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Fission yield studies using mass measurement techniques

A. Solders[1,*], A. Al-Adili[1], L. Canete[2], T. Eronen[2], Z. Gao[1], A. Jokinen[2], A. Kankainen[2], M. Lantz[1], A. Mattera[1], I.D. Moore[2], D.A. Nesterenko[2], M. Österlund[1], H. Penttilä[2], S. Pomp[1], V. Rakopoulos[1], M. Reponen[2], S. Rinta-Antila[2], A. de Roubin[2], M. Vilén[2]

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[2]Department of Physics, University of Jyväskylä, Finland
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Nuclear Reactions Research Group
Applied Nuclear Physics, Uppsala University

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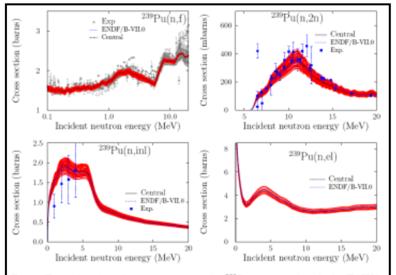
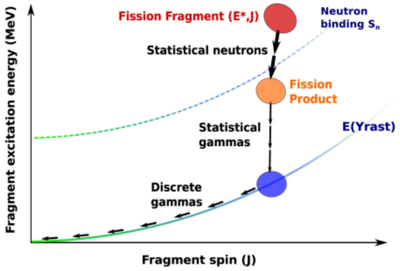
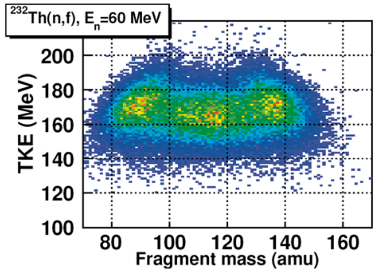


Fig. 3. Examples of random cross sections for ^{239}Pu, generated with the TALYS system and compared to ENDF/B-VII.0. Random cross sections are presented in red.

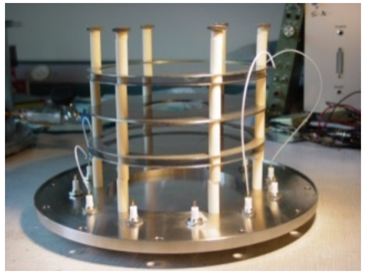


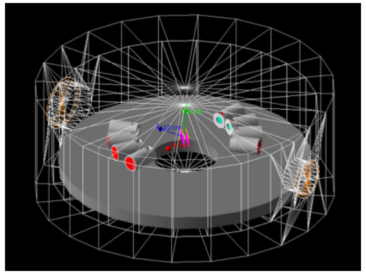


Experiments

"Fission is the mission"

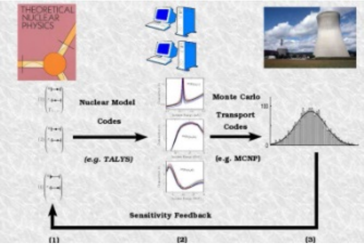
Computational methods

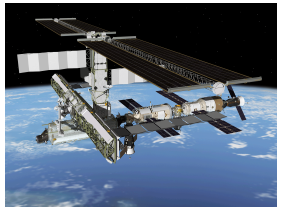




Evaluation methods,
Uncertainty quantification
TENDL

Applications





Main academic partners:

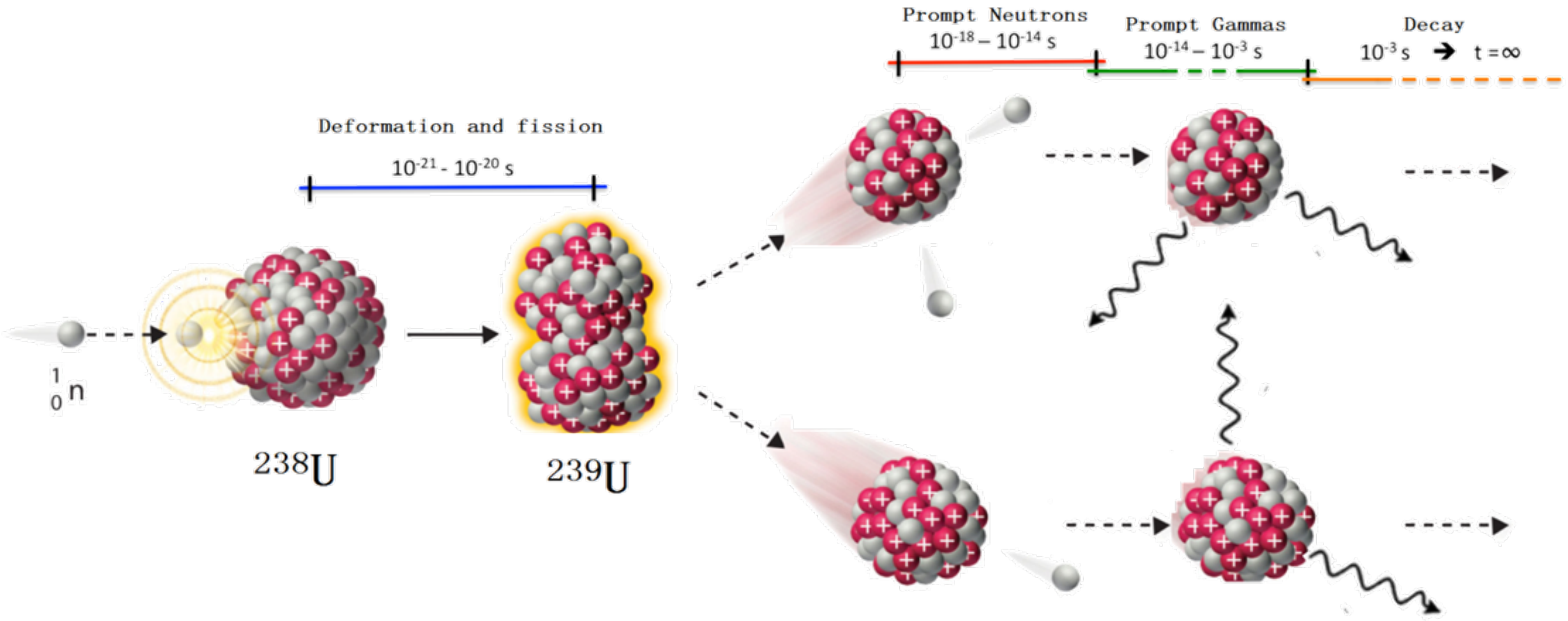
JRC EUROPEAN COMMISSION

JYVÄSKYLÄN YLIOPISTO UNIVERSITY OF JYVÄSKYLÄ

GANIL spiral2 laboratoire commun CEA/DSM CNRS/IN2P3

PAUL SCHERRER INSTITUT PSI

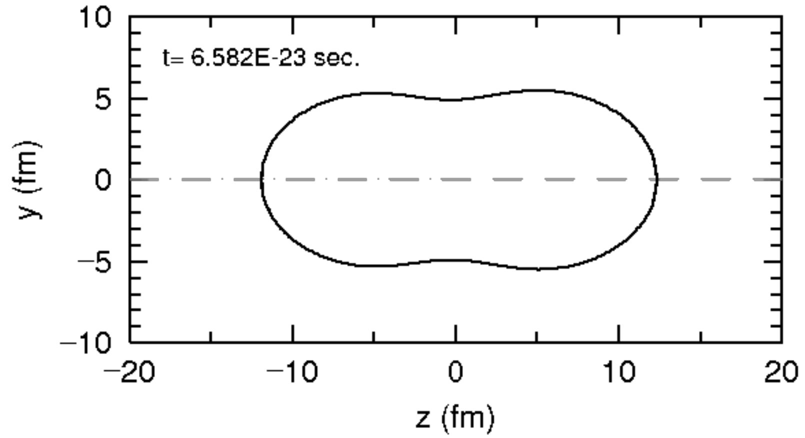
Fission is the mission



The complete nuclear physics lab

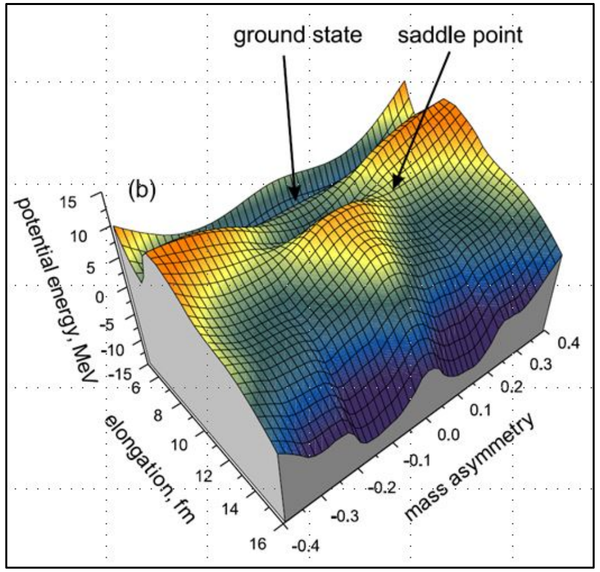
Fission is a slow, dynamic process which can be viewed as nuclear shape evolution.

Fission comprises many aspects of nuclear physics, e.g. structure of very deformed nuclei far from stability.



Nuclear shape evolution with Langevin equations courtesy S. Chiba

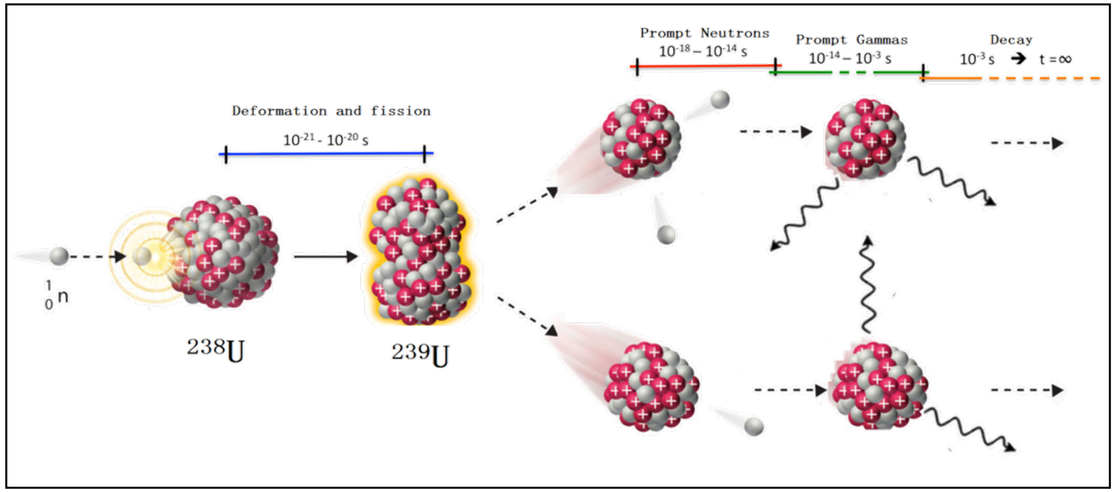
Fission is also used as a means to create and study exotic nuclei.

