Catching the spin:
Isomeric yield ratios by ion counting for studies in fission dynamics

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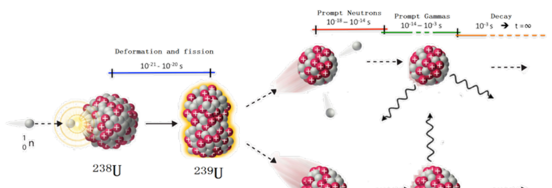
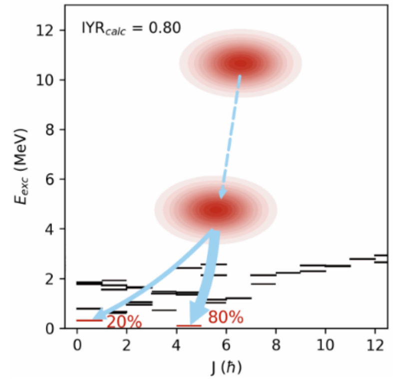
Outline

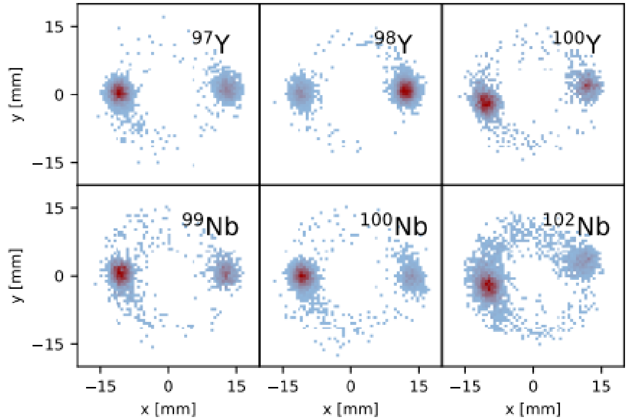




Motivation and background

Isomeric yield ratios (IYRs) for studying

<u>angular momenta of fission fragments</u>

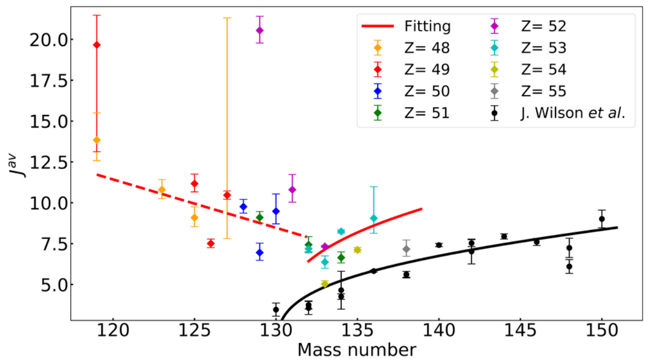


Experimental approach and ...

… results from IGISOL for ^{232}Th(α,f)

highlighting the impact of CN angular momentum

… and with special attention to the ^{98}Y region



Linking isomeric yields from ^{238}U(p,f) ...

… to fission fragment angular momenta

Summary and outlook

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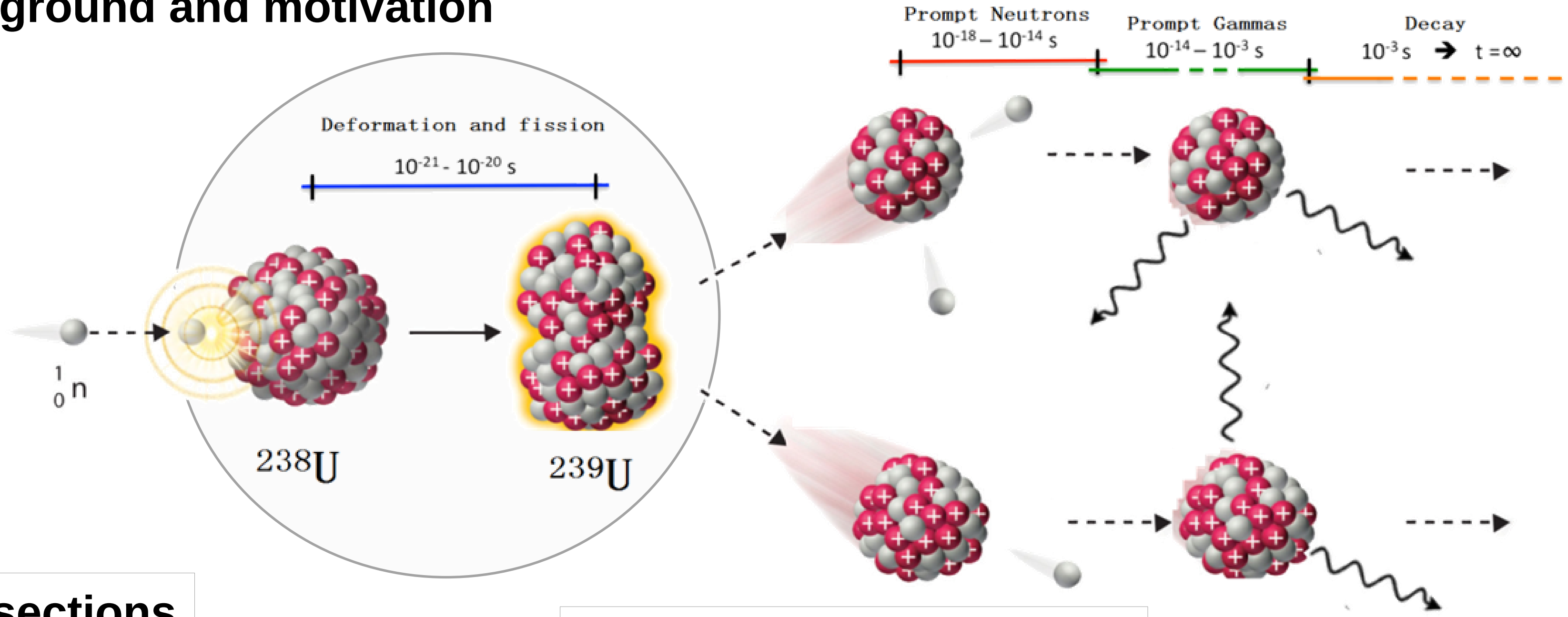
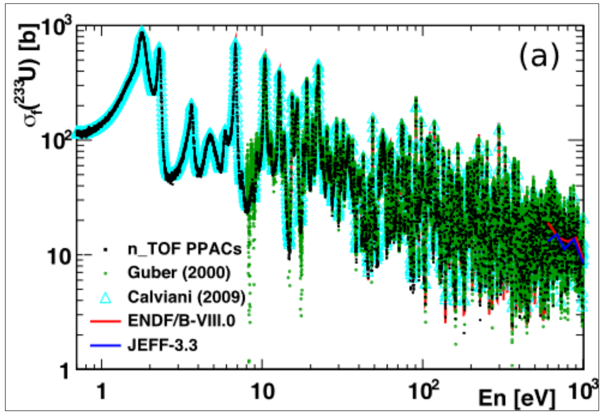
Background and motivation

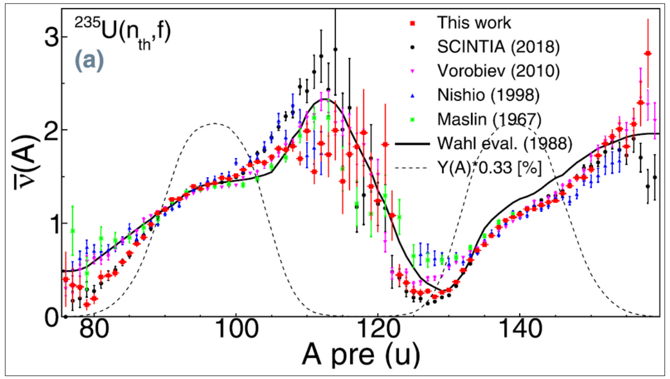


cross sections



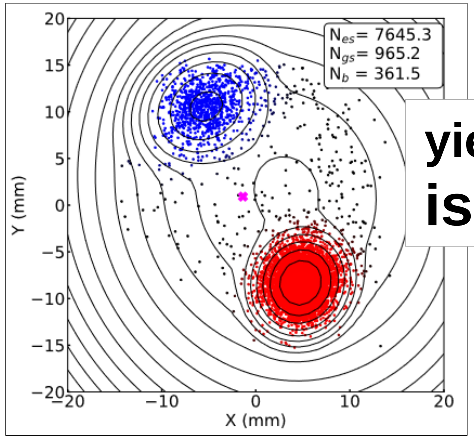
D. Tarrío et al, Phys. Rev. C **107**, 044616 (2023)

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)

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)

Angular momentum of fission fragments

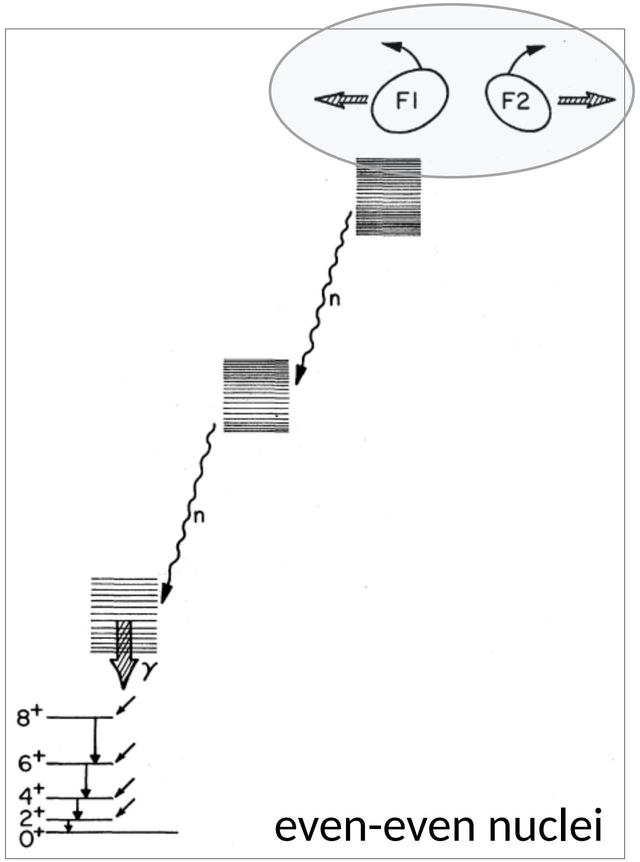
Wilhelmy et al (1972):
Fission fragments from ^{252}Cf(sf)
have **angular momenta of about 7 ħ**.

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** angular momentum generation;
  collective vibrations; wriggling, bending, twisting;
  see e.g. J. Randrup and R. Vogt and the FREYA code

- **post-scission** models
  Coulomb forces; microscopic theories (e.g. Bertsch et al. 2019)



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Angular momentum of fission fragments

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

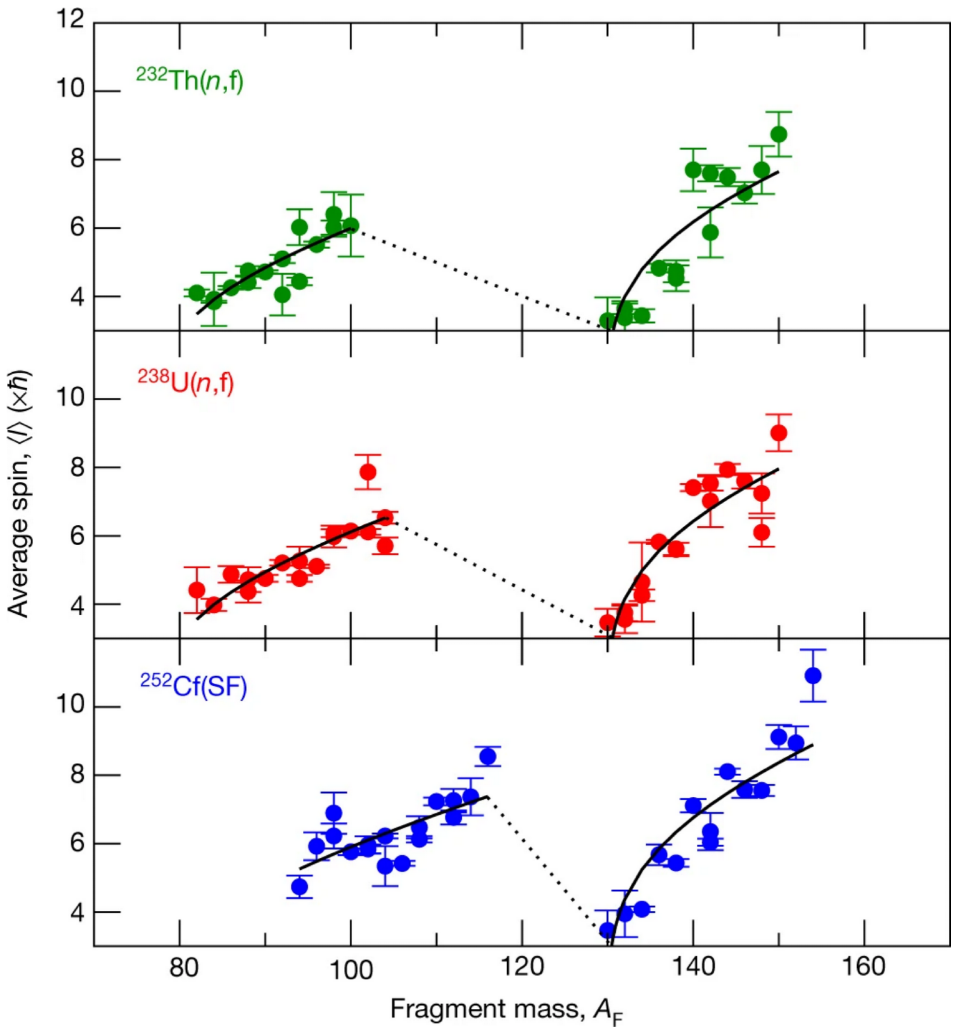
Method: γ-ray spectroscopy on 0^+ fission products

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

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).



