The ALTO facility of IJC Lab, Orsay




High energy **Stable Beams**

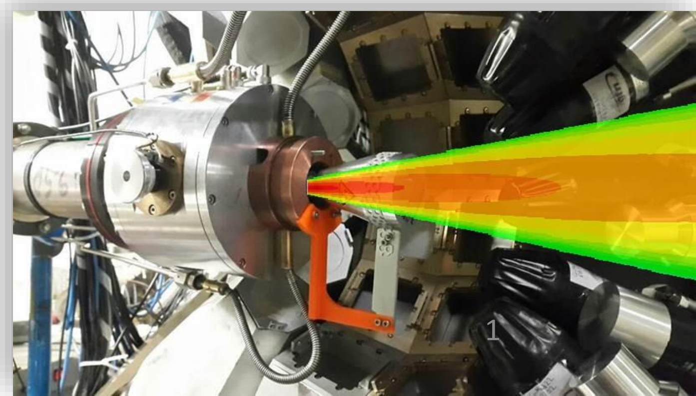
- 15 MV tandem accelerator
- H, ^{3}He, ^{4}He, ..., ^{14}C, ... up to ^{127}I
- Pulsed beams: 100 ns - 100 µs period. 1-2 ns width
- Rare beams (^{3}He, ^{14}C, ^{24}Mg, ^{40}Ca)

Low energy **Radioactive beams**

- Electron linear accelerator 50 MeV & 10 µA + Ucx target (~70 g)
- Isotope Separation Online (**ISOL**) photofission of ^{238}U (~10^{11} f/s)
- RIALTO : Laser ion source → Z selection
- Dipole magnet PARRNe → Mass separation (M/ΔM = 1500)

Naturally directional **Neutron Beams**

- LICORNE neutron converter (hydrogen gas target)
- Up to 800 nA ^{7}Li primary beam: p(7Li,n) reaction
- Up to 10^{8} neutrons/second in 1 steradian



The nu-Ball2: Hybrid γ-ray spectrometer at ALTO

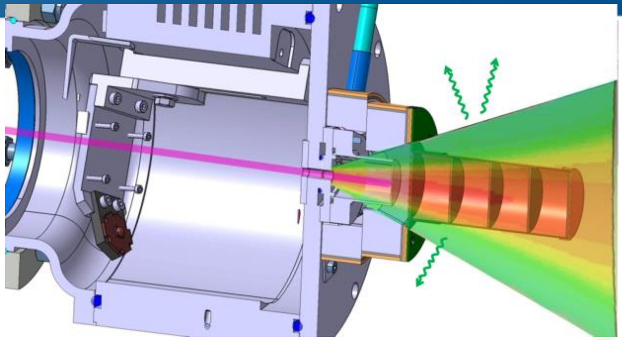
Study of: nuclear fission, neutron rich isotopes, lifetimes/nuclear moments

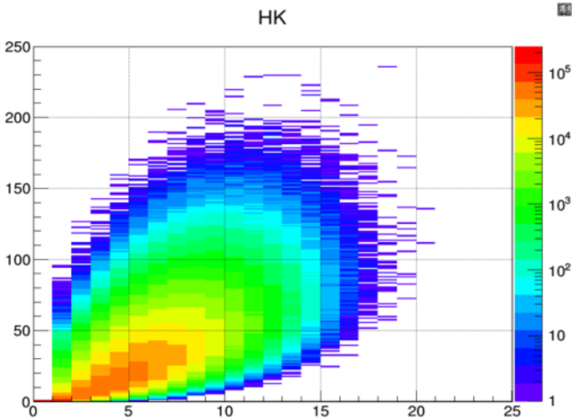
nu-Ball2 under construction 03/03/22

Innovations

- ✓ Hybrid Spectrometer (Ge/BGO/LaBr3/PARIS) high resolution, high efficiency
- ✓ Different geometries and couplings
- ✓ Calorimetry for reaction studies/selection
- ✓ Fully digital, 200 channels, including BGO
- ✓ Modes Triggered or Triggerlesss

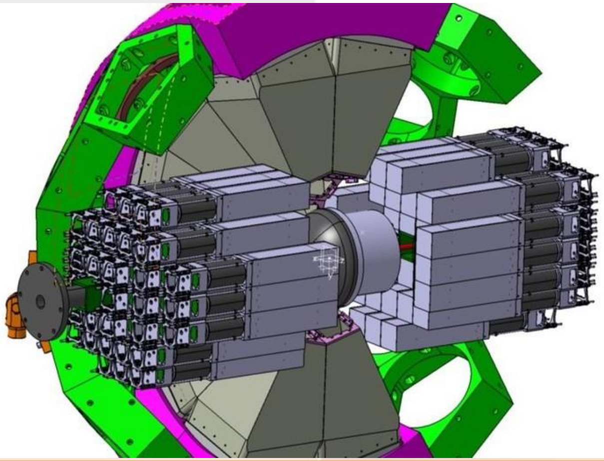
15 approved experiments. 2900 hours beam time march 2022 – june 2023





Gamma detectors

28 Clover Ge's(GammapoolEU consortium)
15 Coaxial Ge's (UK/France loan pool)
36 FATIMA LaBr3 (FATIMA collaboration)
72 PARIS phoswich (PARIS collaboration)

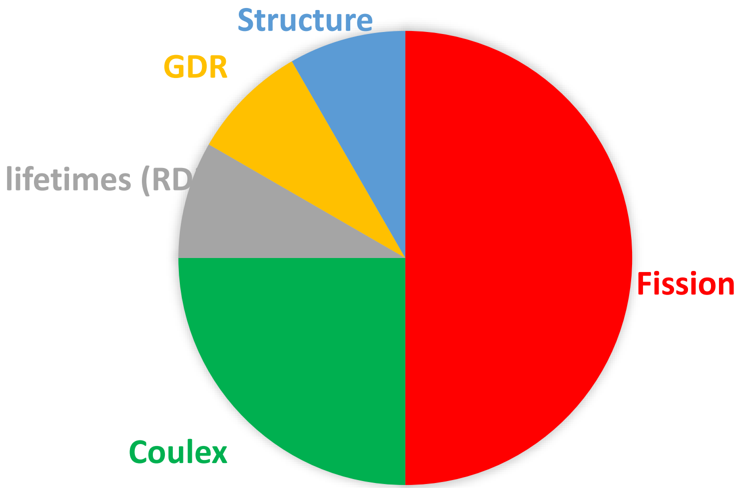


Coupled Devices

TFGIC (European Commission, JRC Geel)
DSSD silicon detectors (HIL Warsaw)
LICORNE neutron source (ALTO)
~~CORSET FF detector (Dubna)~~
OUPS plunger (IJC Lab)
OPSA charged particle detctor (IJC Lab)

nu-Ball2 campaign experiments at ALTO

(April 2022 – June 2023)



Neutron induced fission
- 238U(n,f) – S. Pascu

Heavy ion induced fission
- 197Au(18O,f) – K. Miernik/A. Korgul
- 178W(12C,f) – K. Miernik/A. Korgul Published

Light ion induced fission (fission isomers)
- 235U(d,f), 232Th(d,f) – C. Hiver/J. N. Wilson

Spontaneous fission
- 252Cf(SF) – M. Lebois/S. Oberstedt

Coulex
- 58Fe – G. Pasqualato
- 60Ni – K. Hadynska-Klek
- 40Ca – P. Napiorkowski

Structure
- 44Ti, 42Ca – M. Matejska-Minda

Lifetimes (RDM)
- 60Zn – M.L. Cortes

Giant dipole resonnance (GDR)
- 80Sr links residues to CN shape – M. Ciemala

- 150 international visitors (Including 60 from Eurolabs)
- 12 experiments completed
- > 300Tb of data collected!

nu-Ball2 campaign experiments at ALTO

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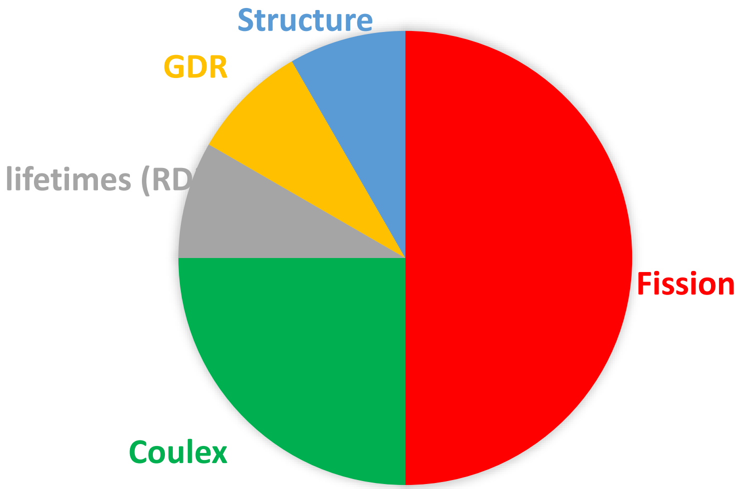

