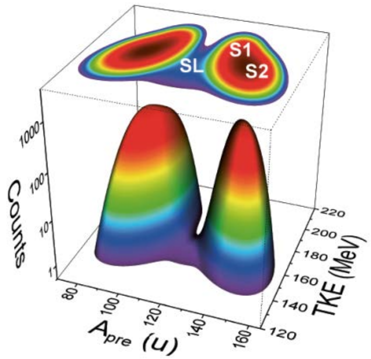
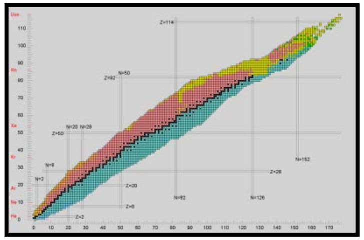
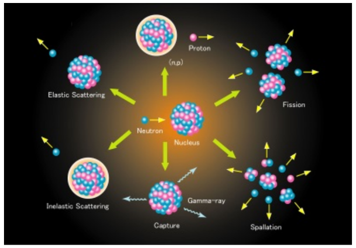
Fission yields



Stephan Pomp
stephan.pomp@physics.uu.se
Department of physics and astronomy
Uppsala University





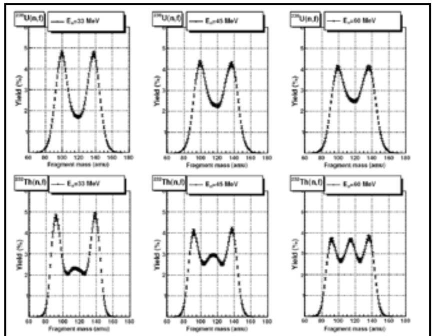
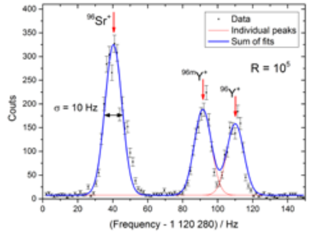
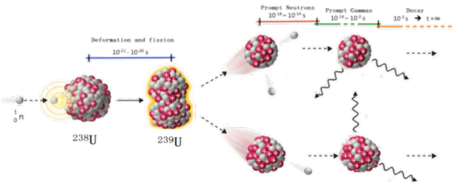


Figure 4.3: Pre-neutron emission fragment mass distributions for neutron-induced fission of ^{238}U (upper row) and ^{232}Th (lower row) at 33, 45 and 60 MeV.

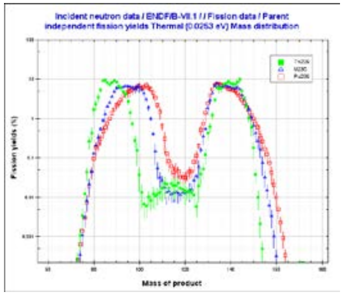


Outline

- Some literature sources



- Introduction:
  - Phenomenology, time scale, obserables, challenges, data needs, …
- Fission yields (FY):
  - Definitions, trends, ….



- Overview on model codes
- Overview on experimental methods
- Examples of experimental efforts
  - 2E with FGIC, 2E-2v (VERDI and FALSTAFF), IGISOL and more …

UPPSALA UNIVERSITET

Literature: some suggestions

Fission in general:

- N. Bohr and J.A. Wheeler, *The mechanism of nuclear fission*, Phys. Rev. **56** (1939) 426.
- R. Vandenbosch and J. Huizenga, *Nuclear fission*, Academic Press, 1973.
- C. Wagemans, *The nuclear fission process*, CRC Press, 1991.
- A.N. Andreyev et al., *Nuclear fission: a review of Experimental Advances and Phenomenology*, Rep. Prog. Phys, 2017 (in press).

On measurement techniques etc.:

e.g. PhD theses available for free on the web:

- Ali Al-Adili, PhD thesis, Uppsala, 2013.
- Andrea Mattera, PhD thesis, Uppsala 2017.
- Kaj Jansson, PhD thesis, Uppsala 2017.