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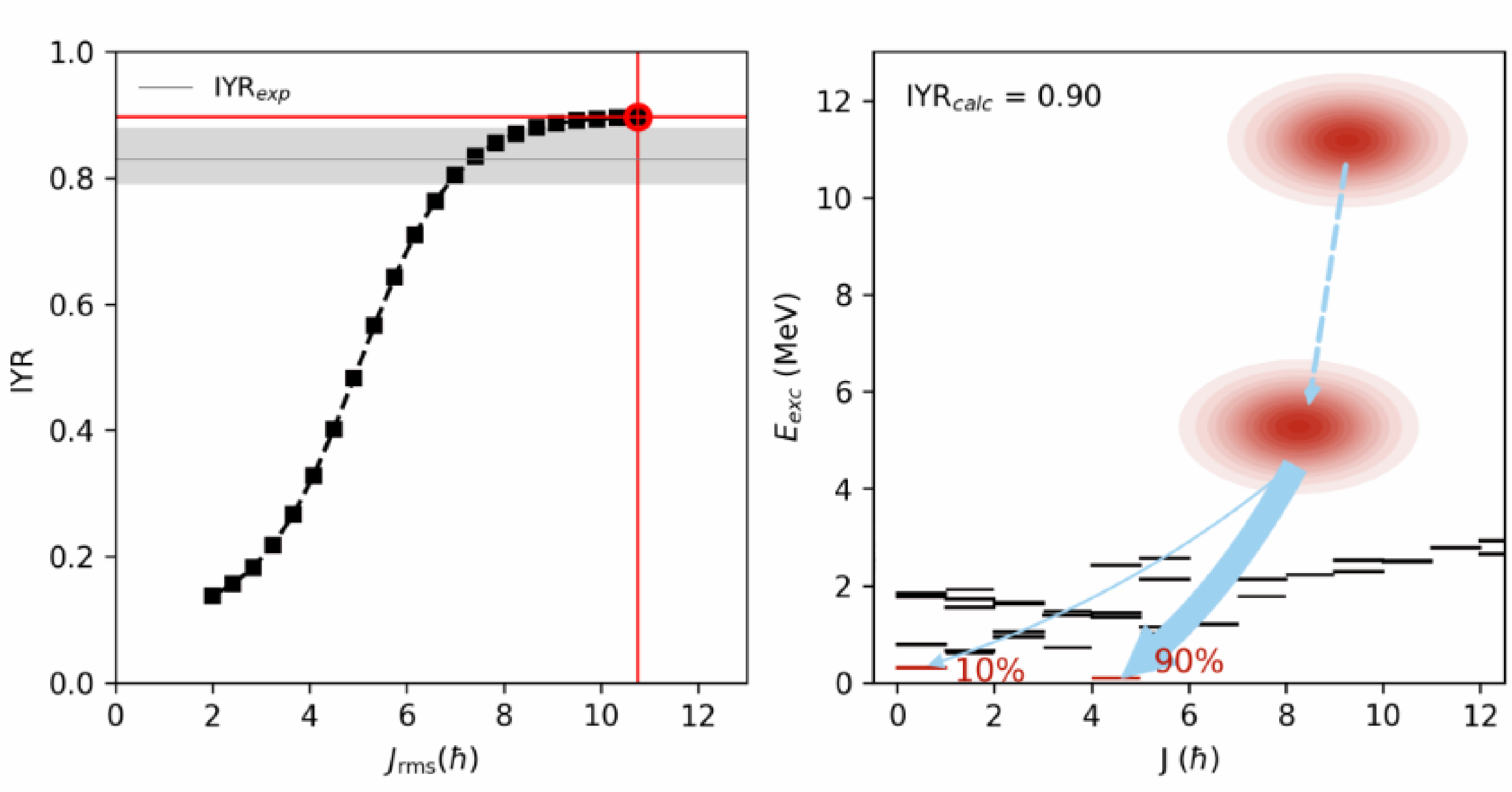
Isomers from fission and fragment angular momenta (using direct ion counting)

1) Measure IYR, i.e., relative population of (long-lived) isomers.

2) Develop methods to “back-track” and determine J_{rms} of fragments.

$$IYR = \frac{Y_{high\ spin}}{Y_{high\ spin} + Y_{low\ spin}}$$



Fission fragment

Prompt neutron emission

Fission product

Prompt gamma emission

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Experimental approach

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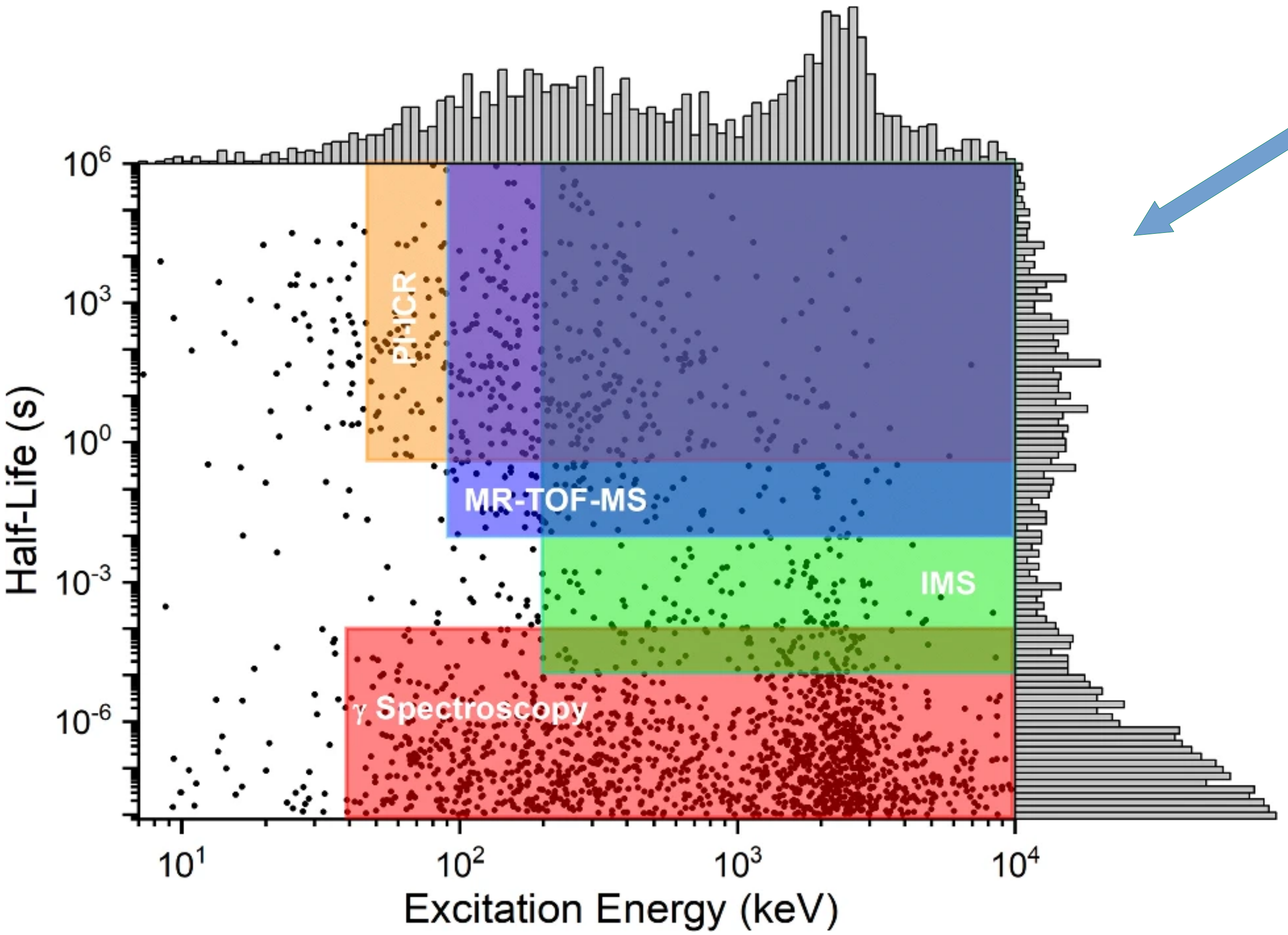
Possible measurement techniques for IYR



Dickel, T., Mollaebrahimi, A., *Eur. Phys. J. Spec. Top.* **233**, 1181–1190 (2024)

We use direct ion counting,
i.e., mass measurement techniques like phase-imaging ion-cyclotron-resonance (PI-ICR) and multi-reflection time-of-flight (MR-TOF)

These techniques offer a significant advantage compared to techniques using γ-ray spectroscopy, since **we do not rely on available knowledge of the nuclear level schemes.**

However, these techniques require relatively “long” half-lives.

This is pioneered by the Uppsala group in collaboration with the IGISOL group at the University of Jyväskylä, Finland.

See, e.g., Rakopoulos et al PRC 2018 and 2019, and R. Korkiamäki, MSc thesis, University of Jyväskylä (2024)

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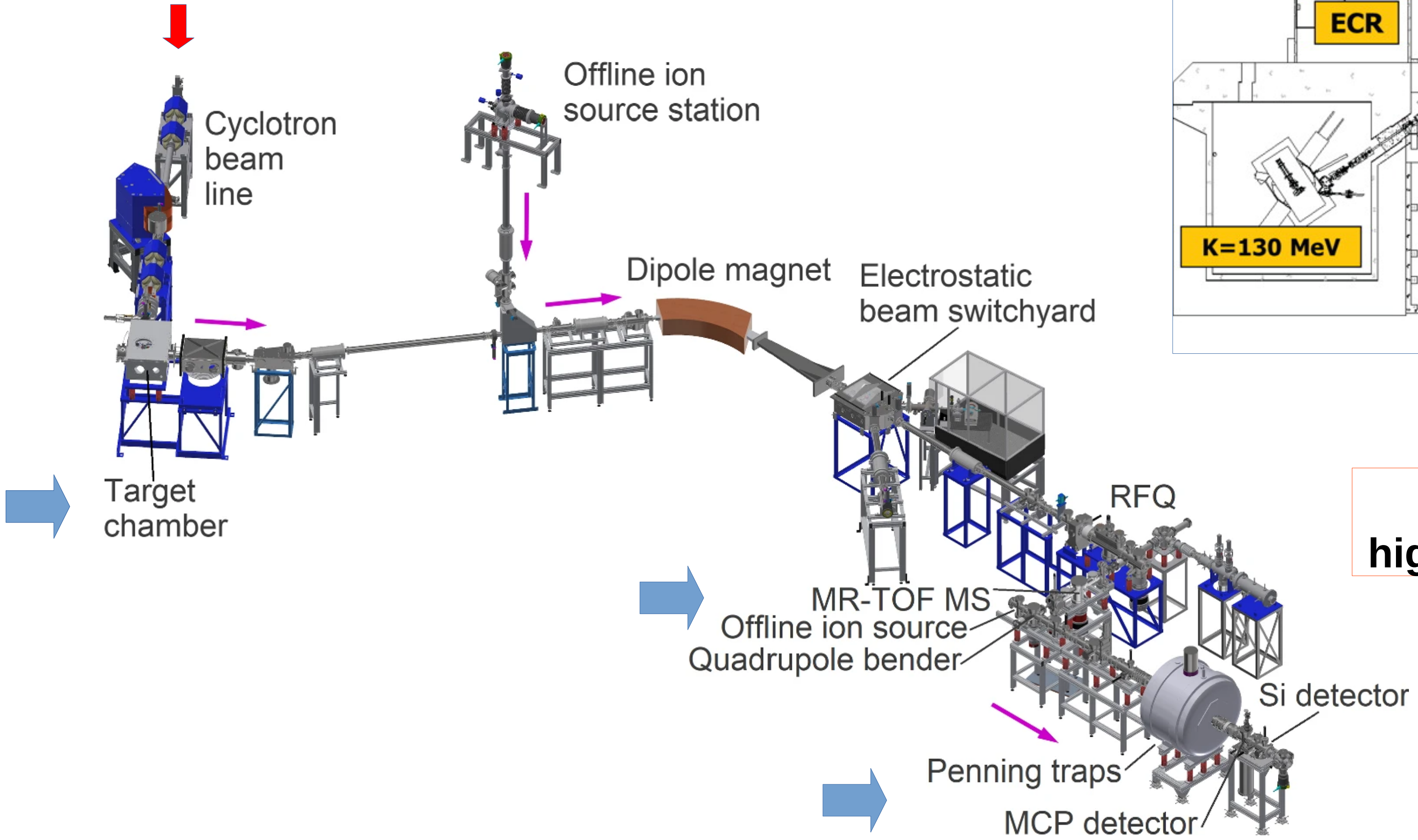
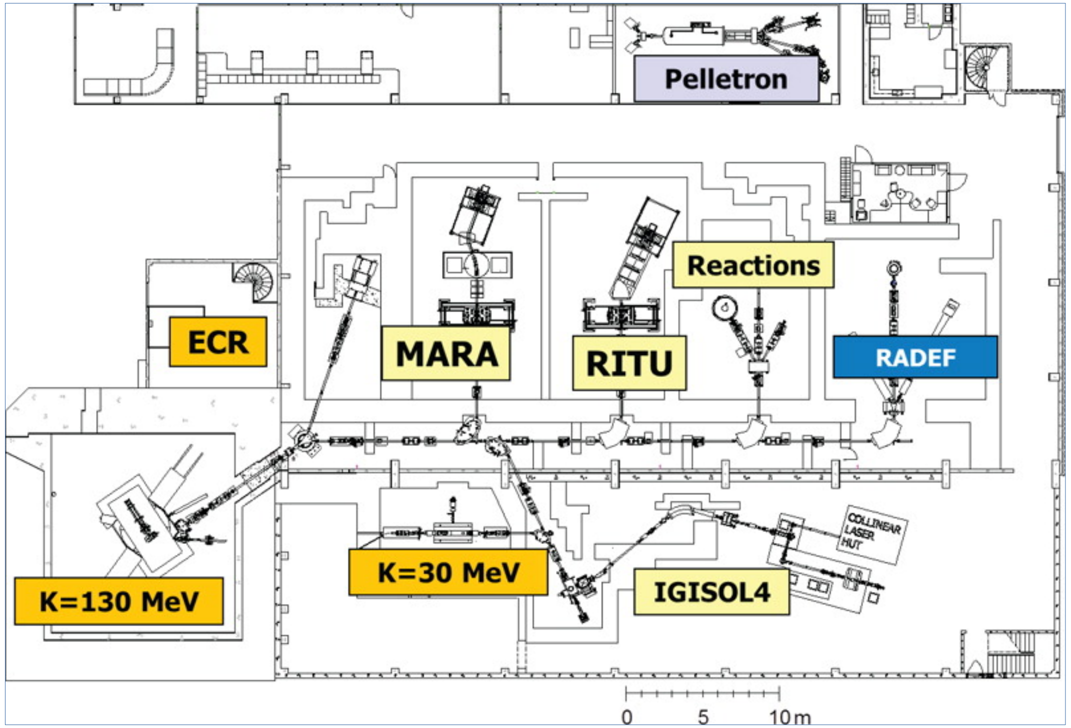
IGISOL with MR-TOF and JYFLTRAP

Beam from K-130 cyclotron





Ari Jokinen, Nuclear Physics News 24(4), 2014
https://doi.org/10.1080/10619127.2014.972165

The lab is well-known for, e.g.,
high-precision mass measurements

Several presentations at EuNPC, see, e.g., talk by Z. Ge (Monday)

