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HAL Id: jpa-00227356
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Submitted on 1 Jan 1987

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L SUBSHELL IONIZATION OF Eu AND Gd BY PROTON, DEUTERON AND ALPHA BOMBARDMENT

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RESUMÉ
Des sections efficaces de production de rayons L-X ont été mesurées pour Eu et Gd sur une zone d'énergie comprise entre 0.2 et 0.9 MeV u⁻¹ pour la collision du proton et du deuteron, et entre 0.2 et 0.45 MeV u⁻¹ pour la collision de la particule alpha. Les raies L₁, L₁ and L₁,2,3 ont servi à la conversion des sections efficaces de production de rayons X en sections efficaces d'ionisation qui sont comparées à la théorie ECPSSR.

ABSTRACT
L X-ray production cross sections have been measured for Eu and Gd in the energy range 0.2 to 0.9 MeV u⁻¹ for proton and deuteron impact and 0.2 to 0.45 MeV u⁻¹ for alpha-particle impact. L₁, L₁ and L₁,2,3 lines were used to convert from X-ray production to subshell ionization cross sections that are compared with the ECPSSR theoretical values.

INTRODUCTION
In the last few years L shell ionization by light ions has been the subject of considerable theoretical and experimental work (1-6).

Theories based on PWBA have been improved by the incorporation of the binding and Coulomb deflection effects and by taking into account the effects of relativity and projectile energy loss on the ionization cross sections. Vacancy transfer mechanisms (7,8) have been proposed to account for the experimental L₂ subshell ionization enhancement and they induce a significant improvement for projectiles with atomic number Z₁ > 2. However, for L subshell cross sections some discrepancies remain unexplained; the atomic parameters used in the conversion from X-ray production to ionization introduce a further source of uncertainty that difficults the comparison between experiment and theory (9,10).

Experimental results for deuterons and alpha-particles are very scarce, while for protons results from different authors show large variations (6). More experimental work is clearly needed, in particular alpha to deuteron and deuteron to proton cross section ratios as they can test the binding and Coulomb deflection effects rather accurately (10-12).

In this work we measured Eu and Gd L X-ray production cross sections induced by protons and deuterons, with energies from 0.2 to 0.9 MeV u⁻¹, and by alpha-particles, in the energy range 0.2 to 0.45 MeV u⁻¹, and compare the ionization cross sections with Brandt and Lapicki ECPSSR theory (1).
EXPERIMENT

The experimental set-up has been described in detail elsewhere (13) and the experimental procedure is the same that we used in ref. 9. The statistical uncertainty was generally better than 1% for \( L_\alpha \). Dead time and target thickness corrections (12) never exceeded 5% and 10% respectively.

RESULTS AND DISCUSSION

Results for \( L_\alpha \), \( L_\gamma_1 \) and \( L_\gamma_{23} \) production cross sections and an estimate of the percentual error are presented in table 1. For deuterons and alpha-particles we are unaware of results published in numerical form in the energy range covered in this work. For protons in Gd at 1 MeV the results of Avaldi et al. (14) agree with ours within the quoted errors.

Atomic parameters used in the conversion of X-ray production into ionization cross sections were taken from the tables of Krause (15) and Scofield (16). Comparison between our experimental results and ECPSSR theory is made in the figures. In figure 1 we can see that the plateau predicted by the theory for the \( L_1 \) ionization cross section, due to the extra node of the 2s atomic wave function, is present and, indeed, enhanced in the experimental results. At both the lowest and the highest energy points, experiment is about 30% above the theoretical curve.

