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Fission shape isomers – new opportunities with ν-Ball

Stephan Oberstedt

ν-Ball workshop, IPN Orsay, May 19 – 20, 2016

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- Fission observables
- Open question(s) after 75 years

- Where do shape isomers come in

- Opportunities offered by ν-Ball
- Some first cases

The fission process

prompt neutrons (10^{-18} s)

prompt γ-rays (10^{-16} s)

fission fragments (10^{-21} s)

ternary α, t, d, ^{10}Be…

kinetic energy prompt γ-rays	heat
prompt neutrons (delayed neutrons)	chain reaction
ternary α, t, d	gas production in the fuel (waste)
fission fragments	decay heat, toxicity (waste)

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The fission process

prompt neutrons (10^{-18} s)

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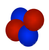
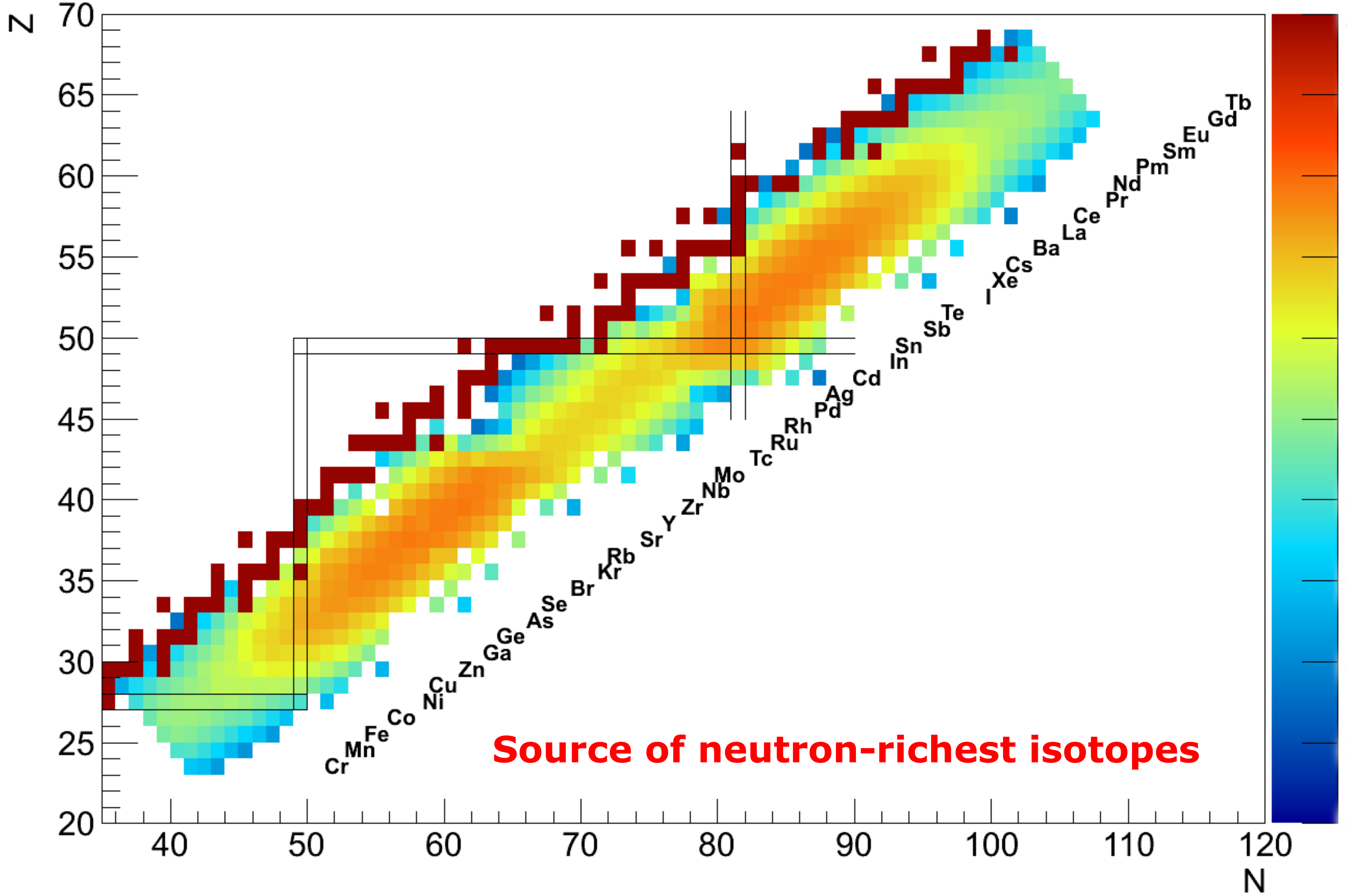
prompt γ-rays (10^{-16} s)



ternary α, t, d, ^{10}Be…

kinetic energy **prompt γ-rays**	**heat**
prompt neutrons **(delayed neutrons)**	**chain reaction**
ternary α, t, d	**gas production in the fuel (waste)**
fission fragments	**decay heat, toxicity (waste)**

The fission process



The fission observables

- **Fission fragment yields**
  - **Pre-neutron mass distributions**
  - **Post-neutron mass-distributions**
- **Fragment kinetic energy**
- **Fragment excitation energy**
  - **Prompt fission neutrons**
  - **Prompt fission γ-rays**

- **Fragment angular distribution (anisotropy)**
- **Ternary particles (LCP: α, $^{6,8}He$, ^{10}Be, ... ^{34}Si)**

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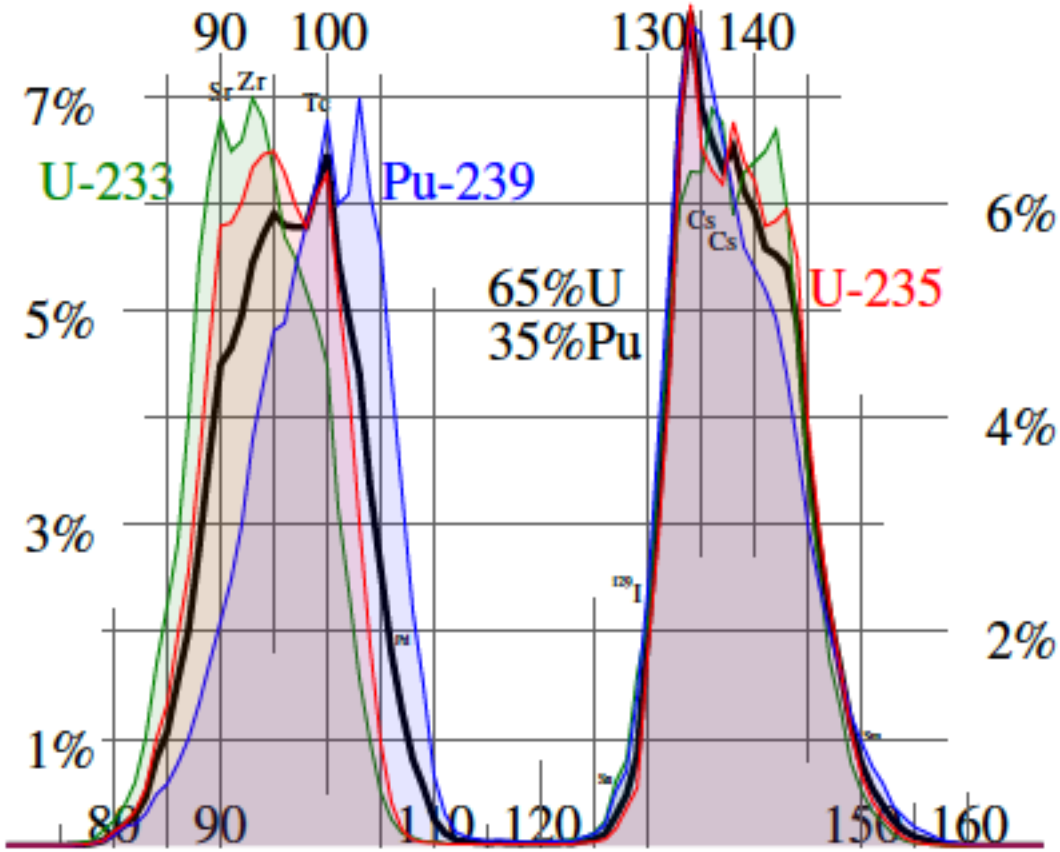
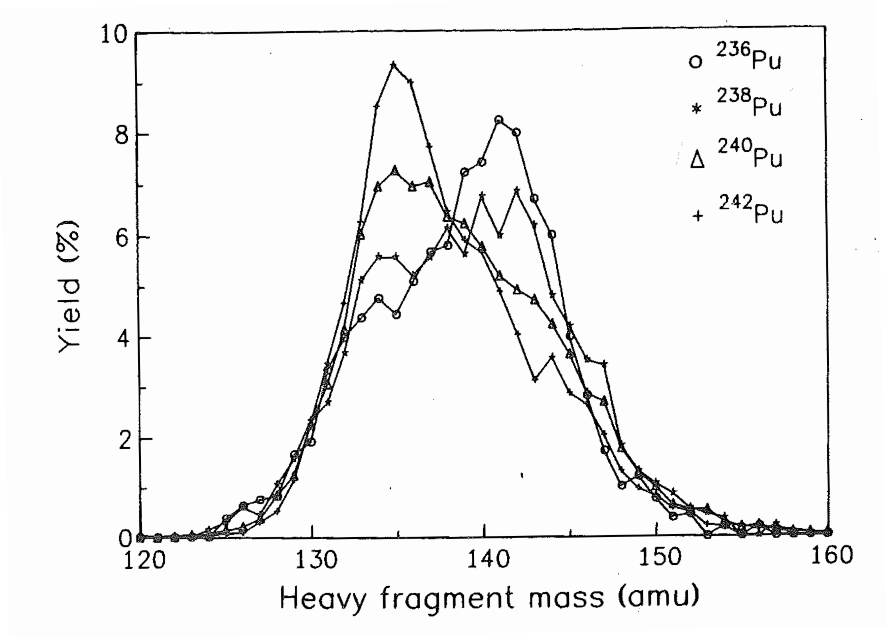
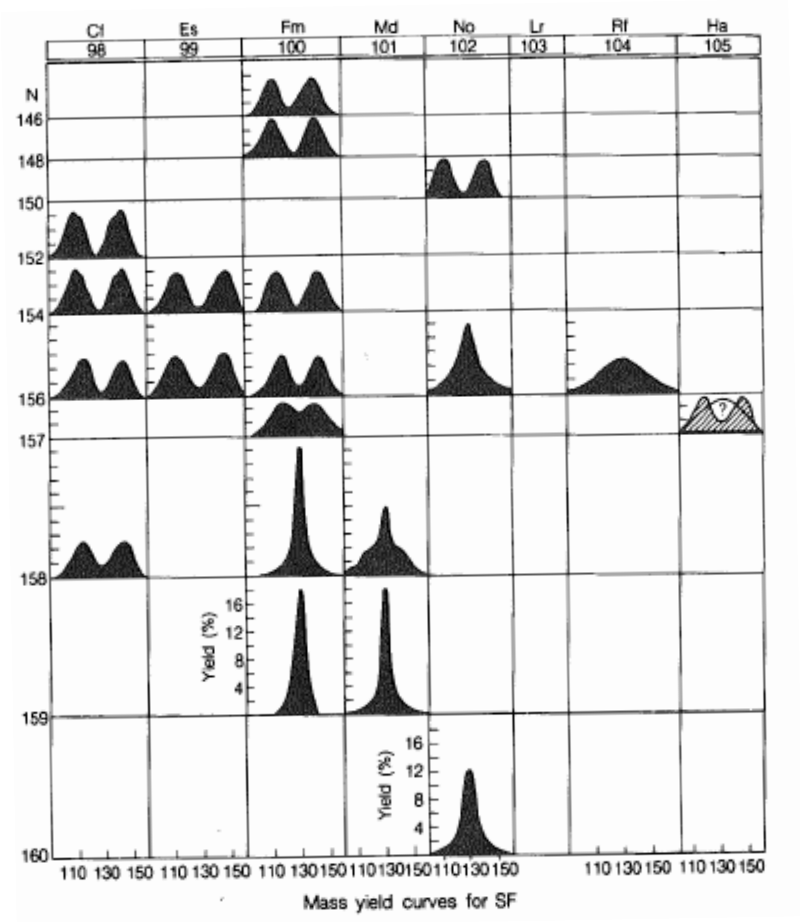
The fission observables



