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## Fission shape isomers – new opportunities with $\nu$ -Ball

**Stephan Oberstedt**

**$\nu$ -Ball workshop, IPN Orsay, May 19 – 20, 2016**



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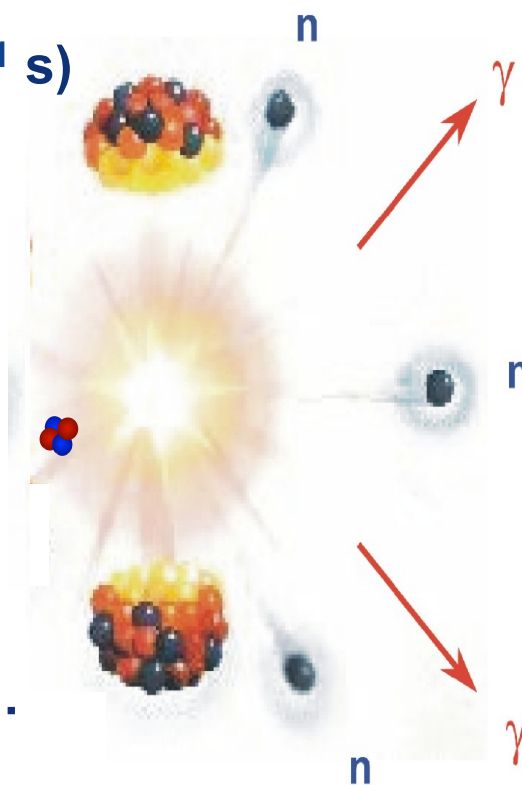
- **Introduction to the fission process**
- **Fission observables**
- **Open question(s) after 75 years**
  
- **Where do shape isomers come in**
  
- **Opportunities offered by  $\nu$ -Ball**
- **Some first cases**

# The fission process

prompt neutrons ( $10^{-18}$  s)

fission fragments ( $10^{-21}$  s)

prompt  $\gamma$ -rays ( $10^{-16}$  s)



ternary  $\alpha$ , t, d,  $^{10}\text{Be}$ ...

kinetic energy	} heat
prompt $\gamma$ -rays	
prompt neutrons (delayed neutrons)	} chain reaction
ternary $\alpha$ , t, d	} gas production in the fuel (waste)
fission fragments	
	} decay heat, toxicity (waste)

# The fission process

prompt neutrons ( $10^{-18}$  s)

fission fragments ( $10^{-21}$  s)

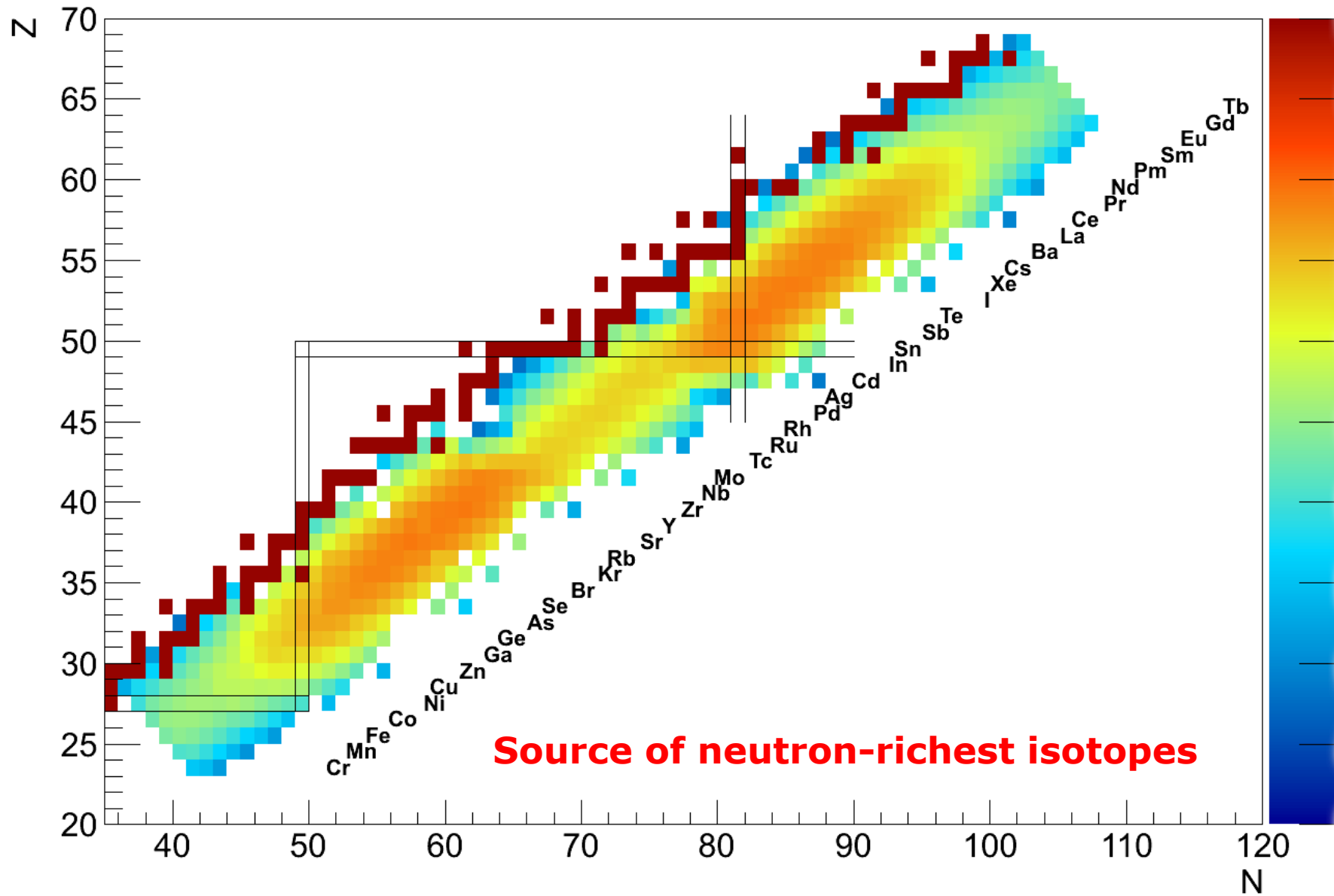
prompt  $\gamma$ -rays ( $10^{-16}$  s)

ternary  $\alpha$ , t, d,  $^{10}\text{Be}$ ...



kinetic energy	}	heat
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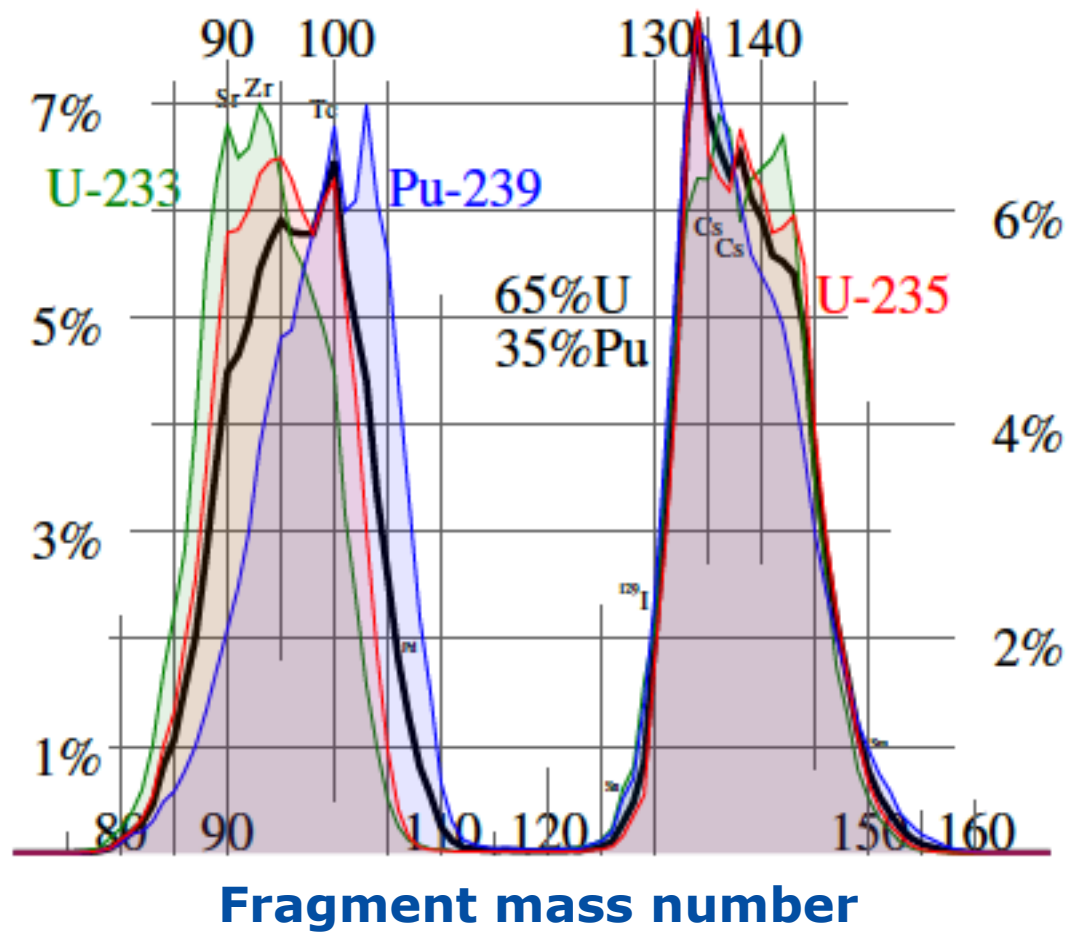
# The fission process



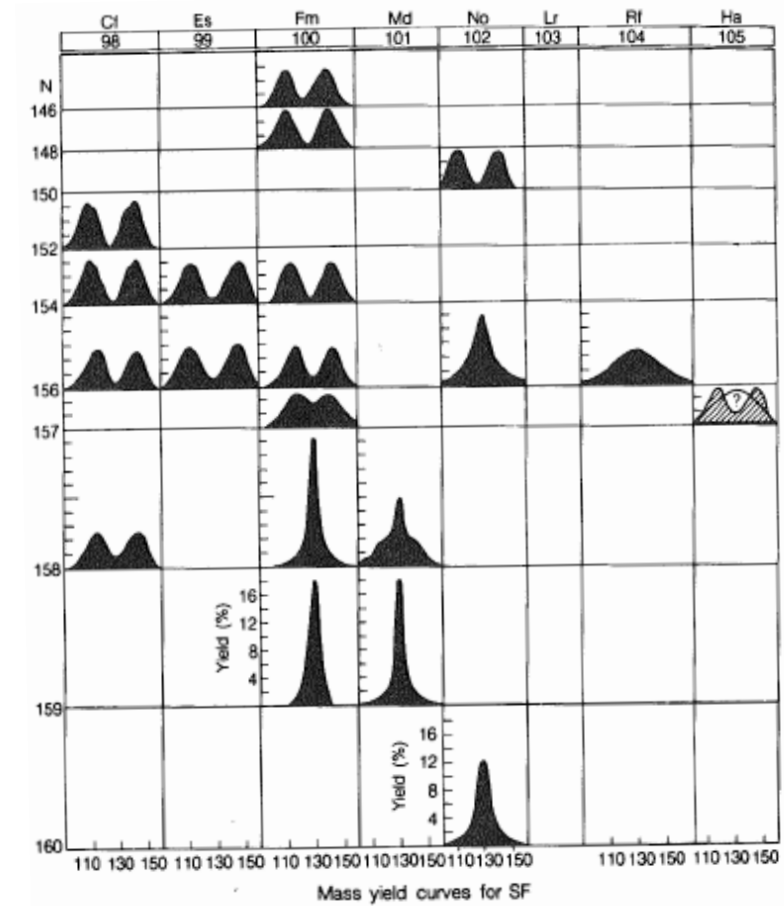
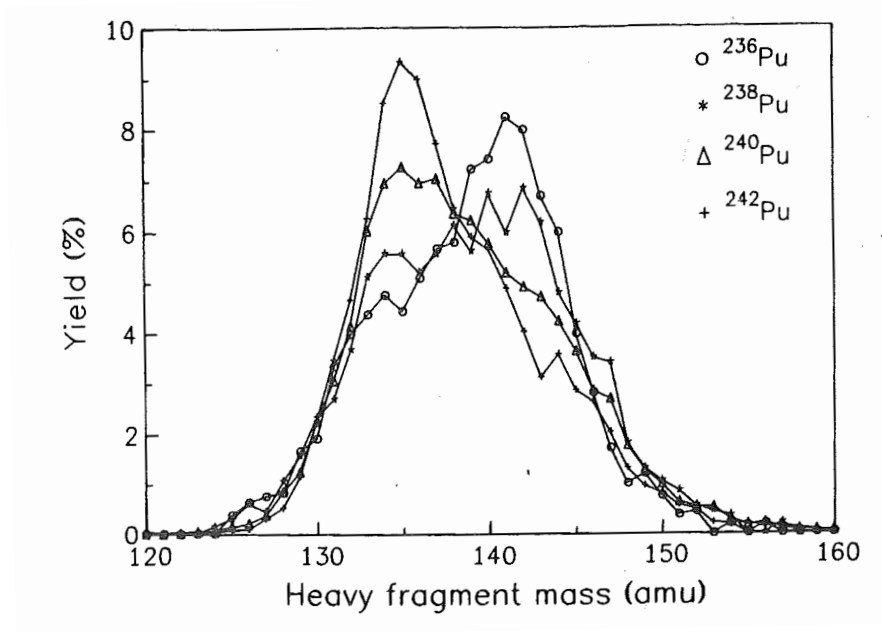
# The fission observables