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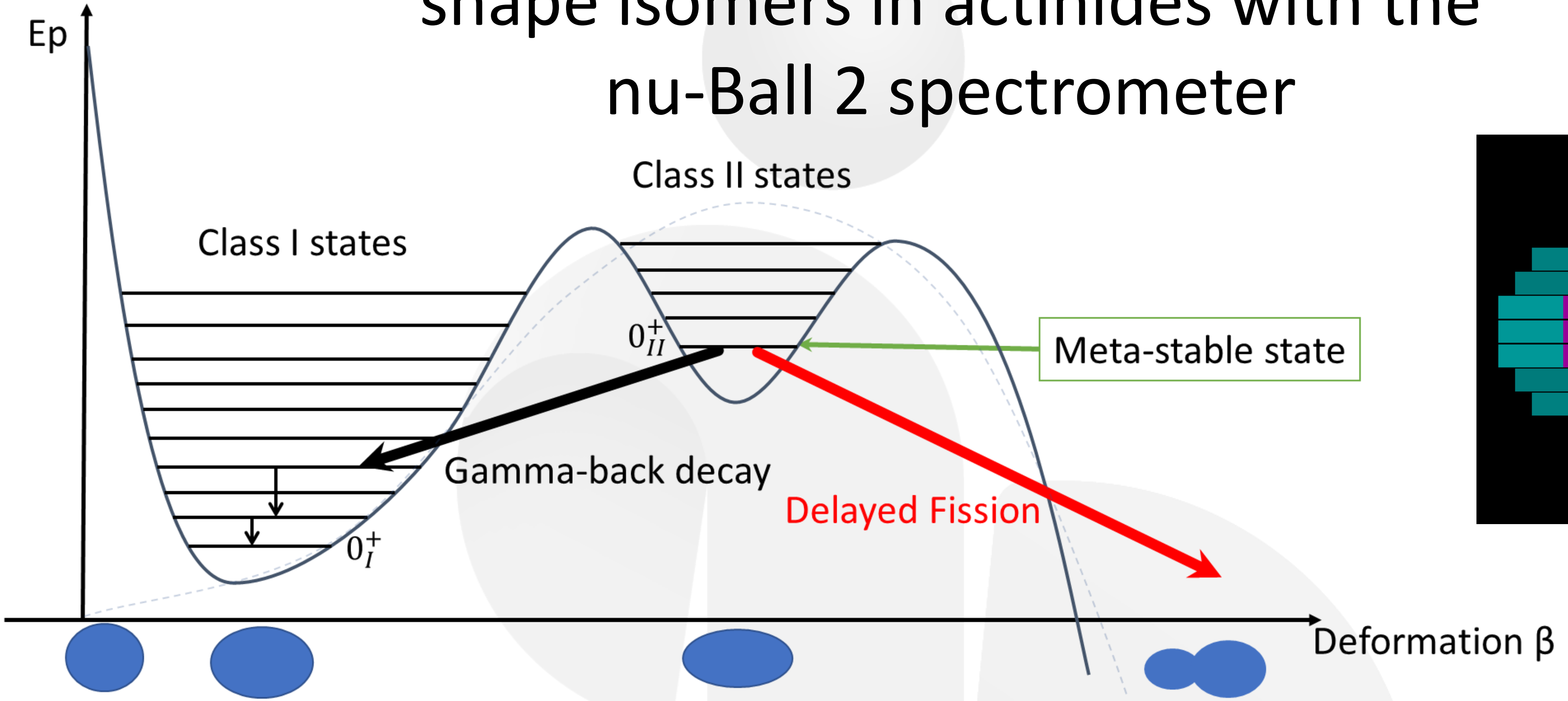
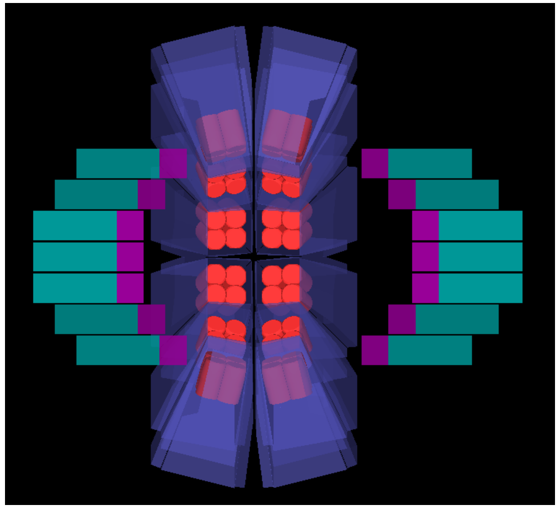
Investigation of the γ-back decay from shape isomers in actinides with the nu-Ball 2 spectrometer

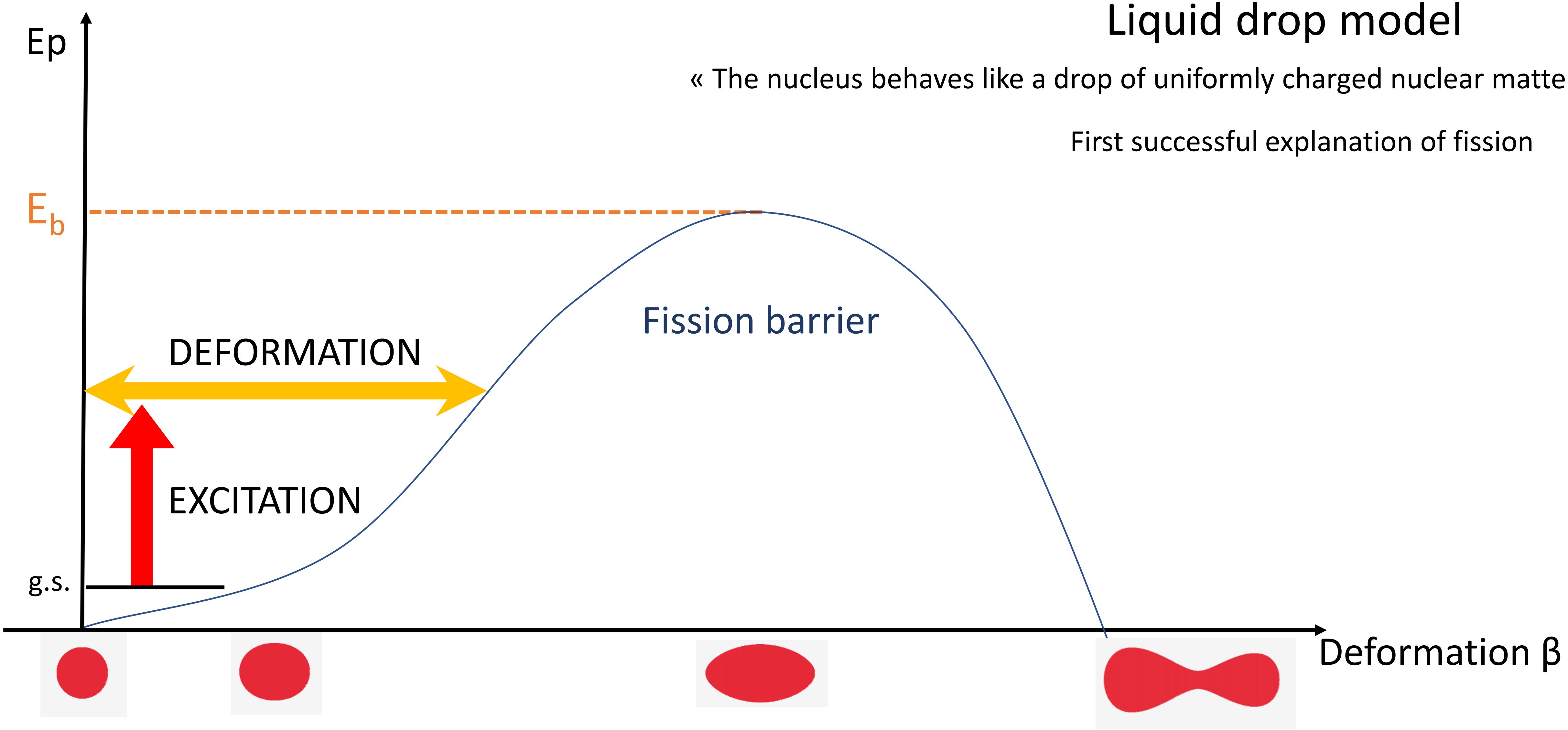




Liquid drop model

« The nucleus behaves like a drop of uniformly charged nuclear matter »

First successful explanation of fission



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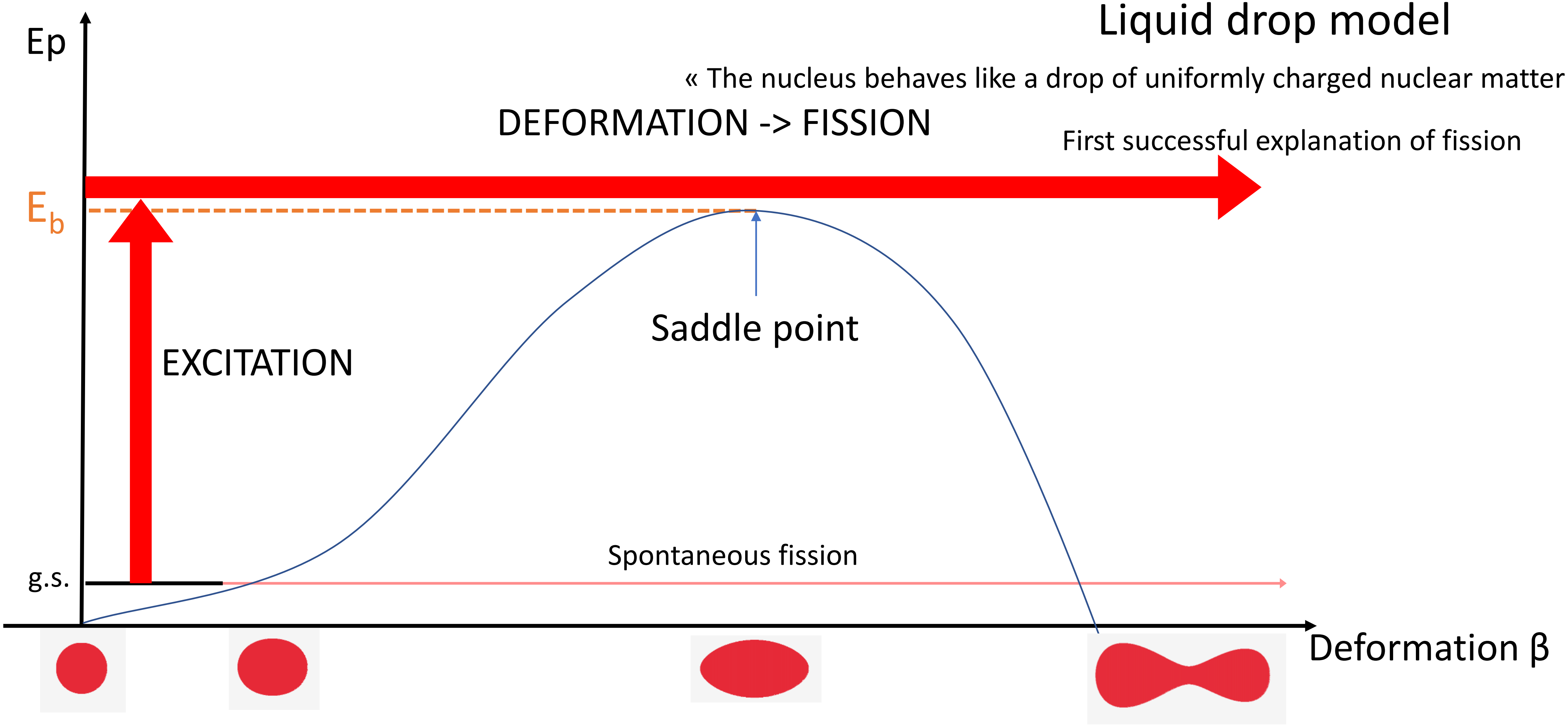
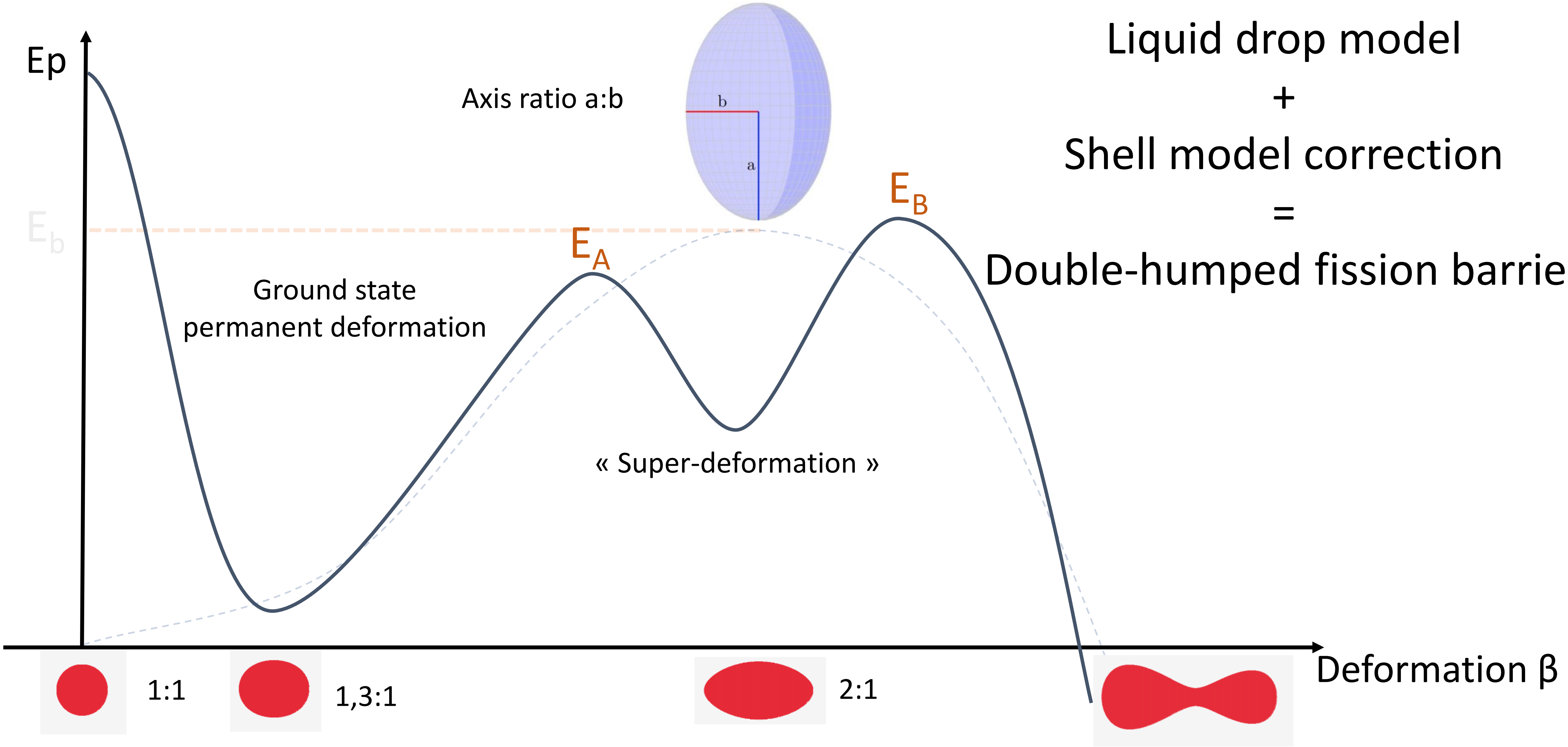