Fragment mass number

The fission observables





D.C. Hoffman, Nucl. Phys. A502 (1989) 21c

After 75 years

- **Fission theory not (yet) able to calculate *realistic* fission fragment characteristics**
- **New concepts are being developed (CEA, LANL; very CPU demanding)**
- **No predictive power, yet…**

- **Phenomenological approaches quite successful (GEF, …), require experimental data**

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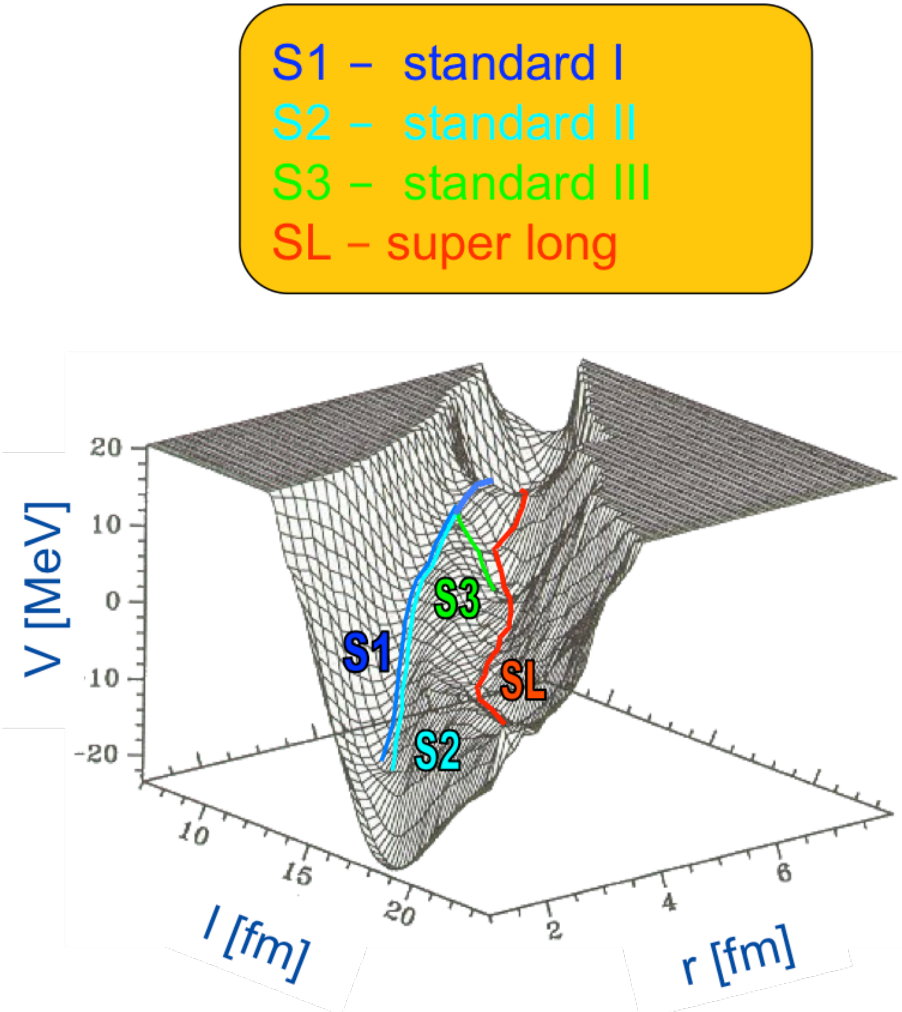
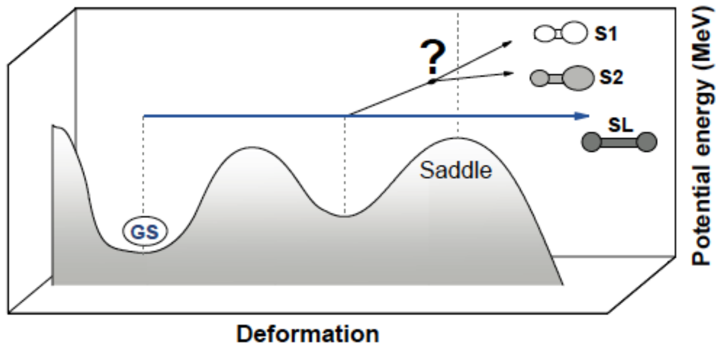
After 75 years

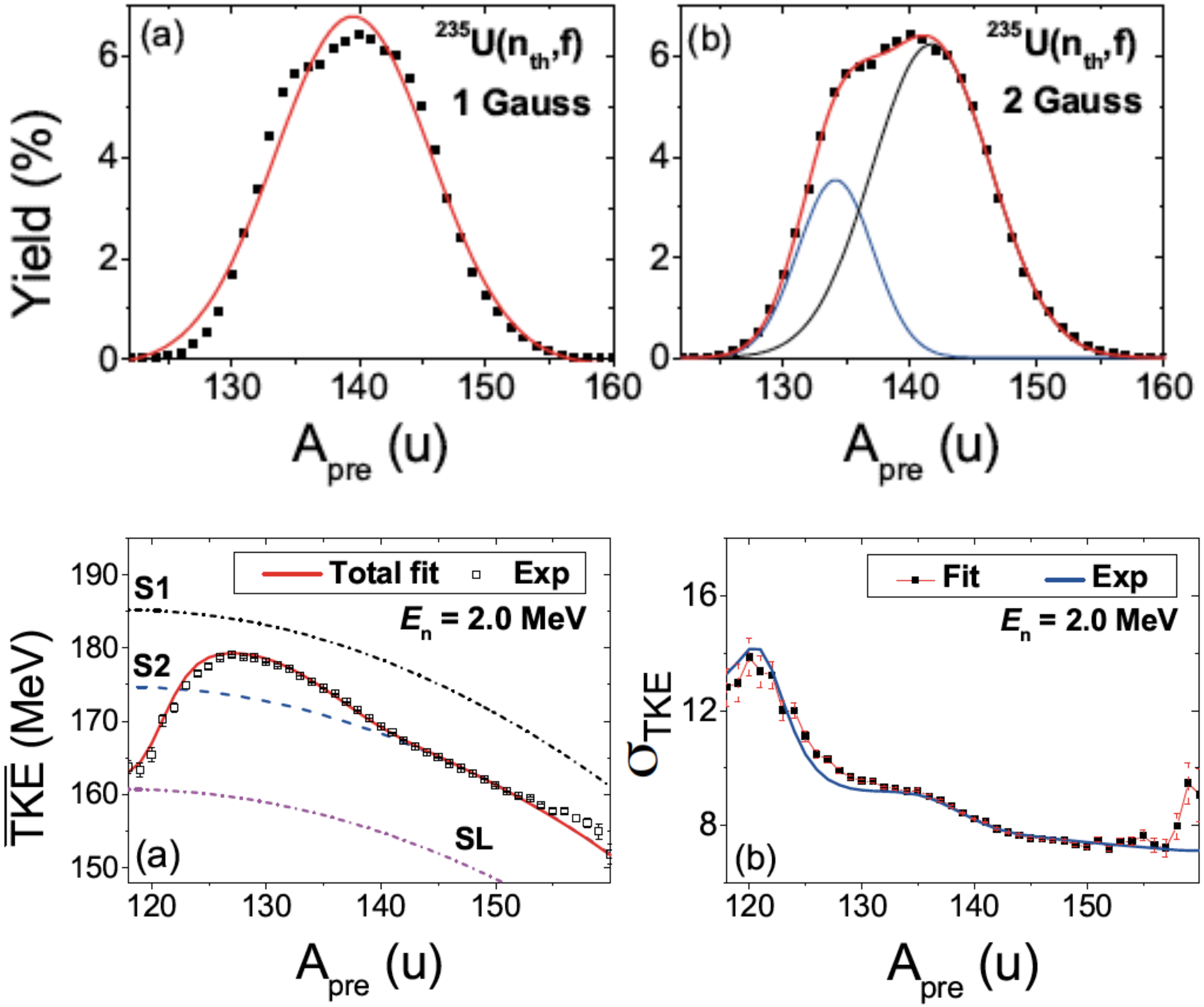


- Fragment characteristics well described when built upon the idea of fission modes

- Where are fission modes formed?
- Does each fission mode has its own barrier?
- No experimental evidence !!!



After 75 years



Details in: A.A. Adili et al., PRC 93, 034603 (2016)

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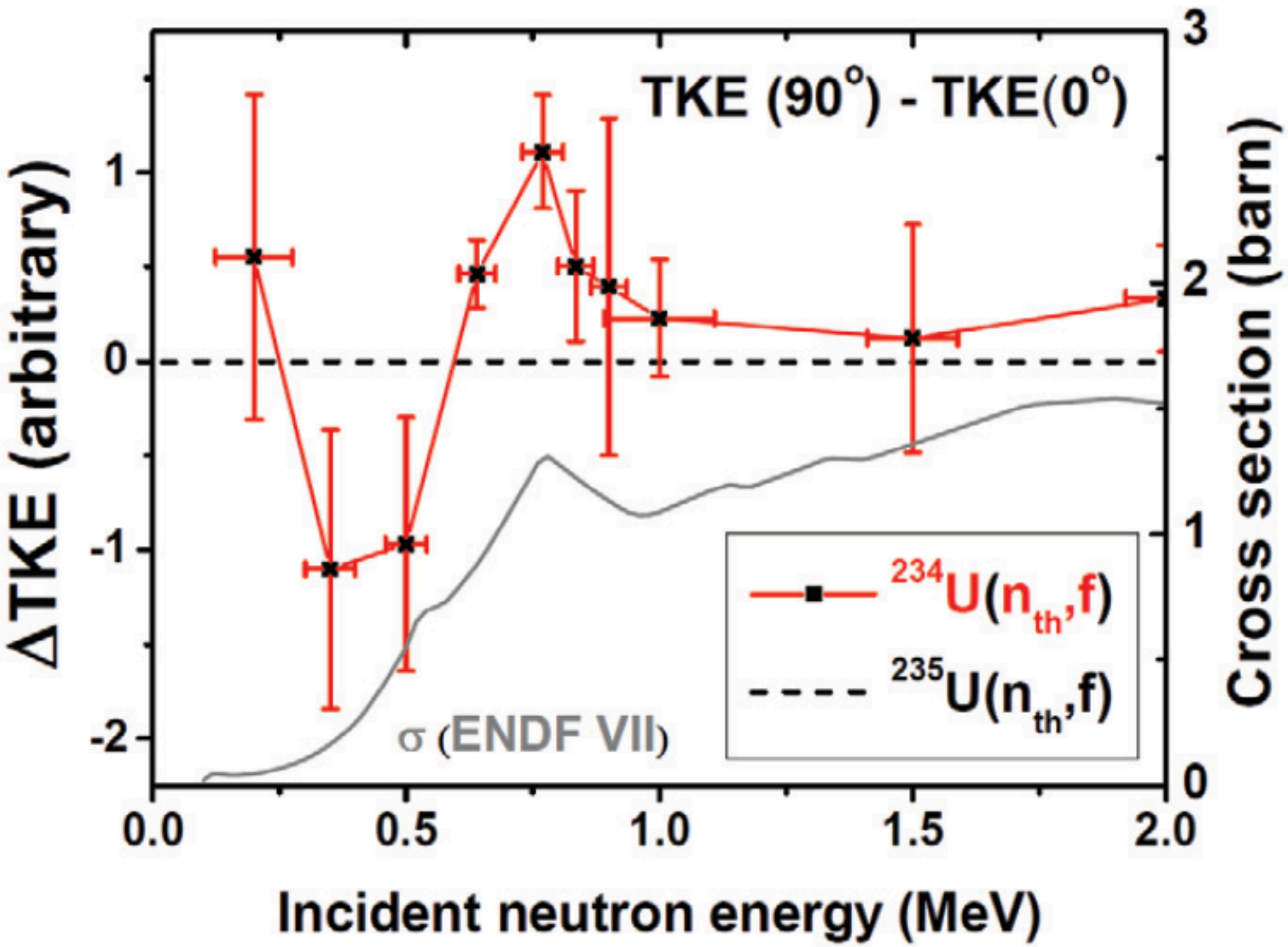
After 75 years



