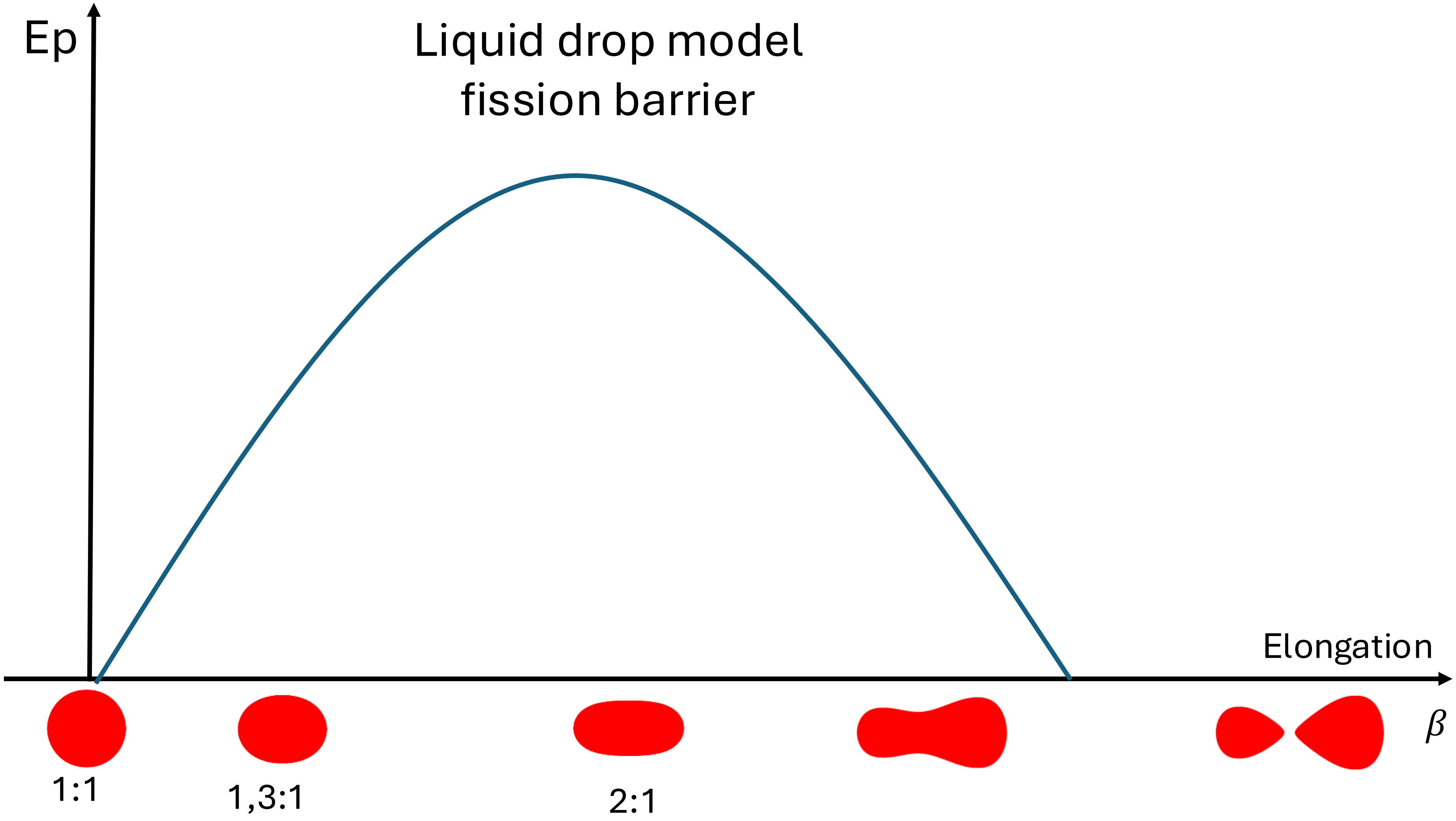
Investigation of the γ-back decay from shape isomers in actinides with the nu-Ball 2 spectrometer

Corentin Hiver

- 1. Theory
- 2. Dispositif
- 3. résultats
- 4. Discussion

1. The shape isomers in actinides



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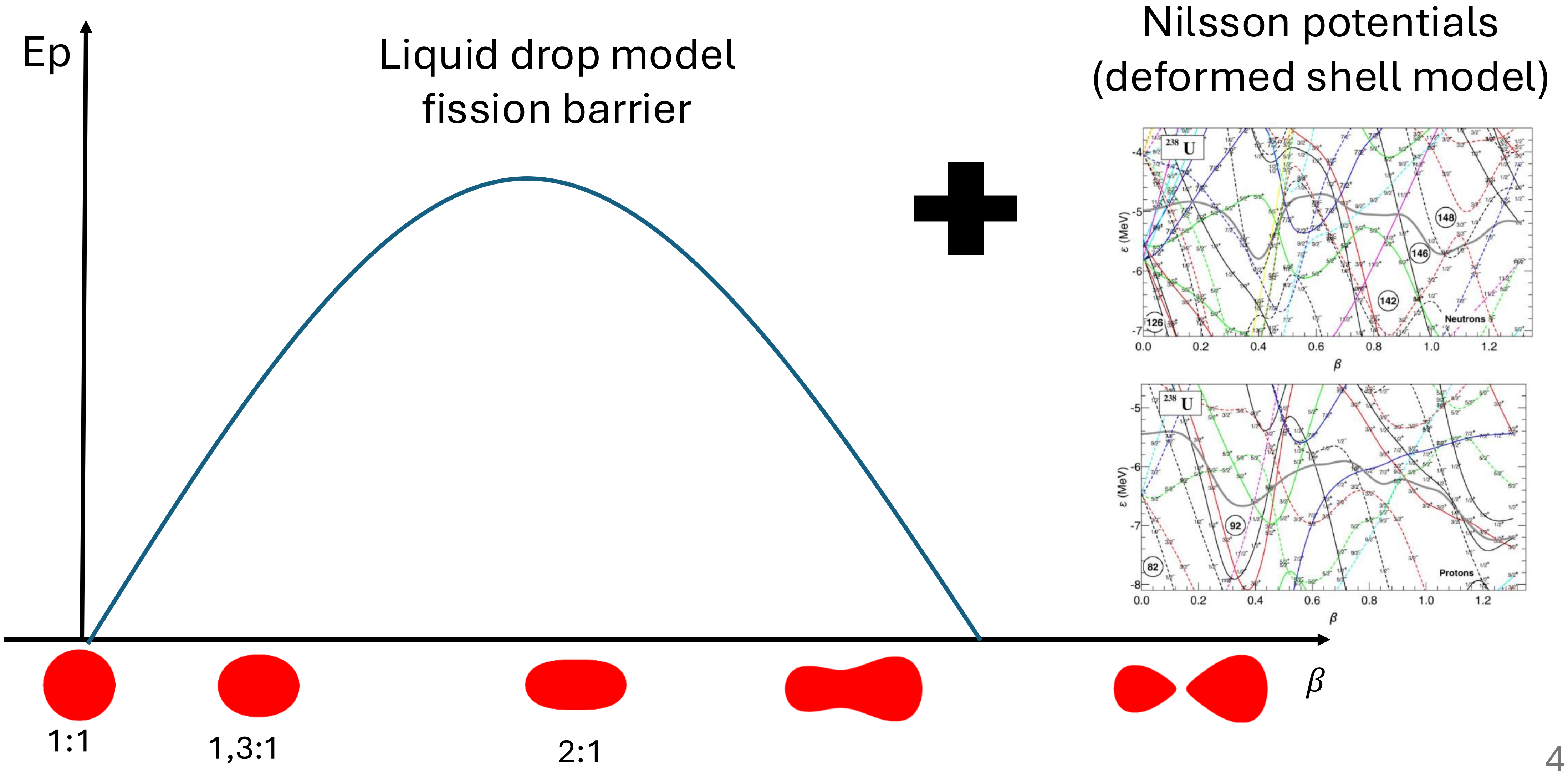

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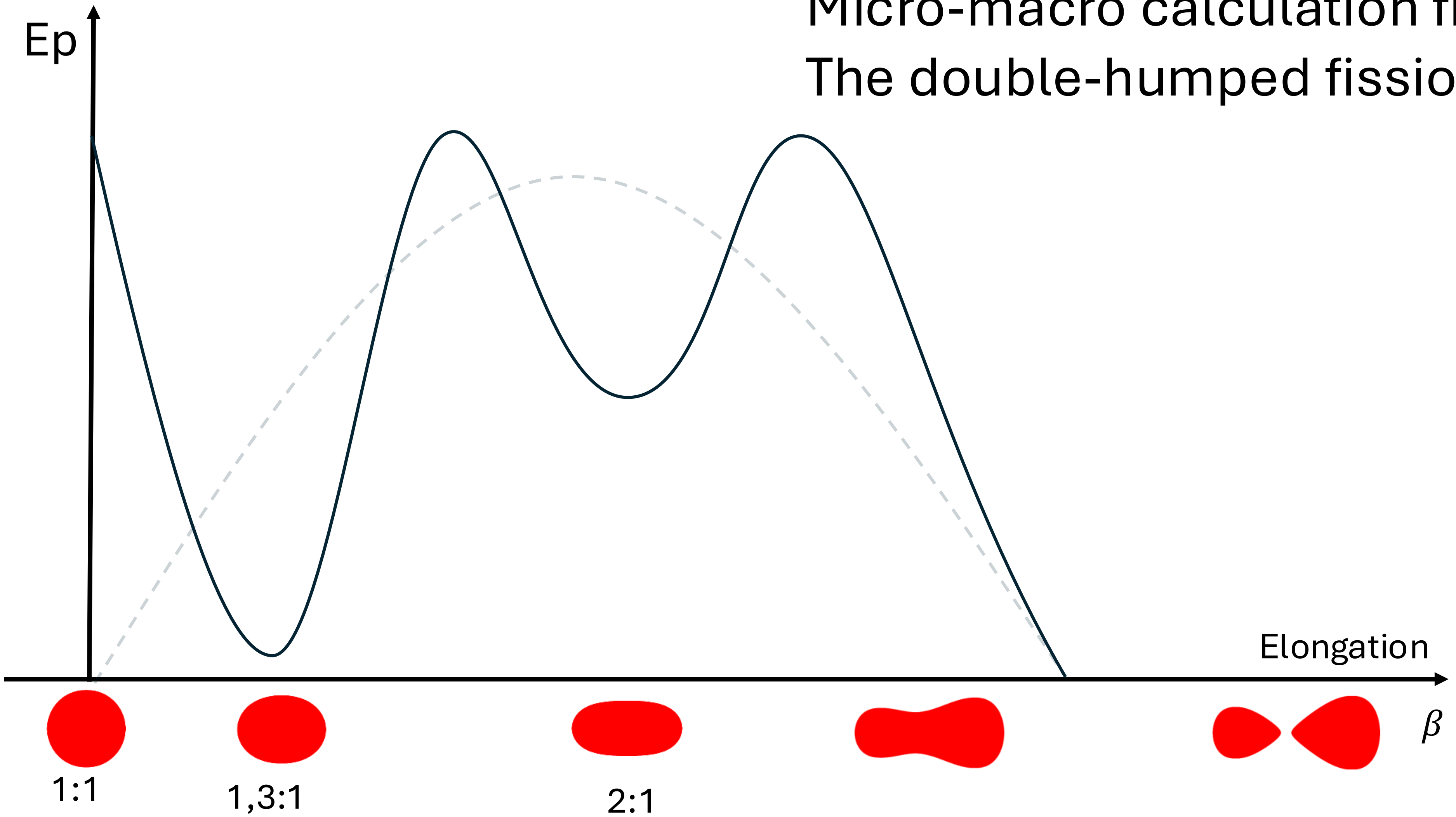
Micro-macro calculation from Strutinski :

The double-humped fission barrier



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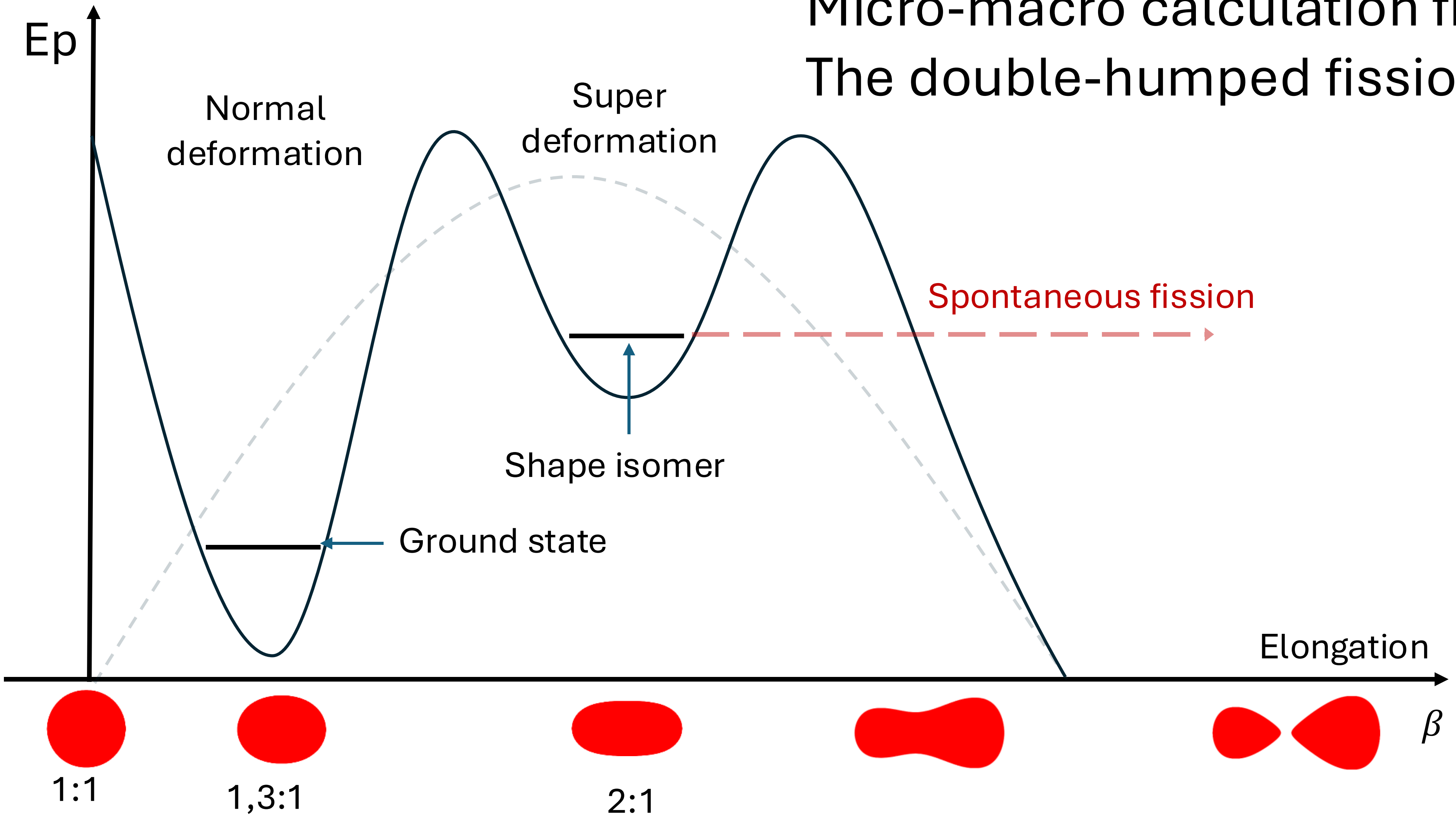

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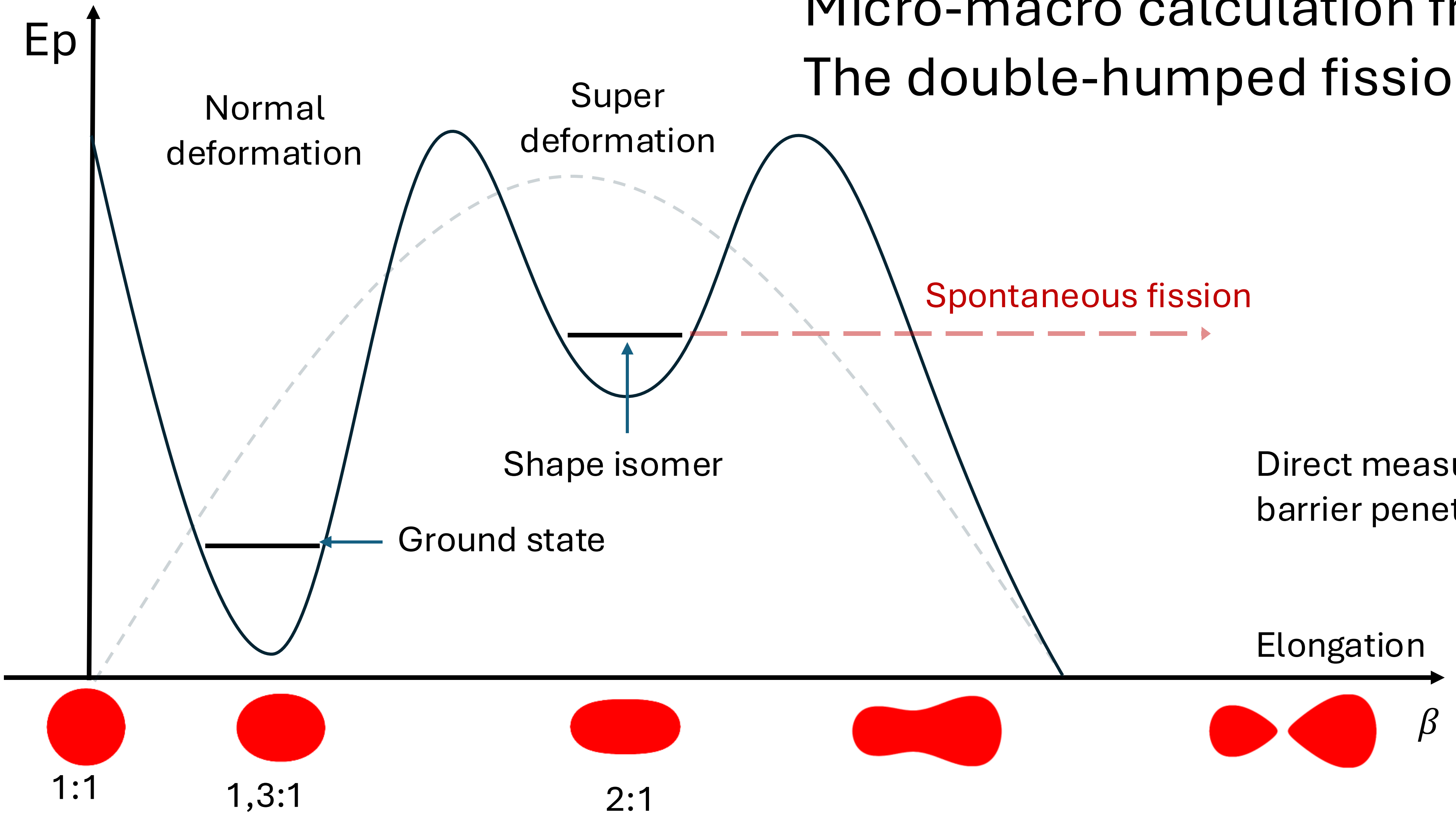

Direct measurement of outer barrier penetration !

1. The shape isomers in actinides

Z	141	142	143	144	145	146	147	148	149	150	151
97 Bk					9,5 ns 600 ns f		820 ns f	2 ns f			
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?				

N

τ K-isomer
τ shape isomer
gamma/fission decay

35 known fission isomers

Very little is known : only the half-life

For some :

- Excitation energy (mostly indirectly)
- Class II spectroscopy ($^{239,240}Pu$, $^{236,238}U$)

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Only 5 below Plutonium
Lower population cross section
Why ?

2. Gamma back-decay

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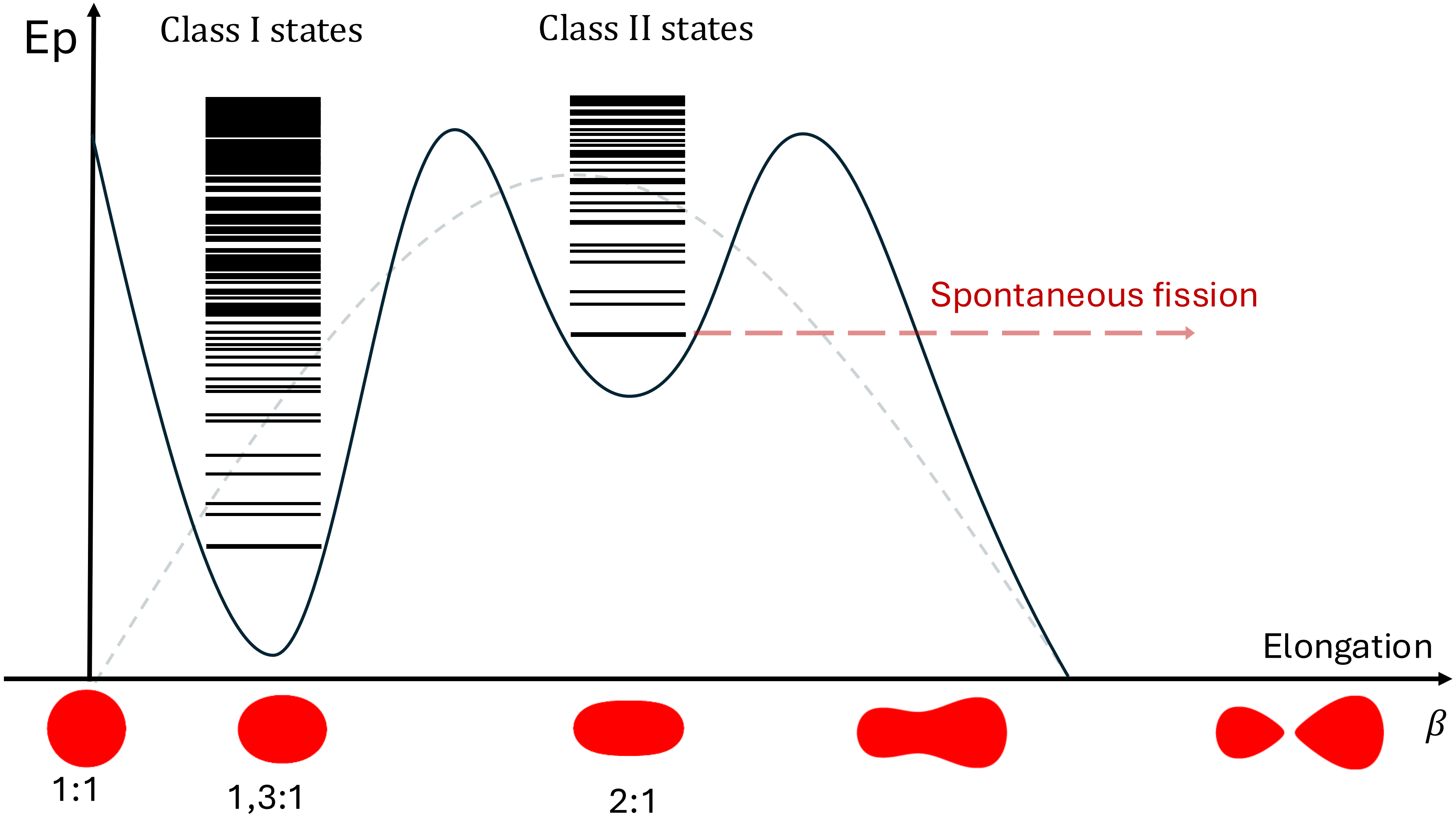

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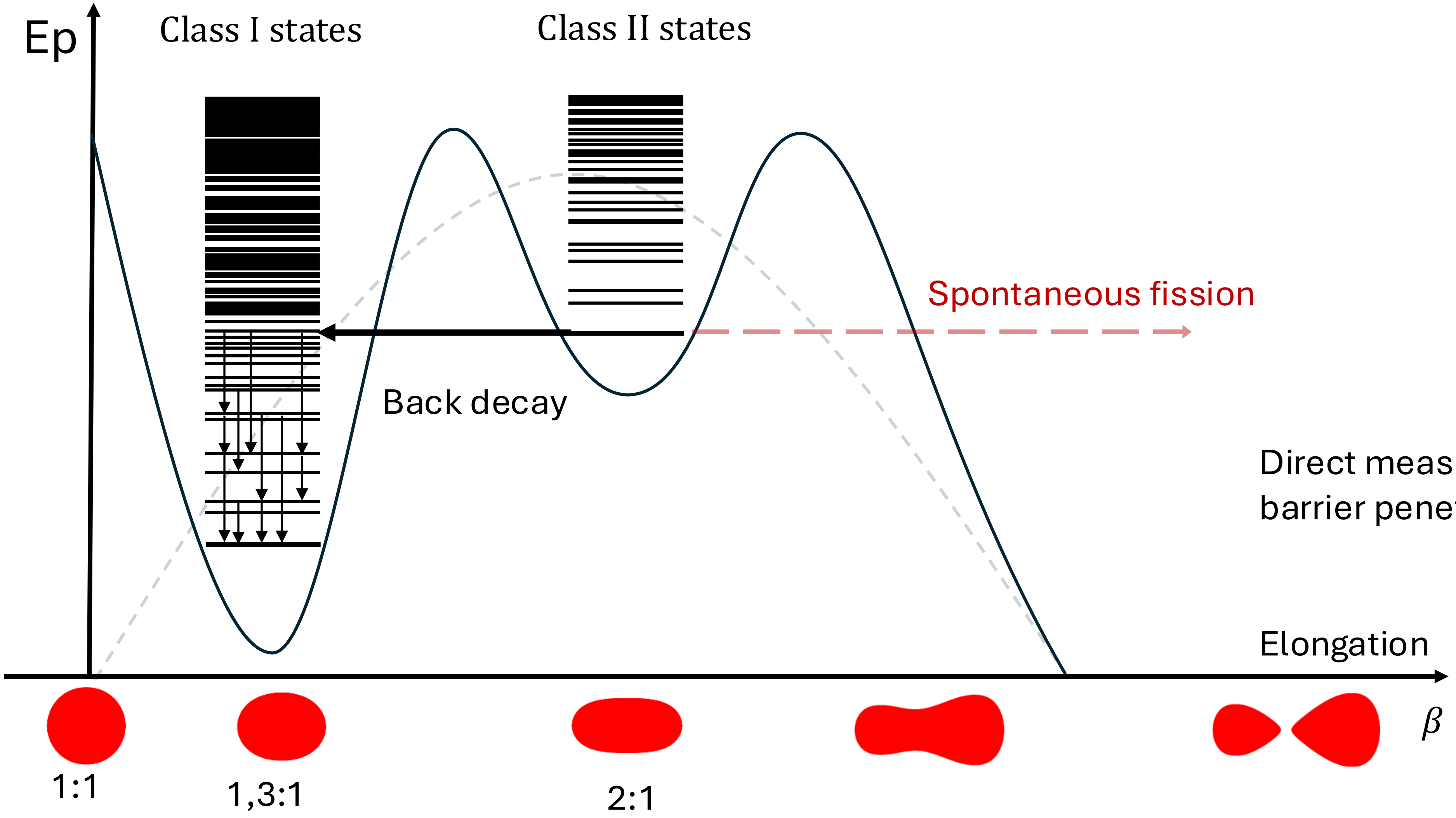

Direct measurement of outer barrier penetration !

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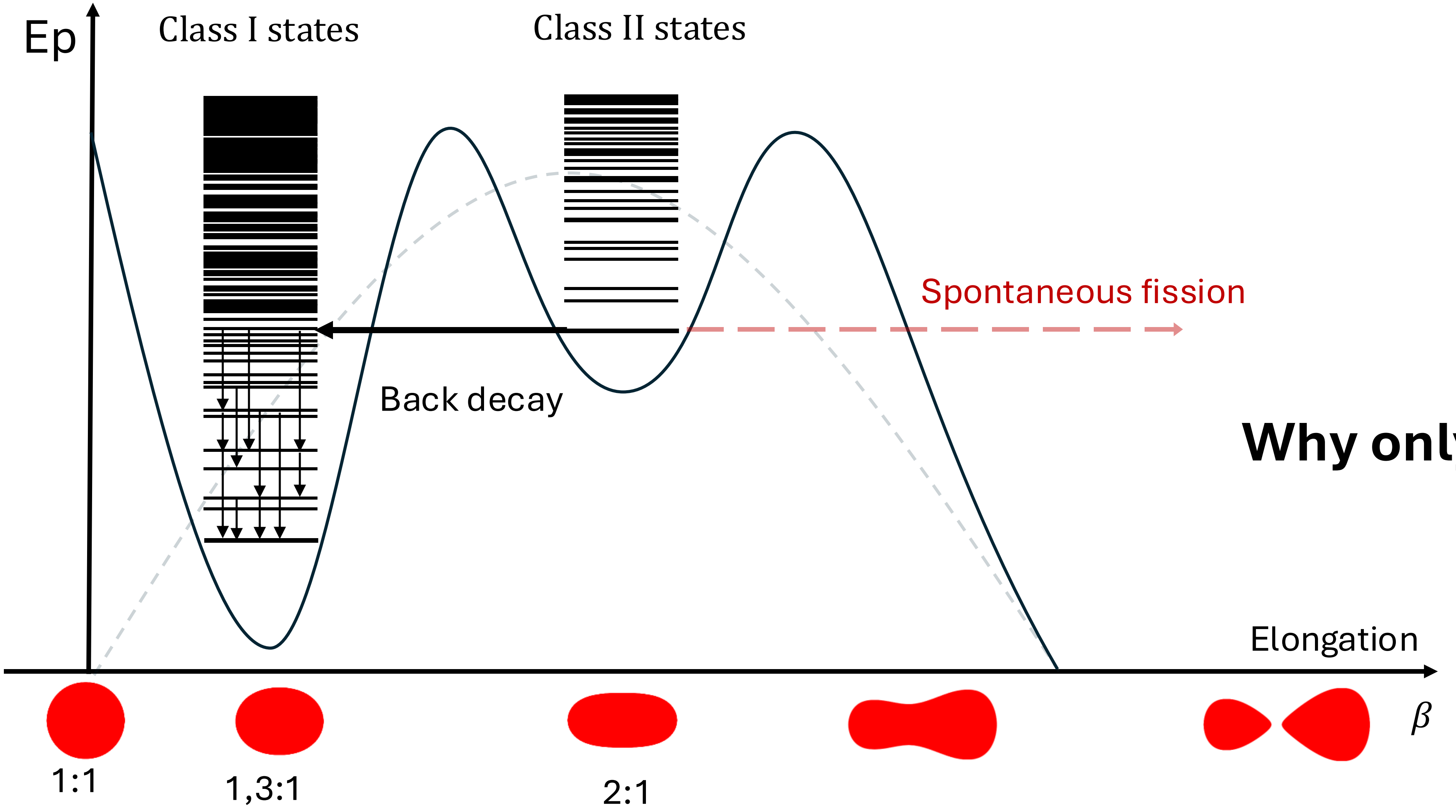
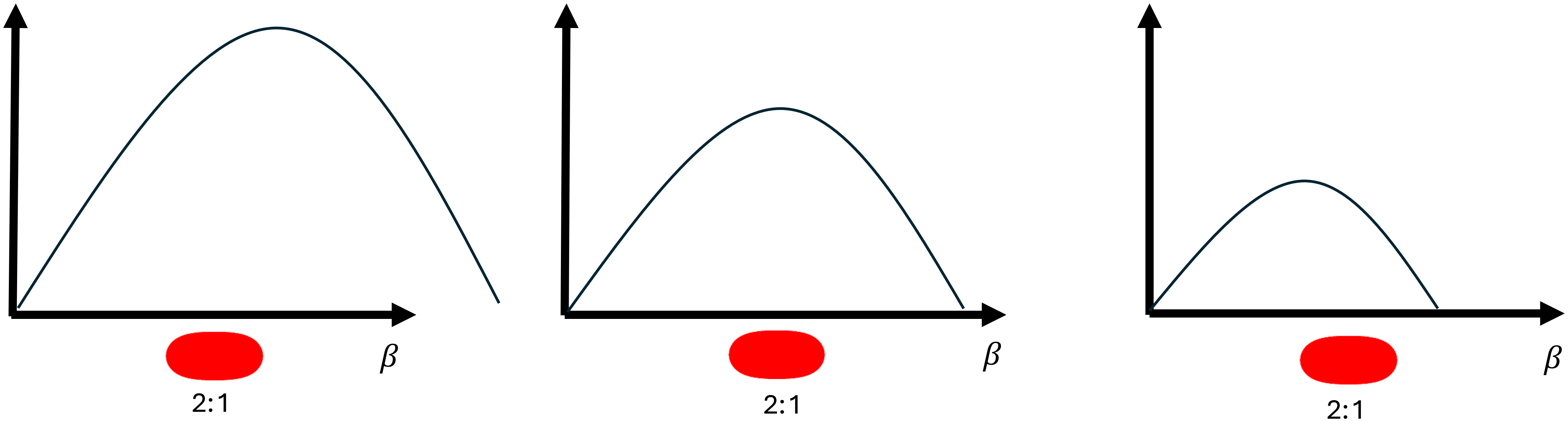


Why only in lower Z?