For Au the use of relativistic Hartree-Slater wave functions (3) improves the agreement between theory and experiment, predicting a more clearly defined plateau. In figure 2 it is shown that, for \( L_2 \), the experimental points at the lowest velocity are a factor of 2 and 2.5 above the theory for deuterons and alphas respectively and for \( L_3 \) about 30% above for the two projectiles. Results of the comparison with theory for protons are similar to those for deuterons, suggesting that the Coulomb deflection and energy loss effects (in spite of corresponding to a correction factor of 6 for Gd \( L_1 \) subshell bombarded by protons with 0.2 MeV) are well taken care of by the ECPSSR theory for all the subshells. In figure 3 ratios of alpha to deuteron cross sections are displayed; we can infer that the binding effect is not the origin of the discrepancies between theory and experiment. A vacancy transfer mechanism from the \( L_1 \) to the \( L_2 \) subshell prior to X-ray emission has been proposed (7,8); the corresponding cross sections for protons and deuterons are very small, but are somewhat
Table 1. L X-ray production cross sections (in b) for proton, deuteron and alpha impact on Eu and Gd. Numbers in parenthesis give the error in percent for the line in question and the lines below. The notation a'b stands for a \times 10^b. Errors for ratios of cross sections obtained from the table are generally smaller than 4%.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Protons</th>
<th>Deuterons</th>
<th>Alphas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \sigma_0 )</td>
<td>( \sigma_{12} )</td>
<td>( \sigma_{23} )</td>
</tr>
<tr>
<td>0.20</td>
<td>2.09±1(8)</td>
<td>1.36±2(13)</td>
<td>1.01±2(13)</td>
</tr>
<tr>
<td>0.30</td>
<td>4.98±1</td>
<td>3.05±2</td>
<td>1.82±2</td>
</tr>
<tr>
<td>0.35</td>
<td>7.39±1(7)</td>
<td>5.00±2(12)</td>
<td>2.16±2</td>
</tr>
<tr>
<td>0.40</td>
<td>1.32±0(6)</td>
<td>8.14±2</td>
<td>3.19±2</td>
</tr>
<tr>
<td>0.45</td>
<td>1.99±0(6)</td>
<td>1.30±1(11)</td>
<td>4.31±2(12)</td>
</tr>
<tr>
<td>0.50</td>
<td>2.62±0(6)</td>
<td>1.64±1</td>
<td>3.73±2</td>
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<tr>
<td>0.60</td>
<td>4.84±0(6)</td>
<td>2.68±1</td>
<td>3.23±2</td>
</tr>
<tr>
<td>0.70</td>
<td>6.73±0(6)</td>
<td>4.14±1</td>
<td>4.84±2</td>
</tr>
<tr>
<td>0.80</td>
<td>9.51±0(6)</td>
<td>6.21±1(10)</td>
<td>7.23±2</td>
</tr>
<tr>
<td>0.90</td>
<td>1.28±1</td>
<td>8.28±1</td>
<td>9.09±2</td>
</tr>
<tr>
<td>1.00</td>
<td>1.64±1</td>
<td>1.09±0</td>
<td>1.78±1</td>
</tr>
</tbody>
</table>

**Fig. 2** Ratios of experimental and theoretical a) deuteron-induced and b) alpha-induced cross sections for L\(_2\) and L\(_3\) subshells plotted against the reduced incident velocity, corrected for relativistic and binding effects, \( \xi RB \). Theoretical values are calculated according to ECPPSR theory of Brandt and Lenieki.
higher for alphas as they vary with $Z_1^2$. That may explain partially the differences in the ratios of figure 3 for $L_1$ and $L_2$ subshells, but not the $L_2$ experimental enhancement. The inclusion of second order corrections might improve the agreement between experiment and theory as lower $\sigma_1/\sigma_2$ and $\sigma_3/\sigma_2$ ratios are predicted (4) at low energies, for Au. The uncertainty in the atomic parameters used adds some difficulty to the comparison between experiment and theory. The present experimental results and the theoretical values would come to fair agreement if different atomic parameters were used, particularly the term $\omega S_{11}$, 15% higher and $f_{12}$ a factor of 2 higher (where the symbols have their usual meanings). A factor of 2 cannot be considered very high taking into account the differences between theoretical and experimental Coster-Kronig values (9,17). It should be referred that theoretical calculations are made for a single-hole unperturbed atom and experimental results pertain to photoionization, where multiple ionization is negligible. It is clearly desirable to have other independent ways of estimating the atomic parameters for atoms bombarded by ions (17).

REFERENCES

(6) R.S. Sokhi and D. Crompton, At. Data Nucl. Data Tables 30 (1984) 49

Fig. 3. Ratios of alpha to deuteron-induced ionization cross sections, plotted against the reduced incident velocity, $\xi$. Full and dashed lines are ECPSR theoretical values and best linear fits to the experimental points, respectively.

\begin{figure*}
\centering
\includegraphics[width=\textwidth]{fig3}
\caption{Ratios of alpha to deuteron-induced ionization cross sections, plotted against the reduced incident velocity, $\xi$. Full and dashed lines are ECPSR theoretical values and best linear fits to the experimental points, respectively.}
\end{figure*}