1. Introduction



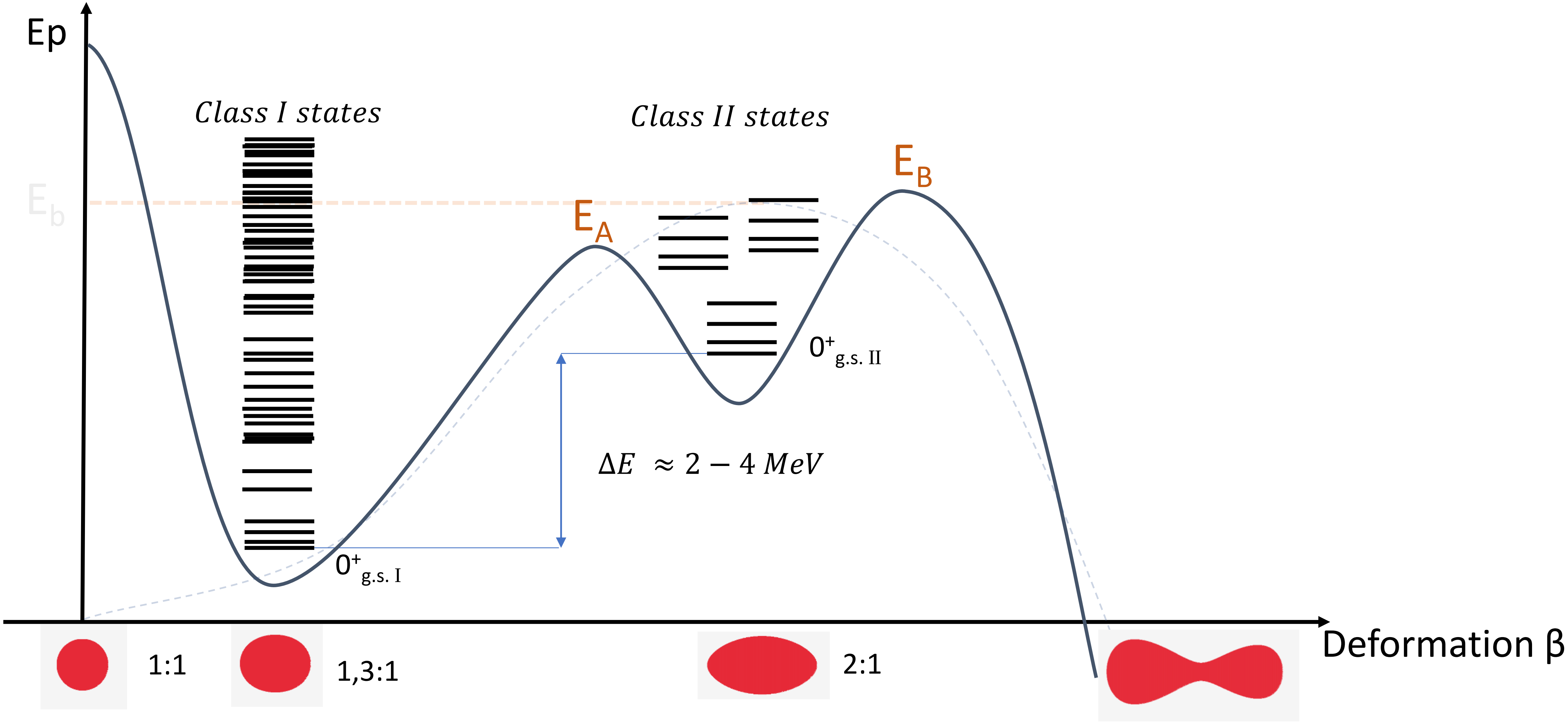
Liquid drop model

+

Shell model correction

=

Double-humped fission barrier



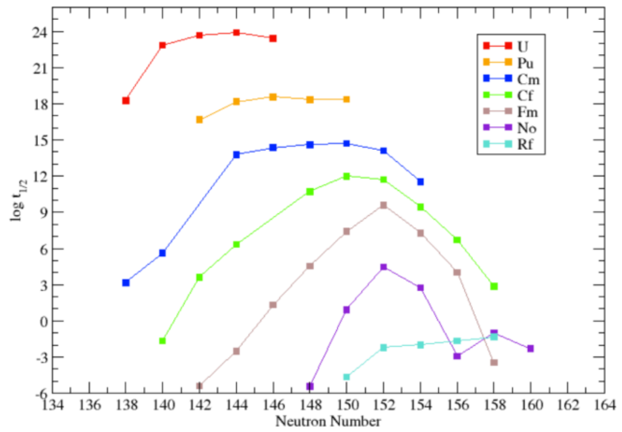
Ep
Class I states
Class II states
E_b
E_A
E_B
0+ g.s. I
0+ g.s. II
ΔE ≈ 2 – 4 MeV
1:1
1,3:1
2:1
Deformation β

Parenthesis :

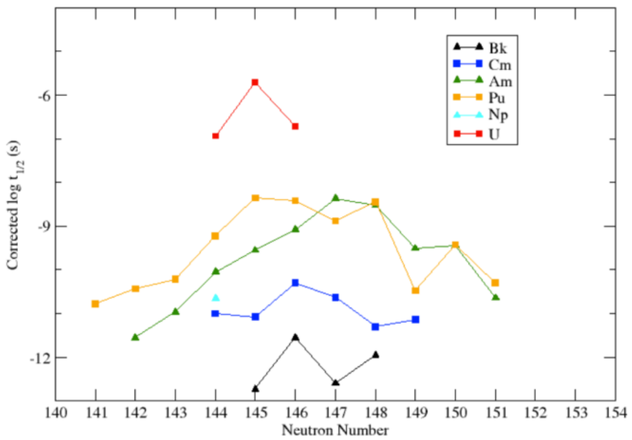
The class II states are still very mysterious

