

# Shape isomerism in uranium isotopes

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# To start with ...

## CONTEXT

Shape of the multi-dimensional(?) energy landscape in actinide nuclei

Only a few observables:

fission cross-section  
(n, $\gamma$ f) process  
shape isomers



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The mystery around uranium isotopes

The fairy tale of a life-long journey



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New measurements

New challenges



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## What we know

Shape-isomer landscape

The landscape a bit different

A glimpse of a systematic

What next 🤖



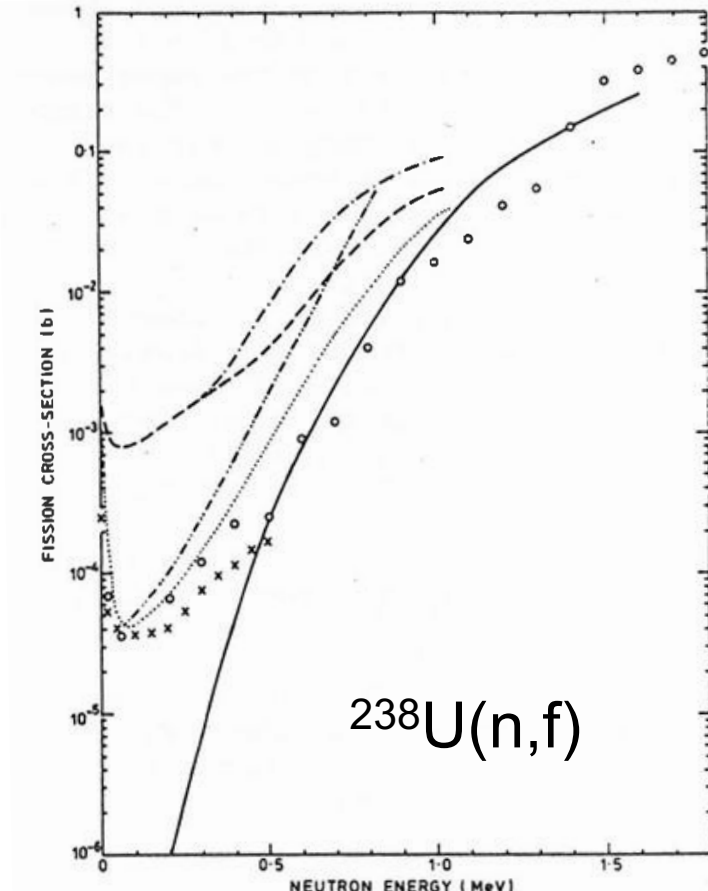
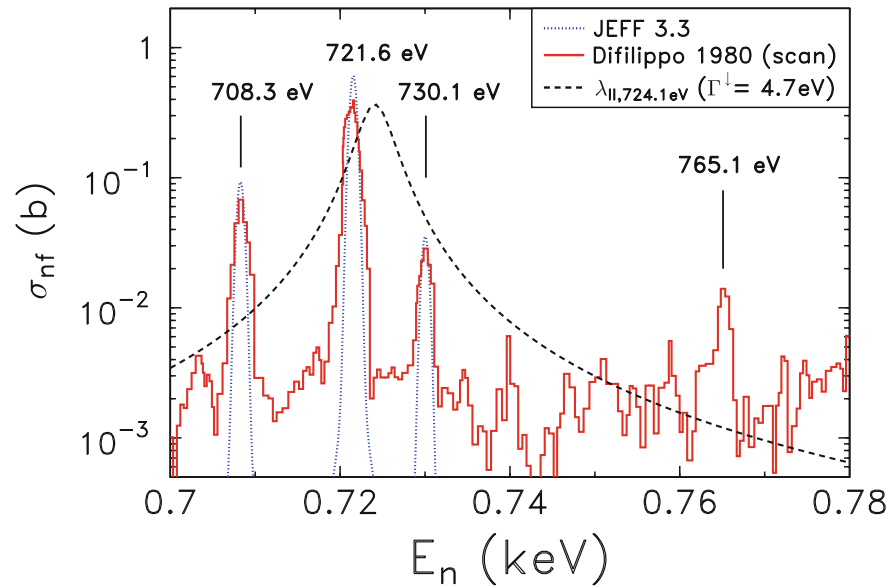
# Shape isomer and “barrier” observables

- Decay half-life,  $T_{1/2,SI}$
- Branching ratio,  $\Gamma_{SI,f}/\Gamma_{SI,\gamma}$
  
- Intermediate structure in sub-threshold fission
- $Y(A^*, TKE)_{SI}$
  
- Together with barrier parameters from cross section data
  - ➡ Image of the potential energy landscape between GS and saddle point



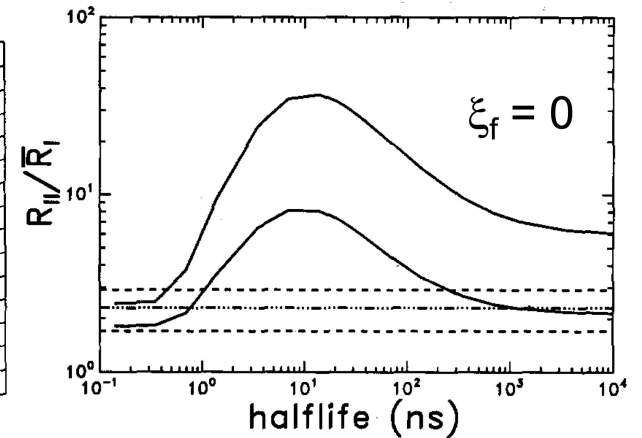
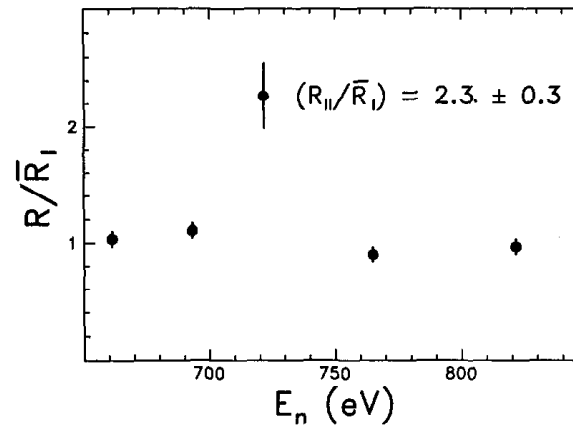
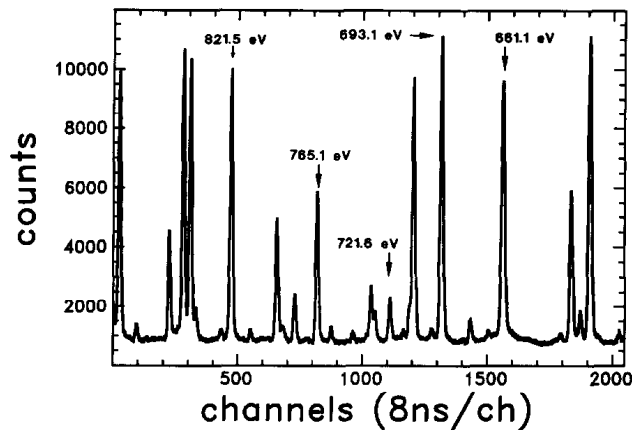
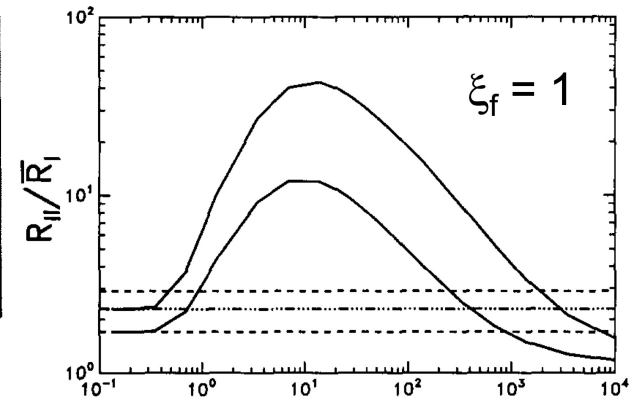
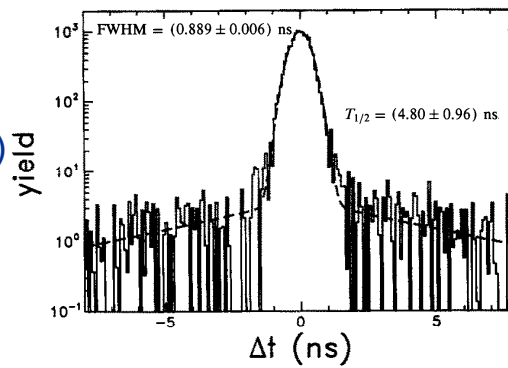
# Once upon a time ...

- ... there was a British scientist, Dr. J.E. Lynn
- Intermediate structure in  $^{238}\text{U}(n,f)$  and  $T_{1/2,SI} < 100 \text{ ns}$  ( $1 \mu\text{s}$ )
- Then came along Prof. J.P. Theobald and Dr. H. Weigmann
- 1989: Go to the CBNM (Geel), have fun and measure it 🤖



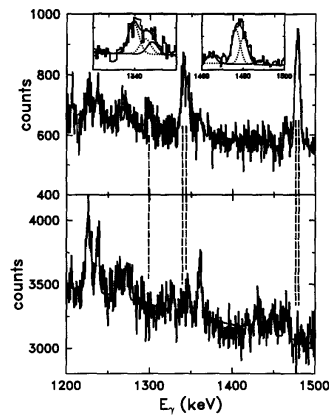
# Once upon a time ... $^{239}\text{fU}$

- 4 BaF<sub>2</sub>, 102 mm × 76 mm (diameter × length)
- high-resolution neutron TOF source (GELINA)
- ¾ inch tape recorders (5 MB/tape 🤖)
- Optimized setup for  $1 \text{ ns} < T_{1/2, \text{SI}} < 100 \text{ ns}$