A.A. Adili et al. (to be published)

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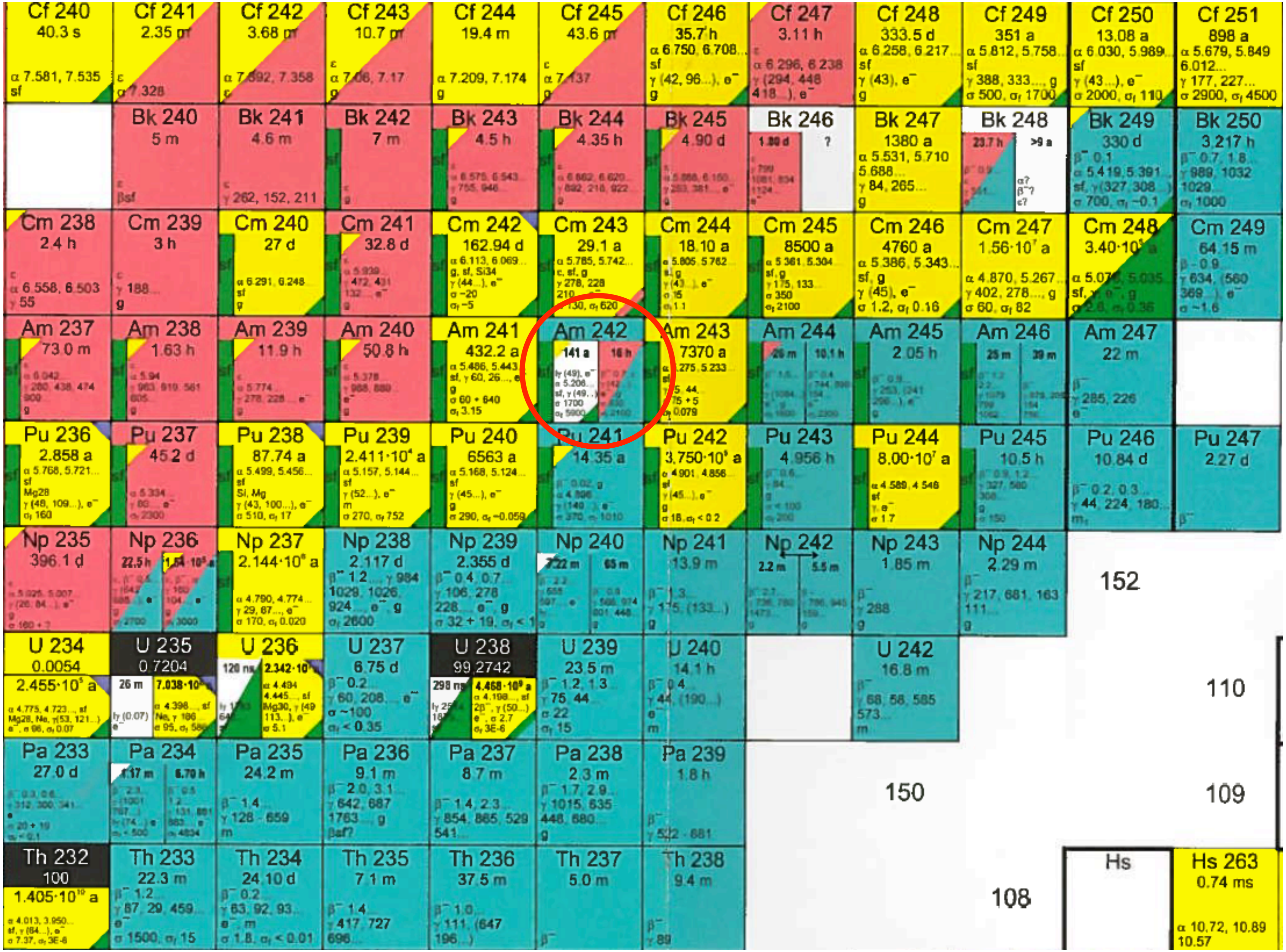
What could help?

- Detailed information about the nuclear energy landscape around the saddle point
- Barrier parameters: height and penetrability
- Number of barriers
- Transition states (fission channels)

This is where now shape isomers come in!



Cf 240 40.3 s
Cf 241 2.35 m
Cf 242 3.68 m
Cf 243 10.7 m
Cf 244 19.4 m
Cf 245 43.6 m
Cf 246 35.7 h
Cf 247 3.11 h
Cf 248 333.5 d
Cf 249 351 a
Cf 250 13.08 a
Cf 251 898 a
Bk 240 5 m
Bk 241 4.6 m
Bk 242 7 m
Bk 243 4.5 h
Bk 244 4.35 h
Bk 245 4.90 d
Bk 246
Bk 247 1380 a
Bk 248
Bk 249 330 d
Bk 250 3.217 h
Cm 238 2.4 h
Cm 239 3 h
Cm 240 27 d
Cm 241 32.8 d
Cm 242 162.94 d
Cm 243 29.1 a
Cm 244 18.10 a
Cm 245 8500 a
Cm 246 4760 a
Cm 247 1.56·10⁷ a
Cm 248
Cm 249 64.15 m
Am 237 73.0 m
Am 238 1.63 h
Am 239 11.9 h
Am 240 50.8 h
Am 241 432.2 a
Am 242 141 a 16 h
Am 243 7370 a
Am 244
Am 245 2.05 h
Am 246
Am 247 22 m
Pu 236 2.858 a
Pu 237 45.2 d
Pu 238 87.74 a
Pu 239 2.411·10⁴ a
Pu 240 6563 a
Pu 241 14.35 a
Pu 242 3.750·10⁵ a
Pu 243 4.956 h
Pu 244 8.00·10⁷ a
Pu 245 10.5 h
Pu 246 10.84 d
Pu 247 2.27 d
Np 235 396.1 d
Np 236
Np 237 2.144·10⁶ a
Np 238 2.117 d
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Np 242
Np 243 1.85 m
Np 244 2.29 m
152
U 234 0.0054 2.455·10⁵ a
U 235 0.7204
U 236
U 237 6.75 d
U 238 99.2742
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U 240 14.1 h
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Pa 233 27.0 d
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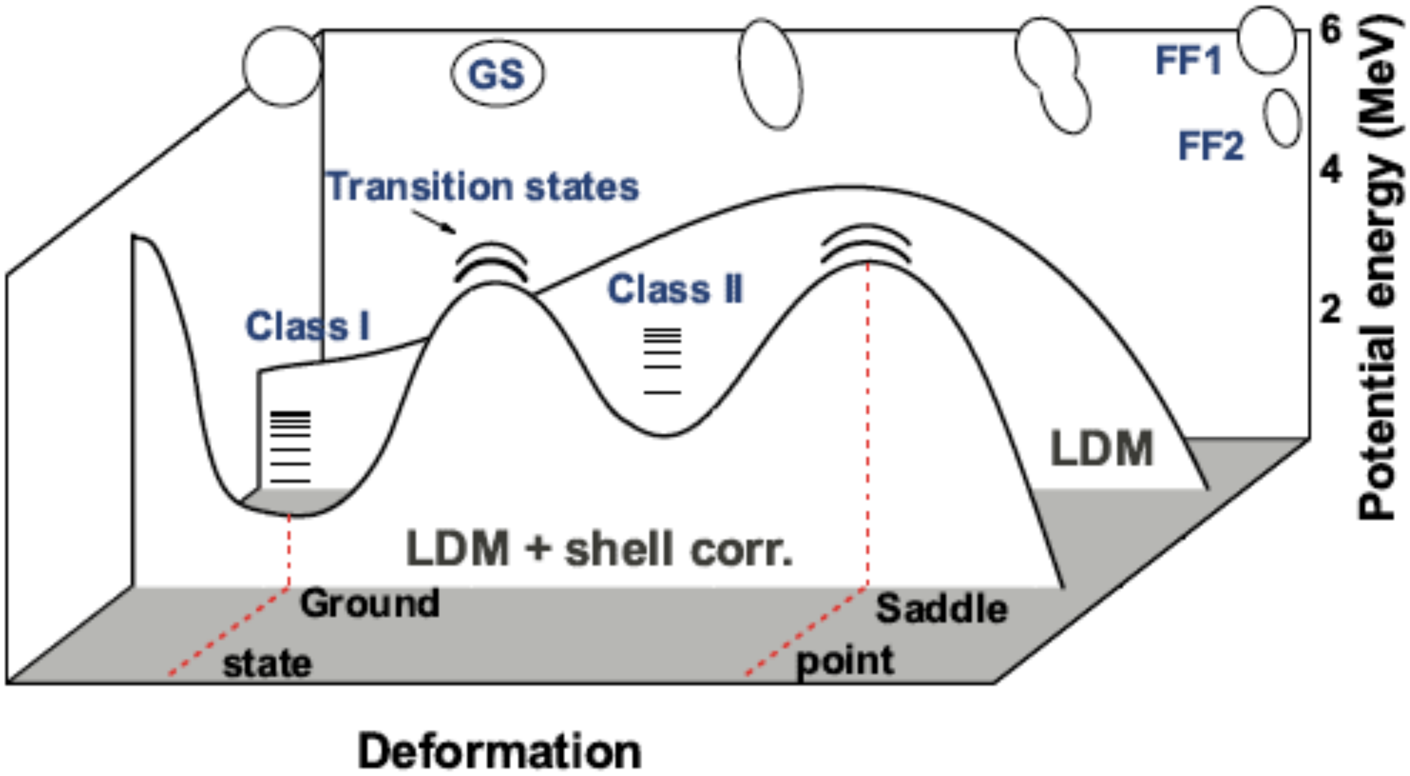
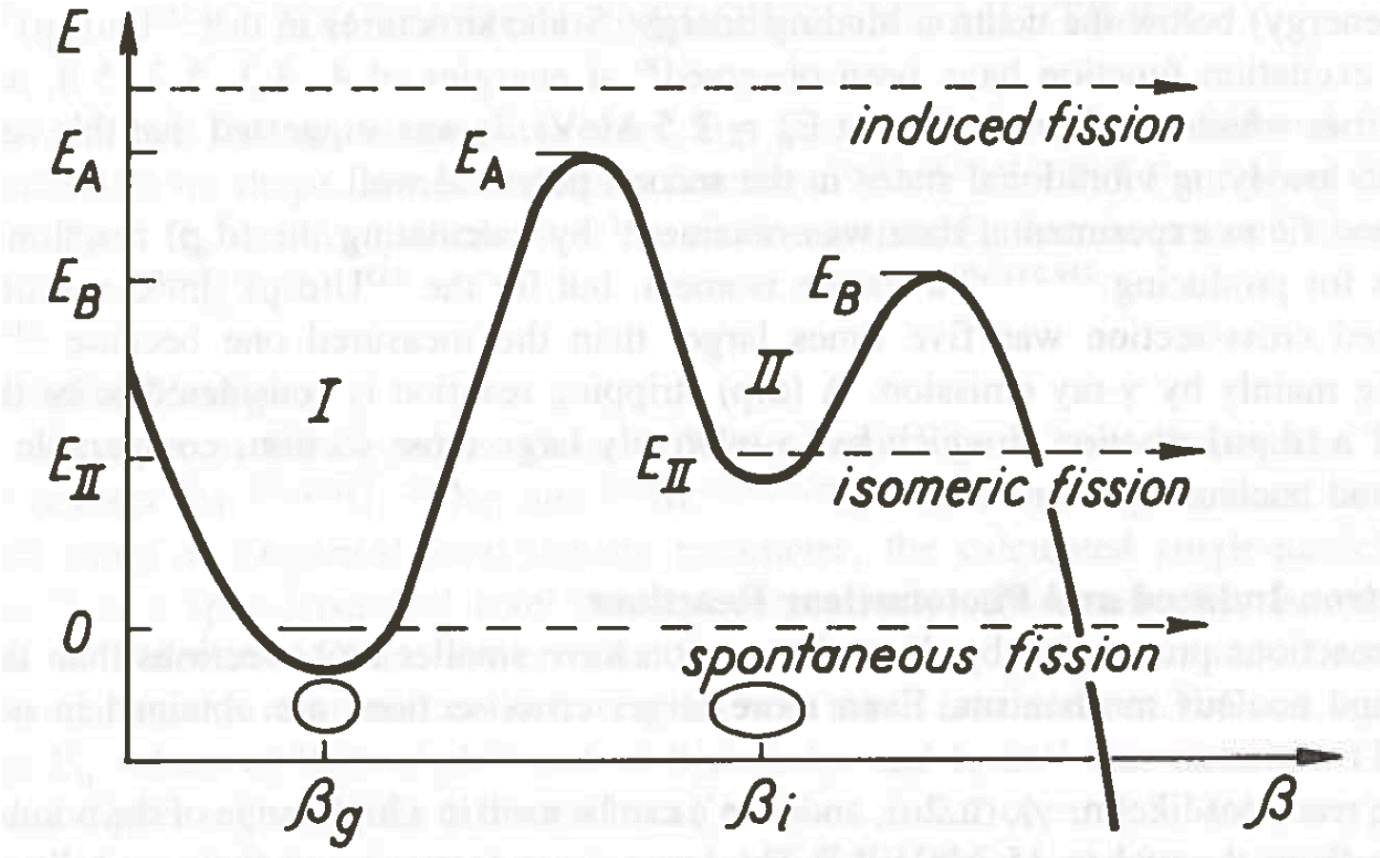
108
Hs
Hs 263 0.74 ms