2. Gamma back-decay

Increasing fissility →lower deformed saddle point



Low Z (Ac, Th)

Intermediate Z (U, Np)

Higher Z (Pu, Am ...)

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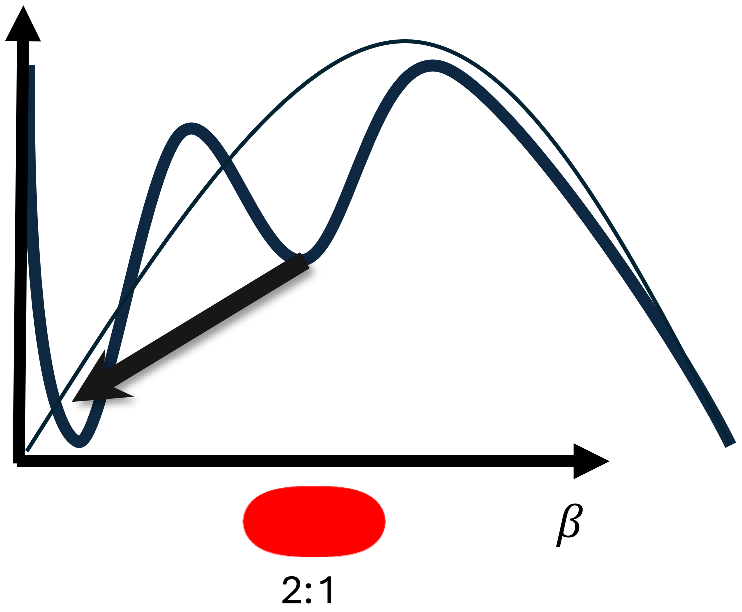

Low Z (Ac, Th)
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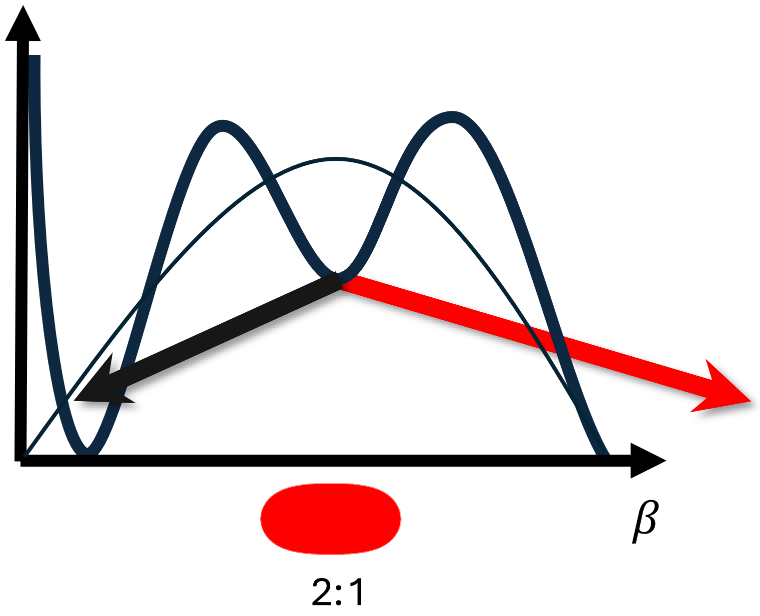
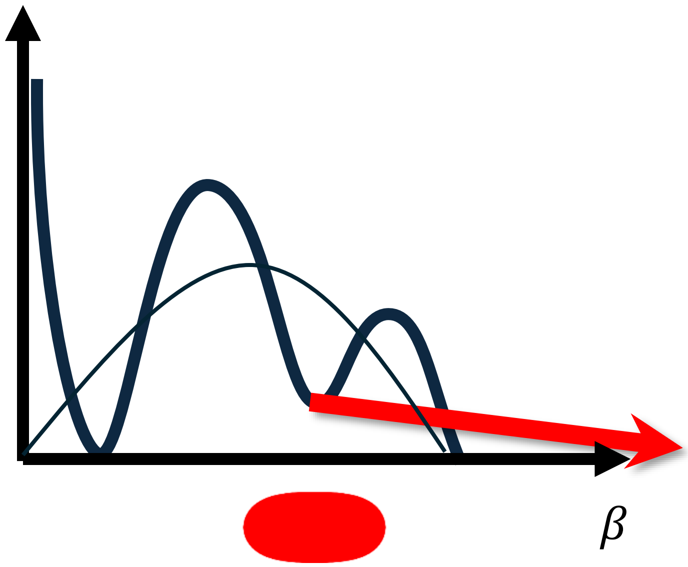
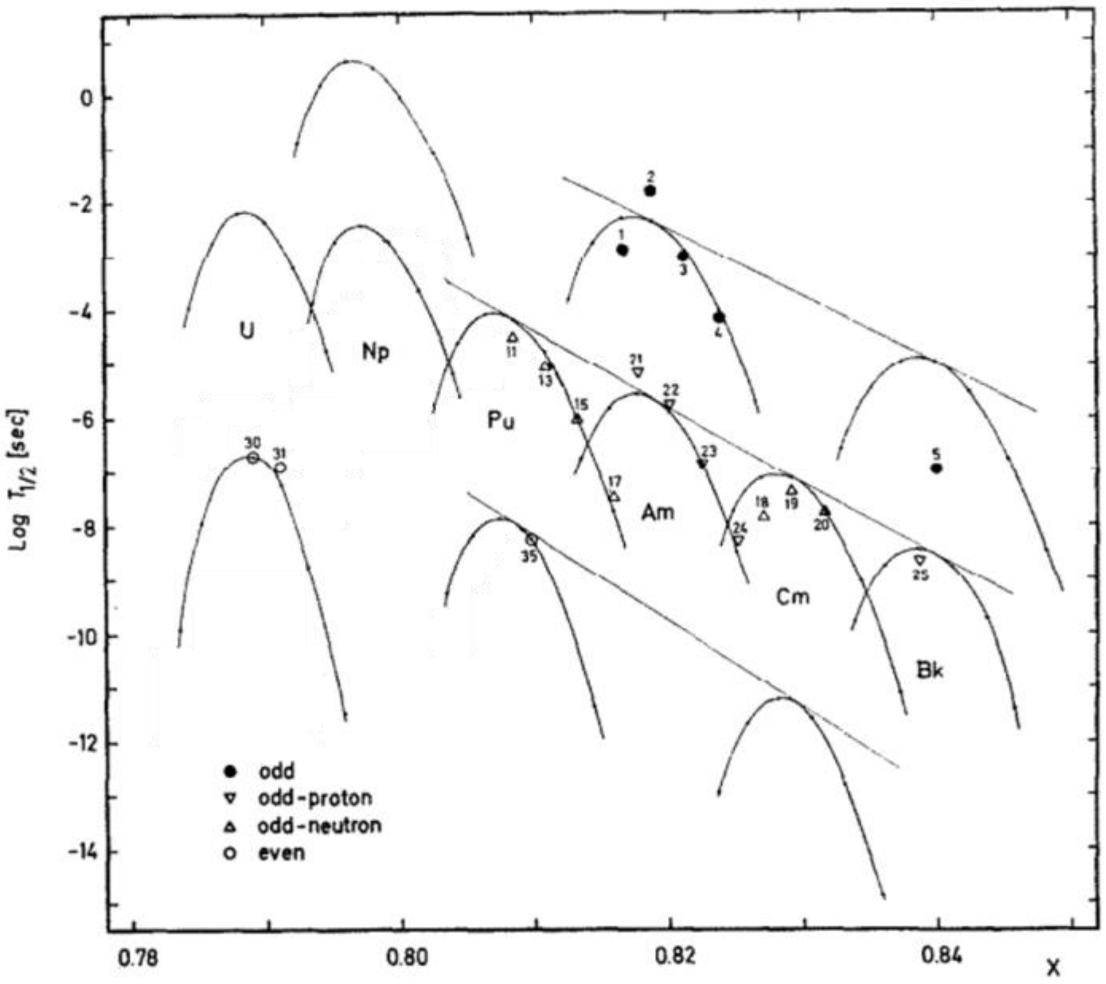


Intermediate Z (U, Np)
Symmetrical barriers



Higher Z (Pu, Am …)
Higher inner barrier

2. Gamma back-decay



Metag's half-life parametrisation

Barrier height parametrisation

$$\tau_{\rm sf}^{\rm isom.} = (\ln 2)(4 \times 10^{-21}) \left\{ 1 + \exp\left(\frac{2\pi}{\hbar\omega} \underbrace{\left[a\chi + b(N - N_0)^2 + S \right]} \right) \right\}$$

$$\hbar\omega = \hbar\omega_0 \begin{cases} 1/\delta & (\text{odd} - \text{odd}) \\ 1 & (\text{odd} - \text{A}) \\ \delta & (\text{even} - \text{even}) \end{cases} \qquad S = \begin{cases} 2S_0 & (\text{odd} - \text{odd}) \\ S_0 & (\text{odd} - \text{A}) \\ 0 & (\text{even} - \text{even}) \end{cases}$$

$$\chi = \frac{Z^2/A}{2(a_s/a_c)\{1 - [\kappa(N - Z)^2/A^2]\}}$$

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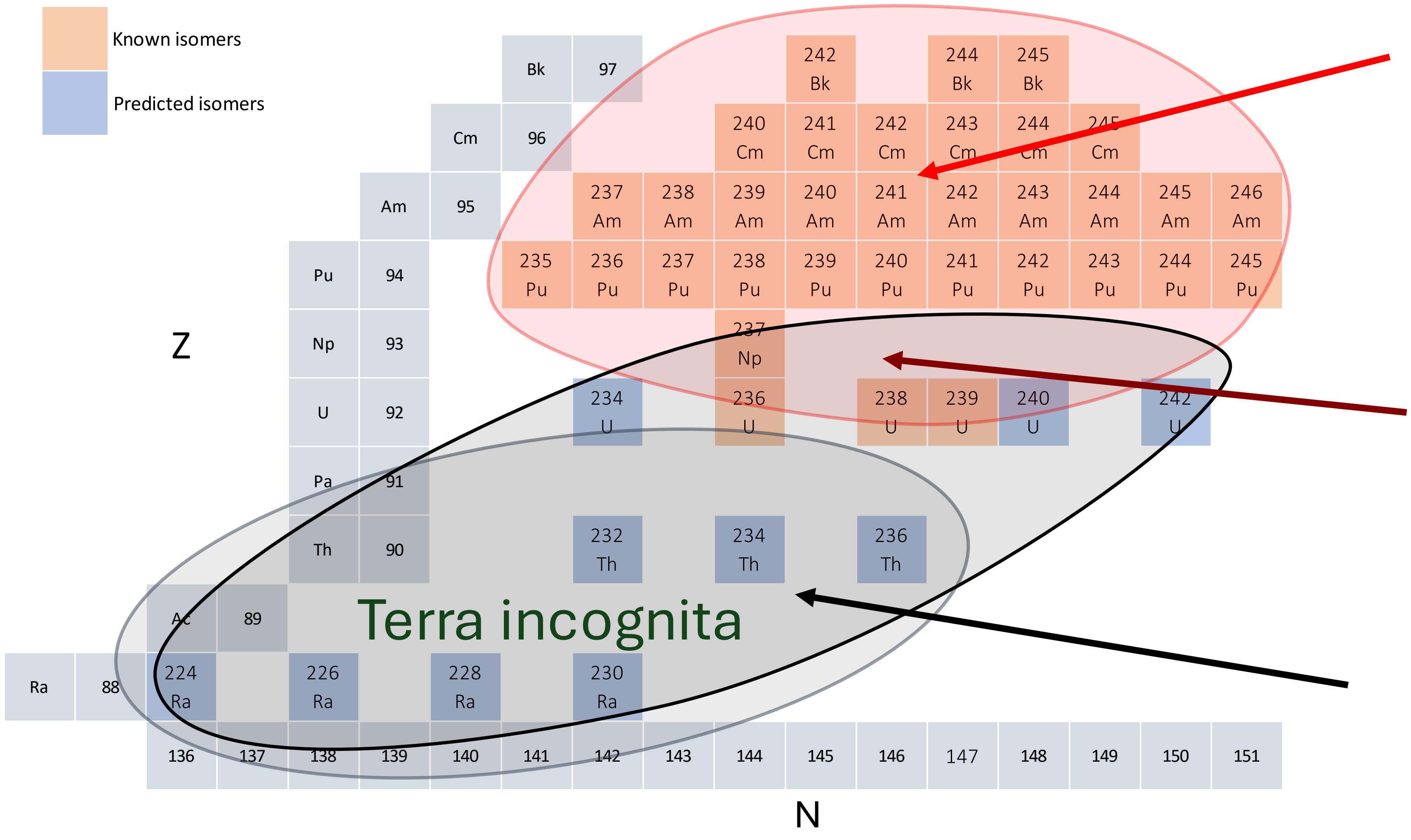

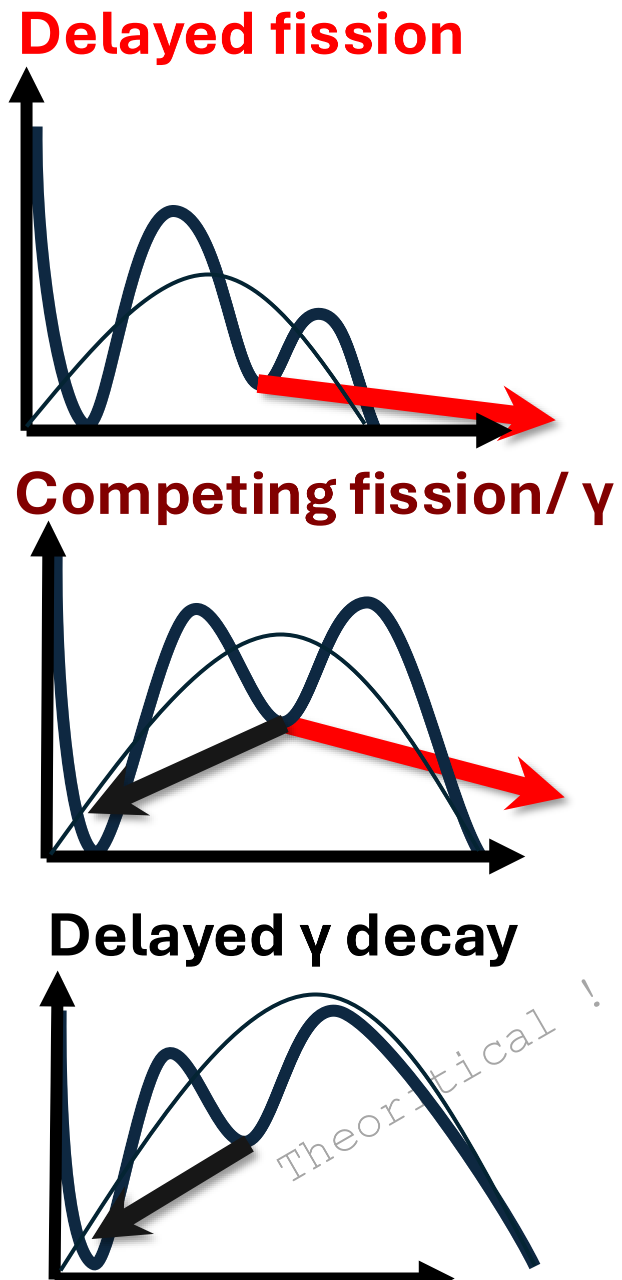

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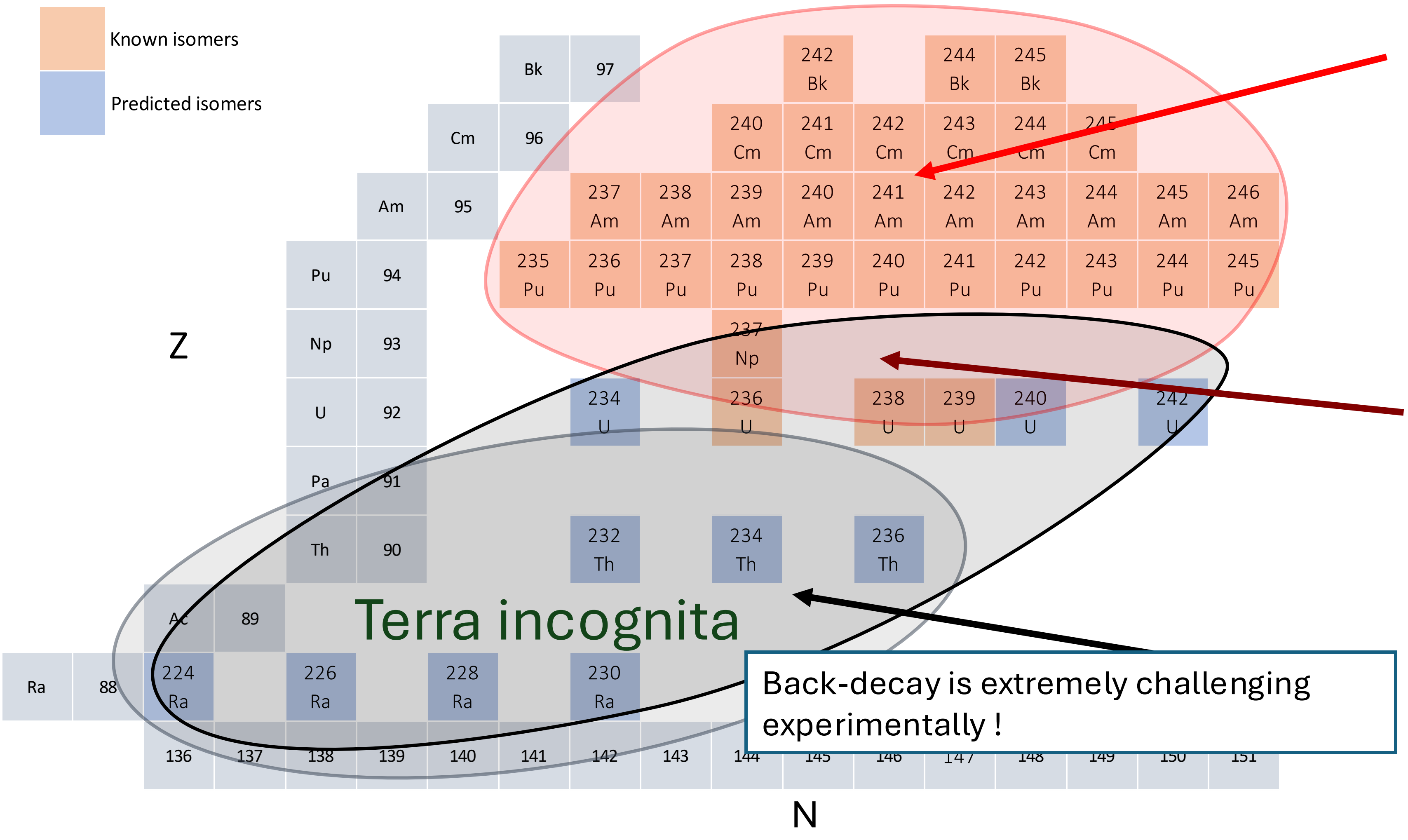
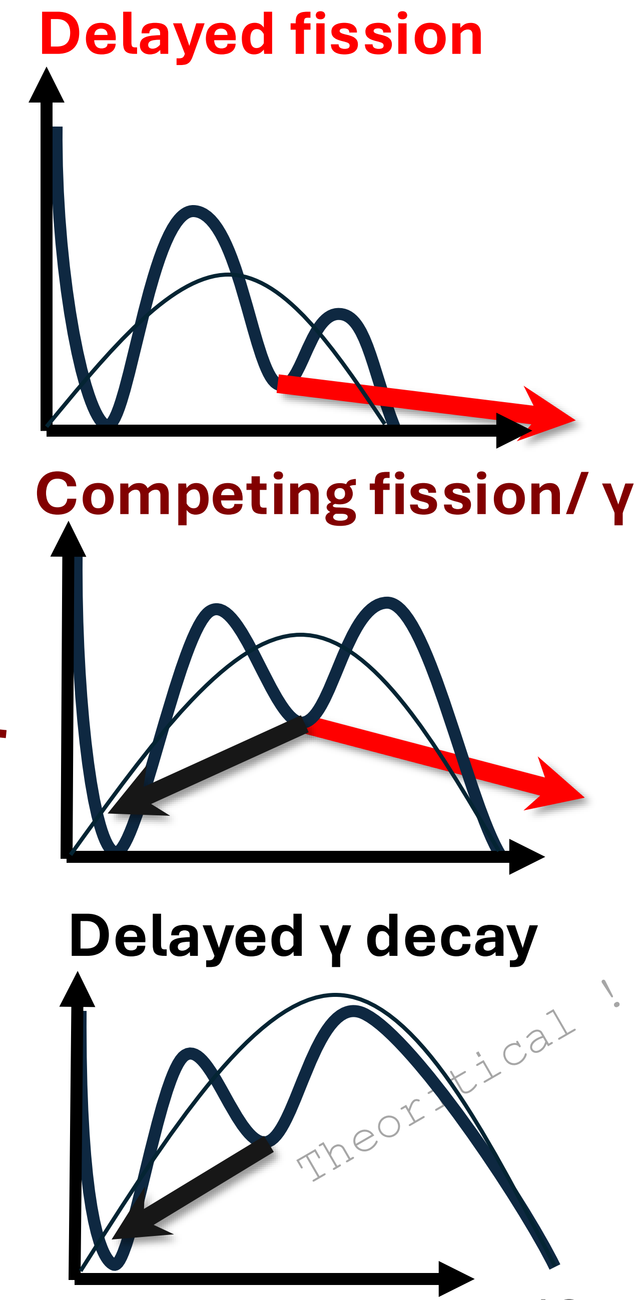


Back-decay is extremely challenging experimentally !



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3 measurements :

Short half-life (Metag's half-life parametrisation)
Low cross section

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^{237}Np : 40ns fission isomer (very short !), but no γ-ray found

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Re-investigation with nu-Ball 2

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2. Gamma back-decay

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

Selectivity from calorimetry,
proton energy and beam pulsation:

Missing energy technique

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

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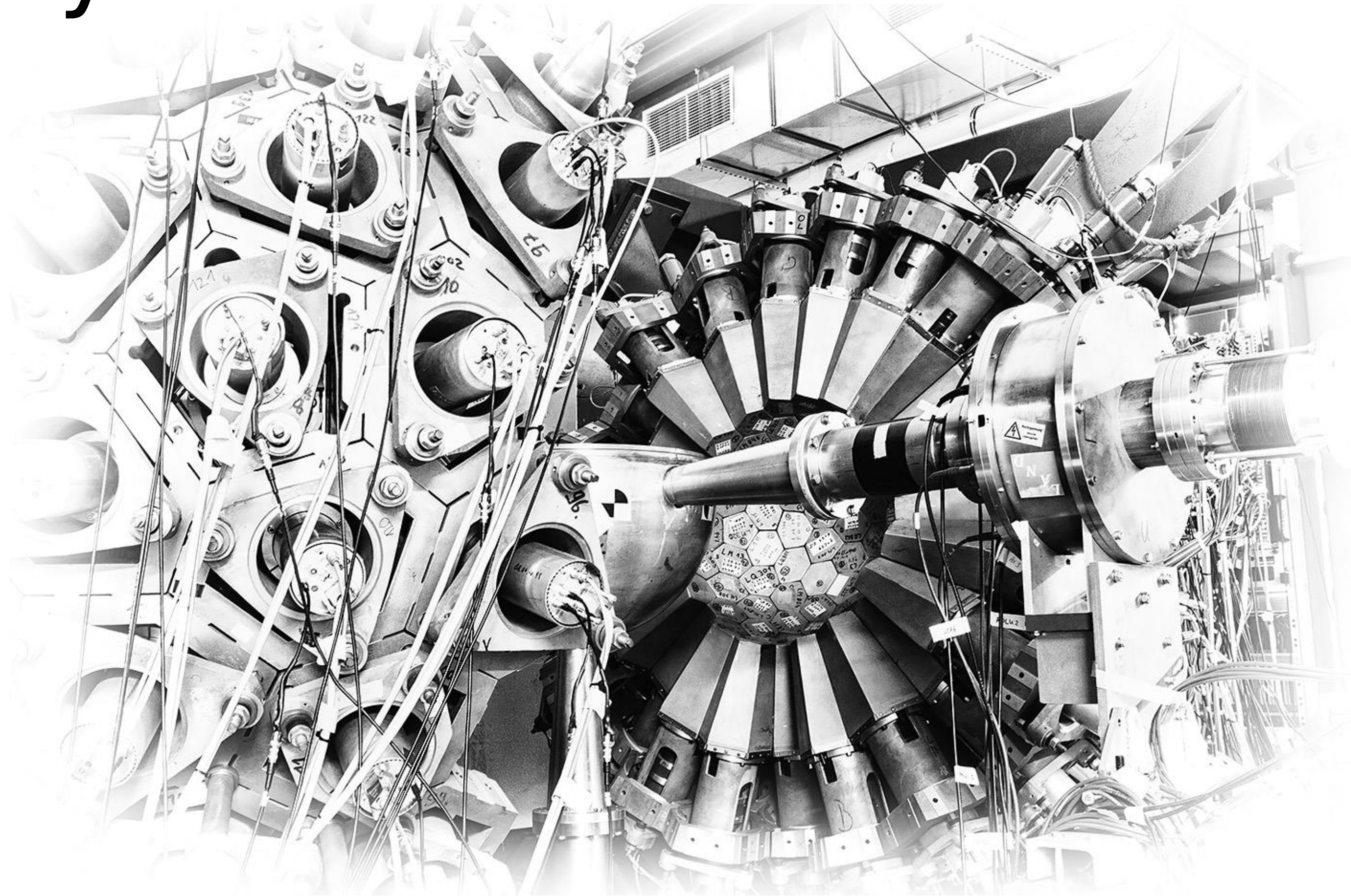


Darmstadt 4π NaI crystal ball :
65% total energy efficiency
calorimeter

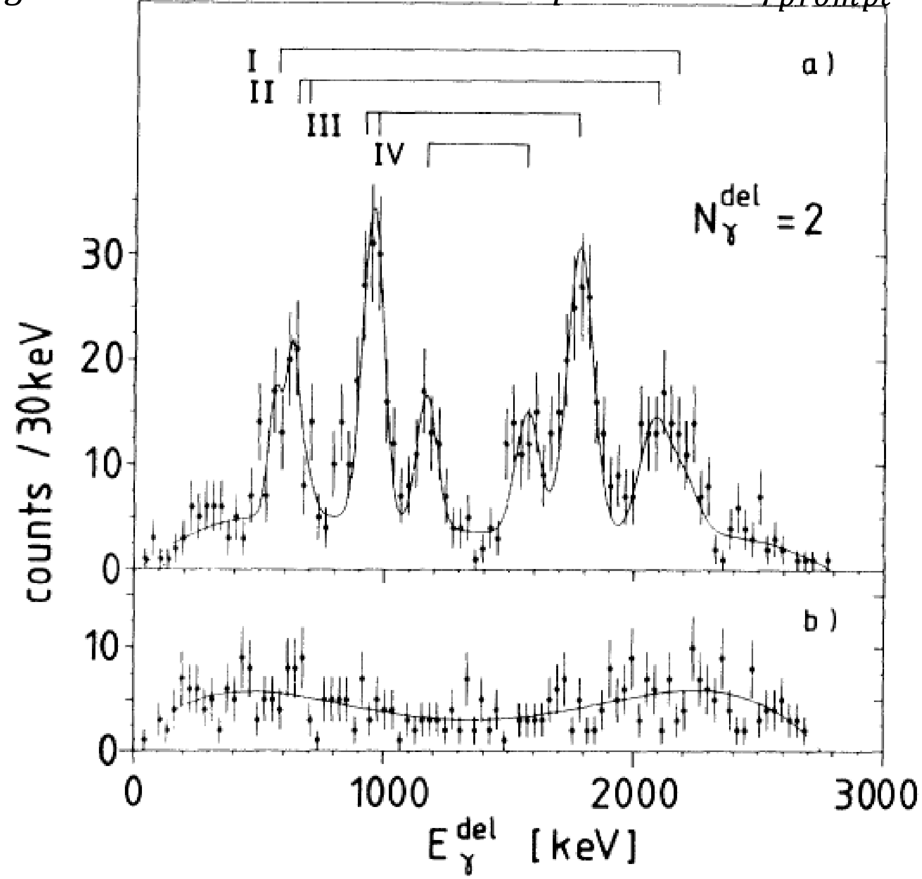
2. Gamma back-decay

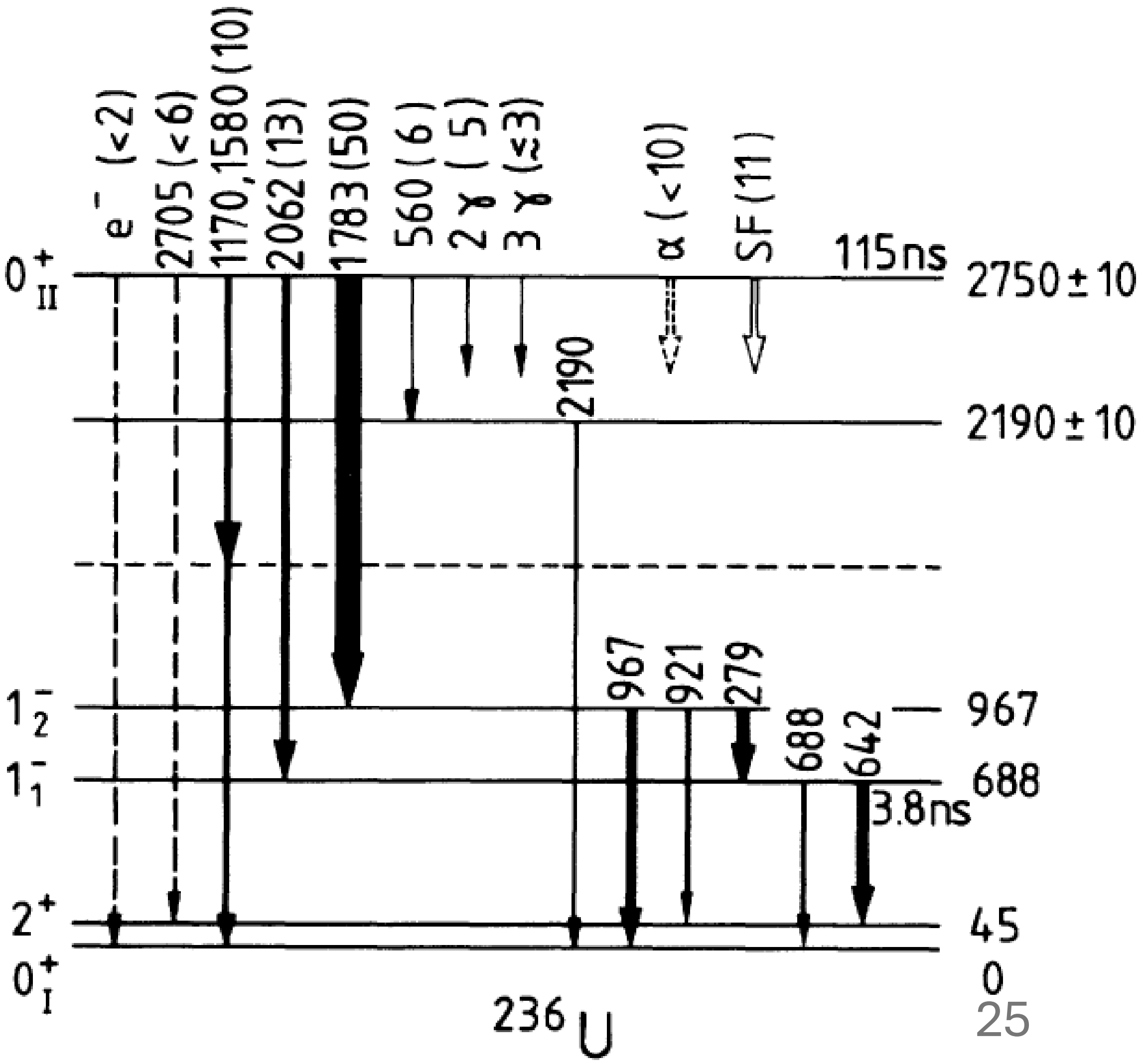
J. Schirmer, J. Gerl, D. Habs and D. Schwalm, Phys. *Rev. Lett. 63 (1989) 2196* .