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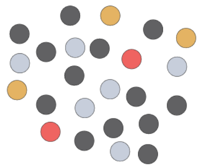
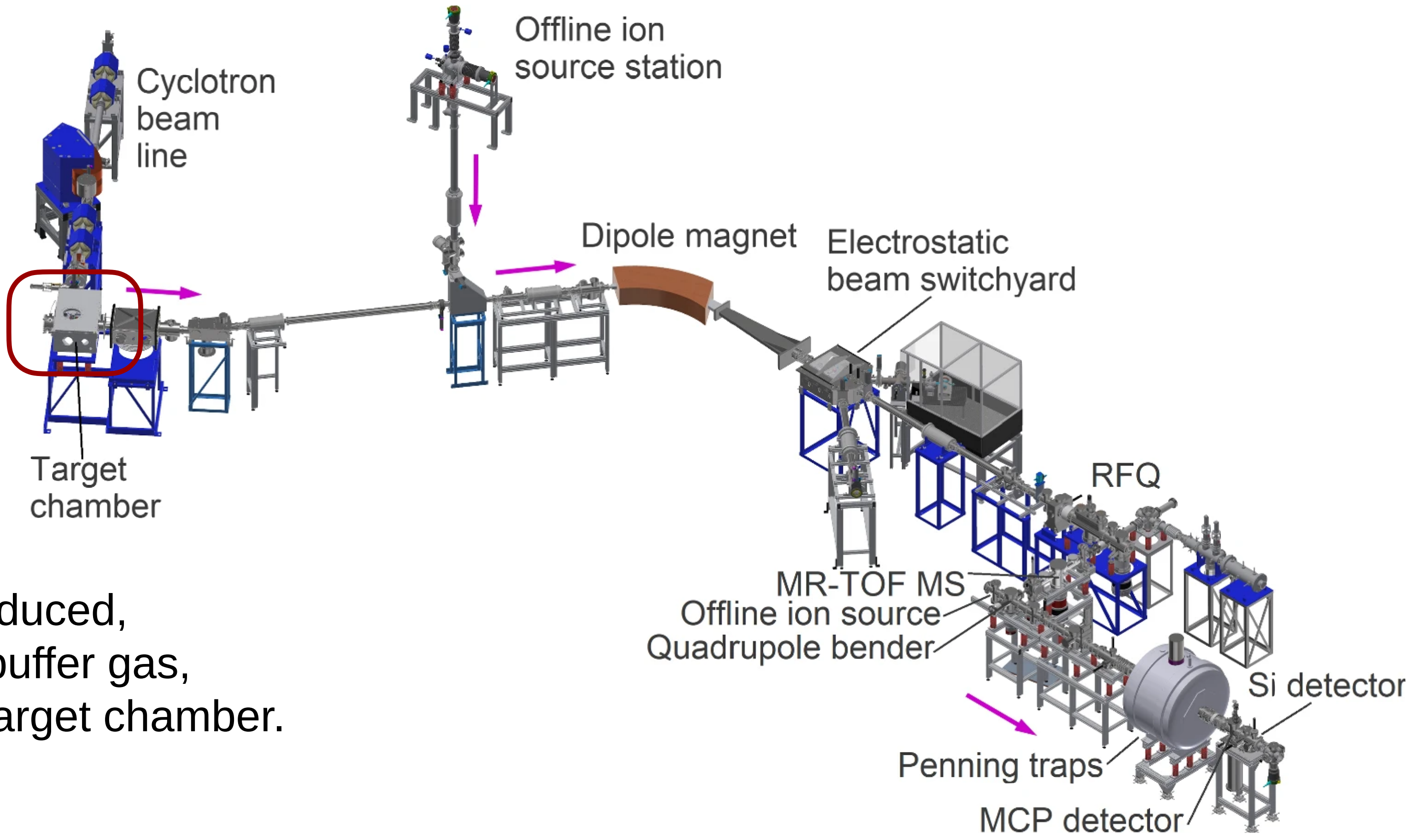
IGISOL with MR-TOF and JYFLTRAP





Fission products produced,
slowed down in He-buffer gas,
and extracted from target chamber.

Nesterenko, D.A., Eronen, T., Ge, Z. et al. “Study of radial motion phase advance during motion excitations in a Penning trap and accuracy of JYFLTRAP mass spectrometer.” Eur. Phys. J. A 57, 302 (2021)

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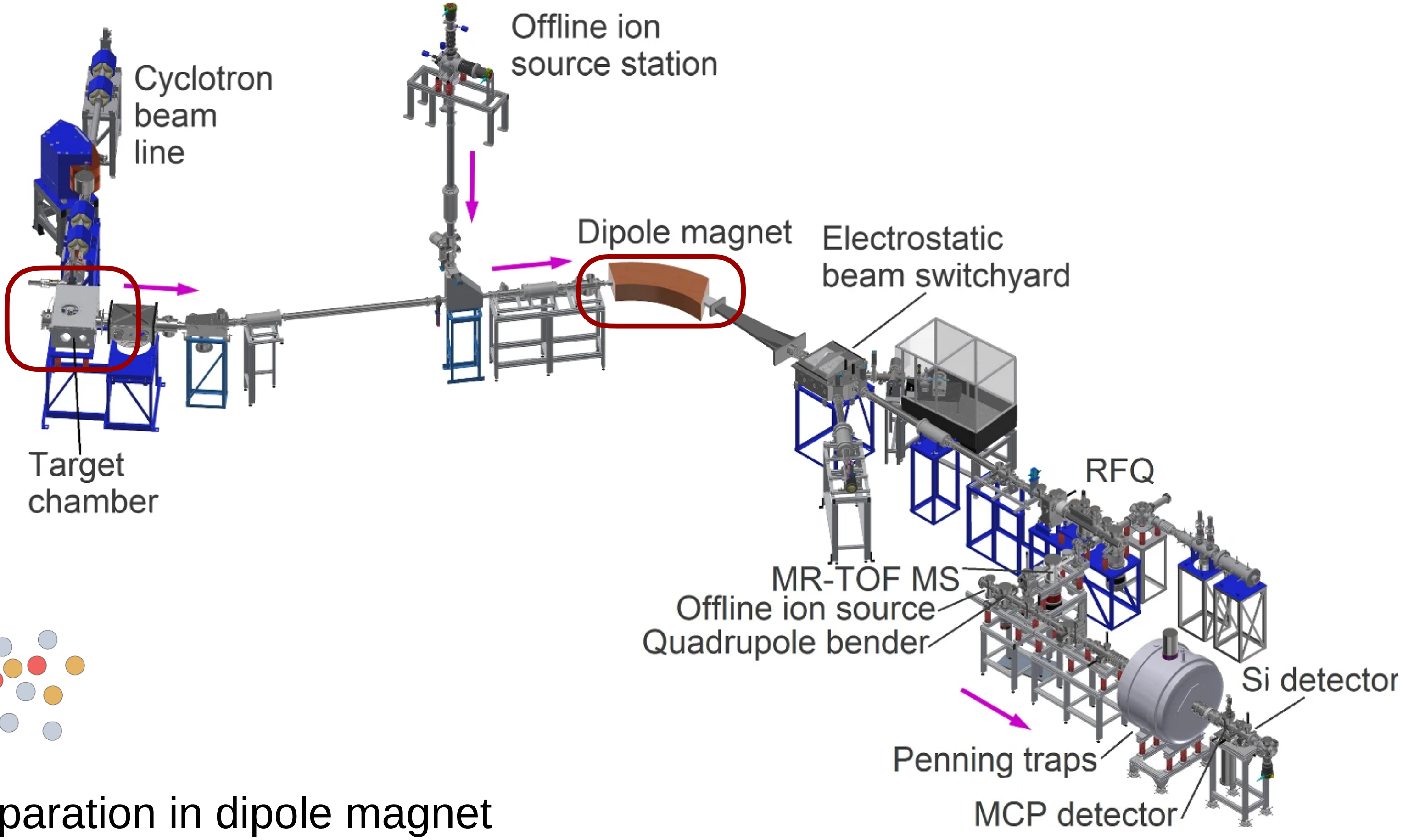
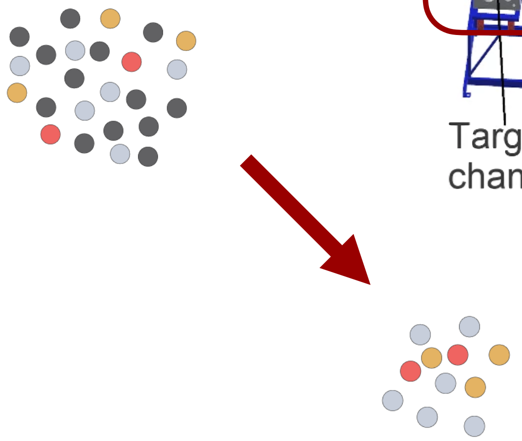
IGISOL with MR-TOF and JYFLTRAP





First mass separation in dipole magnet selects one isobar (usually in 1^{+} state).

Nesterenko, D.A., Eronen, T., Ge, Z. et al. “Study of radial motion phase advance during motion excitations in a Penning trap and accuracy of JYFLTRAP mass spectrometer.” Eur. Phys. J. A 57, 302 (2021)

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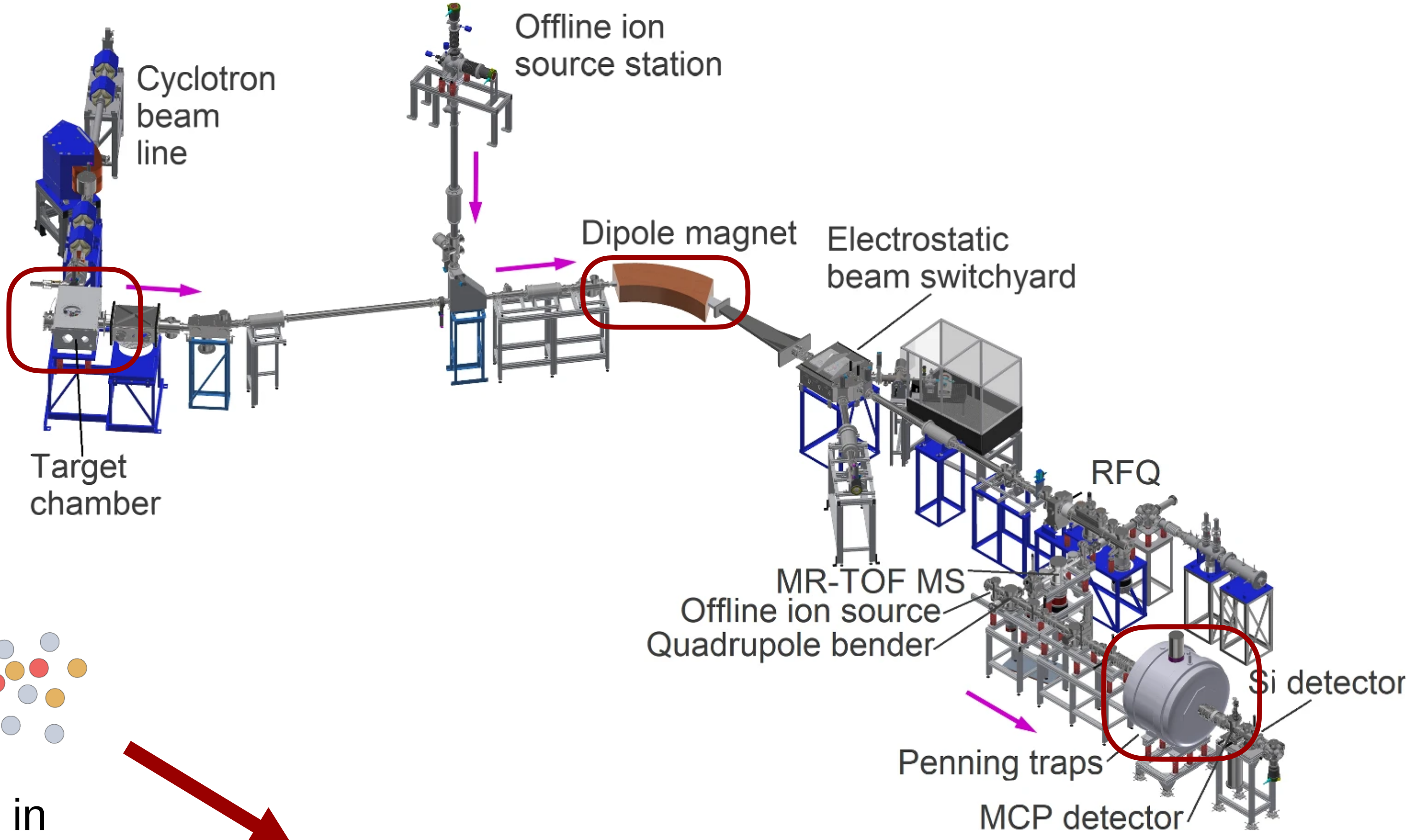
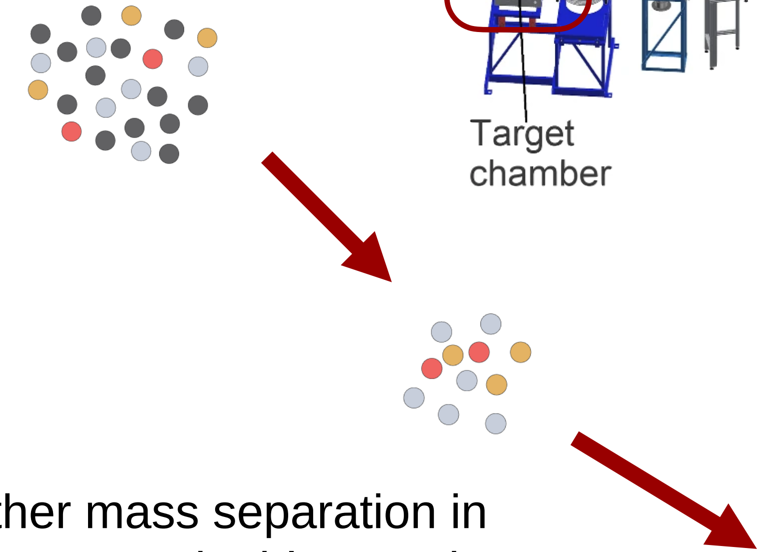
IGISOL with MR-TOF and JYFLTRAP





Further mass separation in
JYFLTRAP double Penning trap
(resolving ΔE of a few 10 keV).