What is a shape isomer?

"Macroscopic-microscopic" or "shell correction" (SCM)



What is a shape isomer?



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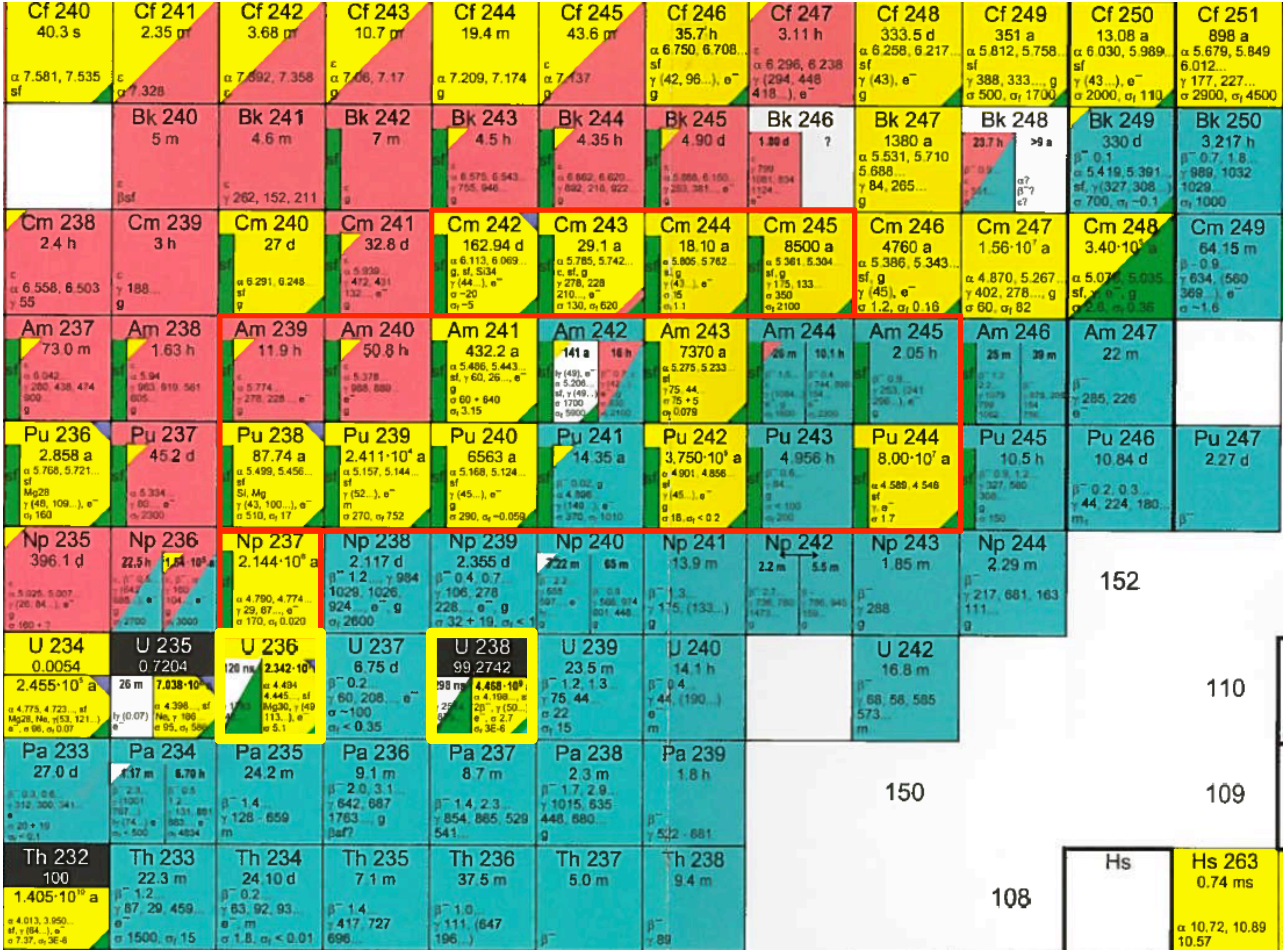

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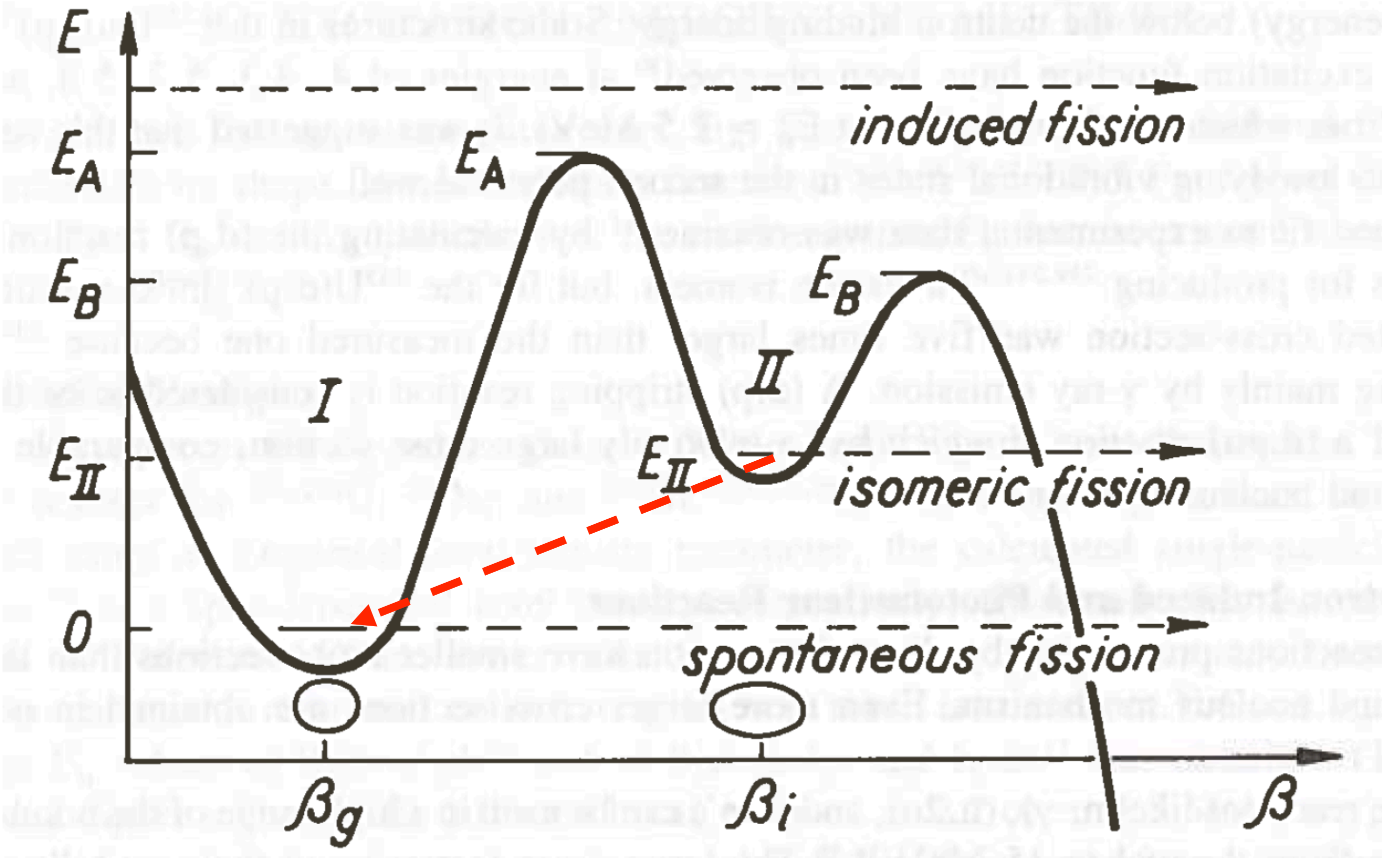
Shape isomer characteristics