More known states in super-heavy elements like Rutherfordium

Similar physics of stability



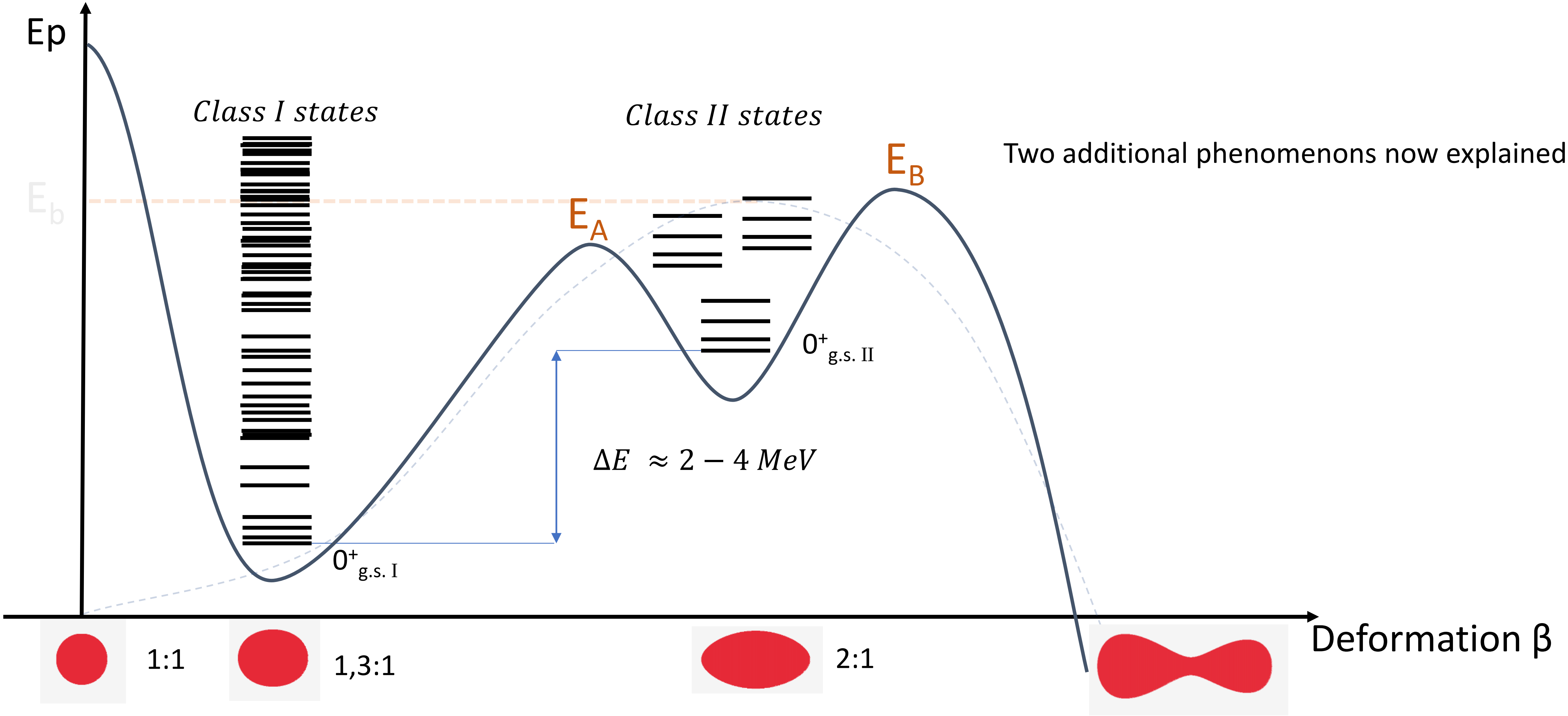
Super-heavies

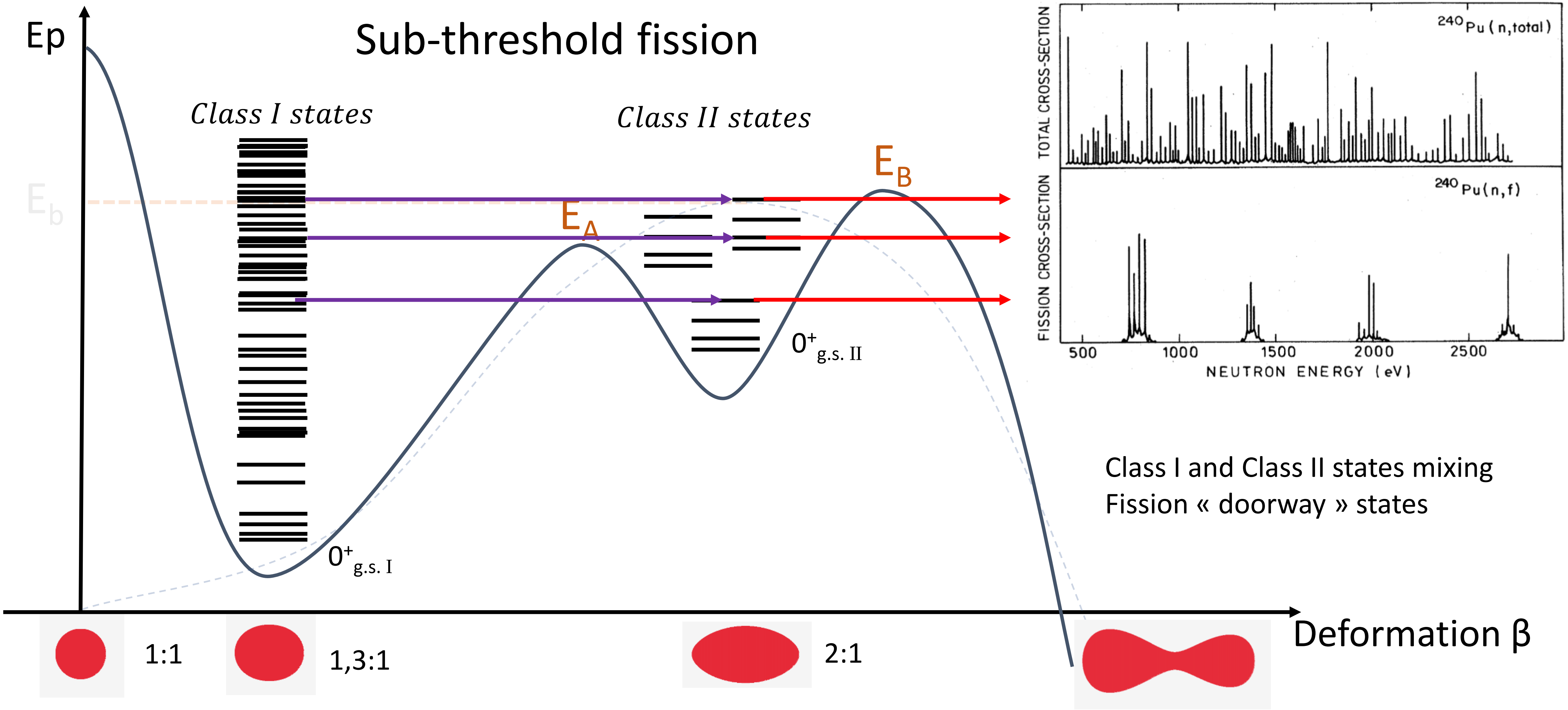


Shape isomers

Class II states : microbarn

Super-heavies : nanobarn

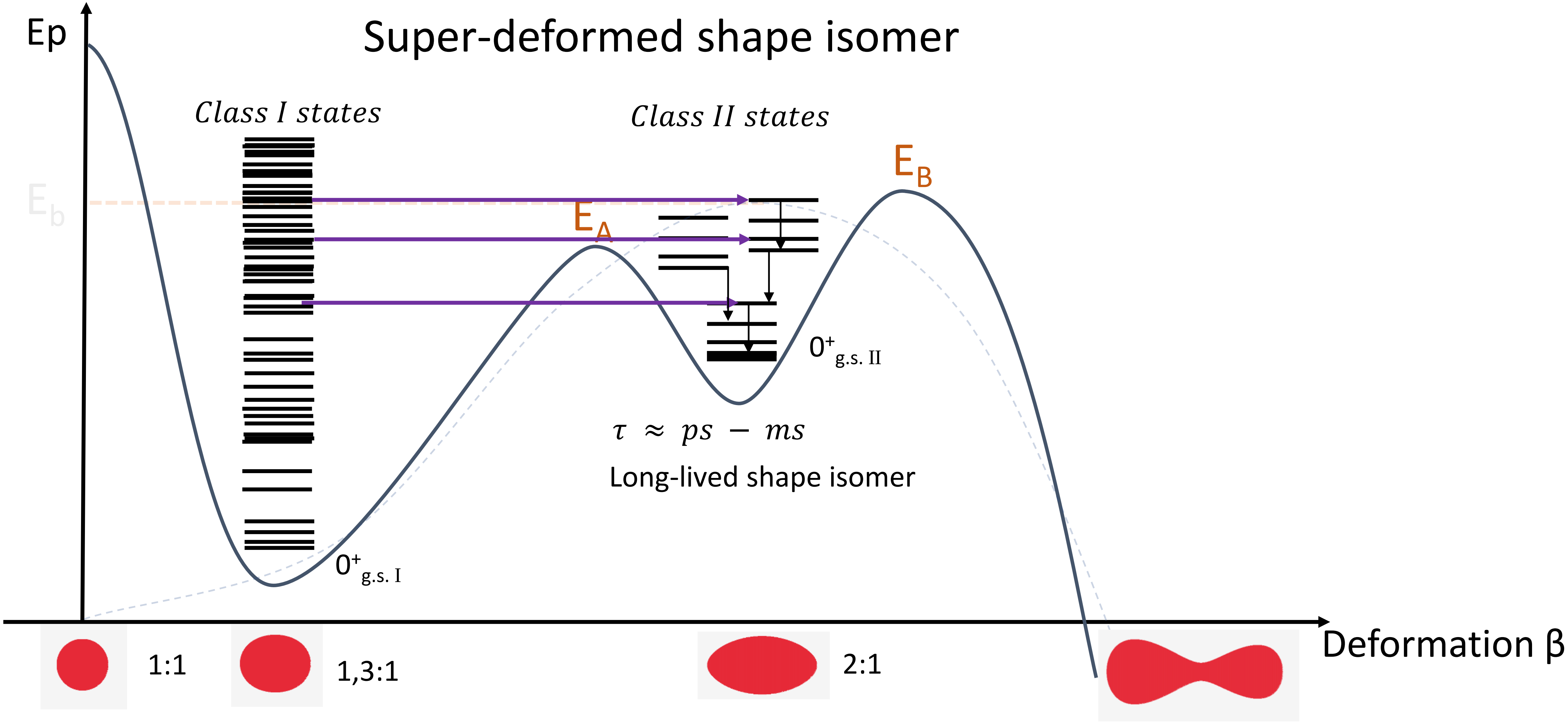

Ep
Class I states
Class II states
Two additional phenomenons now explained
E_B
E_A
E_b
$0^+_{g.s.\ II}$
$\Delta E \approx 2 - 4\ MeV$
$0^+_{g.s.\ I}$
1:1
1,3:1
2:1
Deformation β

