The role of fission in the r-process nucleosynthesis

- or -

What do we need to know about fission

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Importance of fission

Trans-U elements ? 1)

r-process endpoint ? 2)

Fission cycling ? 3, 4)

See also poster by I. Panov (ID 142)

2) Panov et al., NPA 747 (2005) 633
3) Seeger et al, APJ 11 Suppl. (1965) S121
4) Rauscher et al, APJ 429 (1994) 49
What do we need?

- Fission probabilities $\Rightarrow$ fission barriers, masses, nuclear level density

- Fission-fragment distributions

Challenge for experiment and theory

- Large-scale collective motion

- Nuclear structure effects (shell effects, pairing...) at large deformations

- Fission dynamics

- All this for nuclei not accessible in laboratory
Fission barriers

Strong influence on the fission contribution to the r-process nucleosynthesis
Available data on fission barriers, $Z \geq 80$ (RIPL-2 library)
Fission barriers

Relative uncertainty: $>10^{-2}$

GS masses

Relative uncertainty: $10^{-4} - 10^{-9}$

Courtesy of C. Scheidenberger
Experiment - Difficulties

• Experimental sources:
  Energy-dependent fission probabilities

• Extraction of barrier parameters:
  Requires assumptions on level densities

Gavron et al., PRC13 (1076) 2374
Theory

• Recently, important progress on calculating the potential surface using **microscopic approach** (e.g. groups from Brussels, Goriely et al; Bruyères-le-Châtel, Goutte et al; Madrid, Pèrez and Robledo; ...):
  - Way to go!
  - But, not always precise enough and still very time consuming

• Another approach ⇒ **microscopic-macroscopic models** (e.g. Möller et al; Myers and Swiatecki; Mamdouh et al; ...)

• Common for all approaches:
  **Limited experimental information** on the height of the fission barrier ⇒ in any theoretical model the constraint on the parameters defining the dependence of the fission barrier on neutron excess is rather weak.
Open problem

Limited experimental information on the height of the fission barrier

Kelić and Schmidt, PLB 643 (2006)

Panov et al., NPA 747 (2005)
Predictions of theoretical models are examined by means of a detailed analysis of the isotopic trends of ground-state and saddle-point masses.

\[ \delta U_{sad} = E_f^{exp} + M^{exp} - (M^{macro} + E_f^{macro}) \]

- Experimental saddle-point mass
- Macroscopic saddle-point mass

\( \delta U_{sad} \leftrightarrow \text{Empirical saddle-point shell-correction energy} \)
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1. Shell corrections have local character

2. \( \delta U_{sad} \) should be very small (e.g Myers and Swiatecki PRC 60 (1999); Siwek-Wilczynska and Skwira, PRC 72 (2005))

\[ \langle \partial (\delta U_{sad}) / \partial N \rangle_N \approx 0 \]

Any general trend would indicate shortcomings of the model.

Kelić and Schmidt, PLB 643 (2006)
1) **Droplet model** (DM) [Myers 1977], which is a basis of often used results of the Howard-Möller fission-barrier calculations [Howard&Möller 1980]

2) **Finite-range liquid drop model** (FRLDM) [Sierk 1986, Möller et al 1995]

3) **Thomas-Fermi model** (TF) [Myers and Swiatecki 1996, 1999]

4) **Extended Thomas-Fermi model** (ETF) [Mamdouh et al. 2001]

W.D. Myers, „Droplet Model of Atomic Nuclei“, 1977 IFI/Plenum
A. Sierk, PRC33 (1986) 2039.
W.D. Myers and W.J. Swiatecki, PRC 60 (1999) 0 14606-1
A. Mamdouh et al, NPA 679 (2001) 337
Results

Slopes of $\delta U_{sad}$ as a function of the neutron excess

$A_1$ / MeV

- DM, $A_1 = 0.16 \pm 0.02$ MeV
- TF, $A_1 = -0.003 \pm 0.010$ MeV
- FRLDM, $A_1 = -0.03 \pm 0.01$ MeV
- ETF, $A_1 = -0.18 \pm 0.02$ MeV

$\Rightarrow$ The most realistic predictions are expected from the TF model and the FRLD model

$\Rightarrow$ Further efforts needed for the saddle-point mass predictions of the droplet model and the extended Thomas-Fermi model

Kelić and Schmidt, PLB 643 (2006)
Mass and charge division in fission
• Particle-induced fission of long-lived targets and spontaneous fission (~ 80 nuclei)

Available information:
- A(E*) in most cases
- A and Z distributions of light fission group only in the thermal-neutron induced fission on the stable targets

• EM fission of secondary beams at GSI (~ 100 nuclei)

Available information:
- Z distributions at one energy

Available data far from r-process path!
How well can we describe exp data?