- **Fission fragment yields**
  - ✧ **Pre-neutron mass distributions**
  - ✧ **Post-neutron mass-distributions**
- **Fragment kinetic energy**
- **Fragment excitation energy**
  - ✧ **Prompt fission neutrons**
  - ✧ **Prompt fission  $\gamma$ -rays**
- **Fragment angular distribution (anisotropy)**
- **Ternary particles (LCP:  $\alpha$ ,  ${}^6,8\text{He}$ ,  ${}^{10}\text{Be}$ , ...  ${}^{34}\text{Si}$ )**

# The fission observables



# The fission observables



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

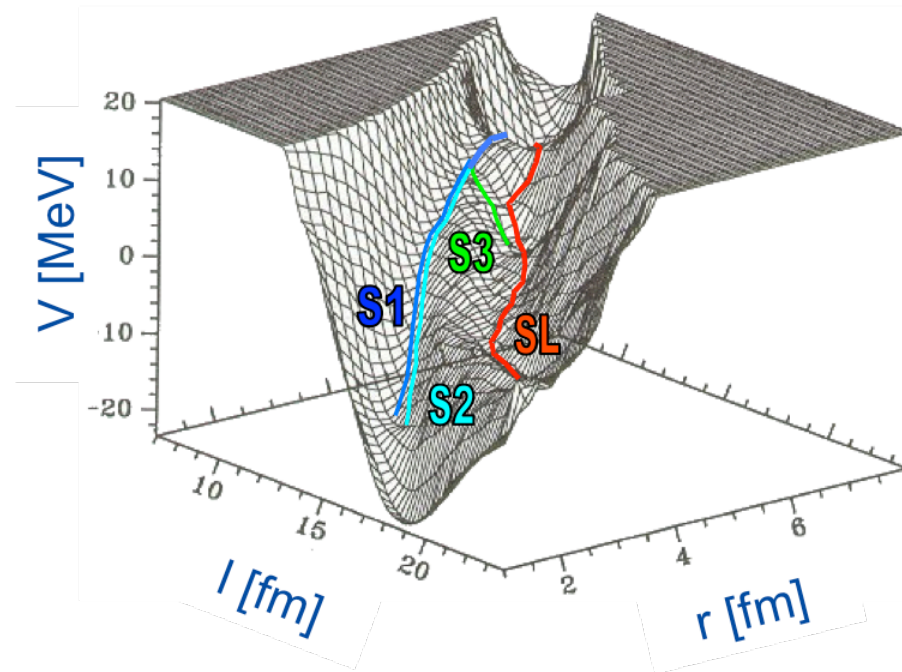


## After 75 years

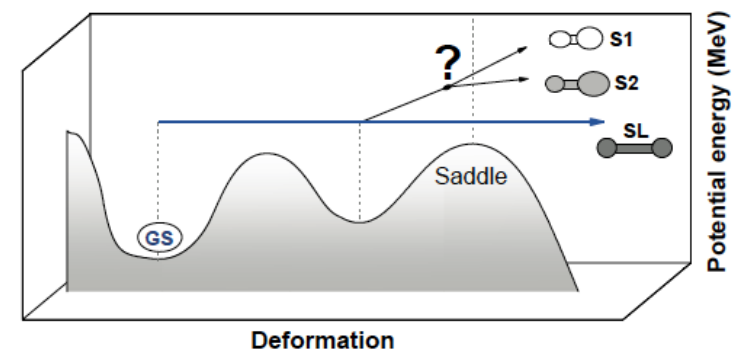
- **Fission theory not (yet) able to calculate *realistic* fission fragment characteristics**
- **New concepts are being developed (CEA, LANL; very CPU demanding)**
- **No predictive power, yet...**
  
- **Phenomenological approaches quite successful (GEF, ...), require experimental data**

# After 75 years

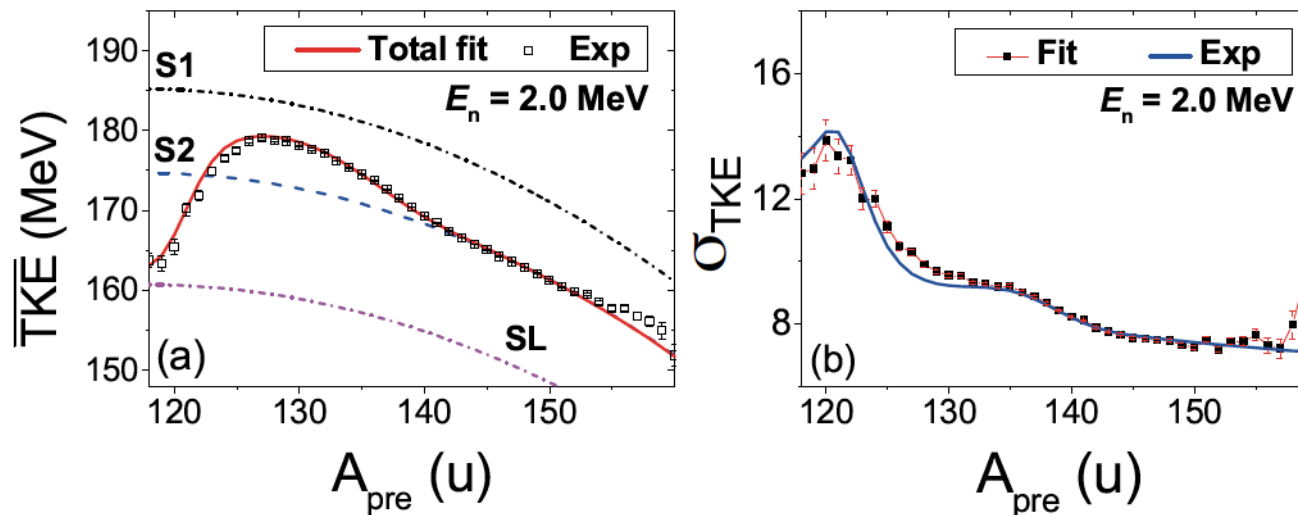
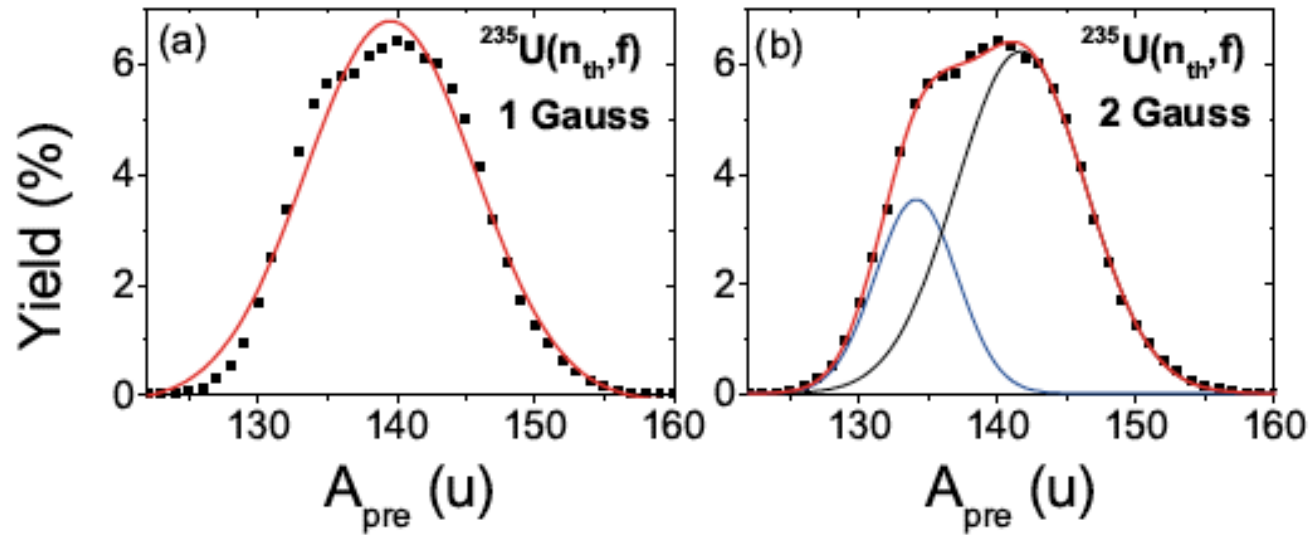
S1 – standard I  
S2 – standard II  
S3 – standard III  
SL – super long