Conditions :

- $E_{missing} = \sum E^{delayed} \approx 2{,}75\ MeV$
- $M_\gamma = 2$

$$E_{missing} = E_{beam} + Q_{reaction} - E_{proton} - E_{\gamma_{prompt}}$$





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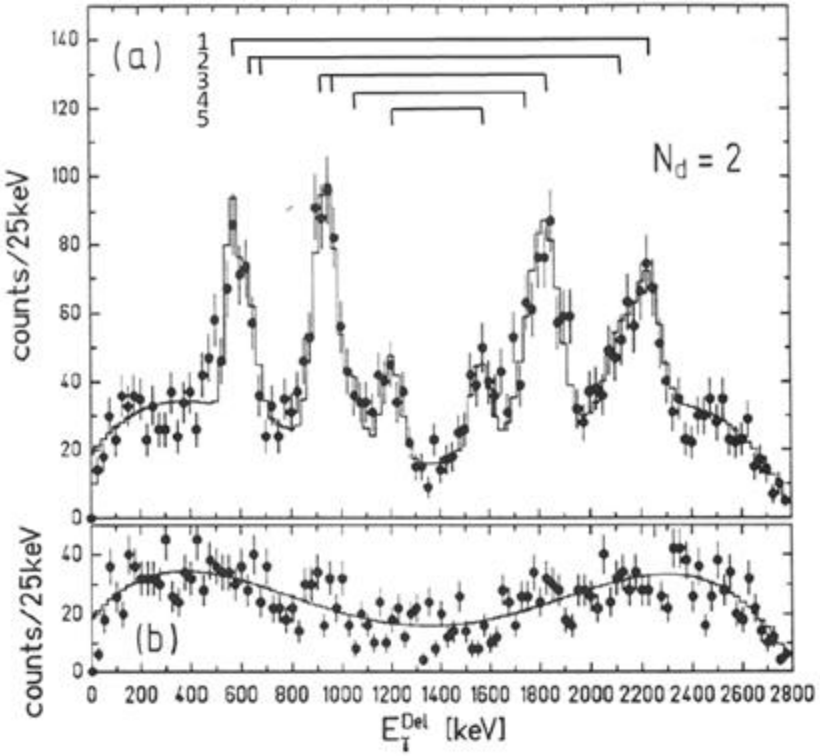
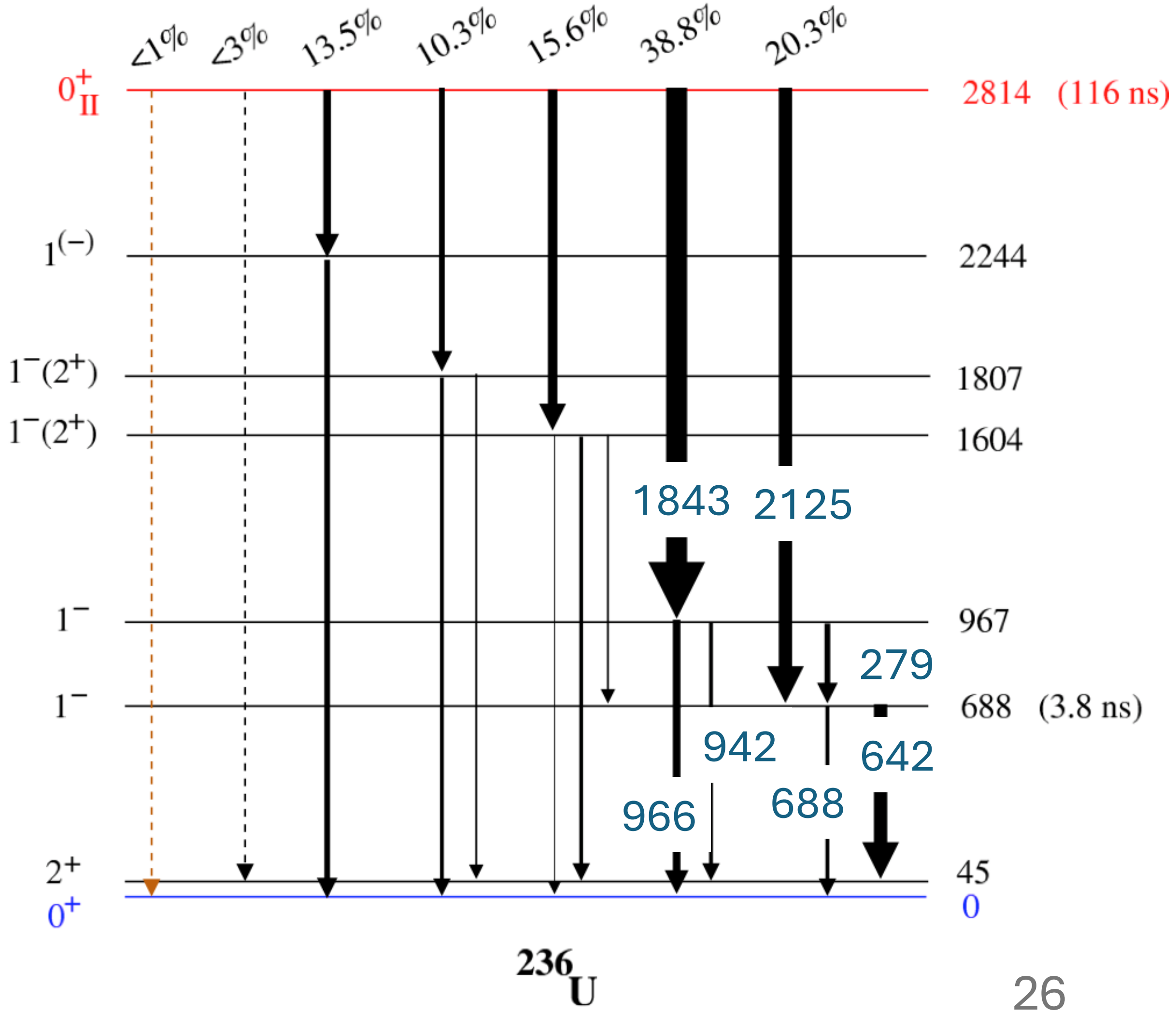
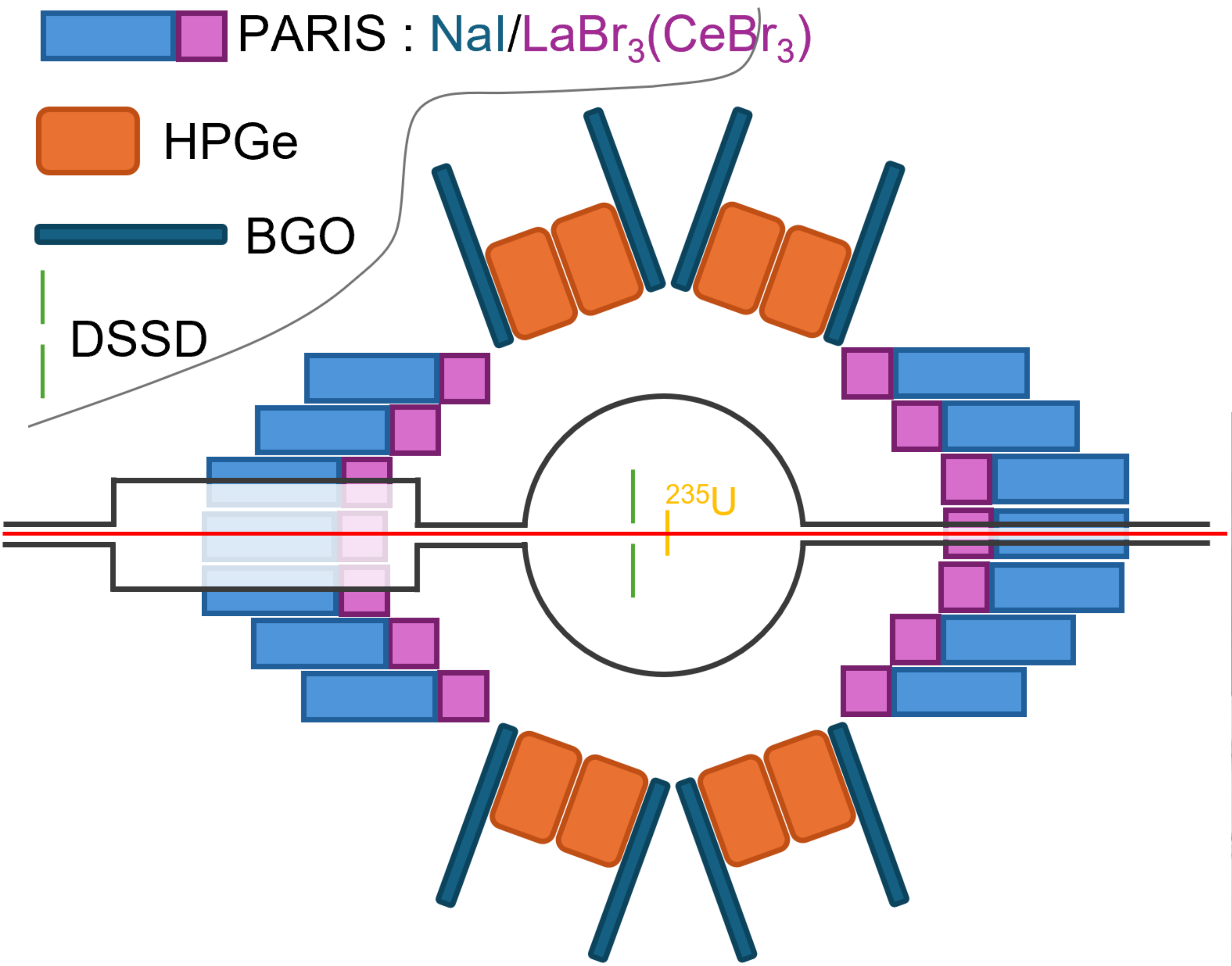




3. Experimental setup

- 24 Ge clovers + BGO,
- 64 PARIS phoswhich
- Double-sided silicon detector, 32+15 channels
- Fully-digital FASTER acquisition system (LPC)



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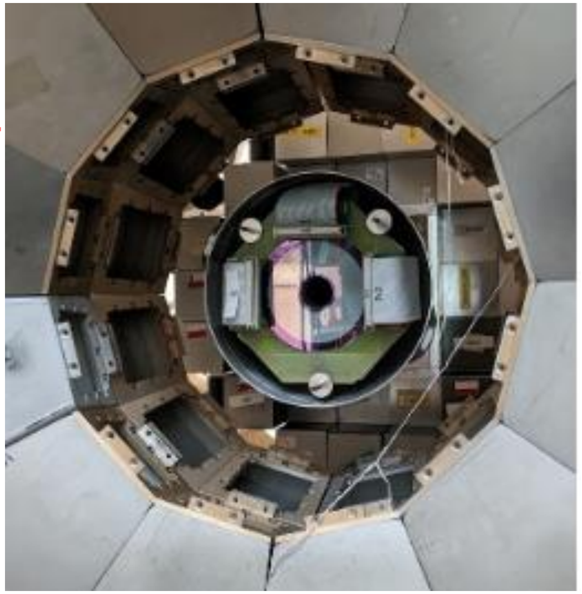
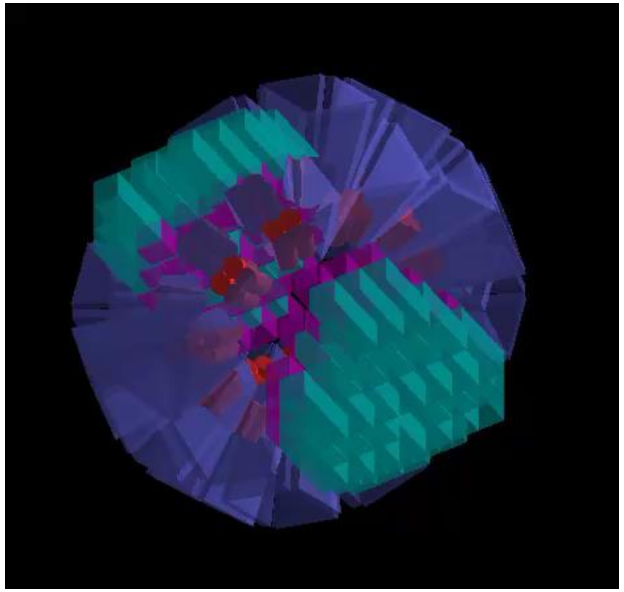


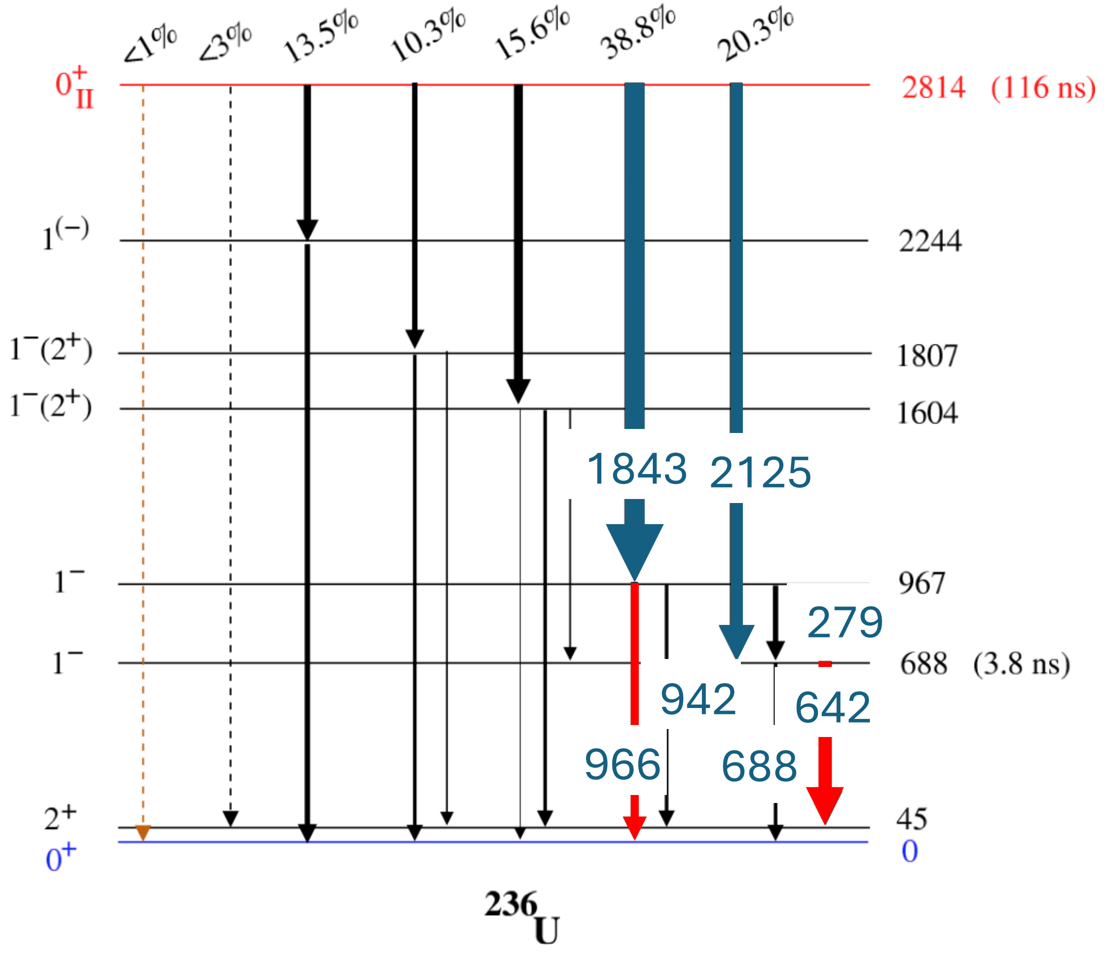
DSSD



Geant visualisation

4. Analysis

- First attempt : γ-gate on particle-conditioned data



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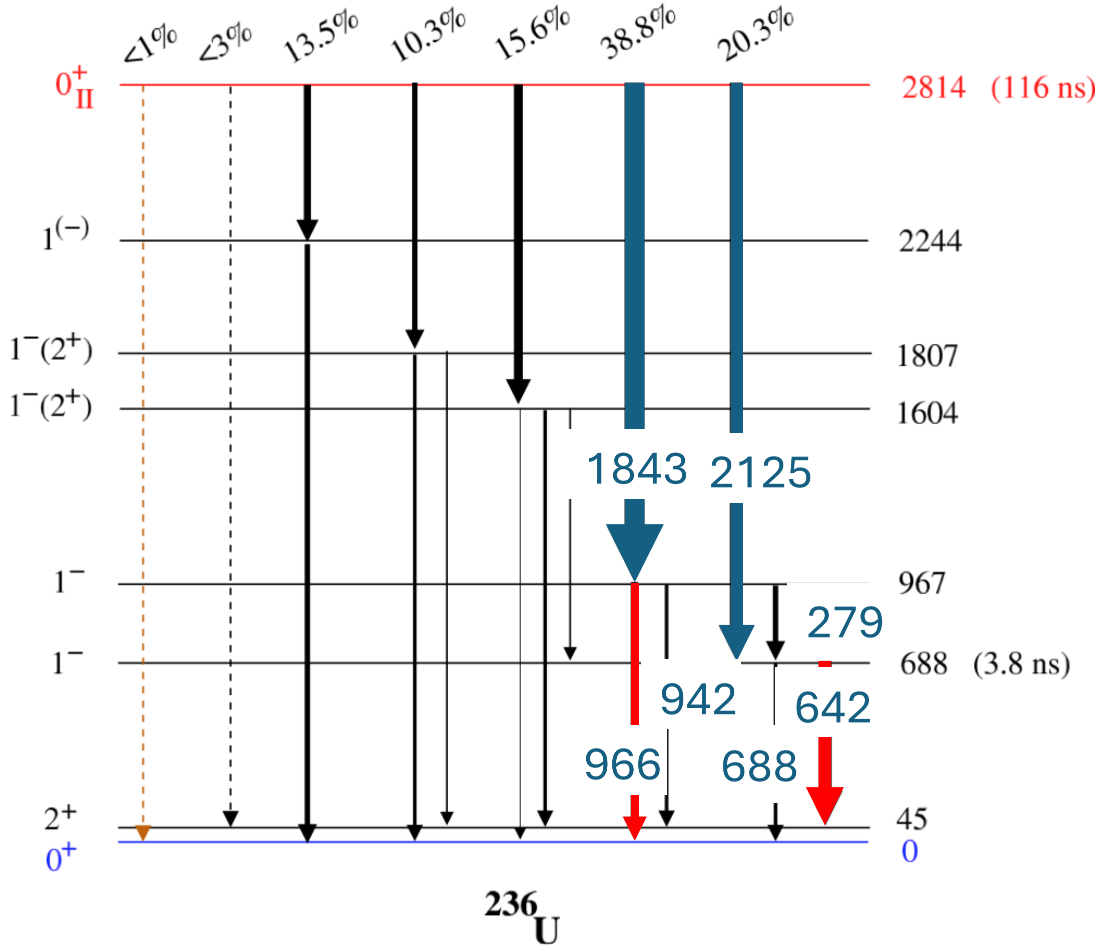

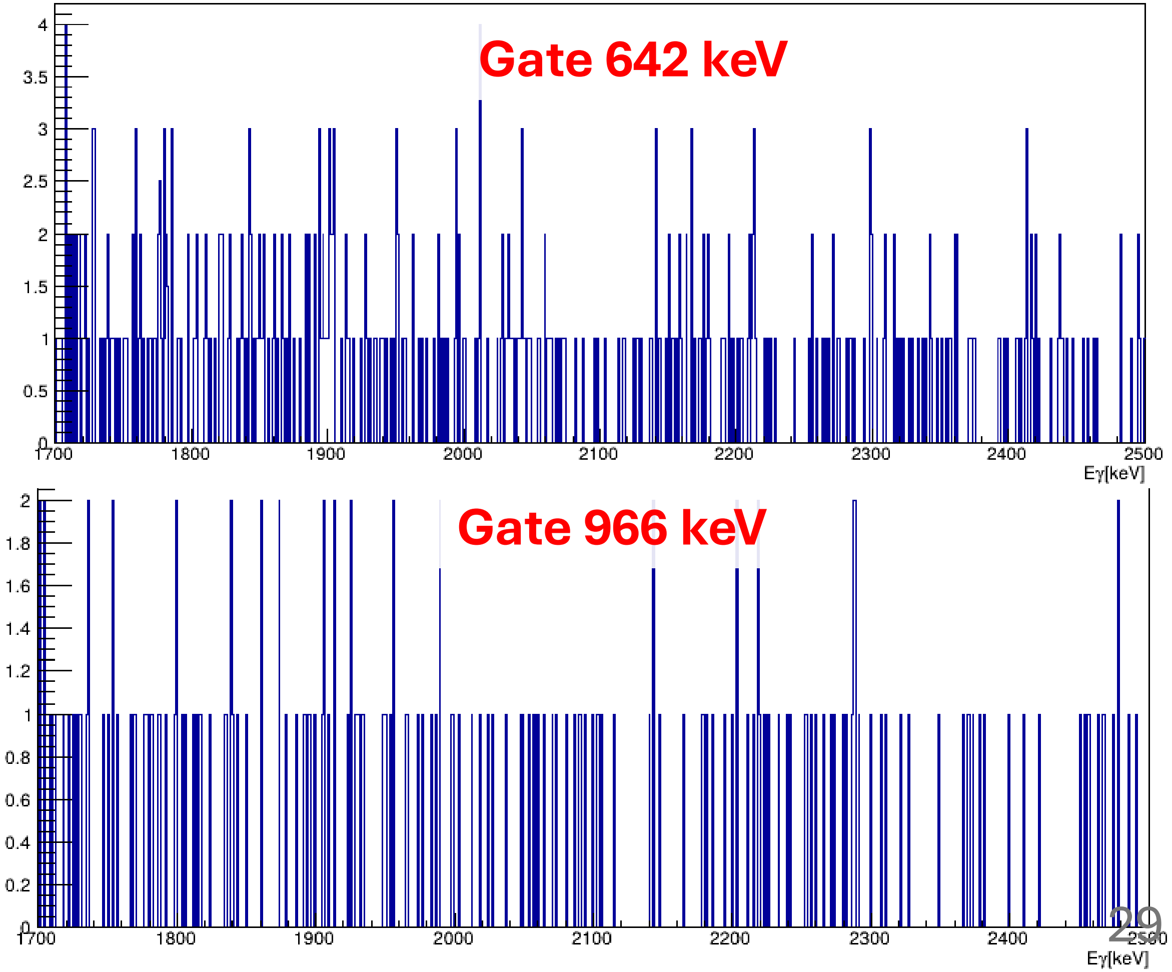

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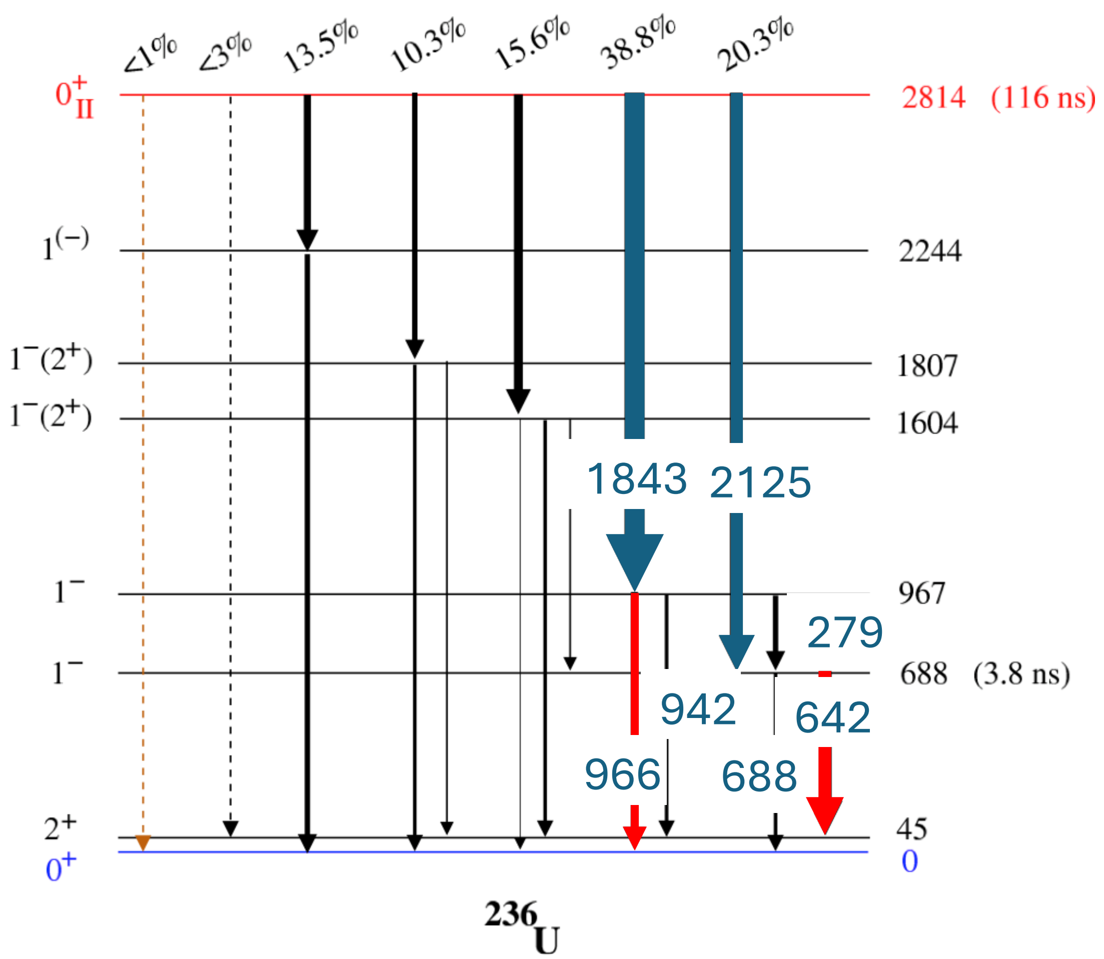
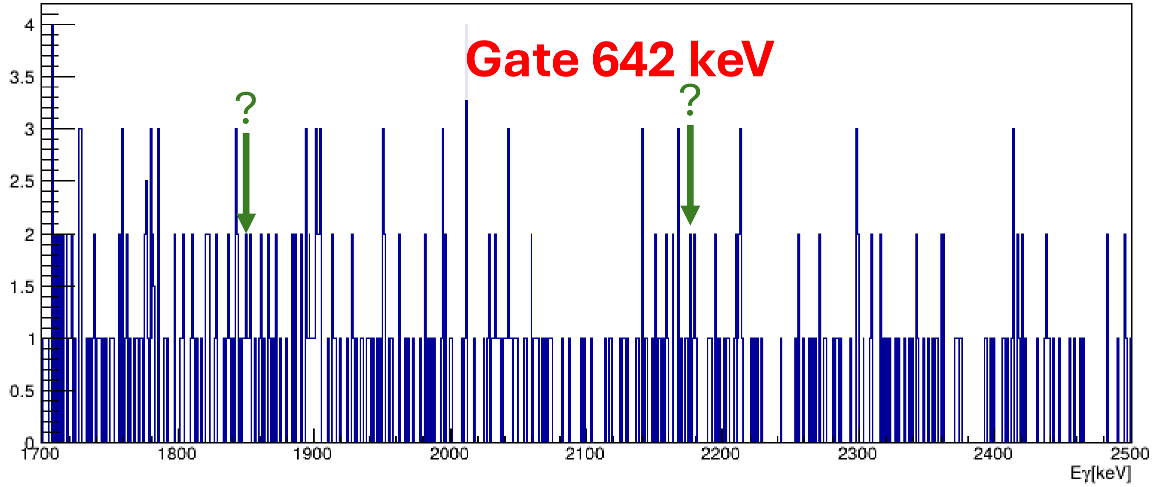
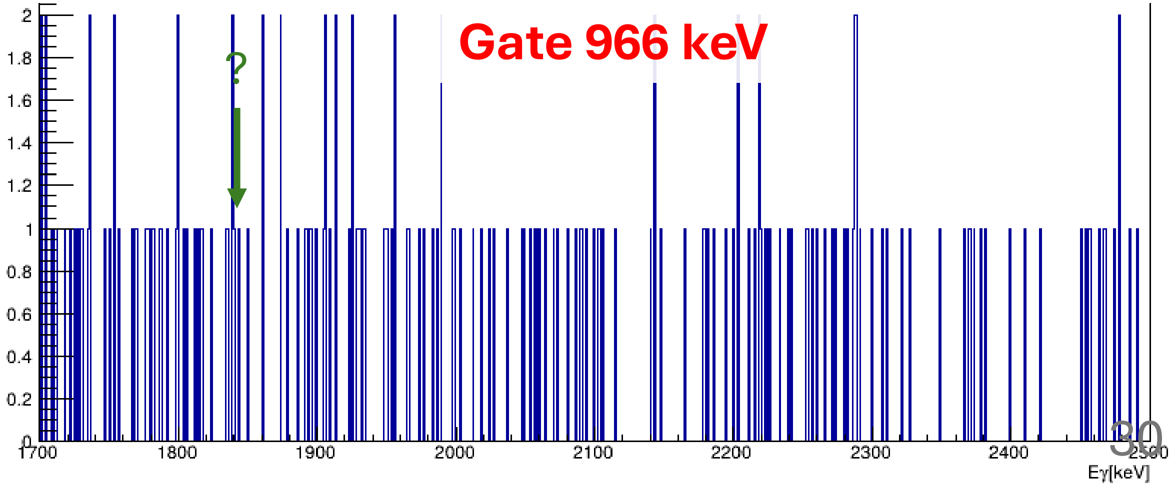
No clear peak !