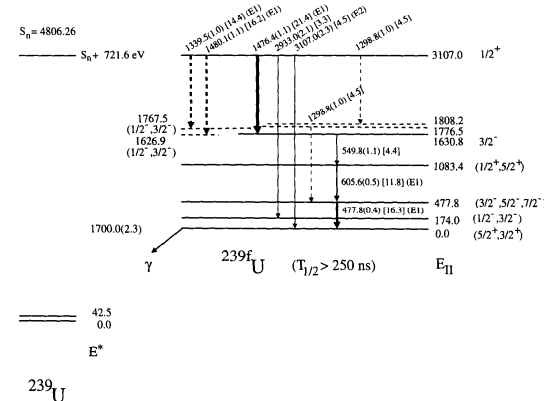


# Once upon a time ... $^{239}\text{fU}$

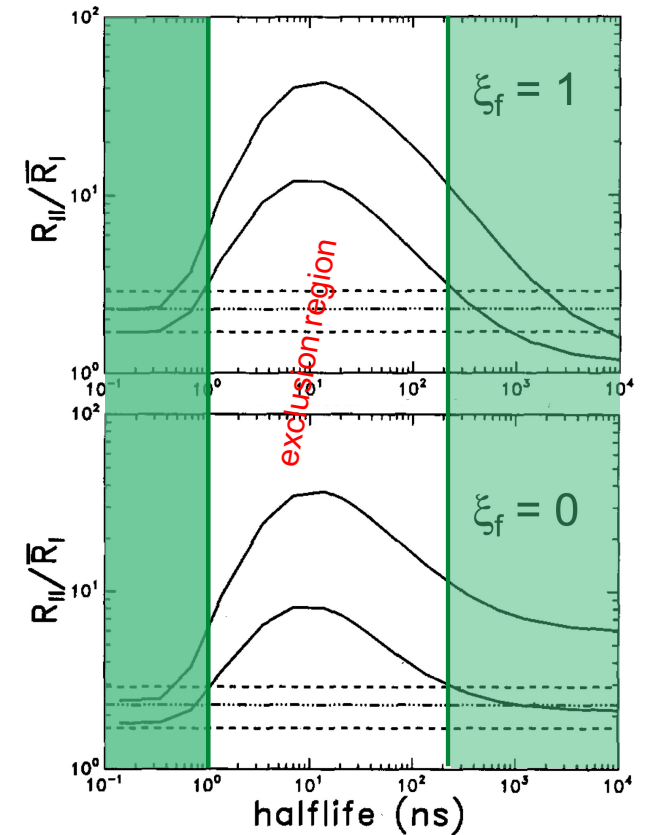
- Optimized setup for  $1 \text{ ns} < T_{1/2, \text{SI}} < 100 \text{ ns}$
- Excluded half-life region [1, 250] ns
- Interpretation: J.E. Lynn's prediction was wrong and lower values for  $T_{1/2, \text{SI}}$  would be in contradiction with  $(E_B - E_{II})$
- No direct observation and  $T_{1/2, \text{SI}} > 250 \text{ ns}$



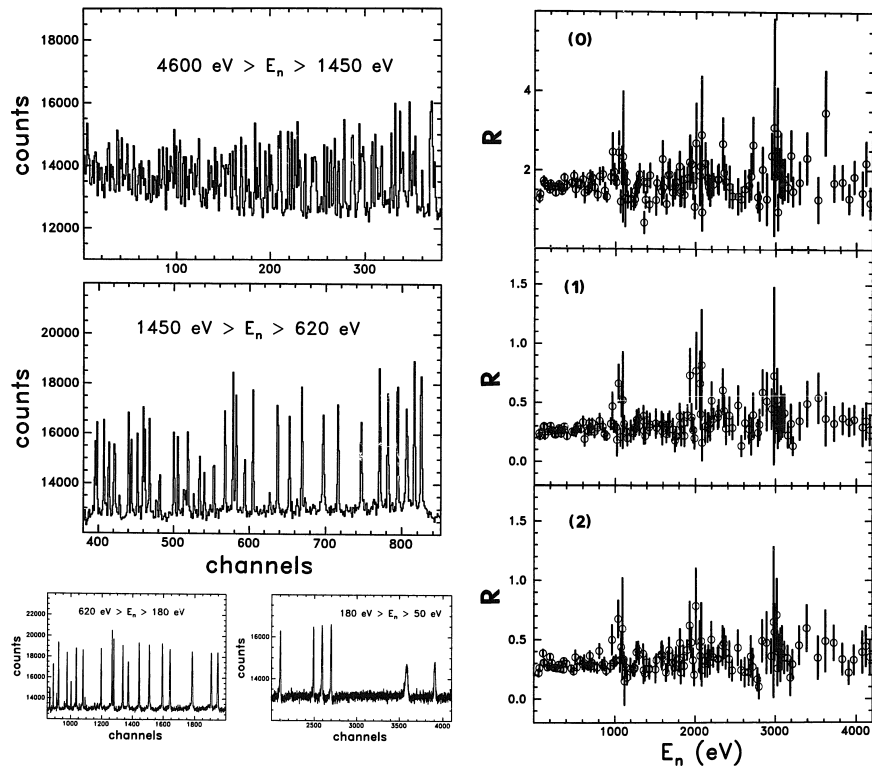
S. Oberstedt and F. Gunsing, NPA (1998)



P.G. Thirolf and D. Habs, Prog. Particle and Nuclear Physics 49 (2002) 325 - 402

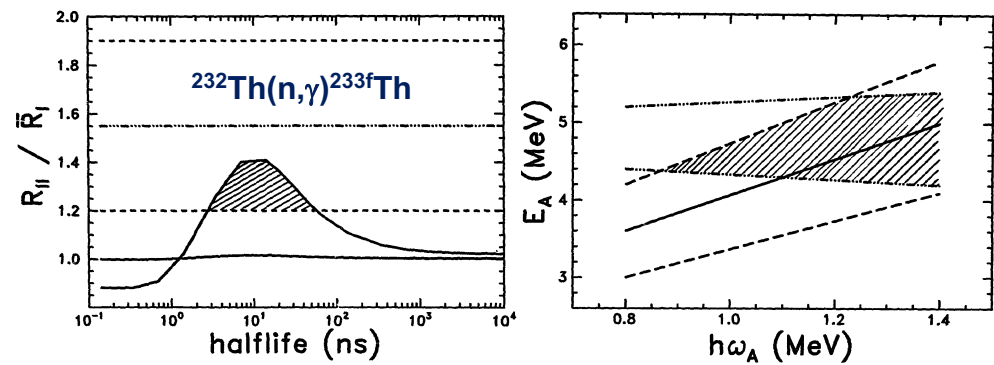


# Once upon a time ... $^{233}\text{Th}$



Comp. nucl.	$E_{\Pi}$ (MeV)	$E_{\Lambda}$ (MeV)	$T_{1/2}$ (ns)	$\hbar\omega_{\Lambda}$ (MeV)	$\Delta_{\hbar\omega_{\Lambda}}$
$^{233}\text{Th}$	$1.85 \pm 0.25$	$4.6^{+0.8}_{-0.4}$	1 ... 100	$1.05 \pm 0.20$	0.25