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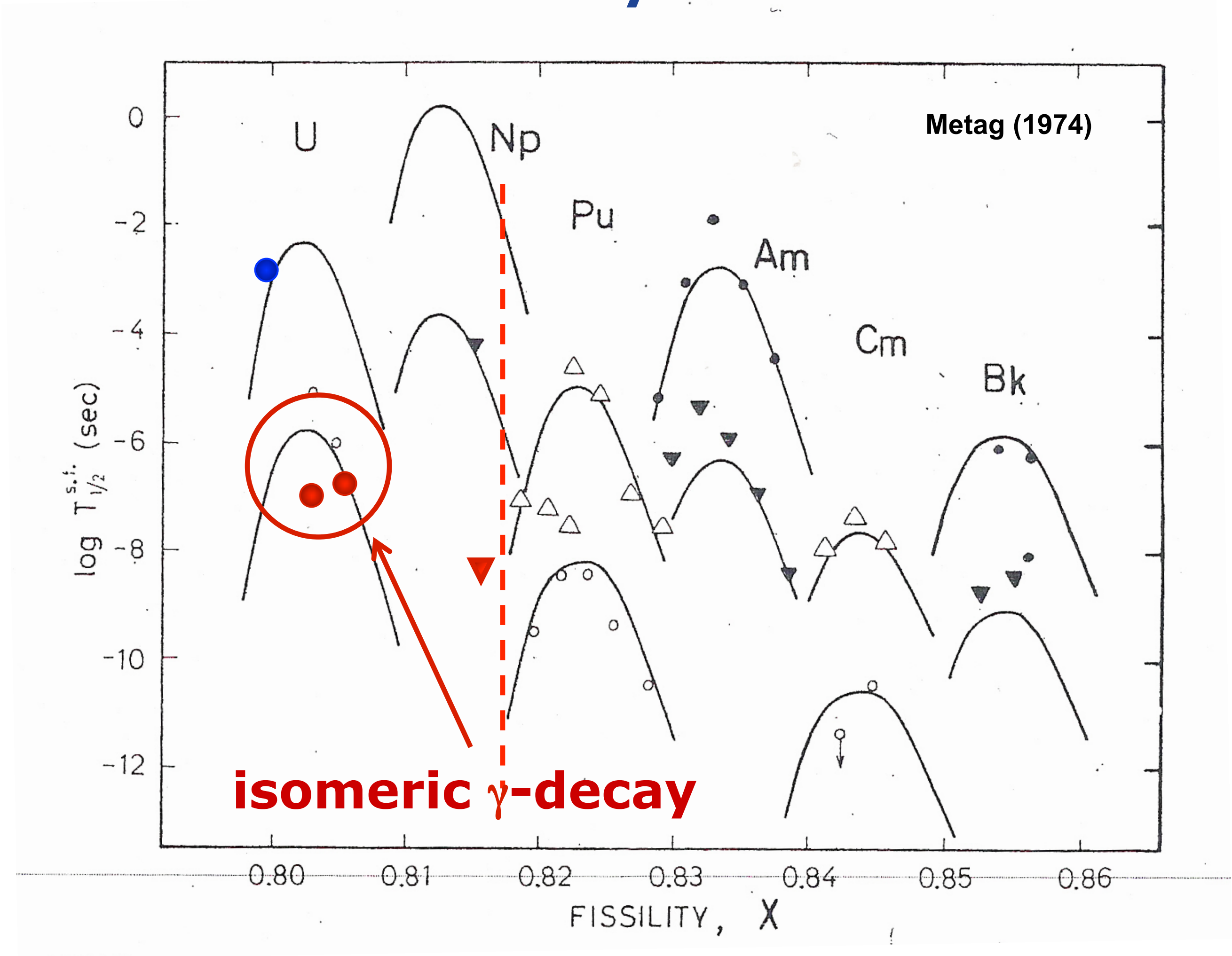
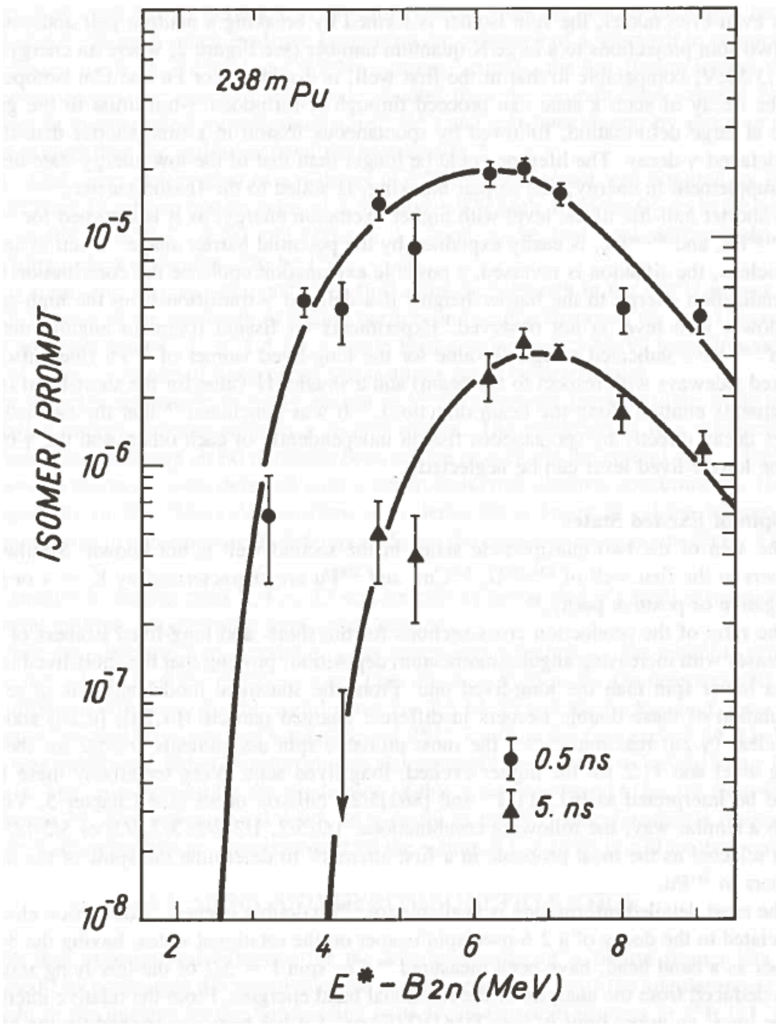
Shape isomer characteristics

Half-life systematics



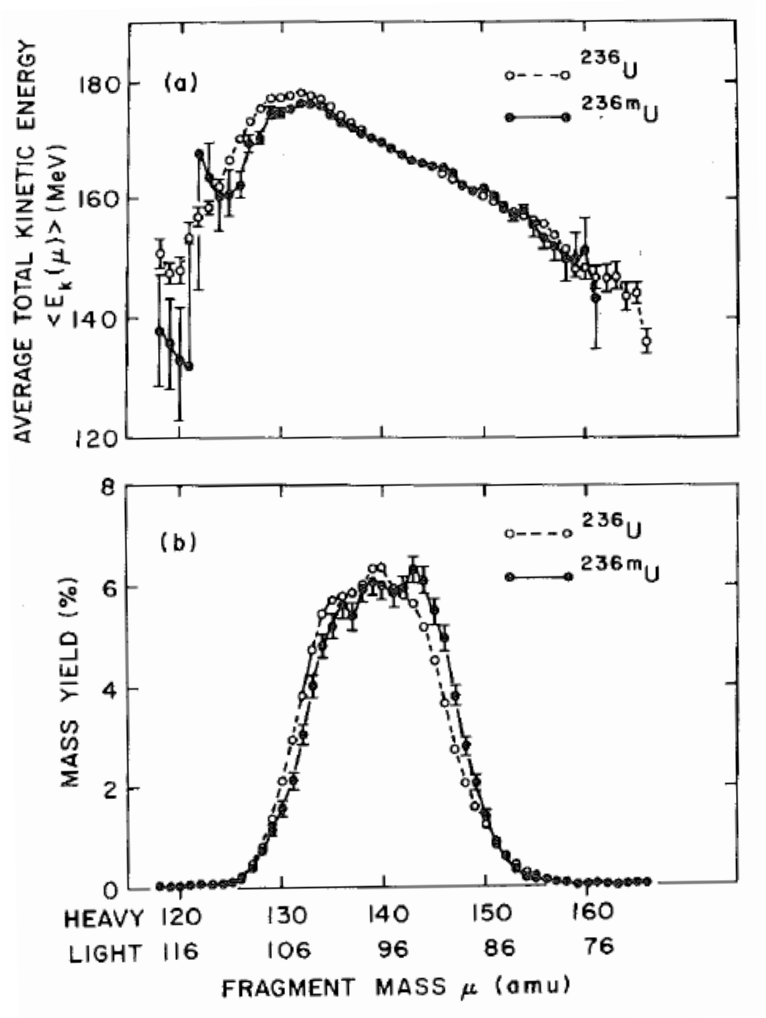
Shape isomer characteristics

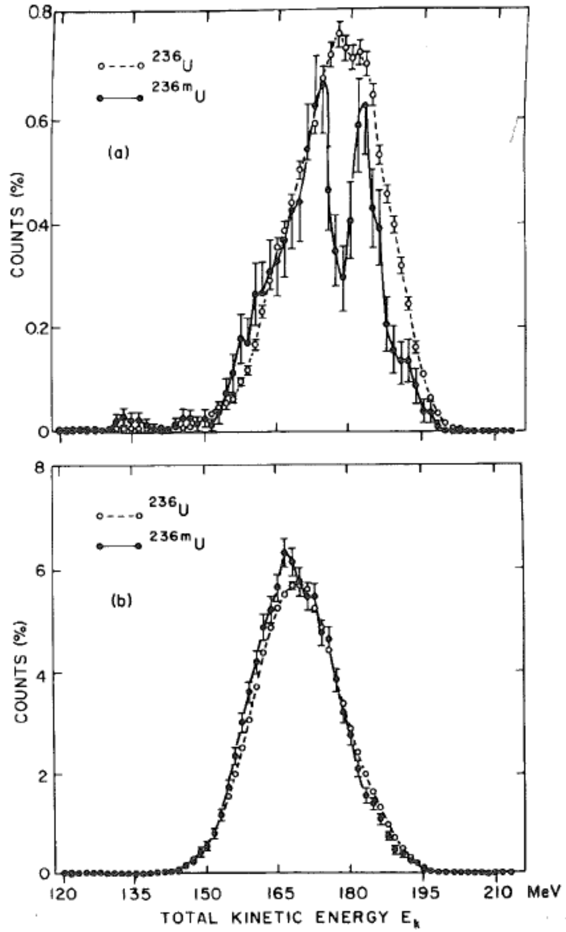
Excitation function



Shape isomer characteristics

Something unique and intriguing!