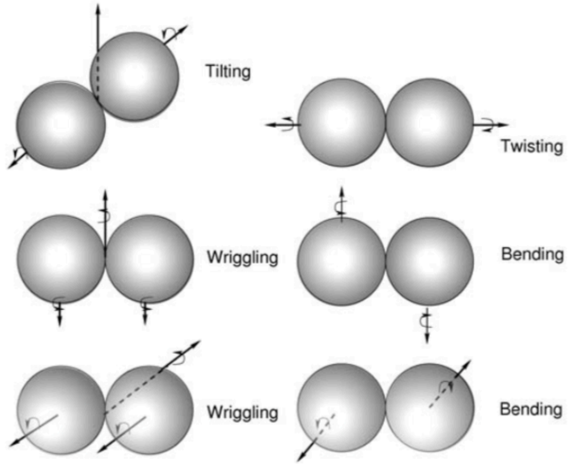


A.V. Karpov et al., *J. Phys. G: Nucl. Part. Phys*. **35** (2008) 035104

Challenges in fission

Open questions: Sharing of excitation energy?
When does the freeze-out of fragment properties occur?
Do scission neutrons exist?
Origin of (large) angular momenta





Linked to that: Prompt neutrons and gamma
Fission yields …

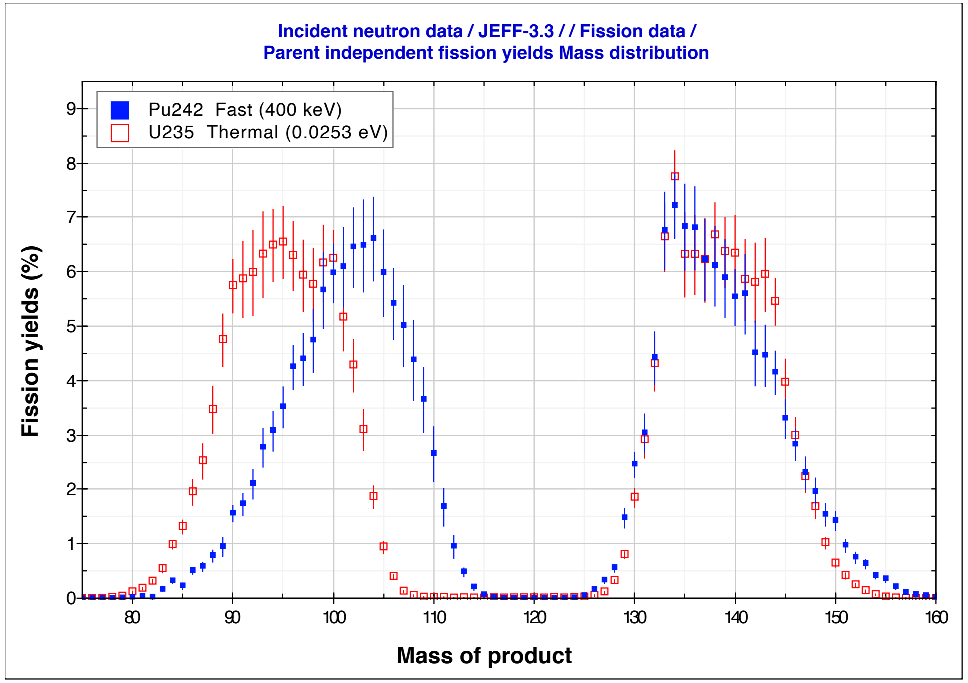
A. Andreyev et al., Rep. Prog. Phys. **81** (2018) 016301

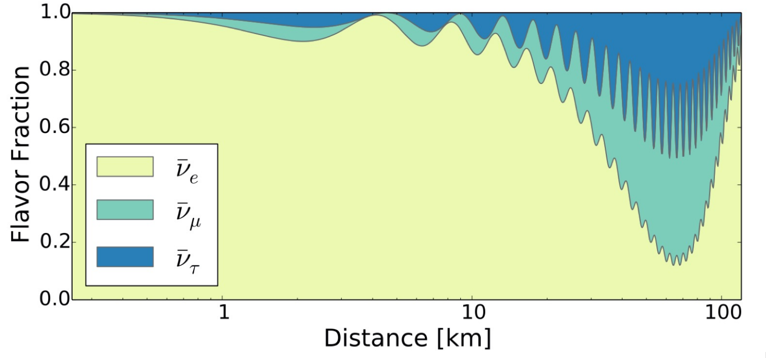
“Applications”

- **Nuclear energy applications - GenIV**
  - Cross sections
  - Neutron multiplicity
  - Fission yields

- **r-process**

- **Neutrino oscillations**





Vogel, P., et al., *Nat Commun* **6,** 6935 (2015).

Fission yields

- **Mass number yields** - is the sum of all independent yields of a particular isobaric chain.
- **Total chain yields** - the cumulative yield of the last, either stable or long-lived member of an isobaric chain.
- **Cumulative fission yields** - number of atoms of a specific nuclide produced directly in fission and after the decay of all of its precursors.
- **Independent fission yields** - number of atoms of a specific nuclide produced directly in fission, before beta-decay.
- **Isomeric yield** – relative yield of an isomer.

Independent and **Isomeric** yields have typically been measured using gamma spectroscopy after chemical (Z) or physical (A) separation.

Often limited by half-life and knowledge of the decay scheme.

Fission yield studies using mass measurement techniques

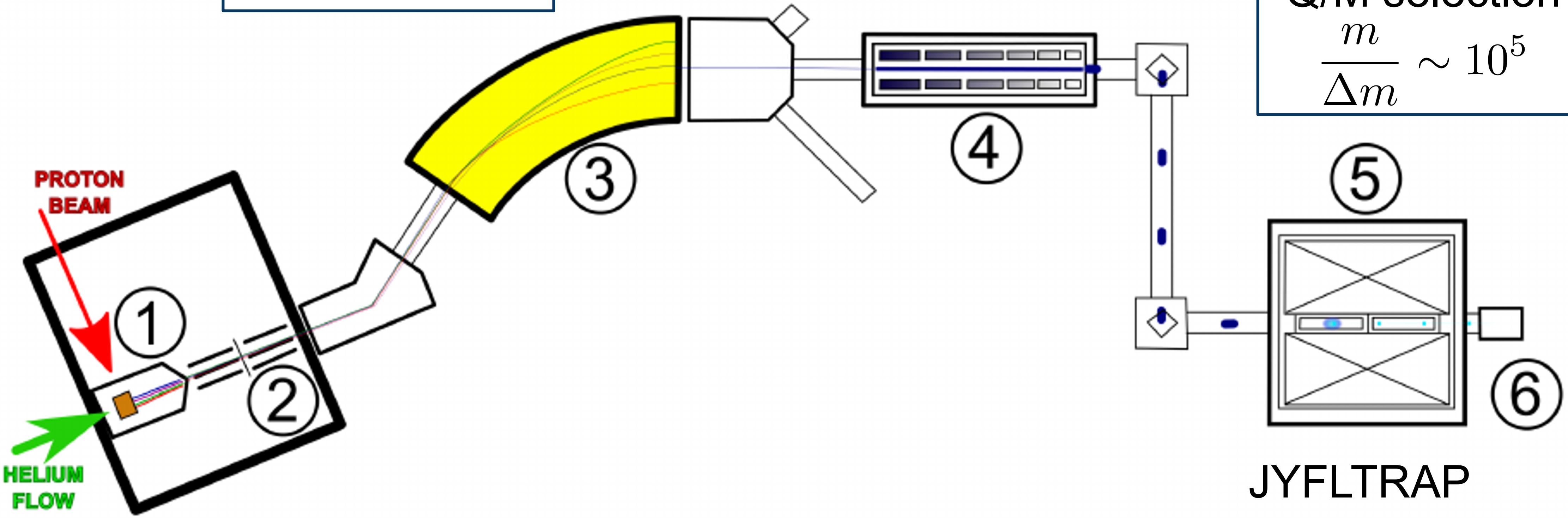
University of Jyväskylä
Finland

Uppsala University
Sweden

IGISOL & JYFLTRAP

Q/M selection
$$\frac{m}{\Delta m} \sim 500$$

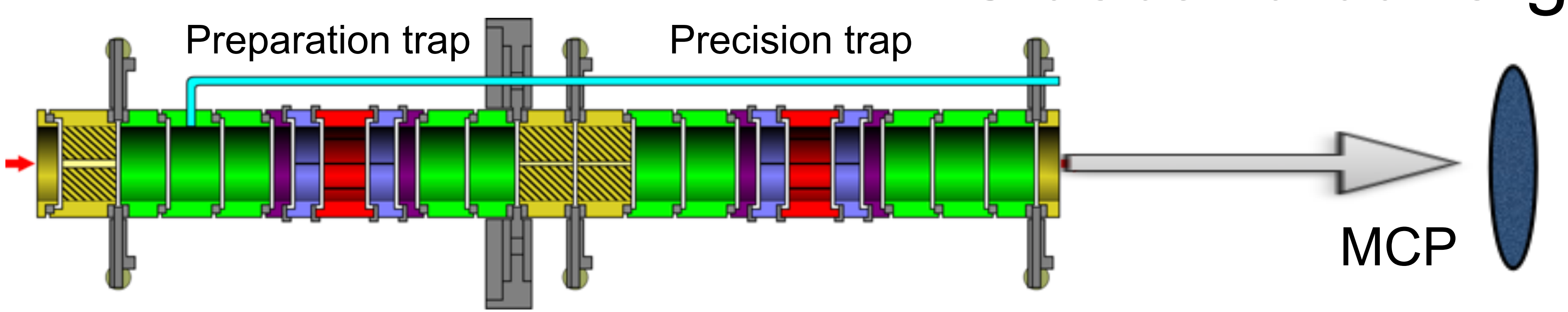
Q/M selection
$$\frac{m}{\Delta m} \sim 10^5$$

