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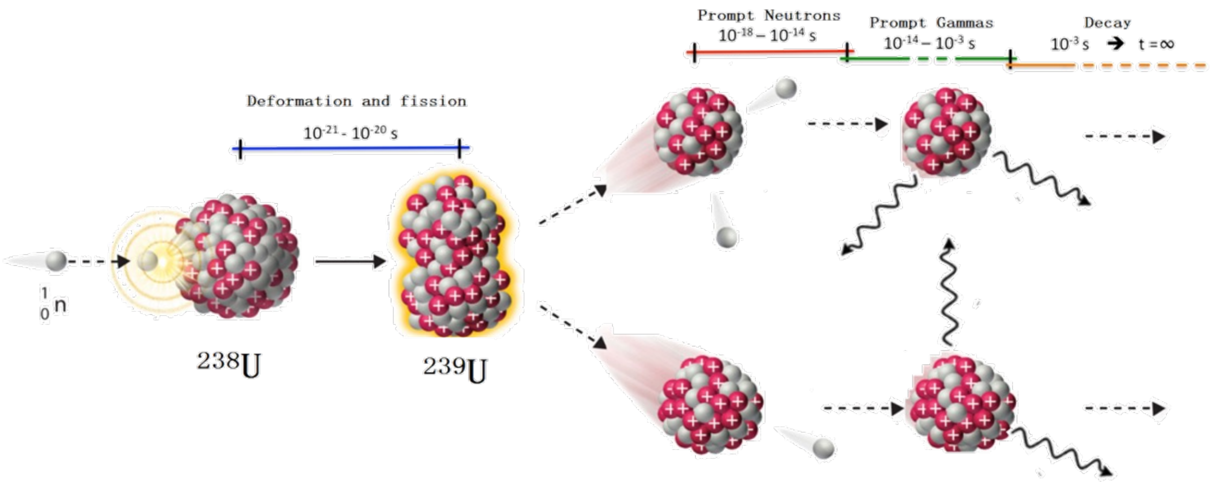
Isomeric yield ratios and angular momenta in nuclear fission

Andreas Solders

Background and motivation



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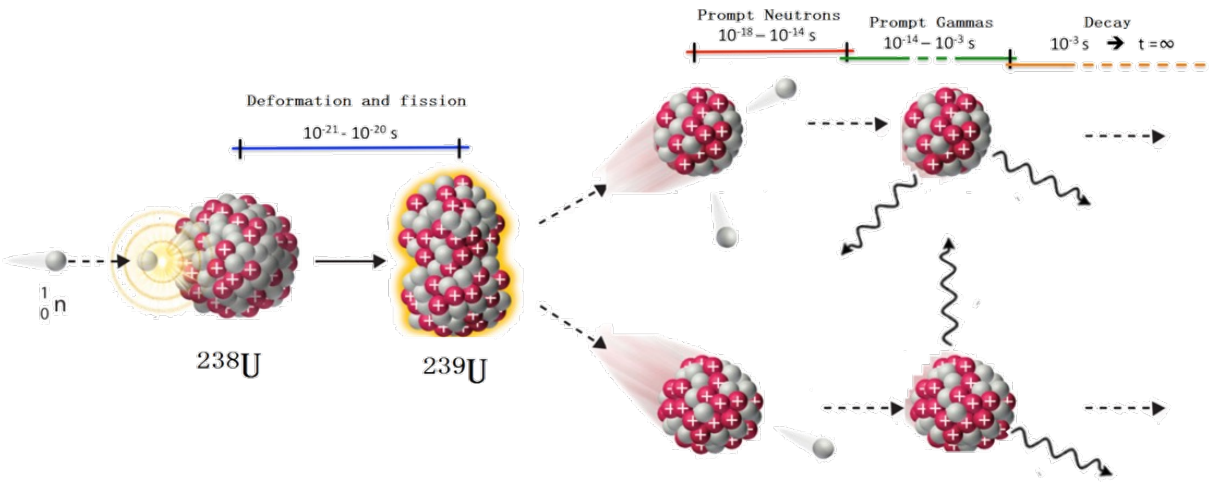
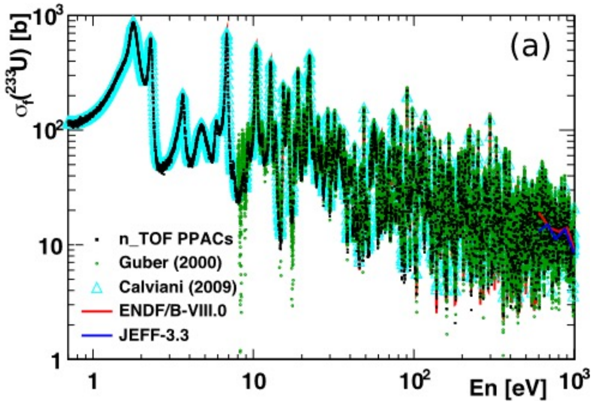
Background and motivation

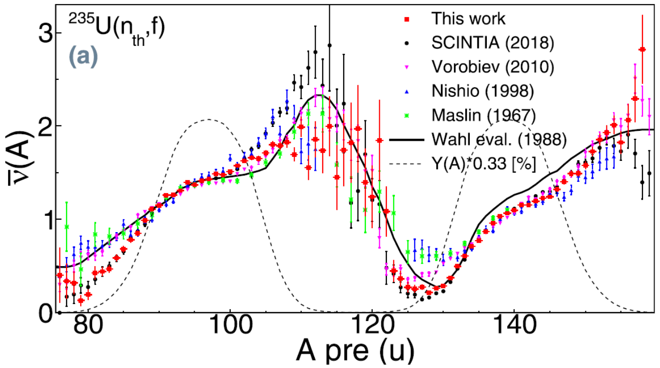


cross sections



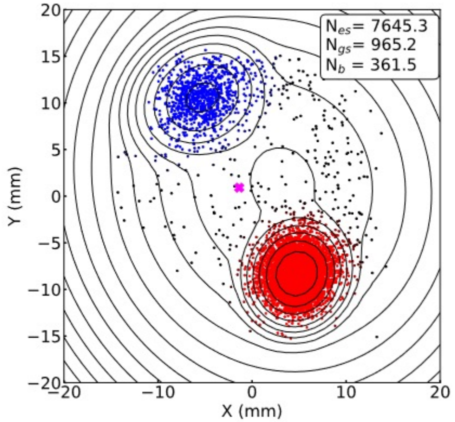
D. Tarrío et al, Phys. Rev. C **107**, 044616 (2023)

prompt neutron emission



A. Al-Adili et al, Phys. Rev. C **102**, 064610 (2021)

yields and isomeric ratios



Z. Gao et al, Phys. Rev. C **108**, 054613 (2023)

Angular momentum of fission fragments

PHYSICAL REVIEW C VOLUME 5, NUMBER 6 JUNE 1972

Angular Momentum of Primary Products Formed in the Spontaneous Fission of ^{252}Cf†

J. B. Wilhelmy,* E. Cheifetz,‡ R. C. Jared, S. G. Thompson, and H. R. Bowman
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

and

J. O. Rasmussen
Chemistry Department, Yale University, New Haven, Connecticut 06520

(Received 22 November 1971)

Wilhelmy et al (1972):

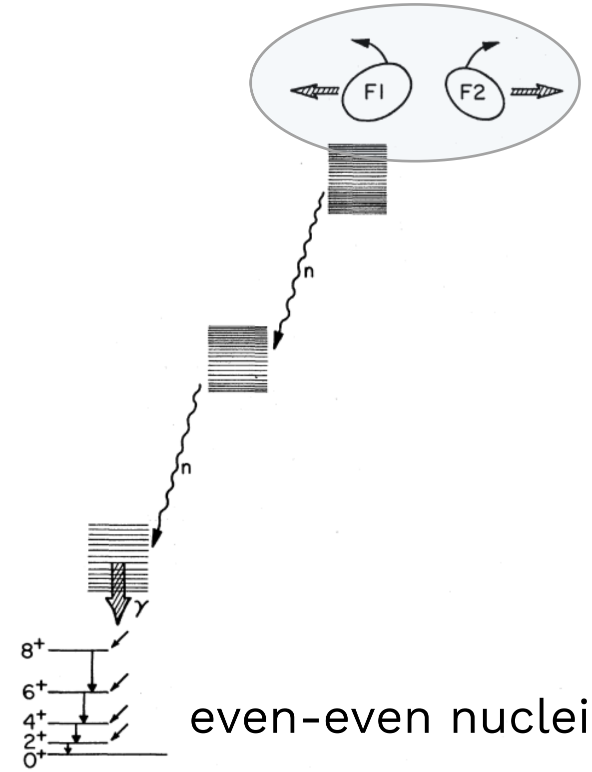
- Fission fragments from ^{252}Cf(sf) have angular momenta of about 7 ħ.