UPPSALA UNIVERSITET

Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 1550

Studying neutron-induced fission at IGISOL-4

From neutron source to yield measurements and model comparisons

ANDREA MATTERA

ACTA UNIVERSITATIS UPSALIENSIS UPPSALA 2017

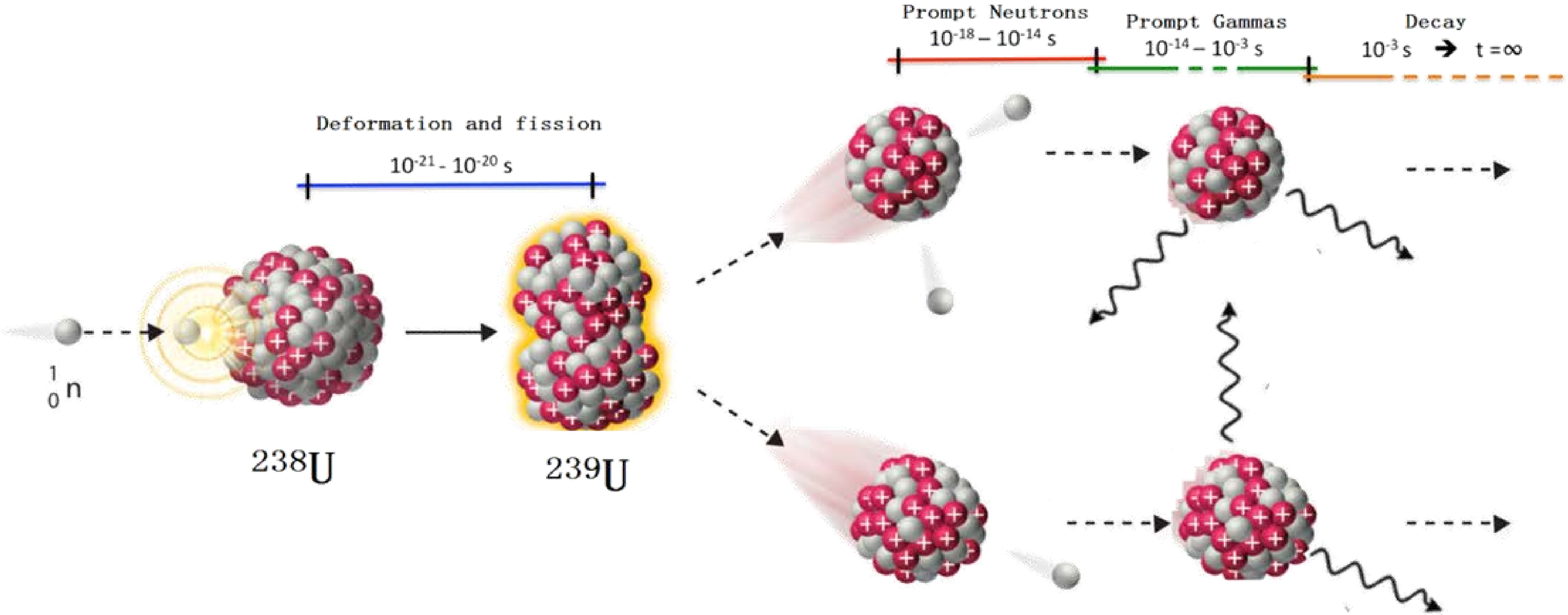
… and of course many other papers and theses from many other universities and labs ☺

http://urn.kb.se/resolve?urn=urn%3Anbn%3Ase%3Auu%3Adiva-328484

Outline

- Some literature sources
- Introduction:
  - Phenomenology, time scale, obserables, challenges, data needs, …
- Fission yields (FY):
  - Definitions, trends, ….
- Overview on model codes
- Overview on experimental methods
- Examples of experimental efforts
  - 2E with FGIC, 2E-2v (VERDI and FALSTAFF), IGISOL and more …

Fission: time line and observables



Cross section,

fission yields (at various stages),

prompt neutron multiplicity and energy spectra

prompt gamma multiplicity and energy spectra

Energy release and time scale

Kinetic energy of fragments:

typically 85 % of total energy release (but large variations!)

