Complete Isotopic Yield Distributions from Transfer-Induced Fission of Minor Actinides

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¹ Ganil, France. ² U. De Santiago De Compostela, Spain. ³ Ipn, France. ⁴ Cenbg, France. ⁵ U. Of Liverpool, Uk. ⁶ Cea/dam, France.
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1 Ganil, France. 2 U. De Santiago De Compostela, Spain. 3 Ipn, France. 4 Cenbg, France. 5 U. Of Liverpool, Uk. 6 Cea/dam, France.
Transfer-induced fission in inverse kinematics

$^{238}\text{U} + ^{12}\text{C} @ 6.1 \text{ MeV/u}$

Transfer - fission
$\sim 100 \text{ mbarn}$

Fusion - fission
$\sim 1000 \text{ mbarn}$

Transfer
- U, Np, Pu, Am, Cm
- different $E^*$

Fission
- M: 70 - 160
- q: 25 - 45
- Z: 30 - 60
- E: 2 - 10 MeV/u

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Experimental set-up at VAMOS

- 21 Si detectors
- Ionization chamber
- Drift chamber
- SeD
- Drift chamber

Acceptance:
- 14 deg $\Theta$
- $\sim$ 3 deg $\Phi$
- 10 % $B_{\rho}$

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Fragments identified from $Z \approx 30$ to $Z \approx 60$ in 600 MeV range

Fragments mass identified from $M \approx 70$ to $M \approx 160$

$\sigma(Z) \approx 0.45$

$\sigma(M) \approx 0.35$

$>300$ fragments identified in mass, $Z$ and $Q$

**Fragment isotopic identification with VAMOS**
Isotopic yields. VAMOS acceptance

We reconstruct the $\cos(\theta_{\text{cm}})$ within the acceptance of VAMOS for each \((A,Z)\).

Once we have a $\cos(\theta_{\text{cm}})$ distribution, we fit the plateau and extend it to the full range:

$$N^{\text{exp}} = \frac{N^{\text{max}}}{2 \cdot \text{bin}}$$
Isotopic yields. VAMOS acceptance

Both $\delta$ and $\nu$ distributions are cut by the acceptance.

Before doing the projection on $\cos(\theta_{cm})$, we have to account for the cut $q$ distributions.
Isotopic yields. VAMOS acceptance

A byproduct of this method is that we have a systematics on the characteristics of the charge state distributions (width and $<q>$) as a function of $(Z,A,v)$. 

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Reaction-channel selection

No isotopic identification of the recoil:
Estimation of the contribution of each channel through its Q:

$$\frac{\sigma(Z,i)}{\sigma(Z,j)} = \frac{\exp Q(Z,i)}{\exp Q(Z,j)}$$

TABLE I. For each expected transfer channel, the $Q$-value, the measured differential cross section ($\theta_{\text{lab.}} = 43-53^\circ$), estimation of the contribution of the main channels and the optimum $Q$-value are reported

<table>
<thead>
<tr>
<th>Recoil</th>
<th>Actinide</th>
<th>$Q_0$ (MeV)</th>
<th>$d\sigma/d\Omega$ (mb.sr$^{-1}$)</th>
<th>$Q_{opt}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$C</td>
<td>$^{238}$U</td>
<td>0.00</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$^{13}$C</td>
<td>$^{237}$U</td>
<td>-1.21</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$^{11}$B</td>
<td>$^{239}$Np</td>
<td>-10.67</td>
<td>$235.0 \pm 2 {234.6$</td>
<td>0.4$}</td>
</tr>
<tr>
<td>$^{10}$B</td>
<td>$^{240}$Np</td>
<td>-17.06</td>
<td>$51 \pm 4.3 {42.3$</td>
<td>8.7$}</td>
</tr>
<tr>
<td>$^{9}$Be</td>
<td>$^{240}$Pu</td>
<td>-15.42</td>
<td>7 $\pm 10 {6.1$</td>
<td>0.9$}</td>
</tr>
<tr>
<td>$^{7}$Li</td>
<td>$^{243}$Am</td>
<td>-24.78</td>
<td>7 $\pm 10 {6.1$</td>
<td>0.9$}</td>
</tr>
</tbody>
</table>
Fusion-fission yields

Fusion-fission is produced via $^{12}\text{C}(^{238}\text{U}, ^{250}\text{Cf})$ with $E^* \approx 42$ MeV.