Somehow the fission fragments are tumbling apart after scission.

What makes them do so?

Already before the experimental evidence for these surprisingly large angular momenta there where theories suggesting:

- pre-fission model:
  - Collective vibrations; wriggling, bending, twisting;
- post-scission model:
  - Coulomb forces; microscopic theories (e.g. Bertsch et al. 2019)



even-even nuclei

Angular momentum of fission fragments

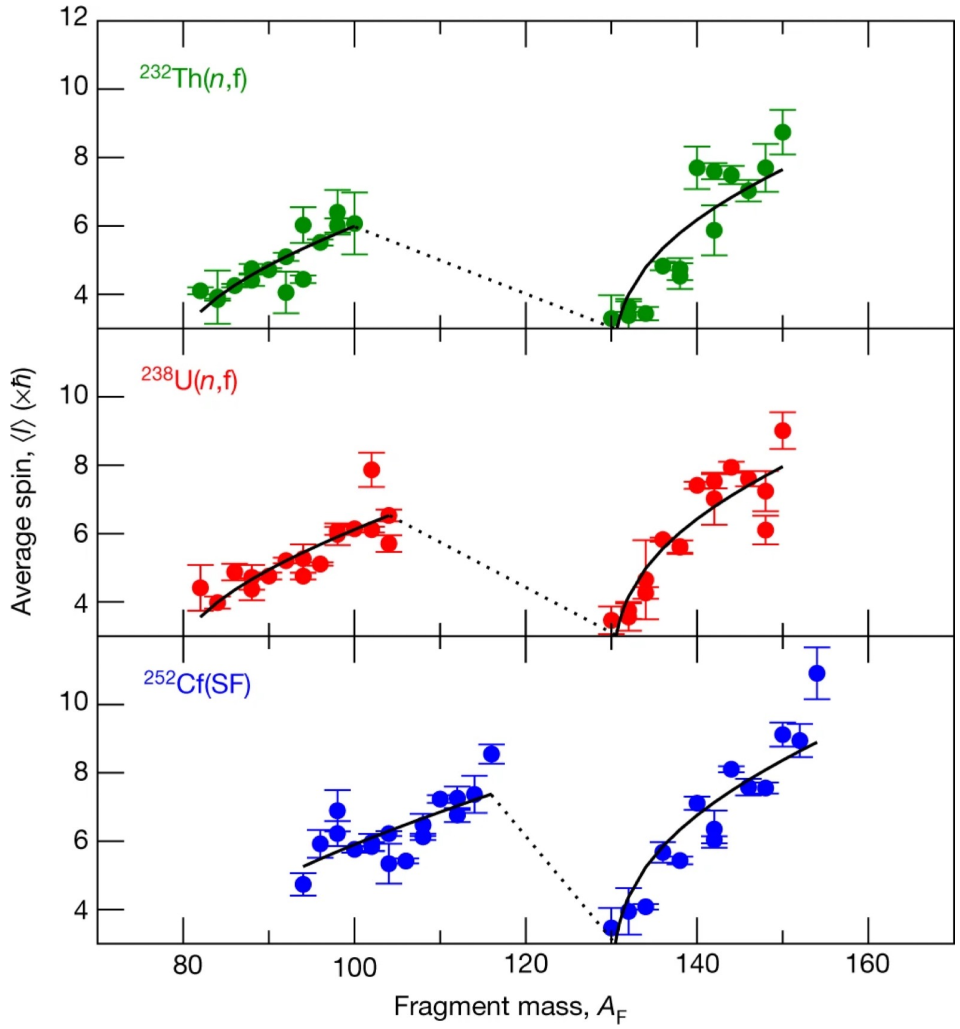
The debate got fresh fuel with the results from J. Wilson et al., Nature 590, 566 (2021).

All three studied systems showed the same sawtooth-like behaviors.

Furthermore:

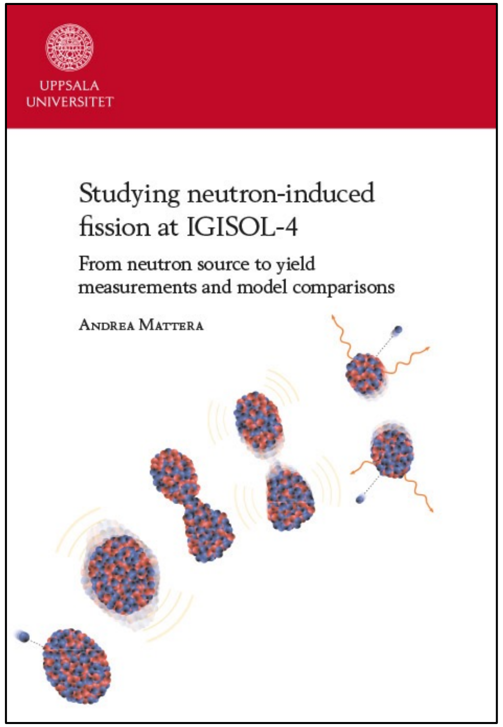
"Here we show that there is **no significant correlation between the spins of the fragment partners, which leads us to conclude that angular momentum in fission is actually generated after the nucleus splits** (post-scission)."

Several subsequent papers challenged this conclusion, e.g., Randrup & Vogt, PRL 127, 062502 (2021).



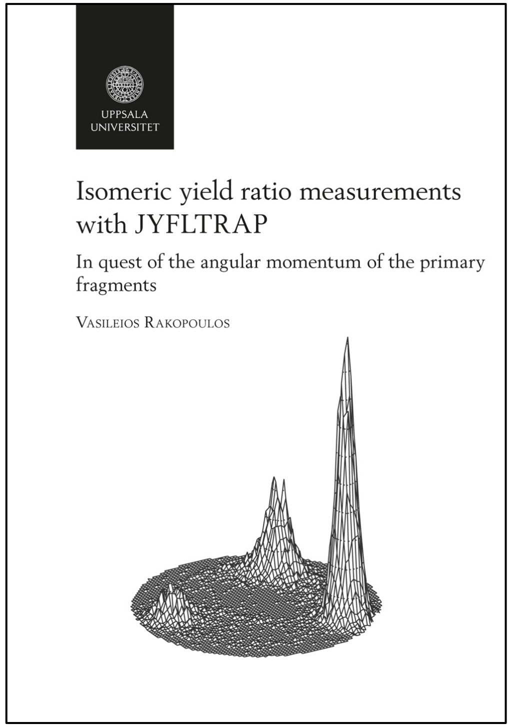
Isomeric yield ratios –
a probe of angular momentum generation in fission

(n,f)



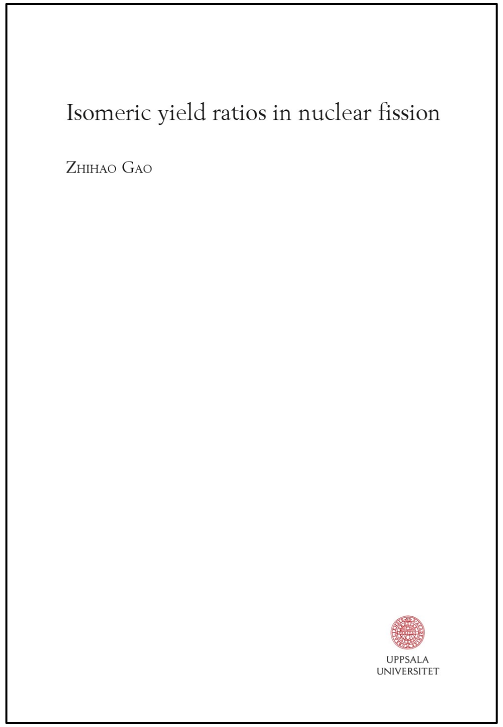
EPJ A (2017) **53**: 173
EPJ A (2018) **54**: 33

(p,f)