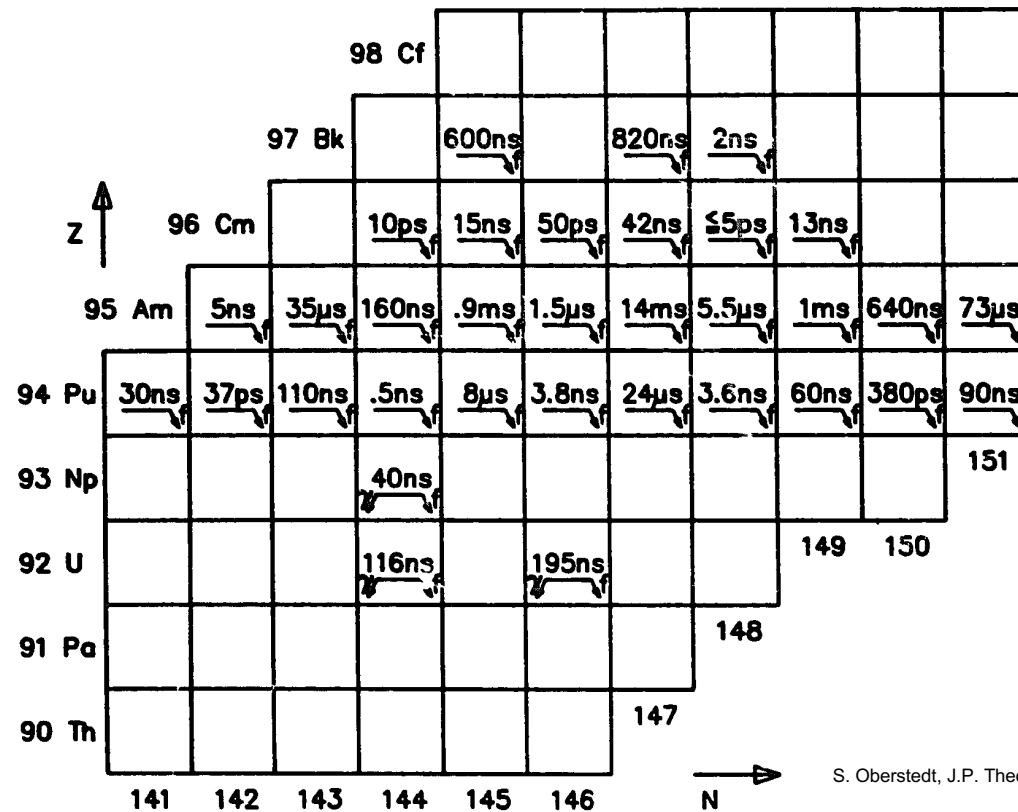
➤ No direct observation ... again 🤔



S. Oberstedt, J.P. Theobald et al., Nuclear Physics A 578 (1994) 31-44



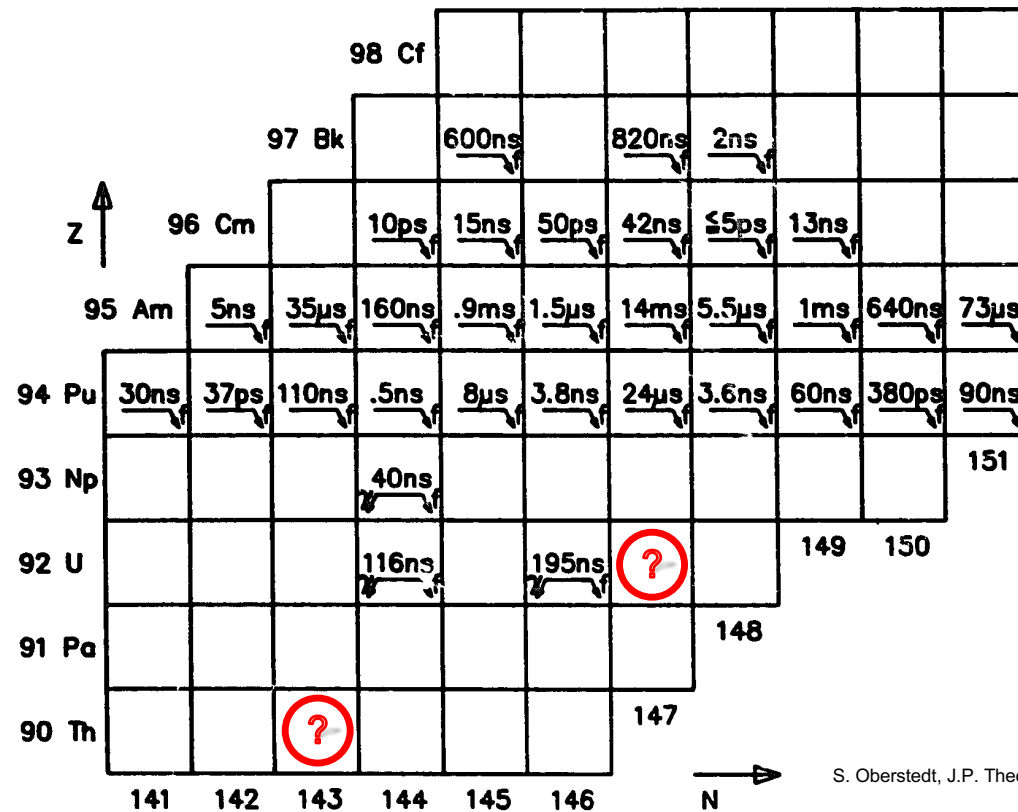
# Landscape of shape isomers



S. Oberstedt, J.P. Theobald et al., Nuclear Physics A 578 (1994) 31-44



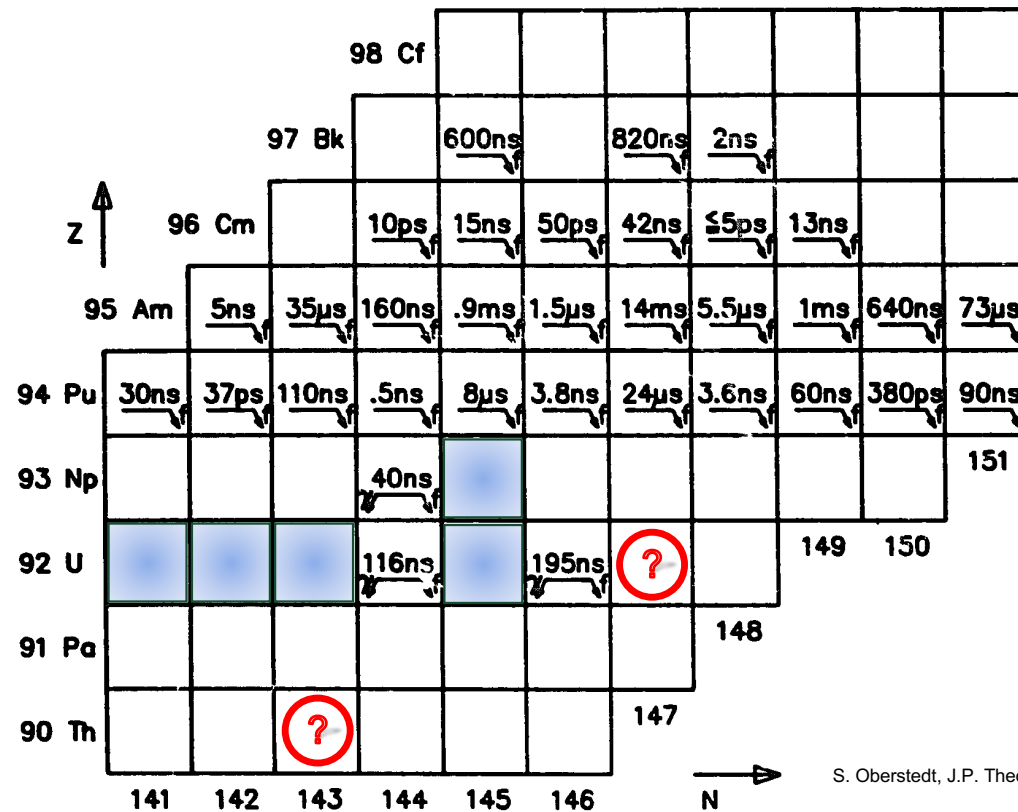
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# “Odd” uranium isotopes ...

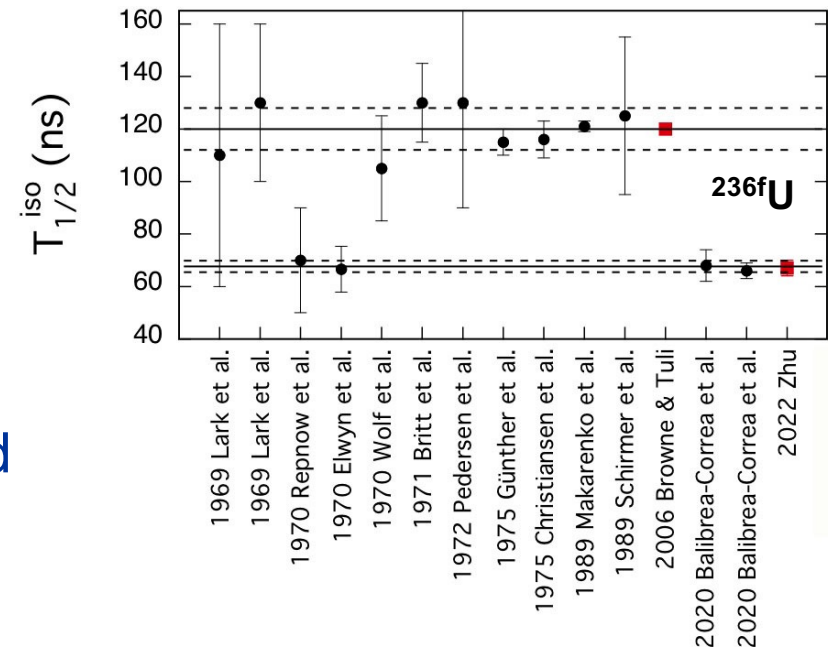
➤ Discovery of first odd-U shape isomers very recent (2005)

➤ Experimental half-lives “quite discrepant”

○  $^{236f}\text{U}$ : either  $\approx 120$  ns or  $\approx 70$  ns

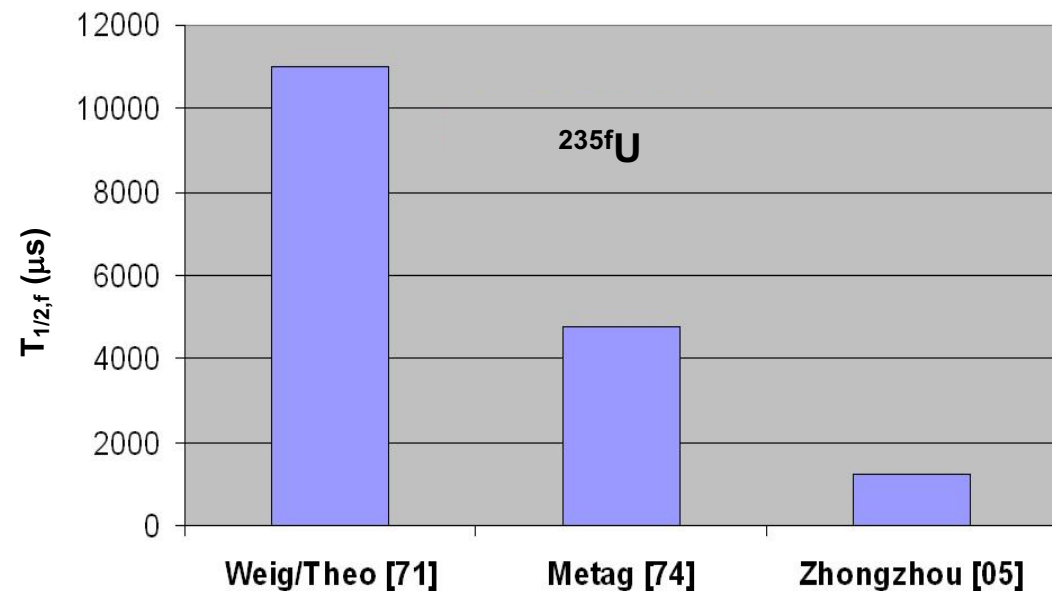
○  $^{238f}\text{U}$ :  $\approx 200$  ns and  $\approx 280$  ns

➤ Extreme range of half-life estimates for odd (and odd-odd) isotopes



# “Odd” uranium isotopes ...

- Extreme range of half-life estimates for odd(-N) isotopes
- most favourable case  $^{235}\text{fU}$ :  $T_{1/2} = (1 - 11) \text{ ms}$

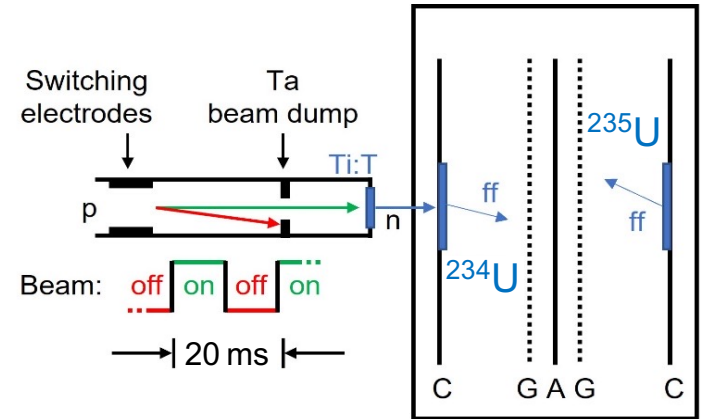


- $^{238}\text{fNp}$  :  $T_{1/2} = 1 \mu\text{s} - 10 \text{ s}$

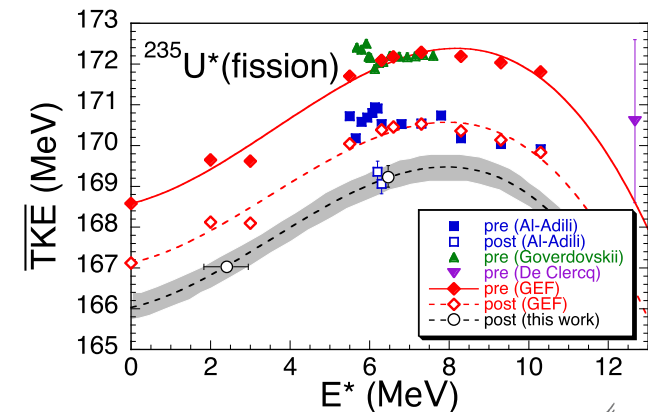
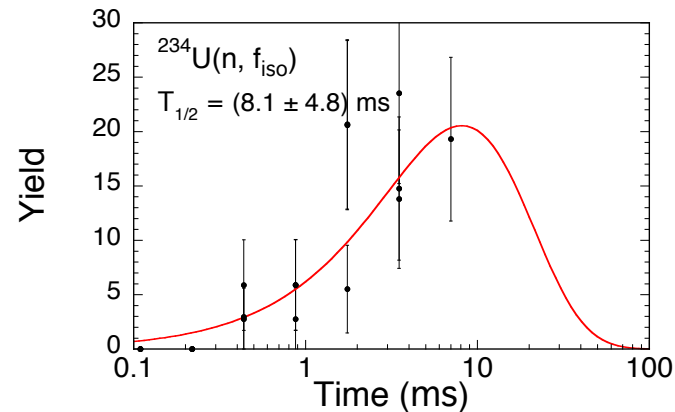