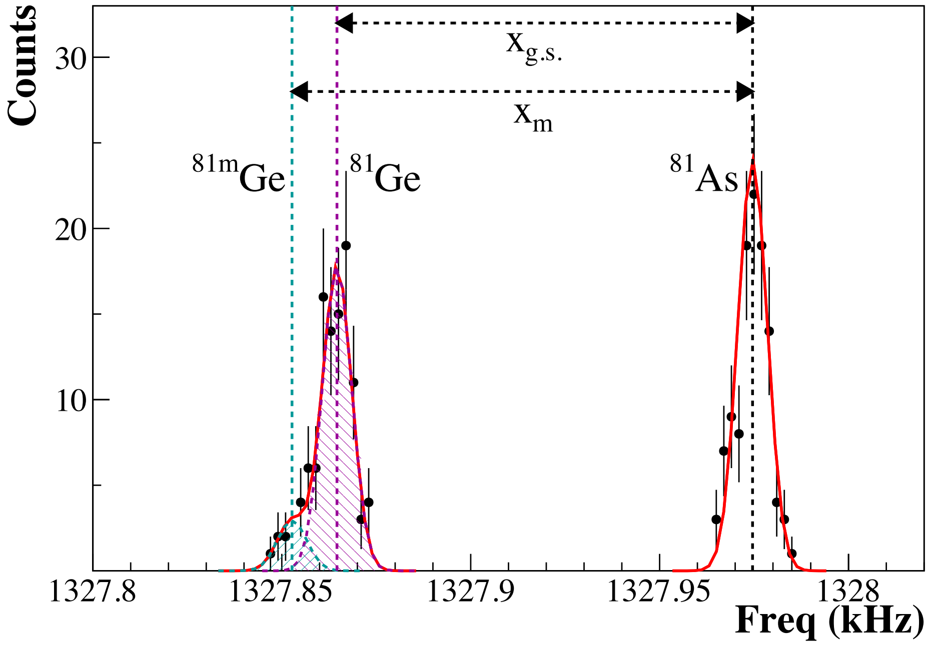


JYFLTRAP
Penning Trap

J. Äystö et al., (eds) ”Three decades of research using the IGISOL technique at the University of Jyväskylä”,
Eur. Phys. J. A **48** Issue 4, 2012

JYFLTRAP
Sideband buffergas cooling





Typical mass resolving power:

$$\frac{m}{\Delta m} \sim 10^5$$

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Independent isotopic yields

proton and deutron induced fission of thorium and uranium

Eur. Phys. J. A 44, 147–168 (2010)
DOI 10.1140/epja/i2010-10936-8
THE EUROPEAN PHYSICAL JOURNAL A
Special Article – Tools for Experiment and Theory

Determining isotopic distributions of fission products with a Penning trap

H. Penttilä[1,a], P. Karvonen[1], T
I.D. Moore[1], K. Peräjärvi[1,c], S.
and J. Äystö[1]

[1] Department of Physics, P.O. Bo
[2] V.G. Khlopin Radium Institute,

Eur. Phys. J. A (2012) 48: 43
DOI 10.1140/epja/i2012-12043-4
THE EUROPEAN PHYSICAL JOURNAL A
Review

Fission yield studies at the IGISOL facility

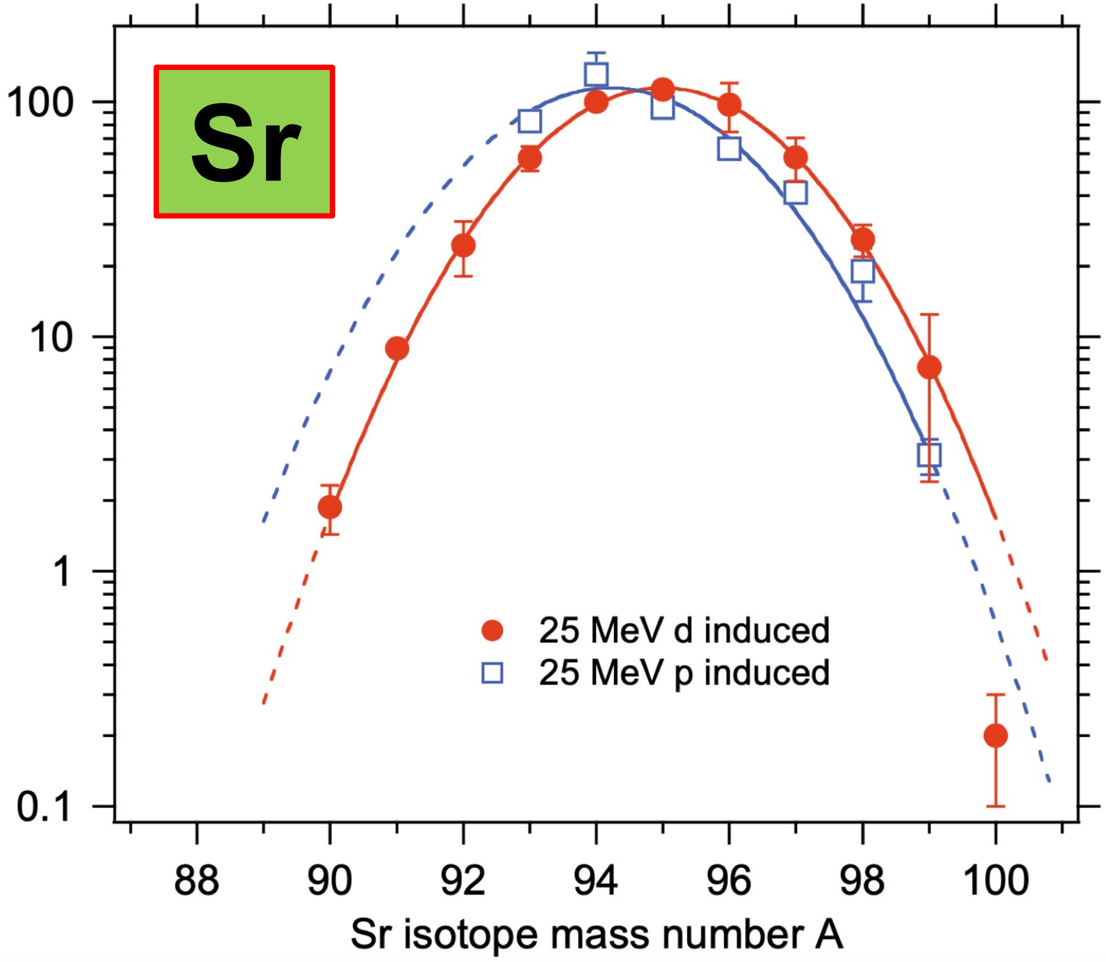
H. Penttilä[1,a], V.-V. Elomaa[1], T. Eronen[1], J. Hakala[1], A. Jokinen[1], A. Kankainen[1], I.D. Moore[1], S. Rahaman[1,b], S. Rinta-Antila[1], J. Rissanen[1], V. Rubchenya[1,2], A. Saastamoinen[1], C. Weber[1,c], and J. Äystö[1]

Eur. Phys. J. A (2016) 52: 104
DOI 10.1140/epja/i2016-16104-4
THE EUROPEAN PHYSICAL JOURNAL A
Regular Article – Experimental Physics

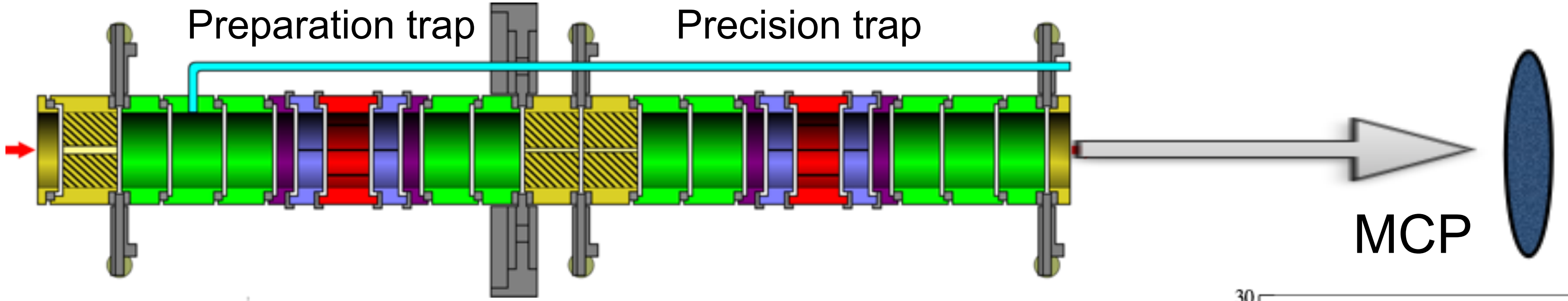
Independent isotopic yields in 25 MeV and 50 MeV proton-induced fission of ^{nat}U

H. Penttilä[1,a], D. Gorelov[1], V.-V. Elomaa[1], T. Eronen[1], U. Hager[1,b], J. Hakala[1], A. Jokinen[1], A. Kankainen[1], P. Karvonen[1,c], I.D. Moore[1], J. Parkkonen[1], K. Peräjärvi[2], I. Pohjalainen[1], S. Rahaman[1,d], S. Rinta-Antila[1], J. Rissanen[1,e], V.A. Rubchenya[1,3], A. Saastamoinen[1,f], V. Simutkin[1], T. Sonoda[1,g], C. Weber[1,h], A. Voss[1], and J. Äystö[1,i]

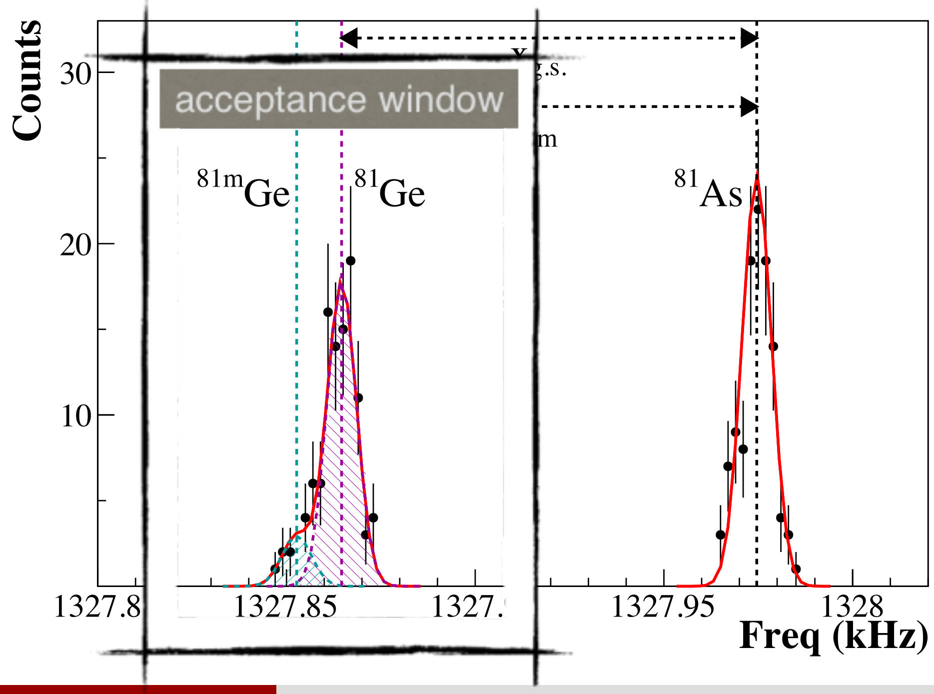
[1] University of Jyvaskyla, Department of Physics, P.O. Box 35 (YFL), FI-40014 University of Jyvaskyla, Jyväskylä, Finland
[2] STUK - Radiation and Nuclear Safety Authority, P.O. Box 14, FI-00881 Helsinki, Finland
[3] V. G. Khlopin Radium Institute, 194021, St. Petersburg, Russia