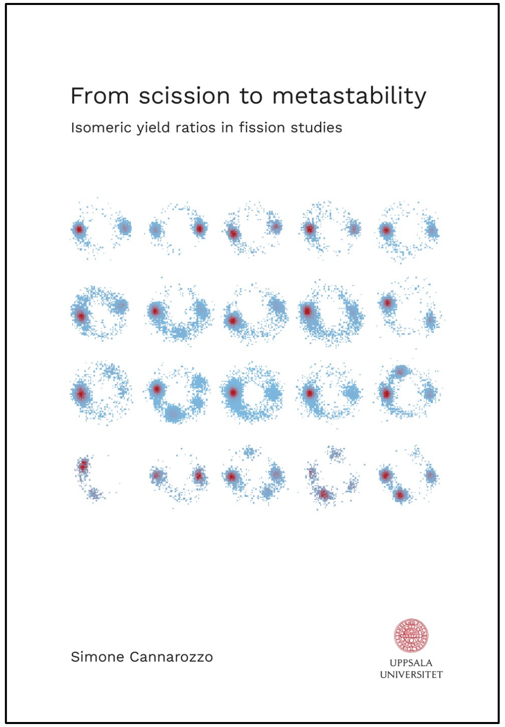
PRC **98** 024612 (2018)
PRC **99** 014617(2019)

(p,f)



EPJ A **58**: 27 (2022)
EPJ A **59**: 169 (2023)
PRC **108** 054613 (2023)
PRC **109** 064626 (2024)

(α,f)



EPJ A (2023) **59**: 295
PRC **111** L031601 (2025)
PLB **871** 140012 (2025)

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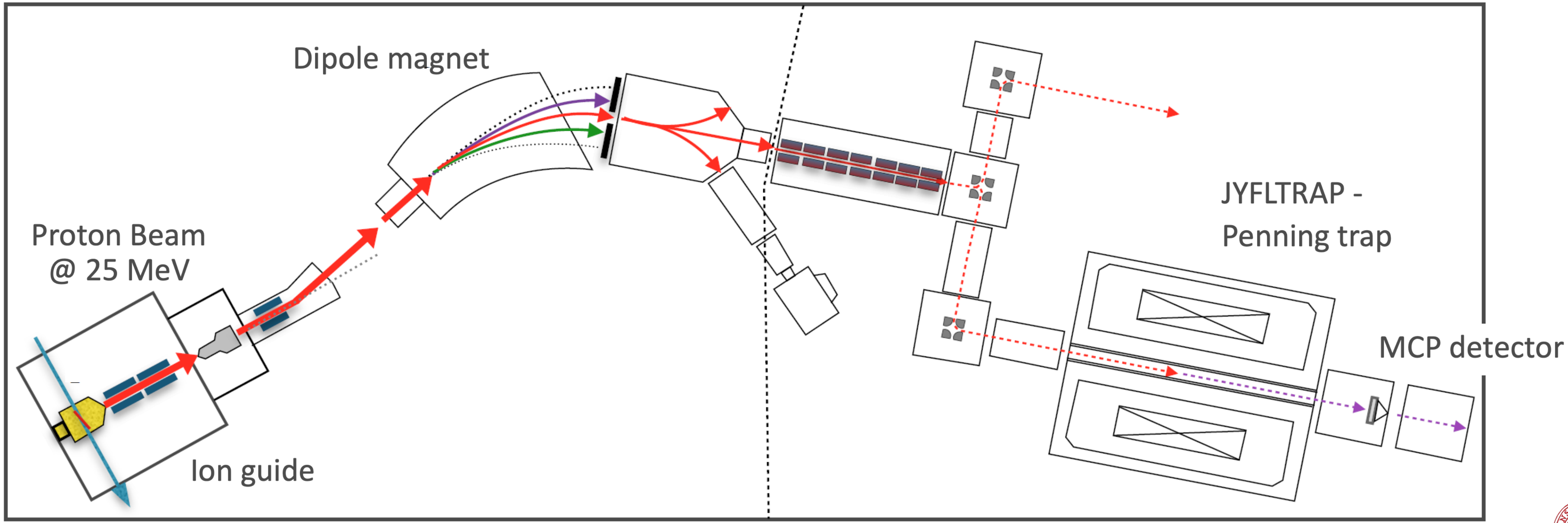
The IGISOL facility

UNIVERSITY OF JYVÄSKYLÄ

Typical measurement cycle 1 s



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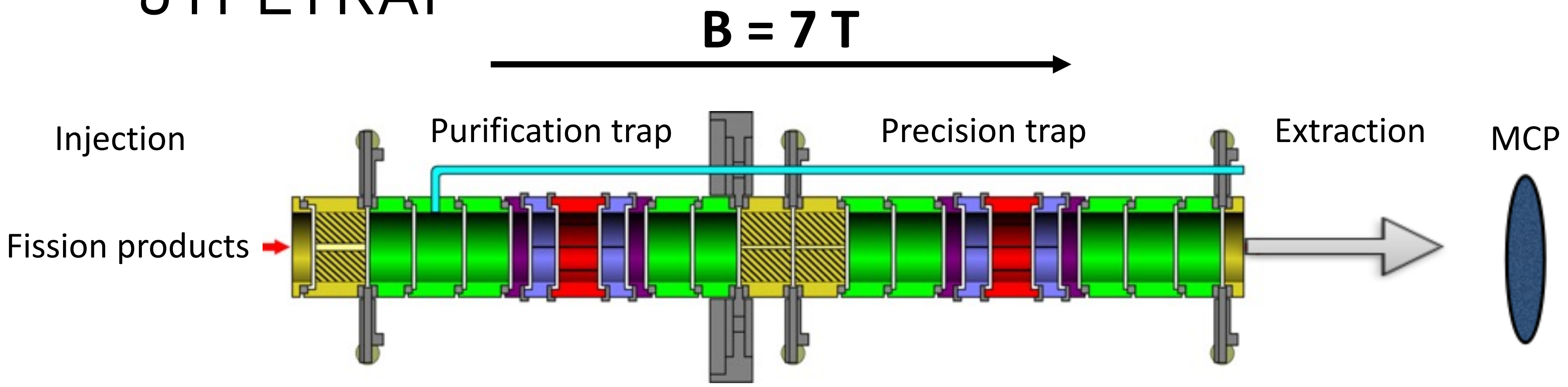
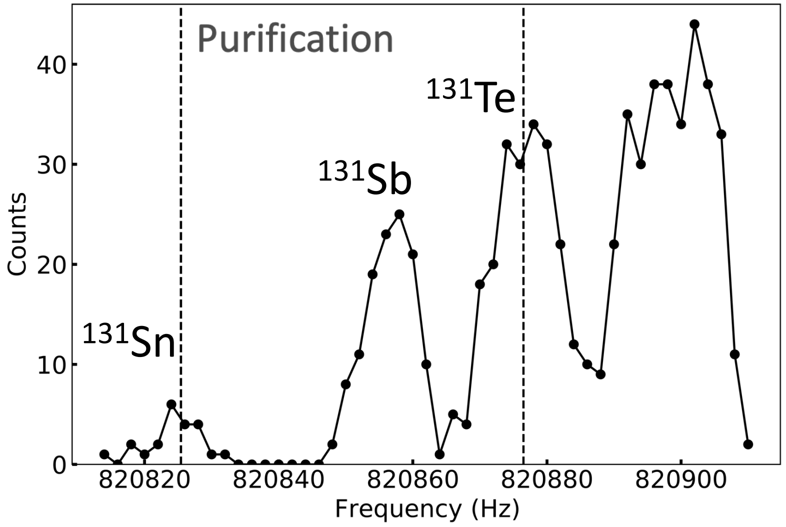
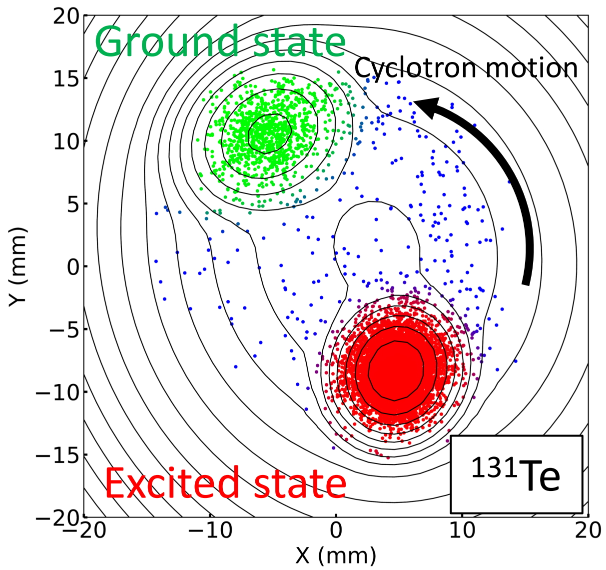
See talk by Simon Rausch