4. Analysis

- Methodology :
  1. Estimate $N^{total}(^{236}U)$
     1. From data :
        - $I(642) \approx 2.10^7$
        - $N(^{236}U)_{tot} = I(642)_{tot} / (34\% \times \epsilon_{642}) \approx 10^9$
     2. From experiment conditions :
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  2. Calculate $N(^{236\,II}U)$
     1. From Schirmer1989 : $\frac{N(^{236\,II}U)}{N(^{236\,I}U)} = 3.10^{-4}$
     2. Deduce $N(^{236\,II}U) = 3.10^5$

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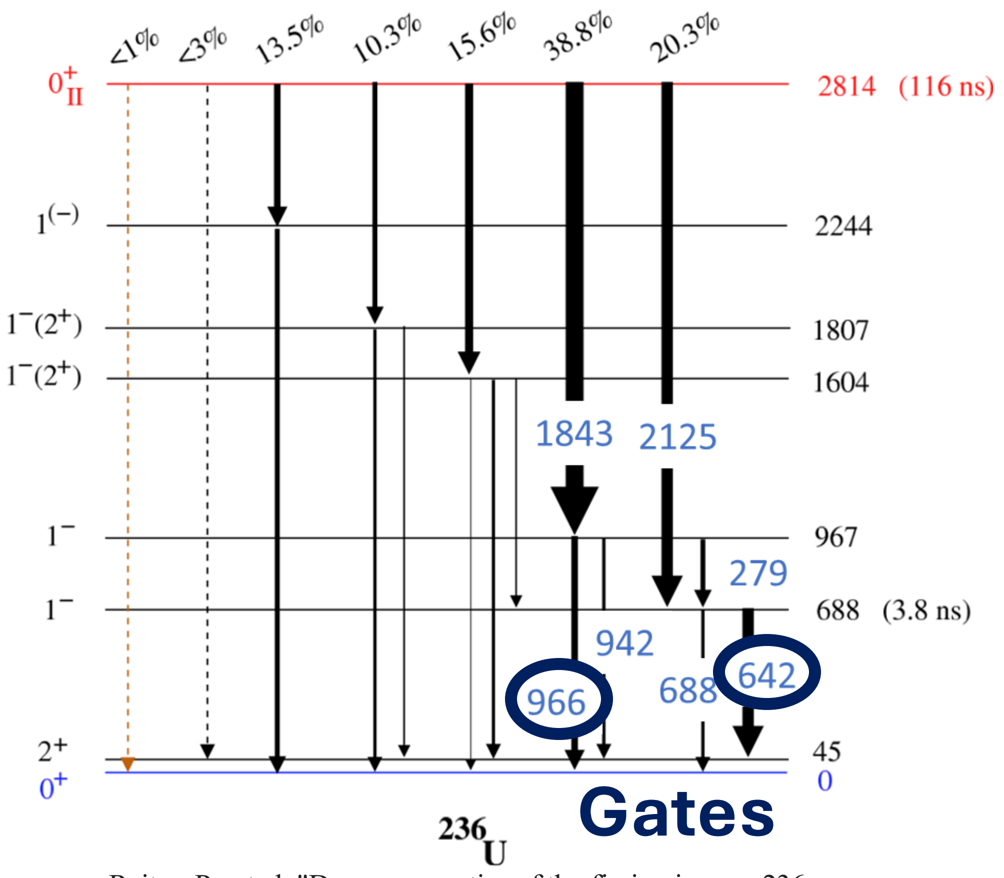
     2. Deduce $N(^{236\,II}U) = 3.10^5$
  3. Apply gamma and condition efficiencies :

Energy [keV]	1843	2122
Intensity [%]	38.8	20.3
Efficiency [%]	2.2	2.1



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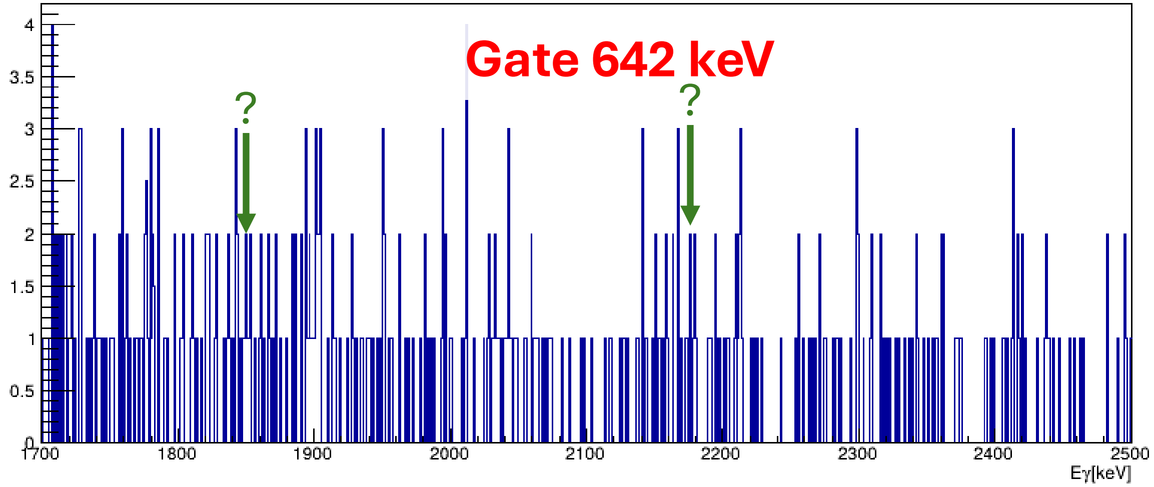
Condition	Efficiency [%]	N_{1843}	N_{2122}
none	100	12000	6300
prompt gate	50	6000	3150
particle gate	10	1200	630
prompt + particle gates	5	600	315

4. Analysis

Expected counts : 1.2



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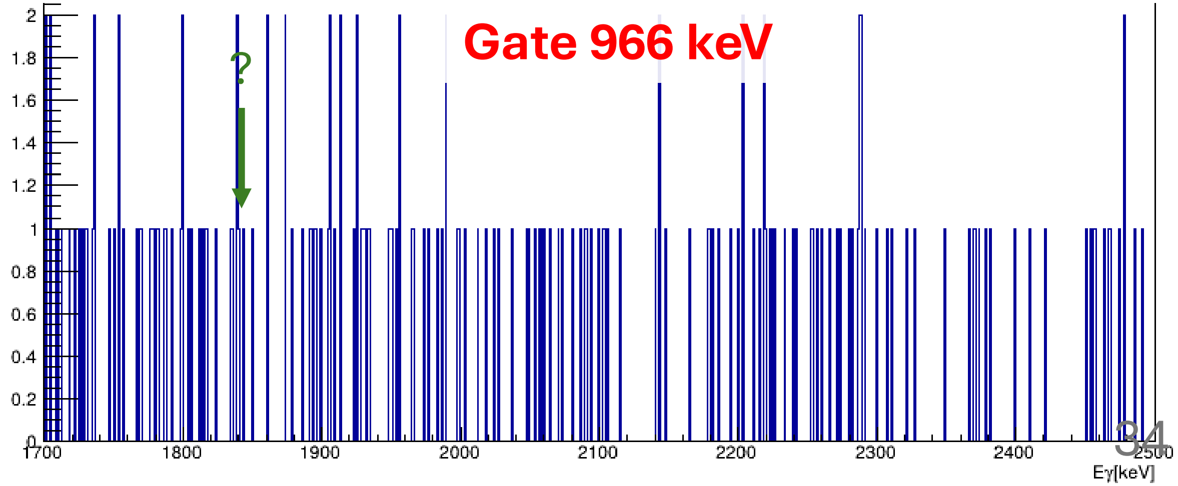

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Not enough statistics !

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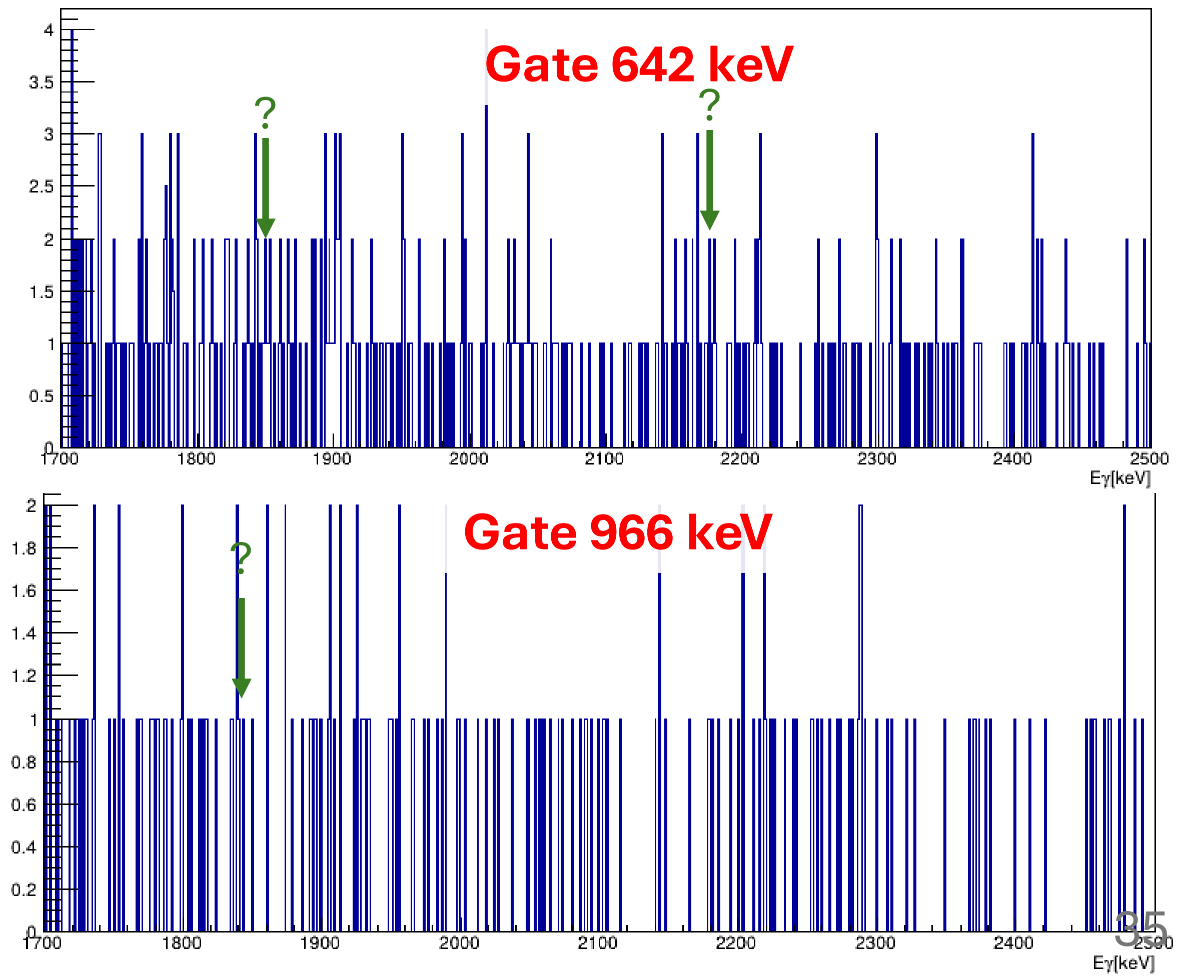
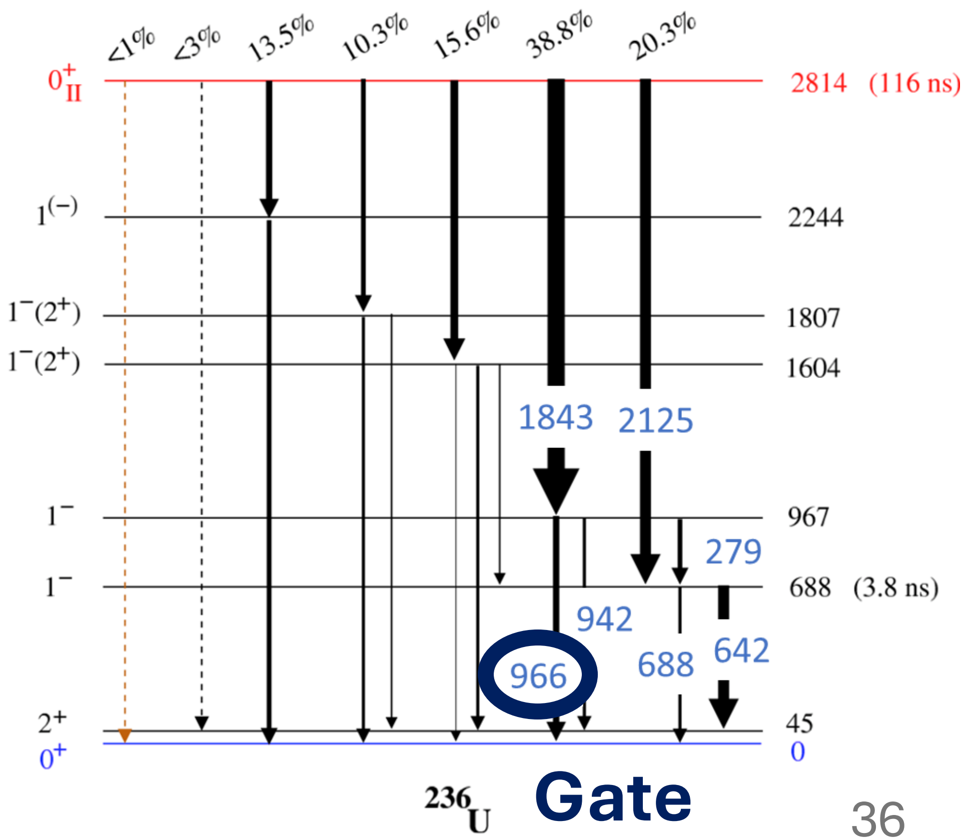


4. Analysis

Most significant coincidence :
gate on 966 keV
look for 1843 keV

Solution : use data without particle condition



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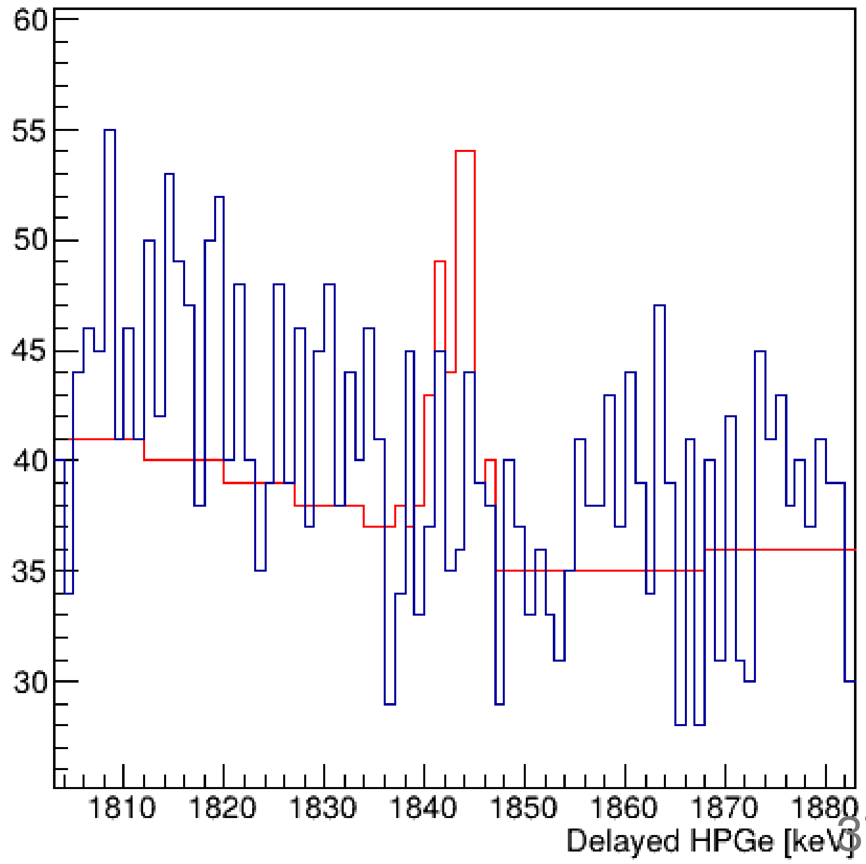
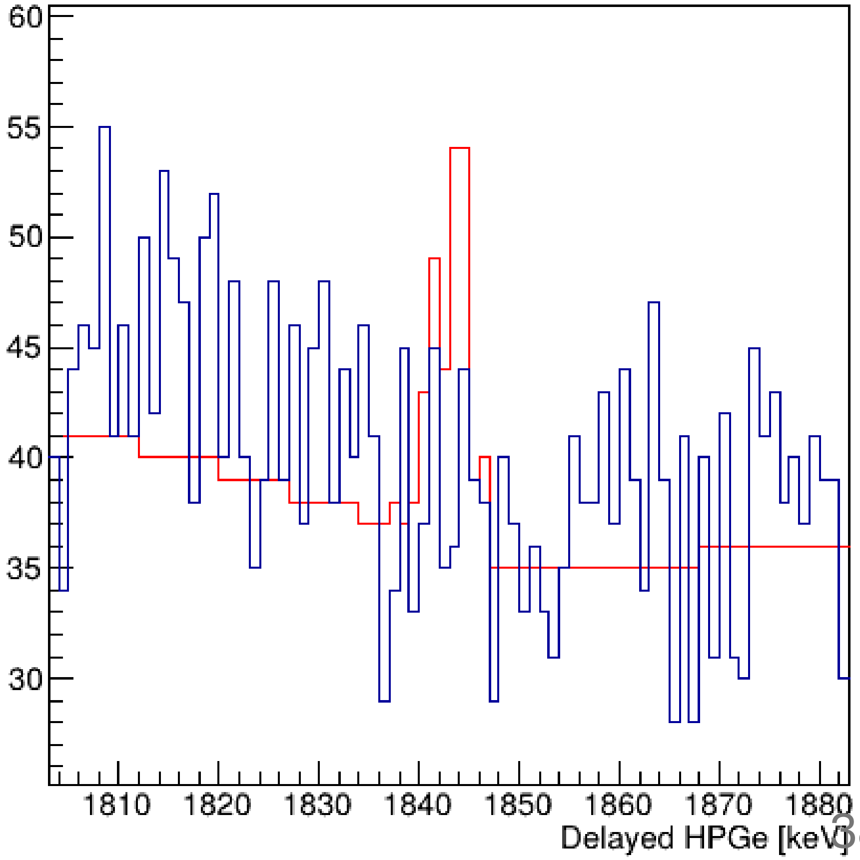


4. Analysis

Solution : use data without particle condition

Expected peak still not significant …

Most significant coincidence :
gate on 966 keV
look for 1843 keV



4. Analysis

Add conditions event-by-event conditions :

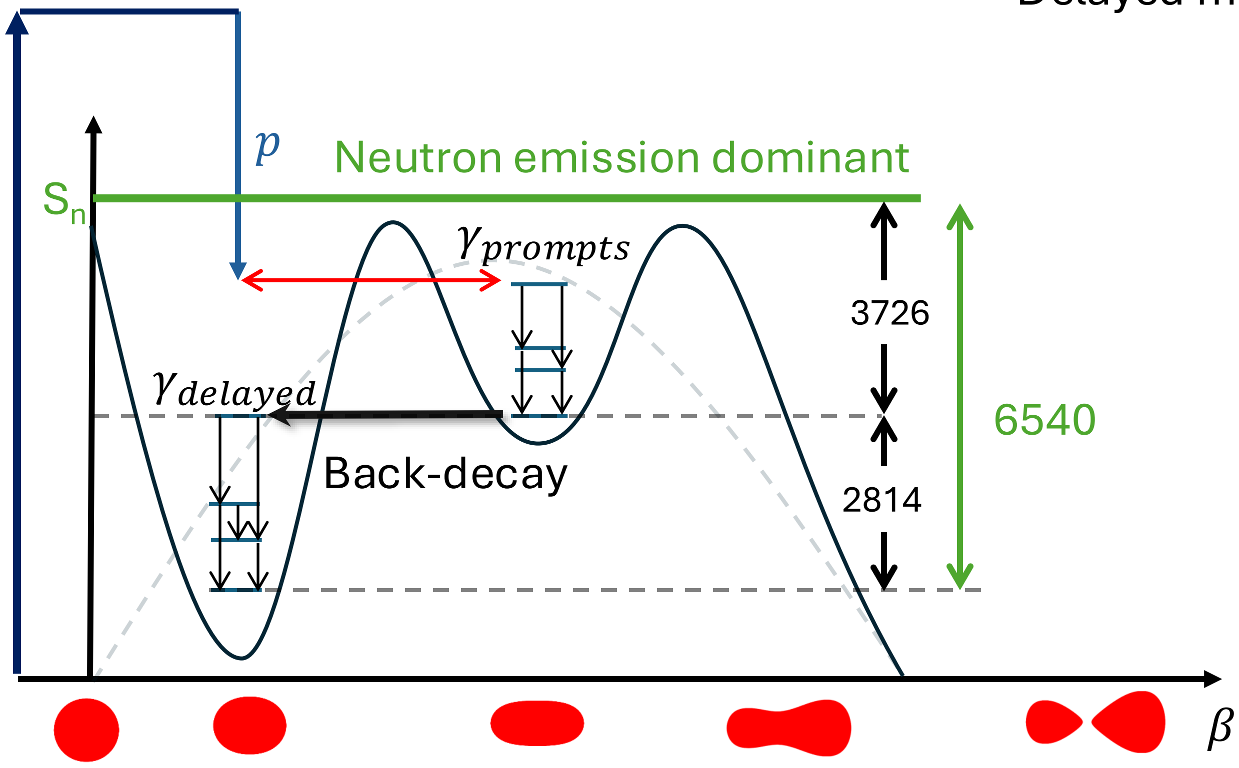
Prompt hit

Prompt calorimetry < 3,5 MeV

Delayed calorimetry < 3 MeV

Total multiplicity < 10

Delayed multiplicity < 5



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Add conditions event-by-event conditions :
Prompt hit
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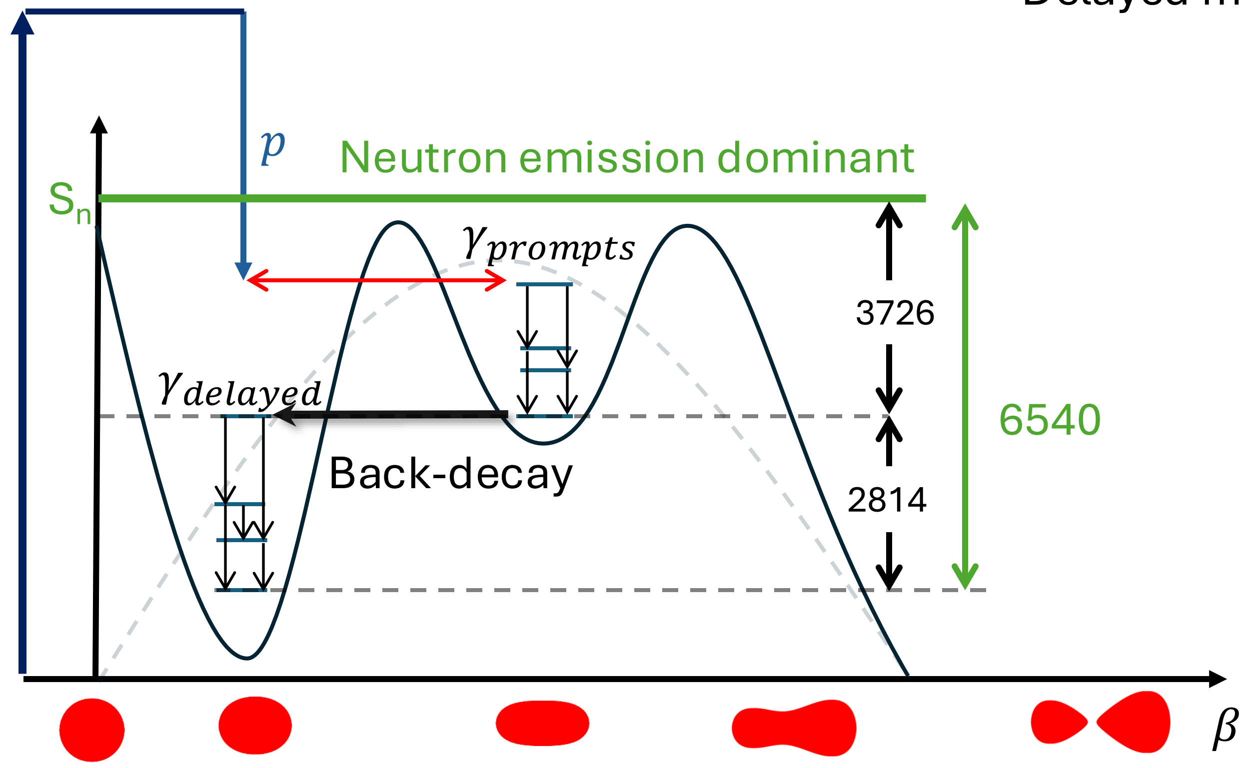
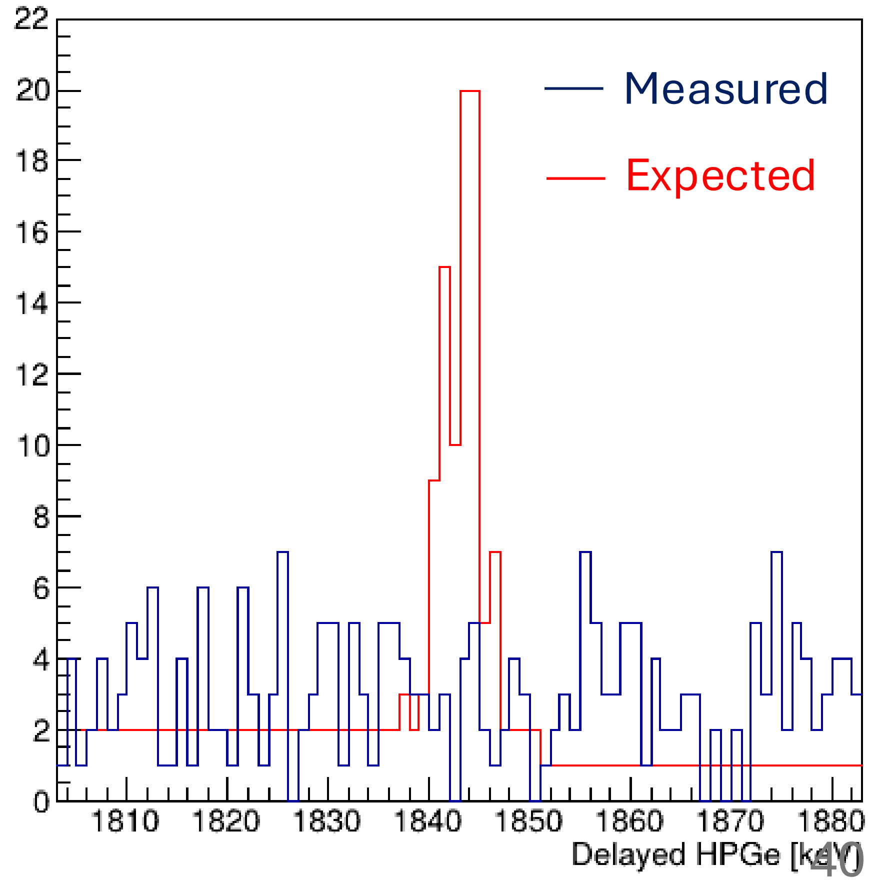


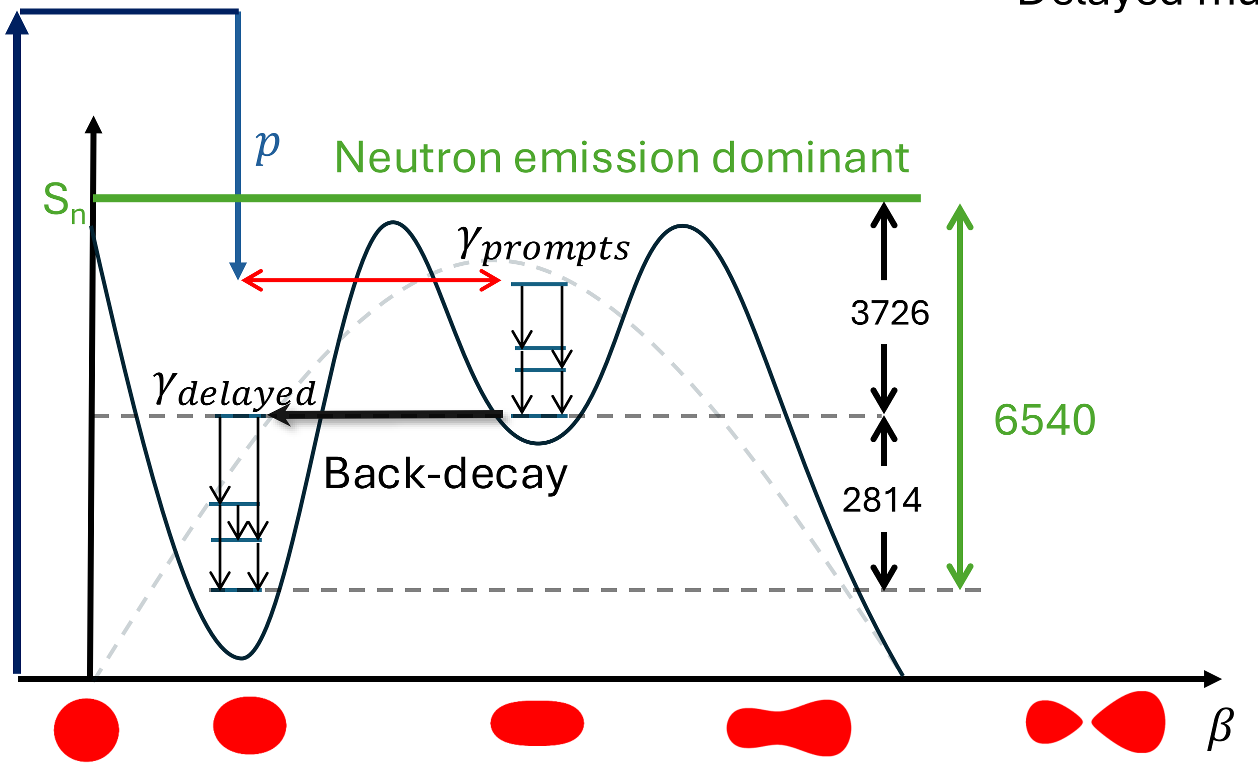


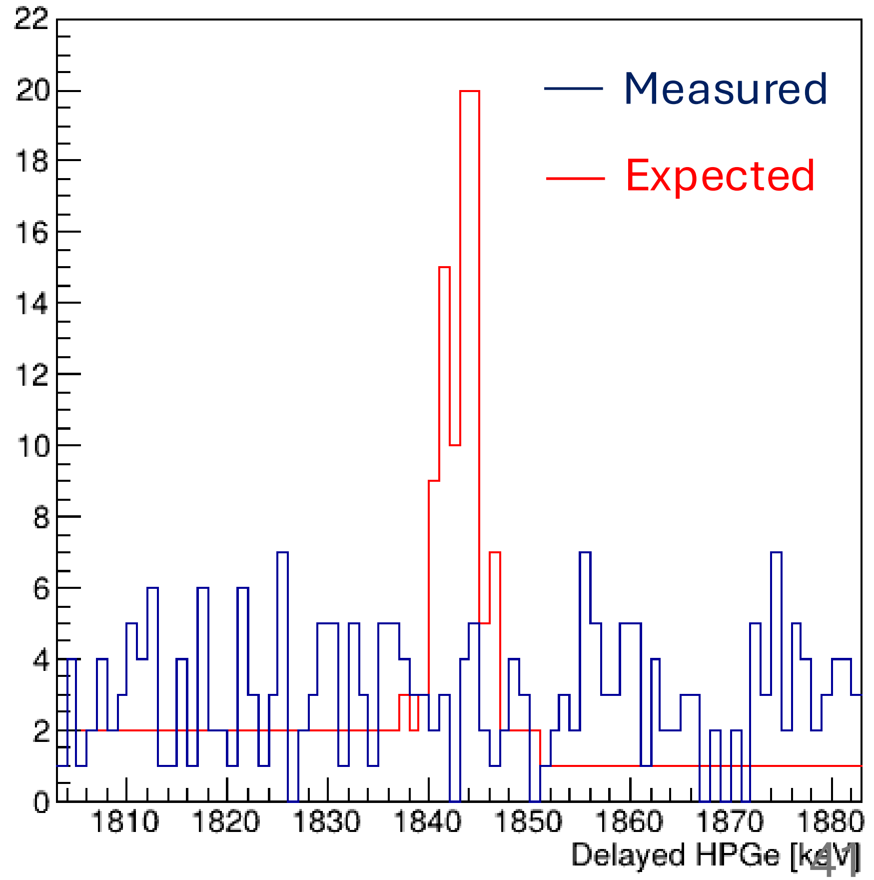
4. Analysis

Add conditions event-by-event conditions :
Prompt hit
Prompt calorimetry < 3,5 MeV
Delayed calorimetry < 3 MeV
Total multiplicity < 10
Delayed multiplicity < 5

Results not reproduced !

