Properties of highly deformed systems studied by fission

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Why study fission?

Deformation landscape of nuclei

Fission barrier $B_f$: mass of saddle
Pairing ($\Delta_0$)
shell corrections ($\Delta_{\text{shell}}$)
single particle level density ($g$)
Congruence Energy (Wigner term masses)

Stationary point:

⇒ Fission spectroscopy
What is known about the detailed properties of the saddle point?

- Very little compared to the ground state.
- ~100 known fission barriers
  - Typically restricted to very heavy nuclei
  - Poor precision
New precision data

Systematic data sets

<table>
<thead>
<tr>
<th>Year</th>
<th>Reaction</th>
<th>CN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>$^3\text{He} + ^{182,184,186}\text{W}$</td>
<td>185-187,189\text{Os}</td>
</tr>
<tr>
<td>1999</td>
<td>$d + ^{204,206-208}\text{Pb}$</td>
<td>206,208-210\text{Bi}</td>
</tr>
<tr>
<td>2000</td>
<td>$p + ^{204,206-208}\text{Pb}$</td>
<td>205,207-209\text{Bi}</td>
</tr>
<tr>
<td>1997</td>
<td>$^3\text{He} + ^{206-208}\text{Pb}$</td>
<td>209-211\text{Po}</td>
</tr>
<tr>
<td>1999</td>
<td>$^3\text{He} + ^{204}\text{Pb}$</td>
<td>207\text{Po}</td>
</tr>
<tr>
<td>1999</td>
<td>$^4\text{He} + ^{204,206-208}\text{Pb}$</td>
<td>208,210-212\text{Po}</td>
</tr>
</tbody>
</table>

- High purity targets
  - Parts per billion uranium
- High purity beams
Example of data

- Cross sections vary by over 8 orders of magnitude!
- Few MeV over the barrier
Example of data

- Old fitting procedure
  - One compound nucleus
  - First chance fission only

\[ P_f(E) = \frac{\Gamma_f}{\Gamma_c} \sim \frac{A(E-E_c)}{(E-E_c)^{1/2}} \]
Old fitting procedure

- Given nucleus, 1st chance
  fission only

\[ P_f(E) = \frac{f_f}{f_i} \frac{\sigma(E - Z_f)}{\sigma(E - Z_f - 2Z_n)} \]

New fitting procedure

- Fit a chain of neighboring
  compound nuclei
- Multiple chance

\[ \sigma_f = \sum_n f_n = \sum_n (n + 1)n^2 \sigma_f^{(n)}(E) \]

Each neutron carriers \(2T + B_n\)
Extracting $\Delta_{\text{shell}}$

- See the shell closure at $N=126$
- Remarkable sensitivity to the shell corrections
- Nearly spectroscopic precision!
More shell effects

- Po, Bi, Pb, Os chains of data
- "Old" fits (single system, first-chance fission only) have large errors ±2MeV
- "Local" measures of Δ_{shell}
- Hg, Pt and Os targets would give more data
Fission barriers

- $B_f$: improved accuracy
- Assume that there are no shell corrections at the saddle

$$B_f = B_{\text{macro}} - \Delta \text{shell}$$

![Graph showing fission barriers for Po isotopes](image)
Potential analyses

**GS properties**
- Level density
- Pairing
- Shell effects
  - Local measurements
- Mass

**Saddle properties**
- Level density (example)
- Pairing
- Shell effects
  - Expected to be small
- Fission barrier
  - Congruence energy
- Fission time delay
Fission time delay

- Fission decay width is suppressed during the time it takes to get to the saddle configuration.
- Fission probability is suppressed.
- Approximate suppression with step function
Fission transient times

- Assume experimental $\Delta_{\text{shell}}$
- Add delay time $\tau_D$ (step function)
  
  Suppresses first chance fission
  
  $\tau_D = 10 \times 10^{-21}$ seconds
Pairing at the saddle

- Currently not a free parameter
- Pairing in the ground state:
  \[ \Delta_0 = \frac{12}{\sqrt{A}} \text{MeV} = S \exp \left( -\frac{1}{gG} \right) \text{MeV} \]
- Pairing at the saddle:
  \[ \Delta_0^f = S \exp \left( -\frac{1}{g_f G} \right) \text{MeV} \]
  \[ g_f = \frac{3}{\pi^2 a_f} \]

Condensation energy:

\[ \Delta E_c^f = \frac{1}{2} g_f \Delta_0^2 - \Delta_0 \]
Why study the macroscopic barrier?