- 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

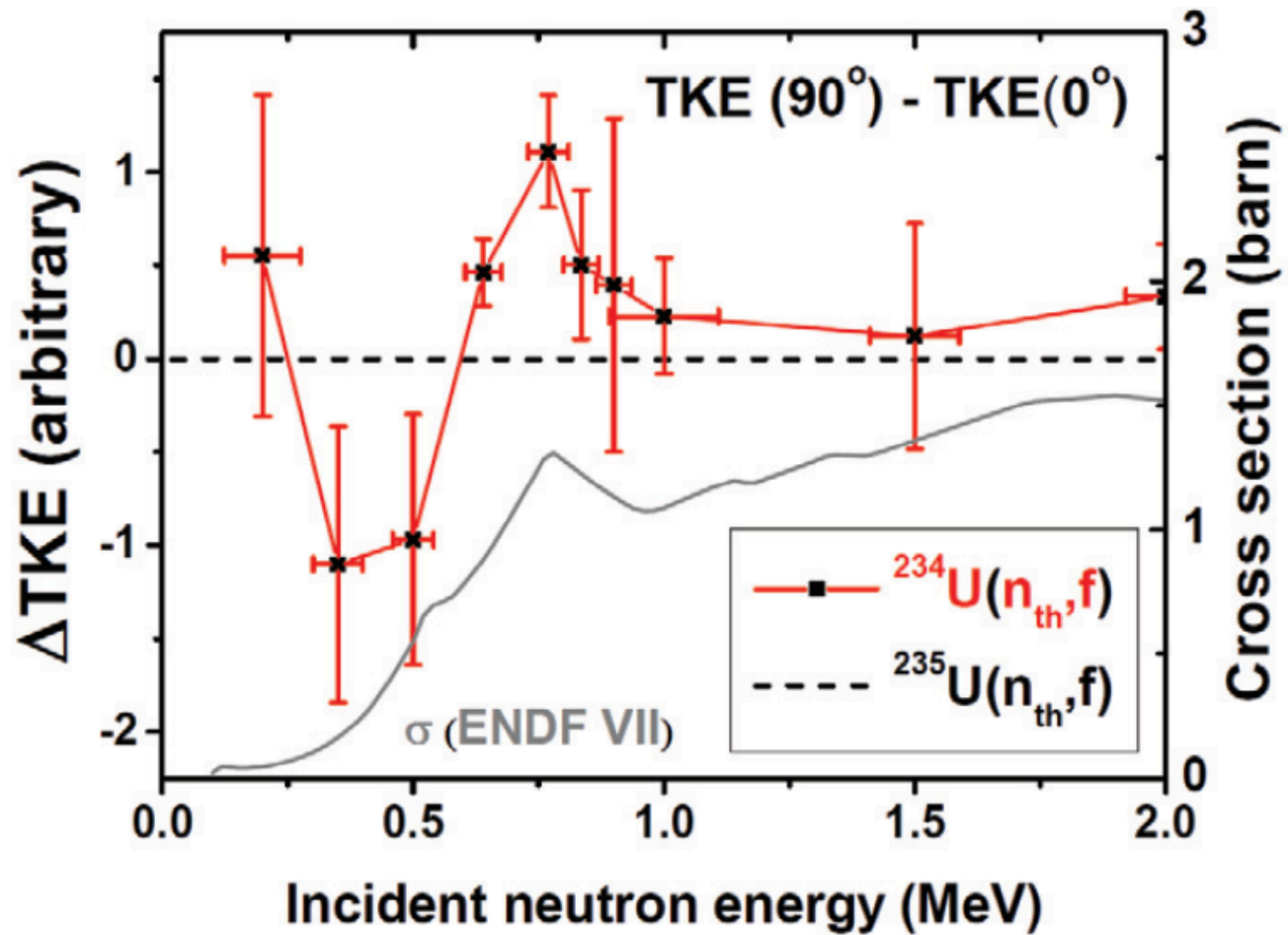


Details in: A.A. Adili et al., PRC 93, 034603 (2016)



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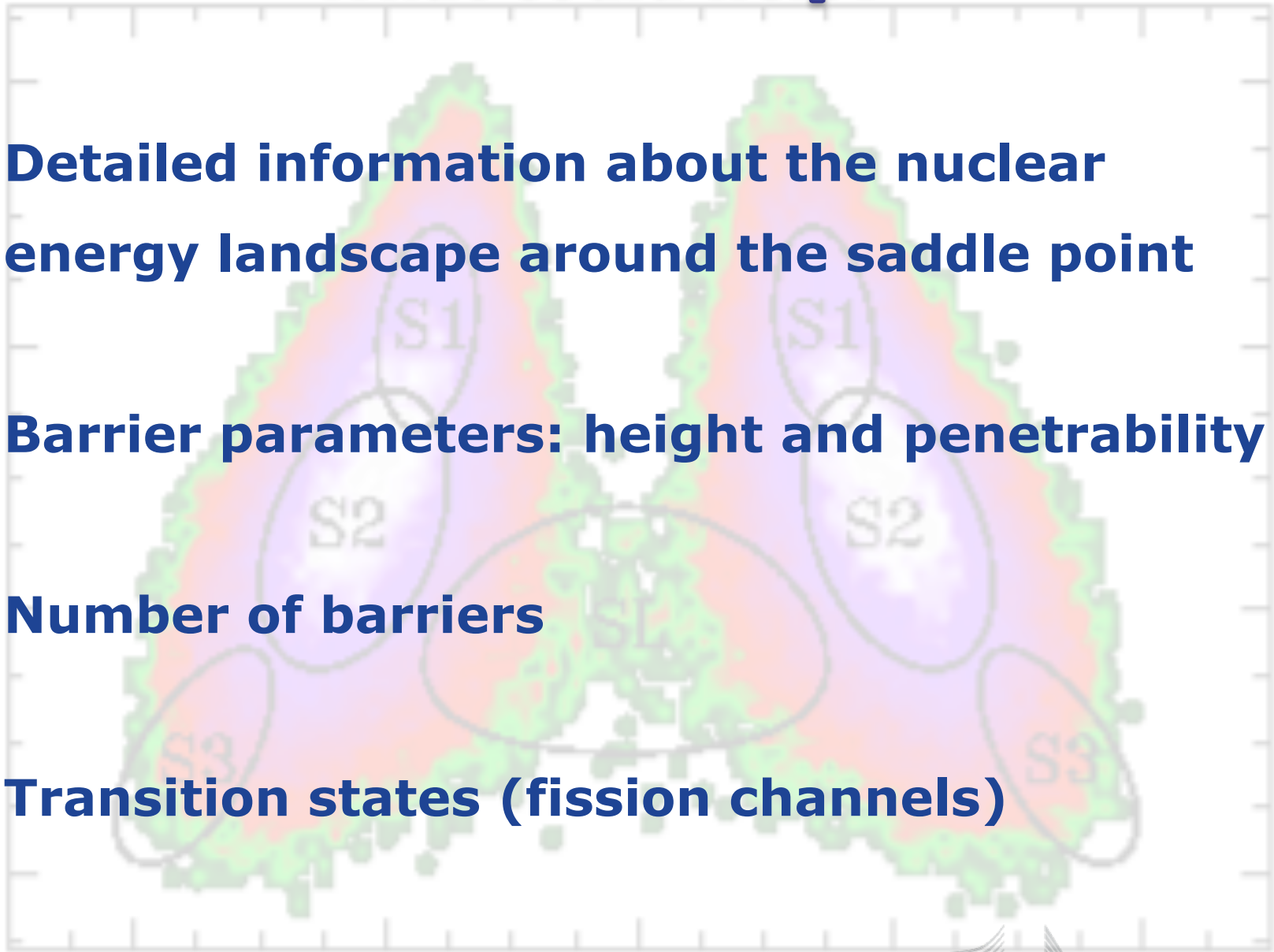
# After 75 years



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

# 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)



Cf 240 40.3 s α 7.581, 7.535 sf	Cf 241 2.35 μr c α 7.328	Cf 242 3.68 μr α 7.892, 7.358 c	Cf 243 10.7 μr c α 7.06, 7.17 g	Cf 244 19.4 m α 7.209, 7.174 g	Cf 245 43.6 μr c α 7.137 g	Cf 246 35.7 h α 6.750, 6.708... sf γ (42, 96...), e <sup>-</sup>	Cf 247 3.11 h ε α 6.296, 6.238 γ (294, 448 418...), e <sup>-</sup>	Cf 248 333.5 d α 6.258, 6.217... sf γ (43), e <sup>-</sup>	Cf 249 351 a α 5.812, 5.758... sf γ 388, 333..., g α 500, α <sub>1</sub> 1700	Cf 250 13.08 a α 6.030, 5.989... sf γ (43...), e <sup>-</sup> α 2000, α <sub>1</sub> 110	Cf 251 898 a α 5.679, 5.849 6.012... γ 177, 227... α 2900, α <sub>1</sub> 4500	
	Bk 240 5 m c [sf]	Bk 241 4.6 m c γ 262, 152, 211	Bk 242 7 m c g	Bk 243 4.5 h α 6.579, 6.543 755, 946 g	Bk 244 4.35 h c α 6.862, 6.620... γ 692, 210, 922 g	Bk 245 4.90 d c α 5.898, 6.190... γ 233, 381... e <sup>-</sup> g	Bk 246 1.88 d ?	Bk 247 1380 a α 5.531, 5.710 5.688... γ 84, 265... g	Bk 248 23.7 h ? >9 a β <sup>-</sup> 0.2... α <sup>?</sup> β <sup>-</sup> γ e <sup>-</sup>	Bk 249 330 d β <sup>-</sup> 0.1 α 5.419, 5.391... sf, γ (327, 308...) α 700, α <sub>1</sub> -0.1	Bk 250 3.217 h β <sup>-</sup> 0.7, 1.8... γ 989, 1032 1029... α <sub>1</sub> 1000	
Cm 238 2.4 h c α 6.558, 6.503 55 g	Cm 239 3 h c γ 188... g	Cm 240 27 d c α 6.291, 6.248 sf g	Cm 241 32.8 d c α 5.939... γ 472, 431 132... e <sup>-</sup> g	Cm 242 162.94 d α 6.113, 6.069... g, sf, Si34 γ (44...), e <sup>-</sup> 20... g	Cm 243 29.1 a α 5.785, 5.742... c, sf, g γ 278, 228 10... e <sup>-</sup> g	Cm 244 18.10 a α 5.805, 5.762... sf γ (43...), e <sup>-</sup> α 350... g	Cm 245 8500 a α 5.361, 5.304... sf, g γ 115, 133... α 350... g	Cm 246 4760 a α 5.386, 5.343... sf, g γ (45), e <sup>-</sup> α 60, α <sub>1</sub> 82	Cm 247 1.56·10 <sup>7</sup> a α 4.870, 5.267... γ 402, 278..., g α 60, α <sub>1</sub> 82	Cm 248 3.40·10 <sup>5</sup> a α 5.076, 5.035... sf, γ e <sup>-</sup> , g α 2.6, α <sub>1</sub> 0.36	Cm 249 64.15 m β <sup>-</sup> -0.9 γ 634, (560 369...), e <sup>-</sup> α -1.6	
Am 237 73.0 m c α 5.942... γ 280, 438, 474 900... g	Am 238 1.63 h c α 5.94... γ 983, 910, 561 805... g	Am 239 11.9 h c α 5.774... γ 278, 228... e <sup>-</sup> g	Am 240 50.8 h c α 5.600, 5.410... γ 278, 228... e <sup>-</sup> α <sub>1</sub> 3.15	Am 241 432.2 a c α 5.443... γ 278, 228... e <sup>-</sup> α <sub>1</sub> 3.15	Am 242 141 a c α 5.170... γ 278, 228... e <sup>-</sup> α <sub>1</sub> 0.079	Am 243 16 h c α 5.15... γ 278, 228... e <sup>-</sup> α <sub>1</sub> 0.079	Am 244 7370 a c α 5.15... γ 278, 228... e <sup>-</sup> α <sub>1</sub> 0.079	Am 245 26 m c α 5.15... γ 278, 228... e <sup>-</sup> α <sub>1</sub> 0.079	Am 246 10.1 h c α 5.15... γ 278, 228... e <sup>-</sup> α <sub>1</sub> 0.079	Am 247 2.05 h c α 5.15... γ 278, 228... e <sup>-</sup> α <sub>1</sub> 0.079	Am 248 29 m c α 5.15... γ 278, 228... e <sup>-</sup> α <sub>1</sub> 0.079	Am 249 39 m c α 5.15... γ 278, 228... e <sup>-</sup> α <sub>1</sub> 0.079
Pu 236 2.858 a c α 5.768, 5.721... sf Mg28 γ (48, 109...), e <sup>-</sup> α <sub>1</sub> 160	Pu 237 452 d c α 5.334... γ 00... e <sup>-</sup> α <sub>1</sub> 2300	Pu 238 87.74 a c α 5.499, 5.456... sf Si, Mg γ (43, 100...), e <sup>-</sup> α 510, α <sub>1</sub> 17	Pu 239 2.411·10 <sup>4</sup> a c α 5.157, 5.144... sf γ (52...), e <sup>-</sup> m α 270, α <sub>1</sub> 752	Pu 240 6563 a c α 5.168, 5.124... sf γ (45...), e <sup>-</sup> g α 290, α <sub>1</sub> -0.059	Pu 241 14.35 a c β <sup>-</sup> 0.02... g α 4.901, 4.856... sf γ (45...), e <sup>-</sup> g α 18, α <sub>1</sub> < 0.2	Pu 242 3.750·10 <sup>5</sup> a c β <sup>-</sup> 0.6... g α 4.589, 4.548... sf γ 1. e <sup>-</sup> e 1.7	Pu 243 4.956 h c β <sup>-</sup> 0.6... g α 4.589, 4.548... sf γ 1. e <sup>-</sup> e 1.7	Pu 244 8.00·10 <sup>7</sup> a c β <sup>-</sup> 0.6... g α 4.589, 4.548... sf γ 1. e <sup>-</sup> e 1.7	Pu 245 10.5 h c β <sup>-</sup> 0.6... g α 4.589, 4.548... sf γ 1. e <sup>-</sup> e 1.7	Pu 246 10.84 d c β <sup>-</sup> 0.2, 0.3... γ 44, 224, 180... m <sub>2</sub>	Pu 247 2.27 d c β <sup>-</sup>	
Np 235 396.1 d c α 5.025, 5.007... γ (20, 84...), e <sup>-</sup> g α 160 + 3	Np 236 22.5 h c α 5.025, 5.007... γ (20, 84...), e <sup>-</sup> g α 160 + 3	Np 237 2.144·10 <sup>6</sup> a c α 4.790, 4.774... γ 29, 87..., e <sup>-</sup> α 170, α <sub>1</sub> 0.020	Np 238 2.117 d c β <sup>-</sup> 1.2... γ 984 1029, 1026... 924... e <sup>-</sup> , g α 2600	Np 239 2.355 d c β <sup>-</sup> 0.4, 0.7... γ 106, 278 228... e <sup>-</sup> , g α 32 + 19, α <sub>1</sub> < 1	Np 240 722 m c β <sup>-</sup> 2.2... γ 555... 597... 801, 448... g	Np 241 13.9 m c β <sup>-</sup> 1.3... γ 175, (133...) g	Np 242 2.2 m c β <sup>-</sup> 2.2... γ 236, 280... 1473... g	Np 243 1.85 m c β <sup>-</sup> 288... g	Np 244 2.29 m c β <sup>-</sup> 217, 681, 163 111... g			
U 234 0.0054 2.455·10 <sup>5</sup> a c α 4.775, 4.723... sf Mg28, Ne, γ (53, 121...) e <sup>-</sup> , α 96, α <sub>1</sub> 0.07	U 235 0.7204 26 m c α 4.398... sf Ne, γ 199 α 95, α <sub>1</sub> 58	U 236 2.342·10 <sup>7</sup> a c α 4.494... γ 444... sf Mg30, γ (49 113...), e <sup>-</sup> α 5.1	U 237 6.75 d c β <sup>-</sup> 0.2... γ 60, 208... e <sup>-</sup> α -100 α <sub>1</sub> < 0.35	U 238 99.2742 298 m c α 4.458·10 <sup>8</sup> a α 4.198... sf γ 25... 28... γ (50...) 18... e <sup>-</sup> , α 2.7 α <sub>1</sub> 3E-6	U 239 23.5 m c β <sup>-</sup> 1.2, 1.3... γ 75, 44... α 22 α <sub>1</sub> 15	U 240 14.1 h c β <sup>-</sup> 0.4... γ 44, (190...) e <sup>-</sup> m	U 242 16.8 m c β <sup>-</sup> 68, 58, 585 573... m					
Pa 233 27.0 d c β <sup>-</sup> 0.3, 0.6... γ 312, 300, 341... α 20 + 19 α <sub>1</sub> 0.1	Pa 234 1.17 m c β <sup>-</sup> 2.3... γ 1001... 197... α 174... α 500	Pa 235 24.2 m c β <sup>-</sup> 1.4... γ 128, 659 m	Pa 236 9.1 m c β <sup>-</sup> 2.0, 3.1... γ 642, 687 1763... g βsf7	Pa 237 8.7 m c β <sup>-</sup> 1.4, 2.3... γ 854, 865, 529 541... g	Pa 238 2.3 m c β <sup>-</sup> 1.7, 2.9... γ 1015, 635 448, 680... g	Pa 239 1.8 h c β <sup>-</sup> 522, 681... g						
Th 232 100 1.405·10 <sup>10</sup> a c α 4.013, 3.950... sf, γ (84...), e <sup>-</sup> α 7.37, α <sub>1</sub> 3E-8	Th 233 22.3 m c β <sup>-</sup> 1.2... γ 87, 29, 459... e <sup>-</sup> α 1500, α <sub>1</sub> 15	Th 234 24.10 d c β <sup>-</sup> 0.2... γ 83, 92, 93... e <sup>-</sup> , m α 1.8, α <sub>1</sub> < 0.01	Th 235 7.1 m c β <sup>-</sup> 1.4... γ 417, 727 696... g	Th 236 37.5 m c β <sup>-</sup> 1.0... γ 111, (647 196...) g	Th 237 5.0 m c β <sup>-</sup>	Th 238 9.4 m c β <sup>-</sup> 89... g						

