First Step Benchmark of Inelastic Collision Cross Sections for Heavy Ions using Charge State Evolutions via Target Penetration

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Single-electron capture cross sections for $W^+$ ions

You require not just accuracy of calculated cross sections but also their completeness.

Experimentalists would like the evaluation of theoretical data to be done with experiments, but in many cases, there exist few experiments directly comparable to theories.

Experimentalists are able to provide very accurate experimental results in some cases.
Experimental apparatus in Japan Atomic Energy Agency

$2.0 \text{ MeV/u } C^q+ (q=2-6)$, $S^q+ (q=6-16)$, $1.0 \text{ MeV/u } W^q+ (q=13,15,28,29,30,38)$

Target C-foil
$0.9 \sim 200 \mu g/cm^2$

Post-stripper
C-foil $\sim 20 \mu g/cm^2$
Equilibrium and pre-equilibrium charge-state distributions of 2.0 MeV/u C ions after C-foils

Equilibrium and pre-equilibrium charge-state distributions of 2.0 MeV/u C ions after C-foils

$$\bar{q} = \sum_{q} q y_q, \quad d = \sqrt{\sum_{q} (q - \bar{q})^2 y_q}, \quad s = \frac{\sum_{q} (q - \bar{q})^3 y_q}{d^3}$$

Computer codes for charge-state evolutions

ETACHA:
a program for calculating charge states at GANIL energies, \((10 - 80 \text{ MeV/u})\)

Matrix Method:
Charge evolution of swift-heavy-ion beams explored by matrix method,
O. Osmani, P. Sigmund, NIM B 269, 813 (2011).

ETACHA3, ETACHA4: Extention of charge state distribution calculations for ion-solid collisions towards low velocities and many-electron ions,

BEAR (Balance Equations for Atomic Reactions)
Set of cross sections on the cutting-board

<table>
<thead>
<tr>
<th>Case</th>
<th>Cross Sections</th>
<th>References</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>(4) ETACHA</td>
<td>( \frac{dy_i}{dx} = \sum_{i \neq j} y_j(x)\sigma_{ij} - \sum_{i \neq j} y_i(x)\sigma_{ij} ) ( \sum_i y_i = 1 )</td>
<td>Scaling used partly</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case</th>
<th>Calculation</th>
<th>Yields ( Y_i )</th>
<th>Density Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>Present</td>
<td>Charge-State ( 7 (C^0 - C^{6+}) )</td>
<td>Not involved.</td>
</tr>
<tr>
<td>(2)</td>
<td>Present</td>
<td>( CS + n = 1,2 )-state ( 18 (C^0 - C^{6+}) )</td>
<td>High ( n ) states are ionized. JPB38,2675 (2005)</td>
</tr>
<tr>
<td>(3)</td>
<td>Present</td>
<td>( CS + n )-substate many ( (C^0 - C^{6+}) )</td>
<td>High ( n ) states are ionized.</td>
</tr>
<tr>
<td>(4) ETACHA4 PRA92,042703 (2015)</td>
<td>CS + ( n/l )-substate many ( (C^0 - C^{6+}) )</td>
<td>Shorter collision intervals are involved in the RE.</td>
<td></td>
</tr>
</tbody>
</table>
Model calculations using sets of cross sections for charge-state distributions of 2.0 MeV/u C ions after C-foils.
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Model calculations using sets of cross sections for charge-state distributions of 2.0 MeV/u C ions after C-foils.
Scores for reproducibility of the equilibrium charge-state distributions of 2.0 MeV/u C ions after C-foils

<table>
<thead>
<tr>
<th>Case</th>
<th>Model</th>
<th>Cross Section</th>
<th>Score1</th>
<th>Score2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>Simple</td>
<td>Better</td>
<td>1602</td>
<td>12.7</td>
</tr>
<tr>
<td>(2)</td>
<td>Simple</td>
<td>Better</td>
<td>699</td>
<td>12.7</td>
</tr>
<tr>
<td>(3)</td>
<td>Intermediate</td>
<td>Better</td>
<td>138</td>
<td>4.8</td>
</tr>
<tr>
<td>(4)</td>
<td>Full</td>
<td>General</td>
<td>776</td>
<td>13.2</td>
</tr>
</tbody>
</table>

Score1 = \[ \sqrt{\frac{\sum_{i=3,4,5,6} \left( \frac{y_i^{eq,cal} - y_i^{eq,exp}}{\sigma_i^{eq,exp}} \right)^2}{4}} \]

Score2 = \[ \sqrt{\frac{\sum_{i=q,d,s} \left( \frac{y_i^{eq,cal} - y_i^{eq,exp}}{\sigma_i^{eq,exp}} \right)^2}{3}} \]
Shifted model calculations using sets of cross sections for charge-state distributions of 2.0 MeV/u C ions after C-foils.
**Shifted** model calculations using sets of cross sections for charge-state distributions of 2.0 MeV/u C ions after C-foils.

![Graphs showing charge-state distributions for C²⁺ ions after C-foils.](image-url)
Shifted model calculations using sets of cross sections for charge-state distributions of 2.0 MeV/u C ions after C-foils.
Shifted model calculations using sets of cross sections for charge-state distributions of 2.0 MeV/u C ions after C-foils.

Graphs showing fraction versus target thickness (μg/cm²) for different charge states and target thickness values.
Shifted model calculations using sets of cross sections for charge-state distributions of 2.0 MeV/u C ions after C-foils.
Shifted model calculations using sets of cross sections for charge-state distributions of 2.0 MeV/u C ions after C-foils.
Scores for reproducibility of the pre-equilibrium charge-state distributions of 2.0 MeV/u C ions after C-foils

\[
Score = \sqrt{\frac{\sum_i (y_i^{pre-eq,cal} - y_i^{pre-eq,exp})^2}{N}}
\]

\( N = 97 \)

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<tr>
<th>Case</th>
<th>Model</th>
<th>Cross Sections</th>
<th>Score</th>
<th>Score1</th>
<th>Score2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>Simple</td>
<td>Better</td>
<td>0.0570</td>
<td>1602</td>
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<tr>
<td>(2)</td>
<td>Simple</td>
<td>Better</td>
<td>0.0792</td>
<td>699</td>
<td>12.7</td>
</tr>
<tr>
<td>(3)</td>
<td>Intermediate</td>
<td>Better</td>
<td>0.0282</td>
<td>138</td>
<td>4.8</td>
</tr>
<tr>
<td>(4)</td>
<td>Full</td>
<td>General</td>
<td>0.0747</td>
<td>776</td>
<td>13.2</td>
</tr>
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Summary and outlook

• You require not just accuracy of calculated cross sections but also their completeness.
• Experimentalists would like the evaluation of theoretical data to be done with experiments, but in many cases, there exist few experiments directly comparable to theories.
• Experimentalists are able to provide very accurate experimental results in some cases.
• It would be possible to evaluate set of calculated cross sections (e-capture, loss, excitation, de-excitation) using charge state evolution data.
• It would be also possible to reduce the collision energy by using dense gas targets.
Vielen Dank und Frohe Weihnachten!
Charge-state distributions of 2.0 MeV/u $C^{q+}$ ions after C-foils

Shifted model calculations using sets of cross sections for charge-state distributions of 2.0 MeV/u C ions after C-foils.
Shifted model calculations using sets of cross sections for charge-state distributions of 2.0 MeV/u C ions after C-foils.