Emission of Characteristic X-rays by Heavy Ion Impact

Javier Miranda
Instituto de Física, UNAM
Collaborators

• Luis Rodríguez-Fernández
• Marcelo F. Lugo Licona
• Óscar Genaro de Lucio
• Karim López
• Francisco J. Jaimes
• Juan Carlos Pineda
• Melitón Galindo
Summary

• Motivation
• Emission of characteristic X-rays
• Measurement of K and L X-ray production cross sections
• Anisotropy in L X-rays
• Future work
Motivation

- X-ray emission due to ion-atom collisions is a phenomenon known several decades ago.
- There are many physical effects involved.
- Origin of analytical technique Particle Induced X-ray Emission (PIXE).
- Important errors found in analytical applications.
Emission of characteristic X-rays

- Nucleus
- Electrons
- Photon
- Incident ion
Electronic transitions
L X-ray Production Cross Sections

\[
\sigma_{X,L_{\alpha}} = (\sigma_{L_1} f_{13} + \sigma_{L_1} f_{12} f_{23} + \sigma_{L_2} f_{23} + \sigma_{L_3}) \omega_3 \frac{\Gamma_{\alpha_{1,2}}}{\Gamma_{L_3}}
\]

\[
\sigma_{X,L_{\beta_{2,15}}} = (\sigma_{L_1} f_{13} + \sigma_{L_1} f_{12} f_{23} + \sigma_{L_2} f_{23} + \sigma_{L_3}) \omega_3 \frac{\Gamma_{\beta_{2,15}}}{\Gamma_{L_3}}
\]

\[
\sigma_{X,L_{\beta_{1,3,4}}} = \sigma_{L_1} \omega_1 \frac{\Gamma_{\beta_{3,4}}}{\Gamma_{L_1}} + (\sigma_{L_1} f_{12} + \sigma_{L_2}) \omega_2 \frac{\Gamma_{\beta_1}}{\Gamma_{L_2}}
\]

\[
\sigma_{X,L_{\gamma}} = \sigma_{L_1} \omega_1 \frac{\Gamma_{\gamma_{2,3}}}{\Gamma_{L_1}} + (\sigma_{L_1} f_{12} + \sigma_{L_2}) \omega_2 \frac{\Gamma_{\gamma_1}}{\Gamma_{L_2}}
\]
Effects during heavy ion impact

Multiple ionization

Free atom

Atom + ion

Ion

Target atom

Electron Capture

Molecular orbitals

Electron Capture

Kα Kβ

Kα Kβ

M

L

K
Ionization cross section: Theoretical models

- Binary Encounter Approx. (BEA)
- Semiclassical Approx. (SCA)
- Plane Wave Born Approx. (PWBA)
- ECPSSR Correction to PWBA
  - Ion energy loss (E)
  - Coulombiana deflection of ion (C)
  - Change in electron energies through Perturbed Stationary States Method (PSS)
  - Relativistic effects in target electrons (R)
  - Improvements: United Atom (UA), multiple ionization (MI), intrashell coupling (IS)
Experimental setup for measurement of X-ray production cross sections

- Accelerator
- Switching Magnet
- Particle detector
- Target
- Ion beam
- Faraday Cup
- Current Digitizer and Integrator
- Multichannel Analyzer
- X-ray Detector
K X-ray production cross sections
Dependence on projectile atomic number

![Graph showing dependence on projectile atomic number](image)
$^{10}\text{B}^{2+}$ Ions: ECPSSR-UA+Puri

![Graph showing the relationship between $\sigma_{\text{Exp}}$ and $\sigma_{\text{ECPSSR-UA}}$ for different elements. The graph includes error bars and various symbols for different elements: Ce, Nd, Sm, Eu, Gd, Dy, Ho, Yb, Au, and Bi. The x-axis represents $\xi_{L}$ and $\xi_{R}$, while the y-axis represents $\sigma_{\text{Exp}}/\sigma_{\text{ECPSSR-UA}}$.](image-url)
$^{10}B^{2+}$ Ions: ECPSSR+MI+Puri
Experimental setup for measurement of X-ray anisotropy

9SDH-2 Pelletron Accelerator
Switching Magnet
Scattering Chamber
Ion Beam
Target
Canberra 2026 Amplifier
X-Ray Detector
Goniometer

Multichannel Analyzer
Multiplexer
Experimental setup

- Si PIN diode X-Ray detector, external to chamber
- 12 µm Mylar window
### Ion-target-energy combinations

<table>
<thead>
<tr>
<th></th>
<th>9 MeV</th>
<th>10 MeV</th>
<th>11 MeV</th>
<th>12 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ce</td>
<td>$^{12}\text{C}^{4+}$</td>
<td>$^{12}\text{C}^{4+}$, $^{16}\text{O}^{4+}$, $^{19}\text{F}^{4+}$</td>
<td>$^{12}\text{C}^{4+}$, $^{16}\text{O}^{4+}$, $^{19}\text{F}^{4+}$</td>
<td>$^{16}\text{O}^{4+}$, $^{19}\text{F}^{4+}$</td>
</tr>
<tr>
<td>Nd</td>
<td>$^{12}\text{C}^{4+}$</td>
<td>$^{12}\text{C}^{4+}$, $^{16}\text{O}^{4+}$</td>
<td>$^{16}\text{O}^{4+}$, $^{19}\text{F}^{4+}$</td>
<td>$^{12}\text{C}^{4+}$, $^{16}\text{O}^{4+}$, $^{19}\text{F}^{4+}$</td>
</tr>
<tr>
<td>Eu</td>
<td>$^{12}\text{C}^{4+}$</td>
<td>$^{19}\text{F}^{4+}$</td>
<td>$^{19}\text{F}^{4+}$</td>
<td>$^{19}\text{F}^{4+}$</td>
</tr>
<tr>
<td>Dy</td>
<td>$^{12}\text{C}^{4+}$</td>
<td>$^{12}\text{C}^{4+}$, $^{16}\text{O}^{4+}$</td>
<td>$^{12}\text{C}^{4+}$, $^{16}\text{O}^{4+}$, $^{19}\text{F}^{4+}$</td>
<td>$^{12}\text{C}^{4+}$, $^{16}\text{O}^{4+}$, $^{19}\text{F}^{4+}$</td>
</tr>
<tr>
<td>Ho</td>
<td>$^{12}\text{C}^{4+}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yb</td>
<td>$^{12}\text{C}^{4+}$</td>
<td>$^{12}\text{C}^{4+}$, $^{16}\text{O}^{4+}$</td>
<td>$^{12}\text{C}^{4+}$, $^{16}\text{O}^{4+}$</td>
<td>$^{12}\text{C}^{4+}$, $^{19}\text{F}^{4+}$</td>
</tr>
</tbody>
</table>
$^{12}\text{C}^{4+}$ Ions
Overall comparison
Correction by Multiple Vacancies
Conclusions

• There are still few experimental data for X-ray production by heavy ion impact
• Atomic parameters databases need an important update
• Theoretical models are inadequate to predict experimental results