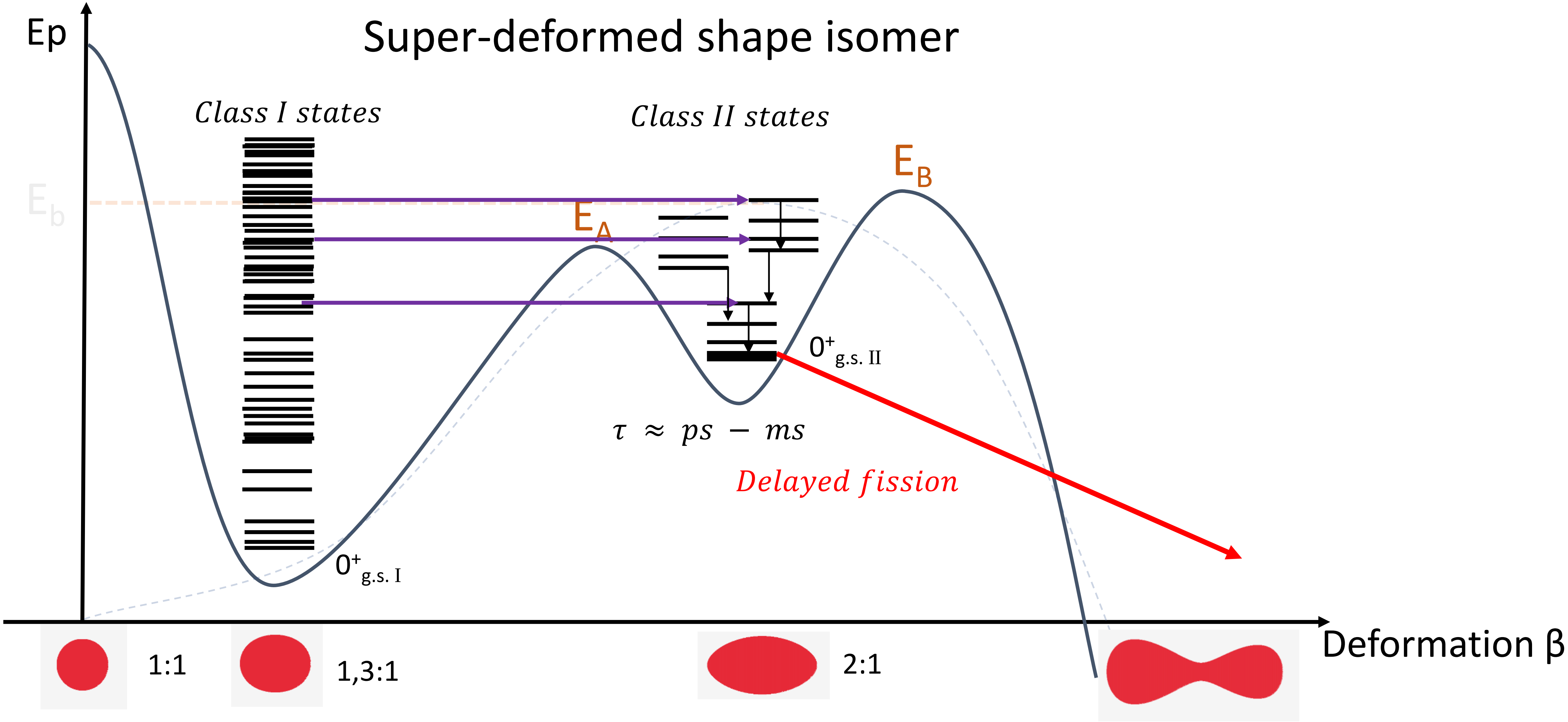


Class I and Class II states mixing

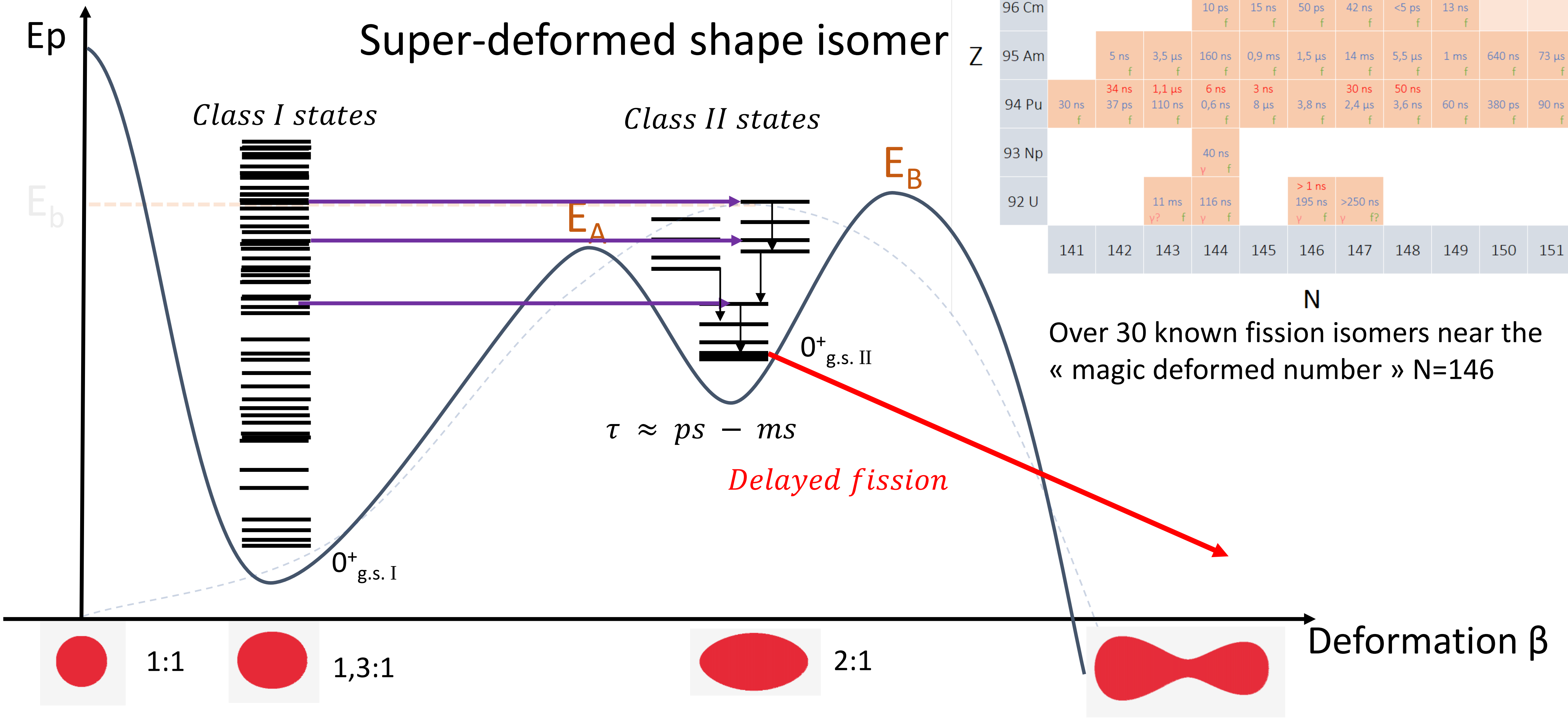
Fission « doorway » states

Super-deformed shape isomer




Ep
Super-deformed shape isomer
Class I states
Class II states
E_B
E_b
E_A
$0^+_{g.s. II}$
$\tau \approx ps - ms$
Delayed fission
$0^+_{g.s. I}$
Deformation β
1:1
1,3:1
2:1

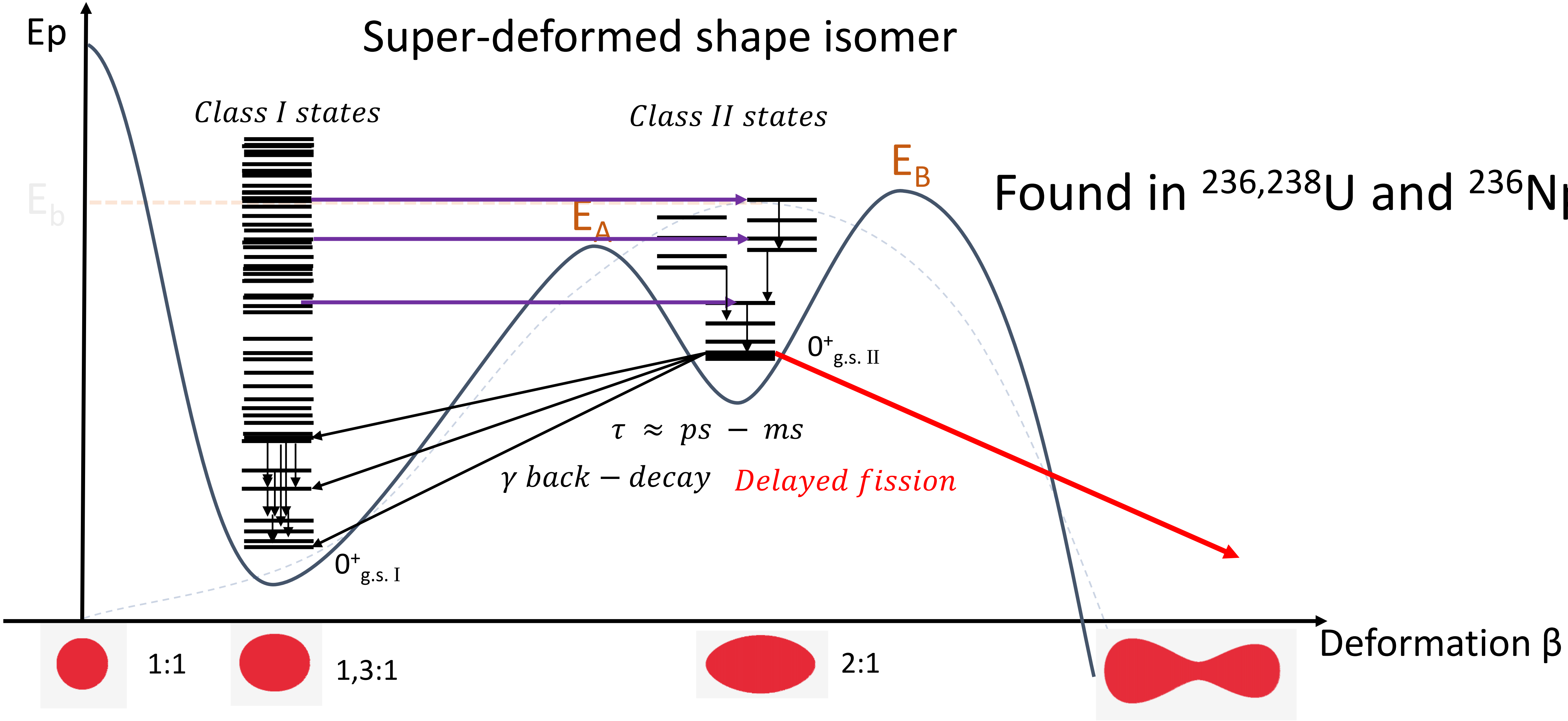
Super-deformed shape isomer



Z \ N	141	142	143	144	145	146	147	148	149	150	151
96 Cm				55 ns 10 ps f	15 ns f	180 ns 50 ps f	42 ns f	>100 ns <5 ps f	13 ns f		
95 Am		5 ns f	3,5 µs f	160 ns f	0,9 ms f	1,5 µs f	14 ms f	5,5 µs f	1 ms f	640 ns f	73 µs f
94 Pu	30 ns f	34 ns 37 ps f	1,1 µs 110 ns f	6 ns 0,6 ns f	3 ns 8 µs f	3,8 ns f	30 ns 2,4 µs f	50 ns 3,6 ns f	60 ns f	380 ps f	90 ns f
93 Np				40 ns γ f							
92 U			11 ms γ? f	116 ns γ f		> 1 ns 195 ns γ f	>250 ns γ f?				