Nesterenko, D.A., Eronen, T., Ge, Z. et al. “Study of radial motion phase advance during motion excitations in a Penning trap and accuracy of JYFLTRAP mass spectrometer.” Eur. Phys. J. A 57, 302 (2021)

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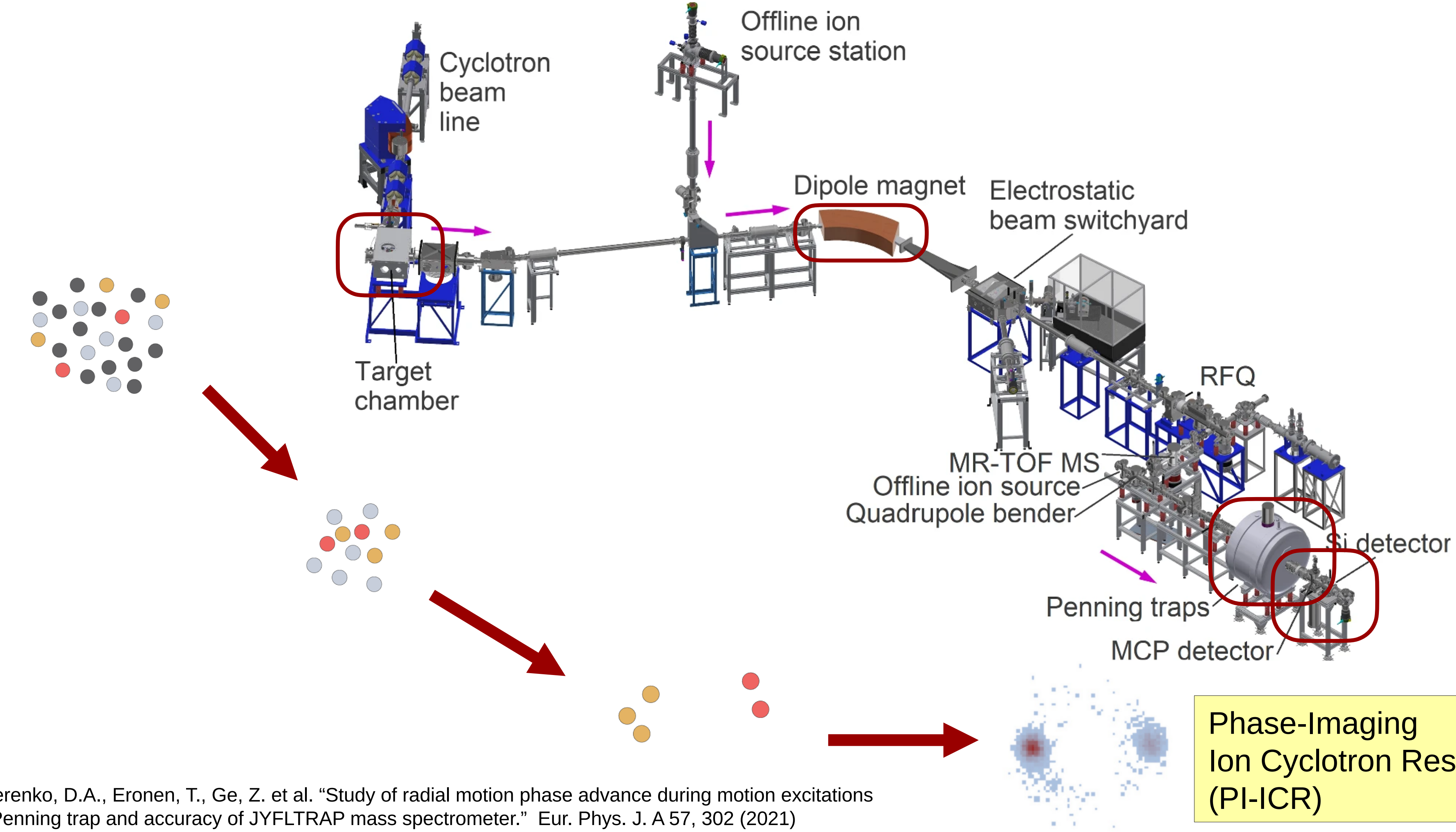
IGISOL with MR-TOF and JYFLTRAP



Phase-Imaging
Ion Cyclotron Resonance
(PI-ICR)

Nesterenko, D.A., Eronen, T., Ge, Z. et al. “Study of radial motion phase advance during motion excitations in a Penning trap and accuracy of JYFLTRAP mass spectrometer.” Eur. Phys. J. A 57, 302 (2021)

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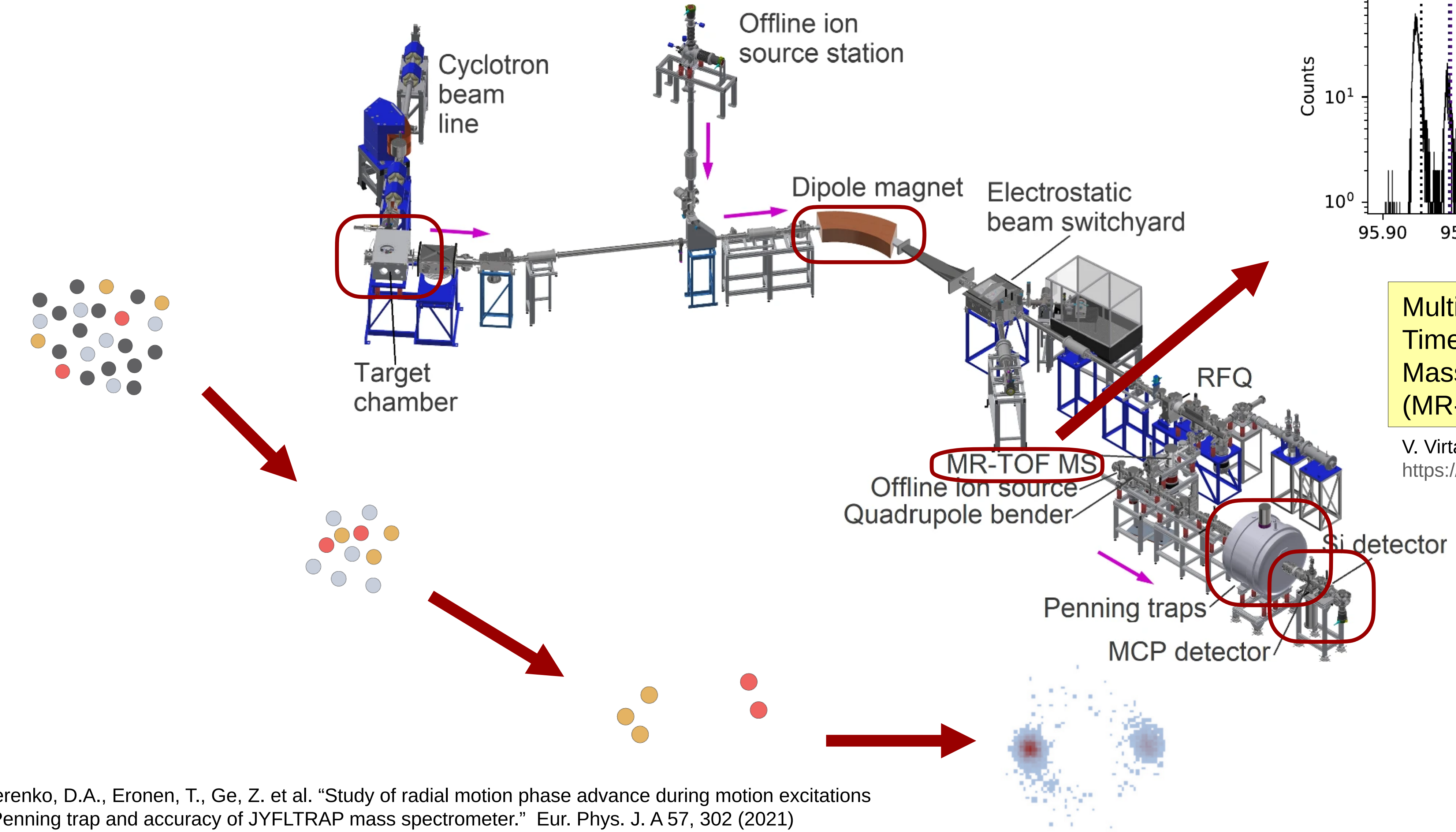
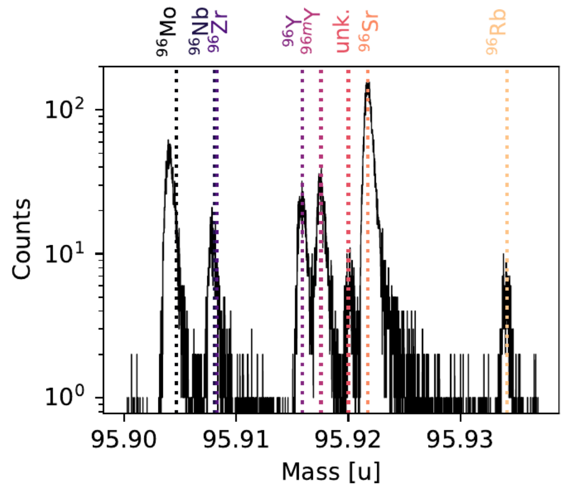
IGISOL with MR-TOF and JYFLTRAP





Multi-Reflection Time-Of-Flight Mass Spectrometer (MR-TOF-MS)

V. Virtanen et al.
https://doi.org/10.48550/arXiv.2508.10048.

Nesterenko, D.A., Eronen, T., Ge, Z. et al. "Study of radial motion phase advance during motion excitations in a Penning trap and accuracy of JYFLTRAP mass spectrometer." Eur. Phys. J. A 57, 302 (2021)

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Experimental results

1) IYR from $^{232}Th(\alpha,f)$ at 28 MeV …

… and comparison to literature data for IYR from $^{233}U(n,f)$ and $^{235}U(n,f)$.

2) IYR from $^{232}Th(\alpha,f)$ at 28 MeV …

… in the ^{98}Y region.

3) IYR from $^{238}U(p,f)$ at 25 MeV …

… and derived fission fragment angular momenta.

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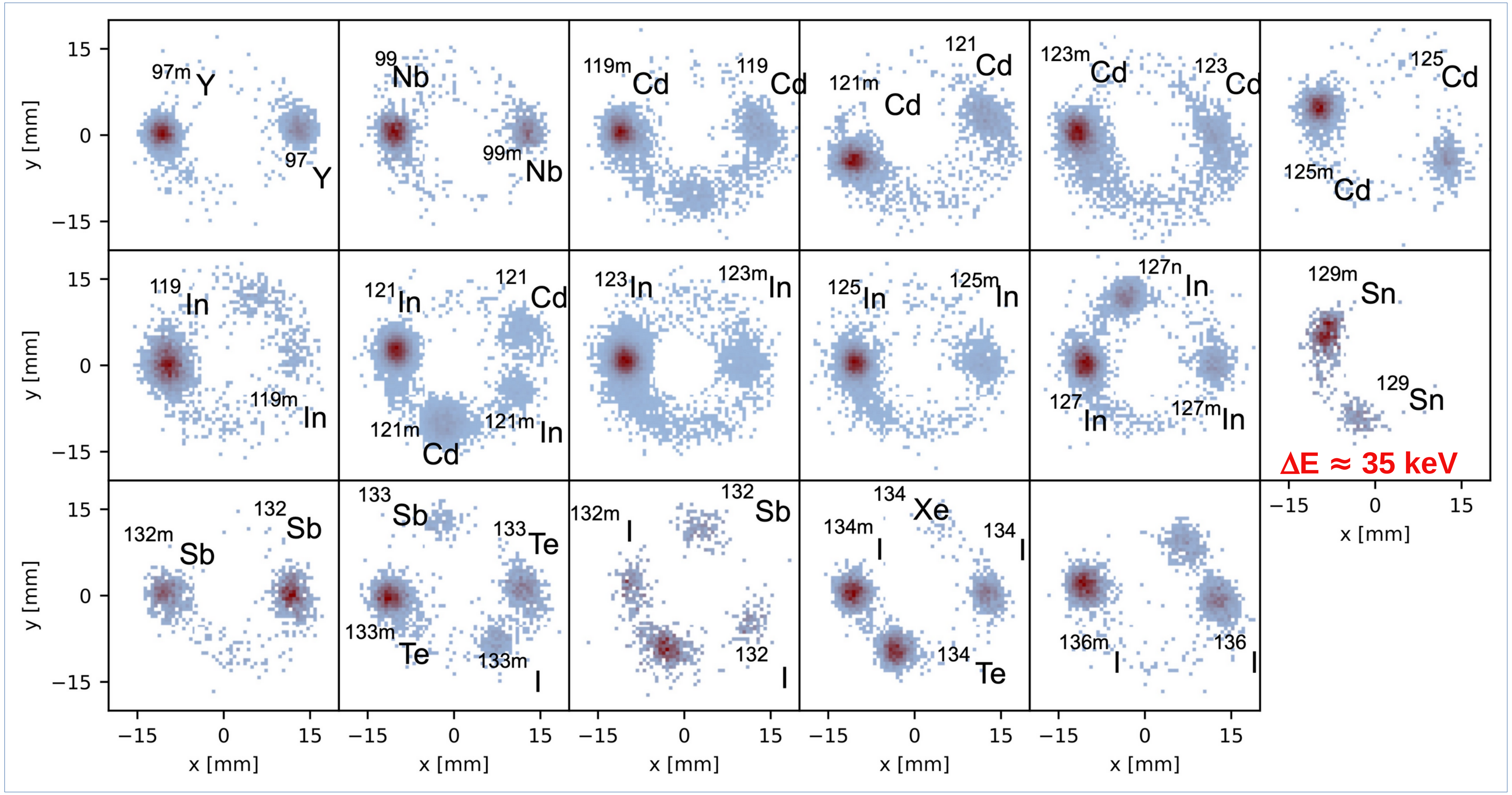
Results (1)   IYR from ^{232}Th(α,f) at 28 MeV



Measured twice
at mirrored MCP positions.

Decay corrections applied.

Obtain number of counts in ground and excited isomeric state.