JYFLTRAP







$^{131}Te^{+}$

Ex = 182.3 keV ≈ $2 \cdot 10^{-4}$ u

$$R_{hs} = \frac{Y_{hs}}{Y_{tot}}$$

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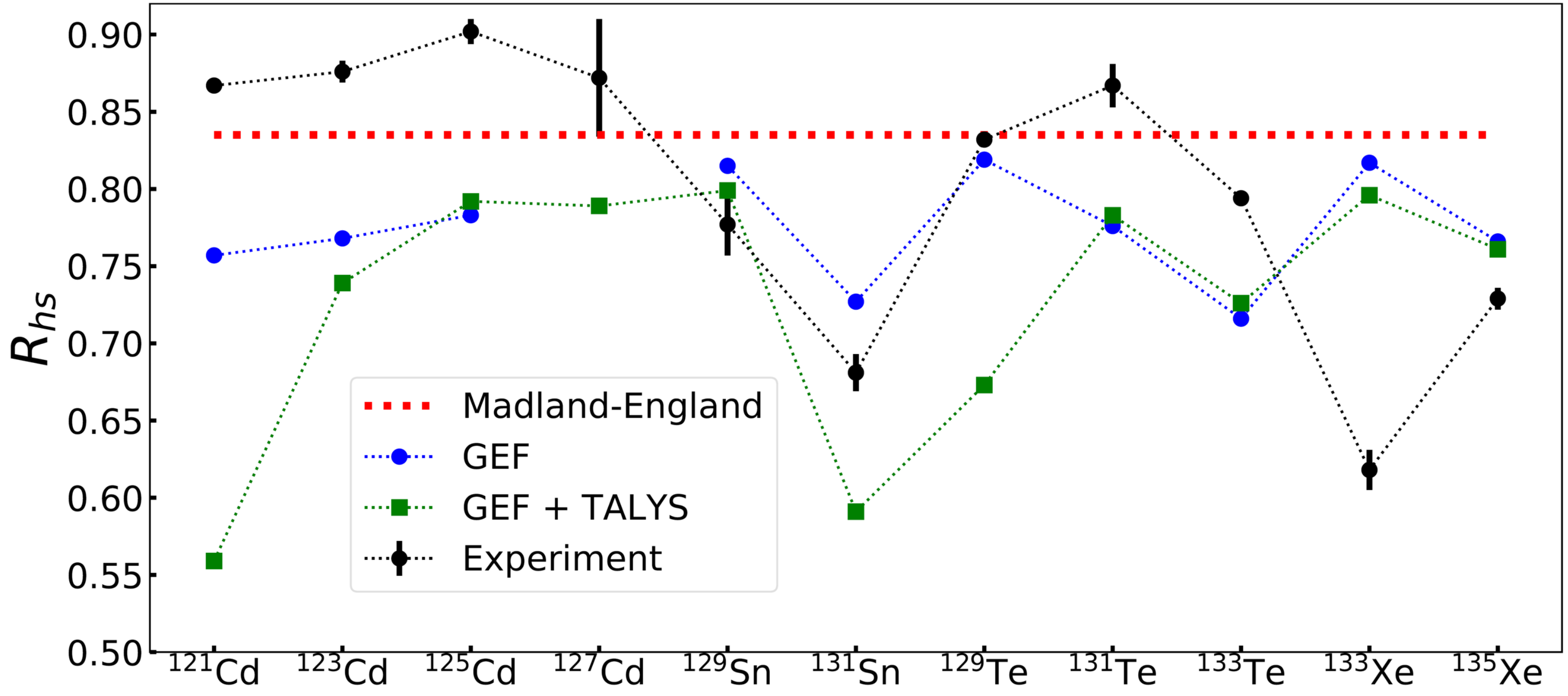
See talk by Simon Rausch

Experimental results

- 35 isomeric yield ratios in $^{238}U(p,f)$
- Comparison with:
  - Madland-England
  - GEF
  - GEF + TALYS

Data for states $3/2^{+}$ and $11/2^{-}$



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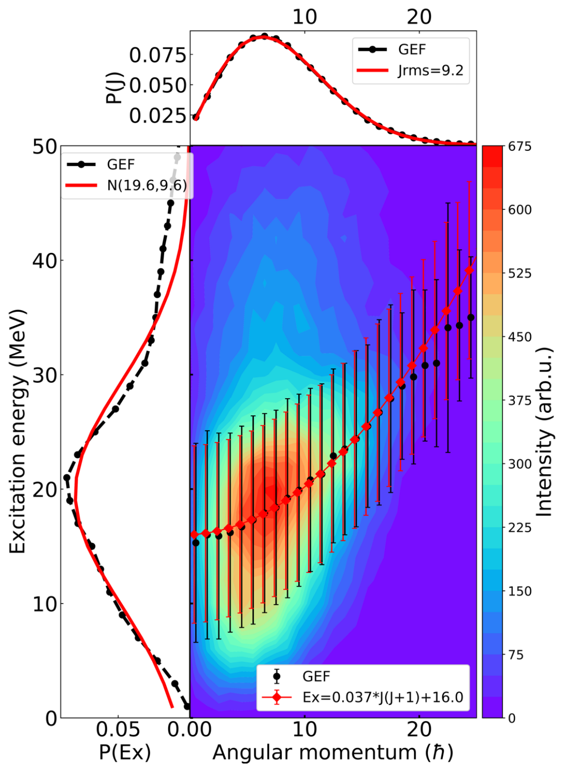
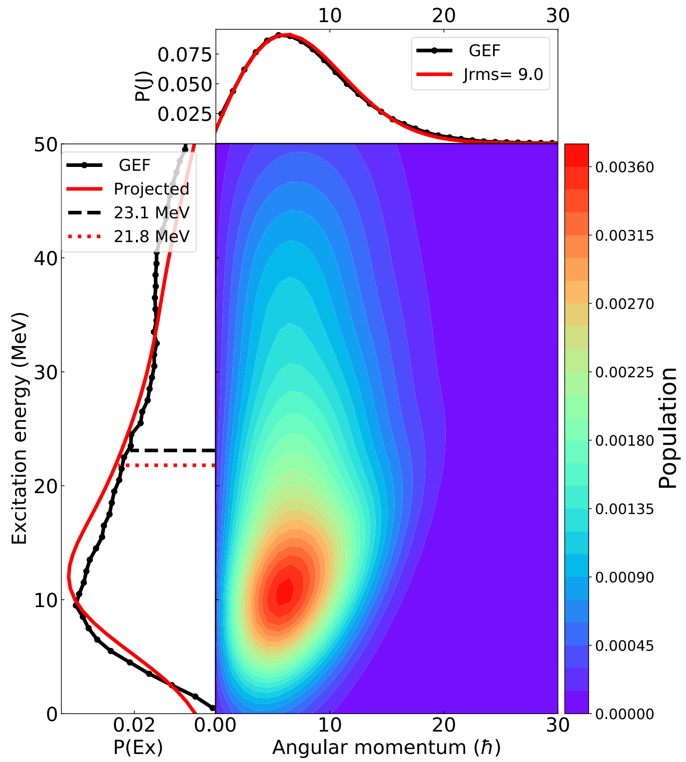
Phys. Rev. C 98, 024612 (2018)
Phys. Rev. C 99, 014617 (2019)
Phys. Rev. C 108, 054613 (2023)