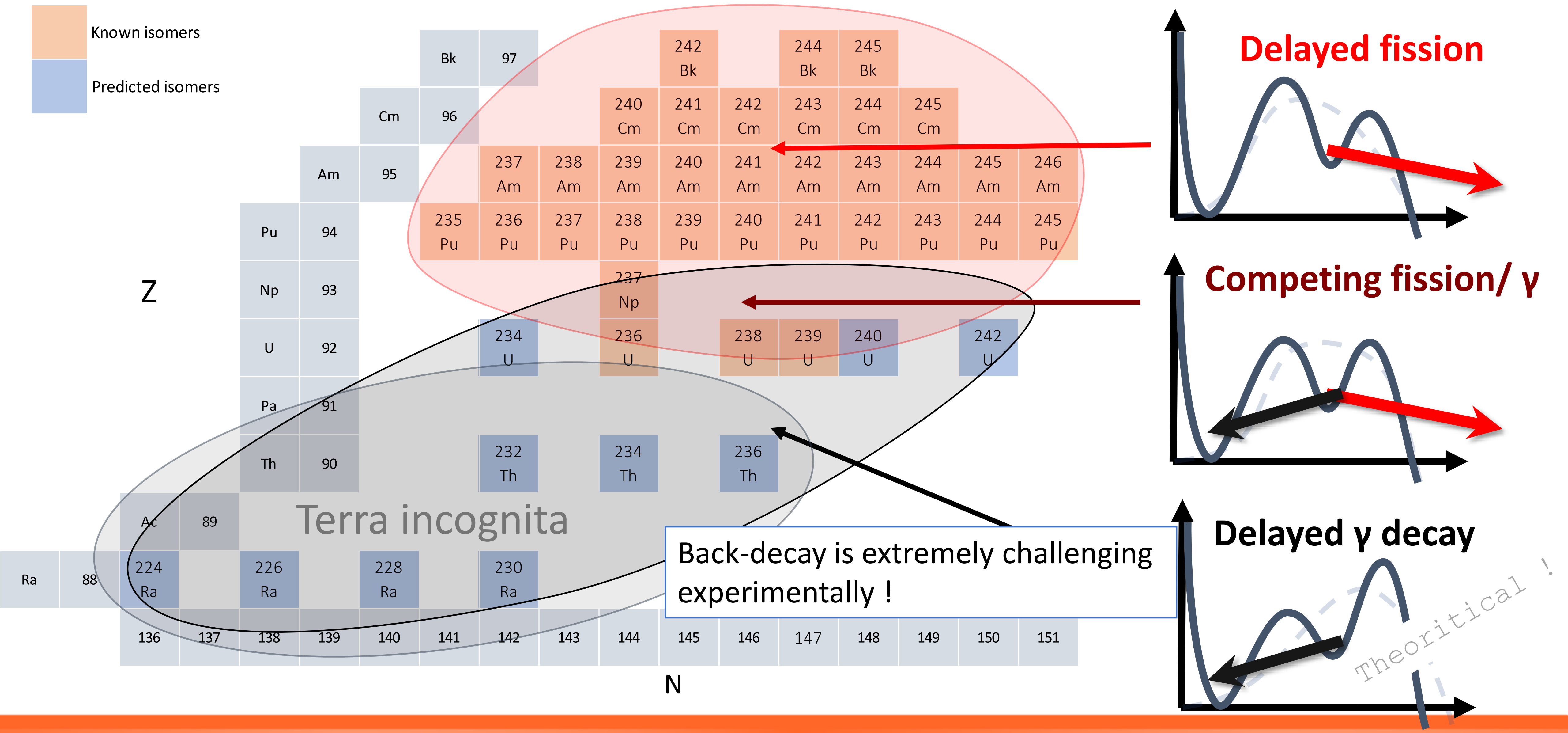
Over 30 known fission isomers near the « magic deformed number » N=146

Super-deformed shape isomer



Found in $^{236,238}U$ and ^{236}Np

1. Introduction



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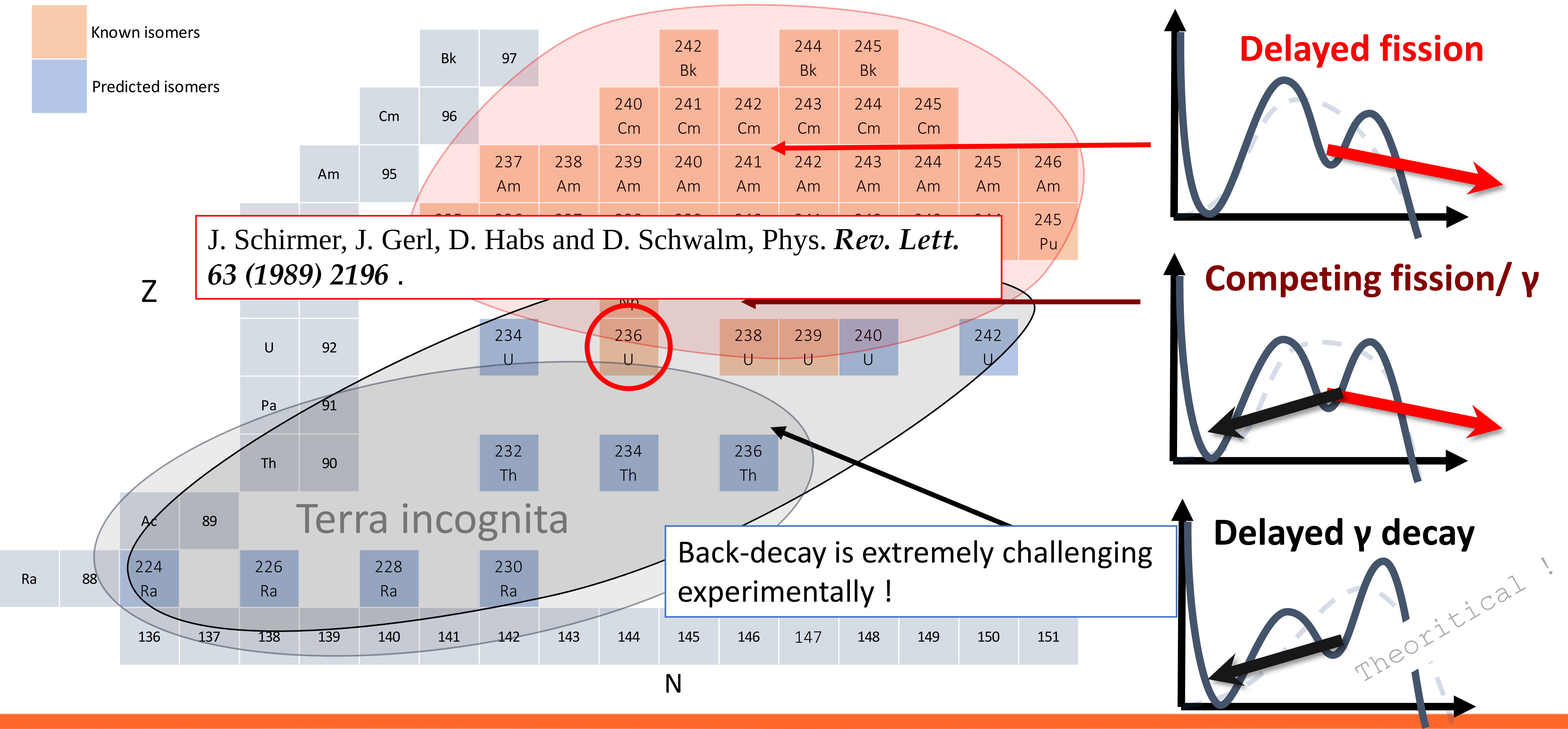


J. Schirmer, J. Gerl, D. Habs and D. Schwalm, Phys. ***Rev. Lett.*** ***63 (1989) 2196*** .

Back-decay is extremely challenging experimentally !

Why study actinides shape isomers ?

- Barrier penetration → good fission simulation
- Shape isomers only direct probe of barrier penetrability
- Fission studies focus on post-scission → « Blind » to the actual path

BUT :

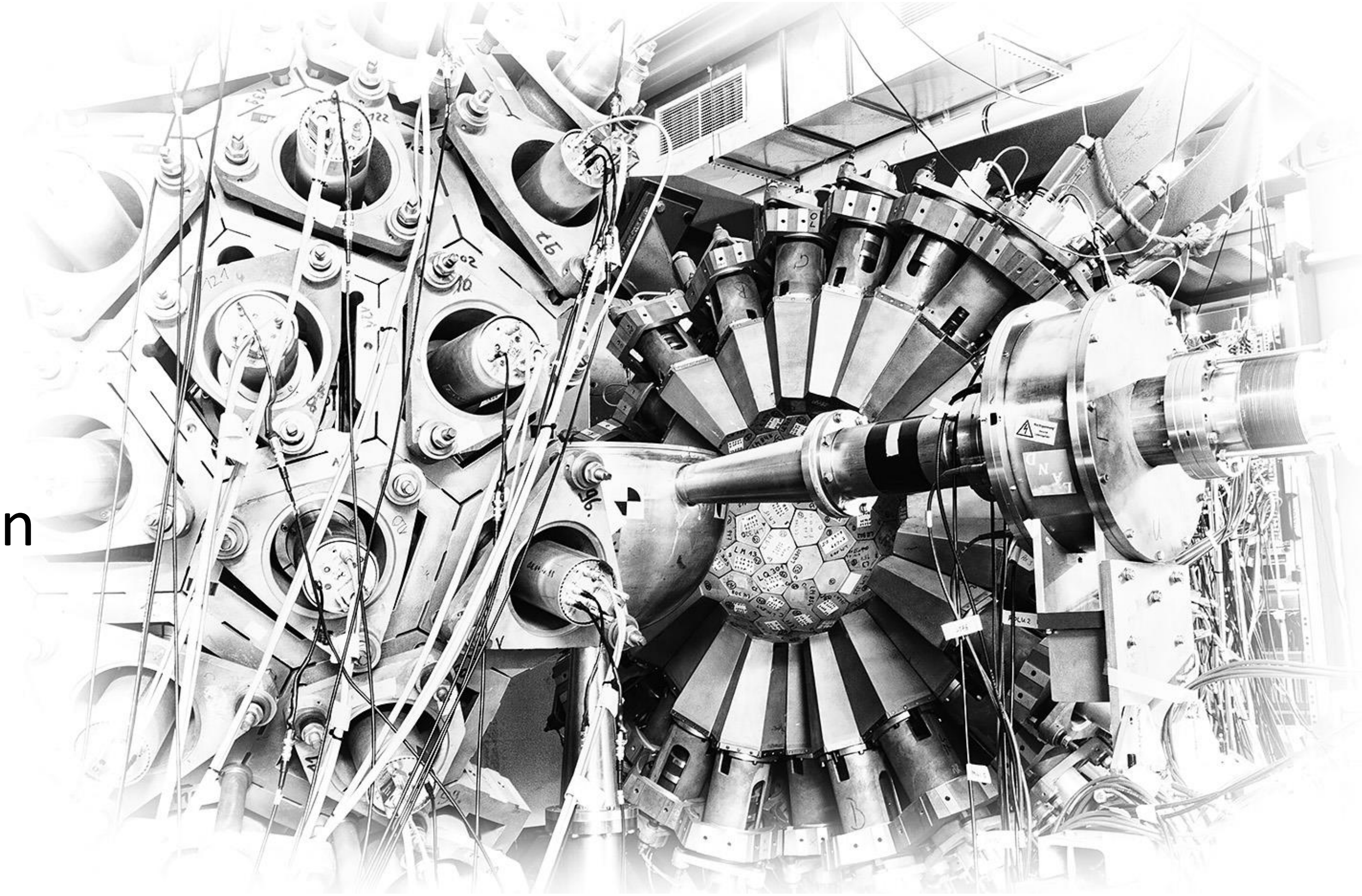
- very low cross section formation $\sim\mu b$
- γ-rays have low interaction cross-section