Kinetic energy to prompt neutrons:

about 5 MeV (then we have fission products)

Energy to prompt gammas:

about 7 MeV

200 MeV released

Energy to beta decay etc:

about 10 %

(cumulative..)

Note: neutrinos take away about 8 MeV

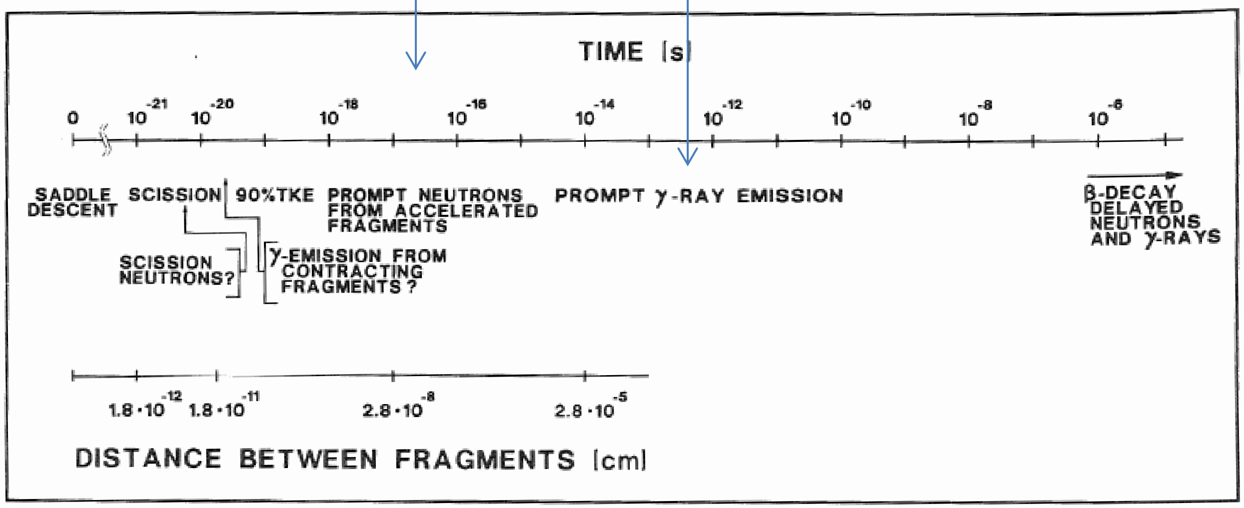


FIGURE 1. Time scale in fission.

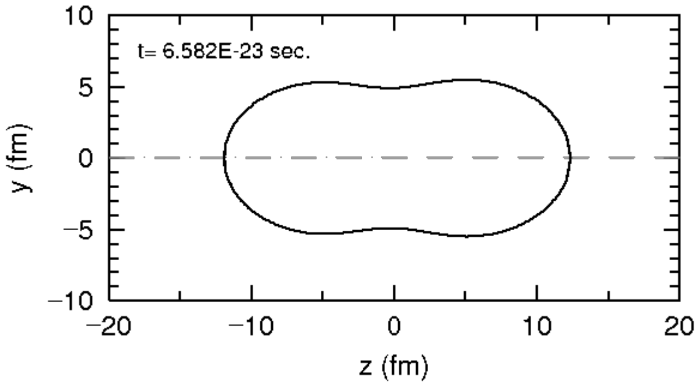
Figure from C. Wagemans (ed.), The Nuclear Fission Process (Boca Raton, 1991)

