pb (■) Present work, (●) data of Sokhi (1), (—) ECPSSR predictions ref (3), (▲) data of Jesus ref. (10)
4. Conclusion

L, L, L, and L, X-ray emission cross sections of Au and Pb were measured for proton bombardment in an energy range of 2 to 2.5 MeV. The reported values of X-ray production cross-sections were compared with the theoretical predictions of ECPSSR model. A good agreement is observed with the experimental data for L and L, lines but the ECPSSR calculations are larger for L and L, lines, namely for Pb.

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