Angular momentum estimation

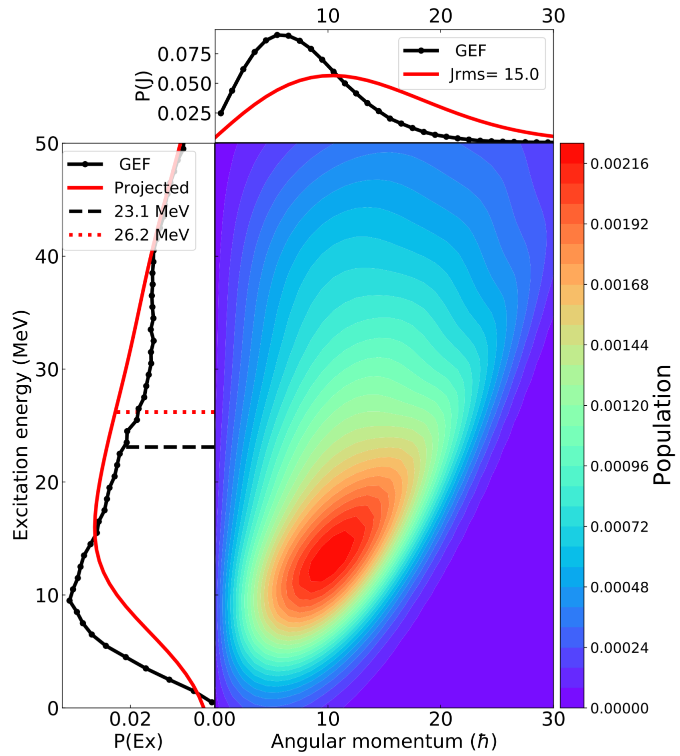
Parametrization of GEF data



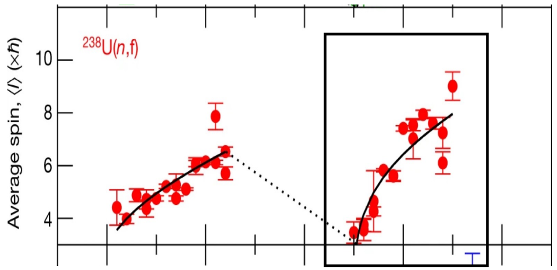
Reconstruction of GEF



Vary J_{rms} and de-excite in TALYS until match measured IYR

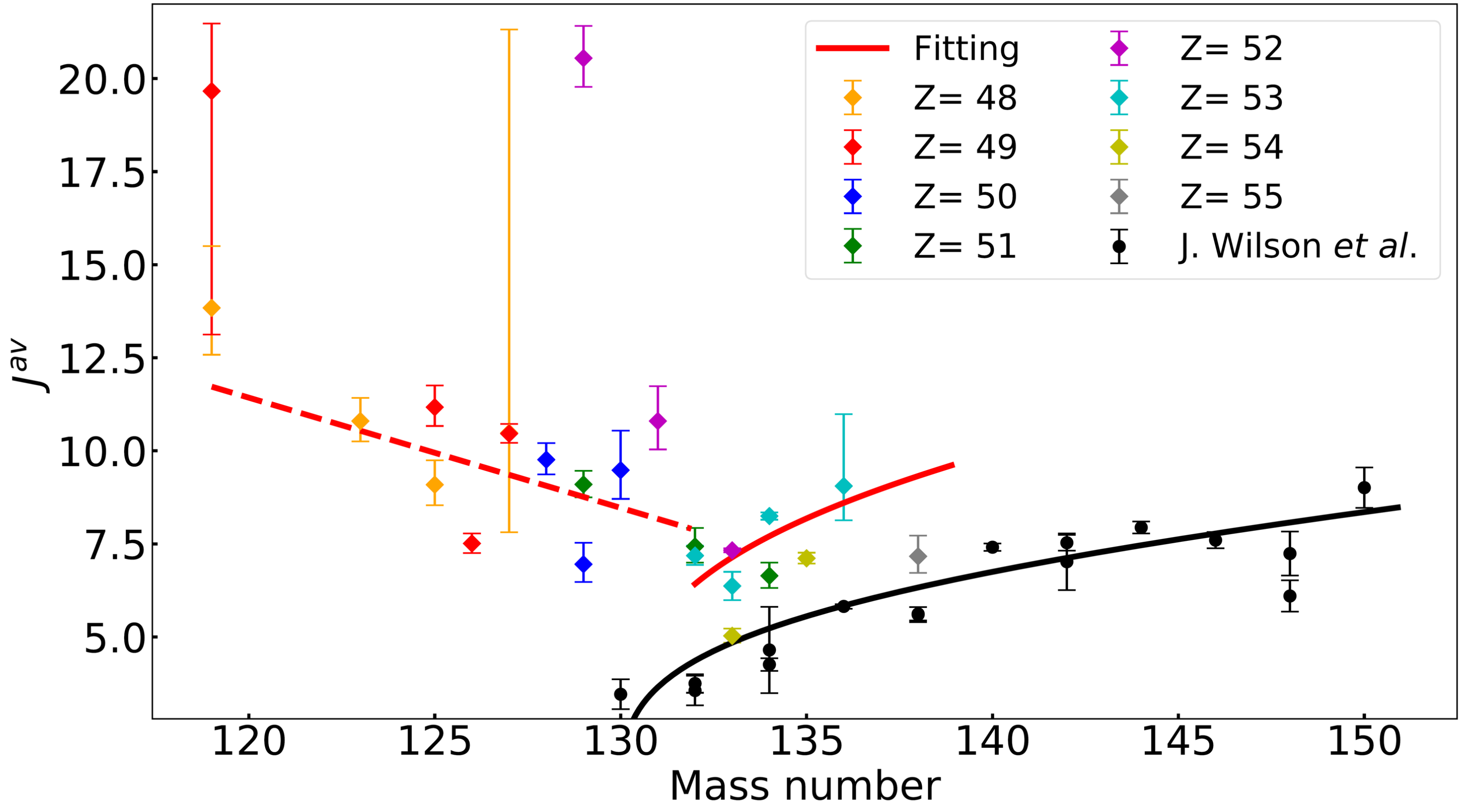


Average angular momenta in $^{238}U(p,f)$



Comparison to Wilson data for $^{238}U(n_{th},f)$.

- Similar saw-tooth shape.
- Larger average angular momenta for all masses.
- Minimum angular momentum around A ≈ 130 - 132.



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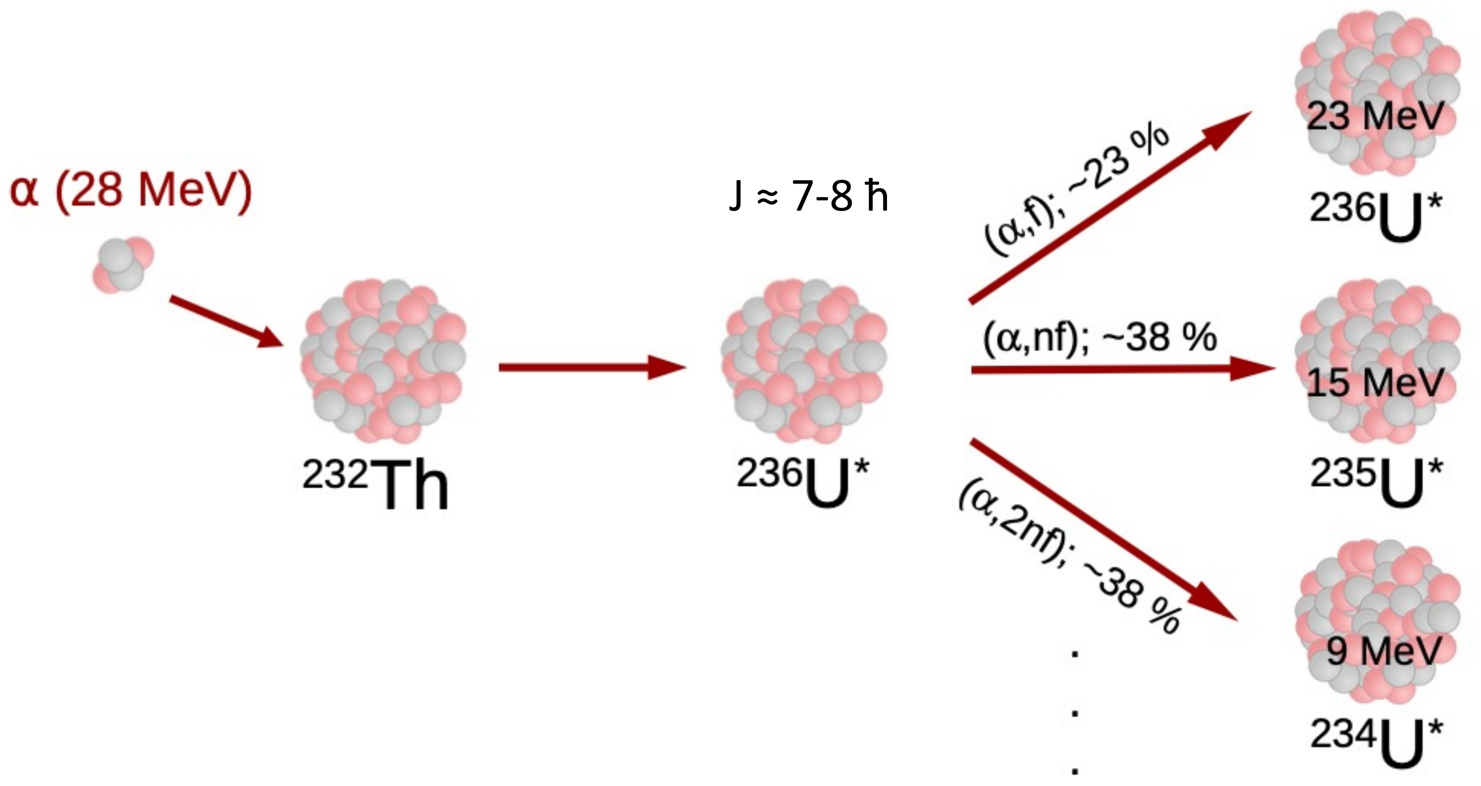
Phys. Rev. C 109, 064626 (2024)