# 235fU

- Setup sensitive for several orders of magnitude
  - ✓ NEPTUNE
- $E_n = 0.95$  and  $1.27$  MeV
- Time distribution of delayed fission
- Kinetic energy of the shape isomeric fragments

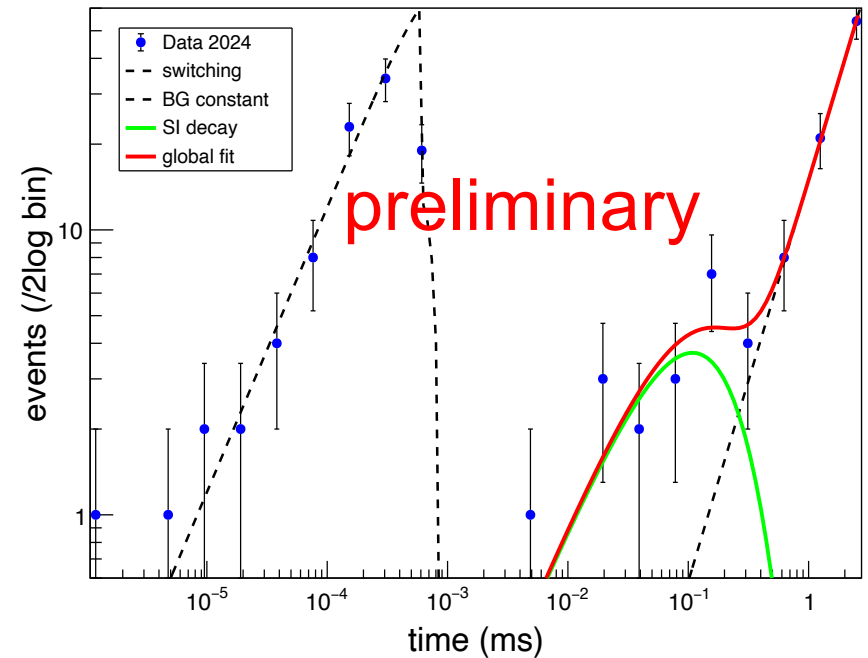


- $E_{||} = 2.4(6)$  MeV
- $P_{SI} = 1.0(4) \times 10^{-5}$



# 237fU

- NEPTUNE@100Hz:  $T_{1/2,f} = 10 \mu\text{s} - 5 \text{ ms}$
- highly-enriched  $^{236}\text{U}$  sample: 99.973%
- level density ratio:  $E_{\parallel} = 2.1(1) \text{ MeV}$
- $T_{1/2,\gamma}/T_{1/2,f} = 9.9$  (Wagemans 1990)
- preliminary:  $T_{1/2} \approx 110 \mu\text{s}$   
 $P_{\text{SI}} < 2 \times 10^{-7}$

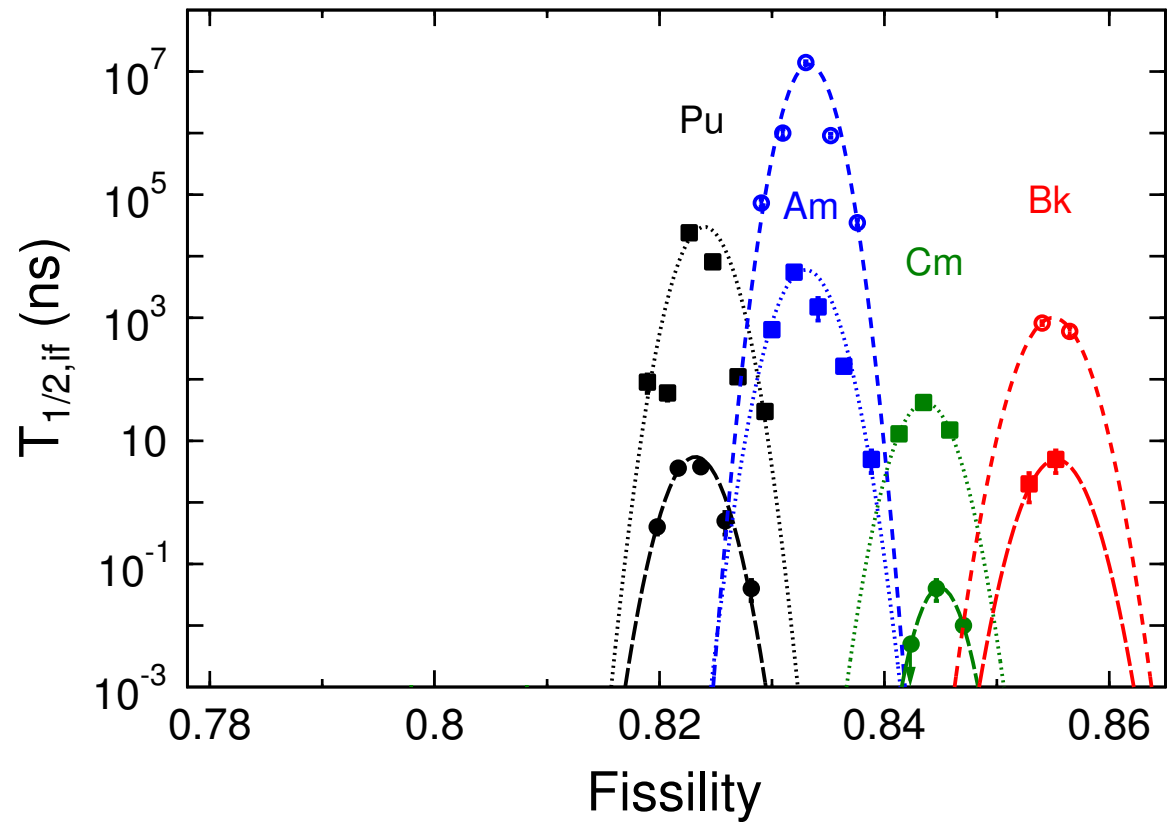


# Landscape of shape isomers (again)

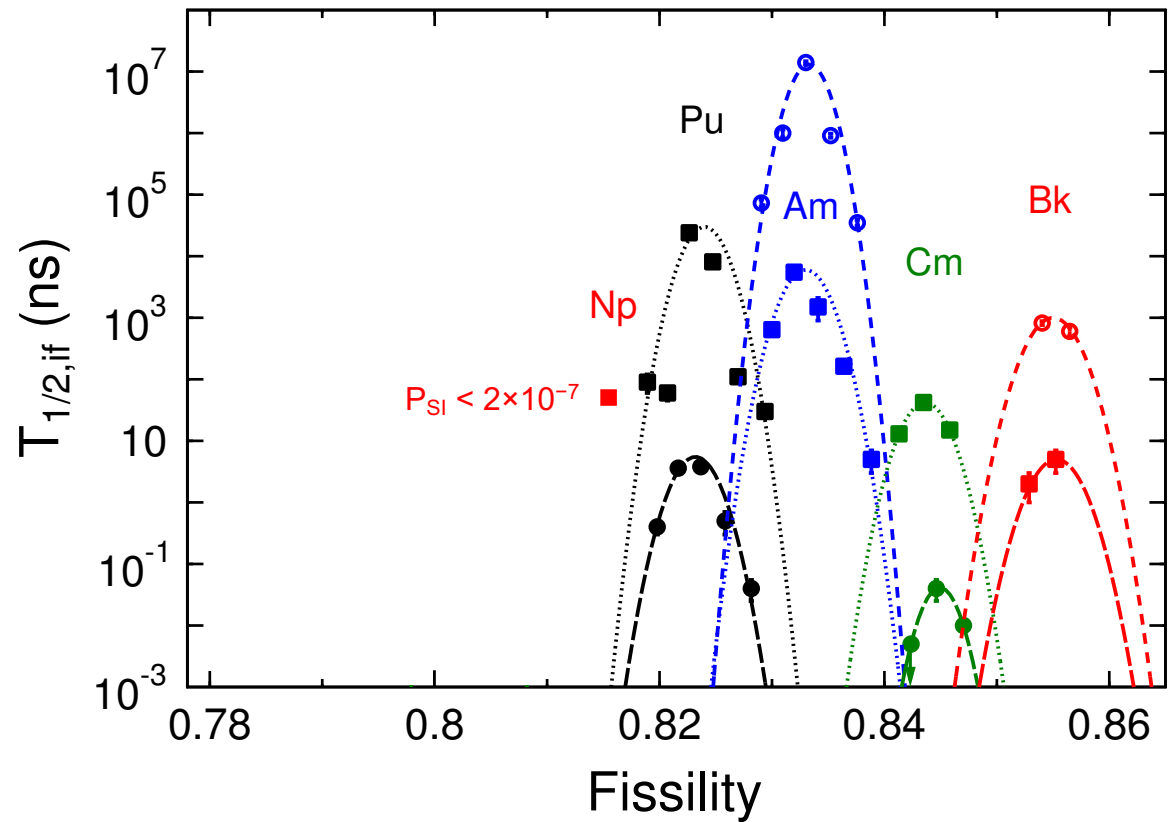
				242Bk 10 ns 600 ns if	243Bk 5 ns if	244Bk 820 ns if	245Bk 2 ns if		247Bk	
			240Cm 55 ns 10 ps if	241Cm 15 ns if	242Cm 180 ns 50 ps if	243Cm 45 ns if	244Cm > 100 ns ≤ 5 ps if	245Cm 13 ns if		
	237Am 5 ns if	238Am 35 μs if	239Am 160 ns if	240Am 900 μs if	241Am 1.5 μs if	242Am 14 ms if	243Am 5.5 μs if	244Am 1 ms if	245Am 640 ns if	246Am 73 μs if
235Pu 30 ns if	236Pu 34 ns 37 ps if	237Pu 1.1 μs 110 ns if	238Pu 6 ns 500ps if	239Pu 3 ns 8 μs if	240Pu 3.8 ns if	241Pu 30 ns 24 μs if	242Pu 50 ns 3.6 ns if	243Pu 60 ns if	244Pu 400 ps if	245Pu 90 ns if
		236Np	237Np 45 ns if / $i\gamma \leq 100$	238Np						
	233U	234U	235U 8.1 ms if / $i\gamma$	236U 120 ns if / $i\gamma = 13/87$	237U <b>110 μs</b>	238U 280 ns if / $i\gamma = 3/97$	239U > 0.25 μs if / $i\gamma$			
231Pa		233Pa								
	231Th	232Th	233Th 1 - 100 ns $i\gamma$							



