Reaction Properties

Working Group report
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• Design Reactions

• Reaction channels:
  – Elastic scattering
  – Quasi-elastic and few-nucleon transfer channels
  – Multi-nucleon transfer channels
  – Fusion

• Preparatory experiment
Design reactions chosen at IRiS 10 (Spring) workshop:

- Various projectiles + Actinide targets
- $^{136}\text{Xe} + ^{208}\text{Pb}$
- Energy < 10% above the Coulomb Barrier

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$E_{\text{LAB}}$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{22}\text{Ne} + ^{238}\text{U}$</td>
<td>125</td>
</tr>
<tr>
<td>$^{40}\text{Ar} + ^{238}\text{U}$</td>
<td>228</td>
</tr>
<tr>
<td>$^{48}\text{Ca} + ^{238}\text{U}$</td>
<td>255</td>
</tr>
<tr>
<td>$^{136}\text{Xe} + ^{238}\text{U}$</td>
<td>799</td>
</tr>
<tr>
<td>$^{238}\text{U} + ^{238}\text{U}$</td>
<td>1606</td>
</tr>
<tr>
<td>$^{136}\text{Xe} + ^{208}\text{Pb}$</td>
<td>789</td>
</tr>
</tbody>
</table>
Classification of collisions

Loveland, W. D.; Morrissey, D. & Seaborg, G. T. Modern Nuclear Chemistry
Figure 10.13  Diagram showing some representative projectile orbits for the interaction of 130 MeV $^{16}\text{O}$ with $^{208}\text{Pb}$. [From Satchler (1990).]

Loveland, W. D.; Morrissey, D. & Seaborg, G. T. Modern Nuclear Chemistry
Elastic scattering – differential cross section

- Up to $\theta_{gr}$ Rutherford cross section

$$\frac{d\sigma}{d\Omega} = \frac{dl}{l_0 d\Omega} = \left(\frac{d_0}{4}\right)^2 \frac{1}{\sin^4(\theta/2)} = \left(\frac{Z_1 Z_2 e^2}{4T_p^{cm}}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

$$\theta_{gr} = 2 \sin\left(\frac{V_C}{2E_{CM} - V_C}\right)$$

- $E_{CM} = 1.1V_C \rightarrow \theta_{gr} = 110^\circ$

- Below that $\sigma_{el}$ drops
Elastic scattering – differential cross section

\[ \frac{d\sigma}{d\theta} \]

Arbitrary scale

\[ ^{48}\text{Ca} + ^{248}\text{Cm} @ 209 \text{ MeV CM} (1.07 \, V_c) \]

\[ ^{238}\text{U} + ^{248}\text{Cm} @ 750 \text{ MeV CM} (~ V_c) \]
Inelastic collisions

$^{86}$Kr+$^{166}$Er at 8.18 MeV/u

\[ \frac{d\sigma}{dE \, d\theta} \]

Inelastic collisions – angular distribution

Behavior scales with “modified Sommerfeld parameter” $\eta'$

$$\eta' = \frac{Z_1 \cdot Z_2 \cdot e^2}{\hbar \cdot v_B}$$

$V_B$ - relative velocity at interaction barrier

a) Orbiting $\eta' < 150$

b) Focusing $250 < \eta' < 400$

c) Coulomb trajectory $500 < \eta'$
Angular distribution for design reactions

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$E_{\text{LAB}}$ [MeV]</th>
<th>$\eta'$</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{22}\text{Ne} + ^{238}\text{U}$</td>
<td>125</td>
<td>200</td>
<td>Focusing</td>
</tr>
<tr>
<td>$^{40}\text{Ar} + ^{238}\text{U}$</td>
<td>228</td>
<td>357</td>
<td>Focusing</td>
</tr>
<tr>
<td>$^{48}\text{Ca} + ^{238}\text{U}$</td>
<td>255</td>
<td>418</td>
<td>Focusing</td>
</tr>
<tr>
<td>$^{136}\text{Xe} + ^{238}\text{U}$</td>
<td>799</td>
<td>1071</td>
<td>Coulomb</td>
</tr>
<tr>
<td>$^{238}\text{U} + ^{238}\text{U}$</td>
<td>1606</td>
<td>1700</td>
<td>Coulomb</td>
</tr>
<tr>
<td>$^{136}\text{Xe} + ^{208}\text{Pb}$</td>
<td>789</td>
<td>802</td>
<td>Coulomb</td>
</tr>
</tbody>
</table>

