Fission Barriers of Neutron-Deficient Nuclei

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Electron-Capture Delayed Fission (ECDF, $T_{1/2}(ff)=T_{1/2}(EC)$)

Discovery: parent isotopes $^{232,234}$Am (1966, Dubna)

- 2 step process: EC decay of a parent $(A,Z)$ nucleus populates an excited state in the $(A,Z-1)$ daughter, which then might fission (in competition with the $\gamma$ decay to the g.s.)
- Low-energy fission! ($E^* \sim 5$-$10$ MeV)
- 12 cases known so far (neutron-def. Uranium region)

$P_{ECDF}$ depends strongly on:
- $Q_{EC}$ of the parent: the higher $Q_{EC}$, the larger the $P_{ECDF}$
- $B_{fis}$ of the daughter: the lower $B_{fis}$, the larger the $P_{ECDF}$
- Actually, $Q_{EC} - B_{fis}$ is important

$P_{ECDF} = \frac{N_{ECDF}}{N_{EC}}$
Before the IS466 experiment: How $^{180}$Hg ($Z=80, N=100, N/Z=1.25$) fissions?

**SYMMETrICAL** mass split in two semi-magic $^{90}$Zr ($Z=40, N=50, N/Z=1.25$)?

**IS466:**

NO! **ASYMMETRICAL** energy (thus, mass) split!

**Asymmetric fission of $^{180}$Hg is not caused by shell structure!**

*First such case observed, new mode of fission!*
Fission into two semi-magic fragments disfavored? Another example

\[ 132 = 50 + 82 \]
Fission barriers - what do we know about them?

• Experimentally fission barriers $B_f$ are known only in the vicinity of the beta stability line (e.g. $N/Z(^{238}U)=1.59$)

• Theoretical models for $B_f$ have been ‘tuned’ by using these data.

Available data on fission barriers, $Z \geq 80$
(RIPL-2 library http://www-nds.iaea.org/ripl-2/)

• For the r-process calculations we need fission data far away from stability: e.g. $^{260}$Po or $^{270}$U ($N/Z>2!$) – they might not be accessible in the Lab at all! – Use calculations?
Fission barriers of neutron-deficient nuclei

- extracted from evaporation residue cross sections using statistical model
- lower than predictions of model calculations by 15% (Sierk) to 30% (Cohen-Plasil-Swiatecki).
- are the macroscopic barriers wrong or is it a problem with description of fission decay width?

Data obtained at VASSILISSA, Dubna

**ECDF Probability: Feeding Part & Decay Part**

\[
P_{\text{ECDF}} = \frac{N_{\text{ECDF}}}{N_{\text{EC}}} = \frac{\int_{0}^{Q_{\text{EC}}} F(Q_{\text{EC}}-E) \times S_{\beta}(E) \frac{\Gamma_{f}(E)}{\Gamma_{\text{tot}}(E)} \, dE}{\int_{0}^{Q_{\text{EC}}} F(Q_{\text{EC}}-E)^5 \times S_{\beta}(E) \, dE}
\]

- **\( F(Q_{\text{EC}}-E) \)** – phase space factor for EC/\( \beta^+ \) decay, \((Q_{\text{EC}}-E)^2\) for EC, \((Q_{\text{EC}}-E)^5\) for \( \beta^+ \)

- **\( S_{\beta}(E) \)** – \( \beta \)-strength function (nuclear matrix element)

**Measurement of \( P_{\text{ECDF}} \) allows to deduce Fission Barrier \( B_f \)**
Saturation of ECDF probability

Usual behavior – $P_{bdf}$ saturates at value few orders lower than unity ($^{196}$At used in the example)

$P_{bdf} \rightarrow 1$

$Q_{ec}$ just above $B_f$, no strength below $B_f$

$B_f$ close to minimal excitation energy
Fission barriers extracted from probability of EC-delayed fission for $^{180}$Tl:

Experimental value: for $^{180}$Tl - $P_{bdf} = 3.2(2) \cdot 10^{-5}$

Fission barrier of $^{180}$Hg - HIVAP-like statistical model analysis (fission and gamma emission included, variant A):
- flat strength function (in the range $\Delta - Q_{EC}$), $B_f = 7.34$ MeV
- strength func., Möller et al., parent nucl. with g.s. deformation, $B_f = 6.76$ MeV
- strength func., Möller et al., daughter nucl. with g.s. deformation, $B_f = 7.23$ MeV
- strength func., Staudt et al., $B_f = 6.77$ MeV

Theoretical values
Möller et al., 2009, $B_f = 9.81$ MeV
$B_f$(Sierk), shell corr. Möller and Nix 1981, $B_f = 9.69$ MeV
$B_f$(Cohen,Plasil,Swiatecki), shell corr. Myers and Swiatecki 1967, $B_f = 11.40$ MeV
EC-delayed fission of $^{180}\text{Tl}$

$P_{bdf} = 3.2(2) \cdot 10^{-5}$

- used to deduce fission barrier height of the daughter isotope $^{180}\text{Hg}$.

- four alternative strength functions (thick lines) and four variants of statistical calculations (A-D) are used to determine the fission barrier. A-C – Fermi-gas level density formula, D – Gilbert-Cameron formula, pairing see explanation below figure.

- deduced fission barriers appear to be 7-30 % smaller than theoretical estimates (thin lines).