See S. Prussin, Nuclear Physics for Applications, p. 401 for a detailed list

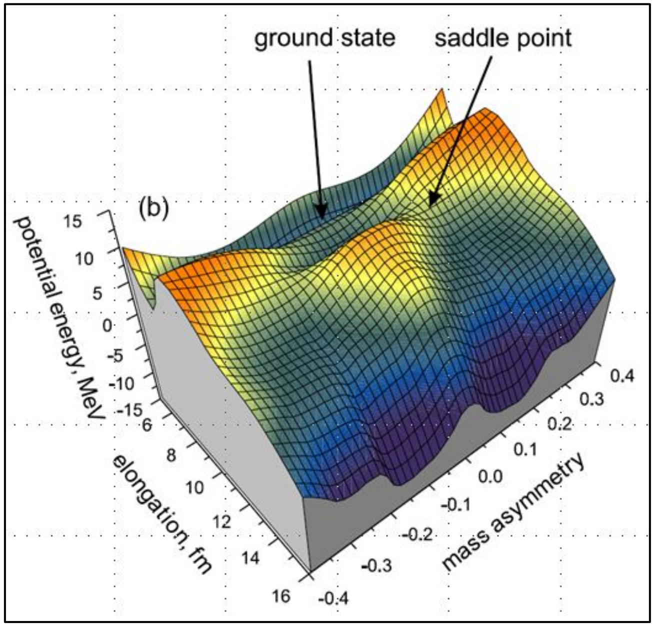
The complete nuclear physics lab (aka fission)