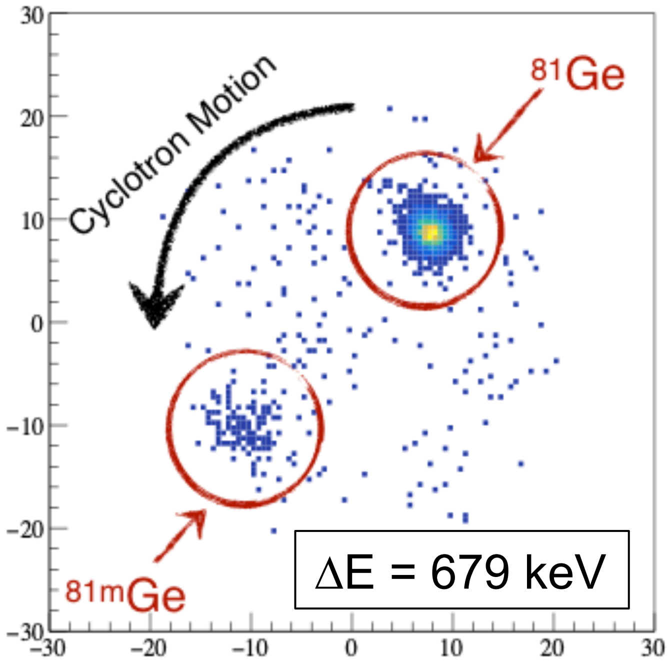


Isomeric Yield Ratios
PI-ICR



$$\frac{M}{\Delta M} > 10^6$$

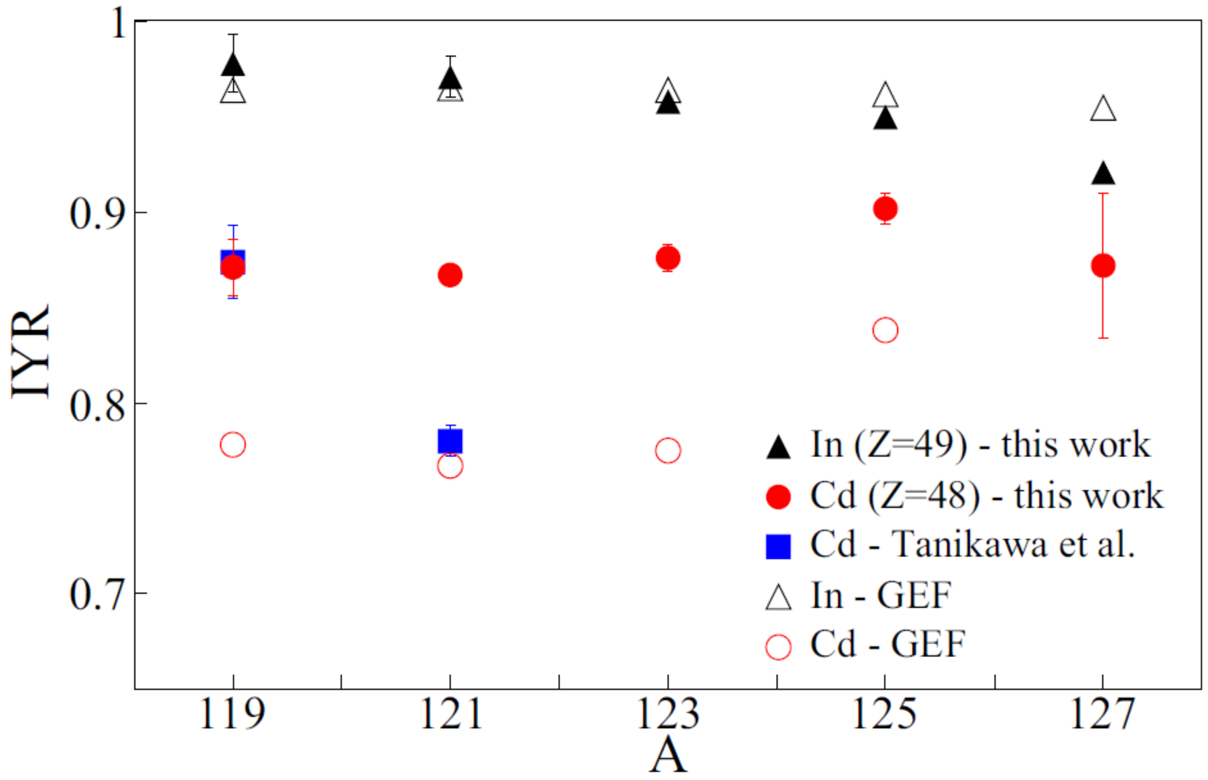




S. Eliseev, Appl Phys B,114(1):107–128, 2014.
D. A. Nesterenko, et al., EPJA, 54(9):154, 2018.

Results for Cd and In

$$IYR = \frac{Y_{HS}}{Y_{total}}$$



$^{238}U(p,f)$ @ 25 MeV

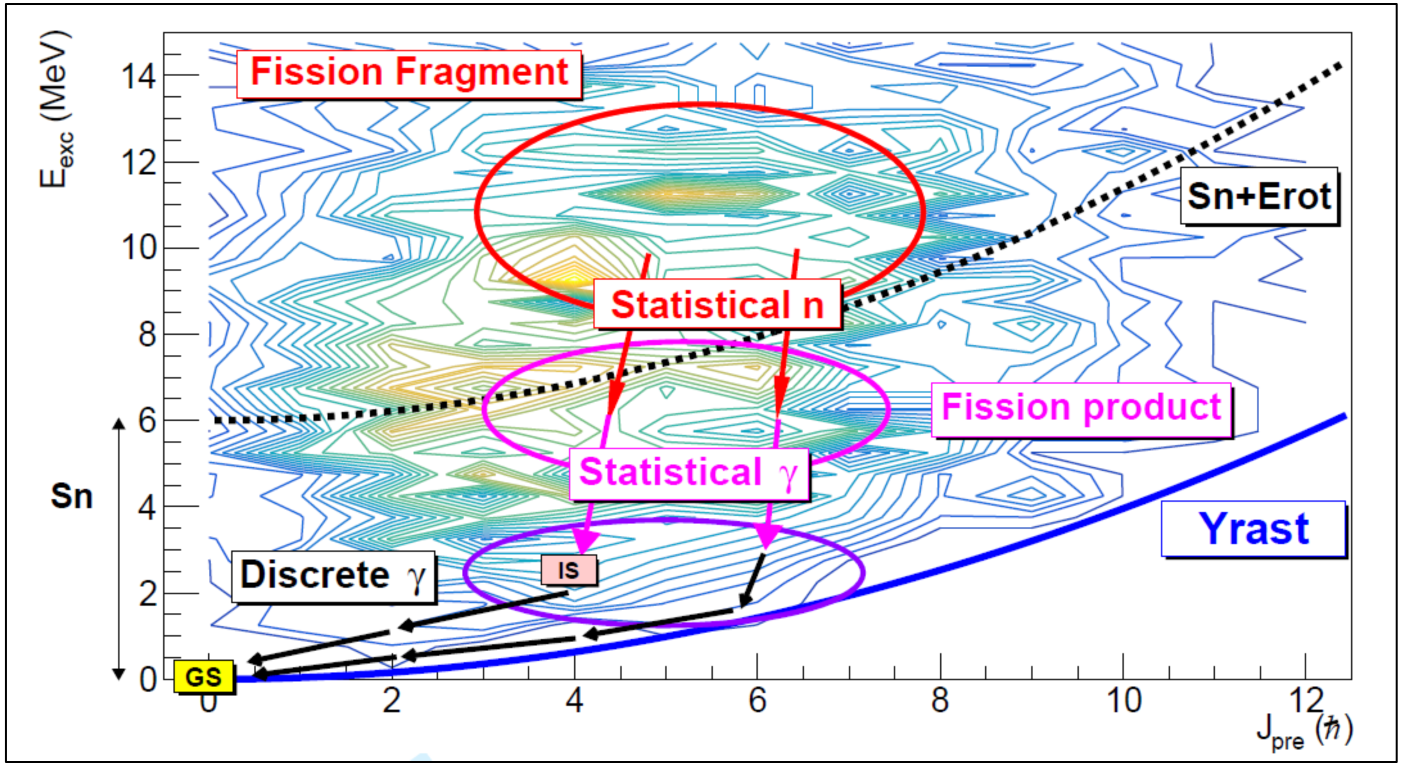
Decreasing trend for In,
less clear for Cd.

Earlier data (γ-spectroscopy):
Very good agreement for ^{119}Cd but large deviation for ^{121}Cd.

GEF: reasonable for In but large discrepancies in Cd case.

Fragment angular momentum

Simplified description



E* vs J – population:

Governs emission of prompt neutrons and gammas.