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





5. Discussion

- The crystal ball experiment could not be reproduced

- Hypotheses :

  - Reported cross section too big ?

  Or …

5. Discussion

- The crystal ball experiment could not be reproduced

- Hypotheses :

  - Reported cross section too big ?

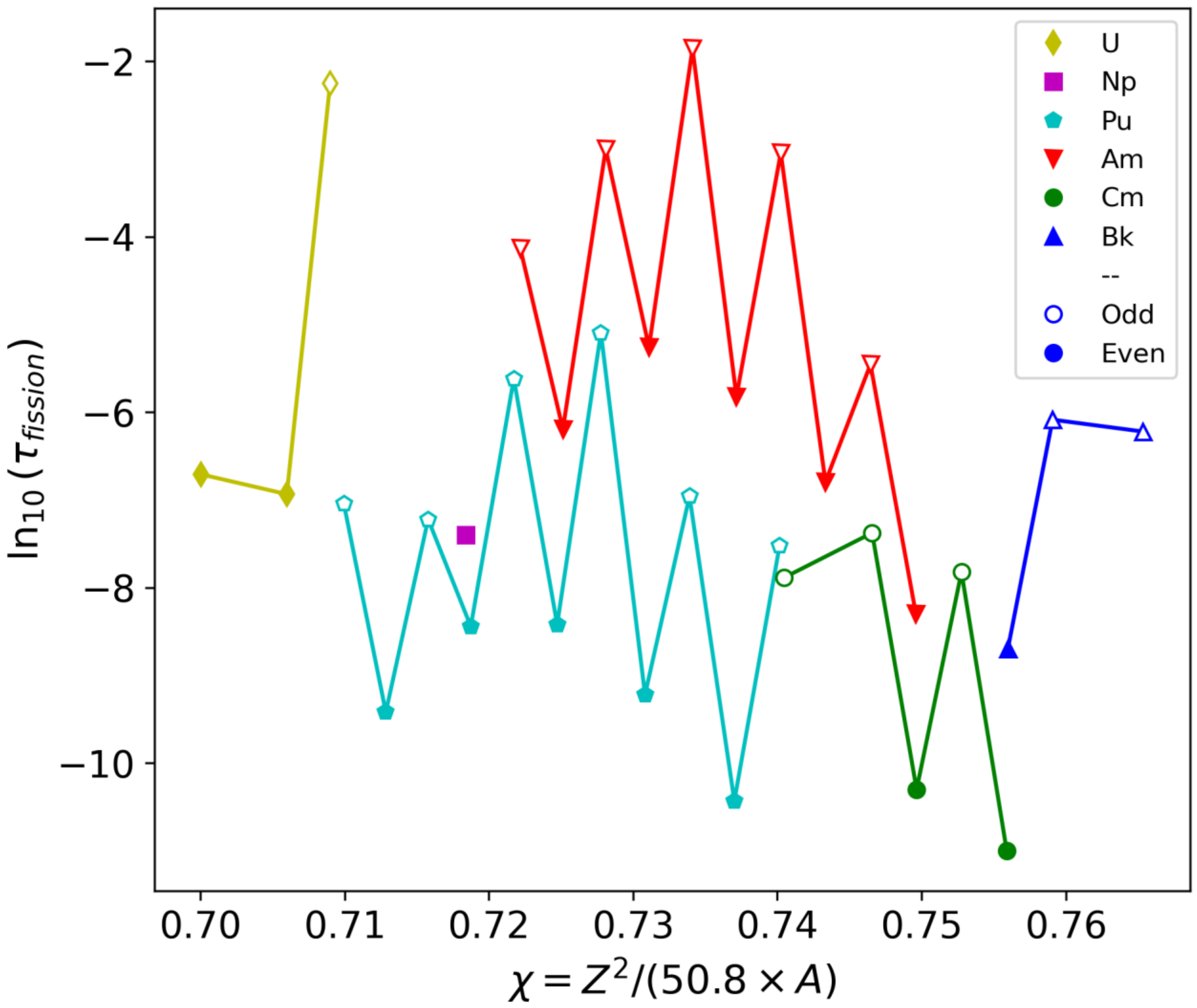
  Or ...

  - There is not back-decay ?

5. Discussion

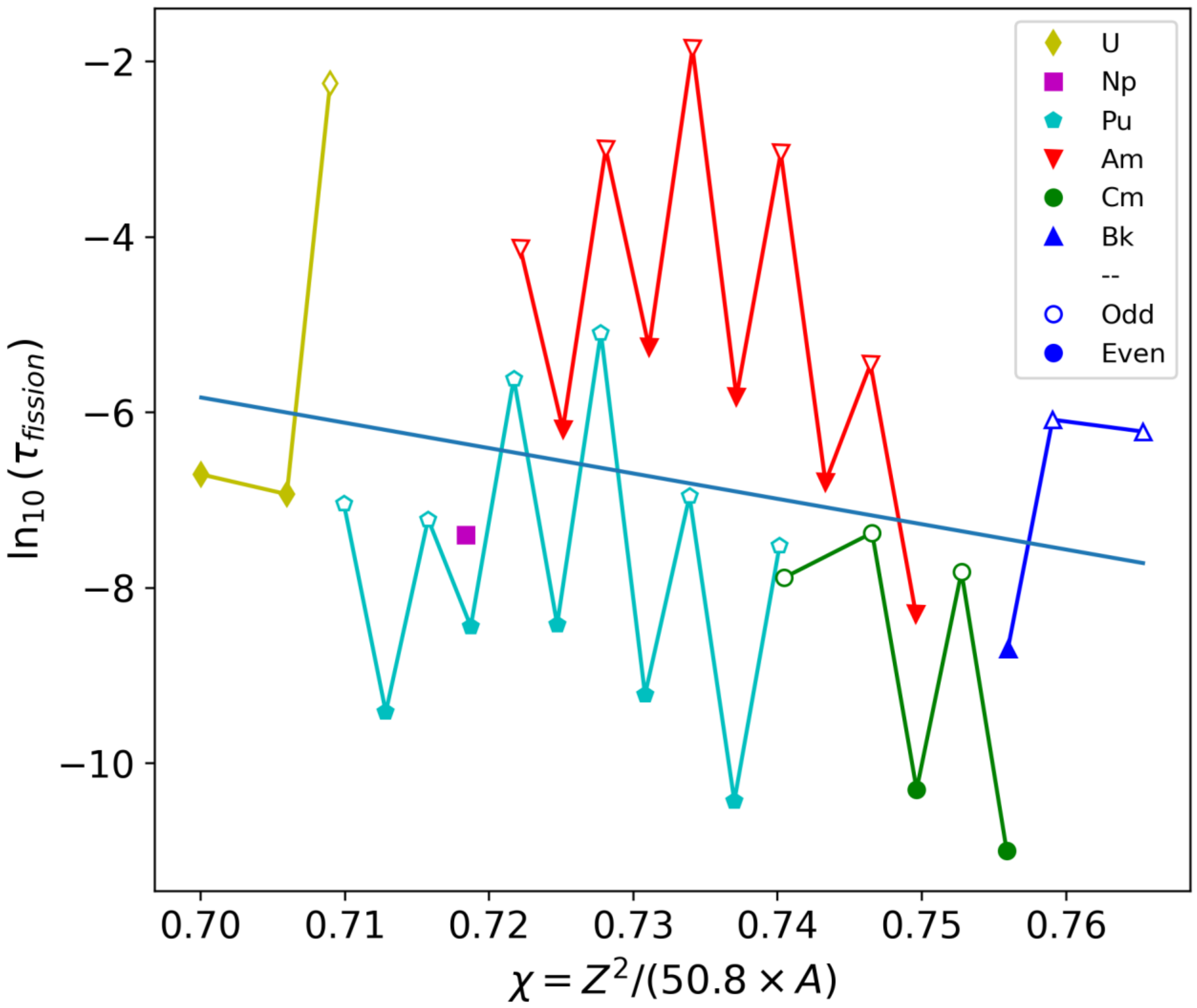
New empirical half-life parametrization

5. Discussion



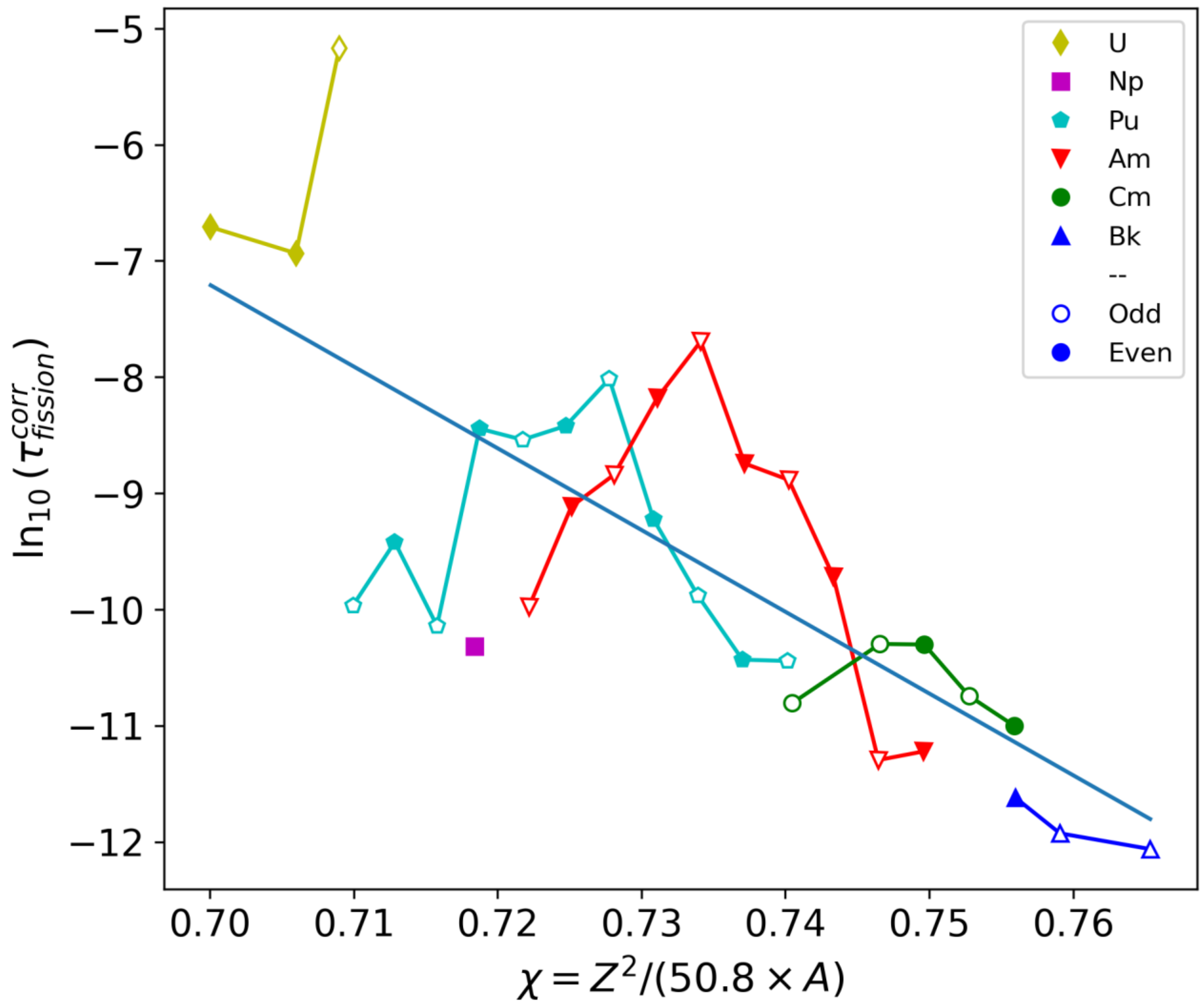
5. Discussion

$$log(\tau_{1/2}) = a\chi + b$$



5. Discussion

$$log\left(\tau_{1/2}^{corr\_N\delta}\right) = a\chi - n\delta + b$$



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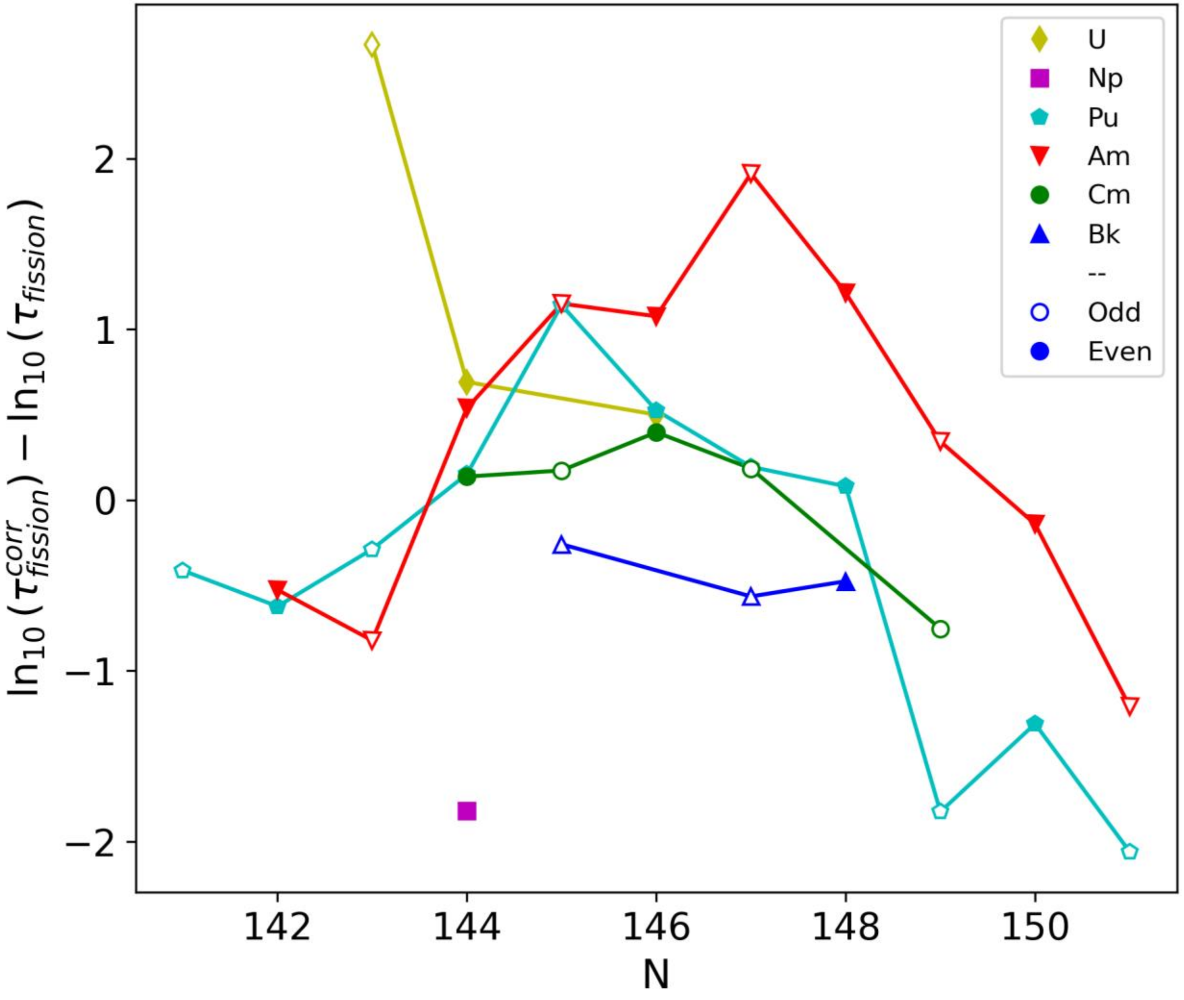
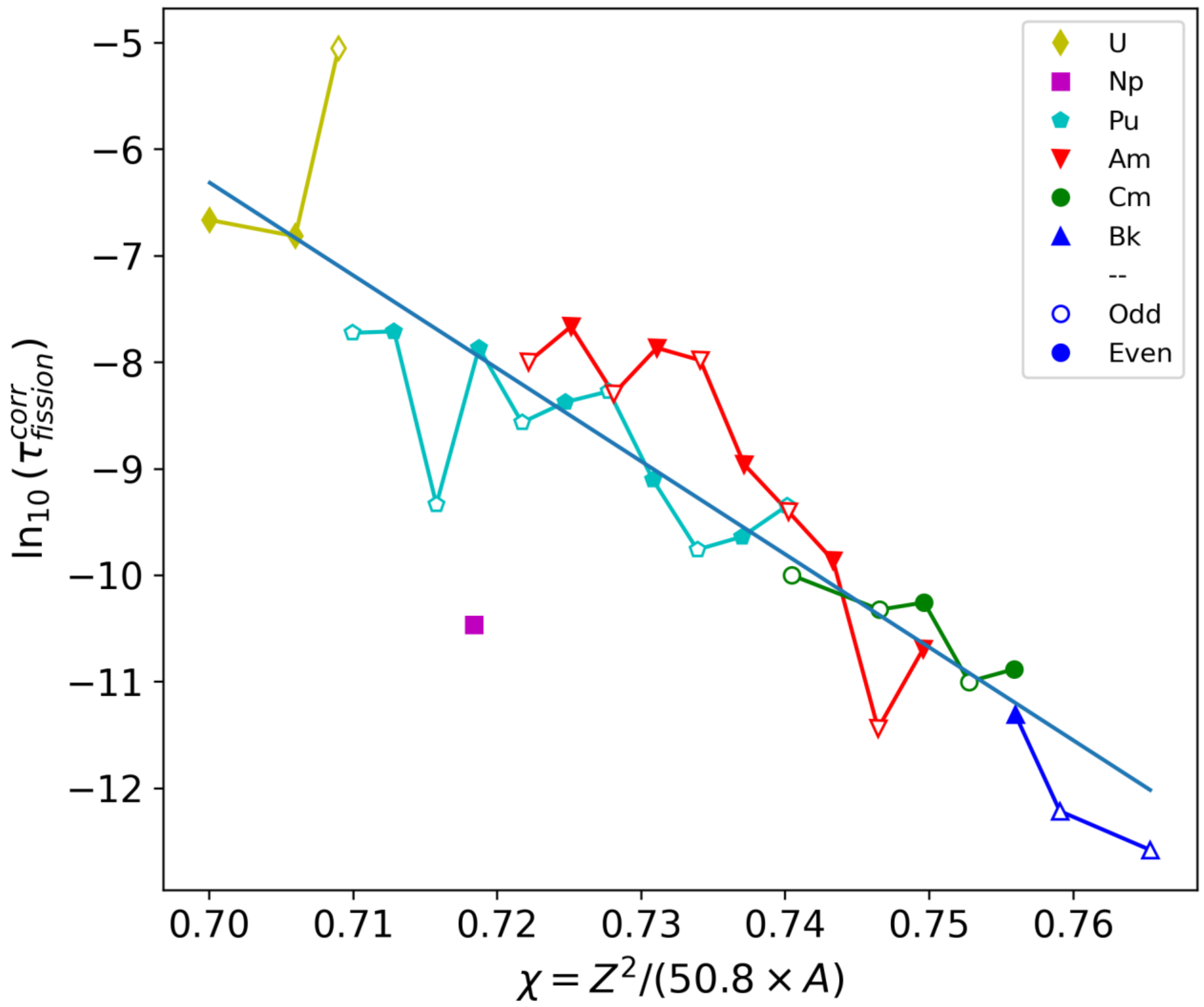


5. Discussion

$$log(\tau_{1/2}^{corr\_N\delta}) = a\chi - \beta_N(N - N_0)^2 - n\delta + b$$



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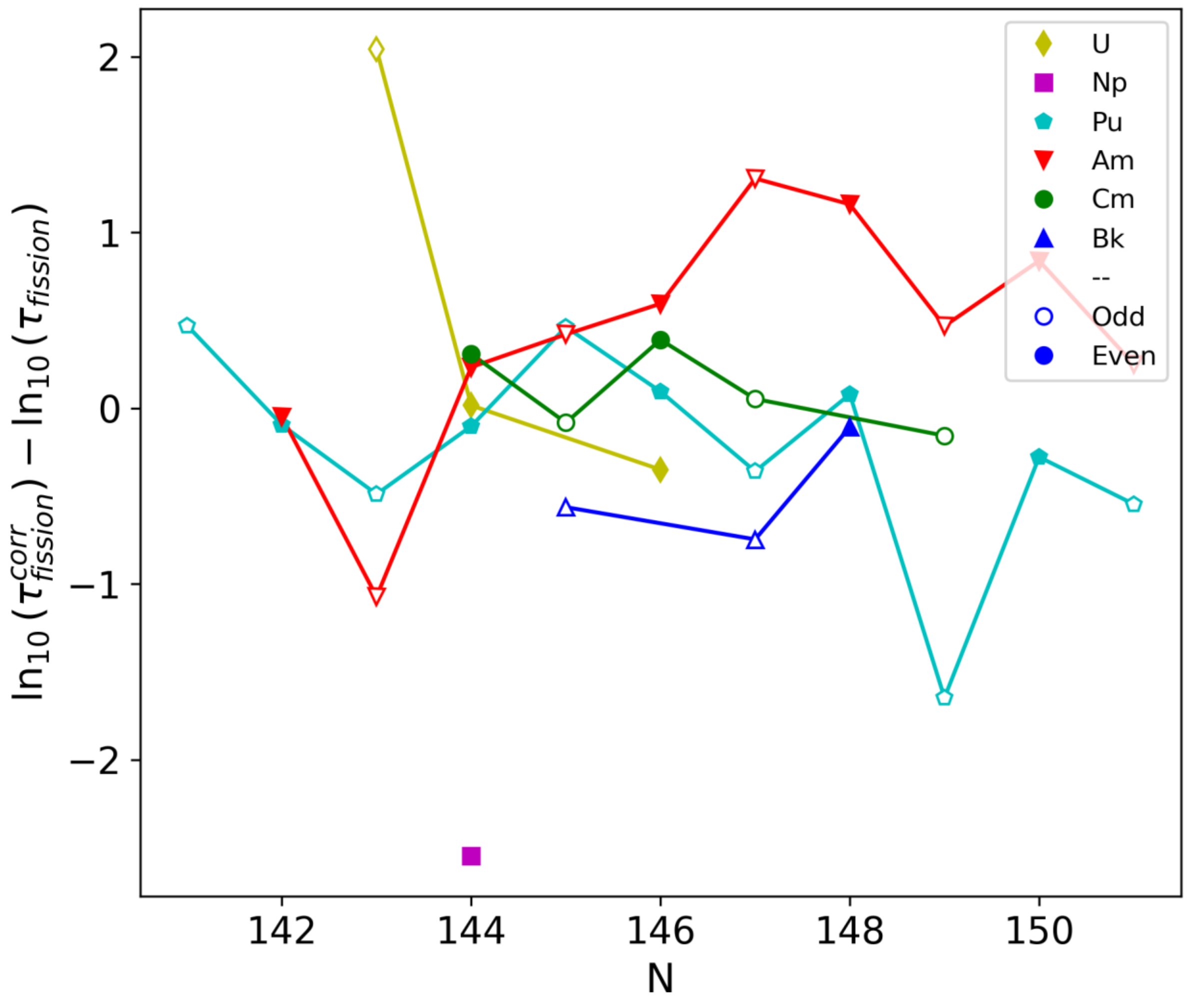

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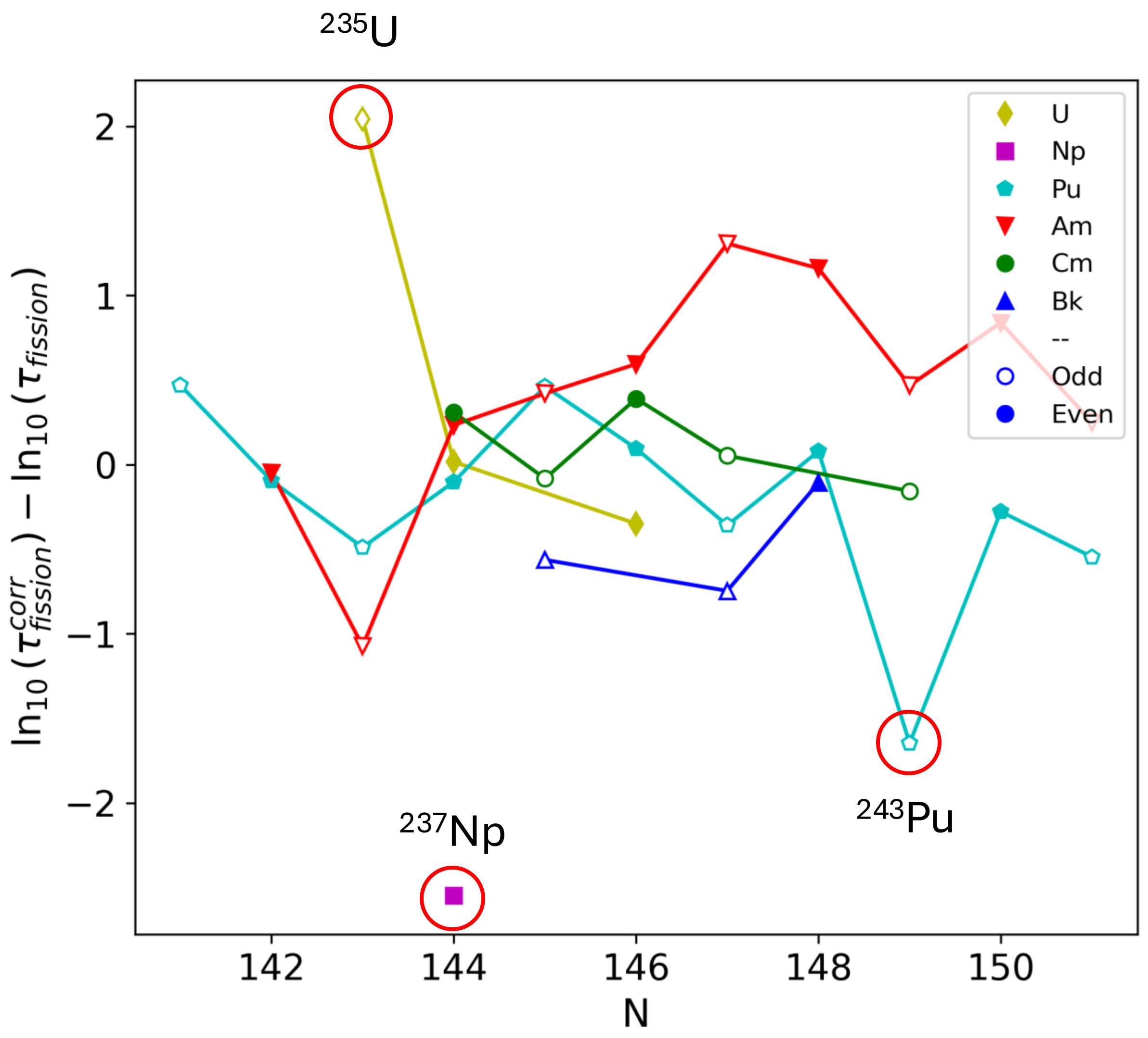


6. What's next ?

- With this data:

  - Current re-investigation after gain correction

  - Investigate the $^{232}Th(d,pxn)^{231,232,233}Th$ data (negative preliminary investigation…)

- A third experiment should be done on ^{236m}U with both fission detector and HPGe.

