Fragmentation reactions and nuclear level densities

Cross sections
Isomeric ratios

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Fragmentation (spallation) reactions at relativistic energies:

- Abrasion
- Ablation
- Multi-hole state

To be discussed:
- Cross section: measures the end product
- Spin: info mainly about abrasion

Fragmentation (spallation) reactions at relativistic energies:

Ablation competes with fission (238U beam)

Survival probability against fission (production cross section) depends on level density
In flight fragmentation (and fission): separation and identification

Fragment Separator (GSI, Darmstadt, Germany)

Production target

238U
1 GeV/A

Beam: 1 GeV/A

dipole: $B\rho$

Degrader

SCI

TOF: $\beta\gamma$

MW: $x,y$

IC: $dE,Q$

MW

SCI

Catcher

$A \frac{Q}{Q} = \frac{B\rho e}{\beta\gamma c u}$

Relativistic energy fragmentation: $\Rightarrow$ heavy ions

Position (final focal point) (mm)

A/q

2.54 2.55 2.56 2.57 2.58 2.59 2.60 2.61 2.62 2.63 2.64

20 40 60 80 100

100 50 0 -50 -100
if $A_{\text{projectile}} - A_{\text{fragment}} \sim \text{large (>10)}$

Statistical abrasion-ablization model

(ABRABLA code)

Excitation energy

$\sim 27 \text{ MeV/abrated nucleon}$

$= 2 \times \text{single particle (holes) energy}$

Ablated nuclei/abraded nuclei $\sim 2$

Fission depends on level density

Good cross sections

$^{238}$U fragmentation

No fission

No shell effects, no collective

With shell effects

$\rho = \frac{\sqrt{\pi} \exp(S)}{12\tilde{a}^{1/4}E^{5/4}}$

$S = 2\sqrt{\tilde{a}(E + \delta U k(E) + \delta Ph(E))}$

Shell effect + collective

Fig. 2. Fission barriers of nuclei in the region of interest for the present investigation. Upper part: The macroscopic part [37] of the fission barrier at zero angular momentum. Lower part: The curves include the contribution of the ground-state shell effect [38].
Rotational enhancement

\[ \rho(E) = K_{\text{coll}}(E) \rho_{\text{intr}}(E) \]

Ground-state deformation

Saddle-point def.

Dumping independent on deformation

A.R. Junghans et al.,
Collective enhancement


rotational

vibrational
Collective enhancement

Damping dependent on def.

Damping independent on def.

+vibrational enhancement

Conclusions from cross section measurements

- No stabilisation against fission near N=126
- Effect of shell stabilisation and collective enhancement on fissility cancels out
- Damping of the collective enhancement in the level density is independent of deformation

if $A_{\text{projectile}} - A_{\text{fragment}} \sim \text{large (}>10\text{)}$

Statistical abrasion-ablation model
(ABRABLA code)

Angular momentum

from single particle states only

$$\rho_n(U, J) = \frac{2J + 1}{2\sigma_n^2} \exp \left( -\frac{J(J+1)}{2\sigma_n^2} \right) \rho_n(U)$$

Spin-cutoff parameter

$$\sigma_n^2 = 0.234 \left(1 - \frac{U}{n\epsilon_f}\right) A_p^{2/3} \frac{n(A_p - n)}{A_p - 1}$$

$U$ – excitation energy from $n$ holes only

Is this good enough?

<table>
<thead>
<tr>
<th>Nuclei</th>
<th>$\bar{U}_1$ [MeV]</th>
<th>$\langle j_z^2 \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>9.25</td>
<td>2.08</td>
</tr>
<tr>
<td>$^{56}$Ni</td>
<td>9.61</td>
<td>2.54</td>
</tr>
<tr>
<td>$^{90}$Zr</td>
<td>10.25</td>
<td>3.01</td>
</tr>
<tr>
<td>$^{120}$Sn</td>
<td>10.76</td>
<td>3.38</td>
</tr>
<tr>
<td>$^{182}$W</td>
<td>11.40</td>
<td>4.56</td>
</tr>
<tr>
<td>$^{208}$Pb</td>
<td>10.94</td>
<td>5.50</td>
</tr>
<tr>
<td>$^{235}$U</td>
<td>11.47</td>
<td>5.12</td>
</tr>
</tbody>
</table>

(from simplified shell model)

\[
\sqrt{\langle J^2 \rangle} = \sqrt{2} \sigma
\]

In flight fragmentation (and fission): separation and identification

Relativistic energy fragmentation: \( \Rightarrow \) heavy ions

Isomeric decay spectroscopy:

- gamma decay correlated with the fragment

- very sensitive
Stopped Rising Array @ GSI: 15 x 7 element CLUSTERs

$\varepsilon_\gamma = 11\%$ at 1.3 MeV, 20% at 550 keV, 35% at 100 keV

flight time ~300ns
Highest spin from fragmentation: $I=(55/2)$ isomer in $^{213}$Rn

Fig. 1. Gamma-ray energy spectrum obtained in coincidence with $^{213}$Rn ions using a time gate of width 1.4 μs starting ~50 ns after the prompt flash. The transitions used to obtain the isomeric ratios for the $^{(55/2)^+}$, $^{43/2^-}$, $^{31/2^-}$ and $^{25/2^+}$ levels are denoted #, *, %, and @ respectively.

Isomeric ratio

\[ R_{\text{exp}} = \frac{N_{\text{isomer}}}{N_{\text{total}}} \]

\[ P(I) = \frac{2I + 1}{2\sigma_f^2} \exp \left( - \frac{I(I+1)}{2\sigma_f^2} \right) \]

\[ \rho_{\text{theo}} = \int_{I_m}^{\infty} P(I) dI \]

\( I_m \) (sharp cut-off approx.)

Isomeric ratios from $^{208}$Pb and $^{238}$U fragmentation
Isomeric ratio vs spin

Comparison with theory

Nuclear structure has to be considered

\[ \phi = I_{\text{isomer}}/(I_{\text{parallel}}+I_{\text{isomer}}) = I_{\text{isomer}} / I_{\text{total}} \]

\[ \rho_{\text{exp}} = R_{\text{exp}} / \phi \]

\( \rho_{\text{exp}} \) - the probability of populating states with higher spin than the isomer – can be compared with theory!
Without structure considerations

![Graph showing data points for different isotopes and spin values. The graph plots \( R_{\text{exp}}/\rho_{\text{th}} \) against spin (hbar). There are data points for \( \sim^{208}\text{Pb} \), \( \sim Z=74, (N=74) \), and \( \sim Z=82, \text{p–rich} \).]
With structure considerations

OK within a factor of two!
Comparison with theory

Fragments are slower than projectile: momentum shift (friction)

\[ I = r \times p_{\text{shift}} \]

\( \rightarrow \) angular momentum produced (collective)  \( I \) perpendicular to the beam
Other sources of spin?


Doubled spin-cutoff parameter

Analytical formula, $R_{th}^f (2\sigma_f^2)$

$R_{exp} / R_{th}$

$l_m (h)$

Conclusions

Production of $^{238}$U fragments hindered by fission

Fission probability described considering the level density

At high-spins the angular momentum from abraded nuclei are not enough: contributions from evaporation, friction, excitations

*High-spin states are produced with higher probability than expected* (isomeric beams)

Can this be related to:

the spin distribution of level density?

level density through spin dependence of fission?