α-induced fission of ^{232}Th



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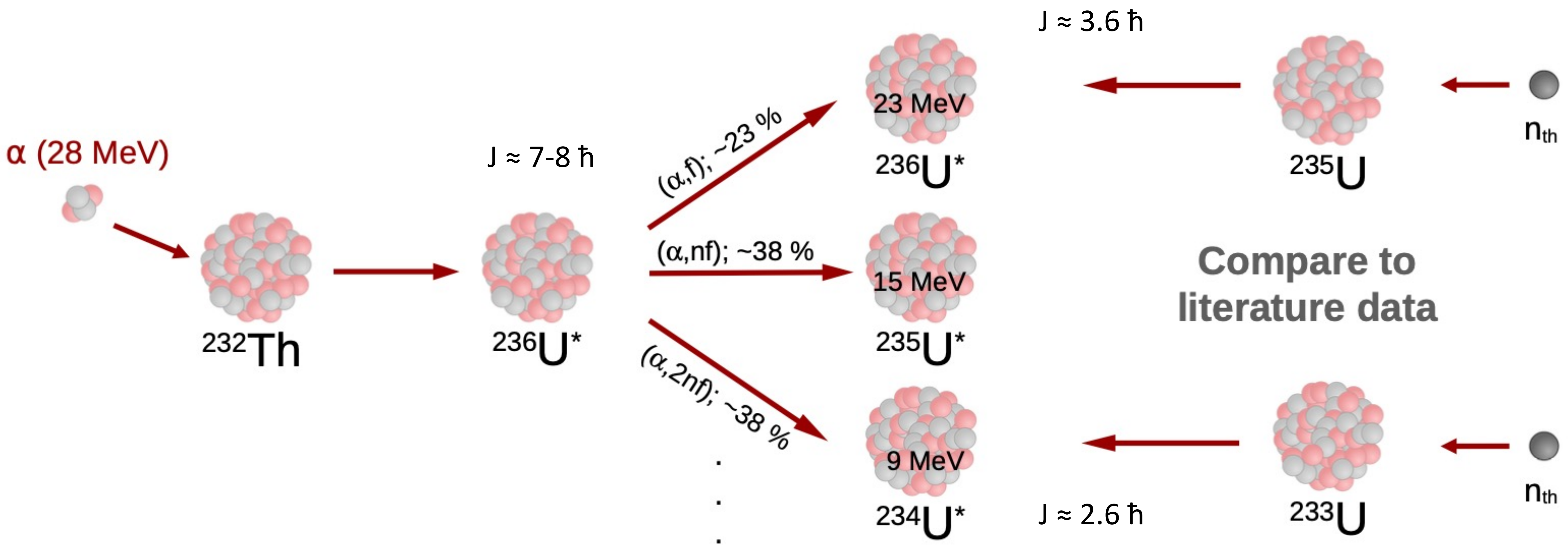

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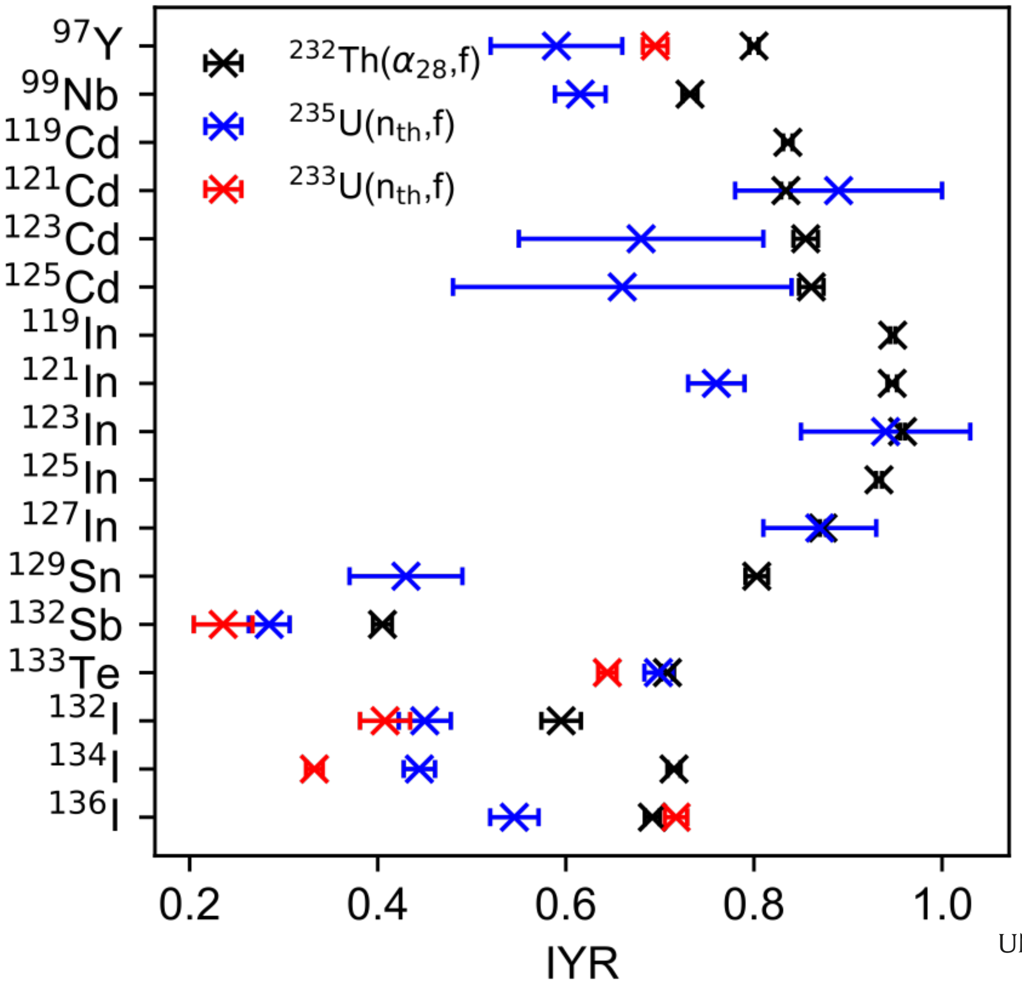
Results

Compared to $^{233,235}U(n_{th},f)$, we observe an increase in the IYR.

We conclude that a significant part (at least 40%) of the extra CN spin goes to the FF. (remaining part likely goes to orbital angular momentum).

The fission fragments <u>do</u> carry a memory of the compound system.



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PRC **111** L031601 (2025)

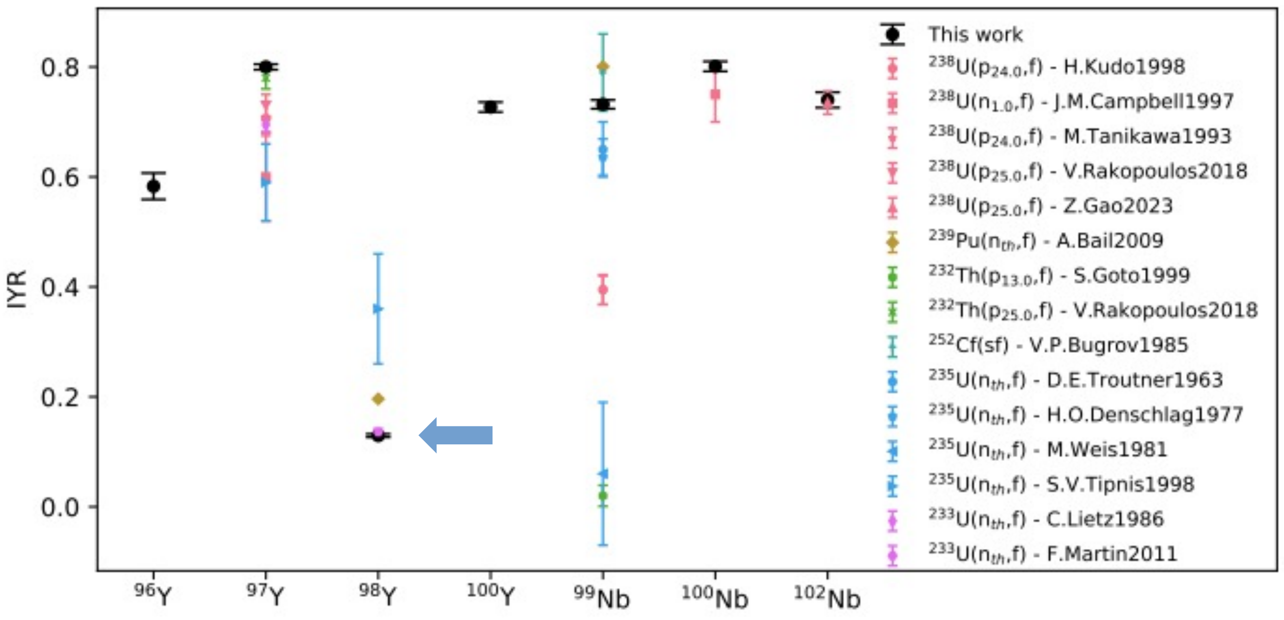
The peculiar case of ^{98}Y

^{98}Y shows a **remarkably low IYR.**

Possible mistake in the spin assignments of the ground and excited states of ^{98}Y?