- ^{243}Pu and ^{237}Np : isomeric fission half-life discrepancy : back-decay candidates.
- Class II states spectroscopy (and K isomers)

Summary and outlook

- Crystal ball results questionned
- Gamma back-decay is still debated

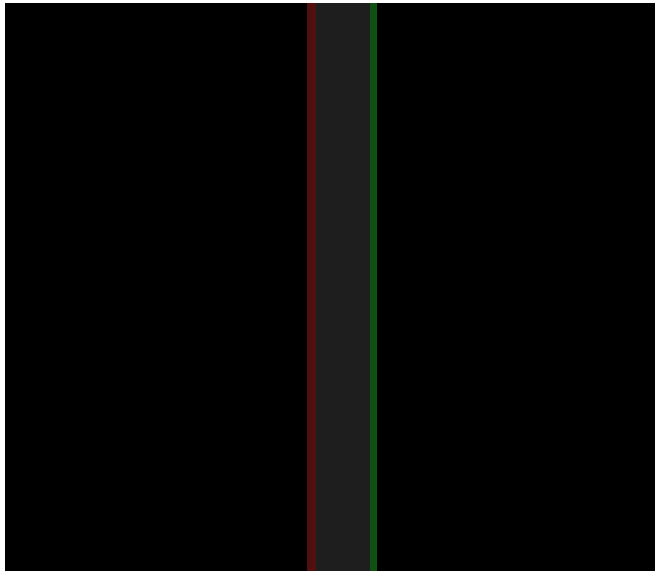
More generally :

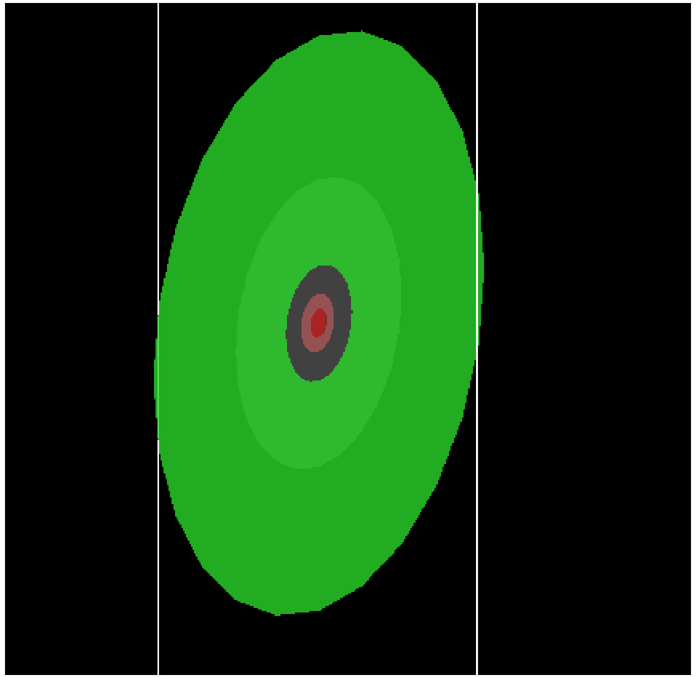
- ^{243}Pu and ^{237}Np : isomeric fission half-life discrepancy (back-decay candidates !)
- Class II spectroscopy largely unkown
- Class II K-isomerism still in question
- ^{232f}Th data still under investigation More precise experiments needed !

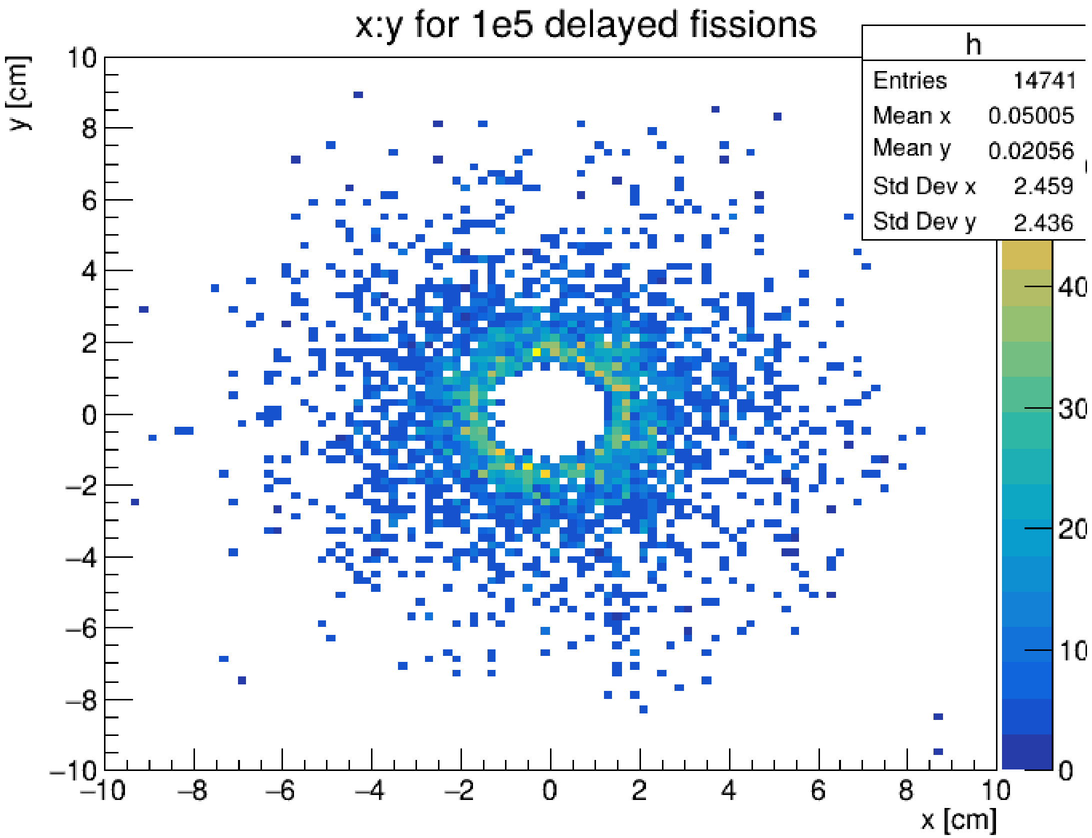
Backup

Recoil-shadow technique

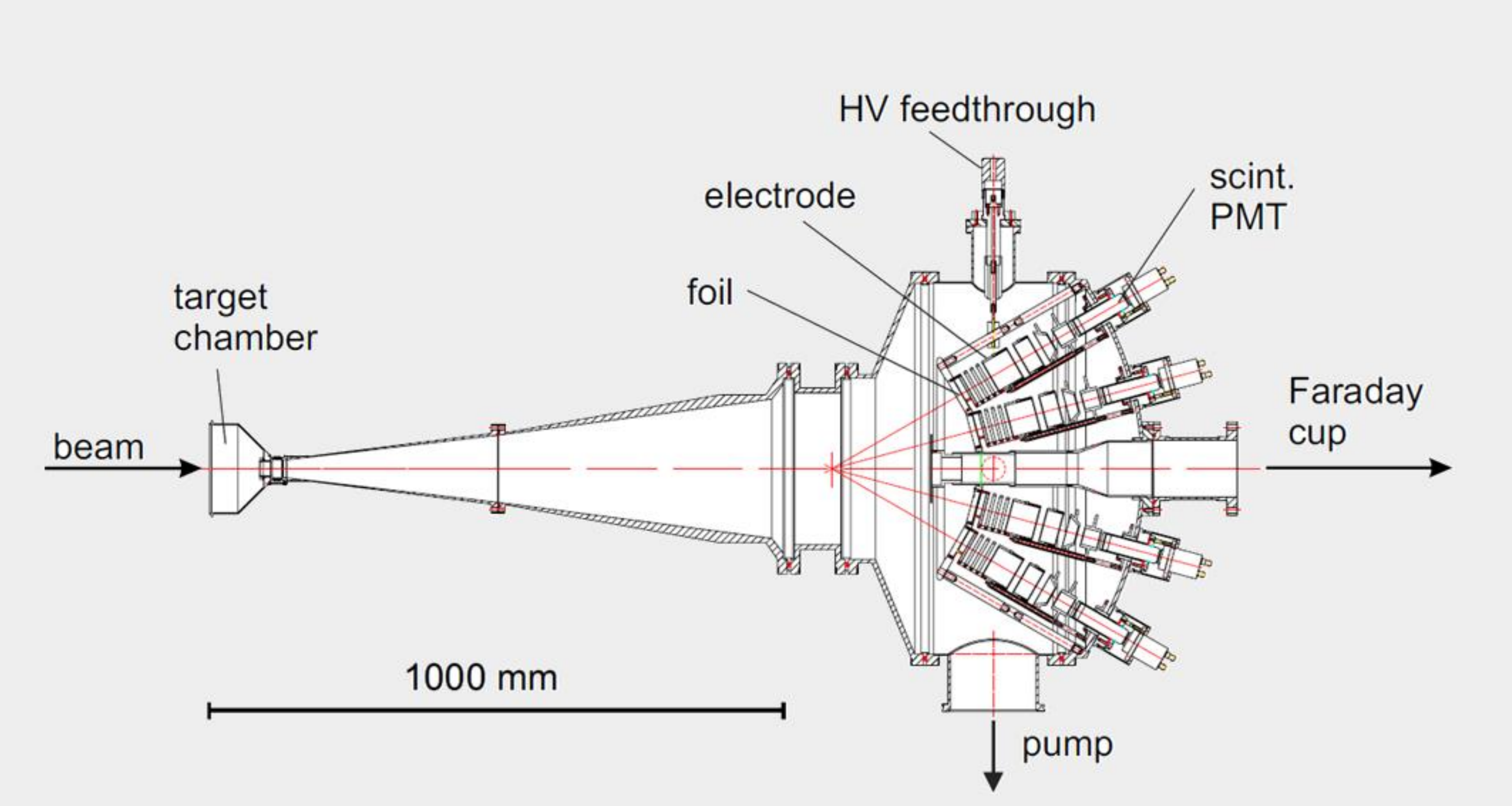
- Target
- Lead collimator
- Si detector





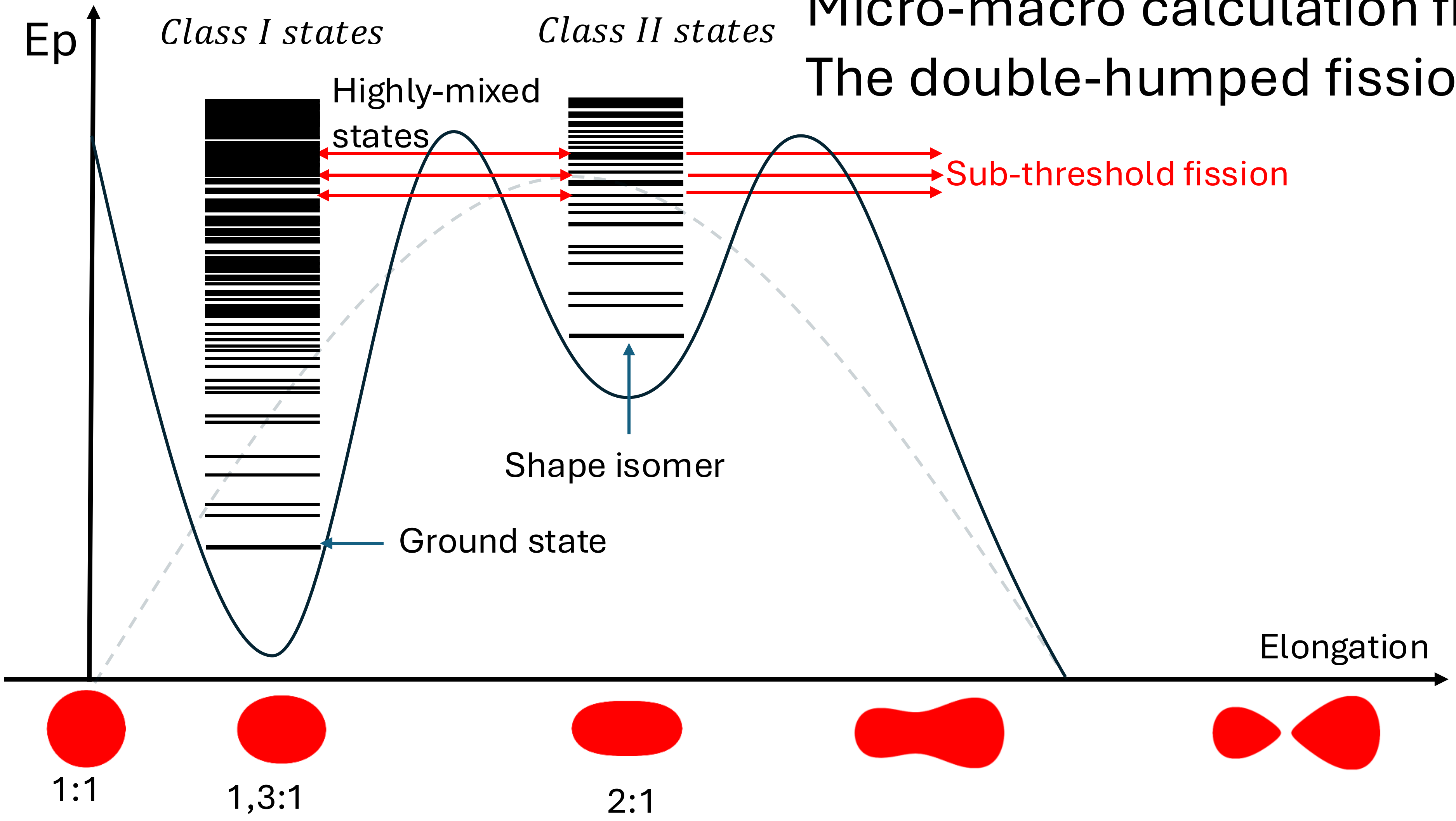


Recoil Filter Detector



1. The shape isomers in actinides

Micro-macro calculation from Strutinski :
The double-humped fission barrier



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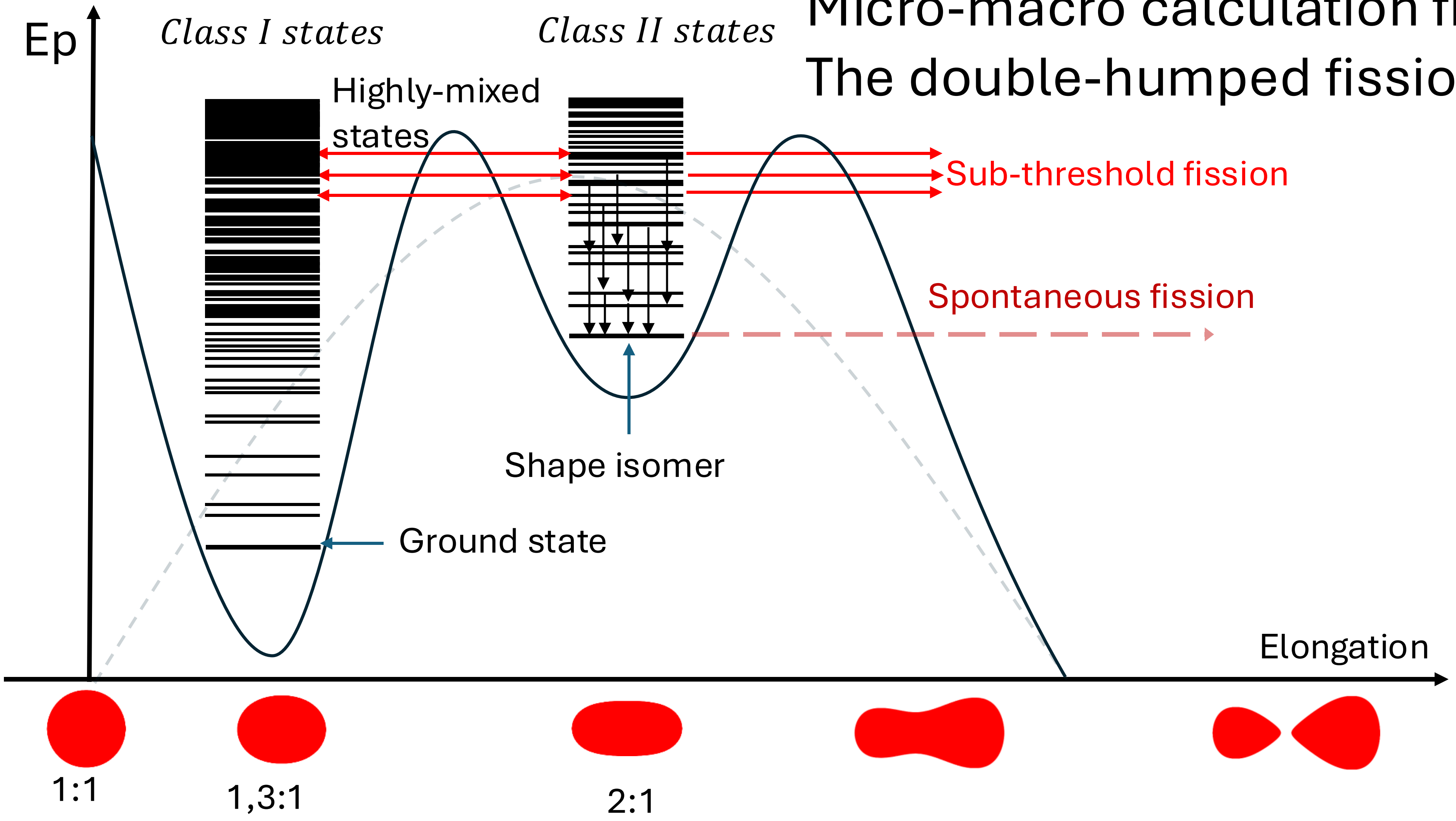
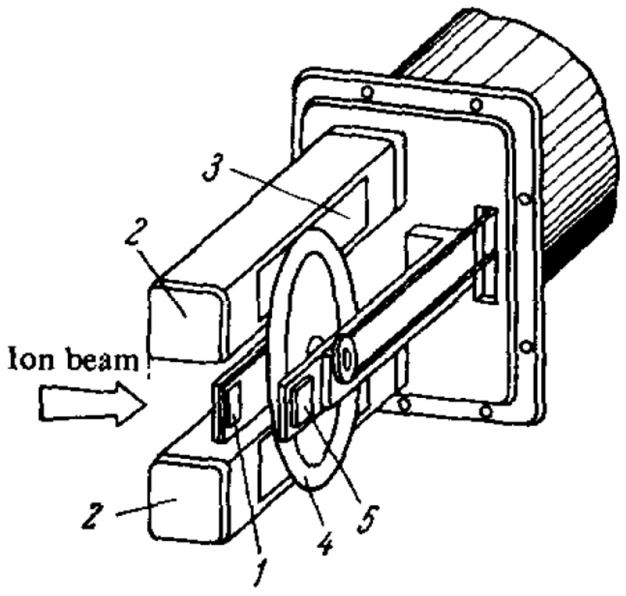


1. The shape isomers in actinides

- 1962, Dubna
- New fission detection setup
- Aim : super-heavy nuclei formation
- Preparatory experiment :

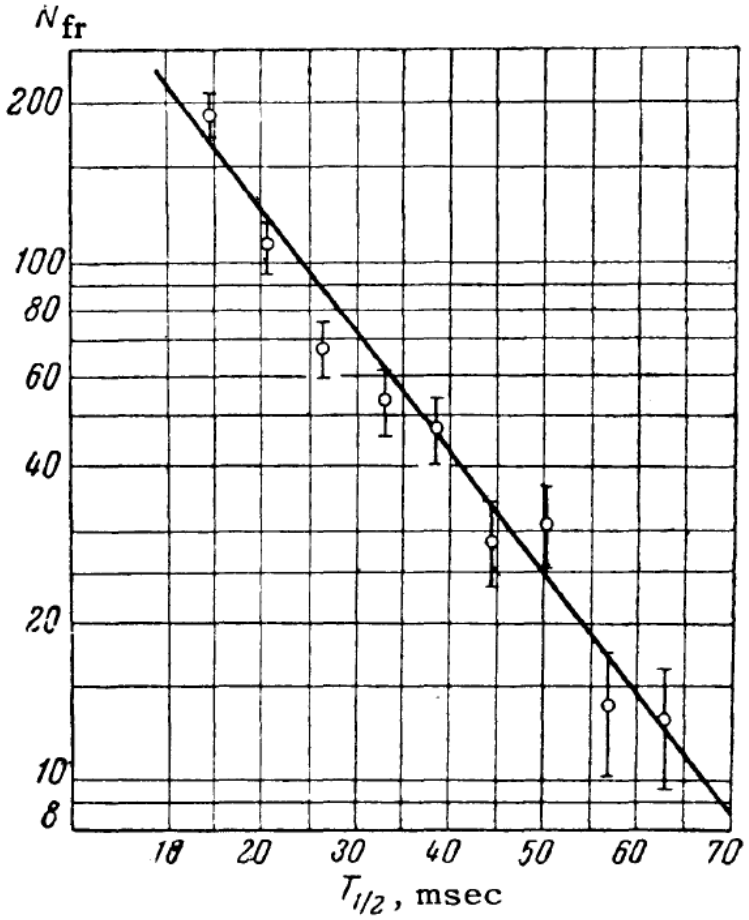
  $^{238}U + ^{16}O$
- Unexpected observation : delayed fission
- Confirmed by later measurements
- All the produced isotopes are known
  - Must be some spontaneously fissioning isomeric state !



Experimental setup

S. Polikanov *et al.* Sov.Phys.JETP **15** (1962)

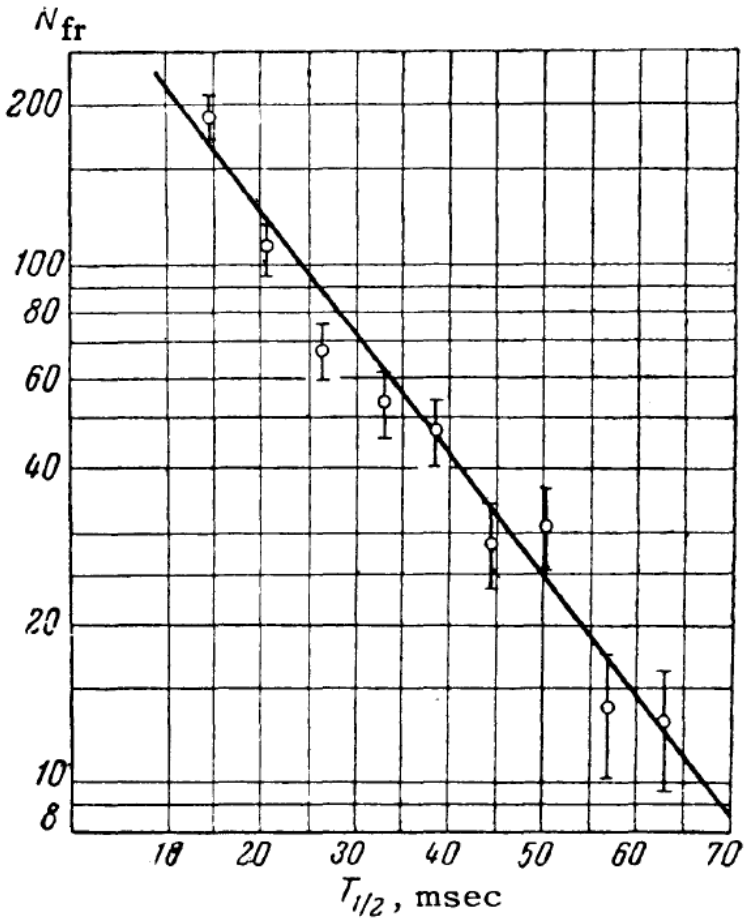
Delayed fission
Short half-life



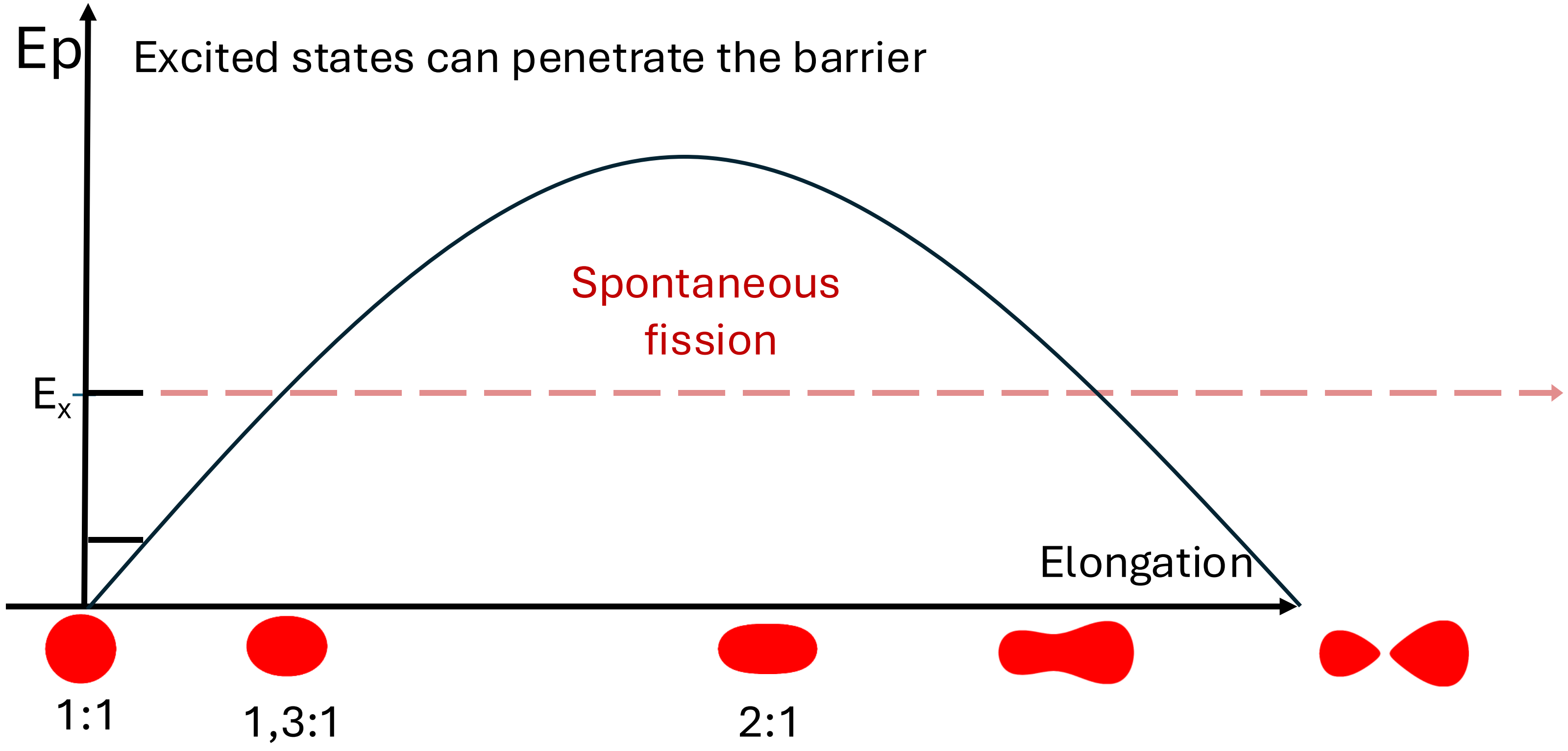
S. Polikanov *et al.* Sov.Phys.JETP **15** (1962)

1. The shape isomers in actinides

How to explain this half-life of 14 ms ?