⇒ **Empirical systematics** - Problem is often too complex

⇒ **Theoretical model** - Way to go, but not always precise enough and still very time consuming. Encouraging progress for a full microscopic description of fission:

Time-dependent HF calculations with *GCM*: Goutte et al., *PRC* 71 (2005)

⇒ **Semi-empirical models** - Theory-guided systematics

FIG. 14. Theoretical mass distributions (solid lines) are compared with the Wahl evaluations of neutron-induced fission of $^{238}\text{U}$ [24] (dashed lines). Excitation energies of the compound $^{238}\text{U}$ nucleus measured above the barrier are (a) $E = 2.4$ MeV, (b) $E = 1.1$ MeV.
Macroscopic-microscopic approach

- Transition from single-humped to double-humped explained by macroscopic (fissioning nucleus) and microscopic (nascent fragments) properties of the potential-energy landscape near the saddle point.

- For each fission fragment we get:
  - Mass
  - Charge
  - Velocity
  - Excitation energy
Comparison with data

Fission of secondary beams after the EM excitation:

- **black - experiment** (Schmidt et al, NPA 665 (2000))
- **red - calculations**

With the same parameter set for all nuclei!
Applications

FF masses and nuclear charges, number of emitted pre- and post-scission particles used as input for r-process network calculations ⇒ talk by Gabriel Martinez-Pinedo
Conclusions

- Further experimental and theoretical efforts are needed

- Important progress have been made in microscopic description of fission, but for applications one still has to rely on microscopic-macroscopic models

- Need for more precise and new experimental data using new techniques and methods ⇒ basis for further developments in theory
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Nikolaj Zinner (Aarhus)

* www.gsi.de/charms
Additional slides
What do we need?

Different entrance channels:

- **n-induced fission**
  (e.g. Panov et al, NPA 747)

- **beta-delayed fission**
  (e.g. Staudt and Klapdor-Kleingrothaus, NPA 549; Panov et al, NPA 747)

- **neutrino-induced fission**
  (e.g. Kolbe et al, PRL 92; Kelić, Zinner et al, PLB 616)

- **spontaneous fission**
  (e.g. Ohnishi, Prog. Theor. Phys. 47)
Extraction of barrier parameters:

Requires assumptions on level densities.

Gavron et al., PRC13
Theoretical difficulties

**Dimensionality** (Möller et al, PRL 92) and **symmetries** (Bjørnholm and Lynn, Rev. Mod. Phys. 52) of the considered deformation space are very important!
Example for uranium

$\delta U_{sad}$ as a function of a neutron number

A realistic macroscopic model should give almost a zero slope!
Ternary fission

Ternary fission $\Rightarrow$ less than 1% of a binary fission

• **Strutinsky-type calculations of the potential-energy landscape** (e.g. P. Möller)
  + Good qualitative overview on multimodal character of fission.
  - No quantitative predictions for fission yields.
  - No dynamics

• **Statistical scission-point models** (e.g. Fong, Wilkins et al.)
  + Quantitative predictions for fission yields.
  - No memory on dynamics from saddle to scission.

• **Statistical saddle-point models** (e.g. Duijvestijn et al.)
  + Quantitative predictions for fission yields.
  - Neglecting dynamics from saddle to scission.
  - Uncertainty on potential energy leads to large uncertainties in the yields.

• **Time-dependent Hartree-Fock calculations with GCM** (Goutte)
  + Dynamical and microscopic approach.
  - No dissipation included.
  - High computational effort.
How well do we understand fission?

Influence of nuclear structure (shell corrections, pairing, ...)

M.G. Itkis et al., Proc. Large-scale collective motion of atomic nuclei, Brolo, 1996

Also dynamical properties (e.g. viscosity) play important role!

K.-H. Schmidt et al., NPA 665 (2000) 221