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Relevant information from SI

Inverted parabolas (Hill-Wheeler)

$$T^{if}_{1/2} = 2.77 \times 10^{-12} ns\ exp(2\pi(E_B - E_{II})/\hbar\omega_B)$$

$$T^{if}_{1/2} = 10^{-5} ns\ exp(2\pi(E_A - E_{II})/\hbar\omega_A)$$

$$\Delta_i(T^{i}_{1/2}) = \frac{E_i - E_{II}}{\hbar\omega_i}\ , \qquad i = A(i\gamma), B(if)$$

$$E_i - \hbar\omega_i\Delta_i(T^{i}_{1/2}) = E_{II}\ , \qquad i = A(i\gamma), B(if)$$

Relevant information from SI

Desired information:

$$E_A, E_B, \hbar\omega_A, \hbar\omega_B, \ (and \ E_{II})$$

Measurable quantities:

$$E_{II}, T_{1/2}^{i\gamma}, T_{1/2}^{if}, R(\frac{\sigma_{if}}{\sigma_{i\gamma}}) \ and \ T_{1/2}^{sf}$$

$$\hbar\omega_B \approx \hbar\omega_A + \Lambda$$

$$\hbar\omega_B < \overline{\hbar\omega_B}$$

$$T_{1/2}^{sf} \sim \ exp(2\pi(E_A/\hbar\omega_A + E_B/\hbar\omega_B)$$

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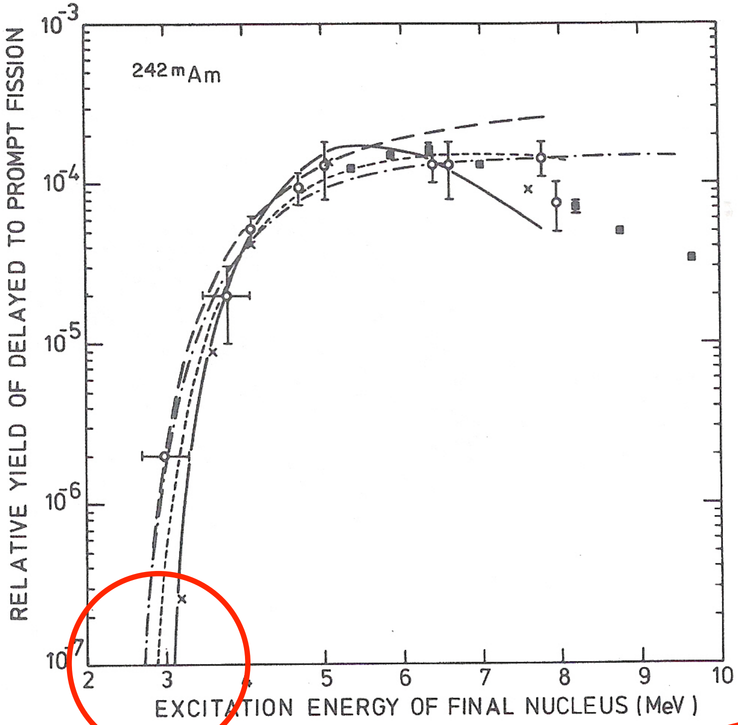
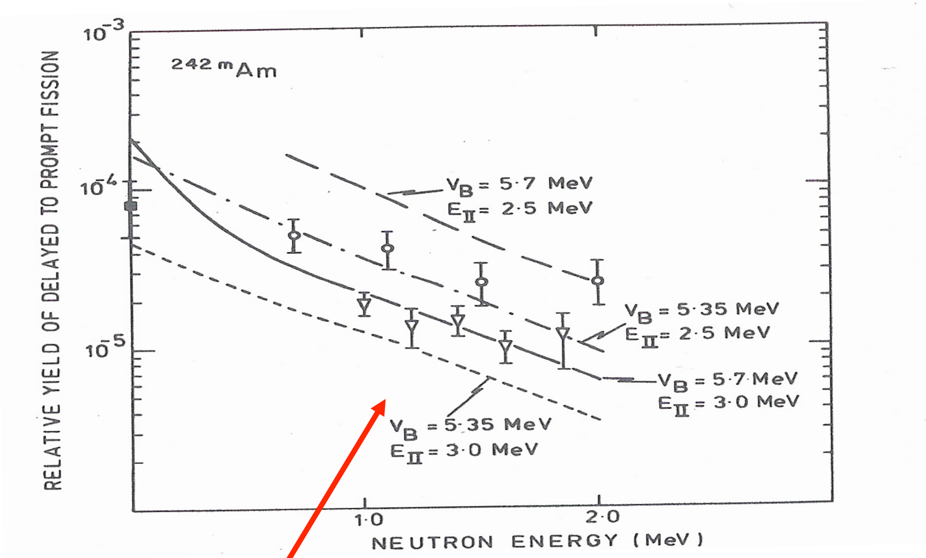
Relevant information from SI

Extraction of barrier parameters





$\Delta E_{B(II)} \approx 0.5$ MeV

Relevant information from SI

But, we can do better!

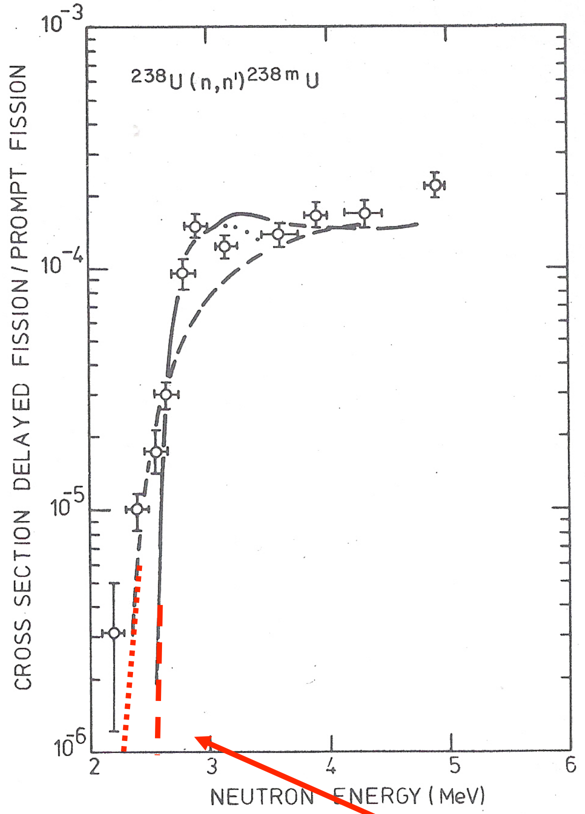
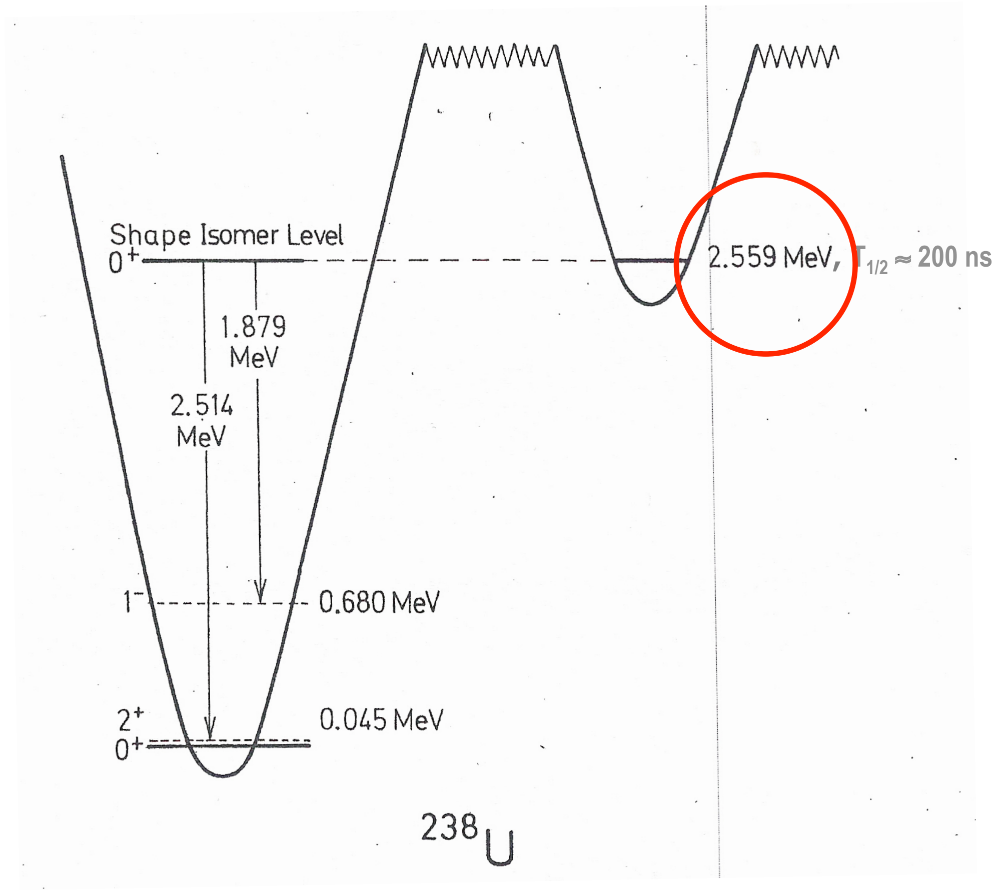


FIG. 61. Data for excitation of ^{238m}U shape isomer by the (n,n') reaction (Wolf and Meadows, 1974 and private communication). The broken curve is a statistical calculation based on constant temperature level density models ($\theta_1 = 0.5$ MeV, $\theta_1^{(s)} = 0.53$ MeV, $E_{II} = 2.35$ MeV). The full curve treats the class-II state spectrum as having an energy gap ($2\Delta = 1.2$ MeV) containing rotational bands based on $K^\pi = 0^+$ ground state, a $K^\pi = 0^-$ vibration at 0.5 MeV higher, and a $K^\pi = 2^+$ vibration at 1 MeV higher. The isomer energy is 2.56 MeV. The dotted curve shows the effect of omitting the $K^\pi = 0^-$ band.