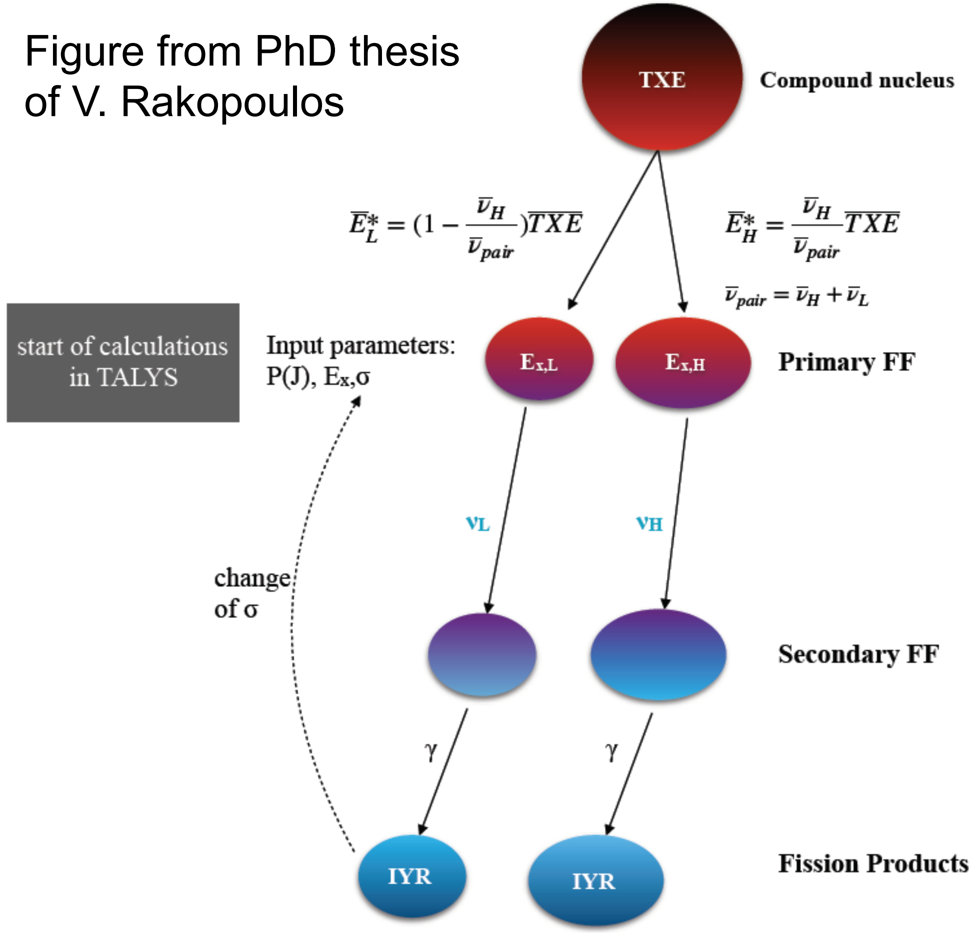
Relates to population of isomer states.

Challenge:

$$\text{IYR} \longrightarrow P(J)$$

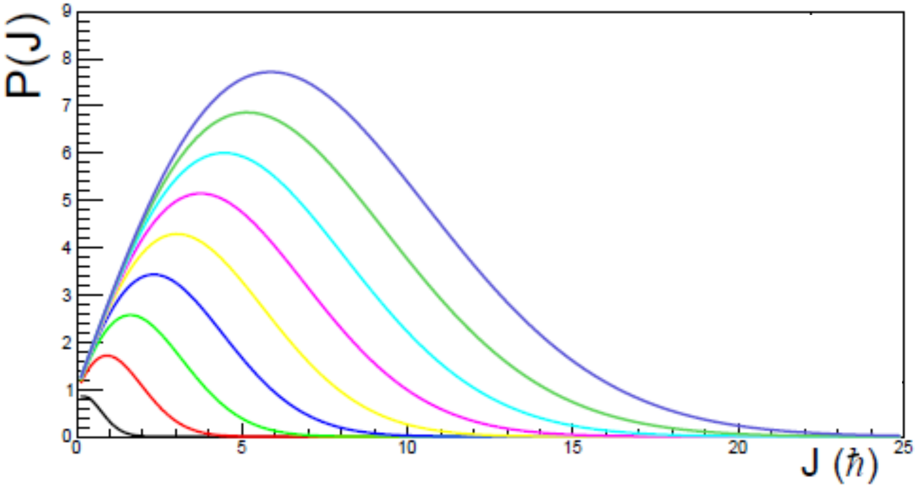
Fragment angular momentum

Figure from PhD thesis of V. Rakopoulos

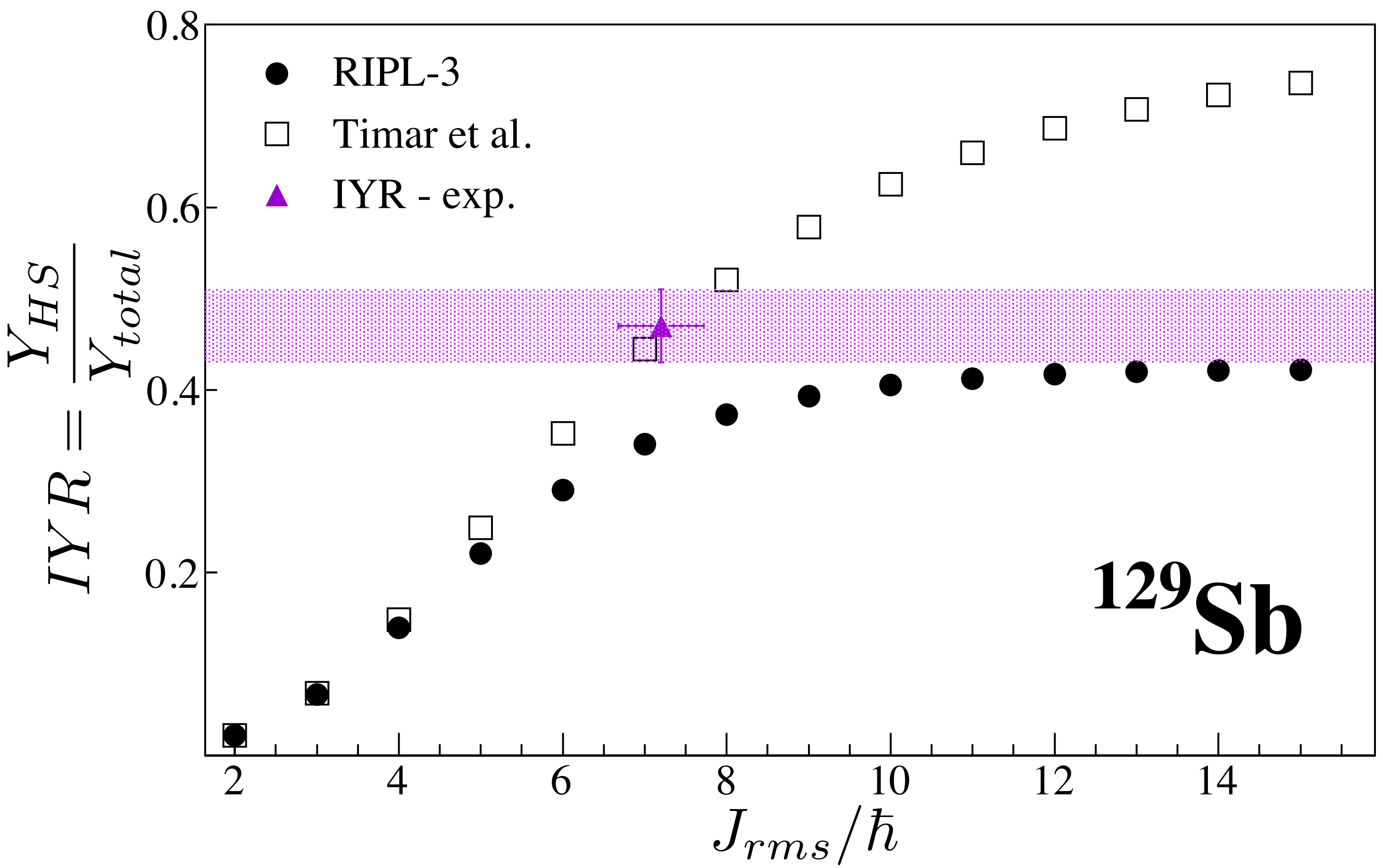


Rayleigh distribution for total angular momentum of the fragments (from level densities):

$$P(J; J_{rms}) = \frac{2J+1}{J_{rms}^2} e^{-\frac{(J+\frac{1}{2})^2}{J_{rms}^2}}$$



Fragment angular momentum



Root-mean-square angular momentum can be derived.

If level scheme is known!

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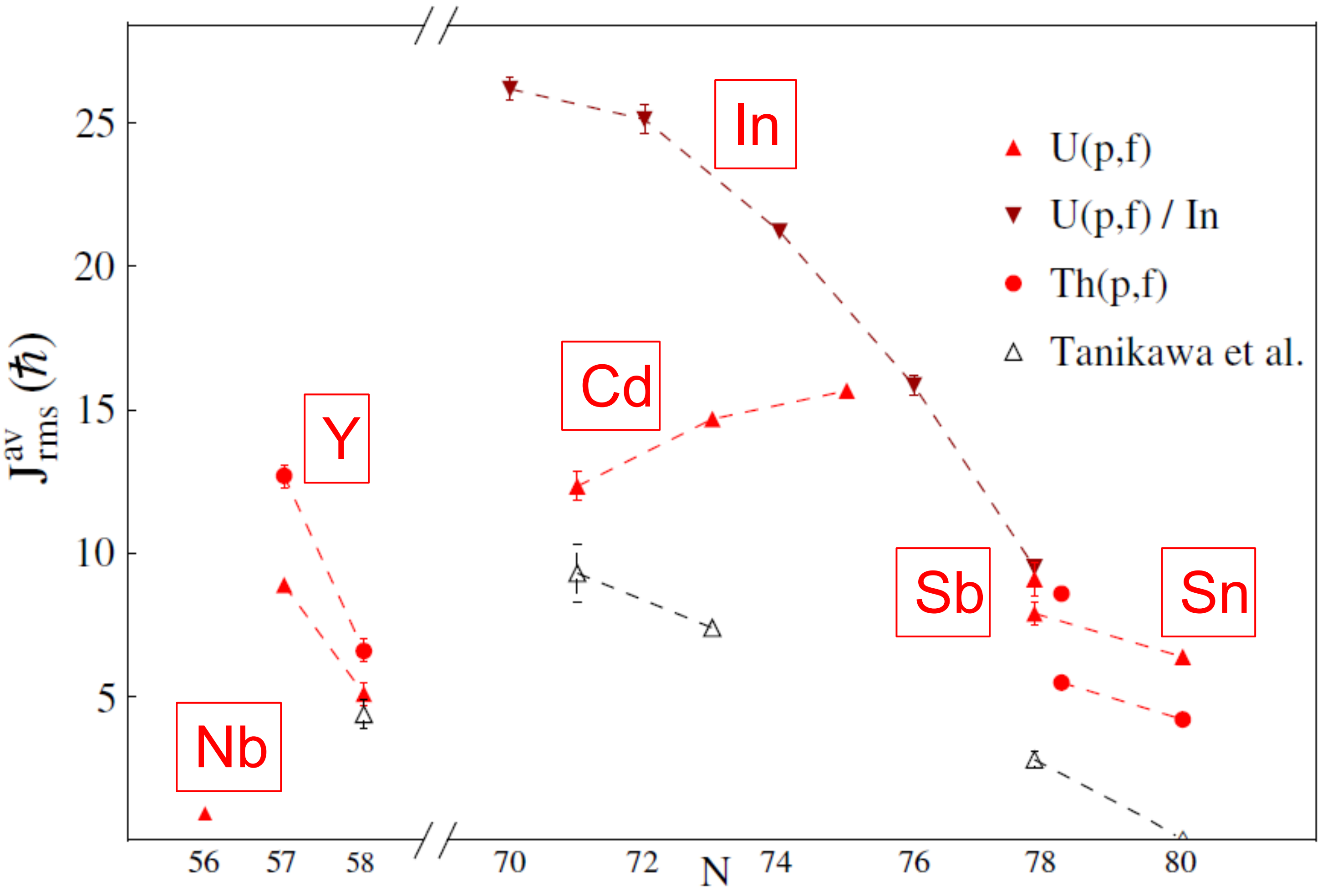
Fragment angular momentum