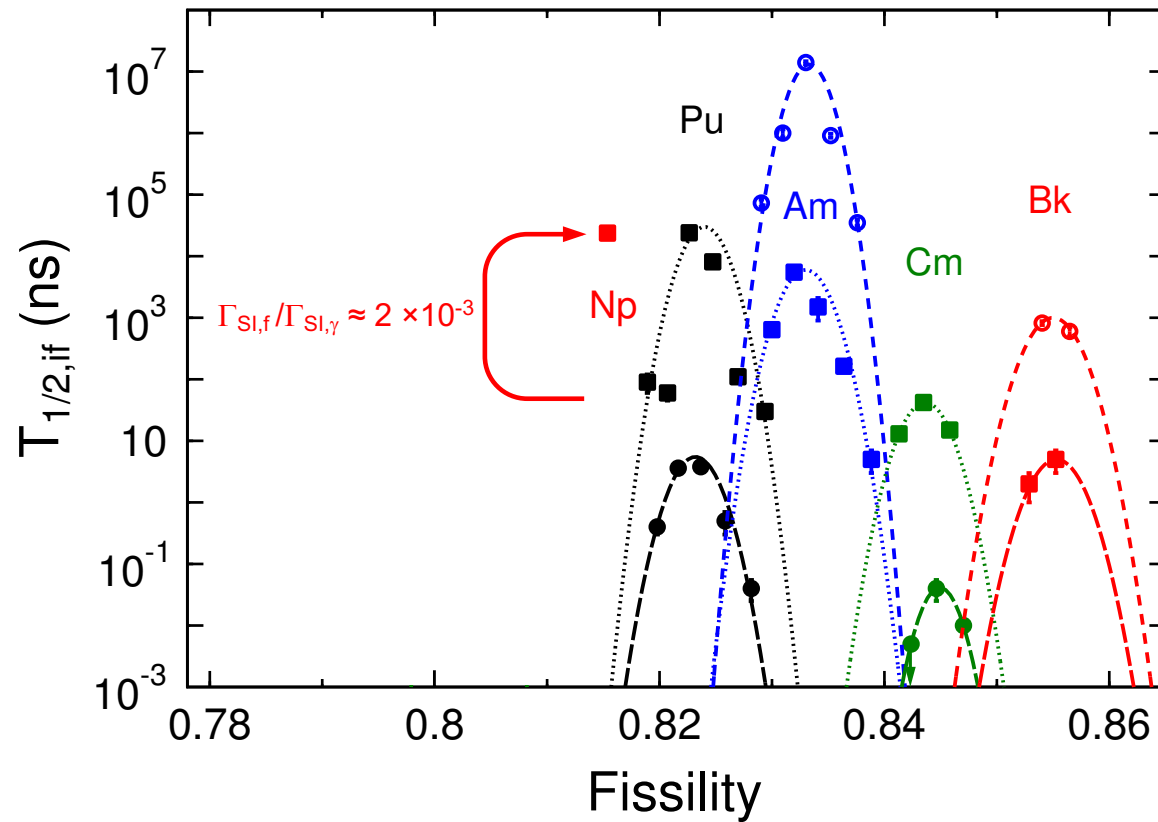
# SI landscape a bit different ...