The events are selected in anti-coincidence with the detection of light recoil particles.
Carbon-channel fission yields

$^{12}\text{C}(^{238}\text{U}, ^{238}\text{U} f)^{12}\text{C}$ and $^{12}\text{C}(^{238}\text{U}, ^{237}\text{U} f)^{13}\text{C}$ with $E^* < 10$ MeV

Most of the reactions are inelastic with a small contribution from 1n transfer
Carbon-channel fission yields

$^{12}\text{C}(^{238}\text{U}, \, ^{238}\text{U} f)^{12}\text{C}$ and $^{12}\text{C}(^{238}\text{U}, \, ^{237}\text{U} f)^{13}\text{C}$ with $E^* < 10 \text{ MeV}$

Background from random coincidence with $^{12}\text{C}$ elastic scattering and Fusion-Fission

Comparisons with GEF code [1]


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Boron-channel fission yields

$^{12}\text{C}(^{238}\text{U}, \text{239Np f})^{11}\text{B}$ with $E^* < 1\text{ MeV}$ and $^{12}\text{C}(^{238}\text{U}, \text{240Np f})^{10}\text{B}$

Most of the reactions are $^{239}\text{Np}$ with a minimum contribution from $^{240}\text{Np}$ transfer.
Boron-channel fission yields

\[ ^{12}\text{C}(^{238}\text{U}, ^{239}\text{Np} f)^{11}\text{B} \text{ with } E^* < 1 \text{ MeV} \] and

\[ ^{12}\text{C}(^{238}\text{U}, ^{240}\text{Np} f)^{10}\text{B} \]

Background from \(^{12}\text{C}\) contamination includes some \(^{12}\text{C}\) elastic scattering and Fusion-Fission coincidences
Beryllium-channel fission yields

$^{12}\text{C}(^{238}\text{U}, ^{240}\text{Pu} f)^{10}\text{Be}$ and $^{12}\text{C}(^{238}\text{U}, ^{241}\text{Pu} f)^{9}\text{Be}$ with $E^* \approx 5 \text{ MeV}$

Around 80% of the reactions are $^{240}\text{Pu}$ with a 20% from $^{241}\text{Pu}$
Beryllium-channel fission yields

$^{12}\text{C}(^{238}\text{U}, \, ^{240}\text{Pu} \, f)^{10}\text{Be}$ and $^{12}\text{C}(^{238}\text{U}, \, ^{241}\text{Pu} \, f)^{9}\text{Be}$ with $E^* \approx 5 \text{ MeV}$

Around 80% of the reactions are $^{240}\text{Pu}$ with a 20% from $^{241}\text{Pu}$
Lithium-channel fission yields

$^{12}\text{C}(^{238}\text{U},^{243}\text{Am} f)^7\text{Li}$ and $^{12}\text{C}(^{238}\text{U},^{244}\text{Am} f)^6\text{Li}$ with $E^* \approx 8$ MeV

Around 87% of the reactions are $^{243}\text{Am}$ with a 13% from $^{244}\text{Am}$
Lithium-channel fission yields

\[ ^{12}\text{C}(^{238}\text{U}, ^{243}\text{Am} f)^7\text{Li} \text{ and } ^{12}\text{C}(^{238}\text{U}, ^{244}\text{Am} f)^6\text{Li} \text{ with } E^* \approx 8 \text{ MeV} \]

Around 87% of the reactions are \(^{243}\text{Am}\) with a 13% from \(^{244}\text{Am}\)

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Last iteration of the experiment

In 2011, the experiment was repeated with an improved set-up. Among the improvements, we expect:

- Better Z and A identification resolution
- Larger spectrometer acceptance
- Detection of both fission fragments
- Isotopic identification of the light recoil from transfer and, therefore, accurate systematics with the $E^*$

$^{12}\text{C}(^{238}\text{U},^{240}\text{Pu} \ f)^{10}\text{Be}$
Multi-nucleon transfer induced-fission in inverse kinematics permits the **study of systems not accessible** in the form of targets.

- The reconstruction of the transfer reaction determines the fissioning system and its E*.

- The use of inverse kinematics in VAMOS allows the **complete identification in (Z,A,q)** of the (almost) full fragment distribution, and the measurement of **KE, angular distr., and isotopic yields**.

- The characteristics of the fragment yield distributions can be evaluated as a **function of the E*** of the fissioning system.

- Codes like **GEF** can help to disentangle multi-chance fission by reproducing the features of the distributions (**shape, N/Z, KE, etc.**)