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



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

A 3-D view of a potential landscape

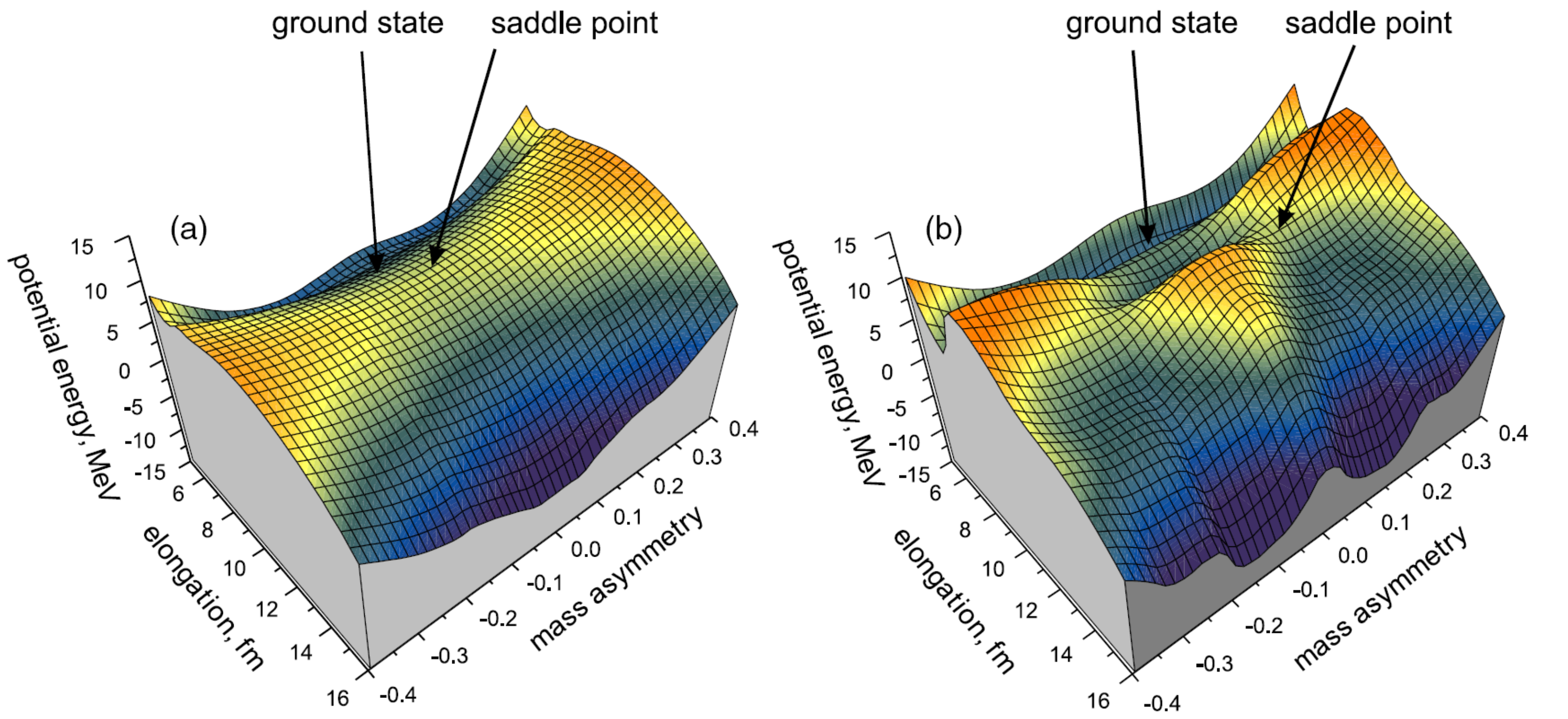
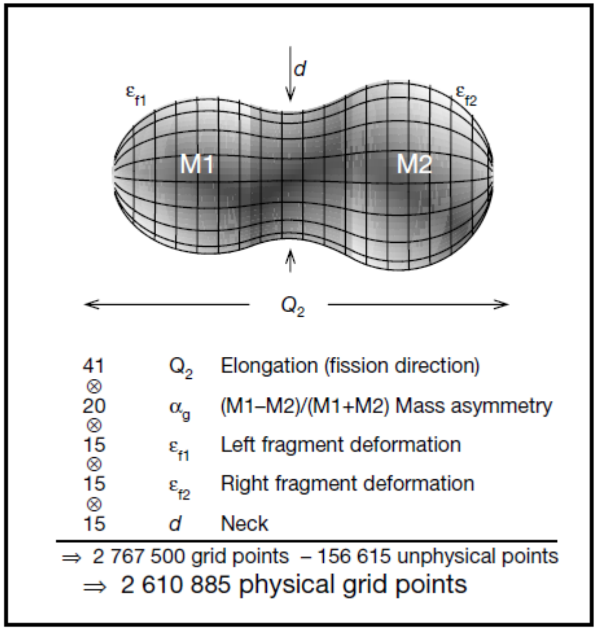


Figure 2. Macroscopic (a) and macro-microscopic (b) potential energy surface for the ^{238}U nucleus in the coordinates (R, η). The potential energy is obtained for $\delta = 0$ and $\varepsilon = 0.35$. The macroscopic part is normalized to zero for the spherical shape of the compound nucleus.

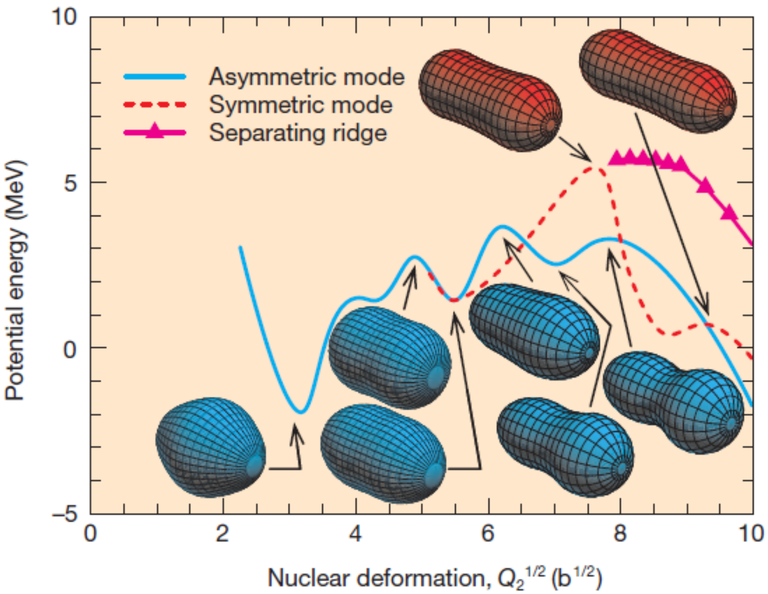
From: A.V. Karpov et al., *J. Phys. G: Nucl. Part. Phys.* **35** (2008) 035104