Calculate the IYR.
(“high-spin state over total”)

S. Cannarozzo et al.,
EPJ Web Conf. **322**, 08007 (2025)
(CNR*24)

S. Cannarozzo et al., PRC **111** L031601 (2025)

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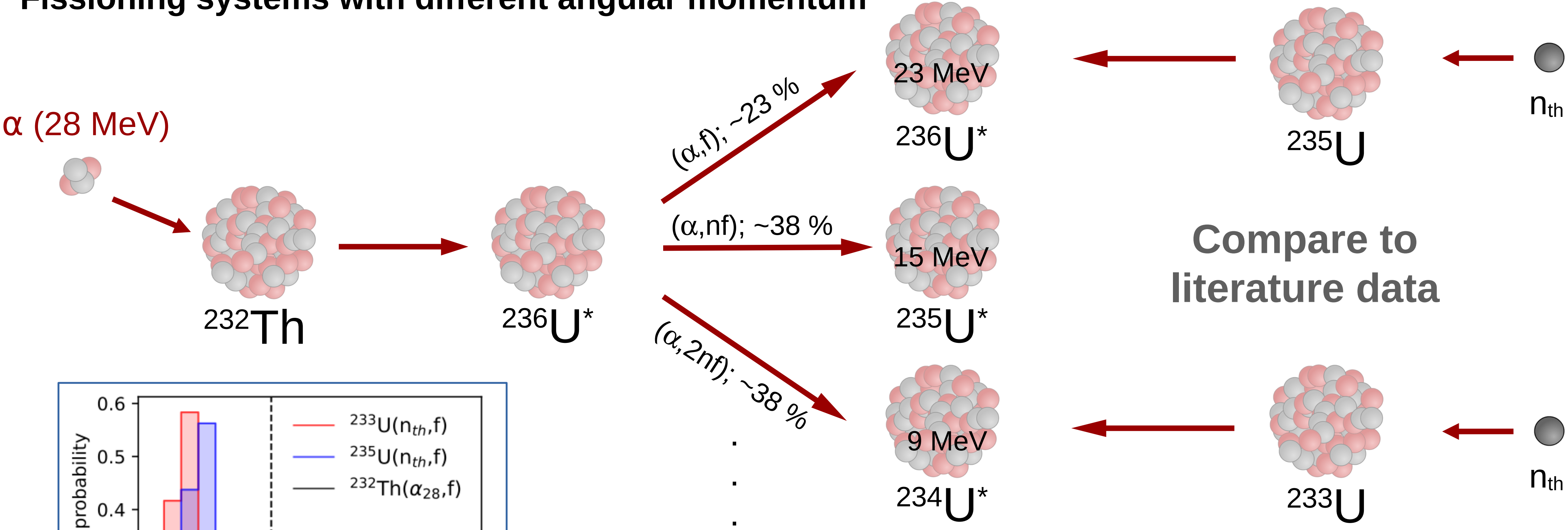
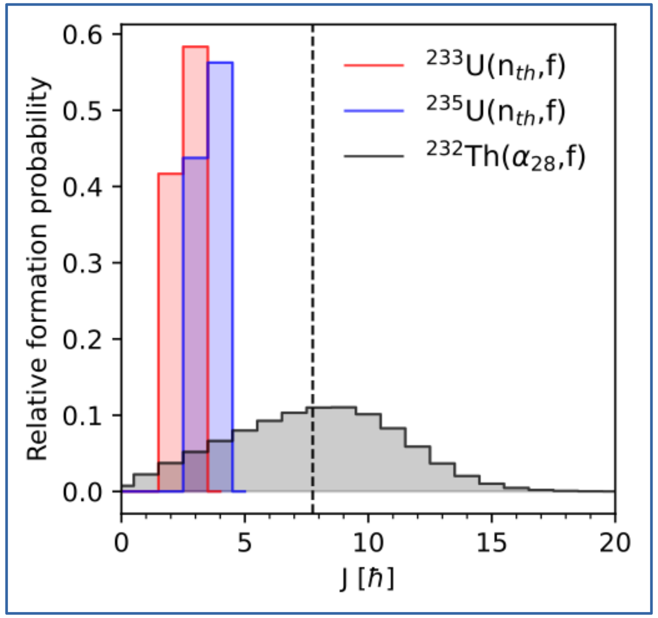
Fissioning systems with different angular momentum



Compare to literature data



Measured fissioning system

Phys. Rev. C 111, L031601 (2025)

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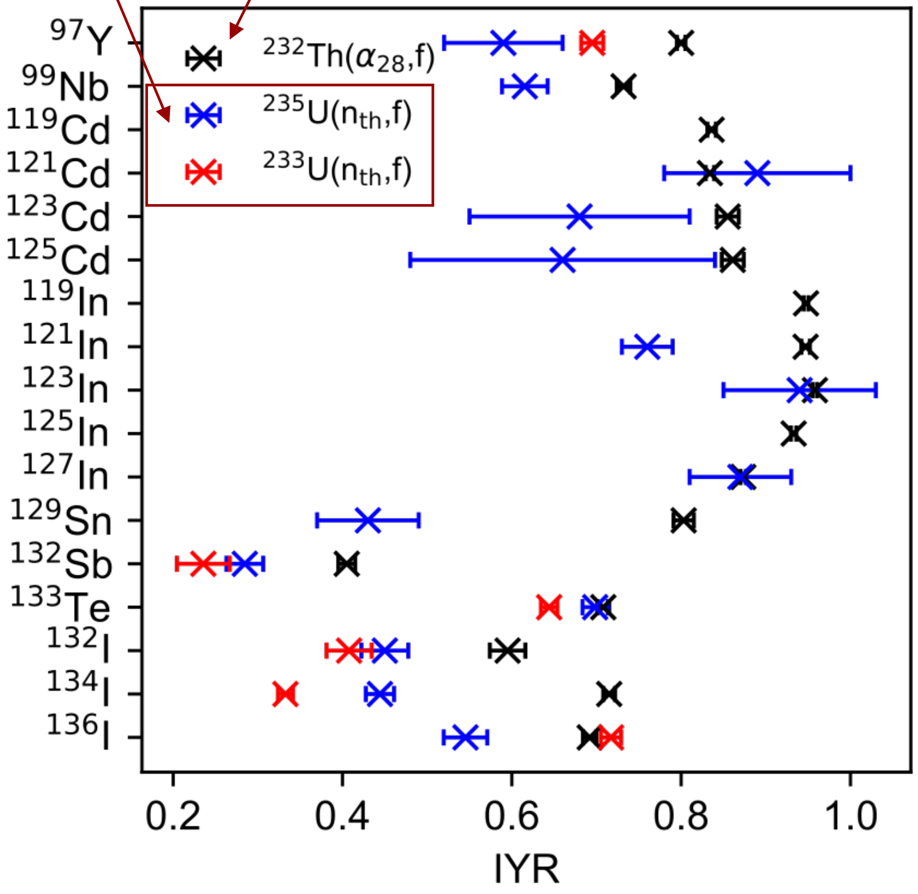
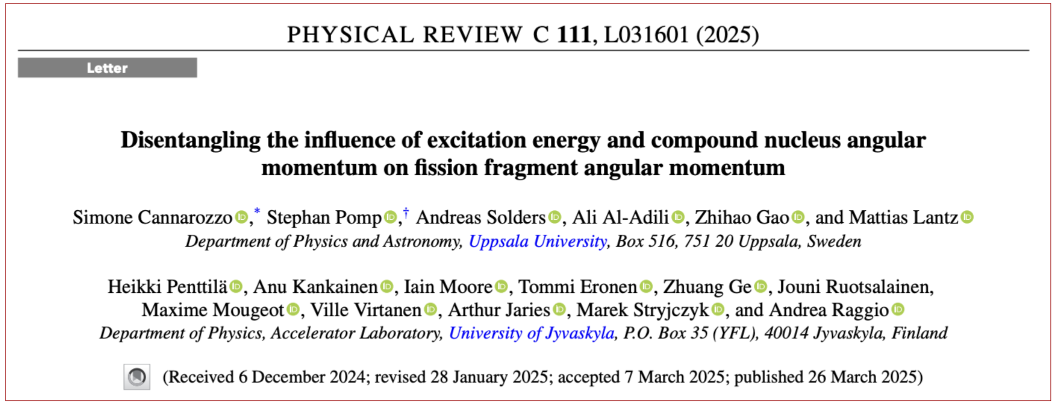
Results (1)   IYR from ^{232}Th(α,f) at 28 MeV

Average of **literature values**

Our IYR data from IGISOL





PHYSICAL REVIEW C **111**, L031601 (2025)

Letter

Disentangling the influence of excitation energy and compound nucleus angular momentum on fission fragment angular momentum

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Heikki Penttilä, Anu Kankainen, Iain Moore, Tommi Eronen, Zhuang Ge, Jouni Ruotsalainen, Maxime Mougeot, Ville Virtanen, Arthur Jaries, Marek Stryjczyk, and Andrea Raggio
Department of Physics, Accelerator Laboratory, University of Jyvaskyla, P.O. Box 35 (YFL), 40014 Jyvaskyla, Finland

(Received 6 December 2024; revised 28 January 2025; accepted 7 March 2025; published 26 March 2025)

Compound nucleus angular momentum is about 7.5 ħ.

Impact on IYR?

Compare to ^{233,235}U(n_{th},f). Average increased 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 ang. momentum)

Could this not be due to the excitation energy?
We think not ...

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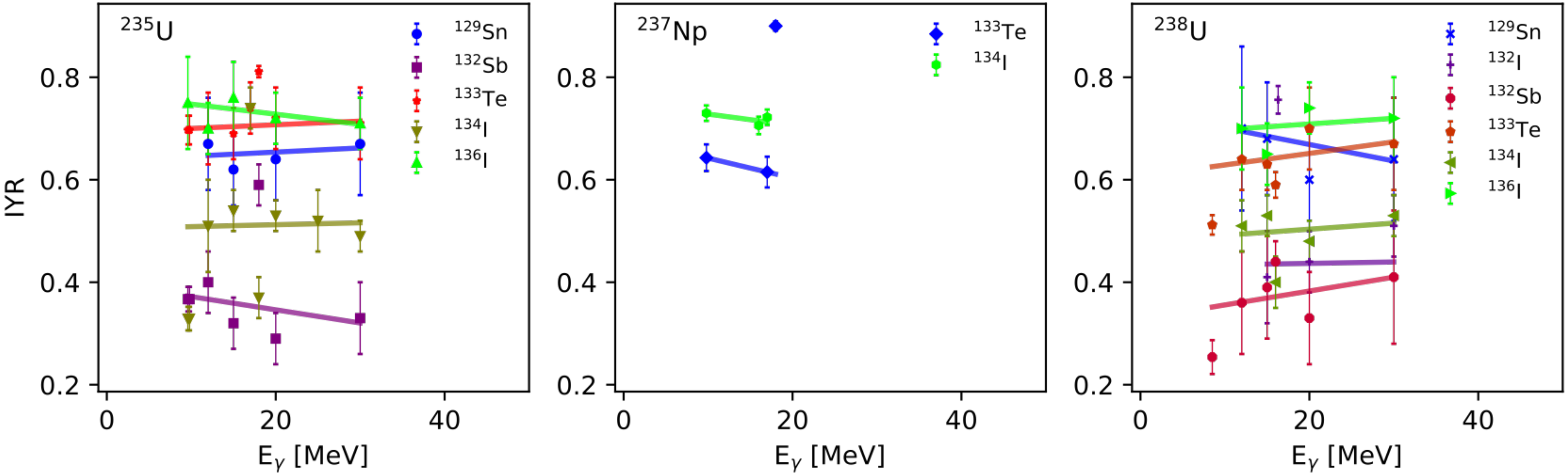
Results (1)   Impact of excitation energy?

- Photo-fission literature data was used to study influence of compound nucleus excitation energy on IYRs.



- $\Delta IYR/\Delta E = 0.0001(5)\ \mathrm{MeV}^{-1}$ ⇒ No significant dependence of the IYRs on the incident γ-ray energy.

S. Cannarozzo et al., PRC **111** L031601 (2025)

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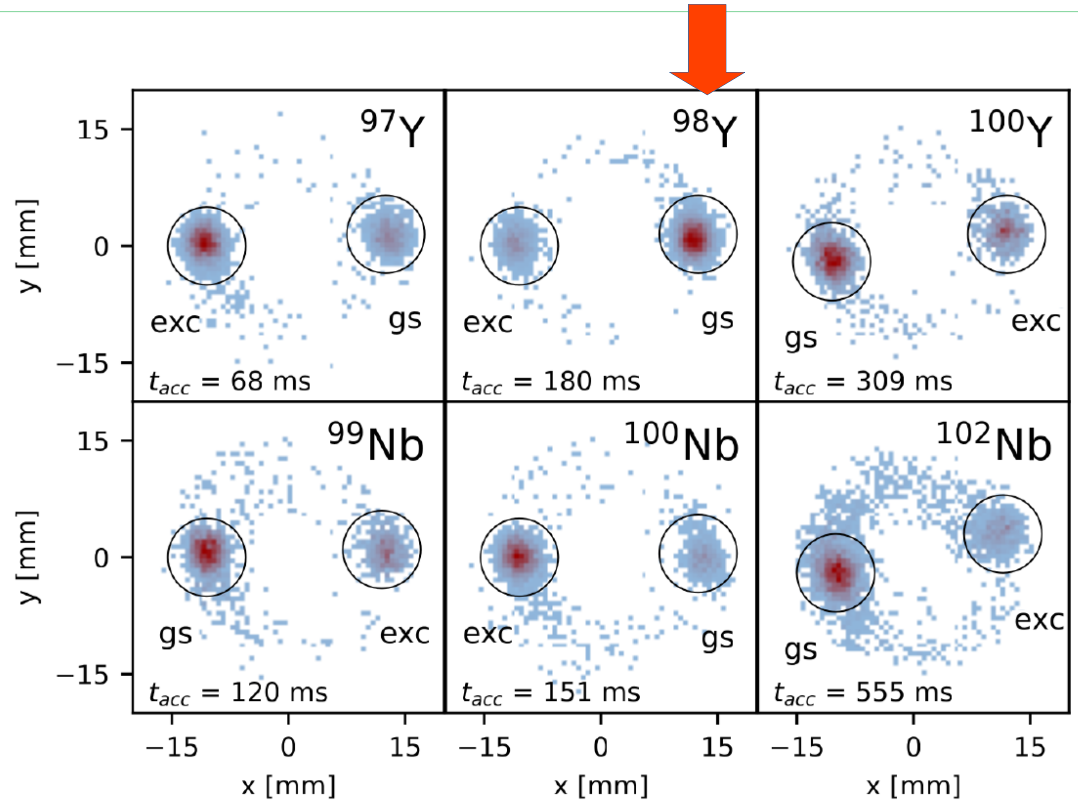
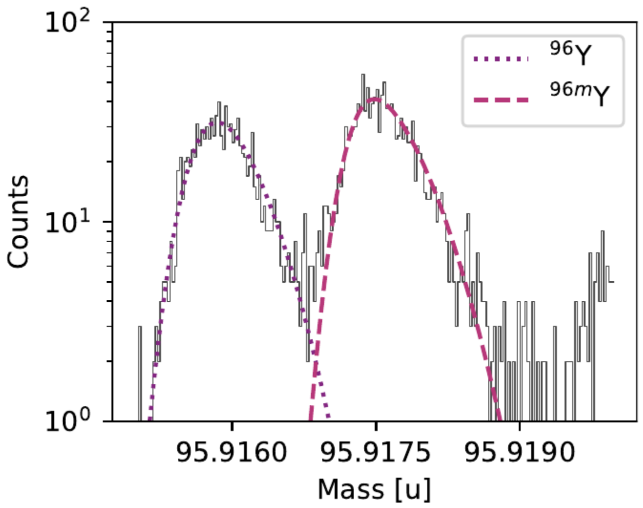
Results (2)

IYR from ^{232}Th(α,f) at 28 MeV
The case of ^{98}Y

High spin state always on the left side in the figure



^{98}Y shows a remarkably low IYR.



Nuclide	Ground state t$_{1/2}$ (s)	Ground state I$^\pi$	Excited state t$_{1/2}$ (s)	Excited state I$^\pi$	Excited state 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)

State ordering of ^{98}Y, ^{100}Y, ^{100}Nb, ^{102}Nb verified.

Confirms NUBASE2020; i.e. reversed order of ^{100}Y in ENSDF.