Polikanov1964



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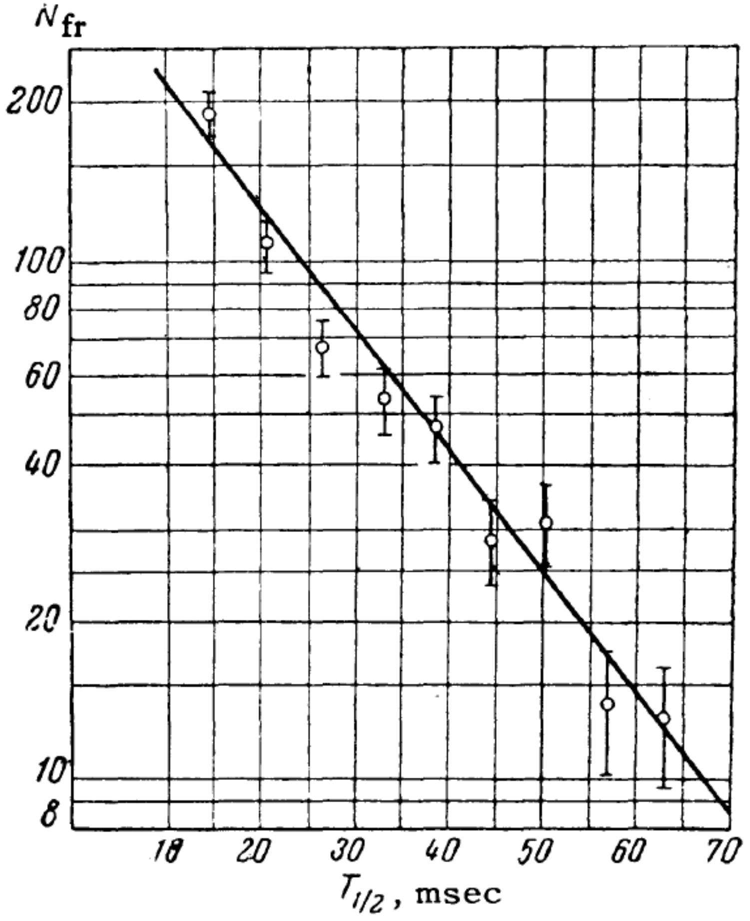
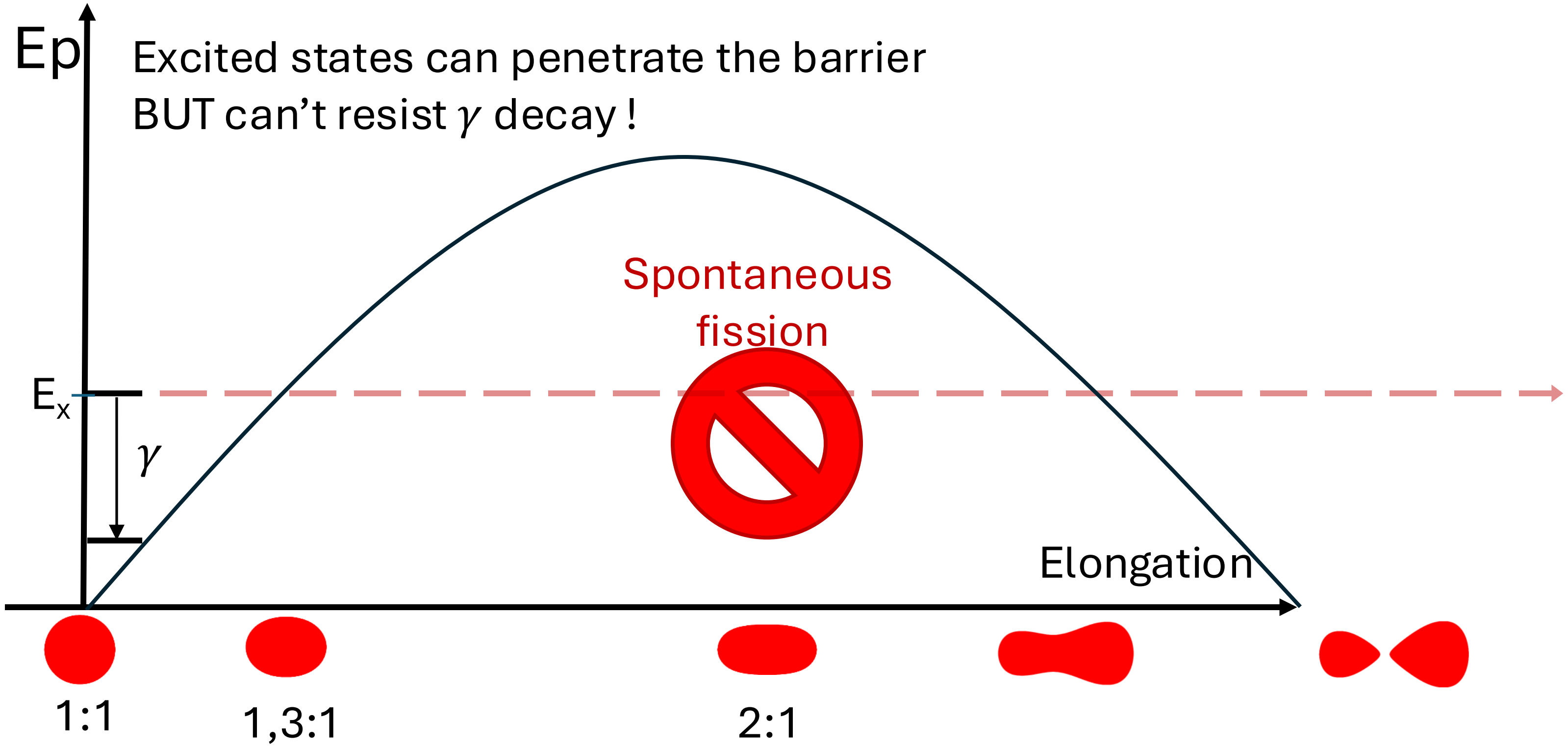


Polikanov1964



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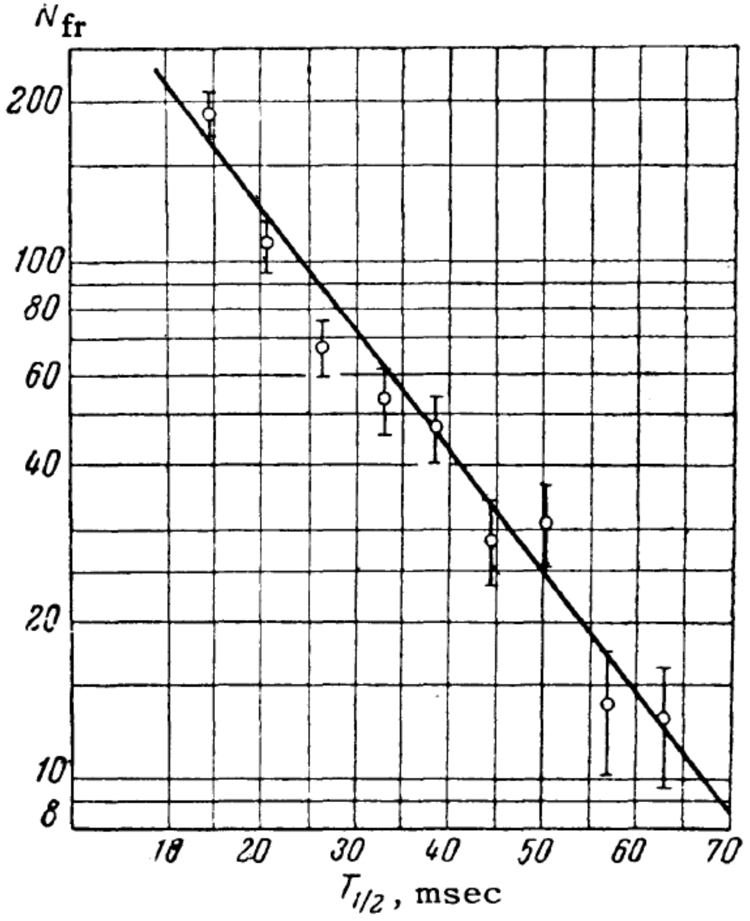
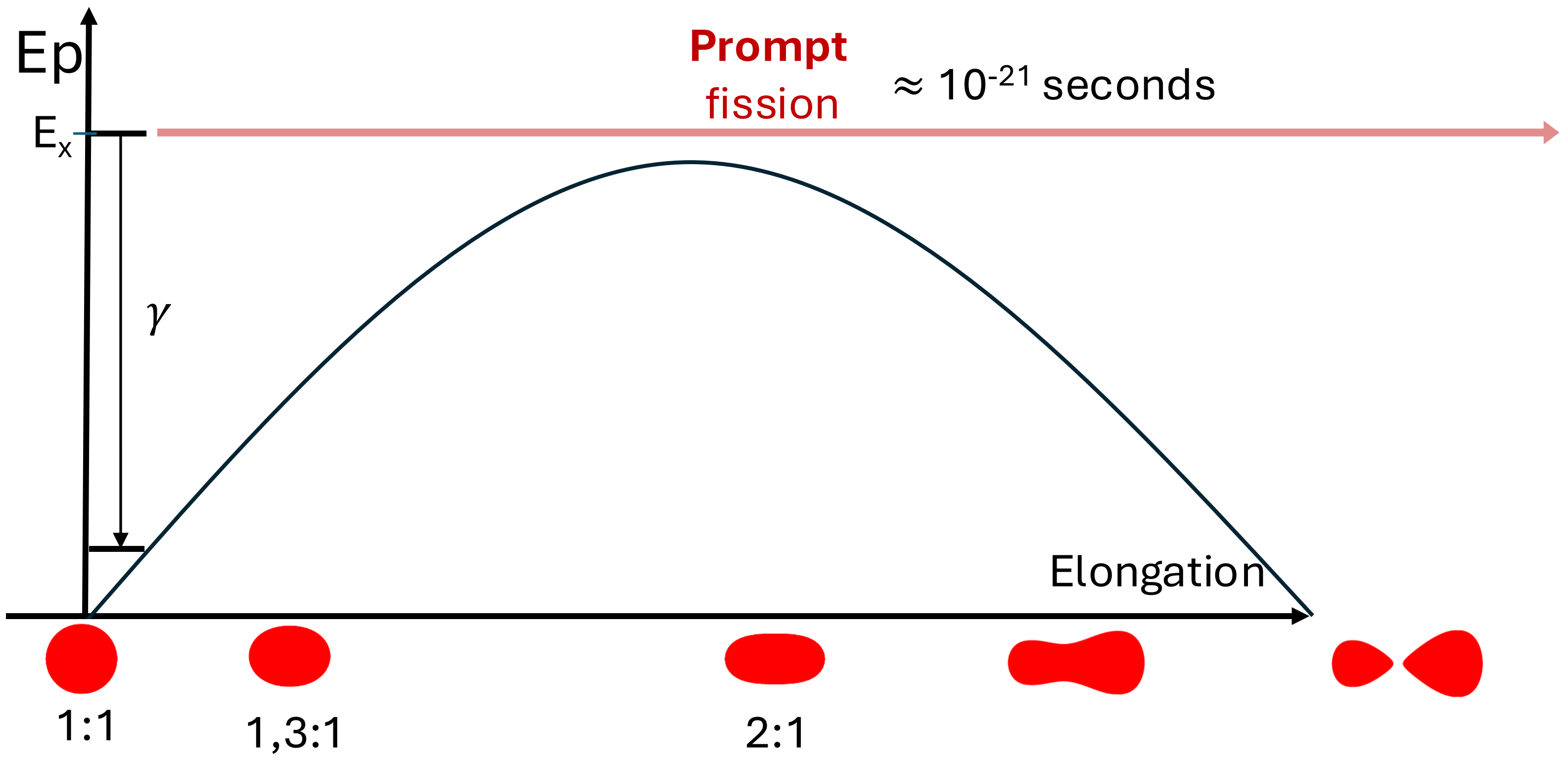
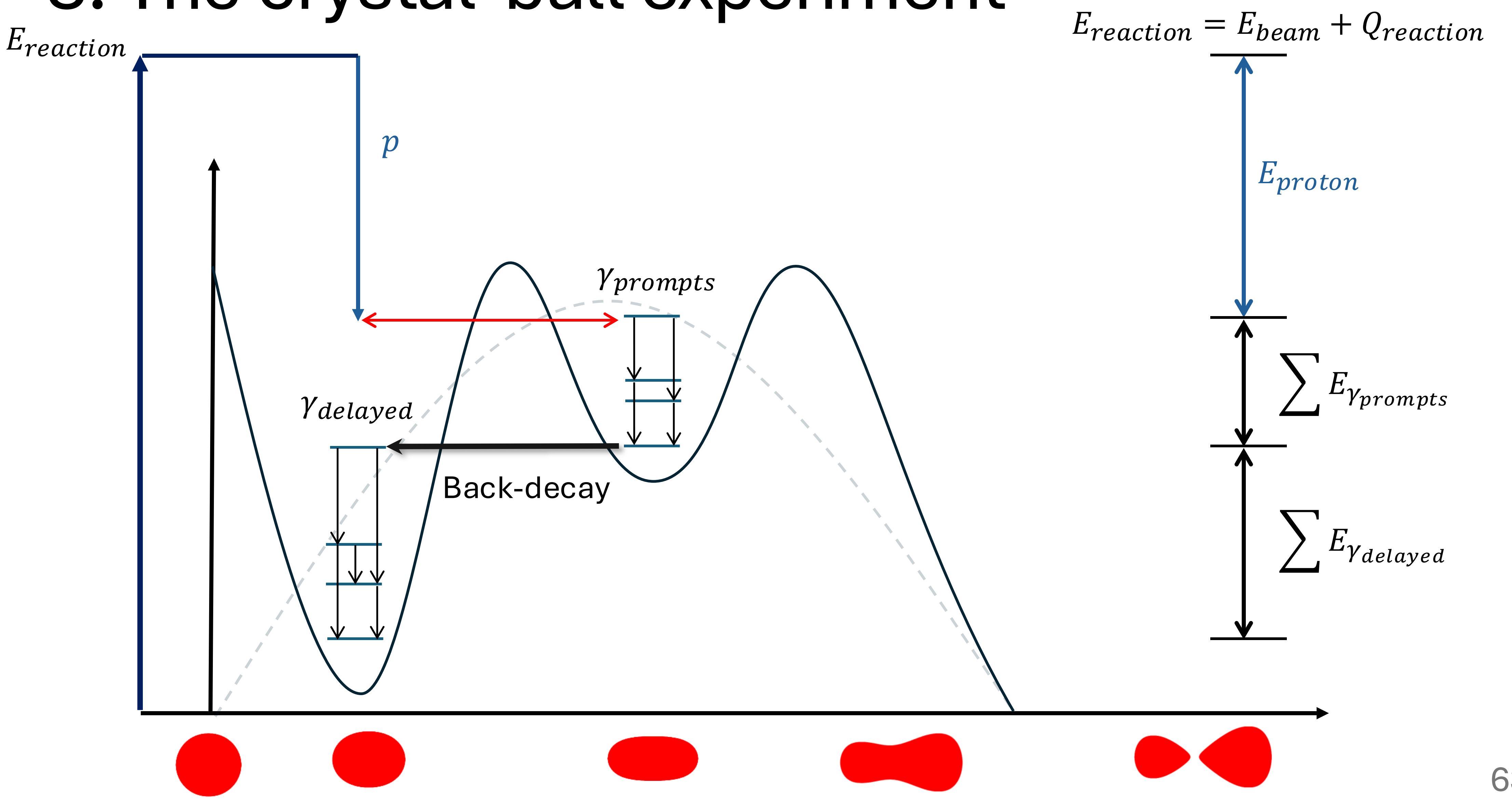


Polikanov1964

Excited stated above barrier can't resist prompt fission or γ decay



3. The crystal-ball experiment



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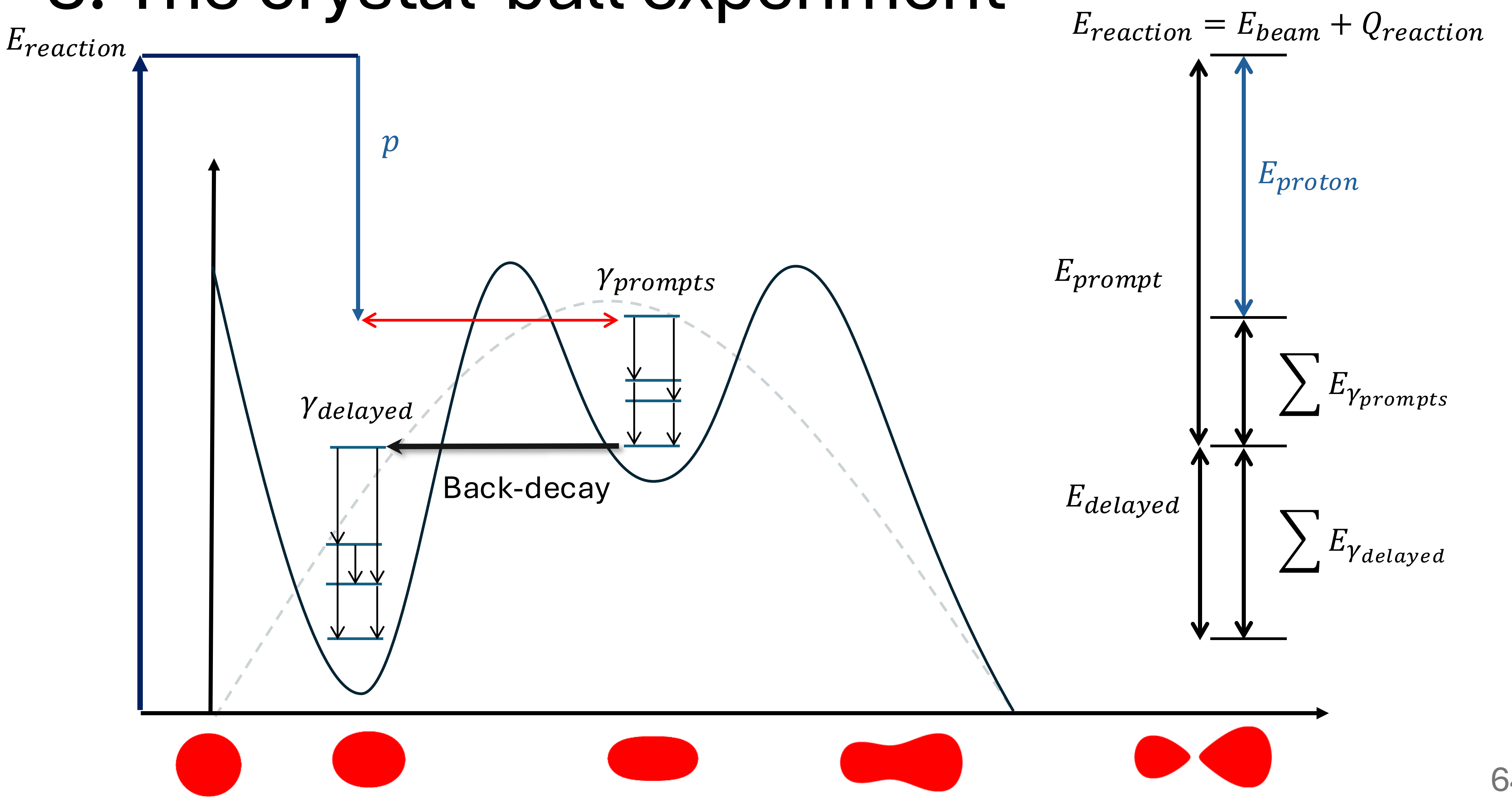

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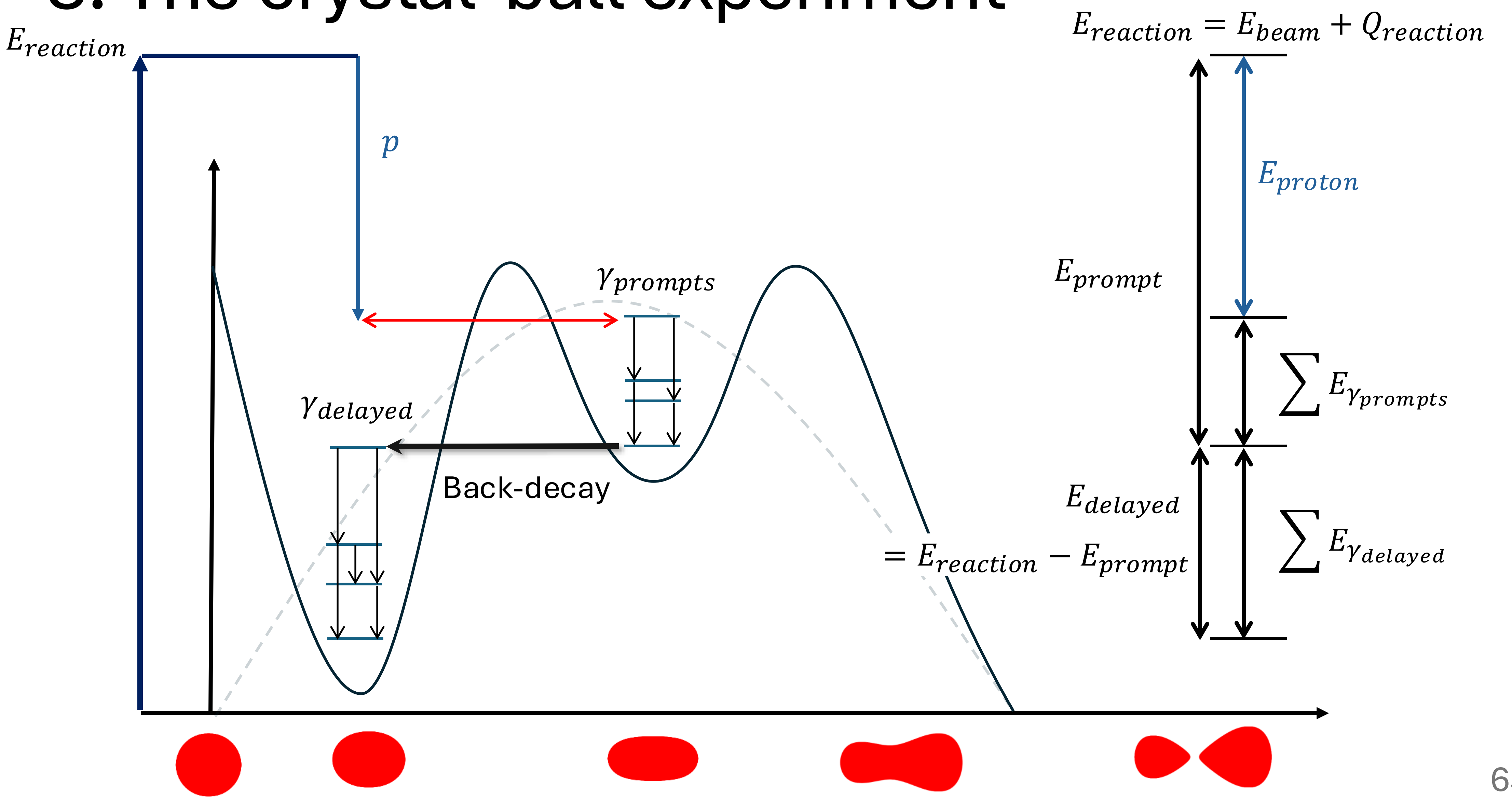

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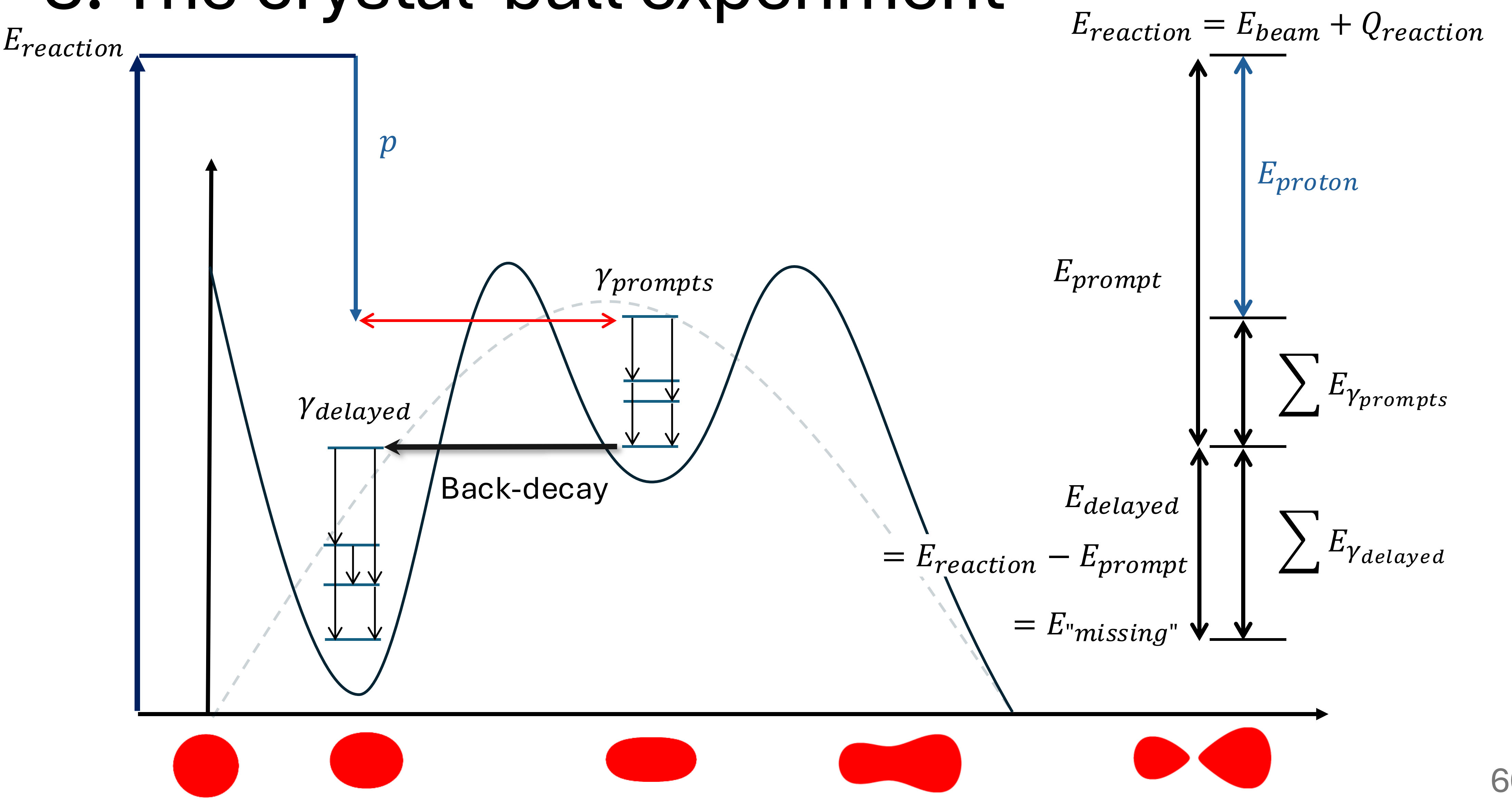
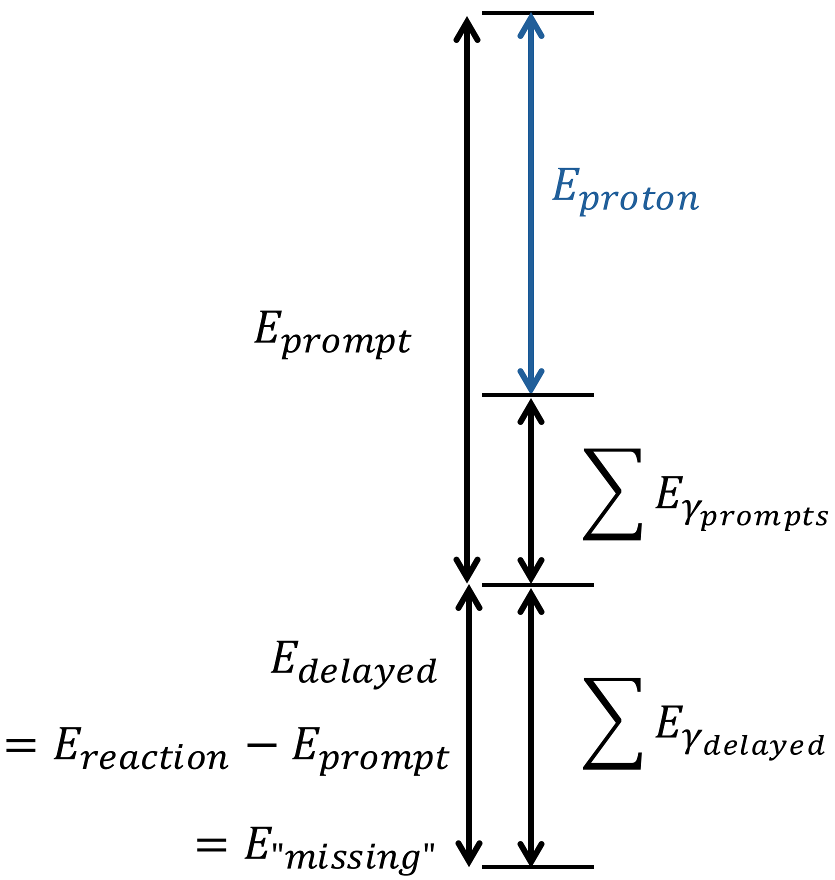
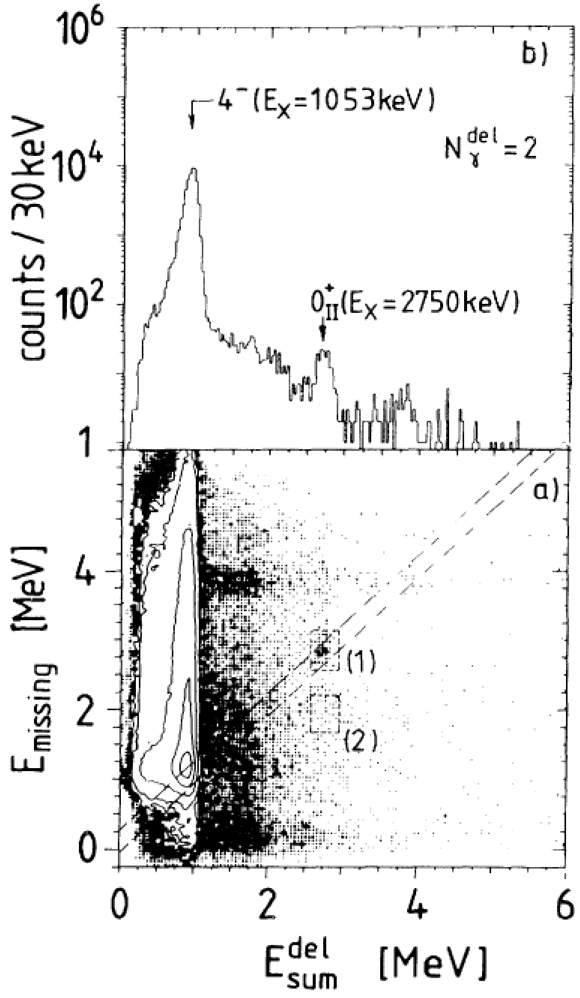


3. The crystal-ball experiment

$$E_{reaction} = E_{beam} + Q_{reaction}$$





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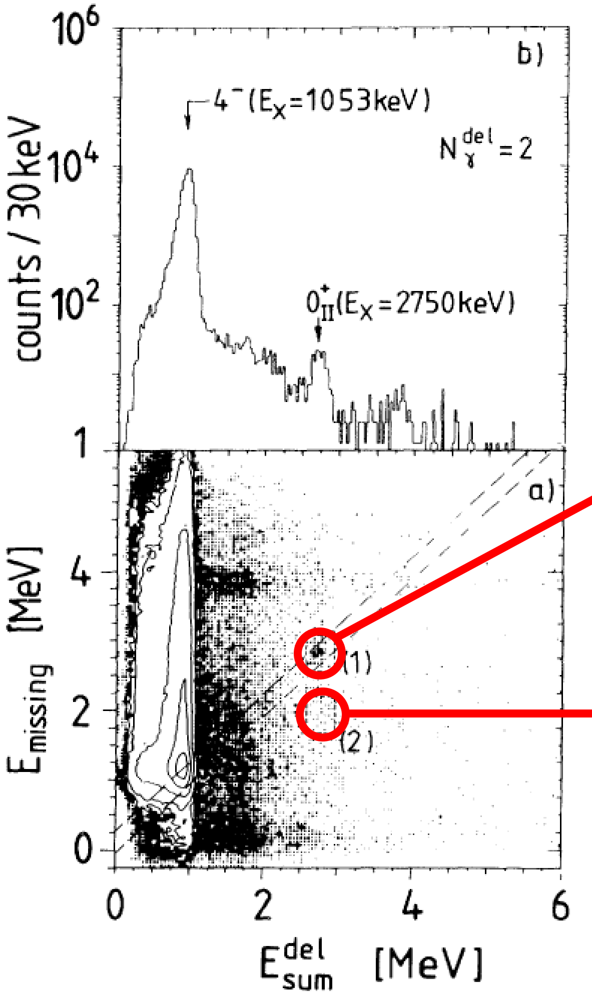
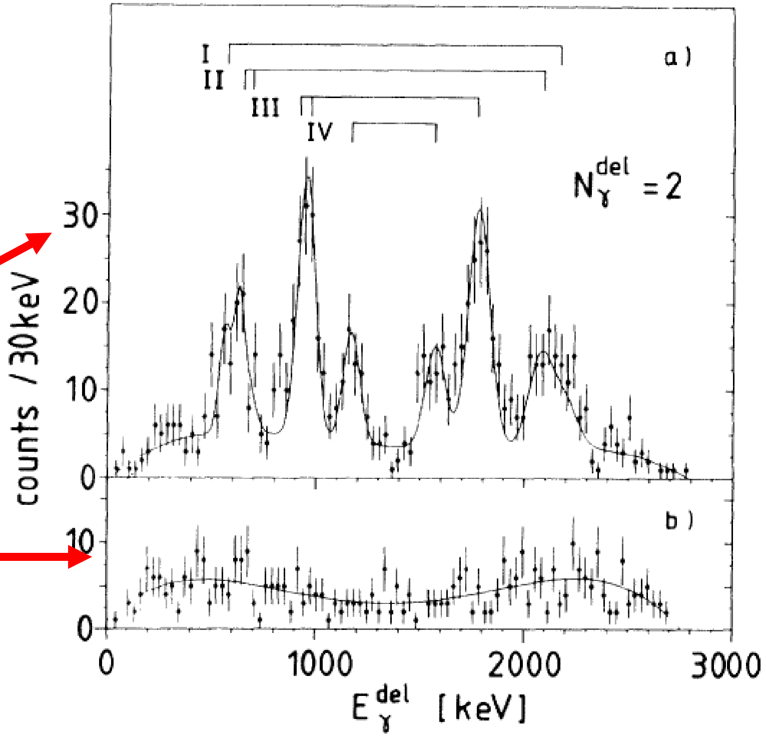
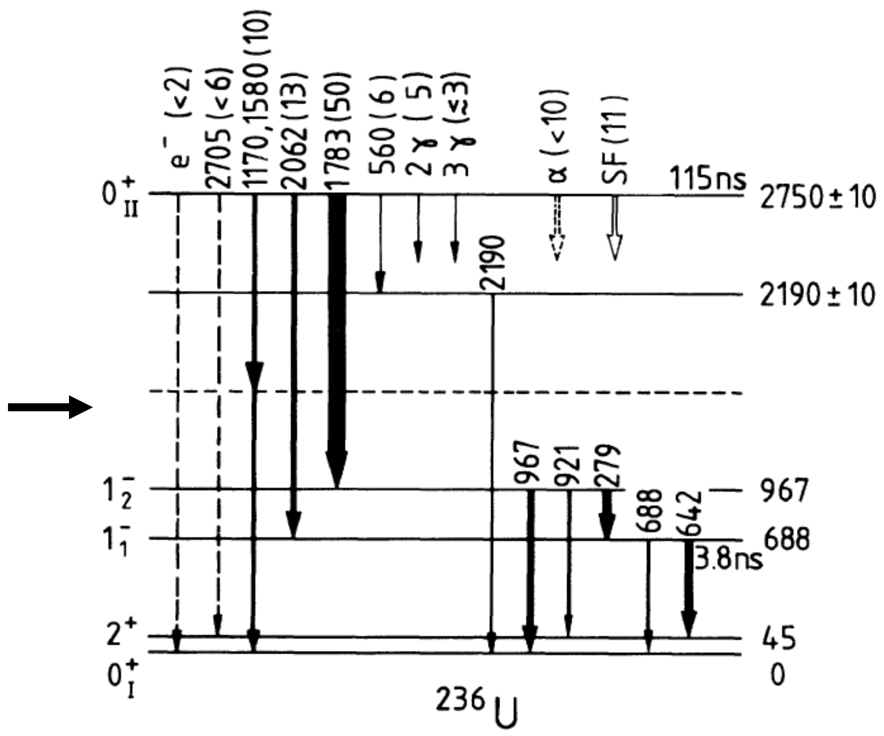