E_{II} = 2.2 – 2.6 MeV

„The double-humped fission barrier“, Bjørnholm/Lynn, Rev. Mod. Phys. 52 (1980)

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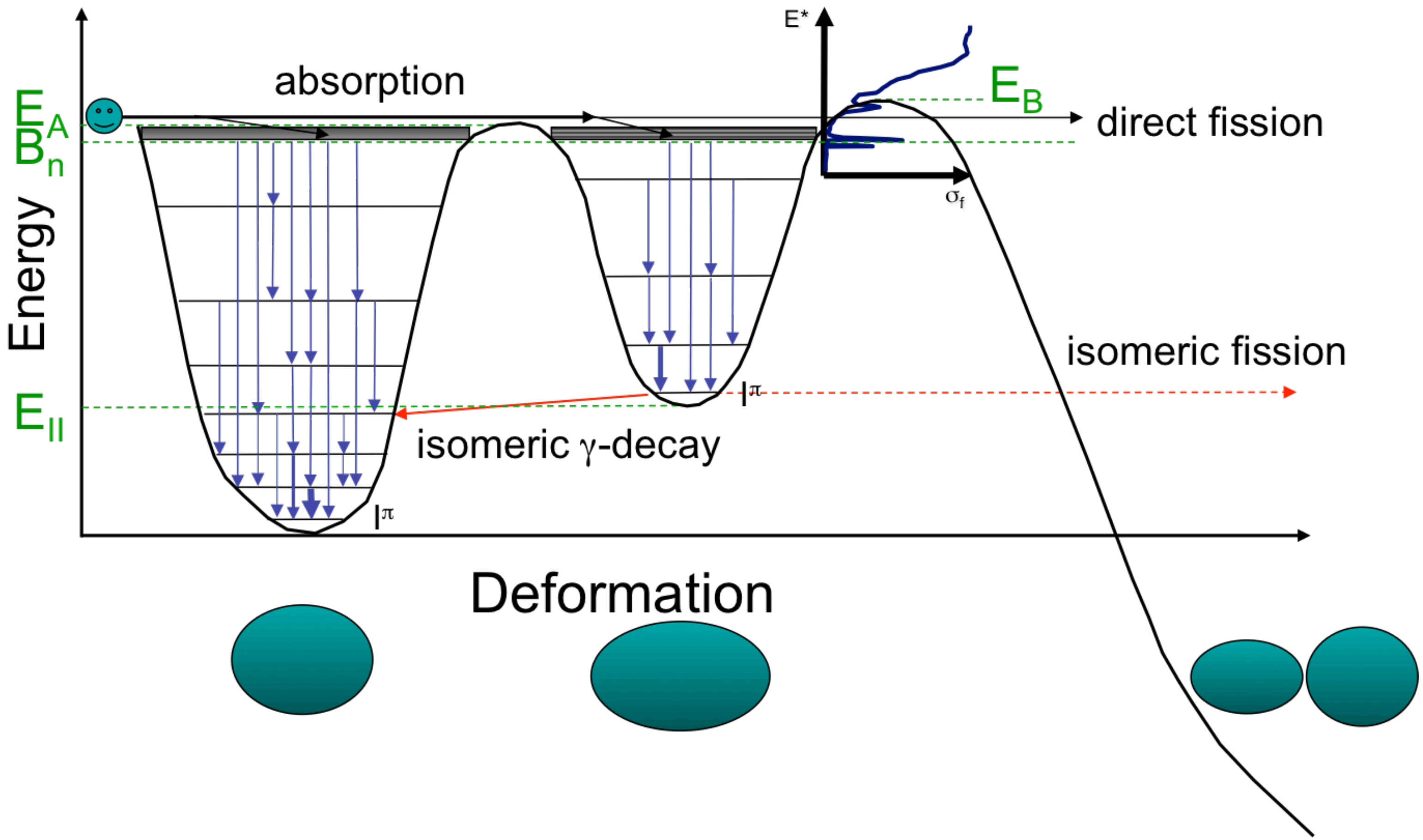
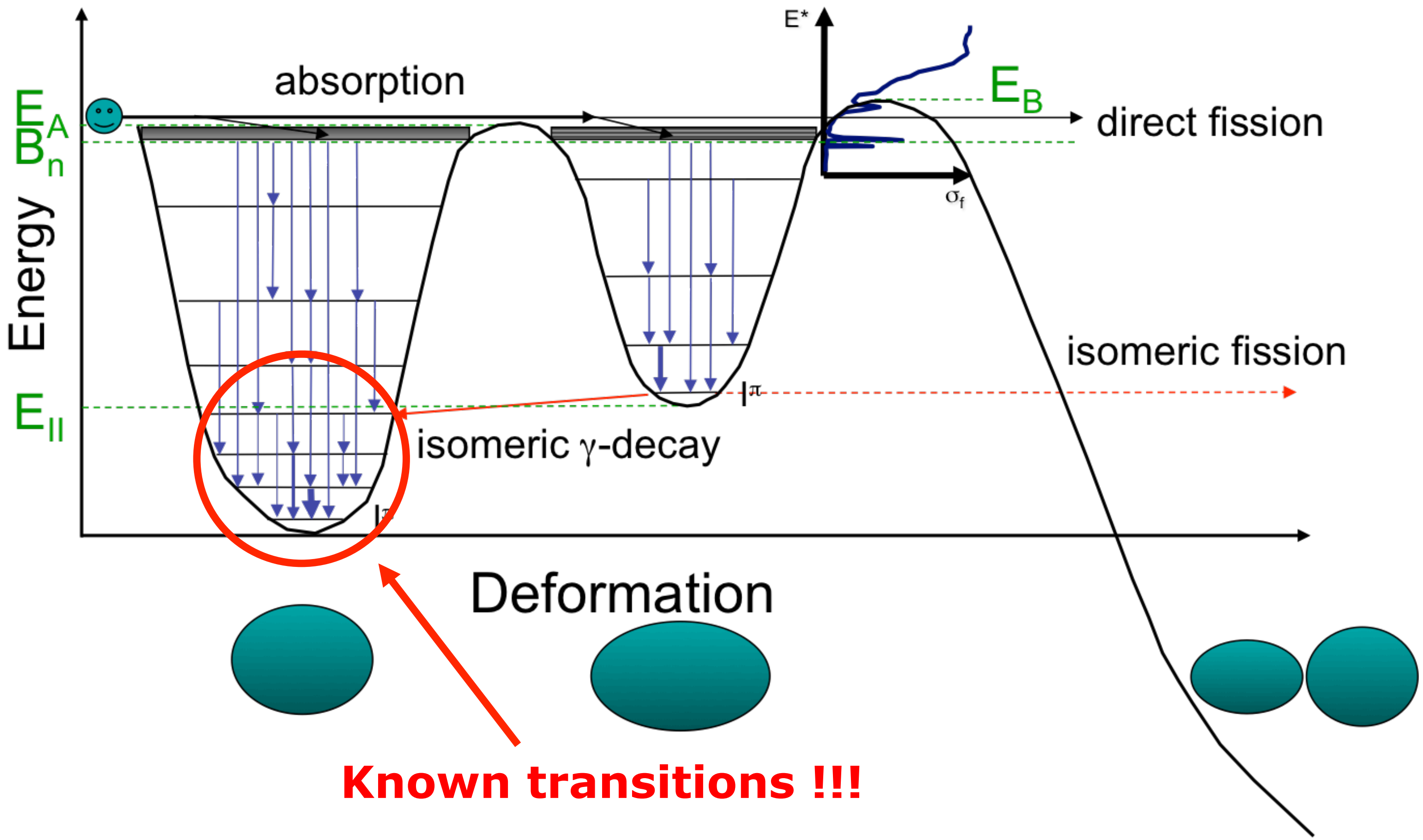
Experimental approach

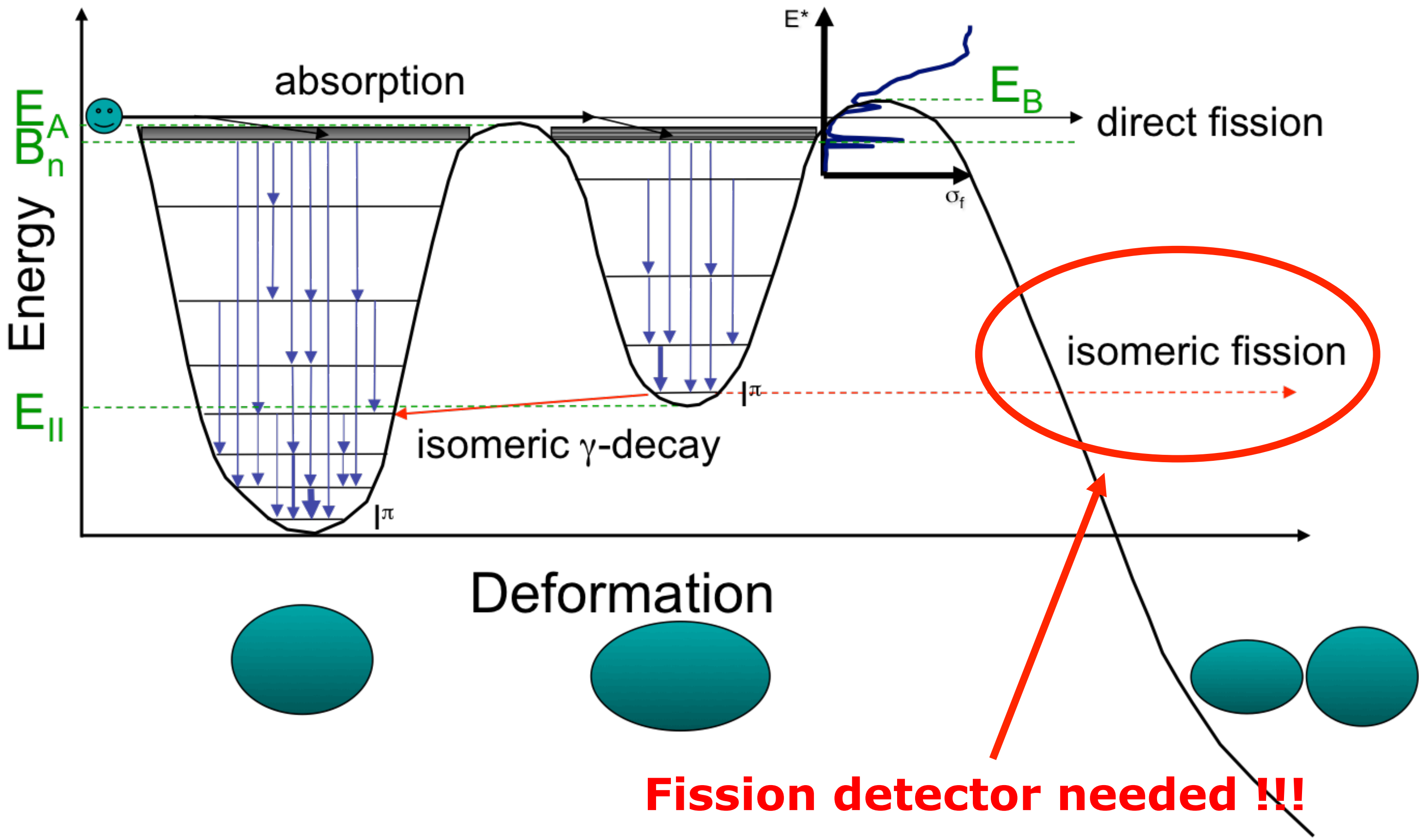


Experimental approach



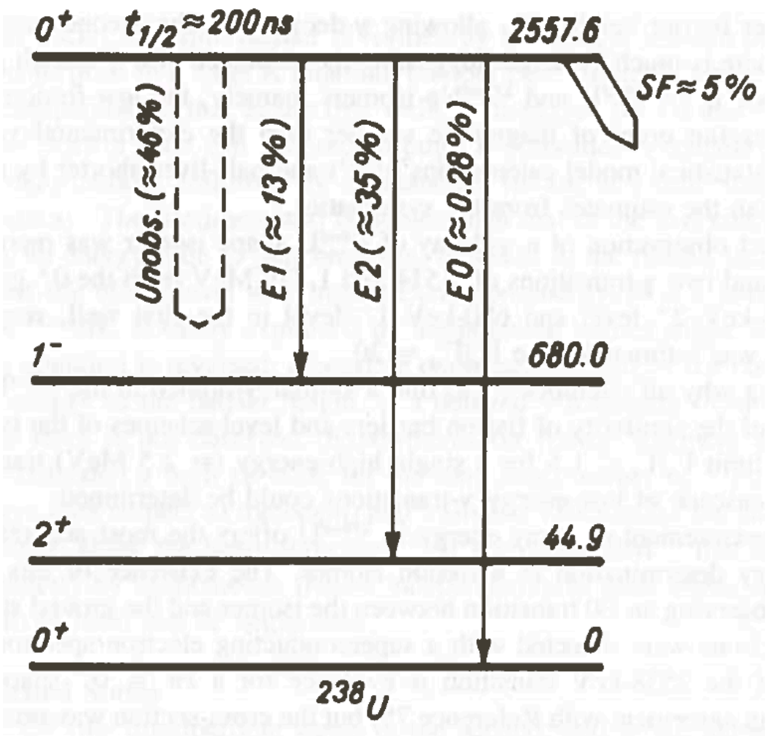
Known transitions !!!