- Myers and Swiatecki have identified an extra binding energy term in their description of the ground state masses. The "normal" symmetry energy describes the dependence of the binding energy upon isospin $I=(N-Z)/A$. It has the form $AI^2$.

- The extra term empirically is:

$$C(I) = -10e^{-4.2/I}\text{MeV}$$

independent of $A$

- Described in terms of the granularity of nucleonic density distributions in a potential well. This "congruence energy" is independent of $A$, and thus doubles when a nucleus is divided into two non-communicating pieces (fission from a very necked-in saddle).

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Studying the surface area dependence of the level density parameter $a$

$$a = \frac{A}{14.61 \text{ MeV}} \left(1 + \frac{4}{A^{1/3}} F_2 \right)$$

$F_2$ is the surface area in units of a sphere

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$a_f/a_n$</th>
<th>estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Os</td>
<td>1.062</td>
<td>1.095</td>
</tr>
<tr>
<td>Po</td>
<td>1.020</td>
<td>1.074</td>
</tr>
</tbody>
</table>

Fission Barrier Measurements with Stable and Radioactive Beams

Near future:
Normal kinematics

Clean, separated isotope targets

Fission Barrier Measurements with Fragmentation Beams from RIA

Long term:
Reverse kinematics
Long term requirements

- **Active target**
  - GSI, 1 GeV/nucleon fission following Coulomb excitation
  - track to know which foil
- **Ideally:**
  - $E/A=20-80$ MeV
  - H, He target (low fusion barriers)
  - Track to find interaction point ($E$). Get the entire excitation function at one bombarding energy
  - **Several** excitation functions at one time (beam tagging)
Summary & Outlook

- Saddle mass surface still largely unexplored
- Systematic fission measurements and systematic analysis (global fits)
- Successes so far:
  - Ground state $\Delta_{\text{shell}}$ (determined "locally")
  - Accurate $B_f$
  - Time delay $\tau_D = 10 \times 10^{-21}$ seconds
- Future:
  - Congruence energy (shape dependence)
  - Single particle level densities at the saddle
  - Pairing at the saddle
  - Shell effects at the saddle
- Extract fission parameters for alpha induced reactions (assuming Bass model fusion cross sections).
- What comes out for $^3\text{He}$-induced reactions?

\[ \sigma_i = \sum \sigma_i^p = \sum \sum (2l+1) a_k^2 P^l_m(\hat{n}) \]

- Vary $l_{\text{max}}$ until we get perfect agreement. What do the fusion cross sections look like?
• It would be useful to make the Bass model more general and include it as part of the fit.
  — Low energy part: \( \sigma_0 = \pi R^2 (1 - V/E) \)
  — High energy part: \( \sigma_0 E = \pi R^2 (E_2 - V) \)
• Marry the two behaviors: adds two more parameters to fit \((R, E_2 - V)\)

\[
\sigma_0 = (E_2 - V) \frac{\pi r^2}{E} \left( \frac{E - V}{E_2 - V} \right)
\]

\( V = 21.315 \text{ MeV} \quad \pi R^2 = 41.77 \text{ mb} \quad \beta = 31.72 \)
“Bass-like” fusion cross sections

- ** Projectile $E_2-V$ **
  - $^4\text{He}$ 32.3 MeV
  - $^3\text{He}$ 23.8 MeV

- $E_2-V=1/2\mu v^2$

- Ratio should go like the reduced masses (about 4/3).

- Actual value is 1.36