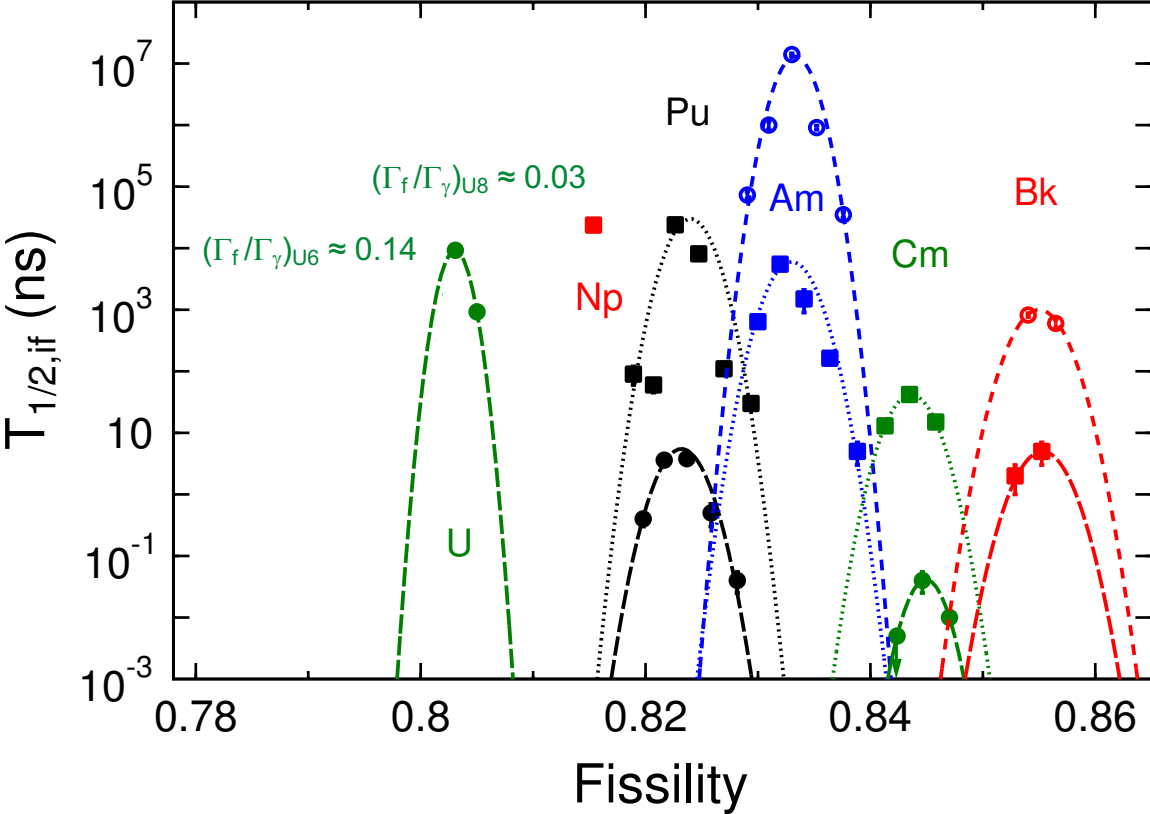
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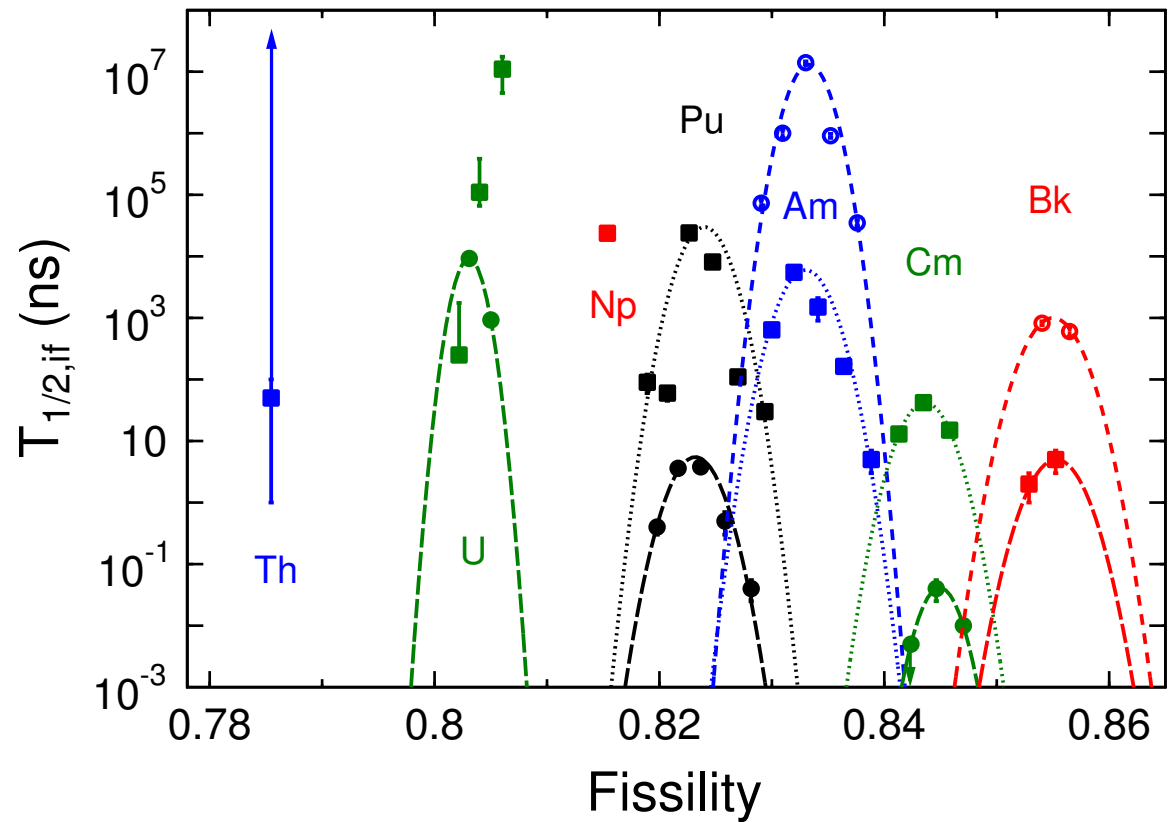
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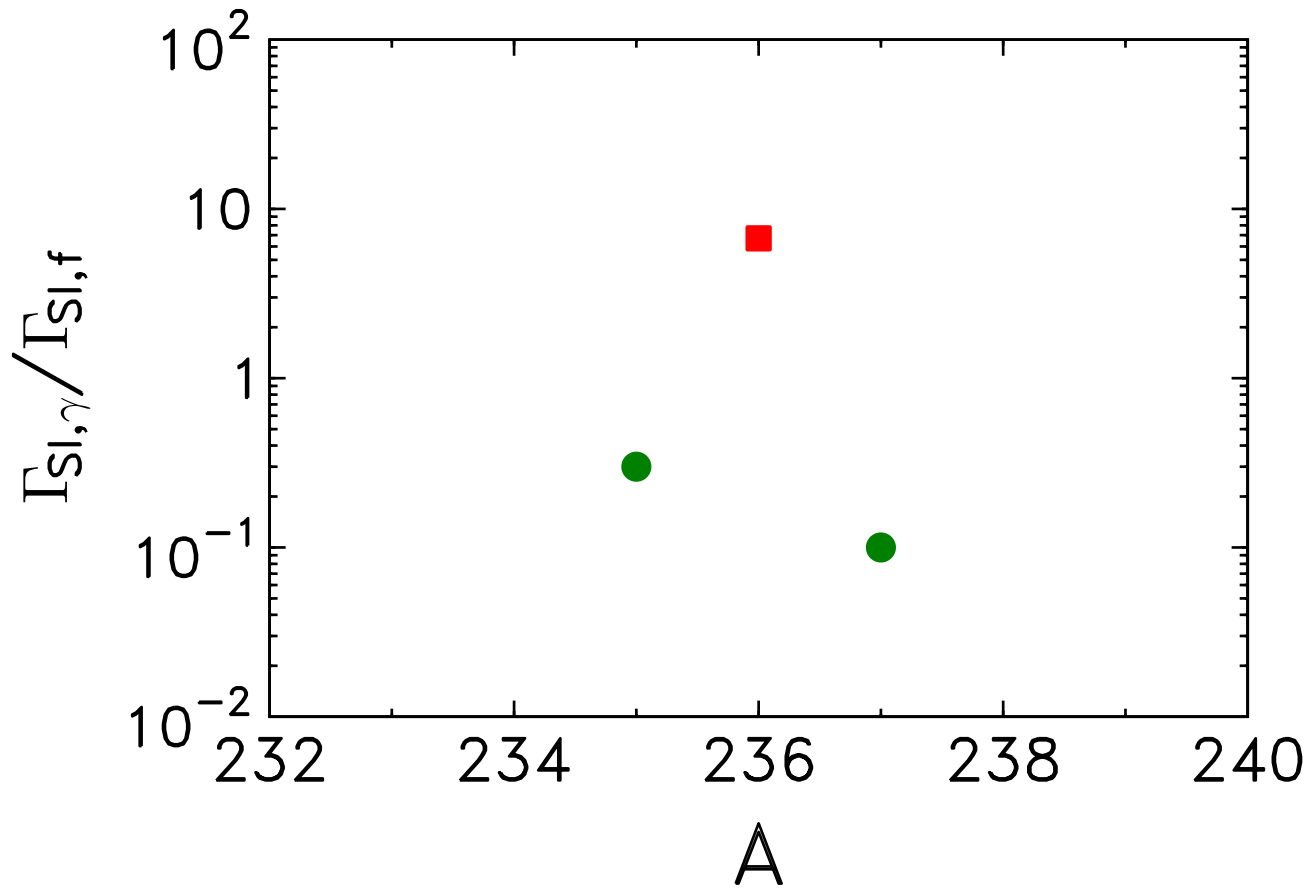
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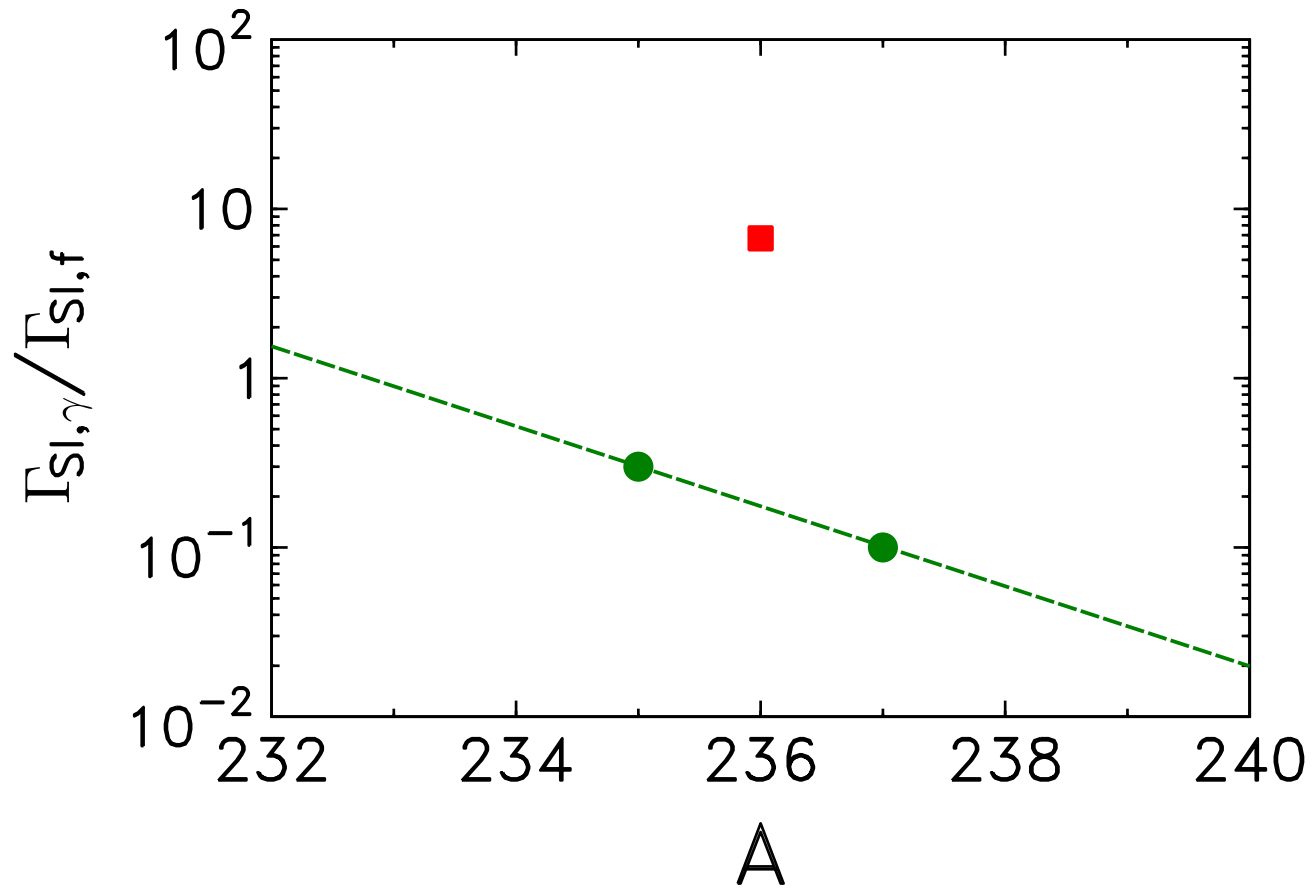
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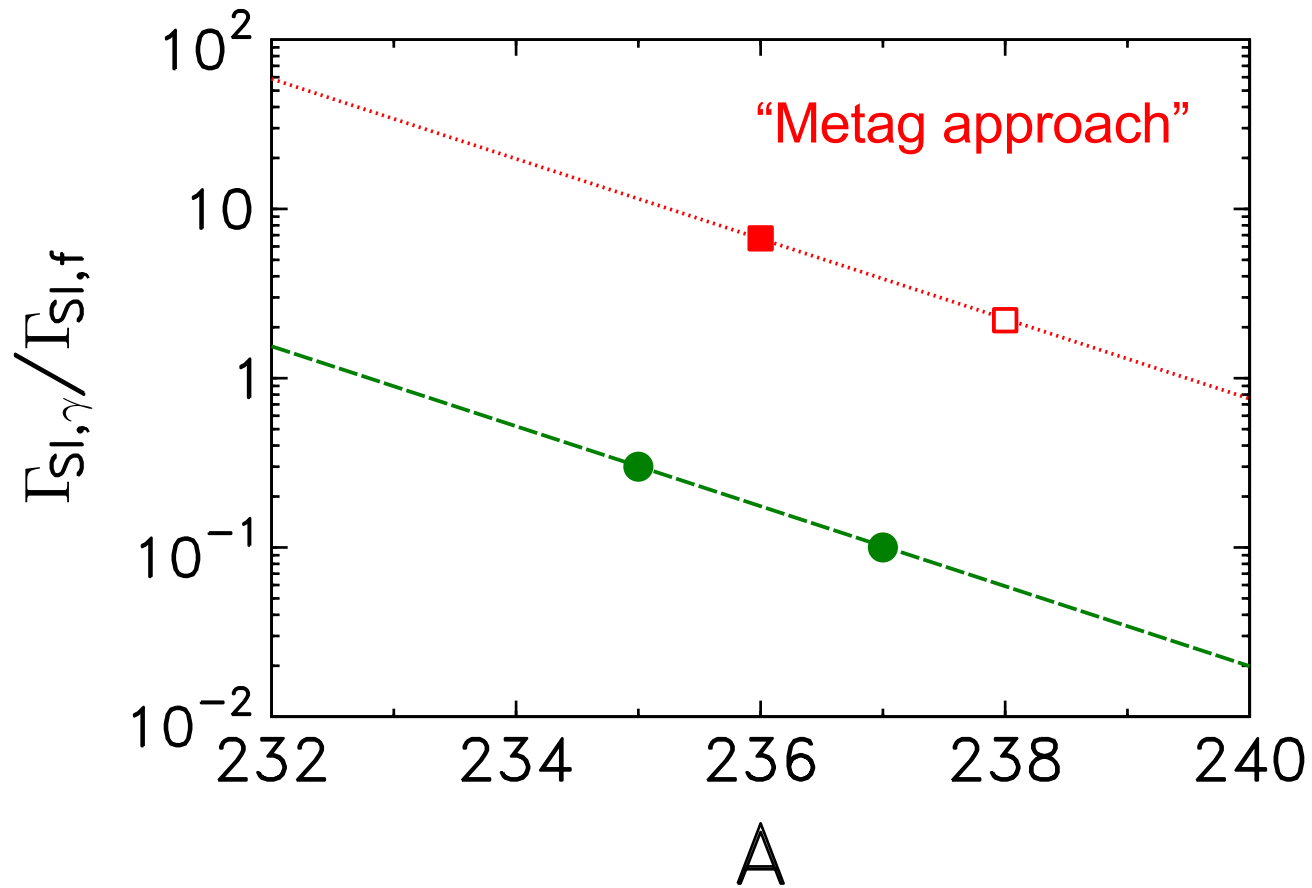
# A simple-minded systematics