Consequent experimental efforts needed

$$^{235}_{92}U(d,p)^{236f}_{90}U$$

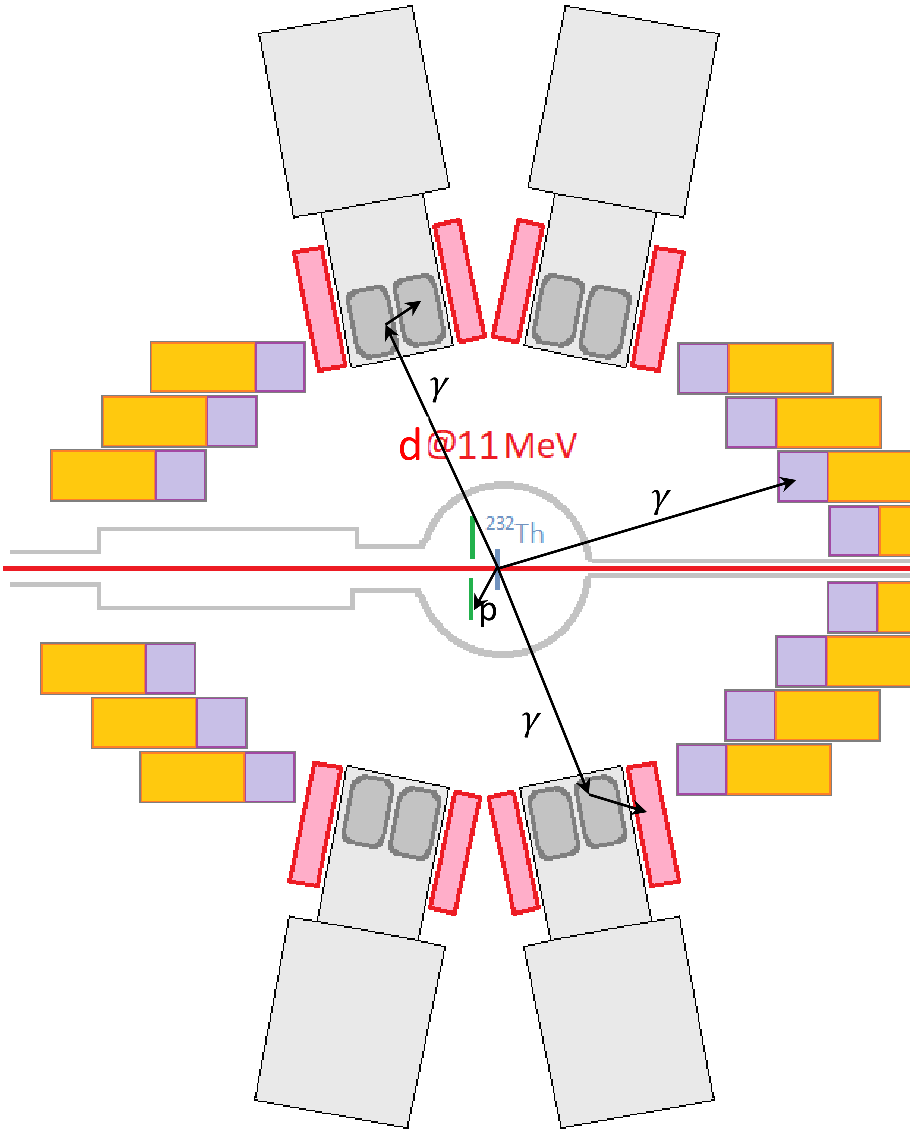
Selectivity from calorimetry, proton energy and beam pulsation

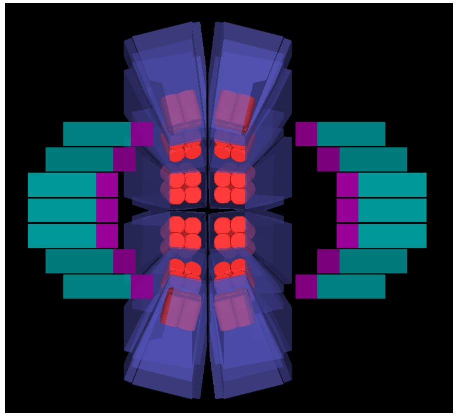
J. Schirmer, J. Gerl, D. Habs and D. Schwalm, Phys. ***Rev. Lett. 63 (1989) 2196*** .



Darmstadt 4π NaI crystal ball :
80% total energy efficiency calorimeter

3. 2023, Orsay : High precision spectroscopy with Nuball2



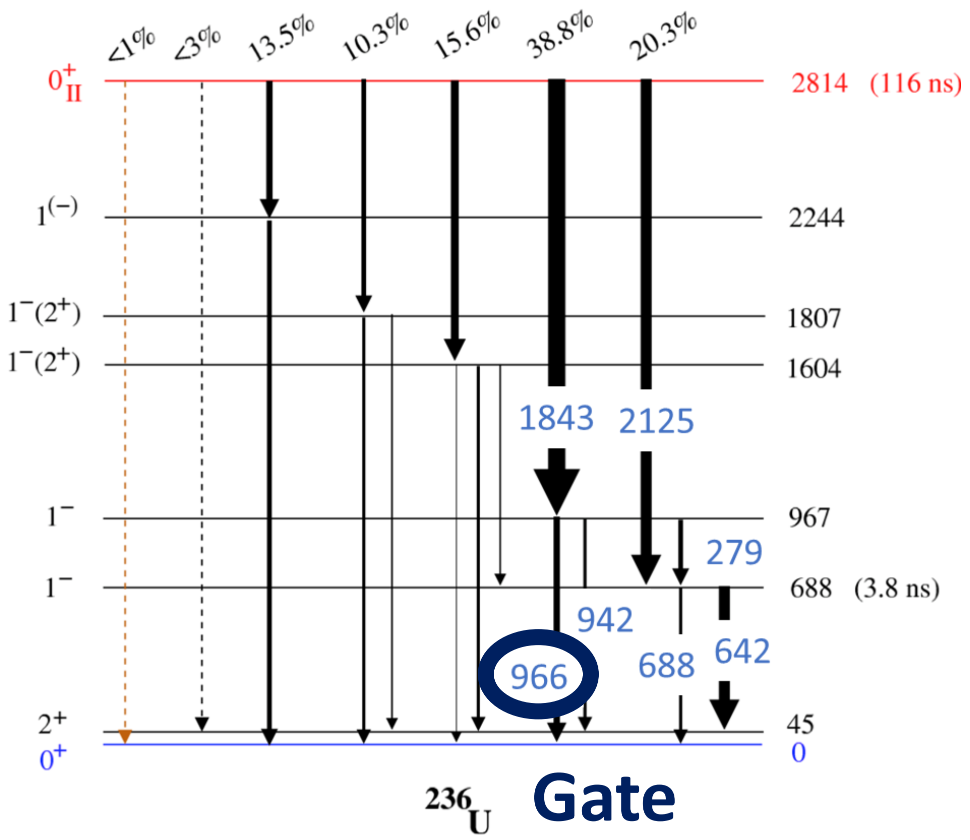


Setup :
24 Ge clovers + BGO, 64 PARIS phoswhich + DSSD
> 300 independent digital channels (FASTER system)

Advantages :
- Energy resolution (HPGe)
- Beam pulsation (2ns wide pulse vs 25 ns)
- Segmented Si DSSD (16 rings, 32 sectors)
  -> 10 kHz particle detection rate vs 800 Hz
- Triggerless DAQ -> Great flexibility in data analysis

Disadvantages :
- Calorimetry ε = 25% vs 80%
- Proton punch through in DSSD

3. 2023, Orsay : High precision spectroscopy with Nuball2



Crystal ball results (P. Reiter dissertation)

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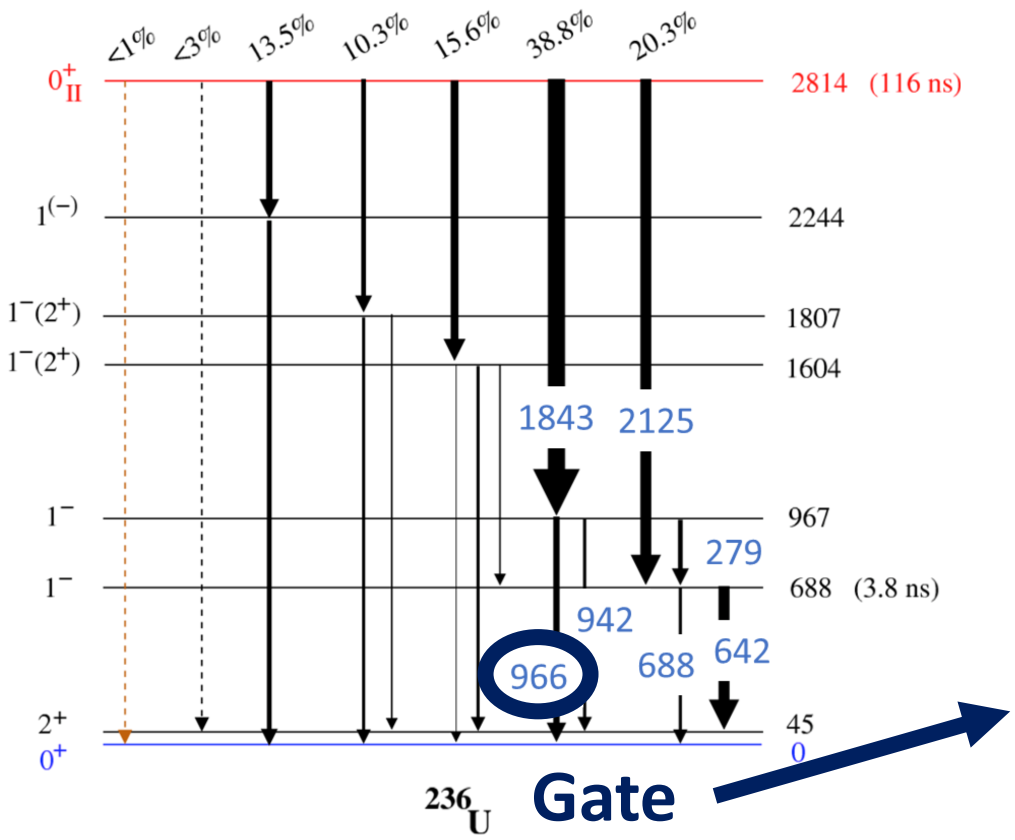

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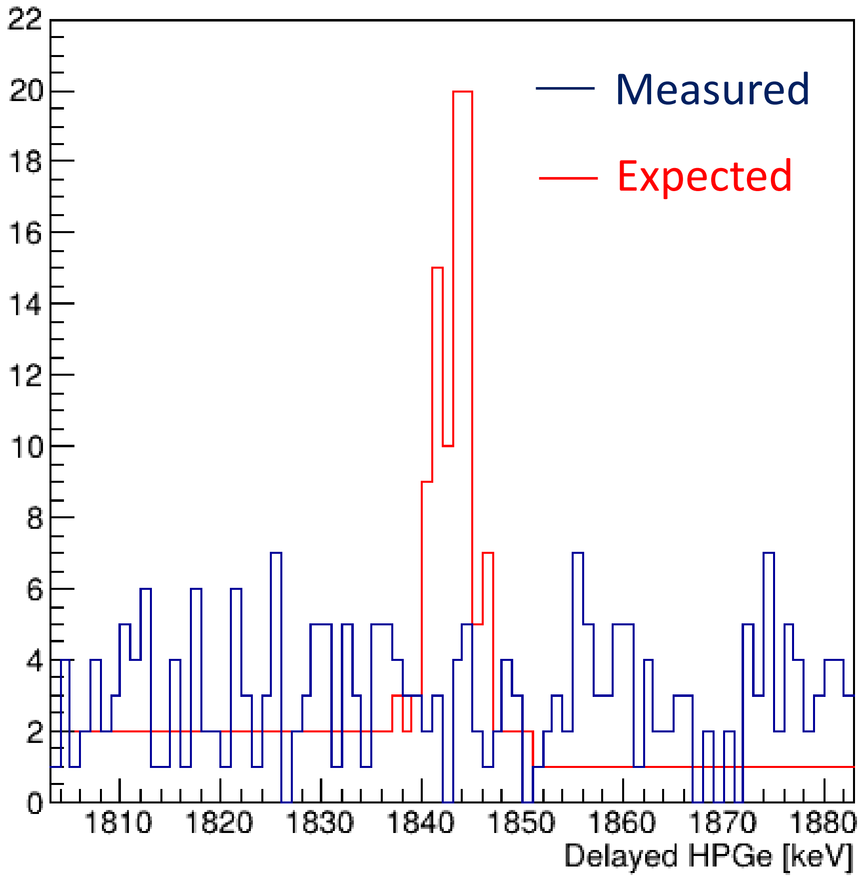

