Decay features of medium mass nuclei at high excitation and spins

Comex5, Kraków
September 16th, 2015
The reaction

\[ ^{48}\text{Ti} \rightarrow ^{40}\text{Ca} \xrightarrow{\cdots} ^{88}\text{Mo} \]

<table>
<thead>
<tr>
<th>( E_b ) [MeV]</th>
<th>( E_{cm} ) [MeV]</th>
<th>( \varepsilon^* ) [MeV/u]</th>
<th>( l_{gr} ) [( \hbar )]</th>
<th>( l_{B_{f=0}} ) [( \hbar )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>135</td>
<td>1.4</td>
<td>91</td>
<td>79</td>
</tr>
<tr>
<td>450</td>
<td>203</td>
<td>2.2</td>
<td>124</td>
<td>79</td>
</tr>
<tr>
<td>600</td>
<td>271</td>
<td>3.0</td>
<td>149</td>
<td>79</td>
</tr>
</tbody>
</table>
### Why $^{88}$Mo?

- large fission barrier up to **high spins**
- mass region not well explored in literature
- **GDR study** performed here in Krakow
  - Michal Ciemała talk
Why $^{88}$Mo?

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This talk will be focused on:

- light charged particles emission in fusion-evaporation channel
- check of **statistical model** parameters
- fusion-evaporation and fusion-fission **cross sections**
Experimental apparatus

The experiment

- performed at *Laboratori Nazionali di Legnaro* (LNL)
- beam from ALPI linac
- Main detectors: Garfield and Hector
Experimental apparatus

**ΔE(gas) - E(Csl(Tl)) telescope array**

- cylindrical symmetry; divided into 24 azimuthal sectors
- detects LCPs and IMFs at $29^\circ < \theta < 85^\circ$
Experimental apparatus

- **Hector**
  - 8 BaF$_2$ scintillators from Hector setup
  - detect high energy $\gamma$-rays ($E_{\gamma} \gtrsim 4$ MeV)
  - not considered in the present work
Experimental apparatus

48 scintillator telescopes from FIASCO experiment

- identify evaporation residues and fission fragments
- at forward angles ($5^\circ < \theta < 15^\circ$)
Experimental apparatus

Phoswiches

- 48 scintillator telescopes from FIASCO experiment
- identify evaporation residues and fission fragments
- at forward angles ($5^\circ < \theta < 15^\circ$)
Evaporation residue selection

Condition for the selection of fusion-evaporation events

1 particle in dotted areal gate in any phoswich
no other particles in continuous areal gates
**Statistical model of Compound Nucleus decay**

The **Gemini++** statistical model code

- is a widely used statistical model code
- adopts a default set of parameters obtained by fitting data from several previous experiments
  - parameters are tuned for heavy nuclei ($A \gtrsim 150$)
  - there aren’t many experimental data to fix parameters for medium-light nuclei
- **We compared experimental data with Gemini++ varying many parameters:**
  - level density
  - Coulomb barrier distribution
  - yrast energy parametrization
  - etc. . .

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Geometry and efficiency filter

- directly compare experimental spectra with filtered simulations
- correct experimental yields for the apparatus efficiency
Comparison between experimental data and Gemini++

300 and 600 MeV ER angular distributions

- Spectra are scaled to the same integral to compare the shape
- Very good agreement
Comparison between experimental data and GEMINI++

300 MeV energy spectra in coincidence with ER

- Spectra are scaled to the same integral to compare the shape
- Very good agreement for protons
- Simulated $\alpha$ spectra have a correct slope, but lower energy
Improvement of the agreement for $\alpha$-particles

Only adopting **RLDM yrast and fission barrier** (instead of linearized Sierk) the agreement improves
Comparison between experimental data and **Gemini++**

**Proton energy spectra at 300 MeV**

**α-particle energy spectra at 300 MeV**
Comparison between experimental data and GEMINI++

proton energy spectra at 450 MeV

(a) 450MeV p 60°

(b) 450MeV p 47°

(c) 450MeV p 35°

α-particle energy spectra at 450 MeV

(d) 450MeV α 60°

(e) 450MeV α 47°

(f) 450MeV α 35°
Comparison between experimental data and \textsc{GEMINI}++

proton energy spectra at 600 MeV

\(\alpha\)-particle energy spectra at 600 MeV
Comparison between experimental data and \textit{GEMINI++}

proton angular distributions

\[ \begin{array}{c}
\text{\(p\) 300MeV} \\
\text{\(p\) 450MeV} \\
\text{\(p\) 600MeV}
\end{array} \]

\(\alpha\)-particle angular distributions

\[ \begin{array}{c}
\text{\(\alpha\) 300MeV} \\
\text{\(\alpha\) 450MeV} \\
\text{\(\alpha\) 600MeV}
\end{array} \]
Comparison between experimental data and **Gemini++**

![Graph showing comparison between experimental data and Gemini++](image-url)

- **Ebeam [MeV]**: 200, 300, 400, 500, 600, 700, 800
- **Multiplicity**: 1, 2, 3, 4, 5, 6
- **Particles**:
  - p total
  - d total
  - \(\alpha\) total
  - p from GARFIELD
  - d from GARFIELD
  - \(\alpha\) from GARFIELD

The graph illustrates the comparison of experimental data with predictions from the Gemini++ model across different multiplicity and energy beam (Ebeam) levels. The data points for various particles (protons, deuterons, and \(\alpha\) particles) are plotted against Ebeam values, showing how the model compares to experimental observations.
Cross section estimations

Rutherford cross-section normalization

It’s possible to measure cross sections via a normalization obtained from a plastic scintillator at 2° that measures elastic scattering

\[
\sigma_{FE}(300 \text{ MeV}) = 0.89(11) \text{ b}
\]

\[
\sigma_{FE}(450 \text{ MeV}) = 0.55(5) \text{ b}
\]

\[
\sigma_{FE}(600 \text{ MeV}) = 0.46(12) \text{ b}
\]

Cross section estimations

Rutherford cross-section normalization

It’s possible to measure cross sections via a normalization obtained from a plastic scintillator at 2° that measures elastic scattering.

\[
\sigma_F(300 \text{ MeV}) = 1.01(11) \text{ b}
\]

\[
\sigma_F(450 \text{ MeV}) = 0.81(6) \text{ b}
\]

\[
\sigma_F(600 \text{ MeV}) = 0.88(16) \text{ b}
\]
We measured the reaction $^{48}\text{Ti} + ^{40}\text{Ca}$ at 300, 450 and 600 MeV to study the decay of nuclei of masses in the region $A \sim 90$.
Conclusions

- We measured the reaction $^{48}\text{Ti} + ^{40}\text{Ca}$ at 300, 450 and 600 MeV to study the decay of nuclei of masses in the region $A \sim 90$
- Gemini++ statistical model code well describes the decay in the evaporative channel at least in Garfield ($\theta > 30^{\circ}$)
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- We found an $\alpha$-particle yield excess, in particular at forward angles and increasing with energy.
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It's difficult to improve the agreement by tuning the model parameters; indication of the onset of minor pre-equilibrium emission or contamination from other processes.
Conclusions

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- It's difficult to improve the agreement by tuning the model parameters; indication of the onset of minor pre-equilibrium emission or contamination from other processes.

- We gave an estimation of fusion-evaporation and total fusion cross section. Especially at higher energies, there is room for DIC and quasi-fission decays.
Thanks for your attention!