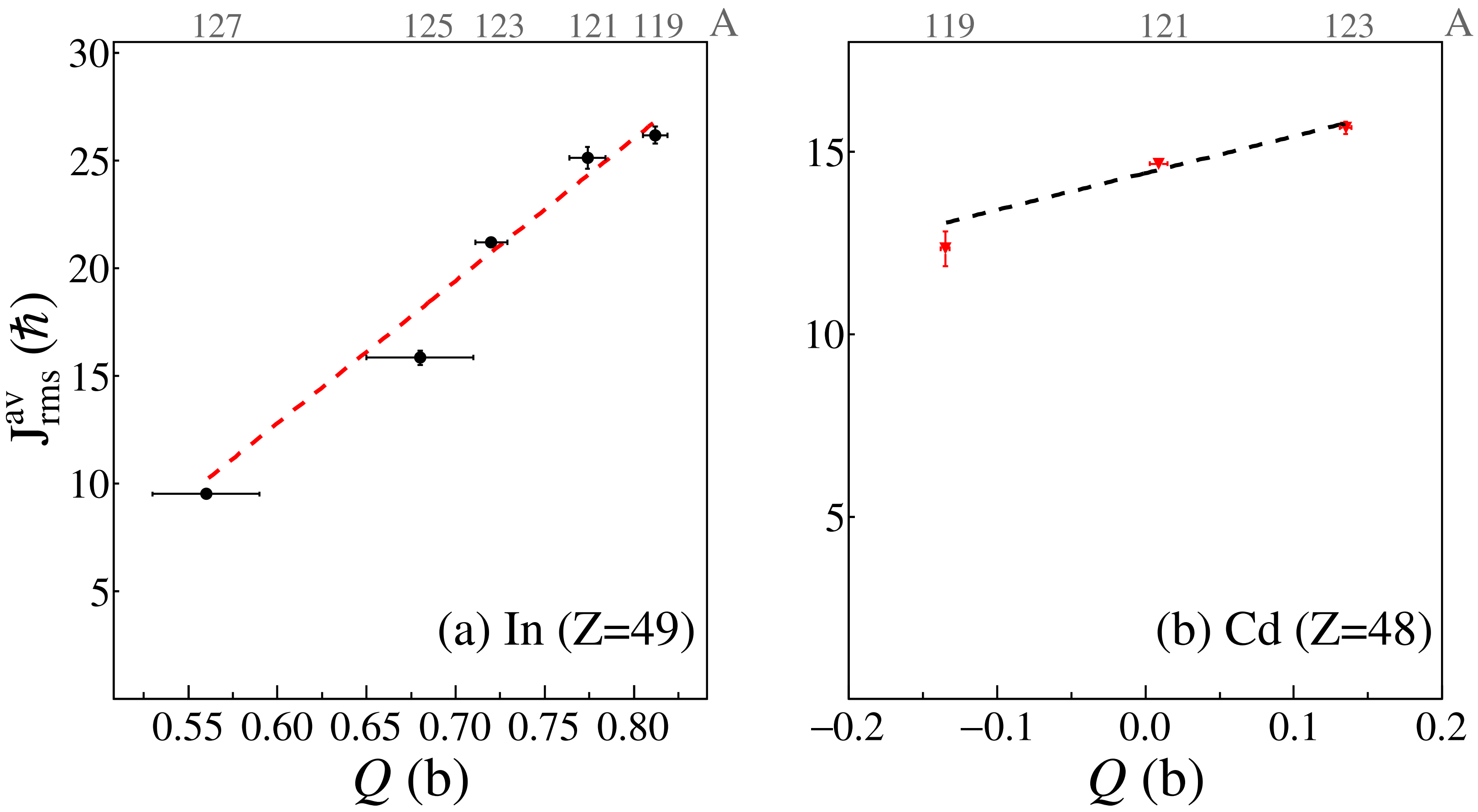


N.B.

J_{rms} is the average angular momentum of the fragments which, after neutron emission, become the named fission product.

V. Rakopoulos et al., PhysRevC 98 (2018)
V. Rakopoulos et al., PhysRevC **99** (2019)

Angular momentum vs quadrupole moment



J_{rms} correlation with the electric quadrupole moment of the high spin state as reported in [1] and [2].

[1] D. T. Yordanov, et al., *Physical Review Letters*, 110:192501, 2013.
[2] N. J. Stone, INDC (NDS)-0658. Technical report, IAEA, 2014.

V. Rakopoulos et al., PhysRevC **99** (2019)

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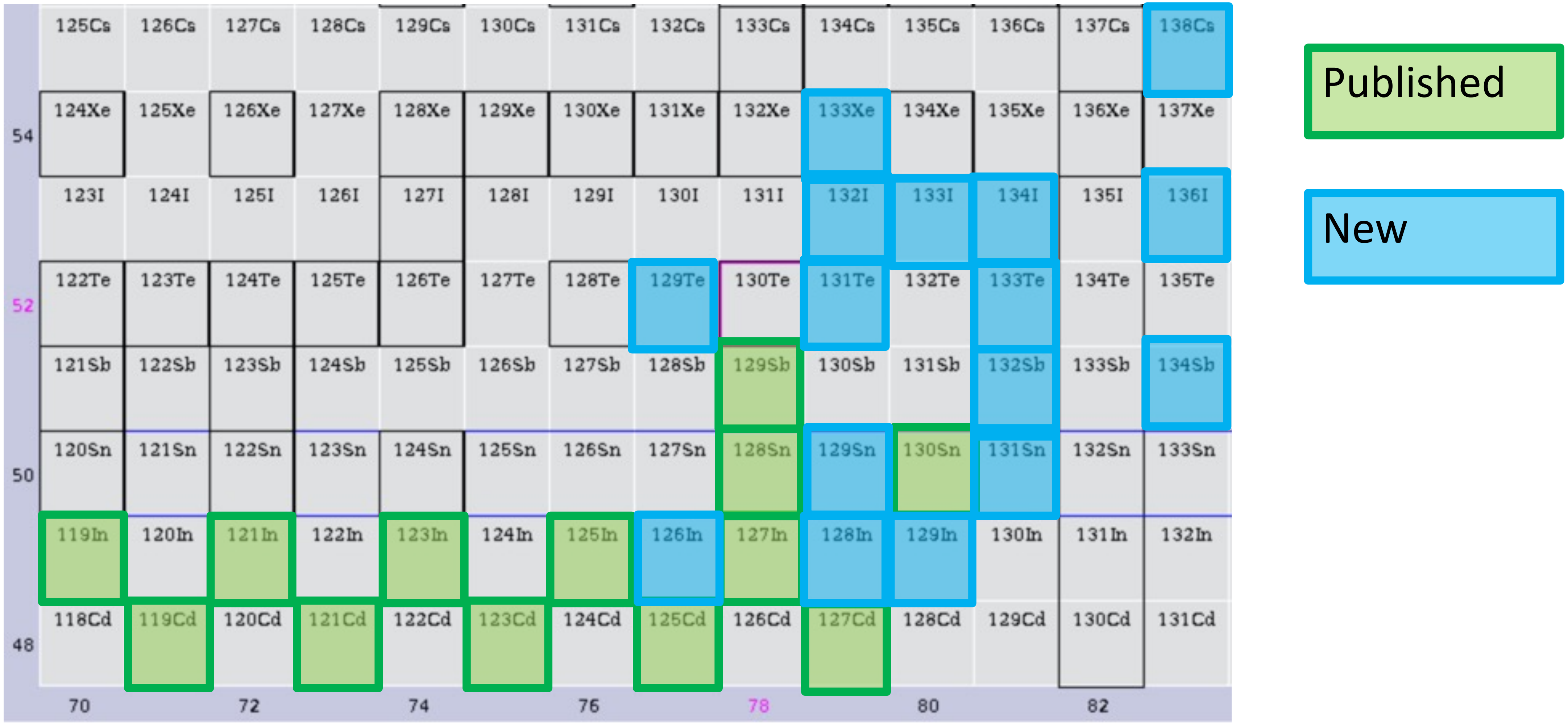
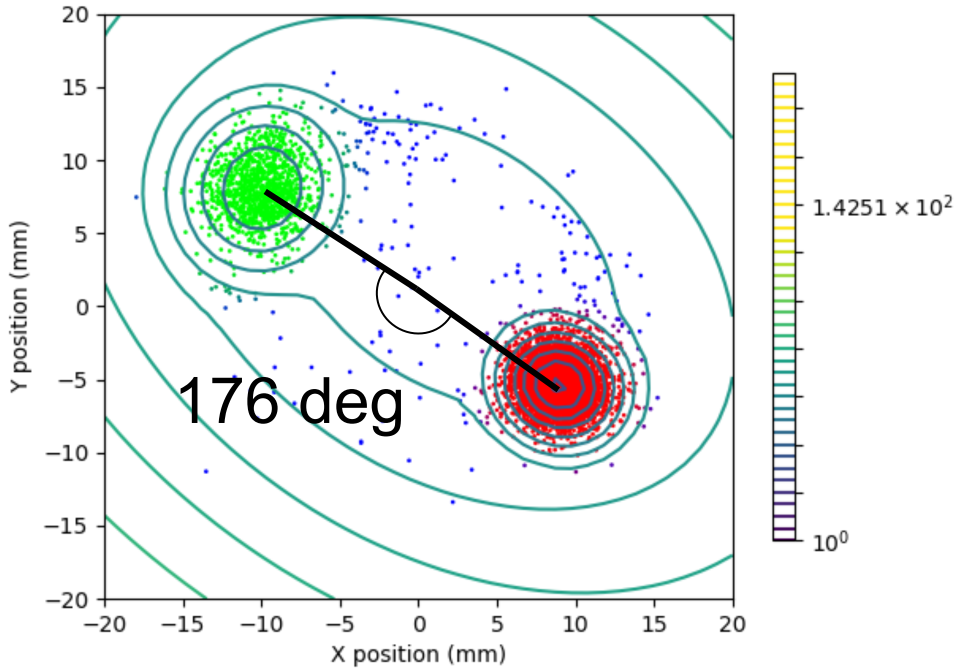
New measurement in 2019