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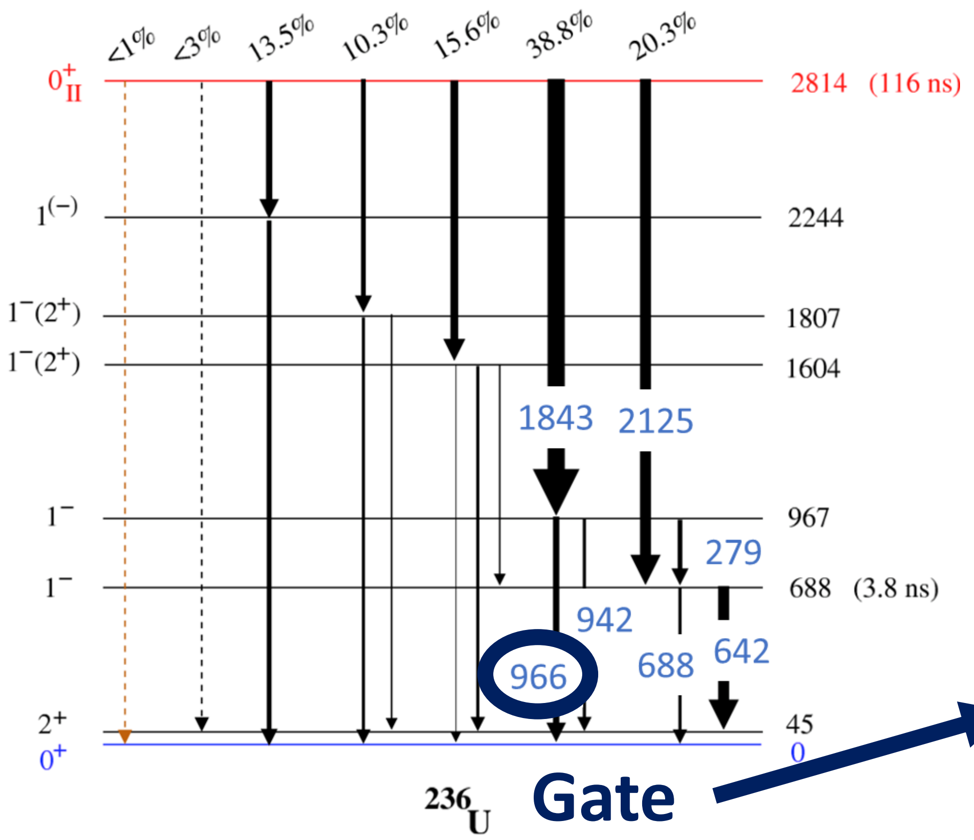

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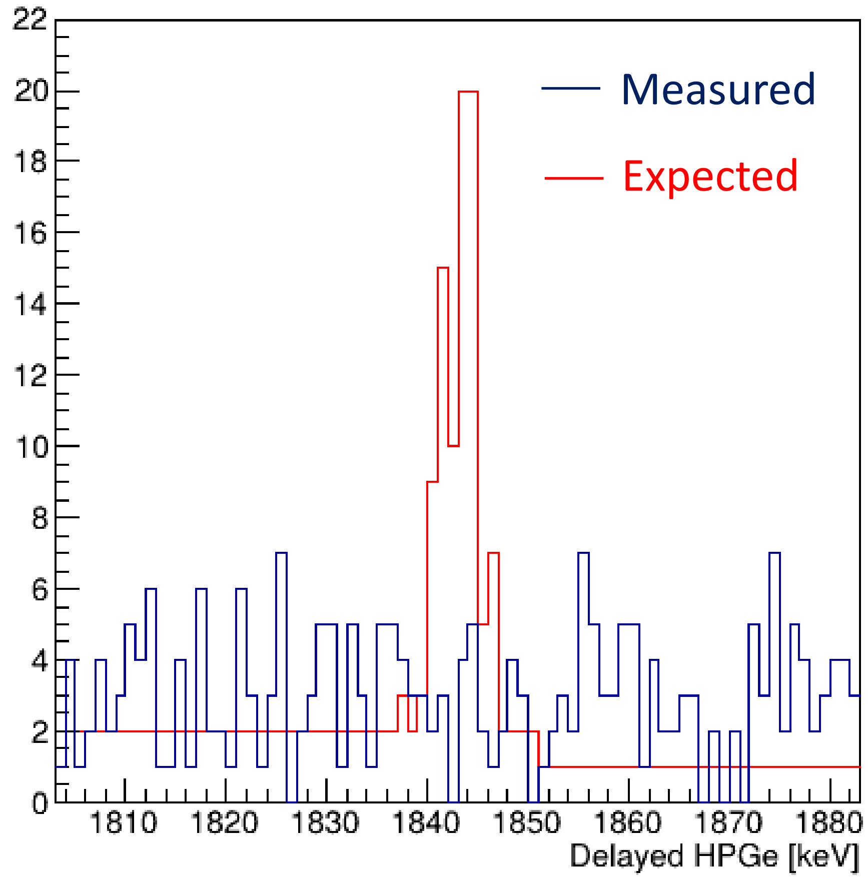


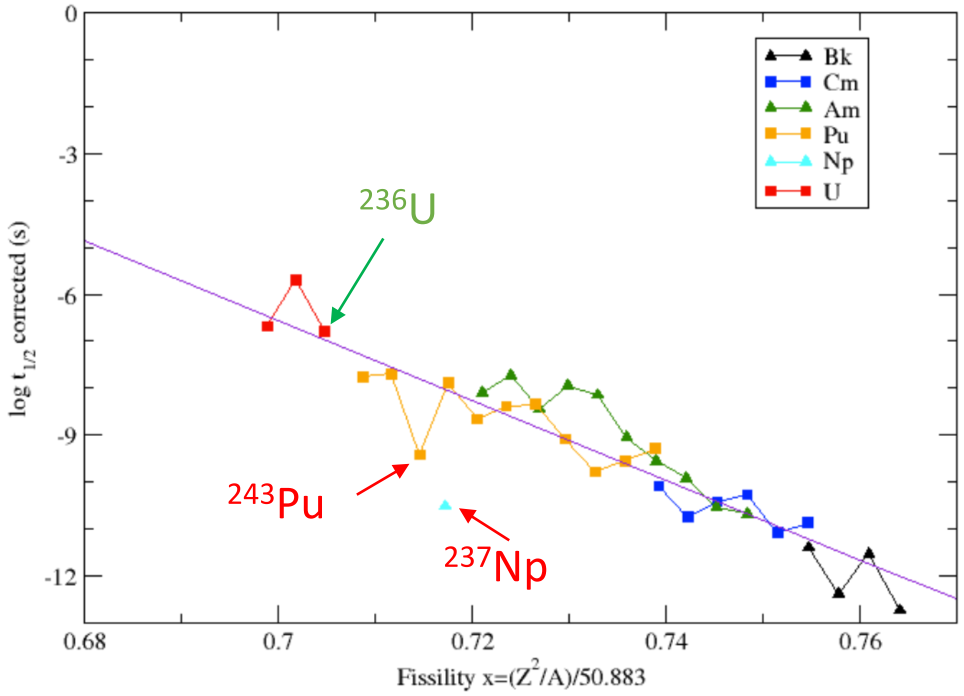
Results not reproduced !

$$\sigma^{this\ work}_{shape\ Isomer} < \mu b$$

Cast doubt on :

- the unambiguity of the Crystal Ball experiment
- the measured cross section used for the estimation

New half-life empirical parametrization : gamma-back may not be expected in ^{236}U



Linear trend with fissility after removing shell effects

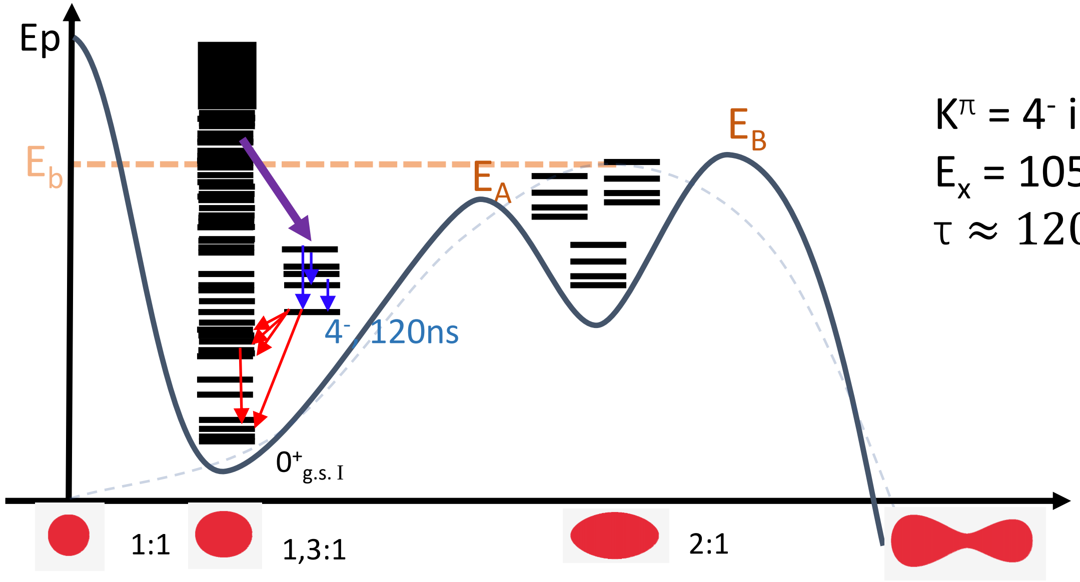
Then why fission isomerism almost vanishes below Pu isotopes ?

And many other mysteries :

- ^{243}Pu and ^{237}Np : delayed fission half-life discrepancy
- Class II states spectroscopy
- Class II K-isomerism
- More efficient production mechanism
- Long-lived fission isomers in lighter elements ?
- Precise shape isomer excitation energy

Note :
Nowadays, great effort to study nanobarn super-heavies elements
While shape isomer microbarn states remains very mysterious
Yet similar physics explain their stability

FIN



$K^{\pi} = 4^{-}$ isomer

$E_x = 1052$

$\tau \approx 120$ ns