S. Cannarozzo et al., submitted to PLB; 2504.11274v3

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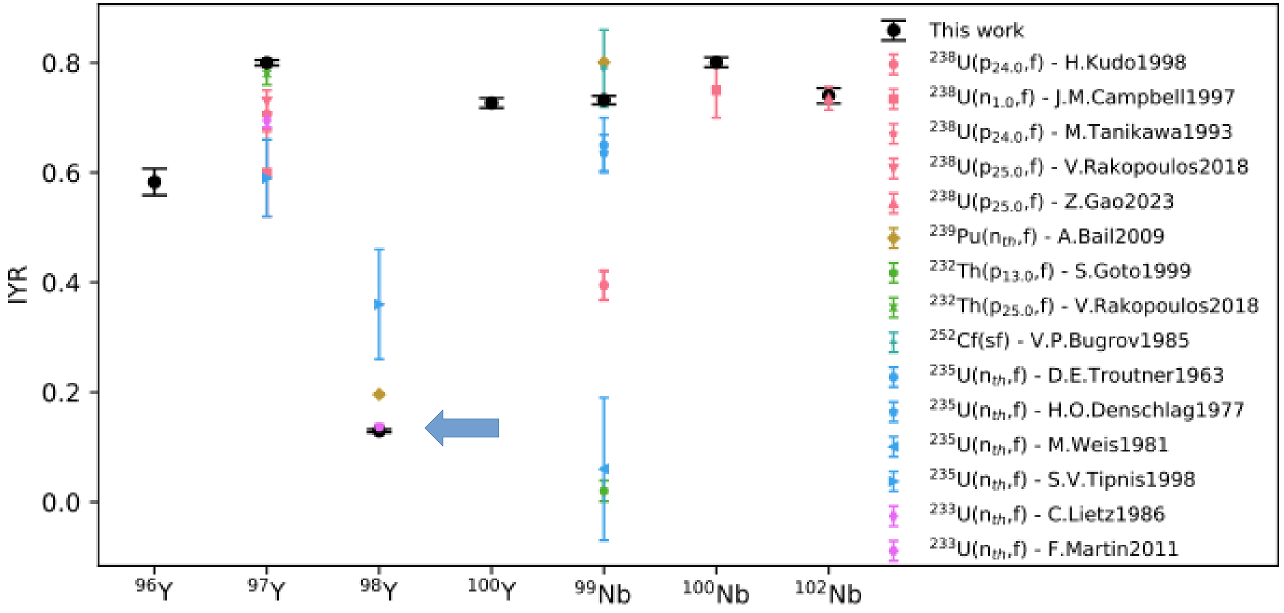
Results (2) IYR from ^{232}Th(α,f) at 28 MeV
The case of ^{98}Y



^{98}Y shows a remarkably low IYR.

Outlier reason?
^{98}Y known for large isomeric shift
But how to explain?
State ordering experimentally verified!

Nuclide	Ground state $t_{1/2}$ (s)	Ground state I^{π}	Excited state $t_{1/2}$ (s)	Excited state I^{π}	Excited state 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)

State ordering of ^{98}Y, ^{100}Y, ^{100}Nb, ^{102}Nb verified.

Confirms NUBASE2020; i.e. reversed order of ^{100}Y in ENSDF.

S. Cannarozzo et al., submitted to PLB; 2504.11274v3

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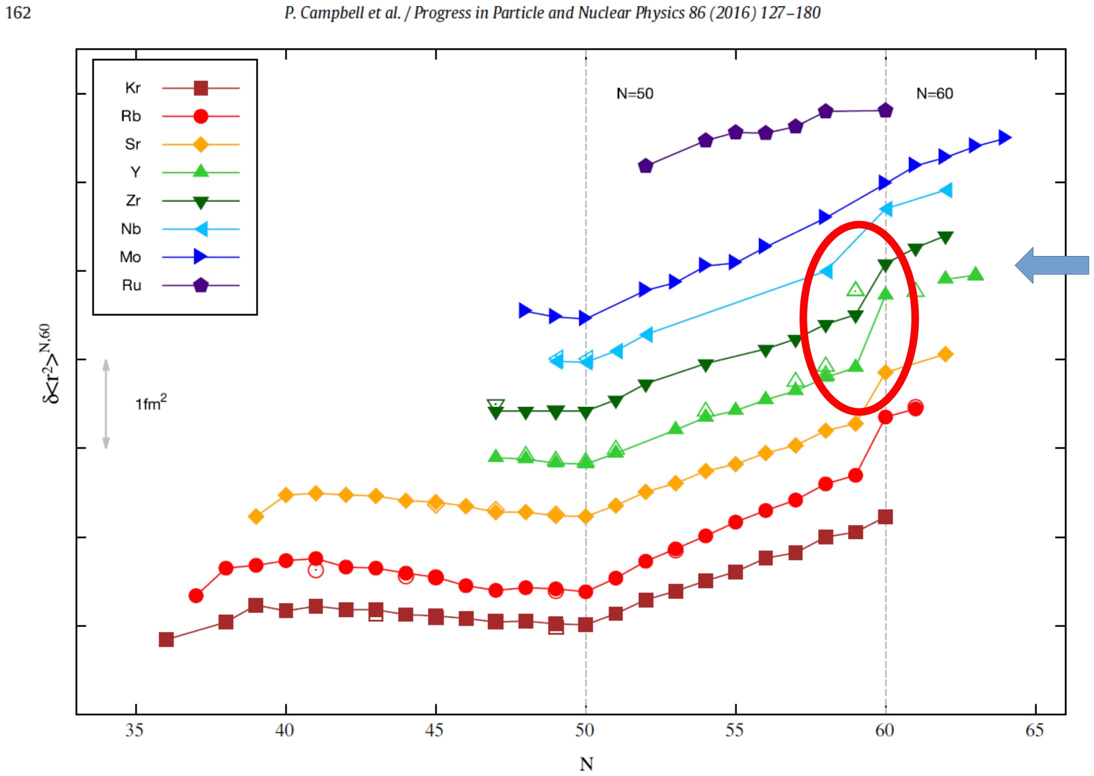
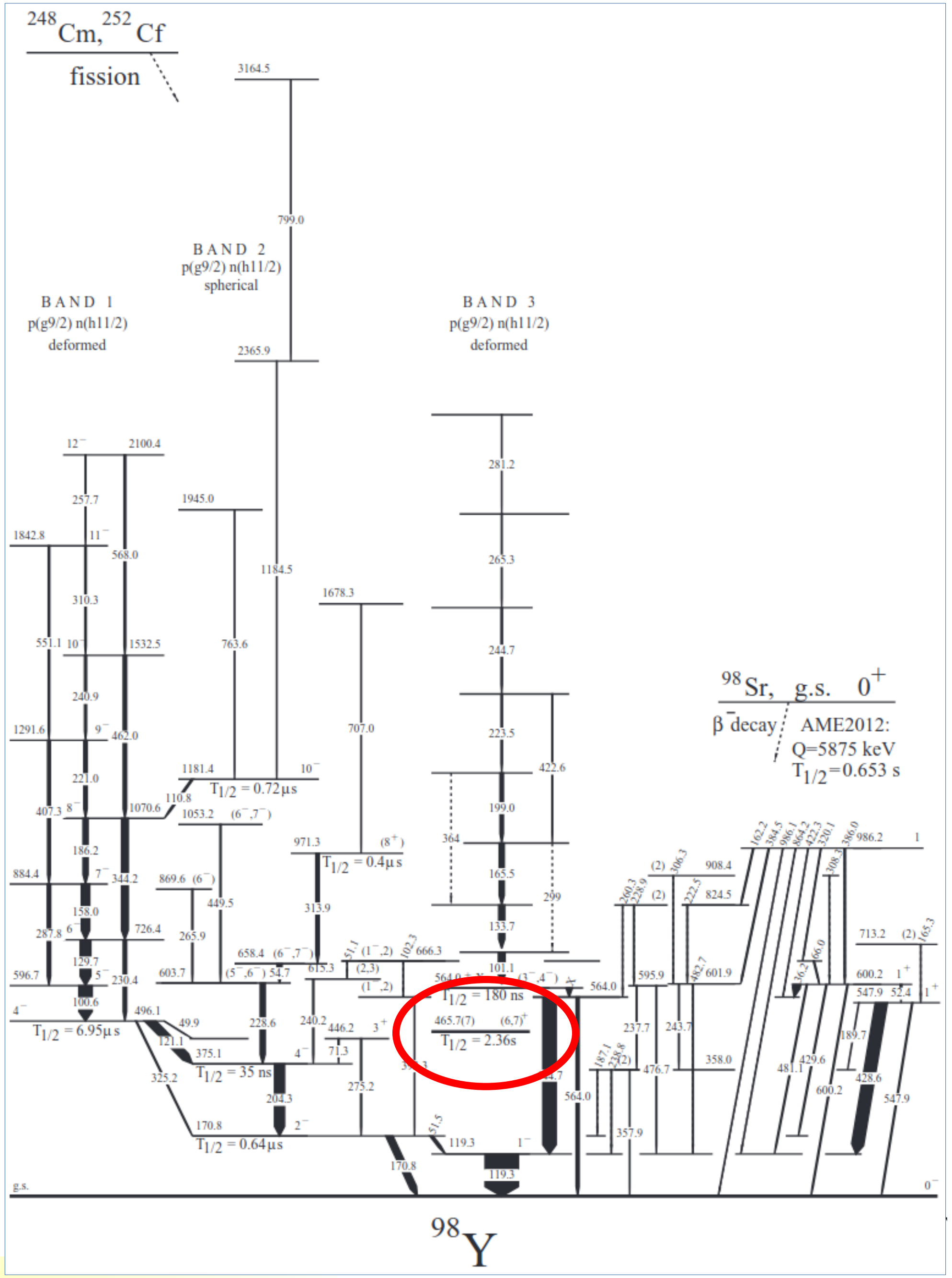
Results (2) IYR from $^{232}Th(\alpha,f)$ at 28 MeV

The case of ^{98}Y



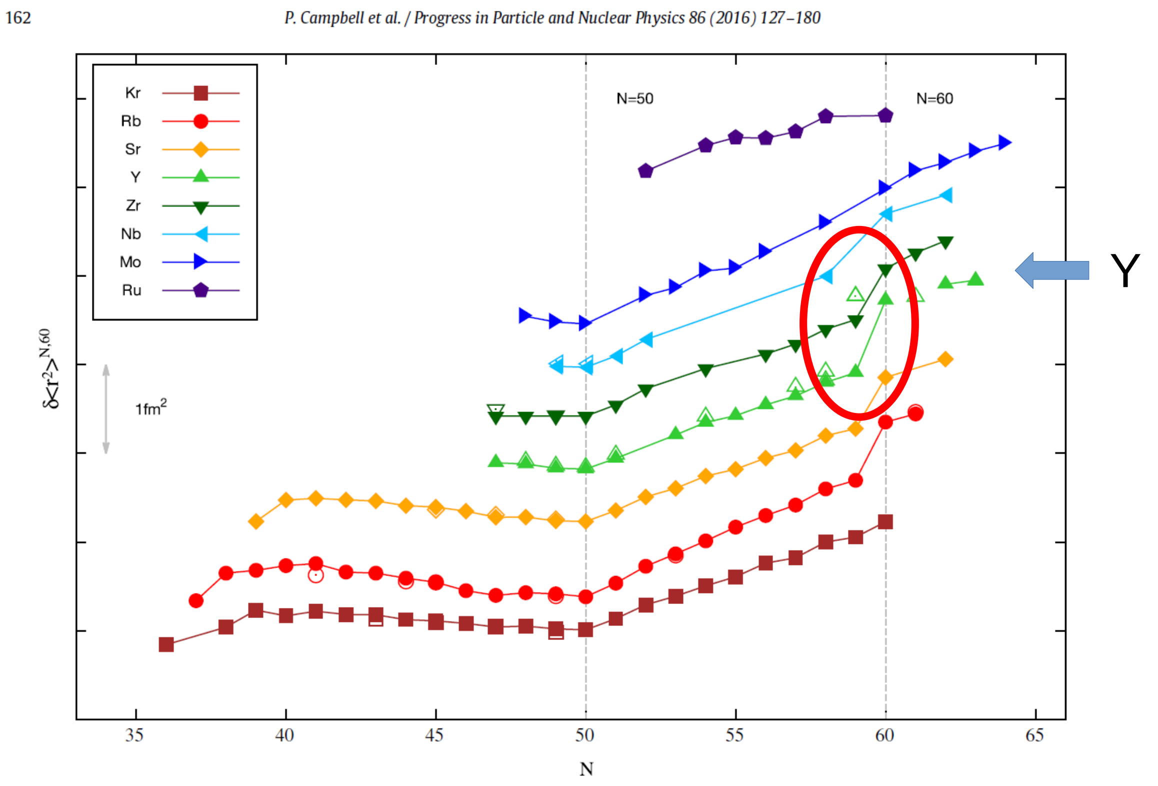
- ^{98}Y shows a large isomeric shift (also ^{79}Zn)
- Shape co-existence
- Isomer rarely populated in fission

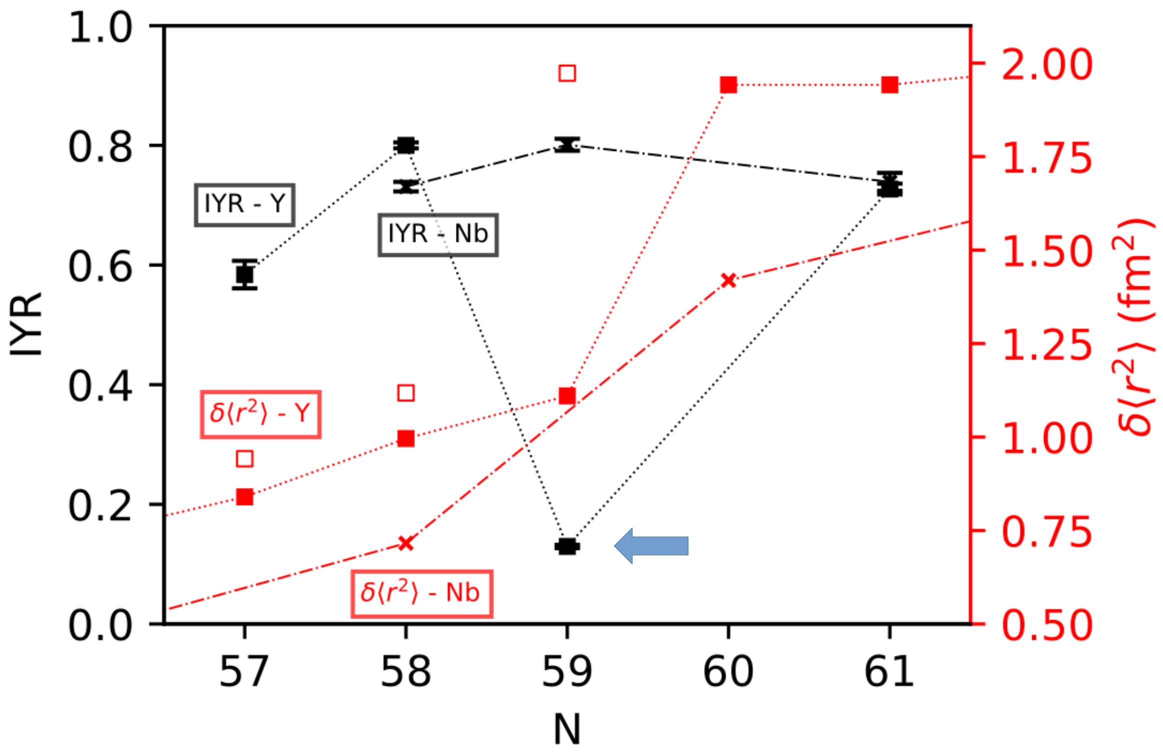


W. Urban et al., Phys. Rev. C **96**, 044333 (2017)

Results (2)