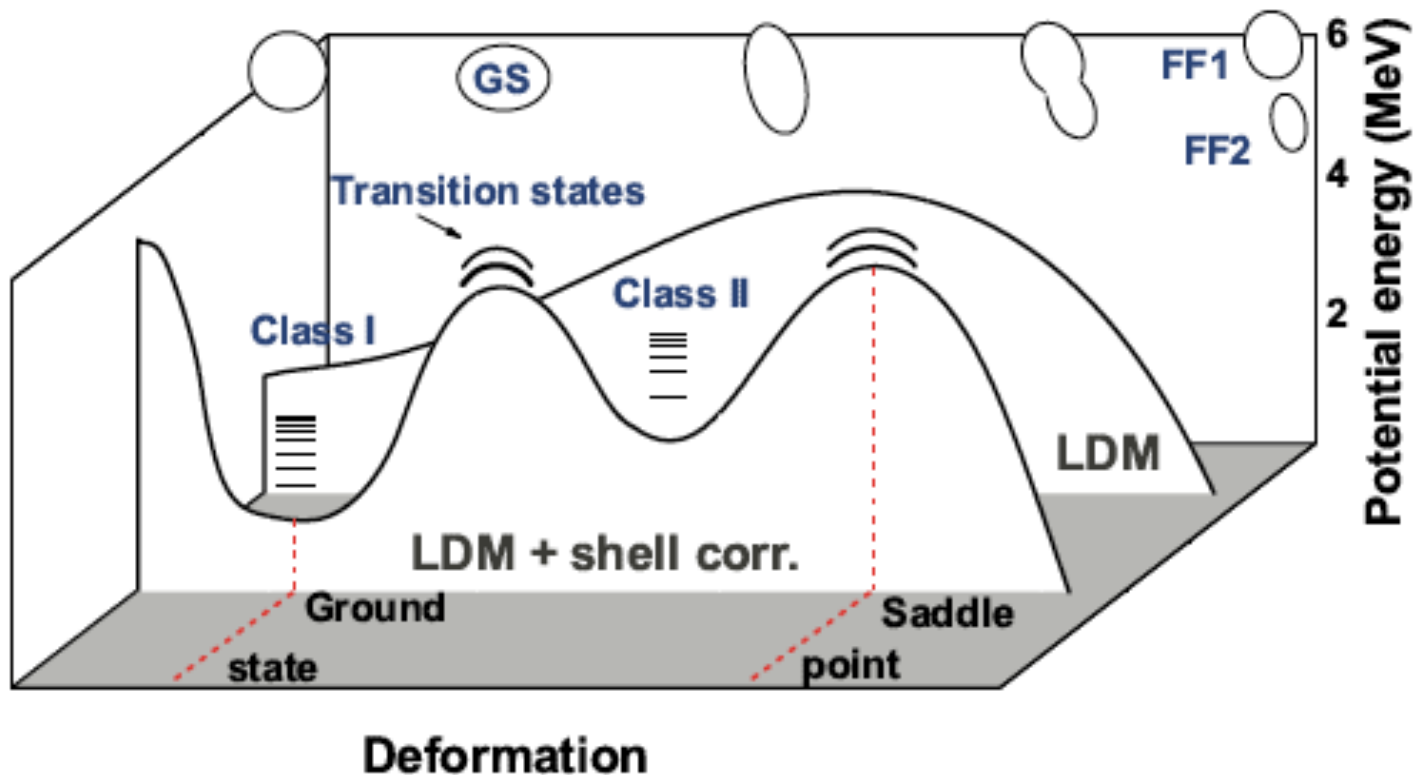
**This is where now  
shape isomers come in!**





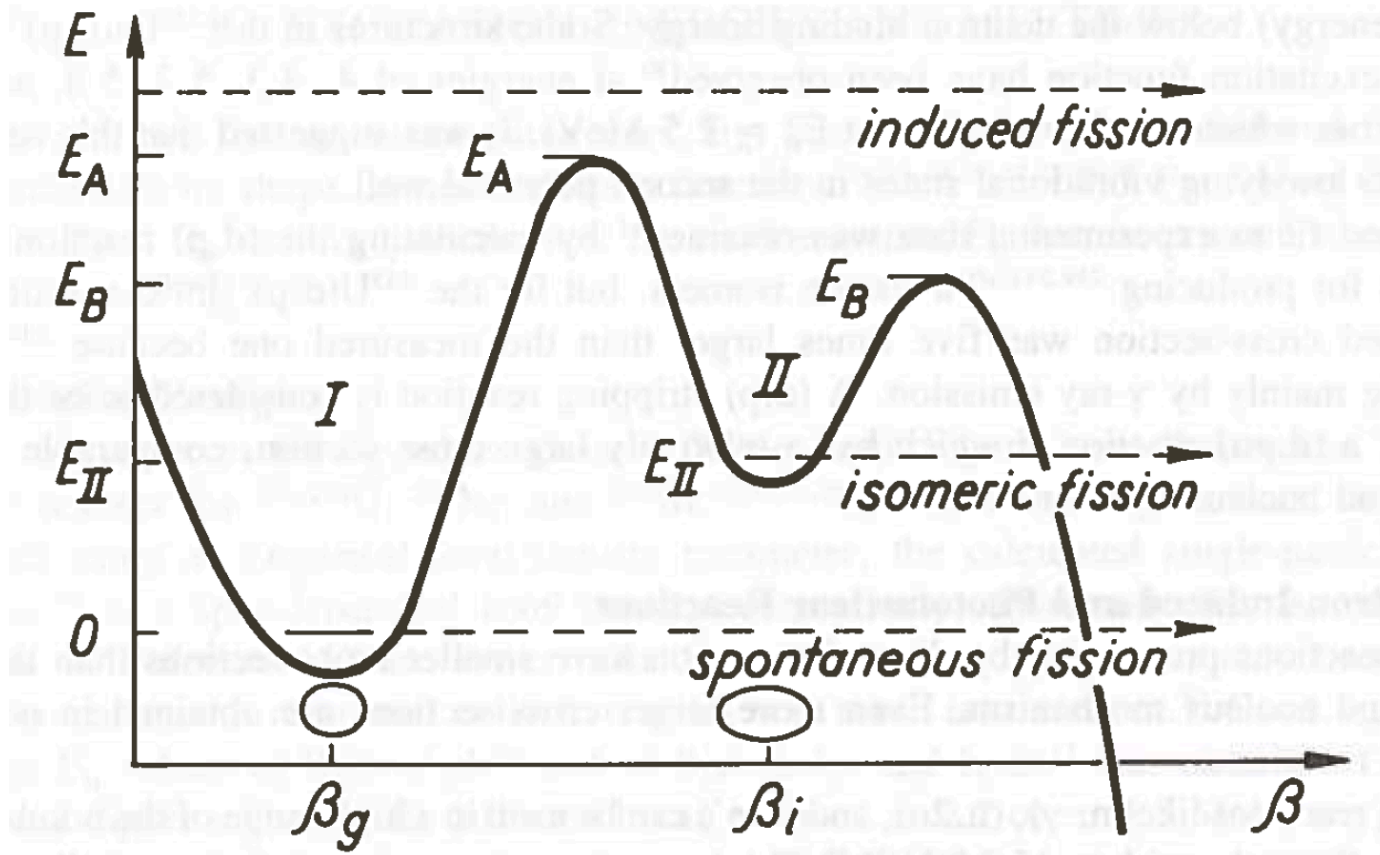
# What is a shape isomer?