- spread in determined fission barrier heights results dominantly from uncertainty concerning the magnitude of the pairing gap in the saddle configuration.
Fission barriers extracted from probability of EC-delayed fission for $^{178}$Tl:

Experimental value: for $^{178}$Tl - $P_{bdf} = 1.5(6) \times 10^{-3}$

Fission barrier of $^{178}$Hg- HIVAP-like statistical model analysis (fission and gamma emission included, variant A):
- variant A, flat strength function (in the range $\Delta - Q_{EC}$), $B_f = 6.48$ MeV
- variant B, flat strength function (in the range $\Delta - Q_{EC}$), $B_f = 8.22$ MeV
- variant C, flat strength function (in the range $\Delta - Q_{EC}$), $B_f = 7.50$ MeV
- variant D, flat strength function (in the range $\Delta - Q_{EC}$), $B_f = 7.36$ MeV

Theoretical values
Möller et al., 2009, $B_f = 9.32$ MeV
$B_f$(Sierk), shell corr. Möller and Nix 1981, $B_f = 9.44$ MeV
$B_f$(Cohen,Plasil,Swiatecki), shell corr.Myers and Swiatecki 1967, $B_f = 10.67$ MeV
EC-delayed fission of $^{178}$Tl

$P_{\text{bdf}} = 1.5(6) \times 10^{-3}$

- used to deduce fission barrier height of the daughter isotope $^{178}$Hg.
- flat strength function and four variants of statistical calculations (A-D) are used to determine the fission barrier. A-C – Fermi-gas level density formula, D – Gilbert-Cameron formula, pairing see explanation below figure.
- deduced fission barriers (thick lines) appear to be 12-30 % smaller than theoretical estimates (thin lines).
- spread in determined fission barrier heights results dominantly from uncertainty concerning the magnitude of the pairing gap in the saddle configuration.
EC-delayed fission of $^{188}$Bi and $^{196}$At

$P_{\text{bdf}}$ from Andreyev et al. PLB 1992, similar observation as for $^{178,180}$Hg is verified also for fission barrier heights extracted delayed fission of $^{188}$Bi and $^{196}$At.

c) $^{188}$Pb

d) $^{196}$Po

| FG level density, full pairing at the saddle | FG level density, no pairing at the saddle | FG level density, no pairing at all | G-C level density, no pairing at the saddle |
| FG level density, full pairing at the saddle | FG level density, no pairing at the saddle | FG level density, no pairing at all | G-C level density, no pairing at the saddle |
Fission barriers of transuranium nuclei – comparison of values extracted from Pb\textsuperscript{bdf} systematics (flat S\textsubscript{b}, variant D) to theoretical values (Sierk, shell corr. by MN81)
Fission barriers of very proton-rich nuclei extracted from probability of ECDF appear to be consistently lower than theoretical predictions, while close to beta-stability they appear to agree. Treatment of symmetry energy?

Fission barriers of even-even nuclei extracted from ECDF depend strongly on magnitude of pairing gap in the saddle configuration which is not known.

Solution – study low energy fission of odd-even and odd-odd nuclei. Use of radioactive heavy ions beams opens opportunities to study of such nuclei.
Letter of Intent to the
ISOLDE and Neutron Time-of-Flight Experiments Committee
for experiments with HIE-ISOLDE

Transfer induced fission of heavy radioactive beams

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Abstract

Transfer induced fission is proposed as a tool to study low energy fission of exotic heavy nuclei. Fission cross sections in transfer reactions calculated for the radioactive beams show strong sensitivity to fission barrier height and thus offer possibility to determine it in experiment. The long lasting question concerning the fission barrier height as a parameter of statistical calculations, relevant e.g. for production of super-heavy nuclei, can be addressed. Depending on determined fission barriers and corresponding fission rates, transfer induced fission will offer a more general tool to study the low energy fission of heavy exotic nuclei at the ISOLDE. Complementary to fission studies, spectroscopic investigations can be carried out for the most prominent transfer reactions products.
Transfer induced fission at HIE-ISOLDE

- Radioactive beams at the ISOLDE can be used to directly determine fission barrier heights of exotic heavy fissile nuclei and thus to continue this work after 30 years!
- Estimates using the Talys code in the region between lead and uranium show that energy upgrade of the REX-ISOLDE post-accelerator to 4-5 AMeV will allow this type of low energy fission studies.
- Fission cross sections for the radioactive beam 182Hg increase dramatically when the fission barrier height is scaled down by 15% (solid line) compared to standard values of fission barriers (dashed line).
- Experimentally observable rates of one fission per minute are estimated after scaling down (assuming thin 0.1 mg/cm² CD₂ target, total fission cross section of 30 mb around 5 AMeV and RIB intensity 10⁵ s⁻¹), while the rates calculated using full theoretical fission barriers [4,5] remain of the order of one event per hour.
- Candidates for this type of measurement for each of considered isotopic chains.
Fig. 1. Fission cross sections in \((d,pf)\) and \((d,nf)\) reactions for the radioactive beam \(^{182}\text{Hg}\) calculated with and without reduction of fission barrier [5] by 15% (solid and dashed line, respectively). Strong sensitivity to fission barrier height offers possibility to determine it experimentally.
Isoscaling in 14 MeV n-induced fission – manifestation of deformed shell structure?

Isoscaling studies of fission of heavy RIBs?

M. Veselský et al., PRC 69(2004)44607
Isocaling in spontaneous fission – manifestation of deformed shell structure
Conclusions:

Fission barriers of very proton-rich nuclei extracted from probability of ECDF appear to be consistently lower than theoretical predictions, while close to beta-stability they appear to agree. Treatment of symmetry energy?

Fission barriers of even-even nuclei extracted from ECDF depend strongly on magnitude of pairing gap in the saddle configuration which is not known.

Solution – study low energy fission of odd-even and odd-odd nuclei. Use of radioactive heavy ions beams opens opportunities to study of such nuclei.

Use of radioactive heavy ions beams opens wide opportunities to study various aspects of nuclear fission, solve open question and observe new phenomena.