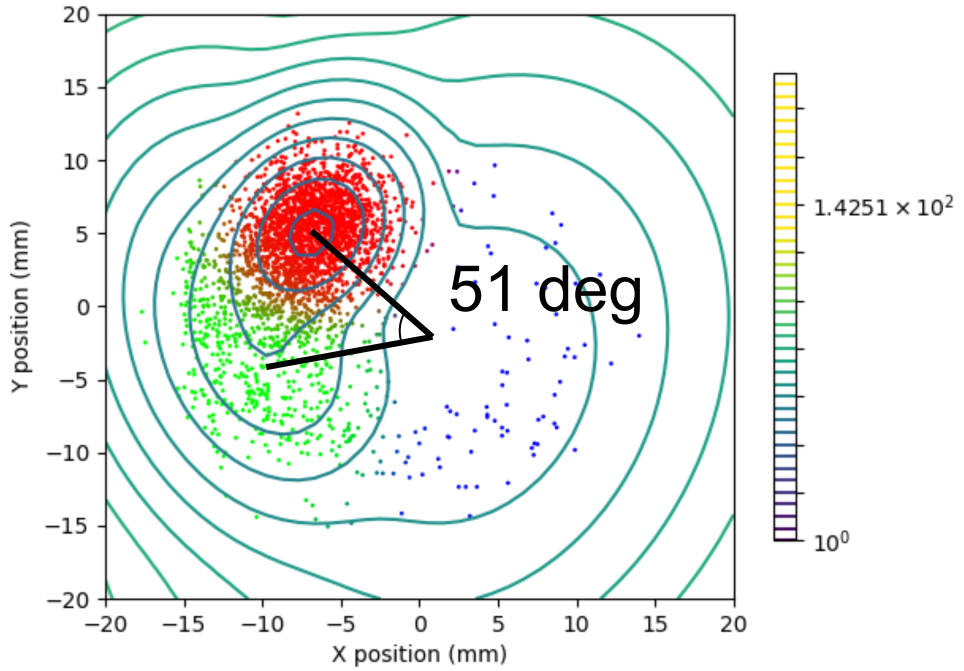
Bayesian gaussian mixture models & Bootstrap

^{133}Te:
E* = 334 keV
T_{acc} = 220 ms

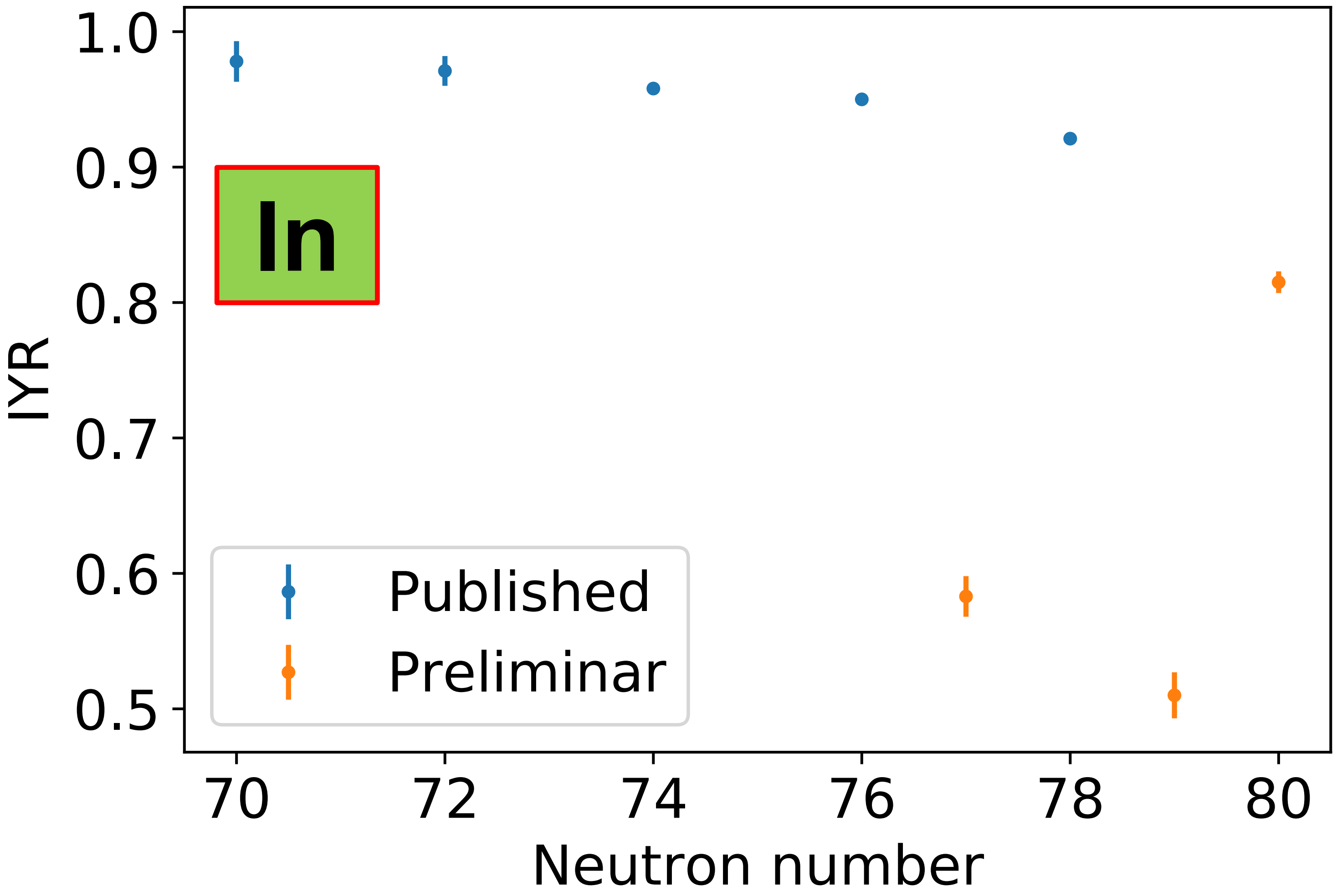


^{129}Sn:
E* = 35keV
T_{acc}=1010 ms

$$\frac{M}{\Delta M} \sim 3 \times 10^6$$



Preliminar result - Indium



Even N isotopes
- gs high spin 9/2+
- Excited state 1/2-

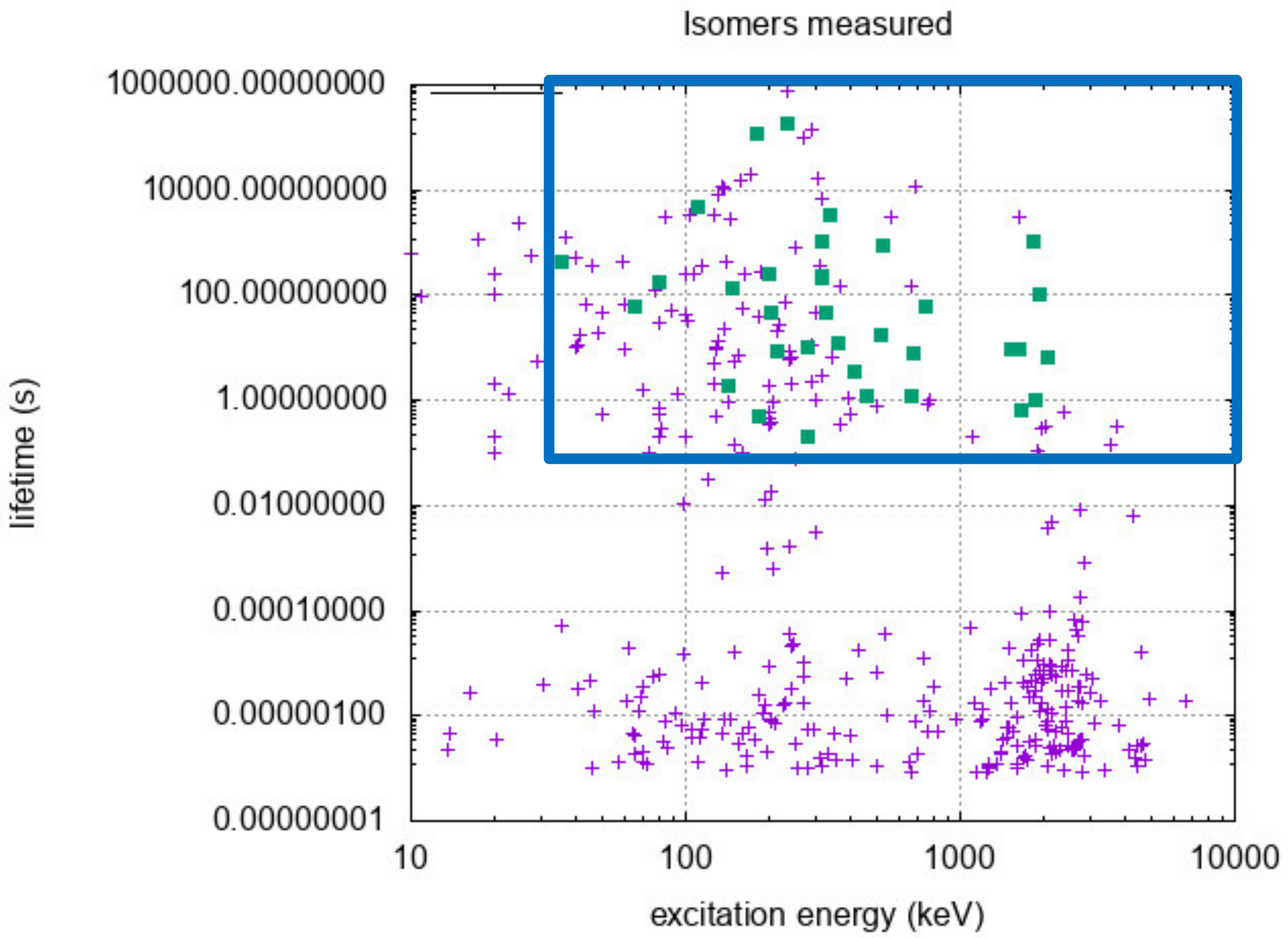
Odd N isotopes
- gs low spin 3+
- Exited state 8-