“Macroscopic-microscopic” or “shell correction” (SCM)



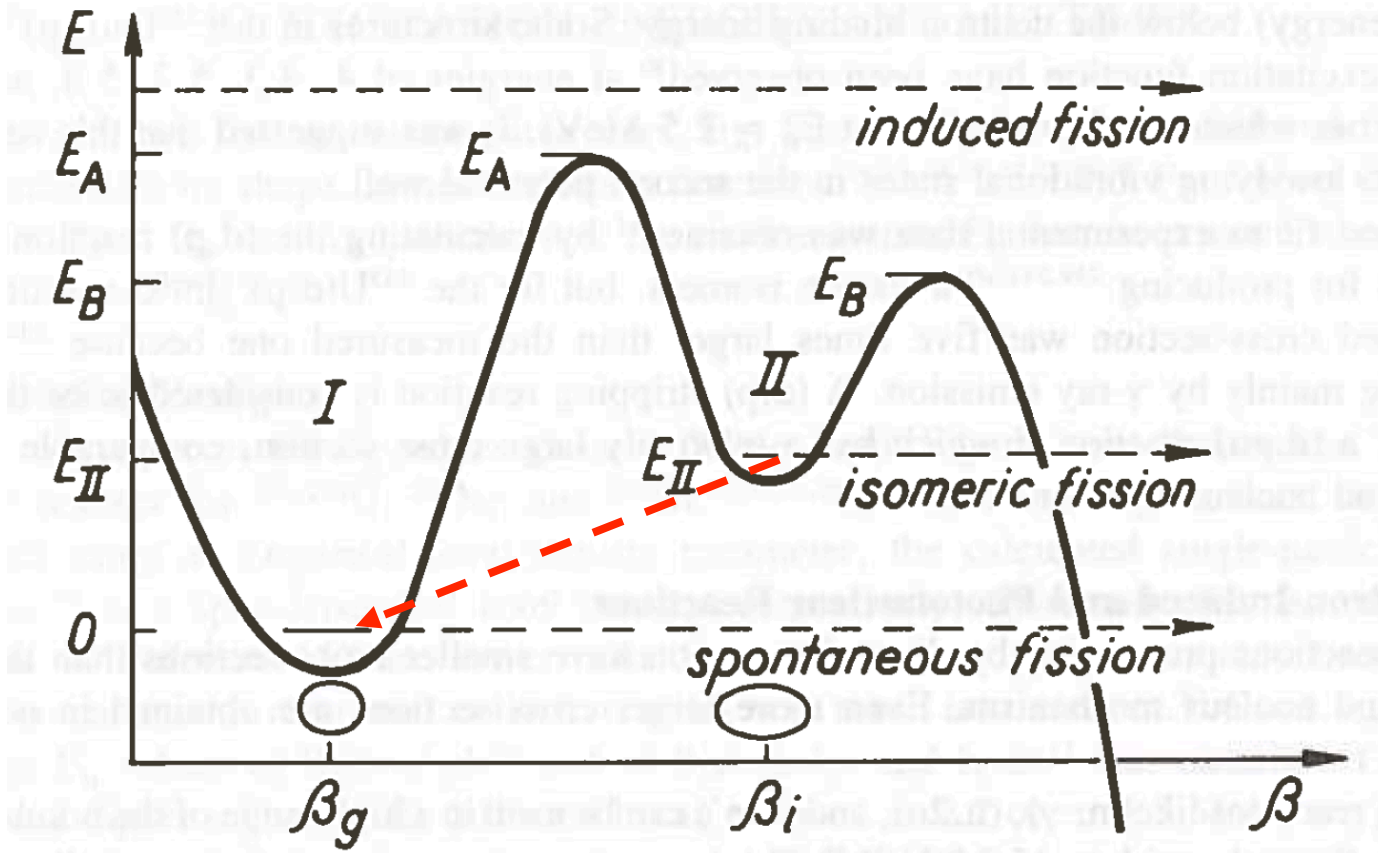


# What is a shape isomer?



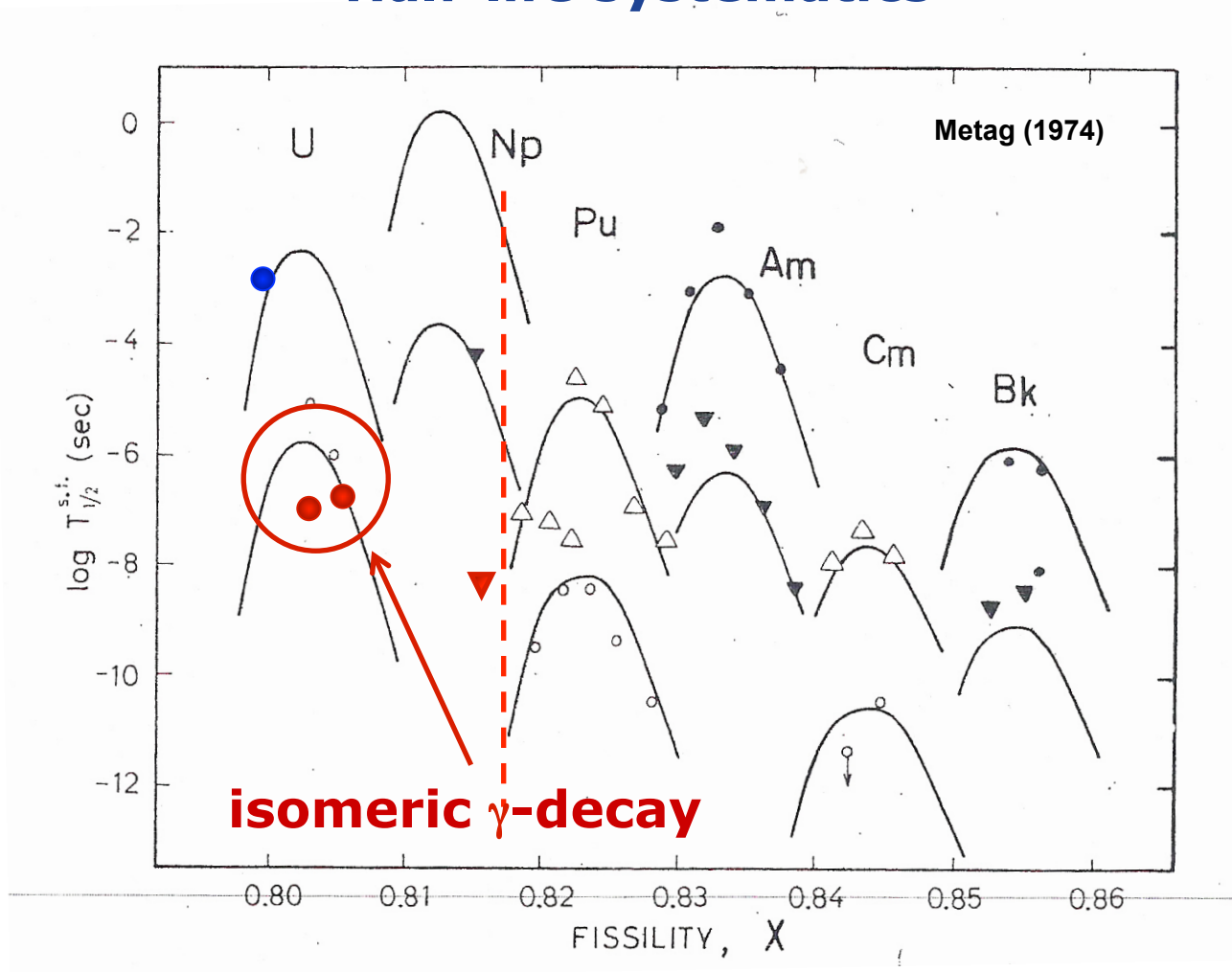


# Shape isomer characteristics



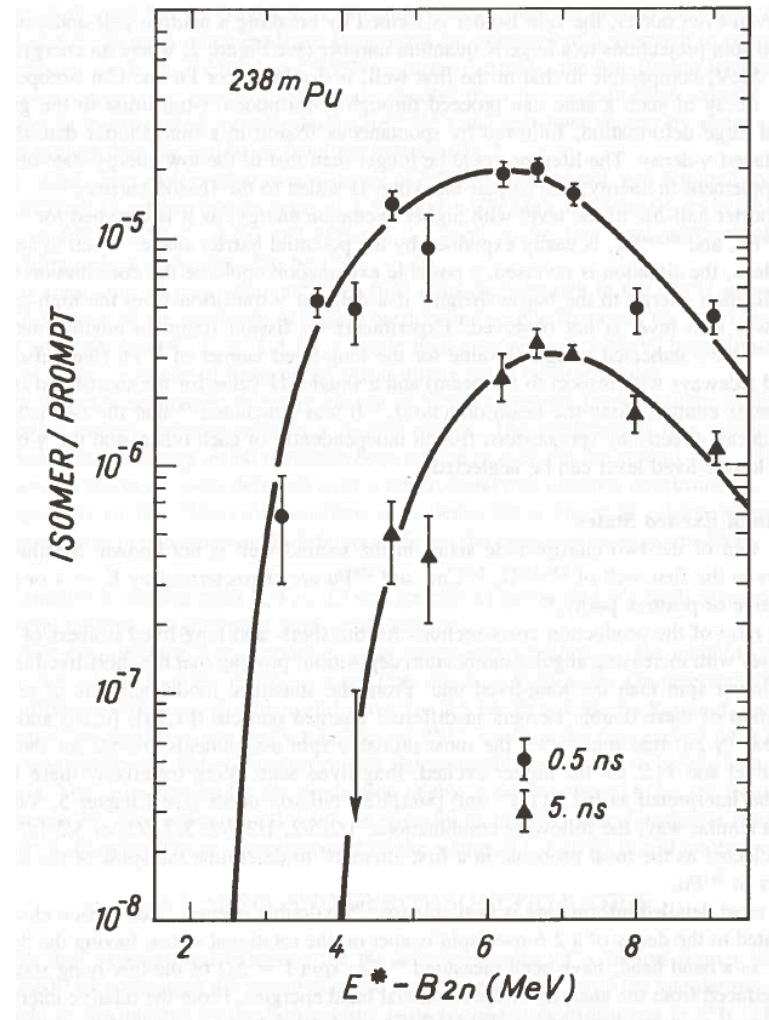
# Shape isomer characteristics

## Half-life systematics



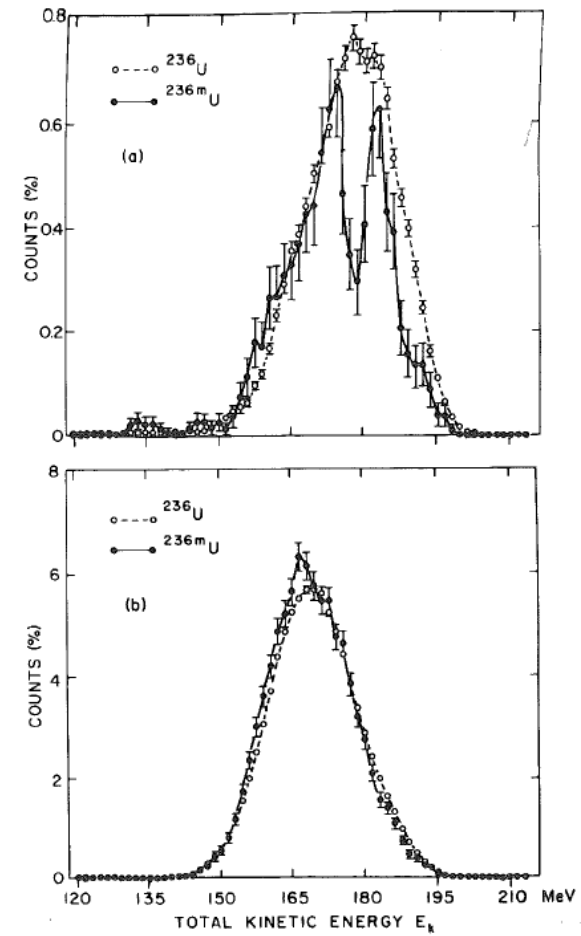
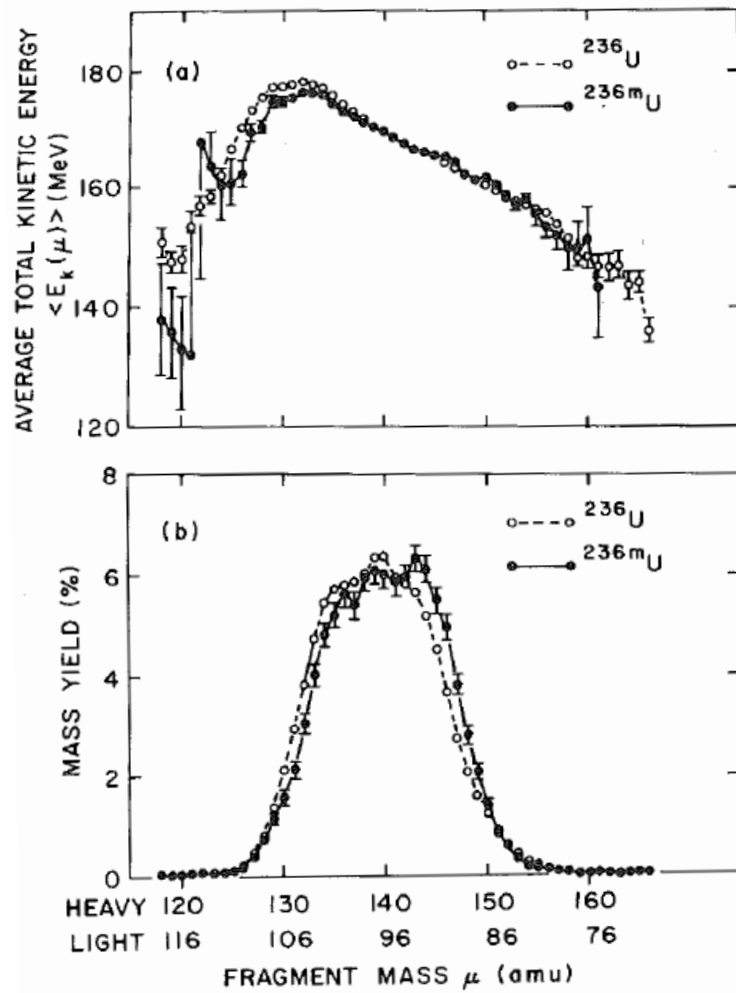
# Shape isomer characteristics

## Excitation function



# Shape isomer characteristics

Something unique and intriguing!



# Relevant information from SI

## Inverted parabolas (Hill-Wheeler)

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

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

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