IYR from $^{232}Th(\alpha,f)$ at 28 MeV
The case of ^{98}Y





S. Cannarozzo et al., submitted to PLB

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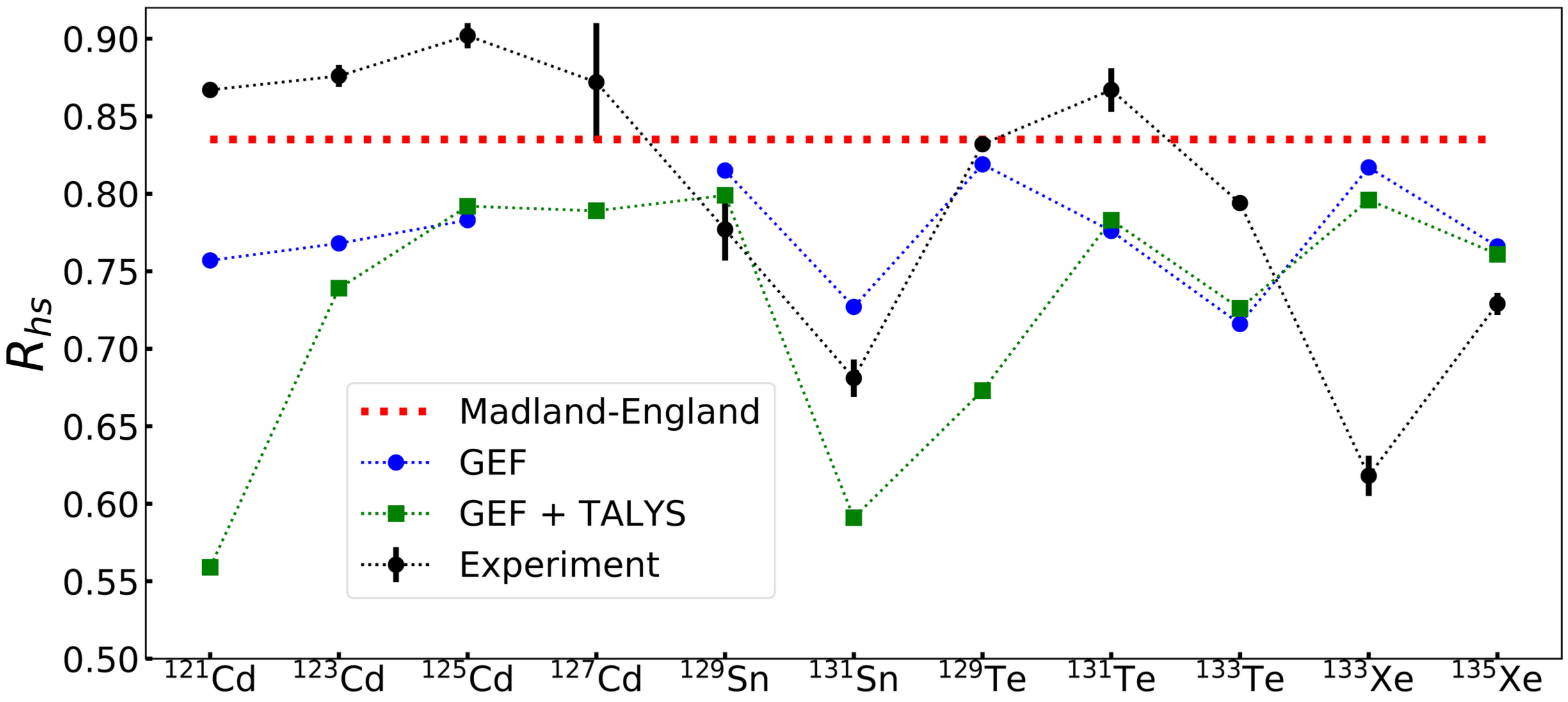
Results (3) 35 IYR from ^{238}U(p,f) at 25 MeV

- 35 isomeric yield ratios in ^{238}U(p,f) measured

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

- Comparison with:
  - Madland-England
  - GEF
  - GEF + TALYS

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



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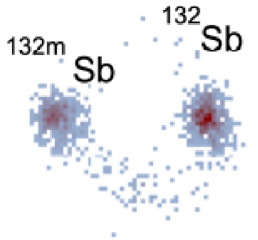
Results (3) 35 IYR from $^{238}U(p,f)$ at 25 MeV

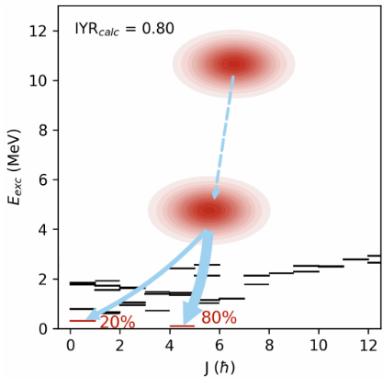


- Nuclear structure data are not needed to obtain IYR by direct ion counting.
  (with the exception of data needed for decay corrections)

- But we actually want to know something about the state of the fission fragment.

- We need nuclear structure data and nuclear level densities to model de-excitation.

- We developed methods for deriving fission fragment angular momenta using TALYS
  see, e.g., Z. Gao et al., PRC **109**, 064626 (2024)

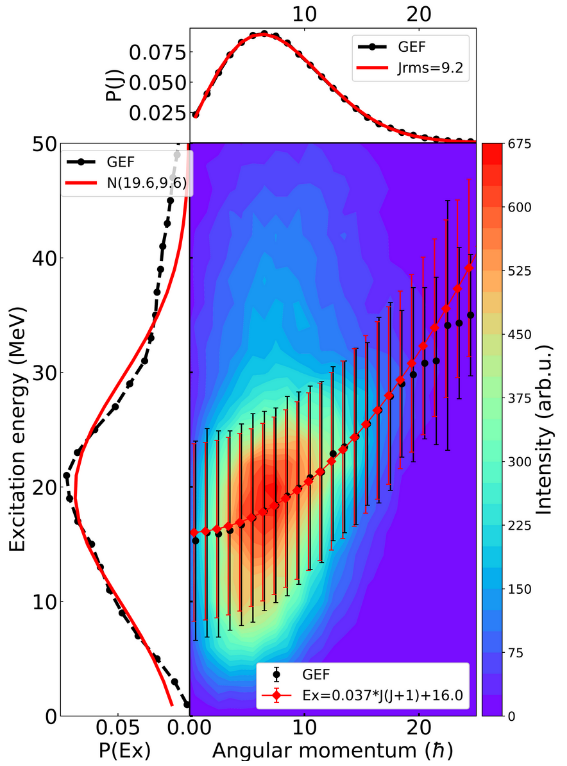


Questions: **does TALYS give reasonable results?**

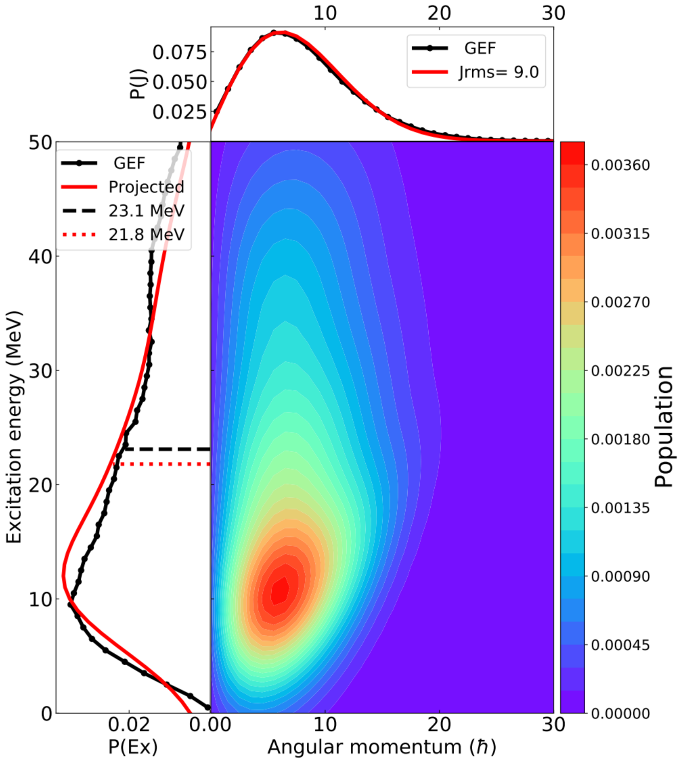
spin distribution in the level densities correct?

Angular momentum estimation – Example of ^{133}Te

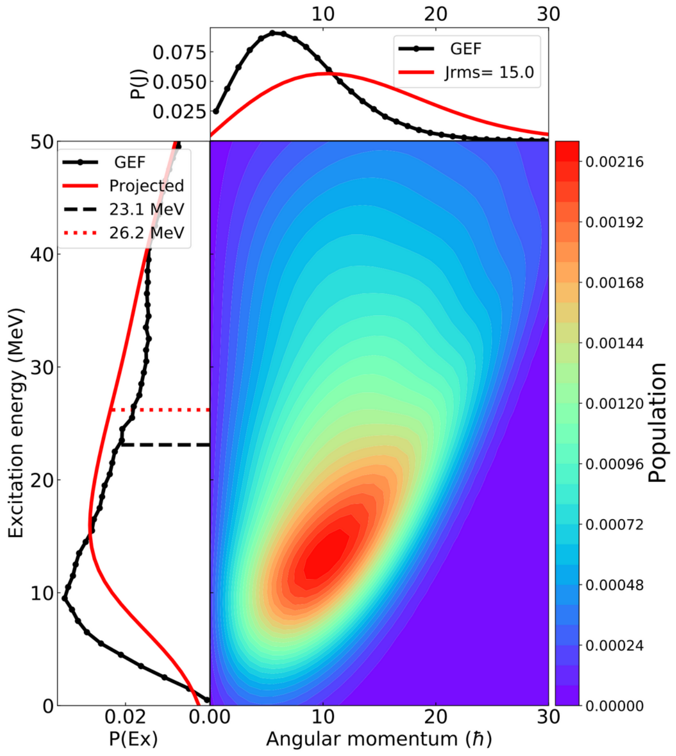
Fit to GEF data for each fission channel.



Weighted sum of matrices for ‘all’ fission channels.



Creation of new matrices for any J_{rms}



Z. Gao et al., PRC **109**, 064626 (2024)

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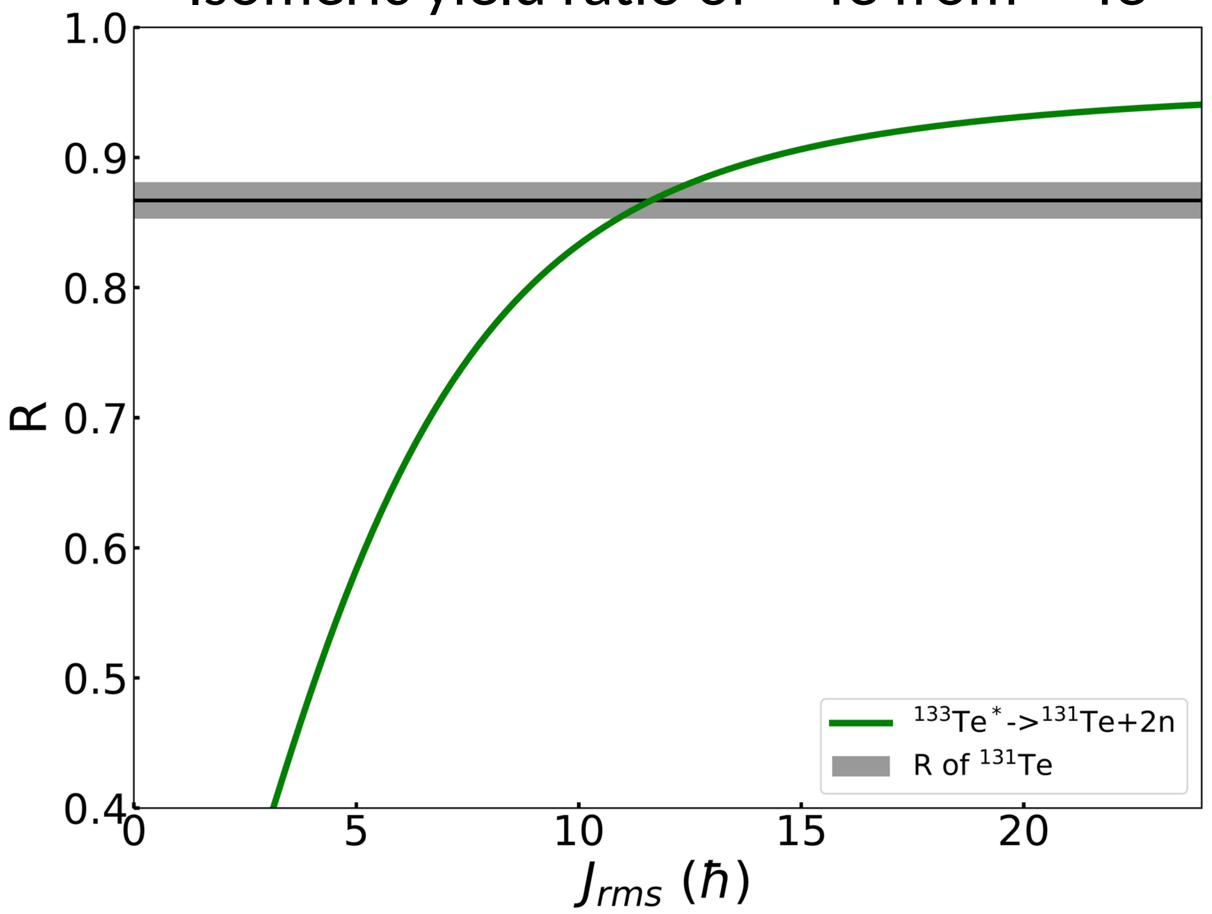
Results (3) 35 IYR from $^{238}U(p,f)$ at 25 MeV

- The E vs J_{rms} matrices from the surrogate model is used as input to TALYS.
- A most likely J_{rms} is estimated for each pre-neutron emission fragment.
- A weighted average of the contributions from the fragments is derived.