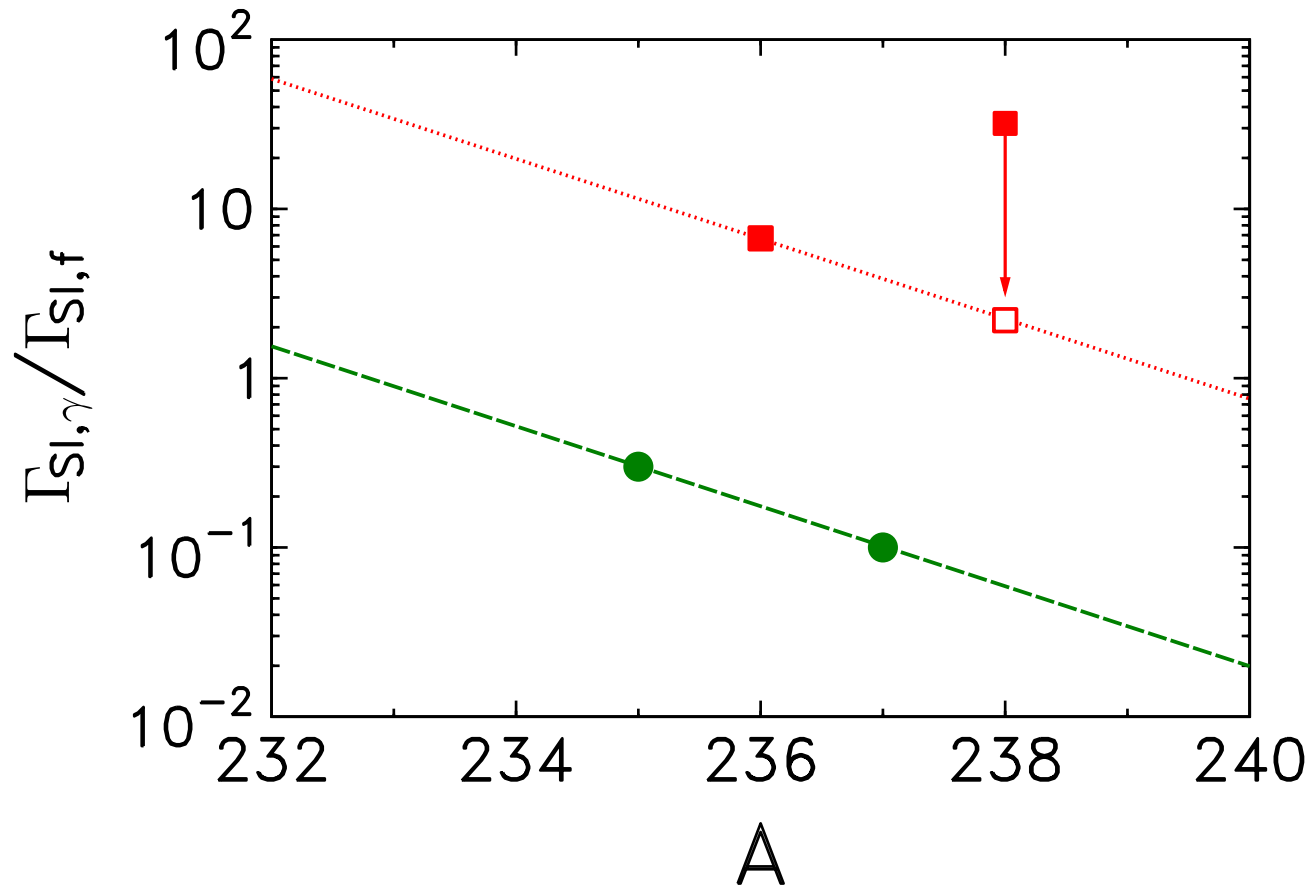
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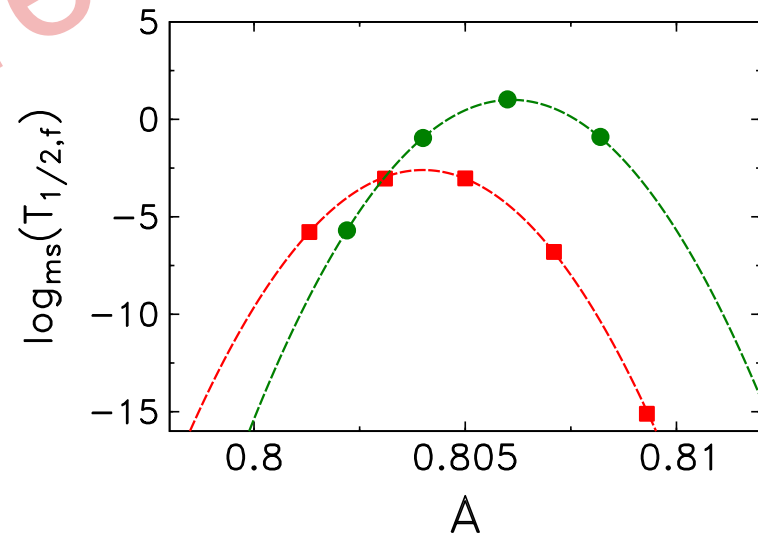
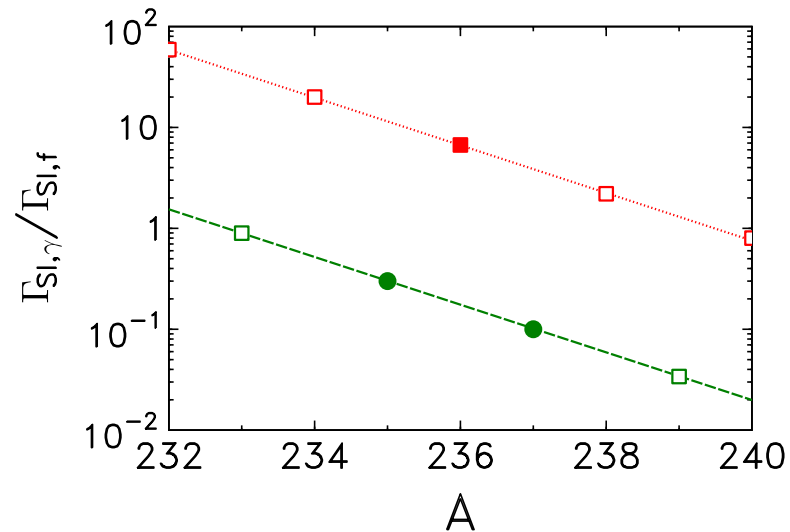


# A simple-minded systematics



# A simple-minded systematics

- “prediction” of branching ratios for the other isotopes
- educated guess for  $T_{1/2,f}$  =====> allows proper design of a measurement

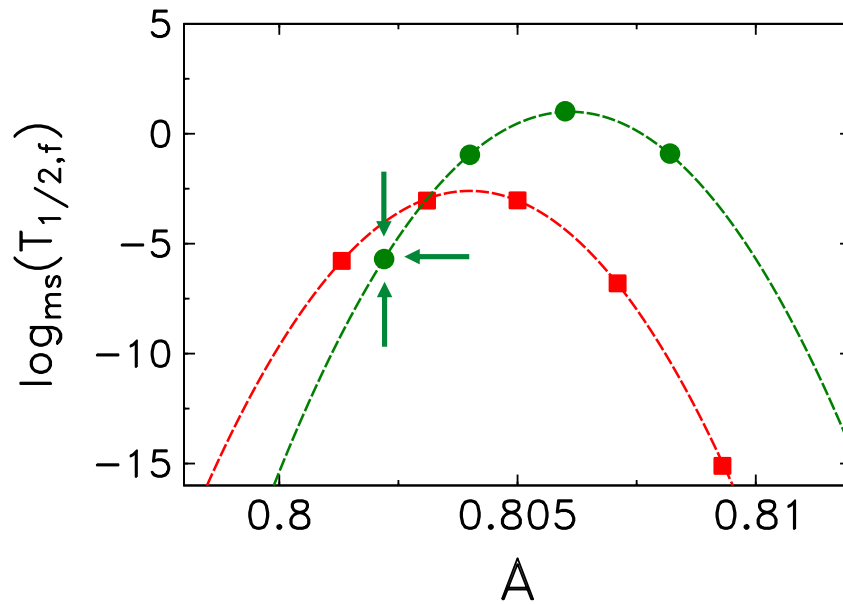


preliminary

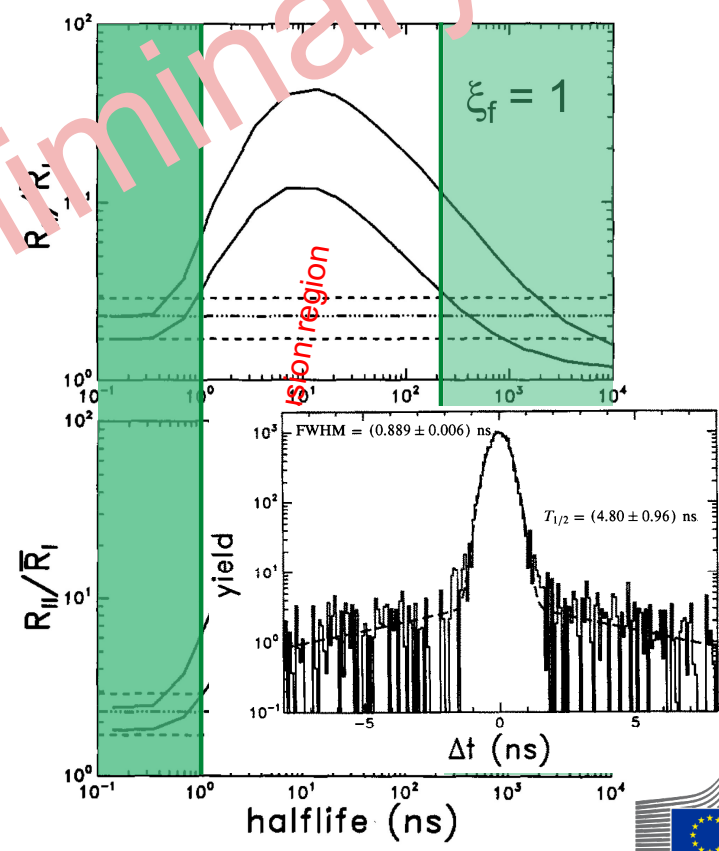


# A simple-minded systematics

- 35 years later new data seems to indicate a half-life for  $^{239}\text{fU}$  of  $\lesssim 2$  ns
- Has Dr. J.E Lynn been right in the end?