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

# Relevant information from SI

**Desired information:**

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

**Measurable quantities:**

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

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

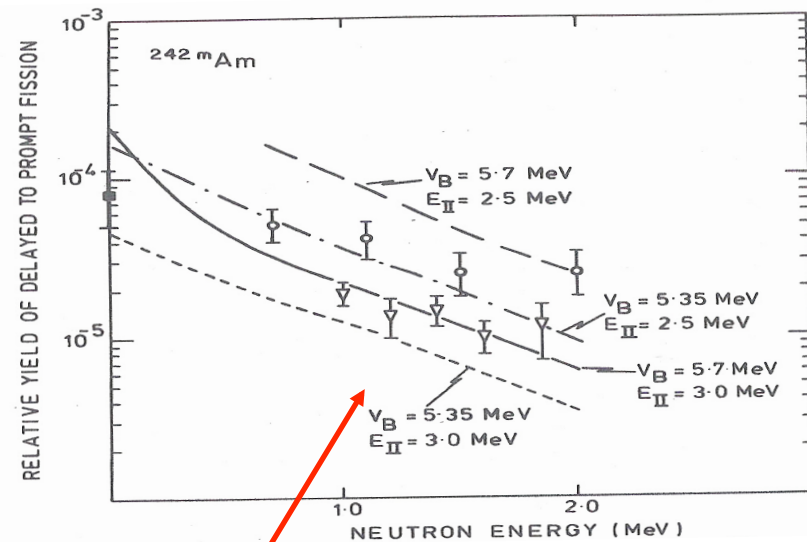
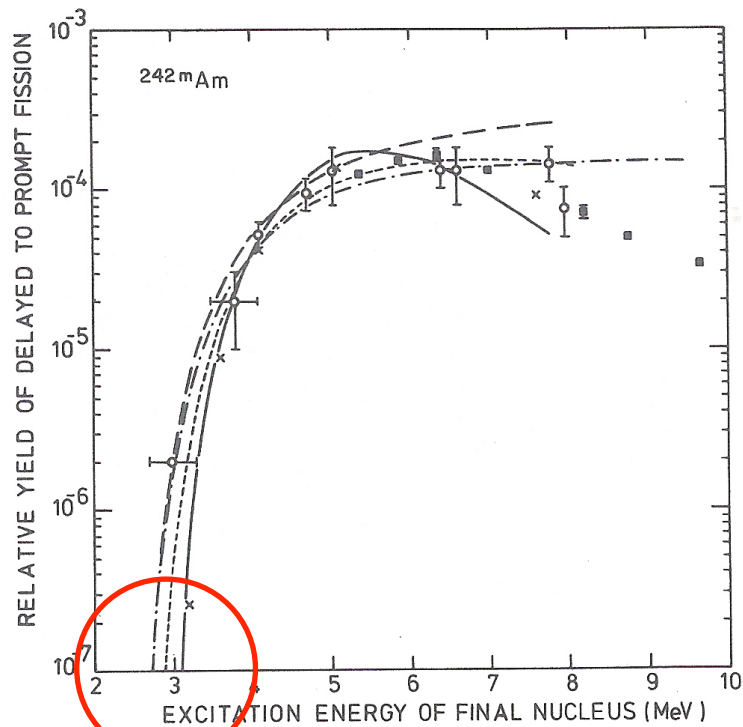
$$\hbar\omega_B < \overline{\hbar\omega_B}$$

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



# Relevant information from SI

## Extraction of barrier parameters



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

# Relevant information from SI

But, we can do better!

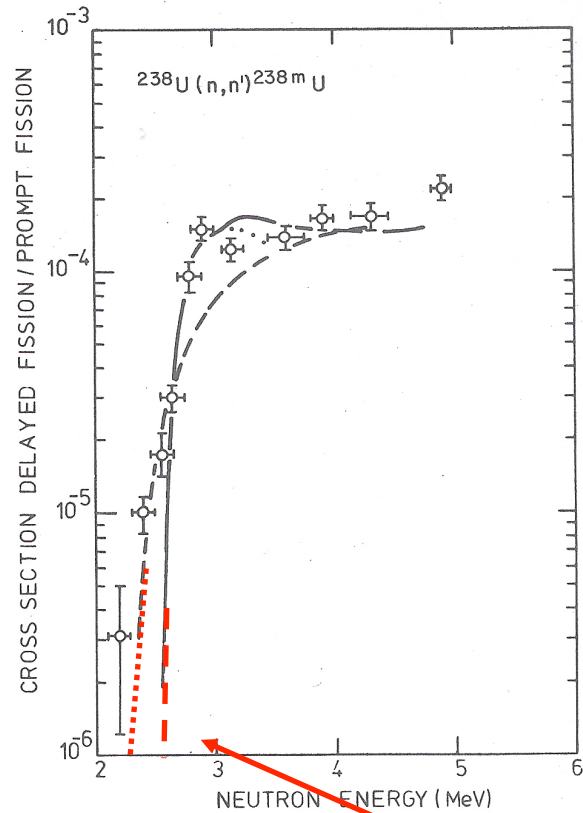
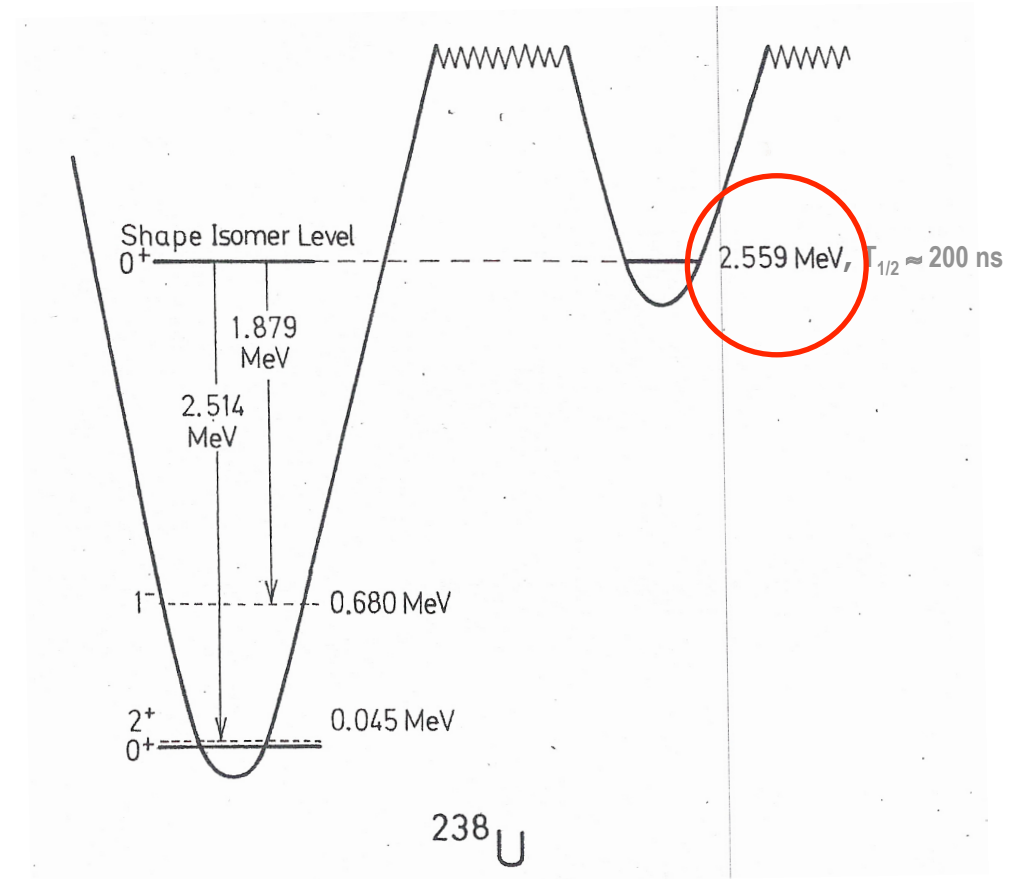
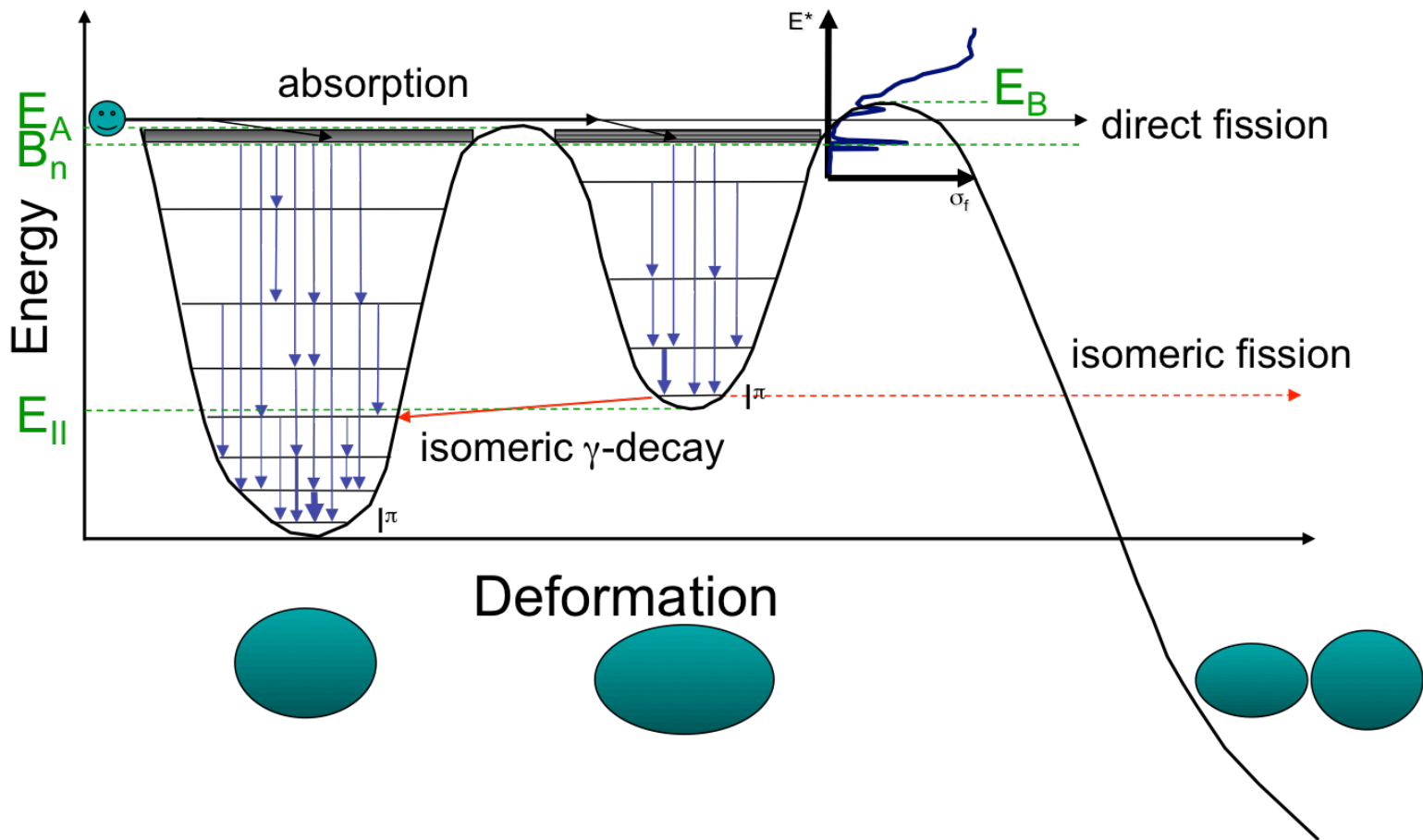