For ^{100}Y the spin assignment in the databases (ENSDF and NUBASE 2020) disagree.

For ^{100}Nb the ENSDF evaluation explicitly calls for a dedicated measurement for the state ordering of the two isomers



	Ground state		Excited state			
Nuclide	$t_{1/2}$ (s)	I^π	$t_{1/2}$ (s)	I^π	E_x (keV)	IYR
^{96}Y	5.34(5)	0^-	9.6(2)	8^+	1540.5(4)	0.58(2)
^{97}Y (*)	3.75(3)	$1/2^-$	1.17(3)	$9/2^+$	667.52(23)	0.800(5)
^{98}Y	0.548(2)	0^-	2.32(8)	$(6^+, 7^+)$	465.7(7)	0.129(4)
^{100}Y	0.94(3)	4^+	0.727(6)	1^+	144(16)	0.727(9)
^{99}Nb (*)	15.0(2)	$9/2^+$	150(12)	$1/2^-$	365.27(8)	0.732(9)
^{100}Nb	1.5(2)	1^+	2.99(11)	(5^+)	313(8)	0.80(1)
^{102}Nb	4.3(4)	(4^+)	1.31(16)	(1^+)	94(7)	0.74(1)

PLB **871** 140012 (2025)

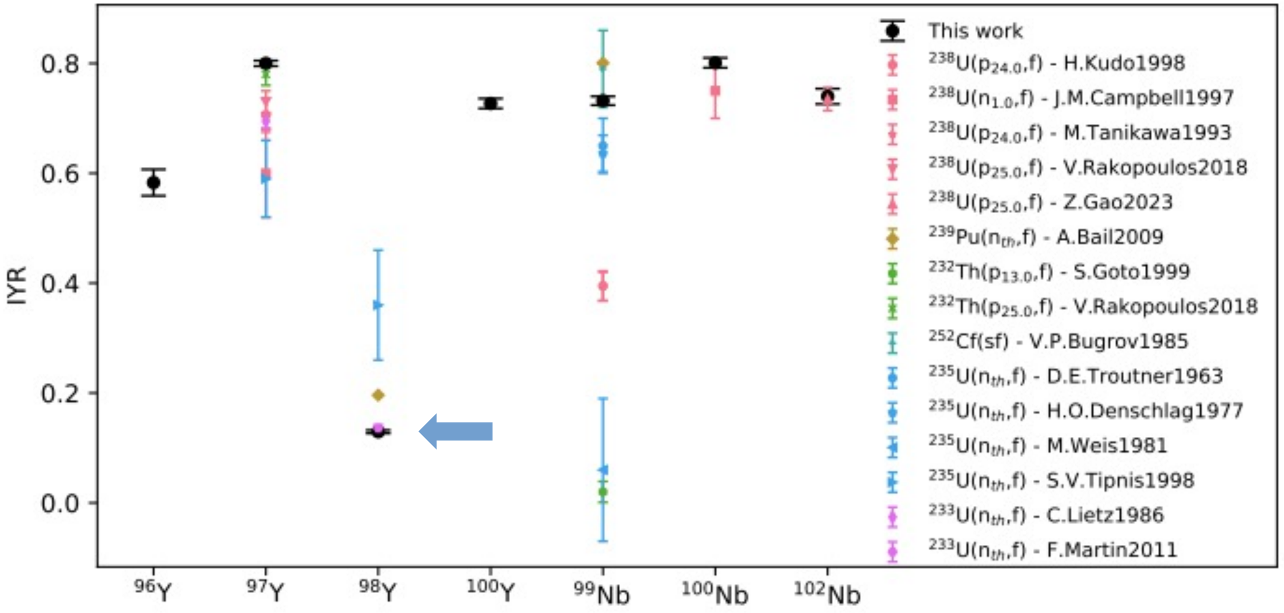
The peculiar case of ^{98}Y

^{98}Y shows a **remarkably low IYR.**

The state ordering of ^{98}Y, ^{100}Y, ^{100}Nb, ^{102}Nb were measured using an in-trap beta decay technique.

The result confirm the state ordering as reported in NUBASE 2020.

Puzzle remain!



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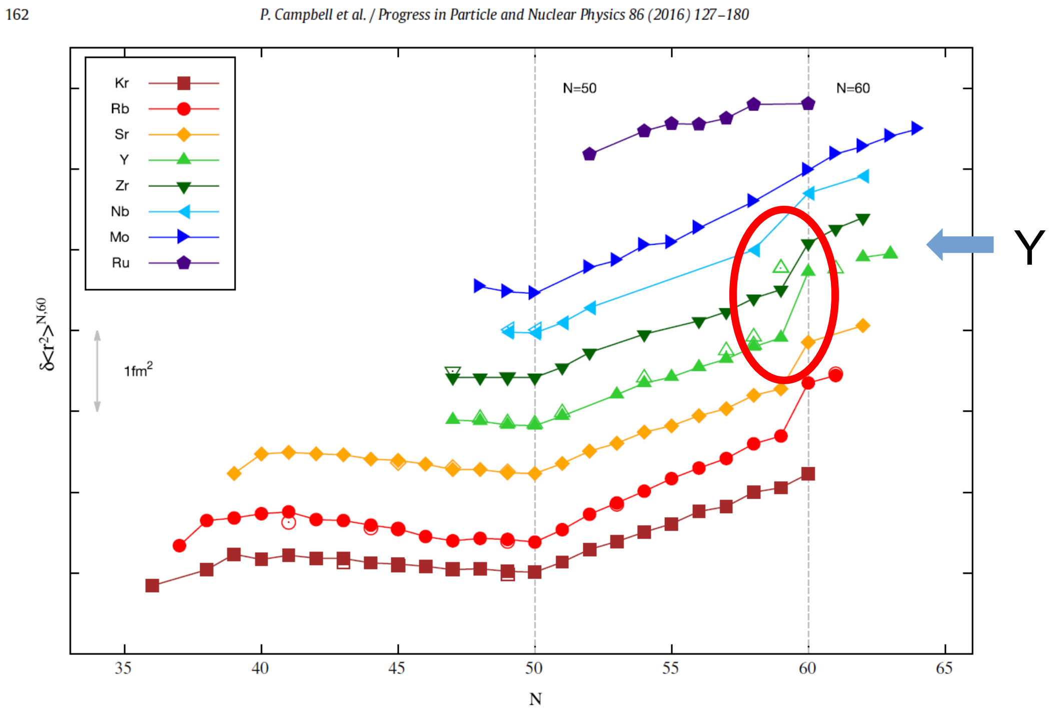
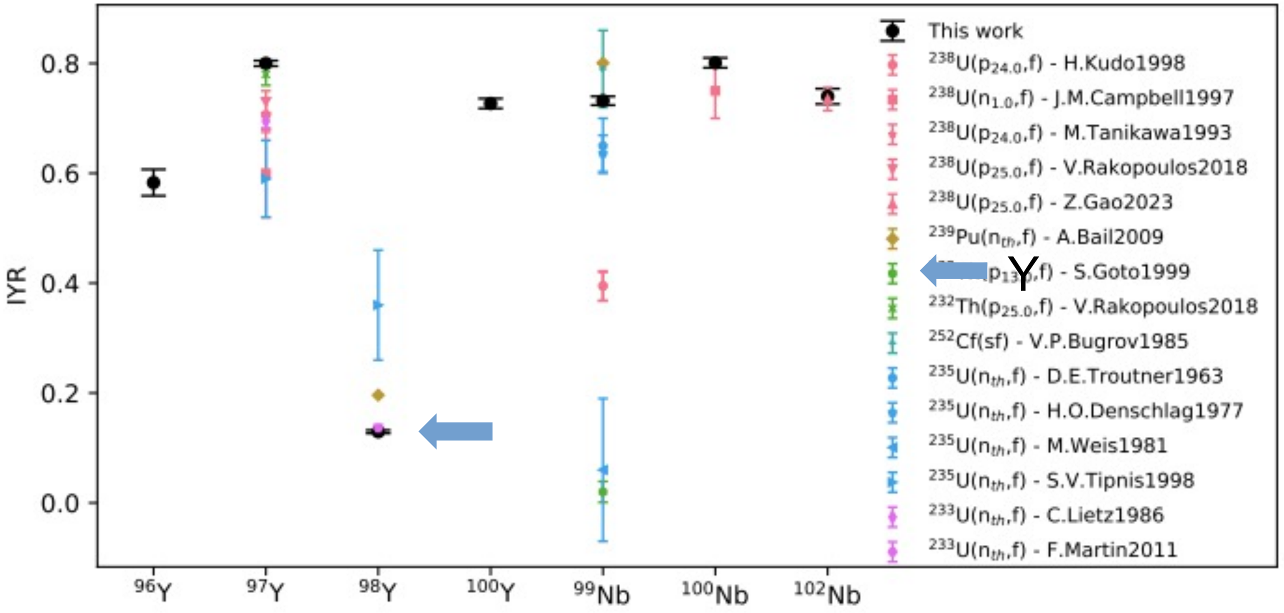
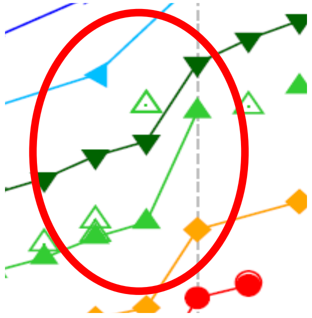
PLB **871** 140012 (2025)

