I. 17 L and M X-ray Production Cross Sections of Heavy Rare Earth Elements in the 3-40 MeV/amu Projectile-Energy Range

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K- and L-shell ionizations have been extensively studied by many researchers over the wide range of the projectile energy, and it has been found that the binding energy effect and the Coulomb deflection play an important role in the ionization process in the energy region of $E/\lambda U < 1$, where $E$ is the projectile-energy, $\lambda$ is the ratio of the projectile mass to the electron mass, and $U$ is the ionization energy. In the energy region of $E/\lambda U > 1$, the atomic polarization becomes effective. The PWBA theory taking account of these effects$^1$ is in good agreement with the experimental measurements.

On the other hand, systematic measurements of the ionization process for M-shell are still scarce owing to the complexing of M X-ray spectrum, therefore almost all studies have given only total M X-ray production cross sections except for our previous report.$^2$

In the present work, we have systematically measured the M X-rays of heavy lanthanides by proton and $^3$He ion impact over the energy range 3-40 MeV/amu to obtain partial M X-ray production cross sections.

Targets of Dy(11.9 $\mu$g/cm$^2$), Er(20.5 $\mu$g/cm$^2$) and Lu(32.5 $\mu$g/cm$^2$) were bombarded with proton beams of 3-40 MeV and by $^3$He$^{2+}$ ion beams of 9-63 MeV. All targets were prepared by vacuum evaporation onto 10 $\mu$m-thick Mylar foils, and thicknesses were determined by comparison of K X-ray yields with those from targets of known thicknesses. The self-absorption by the 4f$^n$ $^7/2$ + 3d$^{n+1}$ $^3$J$^-$ to 4f$^{n+1}$ 3d$^{n+1}$ transition$^3$ in the target is estimated to be less than 2% for Dy and Er. M and L X-rays were measured with an ORTEC Si(Li) detector. The detector head is set in a vacuum chamber on account of the absorption of M X-rays in the window and air.

In Fig. 1 are shown M and L X-ray spectrum of Lu produced by 9 MeV $^3$He-ion impact. The detailed procedure of the background subtraction and the peak separation has been previously reported.$^2$ The partial X-ray production cross sections $\sigma_{xi}$ is obtained by,

$$\sigma_{xi} = \frac{Y_{xi} \times A}{N_p \times N_A \times T \times \text{eff} \times \lambda / 4\pi}$$

where $Y_{xi}$ is the peak yield of i-th subline, $A$ the mass number, $N_p$ the number of incident particles, $N_A$ the Avogadro number, $T$ the target thickness (g/cm$^2$),
eff the detection efficiency, \( \Omega \) the solid angle. Errors are mainly from
target thickness (8%), solid angle (5%), detection efficiency (4-30%) and
fitting (1-60%).

The theoretical X-ray production cross sections are given by Eq. 2-7 of
reference (2) using various values of the transition rates\(^{4,5}\) and the
ionization cross sections calculated by the PWBA theory.

The experimental results are compared with the theoretical predictions in
Figs. 2-7. Figures 2 a)-c) and Figs. 3 a)-c) present X-ray production cross
sections of \( L_{\alpha1,2} \) and \( L_{\beta1} \) versus the energy (MeV/amu) of the incident
particles. As seen in these figures, the experimental results for \( L_{\alpha1,2} \) are
10-14% smaller than the theoretical predictions, while those for \( L_{\beta1} \) are 10-
23% larger than the theoretical predictions. These discrepancies seem to be
due to an error in fluorescence yields.

Figures 4 a)-c) show the results of \( M_{\alpha,\beta} \) line. In the case of M X-rays,
it is necessary to use many theoretical values of X-ray emission rates,
fluorescence yields and Koster-Cronig yields, which have not been verified by
experiment. A decade ago, we measured total M X-ray production cross sections
of Au and Bi and found that the experimental cross sections of Au are in good
agreement with theory using average fluorescence yields \( \bar{\sigma}_M \), however those of
Bi are 0.5 times smaller.\(^6\) We pointed out that this discrepancy may be due
to an inaccuracy of \( \bar{\sigma}_M \). In the case of rare earth elements it is expected
that the existence of open 4f shell has influence upon the transition
probabilities because the number of 4f electrons may change prior to the X-ray
transition.\(^3\) As seen in these figures, experimental results are in excellent
agreement with theory except for Lu, which are somewhat larger than the
predictions. These results suggest that the PWBA theory and the theoretical
values of transition rates for \( M_{\alpha,\beta} \) lines are consistent with the experimental
results. It is also found that the contribution of the excitation (M-4f) to
the M-hole production is not so large, since the results of Lu whose 4f shell
is fully occupied show relatively large values. Furthermore there can be seen
no clear projectile-charge dependence. It means that the secondary effects
mentioned above do not play an important role and the first order PWBA theory
gives good approximation in this energy region.

In Figs. 5 a)-c) are shown the results for \( M_{\gamma} \) line, which corresponds to
the transition to the M5-hole in the same way as \( M_{\alpha} \) line. It can be seen in
these figures that all data are by as much as a factor of 5 above the
theoretical predictions. These results suggest that the theoretical values of
the transition rates are inaccurate.