FIG. 61. Data for excitation of  $^{238m}\text{U}$  shape isomer by the  $(n, n')$  reaction (Wolf and Meadows, 1974 and private communication). The broken curve is a statistical calculation based on constant temperature level density models ( $\theta_1 = 0.5$  MeV,  $\theta_1^{(s)} = 0.53$  MeV,  $E_{11} = 2.35$  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.

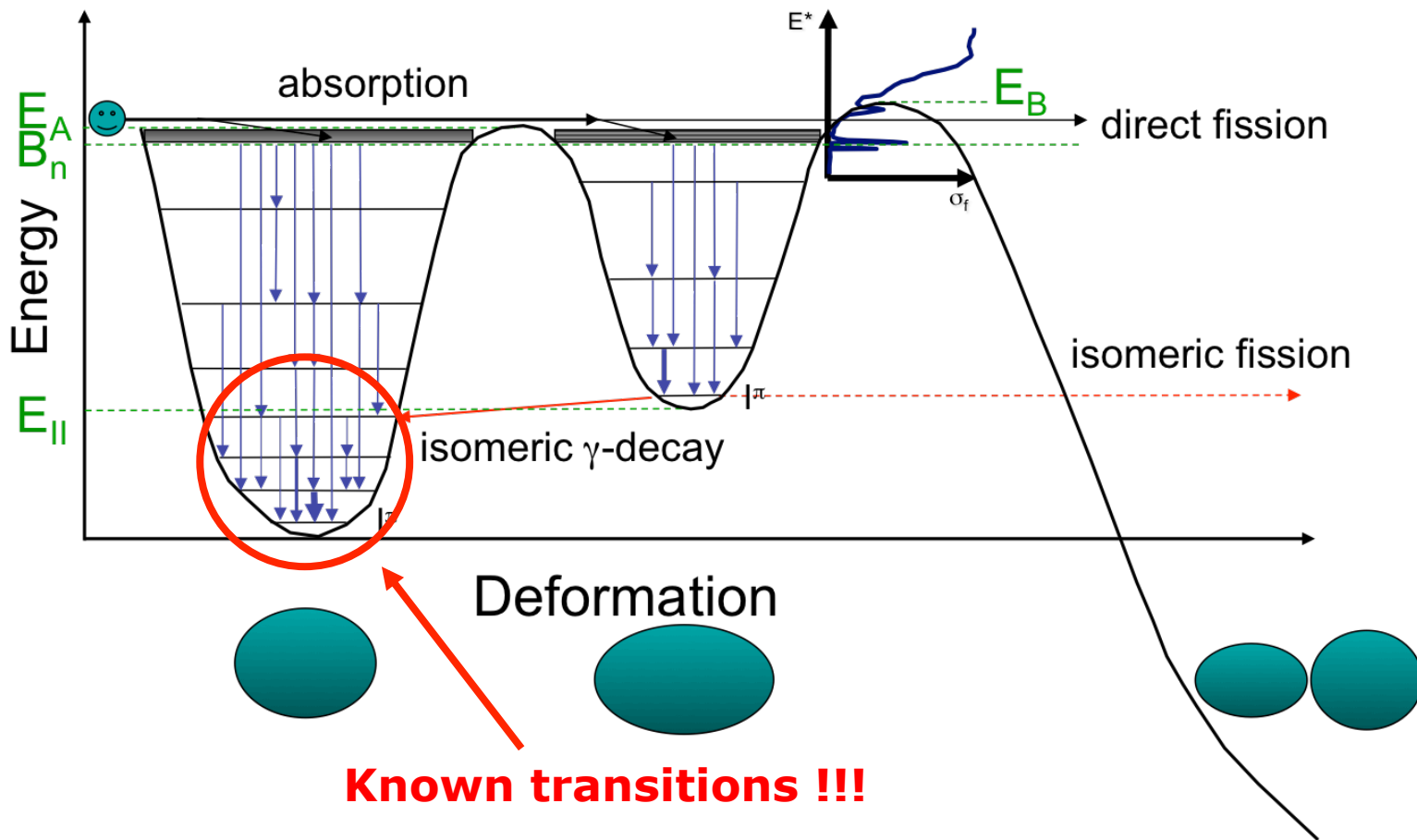
$$E_{11} = 2.2 - 2.6 \text{ MeV}$$



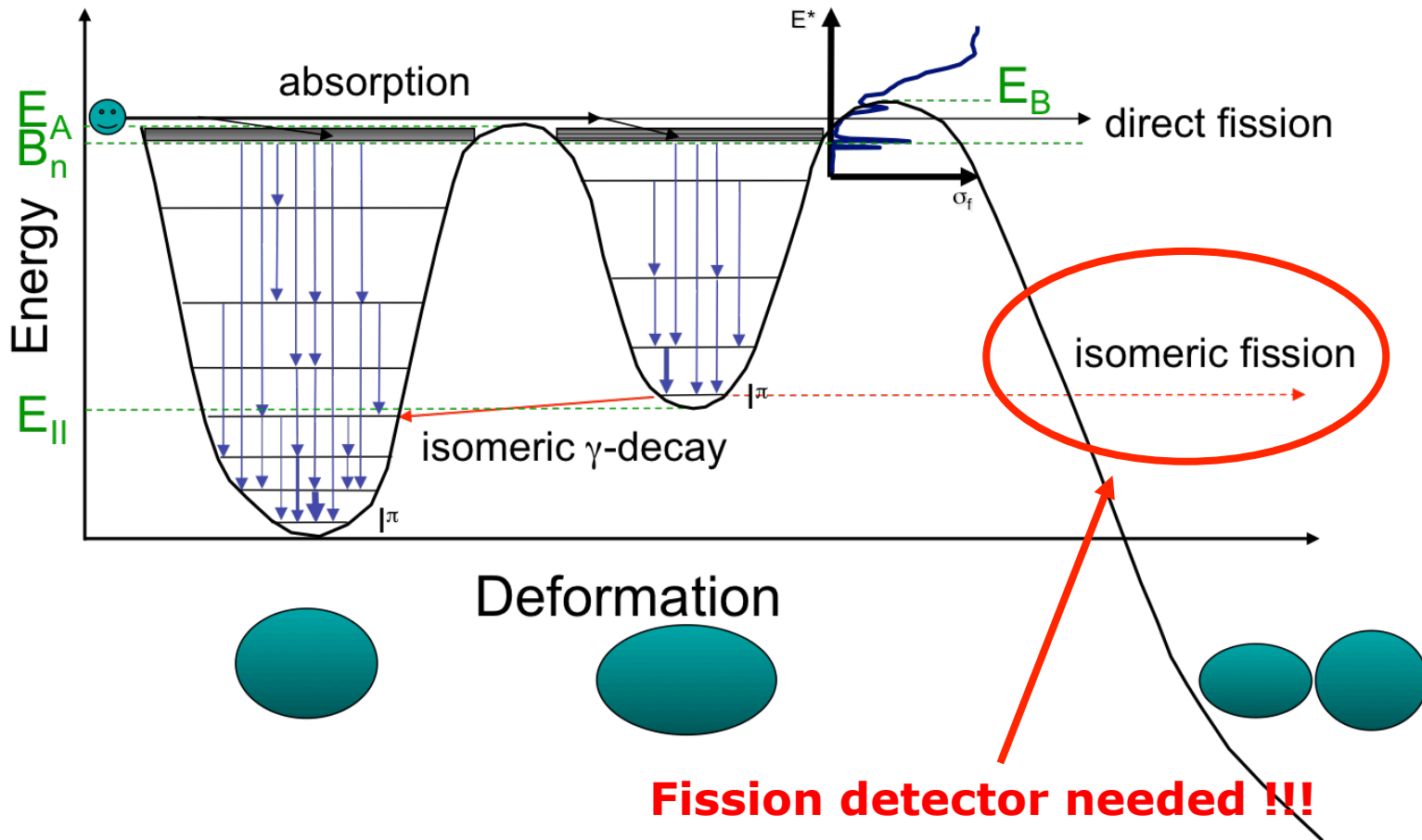
# Experimental approach



# Experimental approach

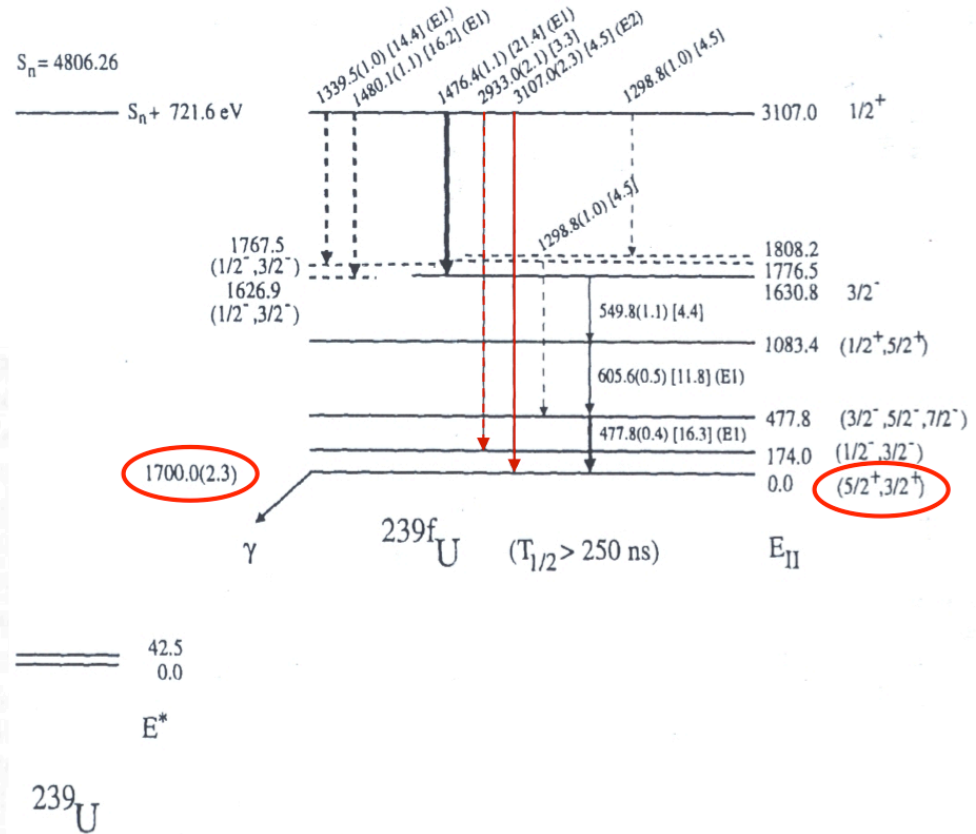
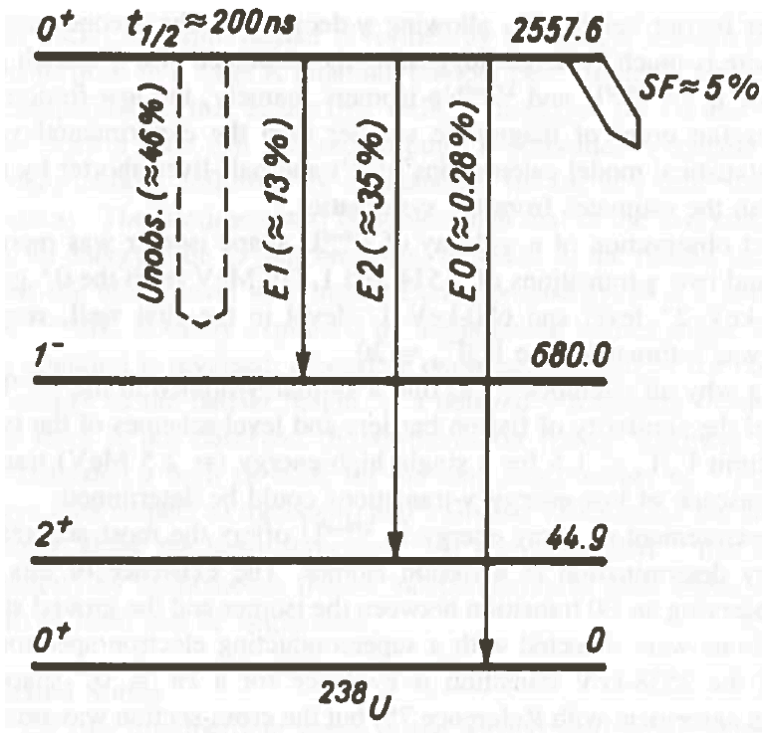


# Experimental approach



# Experimental approach

## HPGe detector used

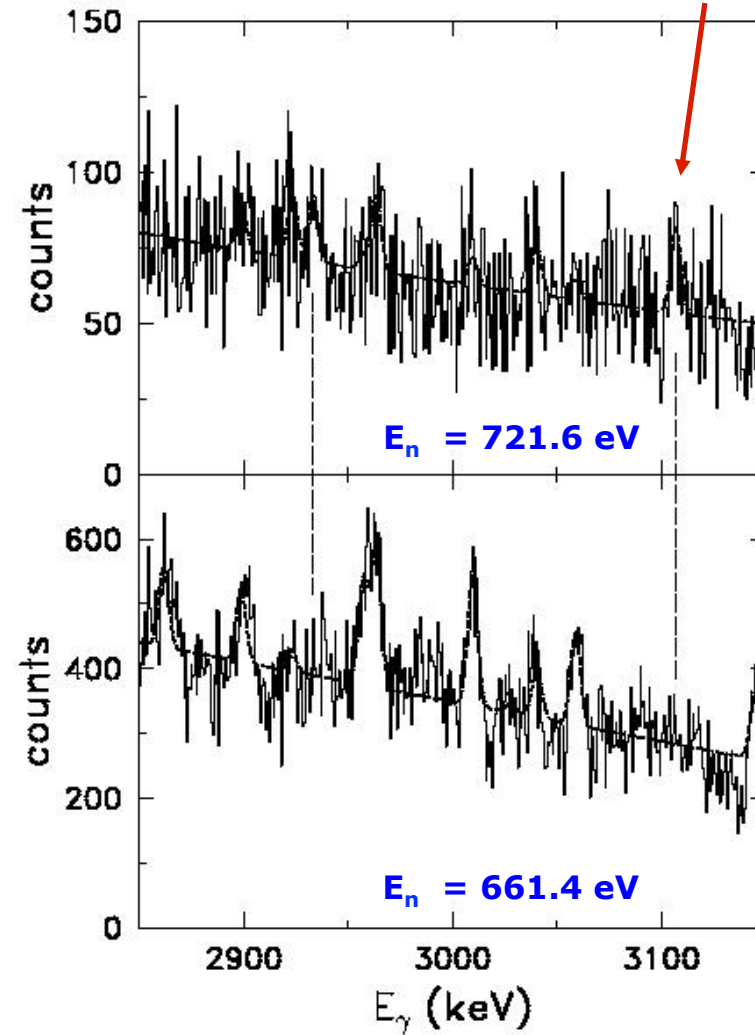
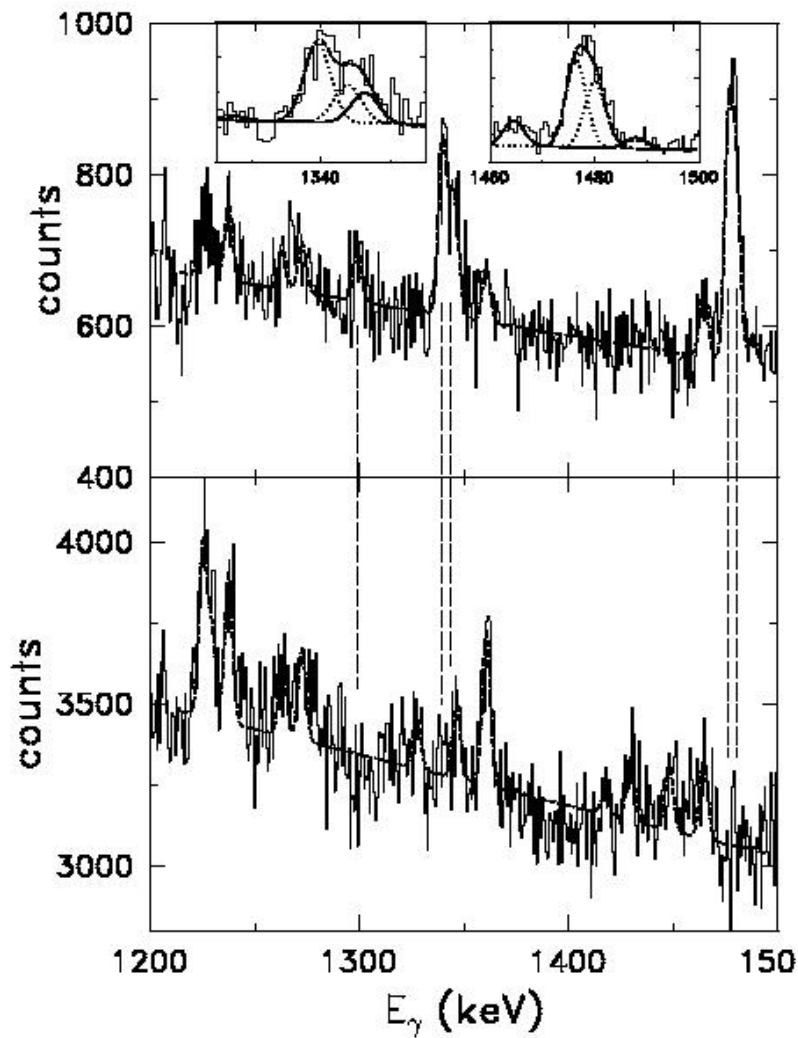


HD-DA Crystal ball (NaI) used for  $^{236}\text{fU}$  and  $^{240}\text{fPu}$

# Experimental approach

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

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



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



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# Experimental approach

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



## Some interesting cases...

- **$^{235}\text{fU}$** :  $E_{\text{II}}$  and  $\gamma$ -rays from SI population and back-decay known > benchmark of the  $\nu$ -Ball arrangement