OUTLOOK

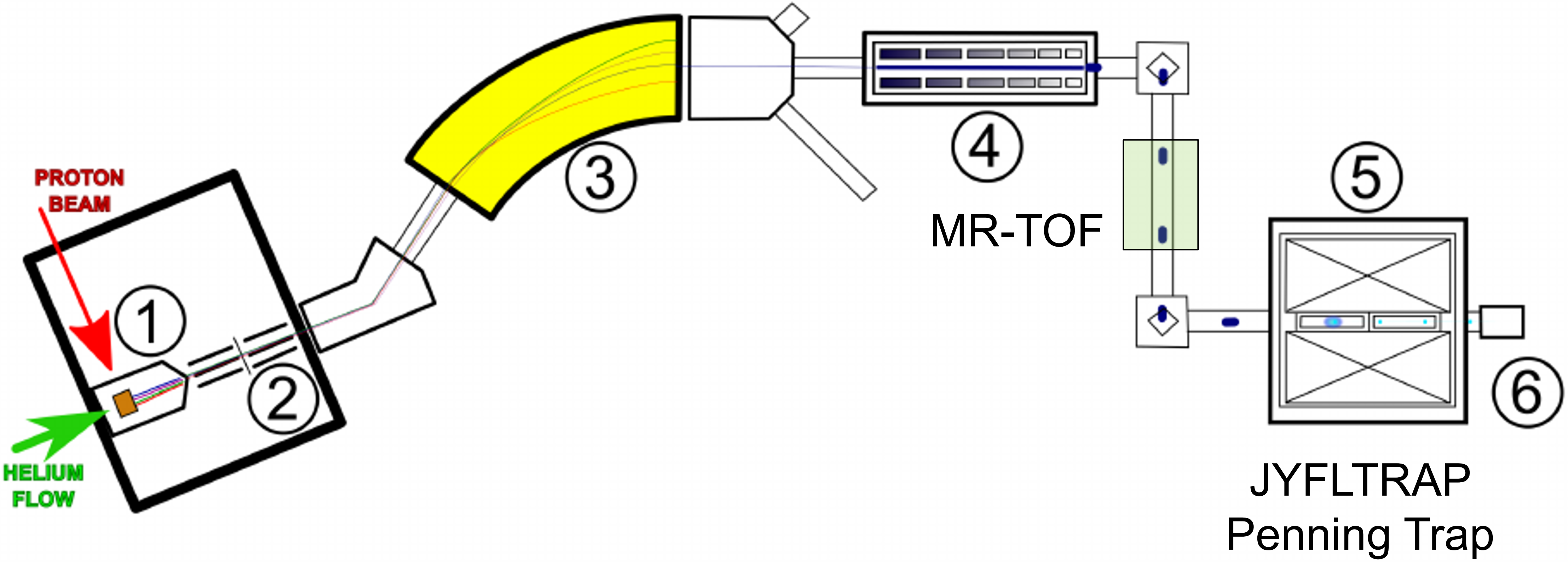
Isomers produced in fission

Fission here means:

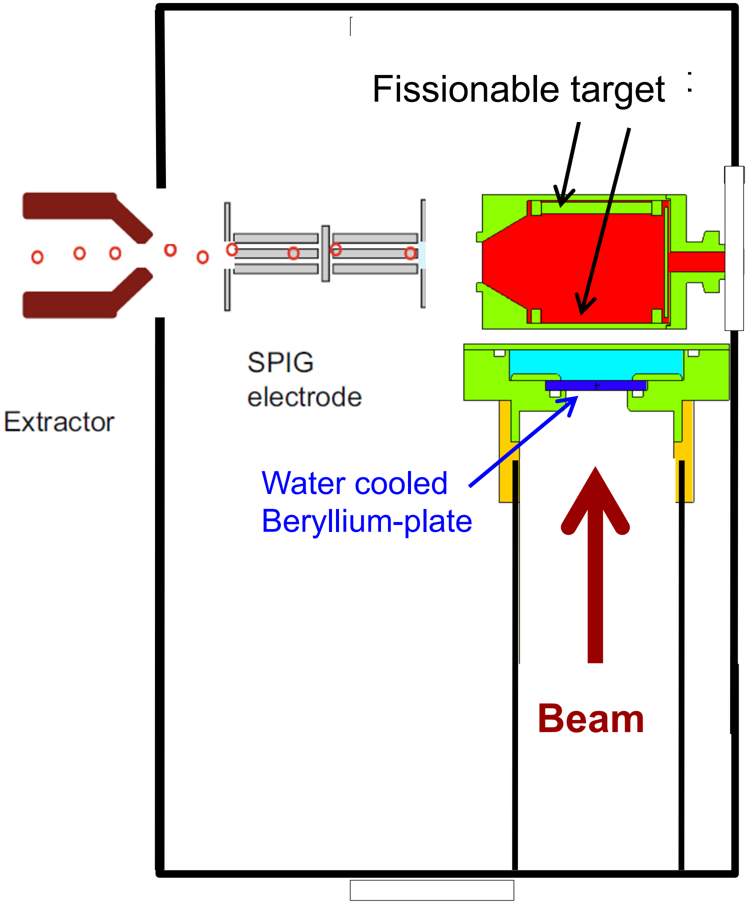
- $^{238}U(p,f)$ at 25 MeV
- $^{252}Cf(SF)$
- $^{235}U(n_{th},f)$
- $^{238}Cm(SF)$



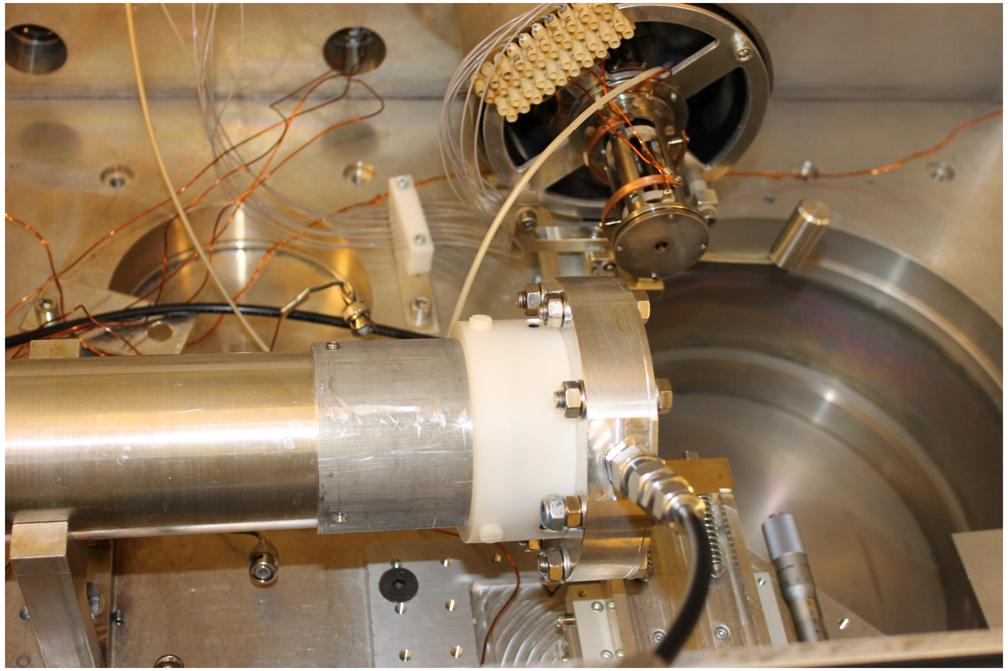
IGISOL & JYFLTRAP



Neutrons for IGISOL

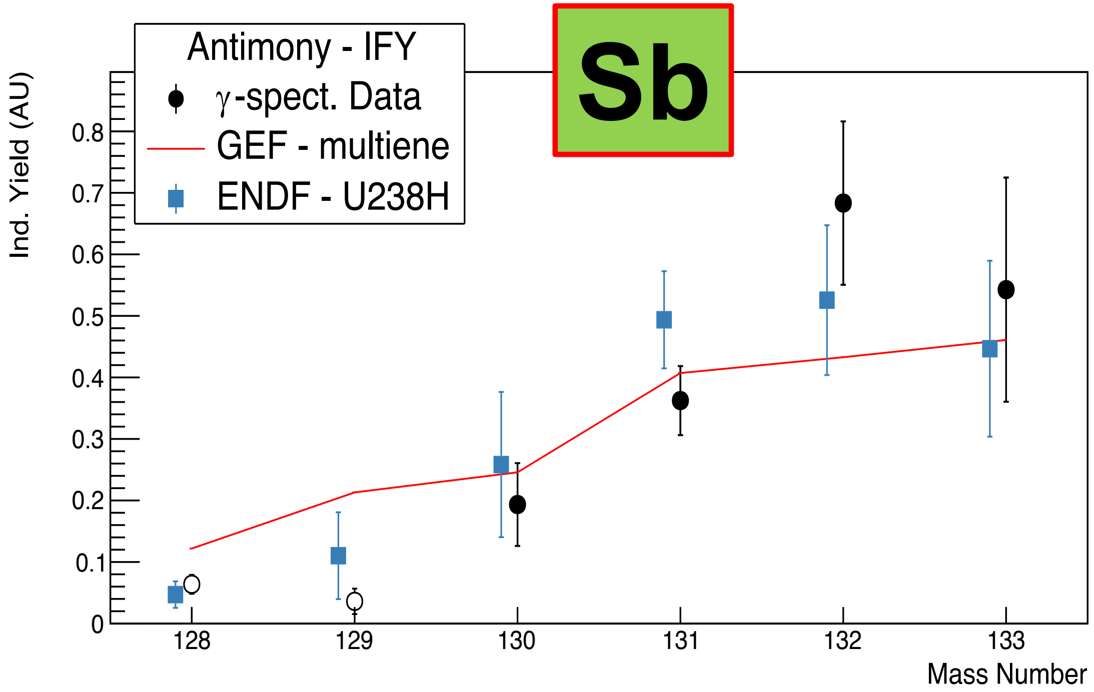


Competitive with other facilities by being very close to the neutron source.



First neutron induced fission yields

Relative independent yields.



A. Mattera et al., EPJ A **54**:13 (2018)

10 uA Proton beam @ 30 MeV

^{nat}U target

average XS-weighed energy:
12.4±8.8 MeV

(97 ± 1) % of fissions from ^{238}U

Measured with gamma spectroscopy

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Other possibilities

Thermal neutron induced @ TRIGATRAP

Spontaneus fission @ FRS ion catcher