Figures 6 a)-c) show the case for \( M_{\gamma} \) line and Figs. 7 a)-c) show for M2-
N4, M1-N3, M1-M2 lines. In these cases, errors from fitting are too large to
make a detailed discussion, but no significant disagreement was observed.

Since it appears that the PWBA theory is consistent with experiment, it
is possible to derive some of the experimental values of transition rates from
the present results by least-squares fitting with theoretical cross section
curves. For Lα1,2 and Lβ1 lines, discrepancies seem to be due to the values of fluorescence yields because differences are so large that errors from Koster-Cronig yields can not explain them. In the case of Mγ line, values of fluorescence yields and Koster-Cronig yields must be accurate since Mα line is in good agreement with theory, therefore the values of X-ray emission rates must be revised. These experimental values thus obtained are tabulated in Table 1. In this Table are also included present values of fluorescence yields for other lines assuming that discrepancies are due to the fluorescence yields only.

In conclusion, the PWBA gives almost good approximation for M-shell ionization in this energy region. It is also concluded that some of the theoretical values of transition rates must be revised. These values were obtained experimentally for the first time.

References

Table 1. Fluorescence yields and X-ray emission rates.

<table>
<thead>
<tr>
<th>Element</th>
<th>Line</th>
<th>$\omega_\xi$ (Theory)</th>
<th>$\omega_\xi$ (Present)</th>
<th>$\Gamma_\xi/\Gamma_\xi$(Theory)</th>
<th>$\Gamma_\xi/\Gamma_\xi$(Present)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dy</td>
<td>$M_{\alpha,\beta}$</td>
<td>M4: 0.0092 M5: 0.0167</td>
<td>(1.063 ±11%)</td>
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<tr>
<td></td>
<td>M$\zeta$</td>
<td>------</td>
<td>------</td>
<td>0.0967</td>
<td>0.523 ±28%</td>
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<tr>
<td></td>
<td>M$\gamma$</td>
<td>M3: 0.00142</td>
<td>0.00195 ±44%</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td></td>
<td>M1-N2N3</td>
<td>M1: 0.000101 M2: 0.00178</td>
<td>(1.020 ±40%)</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td></td>
<td>L$\alpha_{1,8}$</td>
<td>L3: 0.190</td>
<td>0.163 ±11%</td>
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<tr>
<td></td>
<td>L$\beta_{1,2}$</td>
<td>L2: 0.195</td>
<td>0.240 ±13%</td>
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</tr>
</tbody>
</table>

| Er      | $M_{\alpha,\beta}$ | M4: 0.0073 M5: 0.0120 | (1.058 ±11%) | ------ | ------ |
|         | M$\zeta$ | ------ | ------ | 0.0667 | 0.341 ±26% |
|         | M$\gamma$ | M3: 0.00150 | 0.00168 ±38% | ------ | ------ |
|         | M1-N2N3 | M1: 0.00111 M2: 0.00190 | (0.897 ±40%) | ------ | ------ |
|         | L$\alpha_{1,8}$ | L3: 0.212 | 0.185 ±11% | ------ | ------ |
|         | L$\beta_{1,2}$ | L2: 0.220 | 0.242 ±15% | ------ | ------ |

| Lu      | $M_{\alpha,\beta}$ | M4: 0.0092 M5: 0.0167 | (1.228 ±12%) | ------ | ------ |
|         | M$\zeta$ | ------ | ------ | 0.0469 | 0.170 ±24% |
|         | M$\gamma$ | M3: 0.00175 | 0.00281 ±36% | ------ | ------ |
|         | M1-N2N3 | M1: 0.00122 M2: 0.00205 | (0.549 ±43%) | ------ | ------ |
|         | L$\alpha_{1,8}$ | L3: 0.240 | 0.217 ±11% | ------ | ------ |
|         | L$\beta_{1,2}$ | L2: 0.254 | 0.308 ±12% | ------ | ------ |
Fig. 1a). X-ray spectrum of Lu produced by $^3$He 9 MeV ion impact. Besides the raw spectrum, background spectrum from 10 µm Mylar backing and the net spectrum after background subtraction are also shown.

Fig. 1b). M X-rays are separated into 5 sublines by a least-square fitting assuming Gaussian shapes and 5-th order polynomial.
Fig. 2a)-c). Partial M X-ray production cross sections for $M_{α,β}$ lines. The ordinate is the scaled cross section (barns$/Z_1^2$, where $Z_1$ is the charge of the projectile), the abscissa is the projectile energy (MeV/amu). Solid curve represents the PWBA theory: squares, proton impact; circles, $^3$He-ion impact.

Fig. 3a)-c). Same as Fig. 2 but for $M_γ$ line.

Fig. 4a)-c). Same as Fig. 2 but for $M_γ$ line.
Fig. 5a)-c). Same as Fig. 2 but for M1-N2, M3 M2-N4 lines.

Fig. 6a)-c). Same as Fig. 2 but for $L_{\alpha 1,2}$ line.

Fig. 7a)-c). Same as Fig. 2 but for $L_{\beta 1}$ line.