- **$^{238}\text{fU}$** :  $E_{\text{II}}$  and  $\gamma$ -rays from back-decay known > demonstrator run
- **$^{239}\text{fU}$** : unobserved,  $E_{\text{II}} = 1.7 \text{ MeV}$
- **$^{233}\text{fTh}$** : unknown,  $T_{1/2} (i\gamma) < 100 \text{ ns}$  (no fission branch)
- **$^{232}\text{fTh}$** : unknown,  $T_{1/2} (i\gamma) < 10 \text{ ns}$ , isomeric shelf determined in photo-fission ( $E_{\text{II}} = ?$ )
- **$^{237}\text{fNp}$** :  $T_{1/2} (\text{if}) = 40 \text{ ns}$ , very low fission branch
- **$^{238}\text{fNp}$** : unobserved,  $500 \text{ ns} < T_{1/2} (\text{if}) < 10 \text{ s}$

# SI summary

## ➤ Fission isomer characteristics

- Half-life
- Partial half-lives: isomeric fission, back-decay to 1<sup>st</sup> minimum
- Branching ratio

## ➤ Fission barrier parameters:

- Barrier height:  $E_{A'} E_{B'} \dots E_B(S1), E_B(S2), E_B(SL) \dots$
- Transmission (curvature parameter):  $h\varpi_{A'} h\varpi_B$
- Nuclear structure above super-deformed ground-state
- Isomeric fission fragment characteristics

# 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**
- **$\gamma$ -ray detection efficiency (number and size of detectors), efficiency of fission trigger ...**
- **Use of a fission chamber boosts the efficiency**

# CONCLUSION

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

**v-Ball @ LICORNE**