preliminary



# Conclusion

Shape isomers in actinides “south” of plutonium exist

Discovery of the 2<sup>nd</sup> odd uranium shape isomer,  $^{237f}\text{U}$

Extremely low population probability,  $P_{\text{SI}} \approx 10^{-7}$

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The  $\gamma$ -decay back to the normal ground-state can be measured 🤖

$\Gamma_{SI,\gamma}/\Gamma_{SI,f}$   
seems to be strongly isotope dependent

A simple-minded systematic could explain why  $\gamma$  back decay in <sup>238</sup>U is still not confirmed



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A (very) small SI fission branch does not imply a considerably strong  $\gamma$ -branch

Branching ratio and population probability must be considered separately



# Future shape-isomer research

## Priority observables

$T_{1/2}$  for shape isomer identification

include detection of  $\gamma$  branch,

$^{232f,233f}\text{Th}$

SI fission-fragment properties

and in the intermediate structures



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neutron or photon-induced, d,p

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## Measurement campaigns

require highly enriched isotopes

$^{234,236,238}\text{U}$ ,  $^{237}\text{Np}$

- 1)  $^{237}\text{Np}(n, f_{\text{iso}}) @ E_n < E_{\text{II}}(^{237}\text{Np})$
- 2)  $^{237}\text{Np}(n, n' f_{\text{iso}})$  and  $^{237}\text{Np}(n, n' \gamma_{\text{iso}})$

access to sufficiently long beam times



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## Facilities

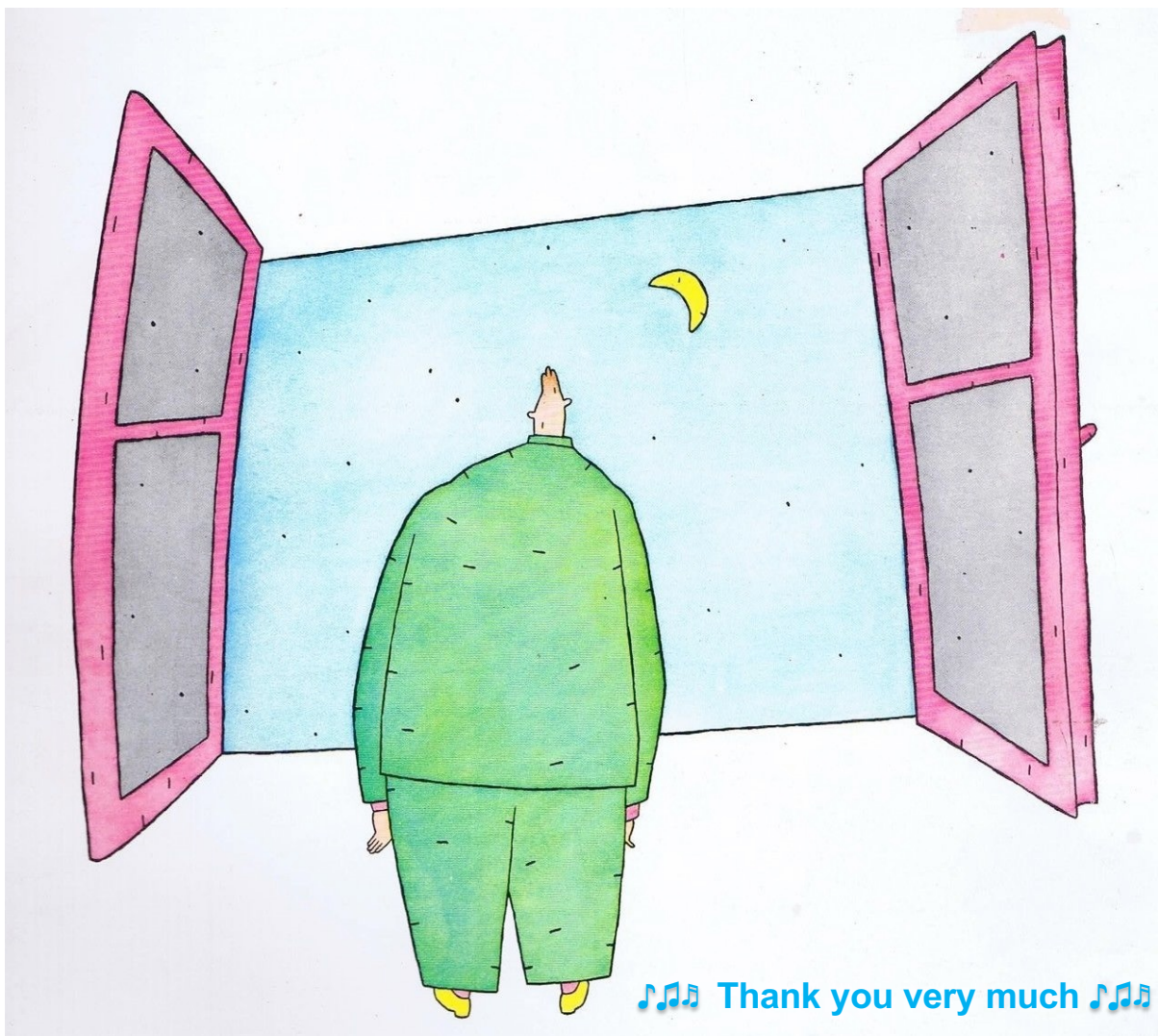
LICORNE  
NFS (if low neutron energies available)

GELINA (resolved resonance region)  
MONNET

IGISOL/JYFL-ACC (long half-lives)  
FRS/GSI (secondary actinide beams)

IFIN-HH/ELI-NP (sub-barrier energies)





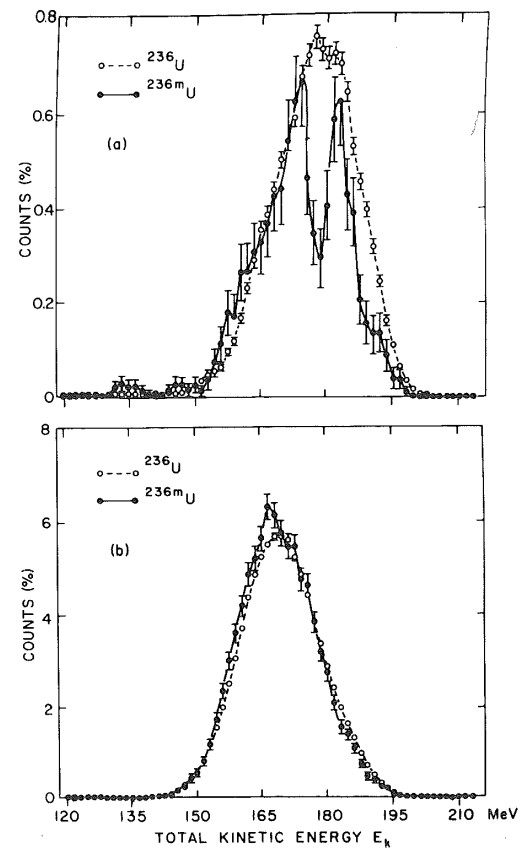
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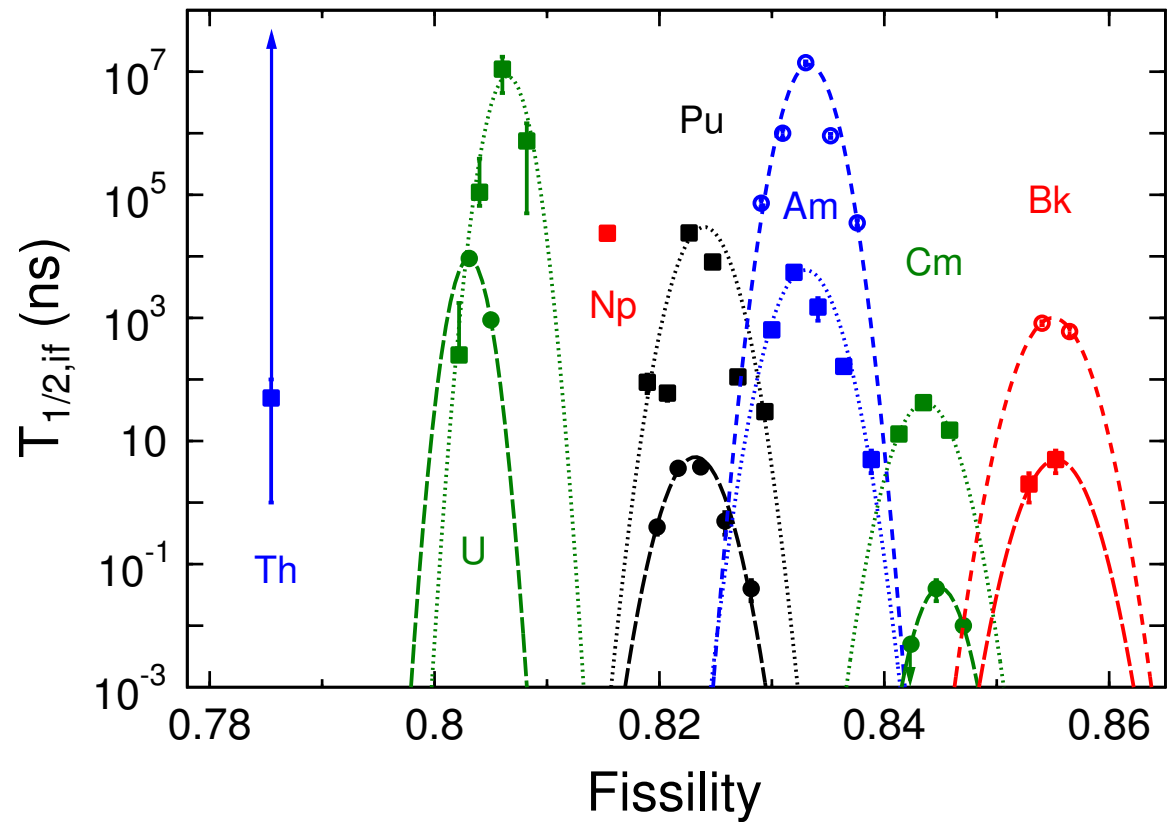
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# “Odd” uranium isotopes ...



# SI landscape a bit different ...



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