The peculiar case of ^{98}Y

- Large isomeric shift in charge radii
- Probable shape co-existence
- High-spin state rarely populated in fission







PLB **871** 140012 (2025)

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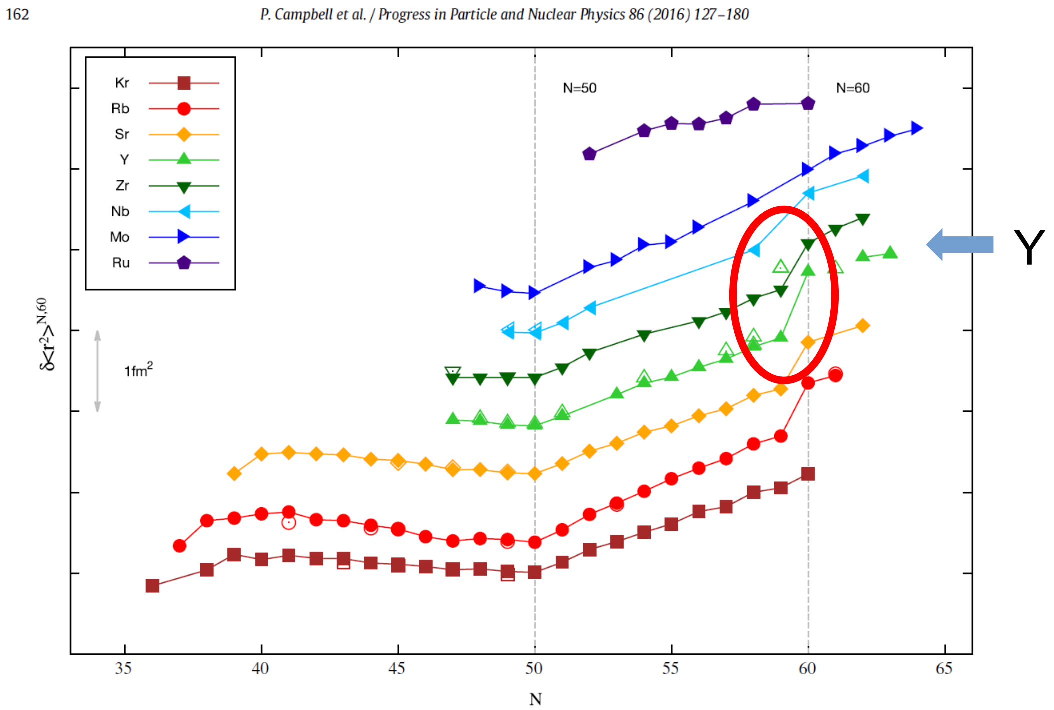
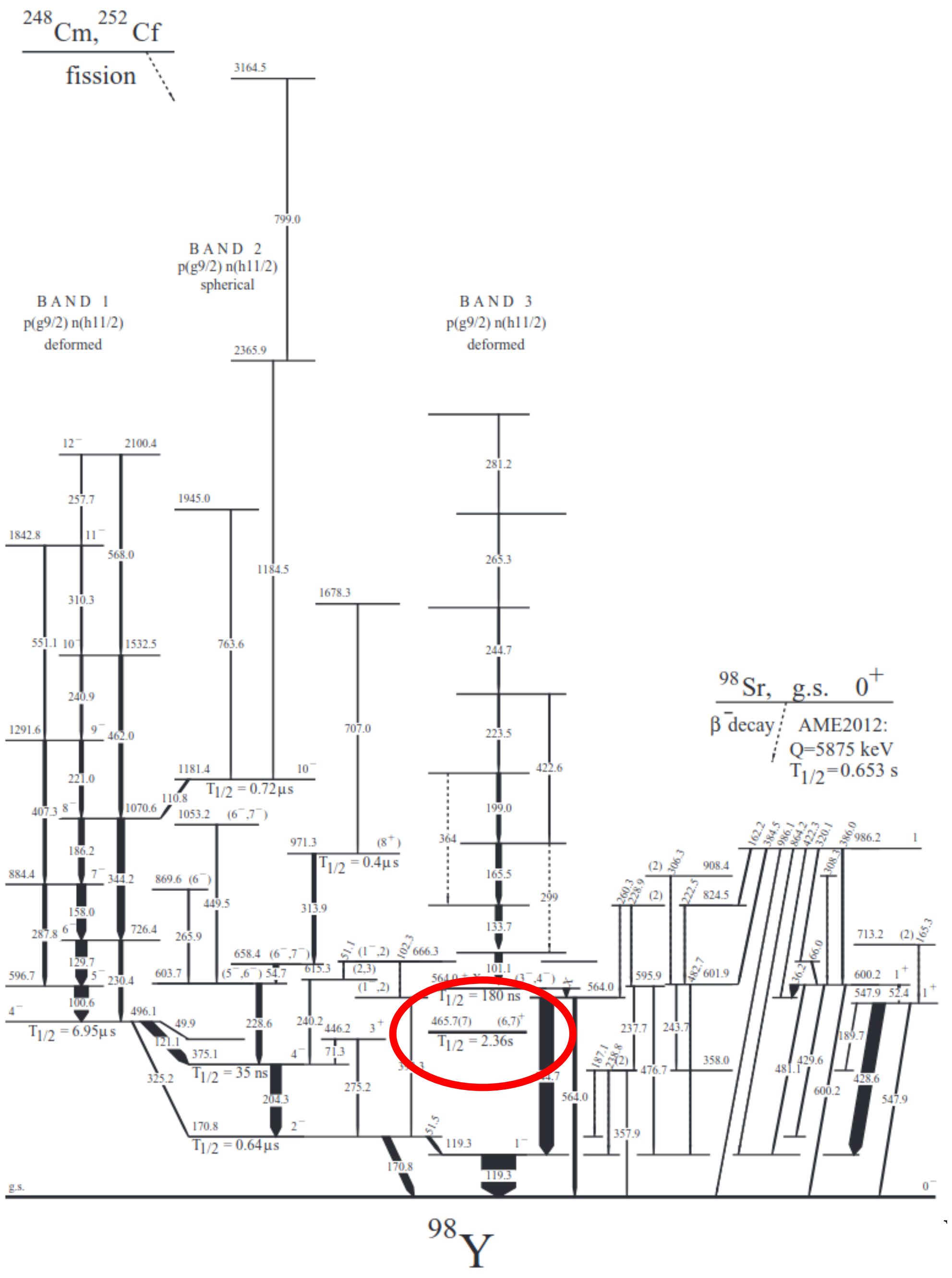


PLB **871** 140012 (2025)



Conclusions

- 35 isomeric yield ratios have been measured in $^{238}U(p,f)$ at 25 MeV.
- Another 22 have been measure in $^{232}Th(\alpha,f)$ at 28 MeV
- A GEF + TALYS based model has been developed to estimate the angular momentum of the pre-neutron-emission fragments that feed the measured isomers.
- Increased CN angular momentum leads to higher fission fragment angular momentum.
- We highlight the unusually small IYR for ^{98}Y and its relation to a large isomeric shift in charge radii.

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Thank You!

Vetenskapsrådet

The Finnish Academy of Science

Strål säkerhets myndigheten
Swedish Radiation Safety Authority

CHANDA

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