$^{48}\text{Ca}$ and $^{238}\text{U} + ^{238}\text{U}$ ($^{248}\text{Cm}$) are representative reactions.
Deep inelastic collisions

\[ \frac{d\sigma}{dE \, dZ} \]

\[^{86}\text{Kr} + ^{166}\text{Er} \text{ at } 8.18 \text{ MeV/u}\]

• Deep-inelastic reactions are complex

• Luckily we have GRAZING
  – coupled channels calculations
  – G. Polarollo

• See his presentation from the last IRiS workshop

http://personalpages.to.infn.it/~nanni/grazing/
GRAZING calculation for $^{48}$Ca + $^{248}$Cm @ 209 MeV

- $d\sigma/(dE.d\theta)$ for different exit channels
- Reliable for quasi-elastic and few-nucleon transfer channels
  - The strongest channels
Many-nucleon transfer reactions

- Two detailed theoretical calculations:
  - $^{48}$Ca + $^{248}$Cm @ 209 MeV CM (1.07 $V_C$) by Adamian and Antonenko
  - $^{238}$U + $^{248}$Cm @ 750 MeV CM ($\sim V_C$) by V. Zagrebaev
Calculated by Adamian and Antonenko

- Diffusion of dinuclear system in the charge and mass asymmetry coordinates
- Long contact times → isotropic angular distribution
- Excitation energy of the system shared between fragments by their mass

Ref e.g.: Adamian, G. G., Antonenko, N. V., Sargsyan, V. V. & Scheid, W., Phys. Rev. C, 2010, 81, 024604
Cross sections for $^{48}$Ca+$^{248}$Cm at 209 MeV LAB - Secondary even-odd products

- Cf
- Fm
- No
- Rf
- Sg
- Hs

(N p b)
Cross sections $^{48}$Ca+$^{248}$Cm - secondary products

Energy in CM (MeV)

cross sections (pb)

- $^{271}$Sg
- $^{259}$No
- $^{267}$Db
- $^{268}$Db
- $^{264}$Lr
• Calculation by V. Zagrebaev
  - Dynamical model based on Langevin-type dynamical equations of motion
  - Promising results presented at the last IRiS workshop
  - Meanwhile new calculations
Multi-nucleon transfer reactions give access to tens of new n-rich SHE isotopes.
Design Reactions – concentrate on $^{48}\text{Ca},^{238}\text{U} + ^{248}\text{Cm}$

Reaction kinematics

Reaction channels:

- Elastic scattering
- Quasi-elastic and few-nucleon transfer channels – GRAZING
- Multi-nucleon transfer channels – Calculations by experts
- Fusion – especially fusion-fission

Preparatory experiments
Fusion-fission

- Fusion-fission – reactions with lighter projectiles
- Rather simple (comparing to other channels)
- Experimental data exist

Itkis at al., Fusion-fission of Superheavy Nuclei, J. of Nuclear and Radiochemical Sciences, 2002, 3, 57–61

Figure 5. Two-dimensional TKE-Mass matrices and mass yields of fission fragments for the reactions $^{48}$Ca + $^{208}$Pb, $^{56}$Fe + $^{208}$Pb, $^{86}$Kr + $^{208}$Pb at an excitation energy of 28–34 MeV.
Preparatory experiments

- Angular distribution of SHE fragments
  - The biggest unknown
  - Critical for separator simulations
  - Experimental data missing
  - A simple radiochemical experiment would help
Thank you for your attention!
2 body kinematics

- [link](http://nrv.jinr.ru/nrv/webnrv/kinematics/two_body.php)

\[ ^{48}\text{Ca} + ^{238}\text{U} \rightarrow ^{26}\text{Ne} + ^{260}\text{No} \text{ at } 255 \text{ MeV LAB} \]

\[ ^{238}\text{U} + ^{238}\text{U} \rightarrow ^{216}\text{Pb} + ^{260}\text{No} \text{ at } 1606 \text{ MeV LAB} \]

\[ \Theta_{\text{LAB}}(^{260}\text{No}) < 32^\circ, \ 8.7 < E_{\text{LAB}}(^{260}\text{No}) < 90 \text{ MeV} \]

\[ \Theta_{\text{LAB}}(^{260}\text{No}) < 65^\circ, \ 3.9 < E_{\text{LAB}}(^{260}\text{No}) < 1594 \text{ MeV} \]