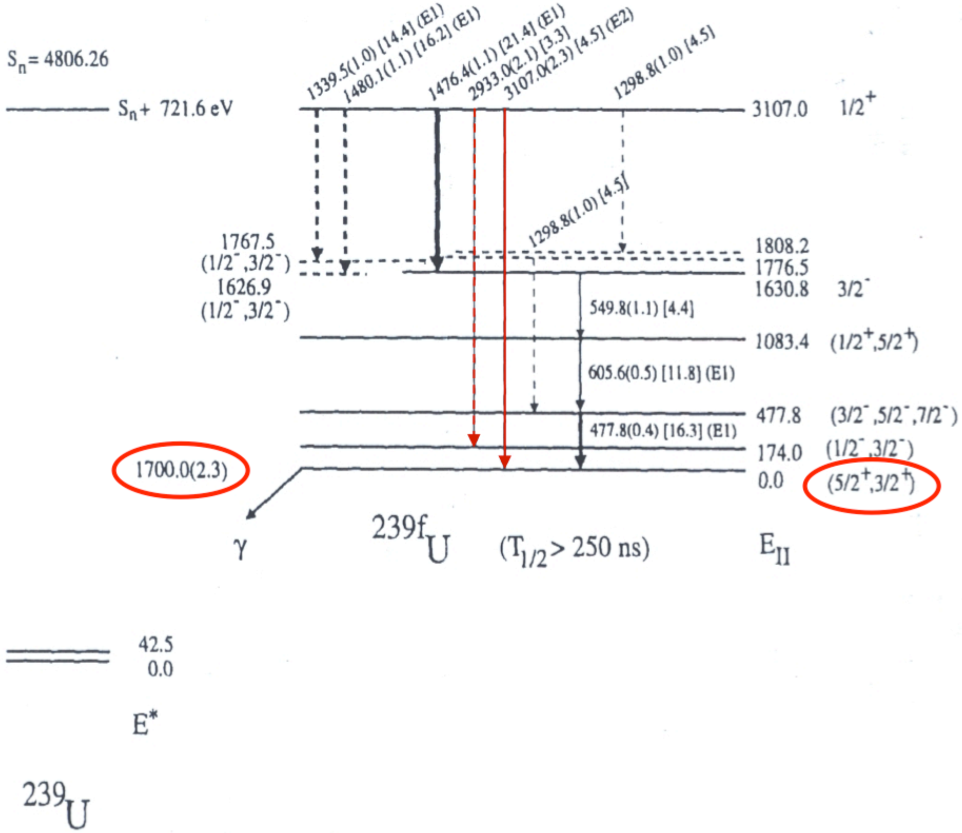
Experimental approach



Experimental approach

HPGe detector used





HD-DA Crystal ball (NaI) used for ^{236f}U and ^{240f}Pu

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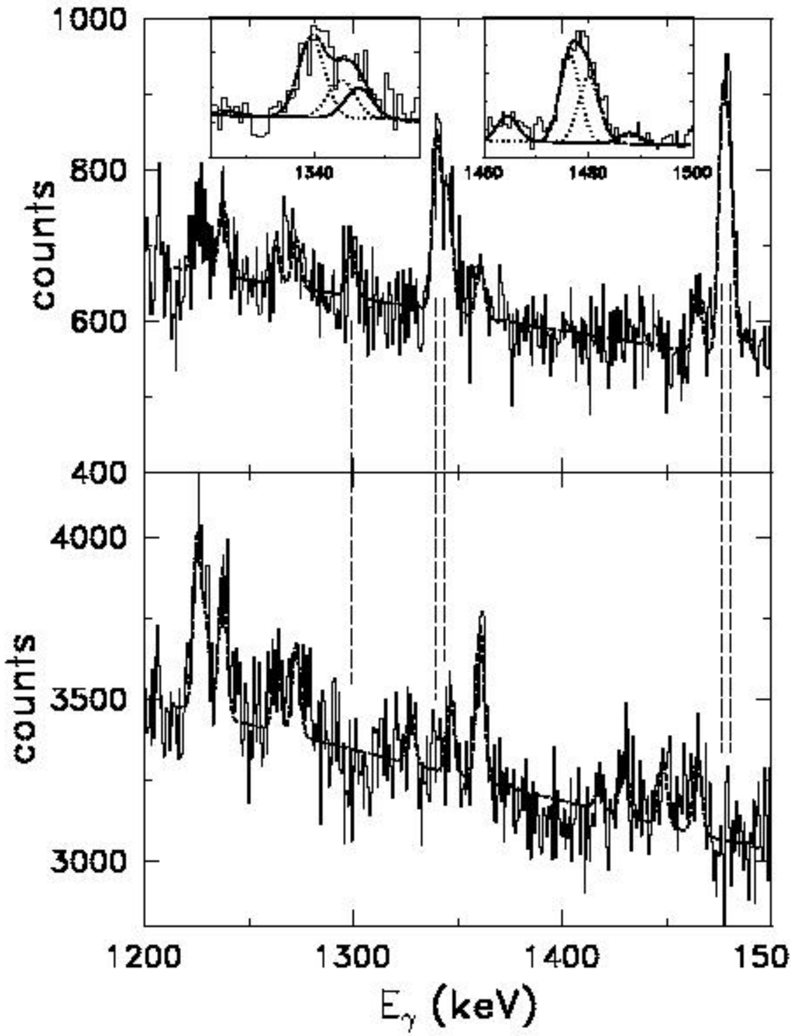
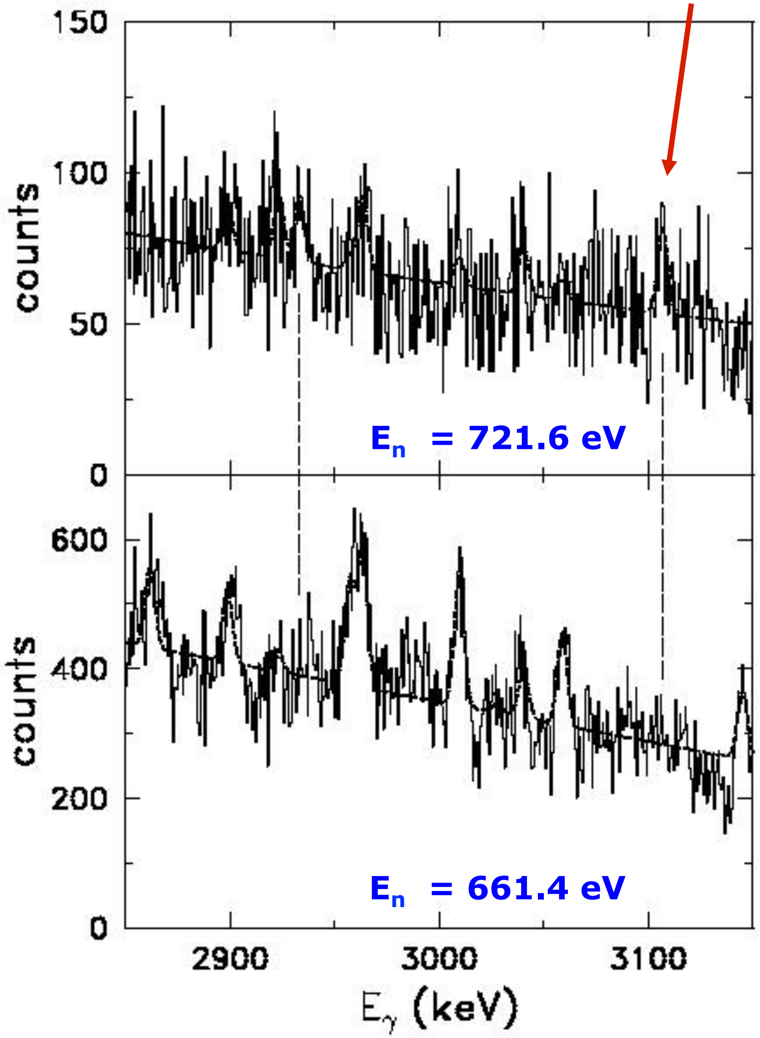
Experimental approach

$^{238}U(n_{res},\gamma)$: only single γ-rays

$E_{II} = S_n - E_{\gamma,max}$





Details in: S. Oberstedt, F. Gunsing, NPA 636 (1998) 129

Experimental approach

- **1^{st} step: choice of reaction**
  - Population via (d, p), (α, 2n), (n, n'), (n, 2n)
  - Population is weak: 10^{-6} – 10^{-4} (10^{-3} at best)
  - Enough target material
- **2^{nd} step: shape isomer γ back decay**
  - Tagging on delayed γ-rays with high energy resolution
  - Coincident $\gamma\gamma$ cascades with high timing resolution
- **3^{rd} step: shape isomer fission studies**
  - tagging on the populating $\gamma\gamma$ cascades
  - measuring fission fragments with 100% efficiency
  - permit use of a DC beam

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Some interesting cases...

- ^{235f}U: E_{II} and γ-rays from SI population and back-decay known > benchmark of the ν-Ball arrangement
- ^{238f}U: E_{II} and γ-rays from back-decay known > demonstrator run
- ^{239f}U: unobserved, E_{II} = 1.7 MeV

- ^{233f}Th: unkown, $T_{1/2}$ (iγ) < 100 ns (no fission branch)
- ^{232f}Th: unknown, $T_{1/2}$ (iγ) < 10 ns, isomeric shelf determined in photo-fission (E_{II} = ?)

- ^{237f}Np: $T_{1/2}$ (if) = 40 ns, very low fission branch
- ^{238f}Np: unobserved, 500 ns < $T_{1/2}$ (if) < 10 s

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SI summary

- **Fission isomer characteristics**
  - **Half-life**
  - **Partial half-lives: isomeric fission, back-decay to 1st minimum**
  - **Branching ratio**

- **Fission barrier parameters:**
  - **Barrier height: E_A, E_B, ... $E_B(S1)$, $E_B(S2)$, $E_B(SL)$...**
  - **Transmission (curvature parameter): $h\varpi_A$, $h\varpi_B$**
  - **Nuclear structure above super-deformed ground-state**
  - **Isomeric fission fragment characteristics**

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CONCLUSION

- **Precise data on fission barriers may advance fission models**
- **Calculation of realistic FF distributions**
- **Cross-section modelling**
- **Experiments are difficult and require major development on e.g. target mass, beam intensity to maximize reaction rates**
- **γ-ray detection efficiency (number and size of detectors), efficiency of fission trigger …**
- **Use of a fission chamber boosts the efficiency**

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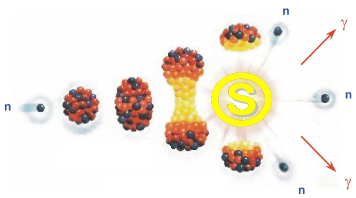
CONCLUSION

If we can make significant progress in this area, it will be with

ν-Ball @ LICORNE



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