Isomeric yield ratio of ^{131}Te from ^{133}Te



Z. Gao et al., PRC **109**, 064626 (2024)

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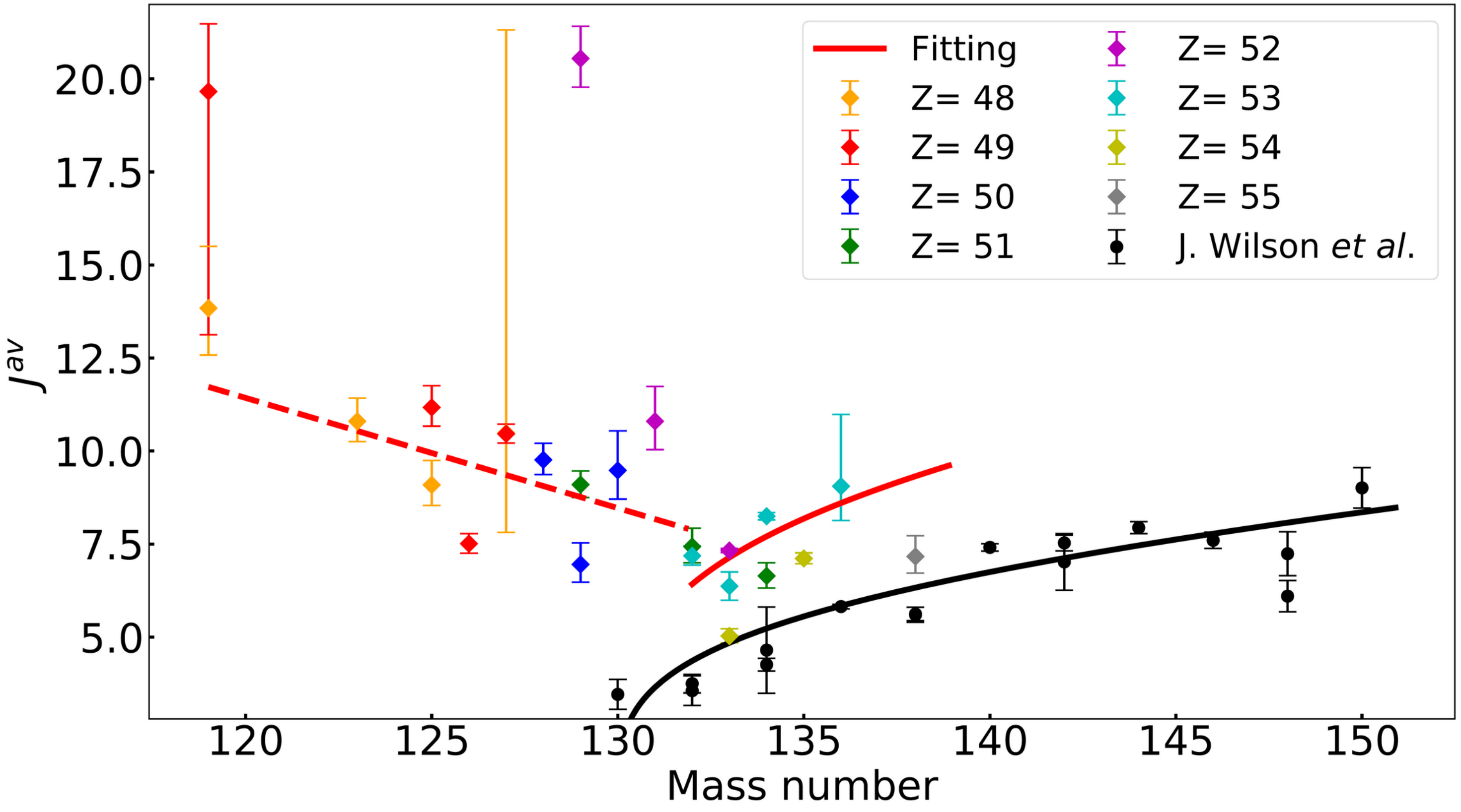
Results (3) 35 IYR from $^{238}U(p,f)$ at 25 MeV

- Comparison to Wilson data for $^{238}U(n_{th},f)$.
  J. Wilson et al., Nature **590**, 566 (2021)

- We find larger average angular momenta for all masses.

- Minimum angular momentum around A ≈ 130.



Gao et al., Phys. Rev. C 109, 064626 (2024)

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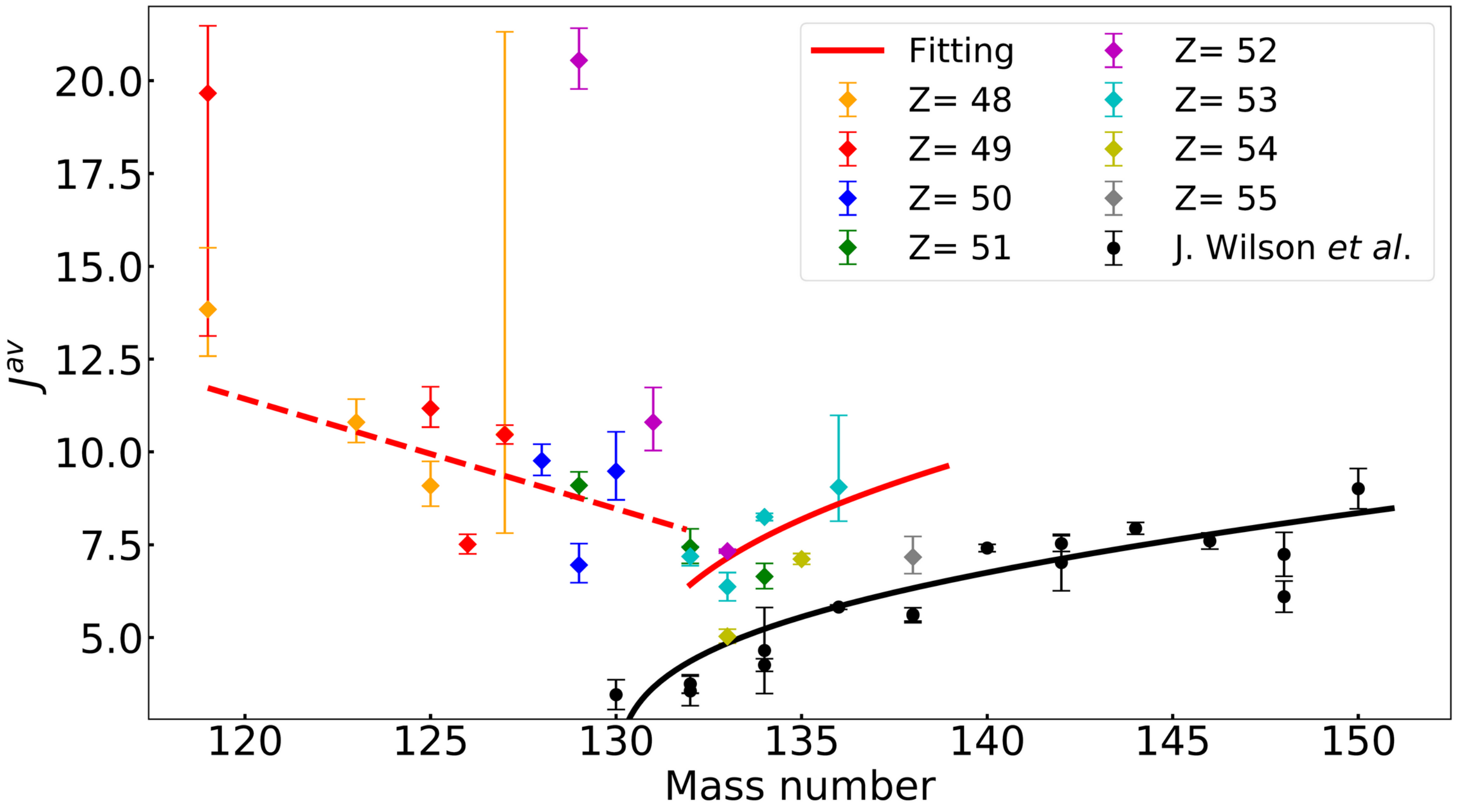

Gao et al., Phys. Rev. C 109, 064626 (2024)

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Summary and outlook

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Summary and outlook

Over the past years **we measured IYR for 37 nuclei at IGISOL**.

Recently we studied **IYR from ^{232}Th(α,f)** and show that:

1) Increased **CN angular momentum** ➡ **larger IYR**
i.e. added CN angular momentum leads to higher fission fragment angular momentum

2) Using literature data, we find **no significant dependence on excitation energy**.

3) We highlight the **unusual IYR for ^{98}Y** (and establish/verify state ordering of 4 Y and Nb isotopes).

Measurements of **IYR from ^{238}U(p,f)** show that:

4) Existing fission models fail to reproduce the IYR.

5) Surrogate model using GEF and TALYS yields estimates of FF angular momenta.

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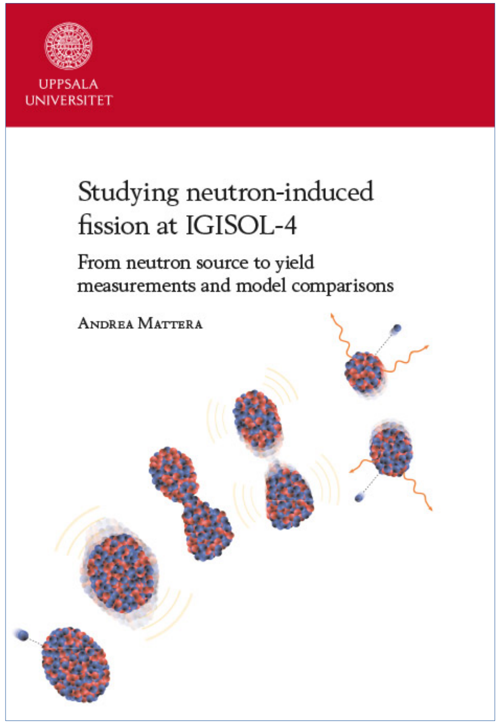
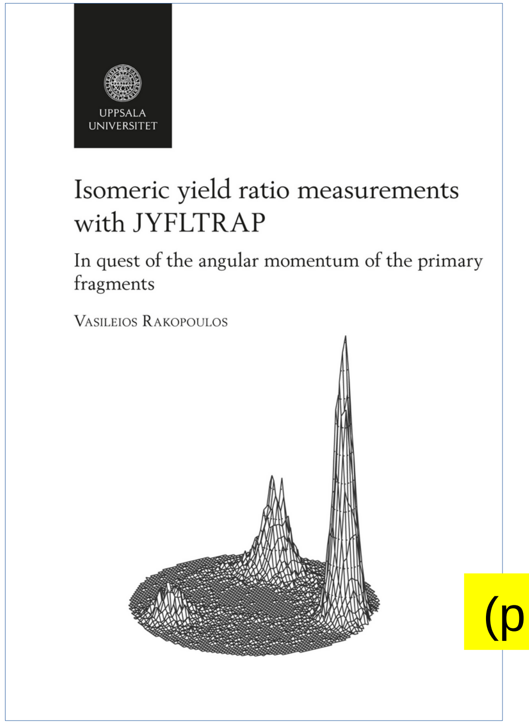
Details can be found in the PhD theses of A. Mattera, V. Rakopoulus, Z. Gao and S. Cannarozzo



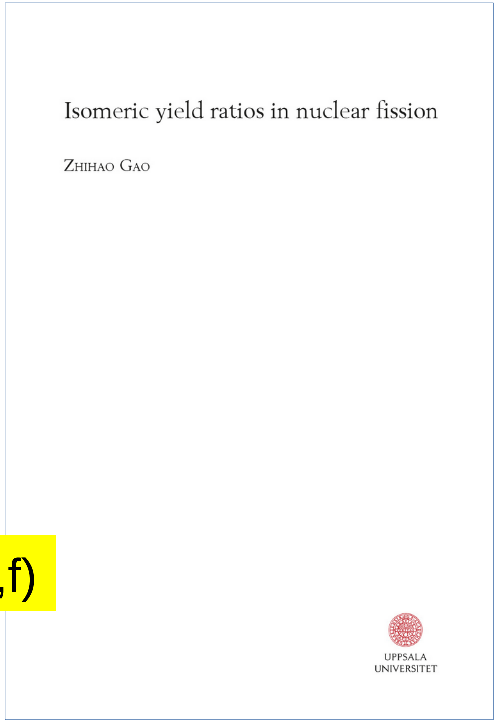
EPJ A (2017) **53**: 173
EPJ A (2018) **54**: 33

(n,f)

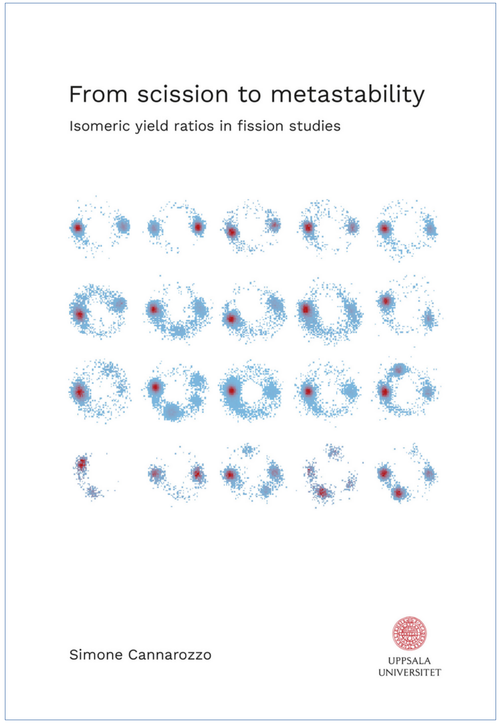


PRC **98** 024612 (2018)
PRC **99** 014617(2019)

(p,f)



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



EPJ A (2023) **59**: 295
PRC **111** L031601 (2025)
Manuscript submitted to PLB

(α,f)

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Summary and outlook

Plans:

A) Additional IYR measurements from $^{232}Th(\alpha,f)$ at IGISOL (symmetry and low mass region).

B) IYR from spontaneous fission of the 0^+ nuclei ^{248}Cm and ^{252}Cf FRS-CSC at GSI, Germany.

C) Continue development of methods to derive fragment angular momenta from the IYR.

In this context the output from the newly starter **IAEA CRP on nuclear level densities** will be valuable.

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Ackowledgements

Results presented here are based on the PhD theses of
Andreas Mattera (2017), **Vasileios Rakopoulos** (2018), **Zhihao Gao** (2023), **Simone Cannarozzo** (June 10, 2025)

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Thank you!