Conditions :

- $E_{missing} = \sum E^{delayed} \approx 2,75\ MeV$
- $N^{\gamma} = 2$

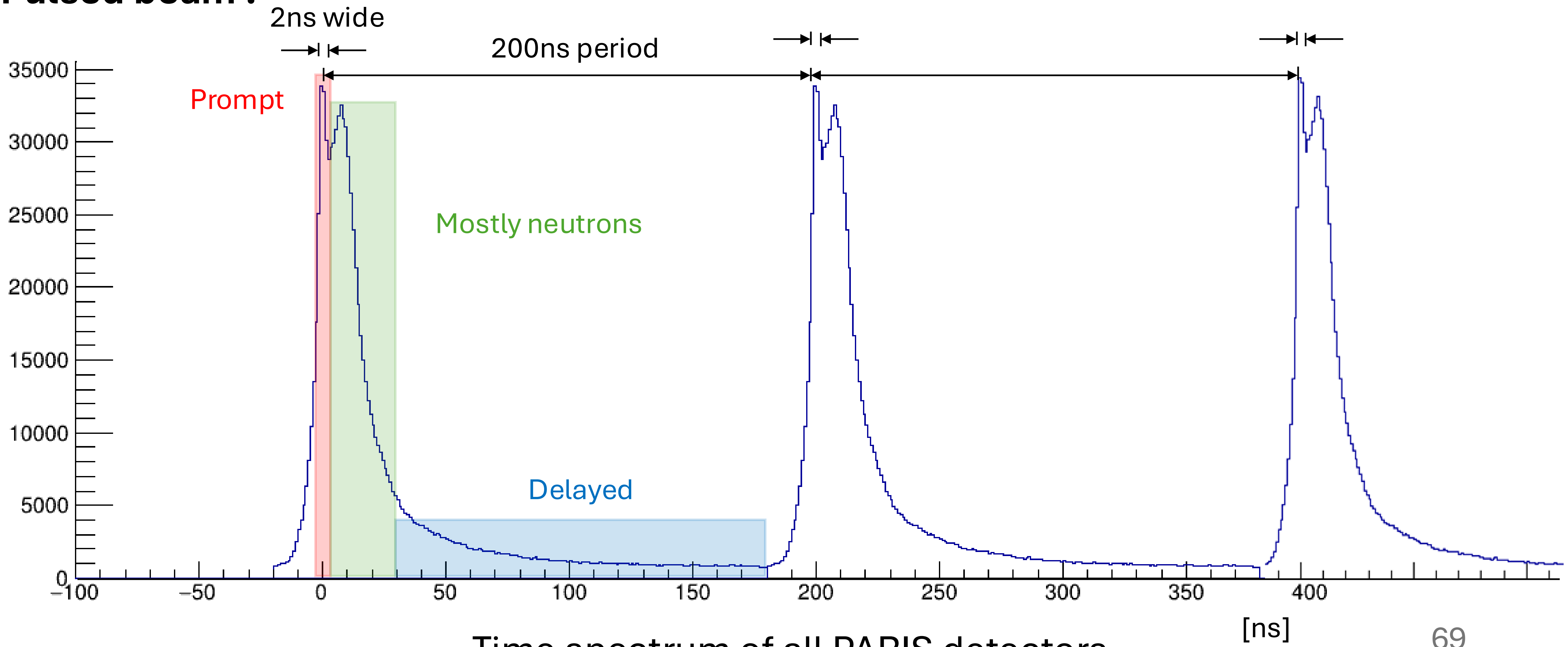




J. Schirmer, J. Gerl, D. Habs, and D. Schwalm (1989)

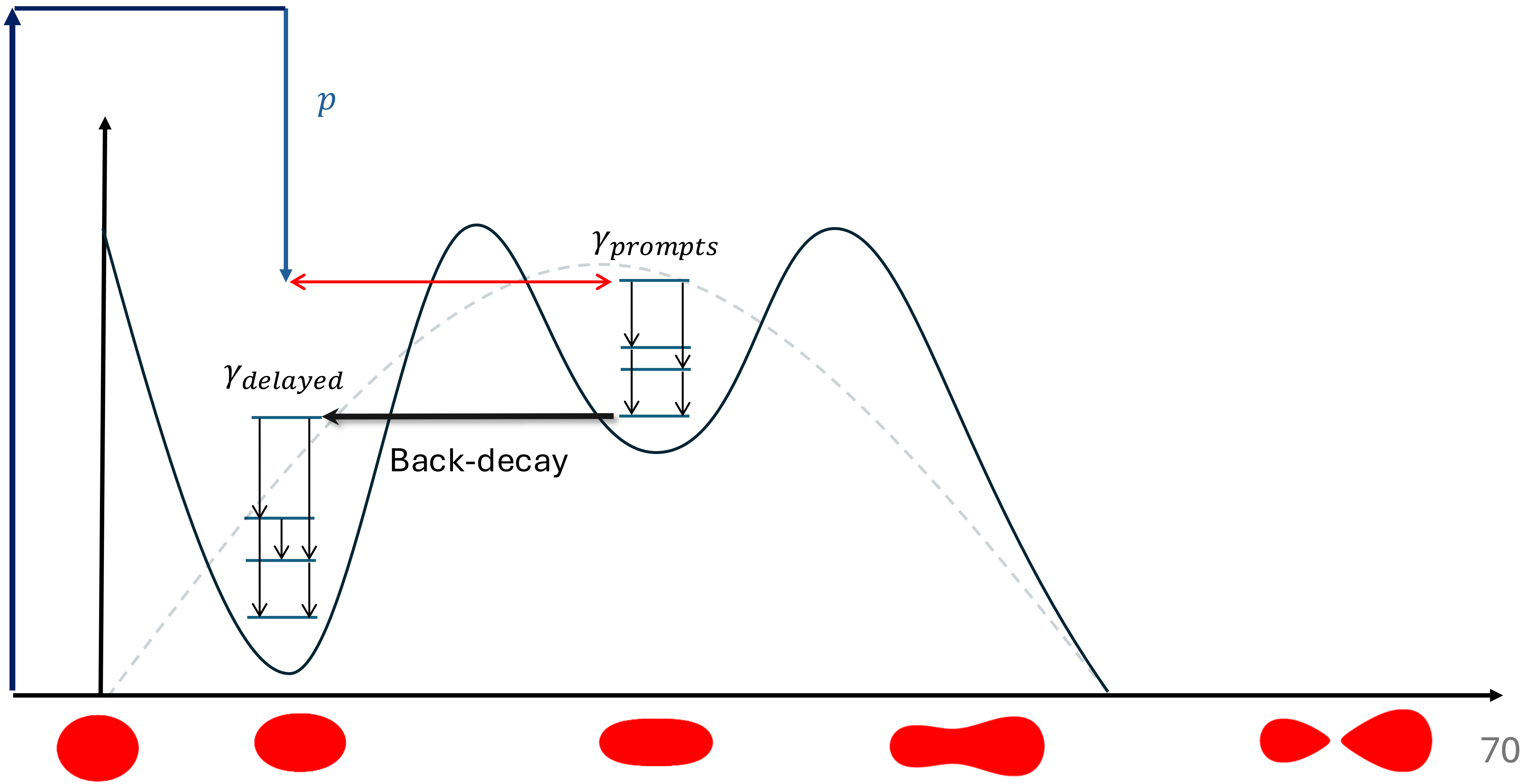
3. Experimental setup

Pulsed beam :



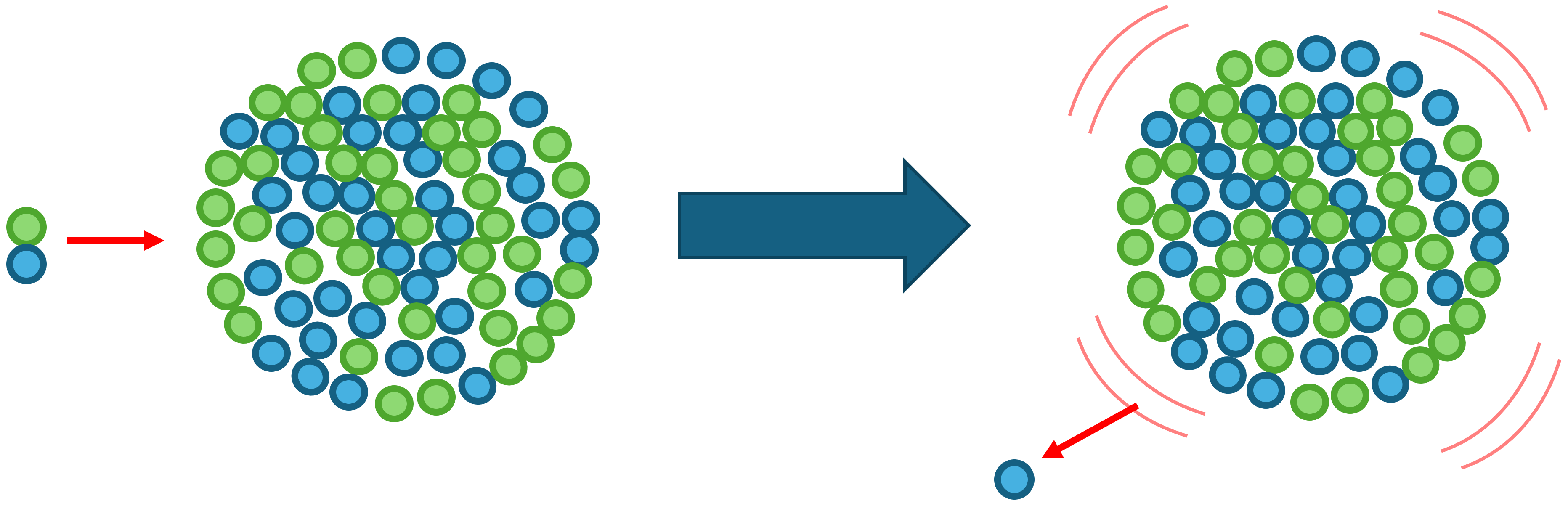
Time spectrum of all PARIS detectors

4. Results

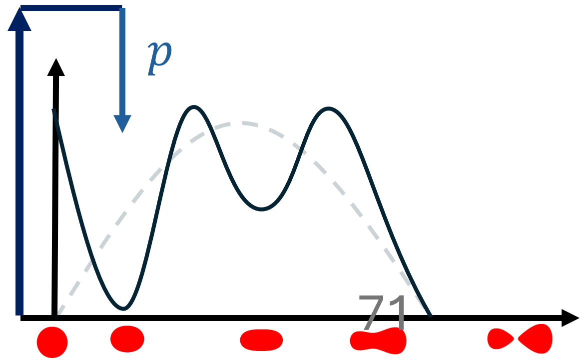


3. Experimental setup

Deuteron beam at 11 MeV



d + ^{235}U → p + $^{236*}U$



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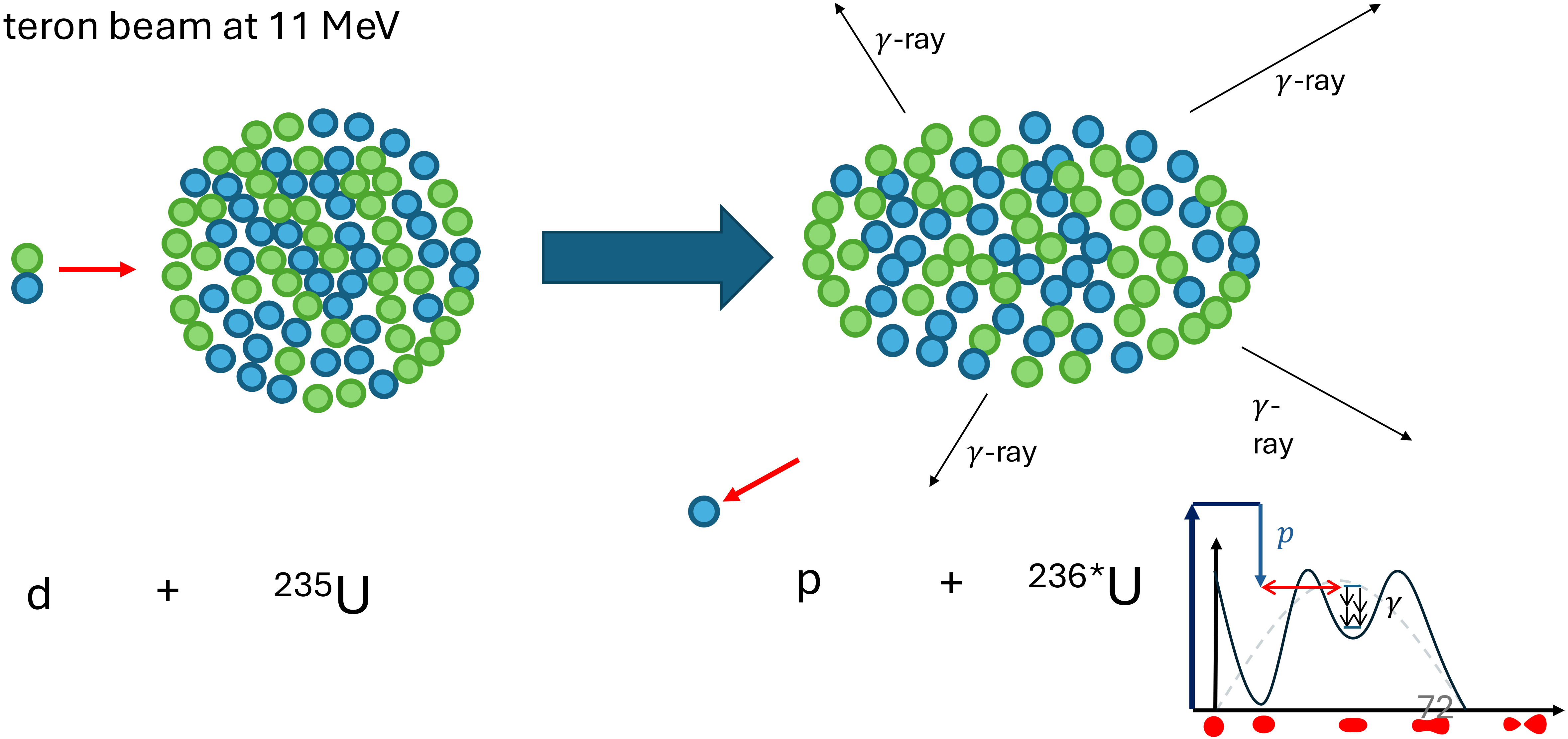

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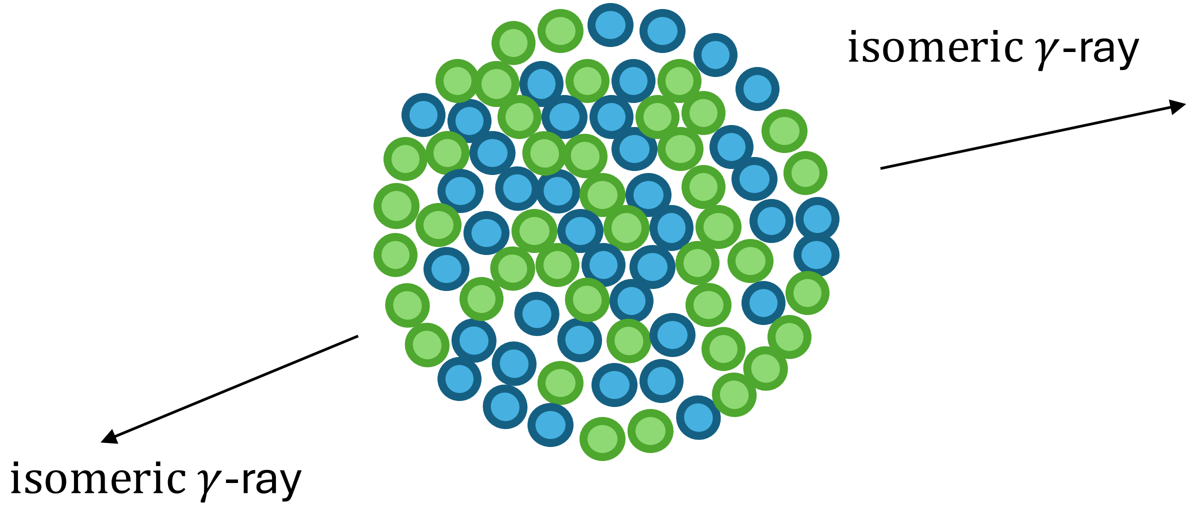
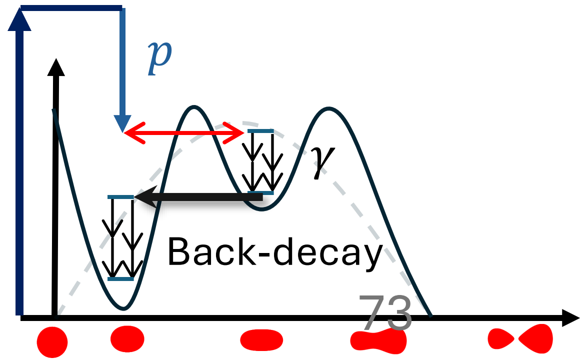
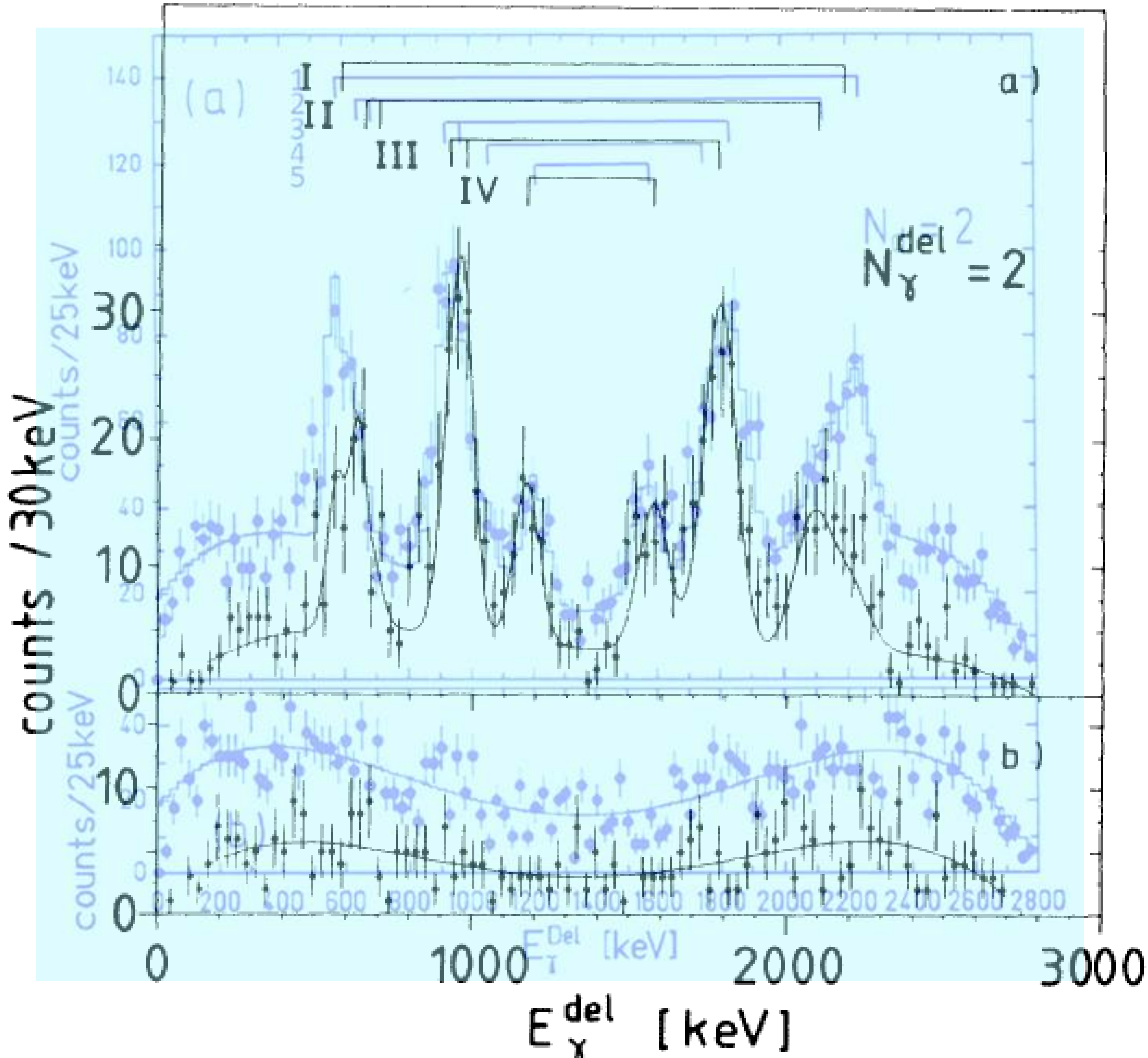
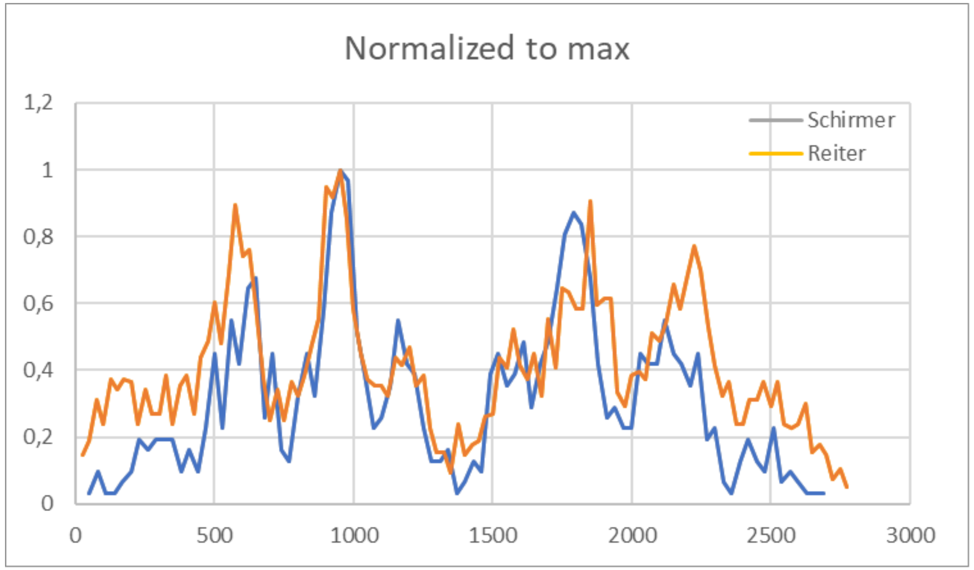
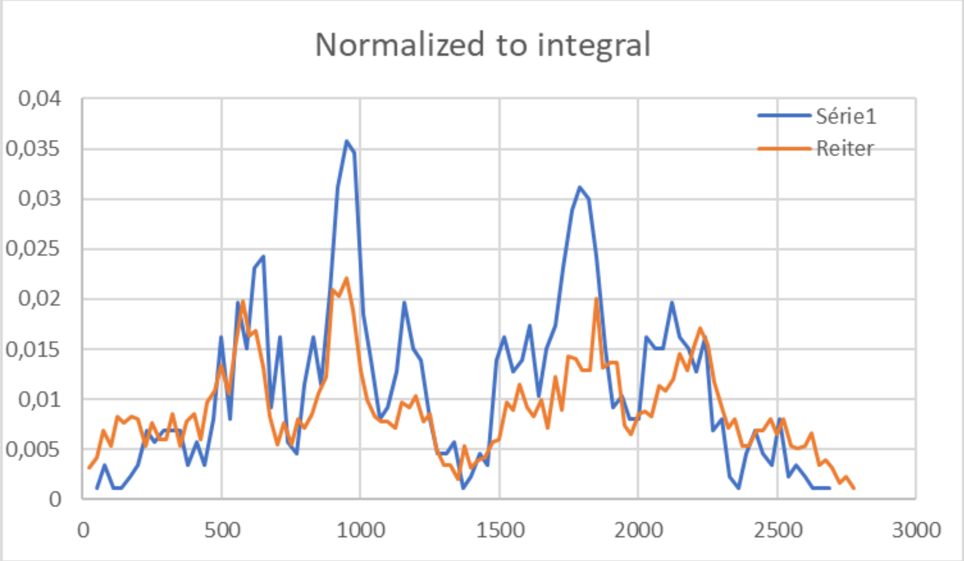
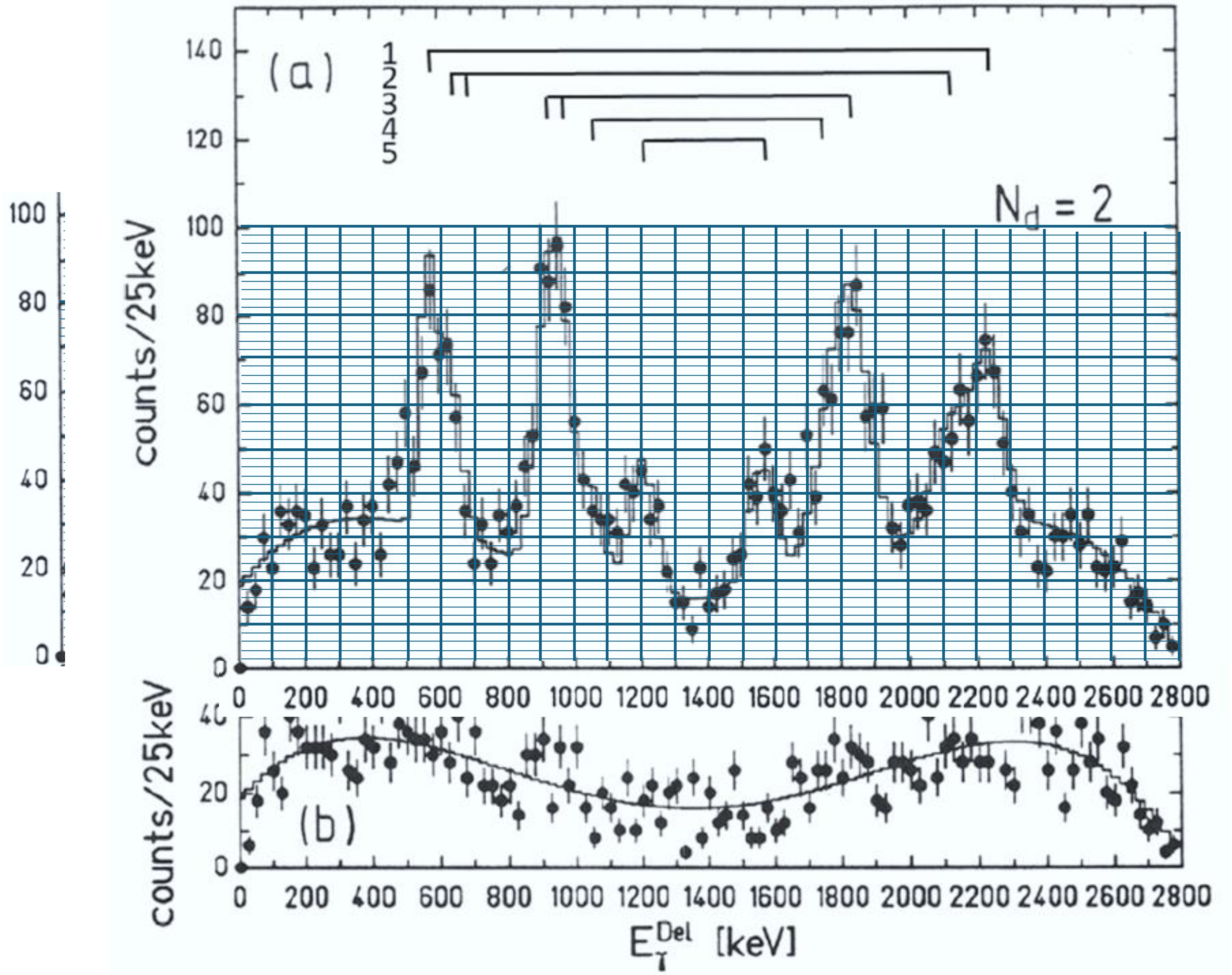





I
II
III
IV
a)
(a)
$N_\gamma^{del} = 2$
counts / 30keV
counts/25keV
b)
0
1000
2000
3000
E_γ^{del} [keV]
E_γ^{Del} [keV]


Normalized to max
Schirmer
Reiter
1,2
1
0,8
0,6
0,4
0,2
0
0
500
1000
1500
2000
2500
3000


Normalized to integral
Série1
Reiter
0,04
0,035
0,03
0,025
0,02
0,015
0,01
0,005
0
0
500
1000
1500
2000
2500
3000


(a)
1
2
3
4
5
$N_d = 2$
counts/25keV
(b)
counts/25keV
E_γ^{Del} [keV]