Computer power and random walk

Five-dimensional shape representation for potential energy calculation:



P. Möller et al., Nature **409** (2001) 785



Potential energy valleys and nuclear shapes for ^{234}U

These calculations can be used to calculate fission yields.
J. Randrup and P. Möller, Phys. Rev. Lett. **106** (2011) 132503.

Other observables: e.g. angular distributions …

PhD thesis A. Al-Adili, Uppsala 2013

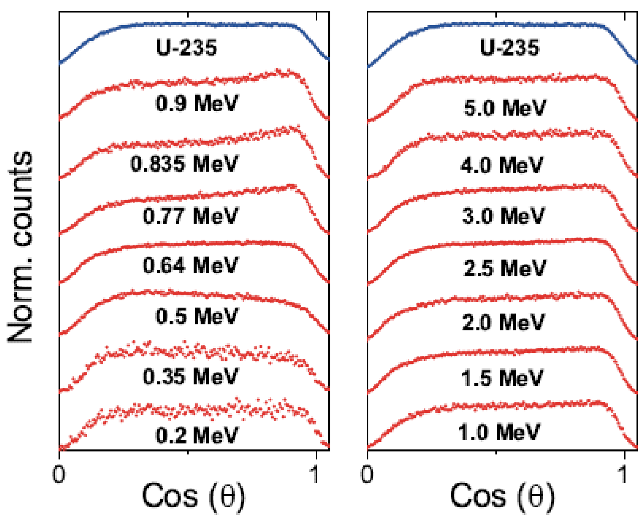


Figure 5.2. The angular distributions of $^{234}U(n, f)$ at all measured energies, E_n, together with the isotropic angular distribution of $^{235}U(n_{th}, f)$. Note the strong difference between E_n = 0.5 and 0.835 MeV.

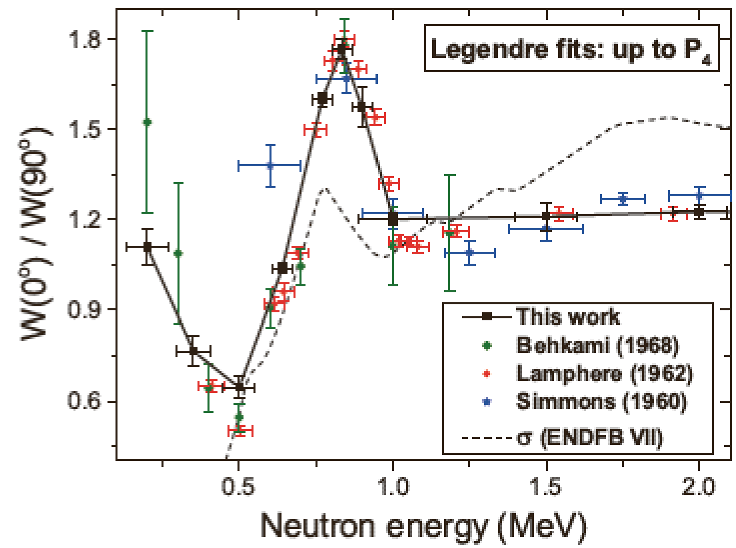


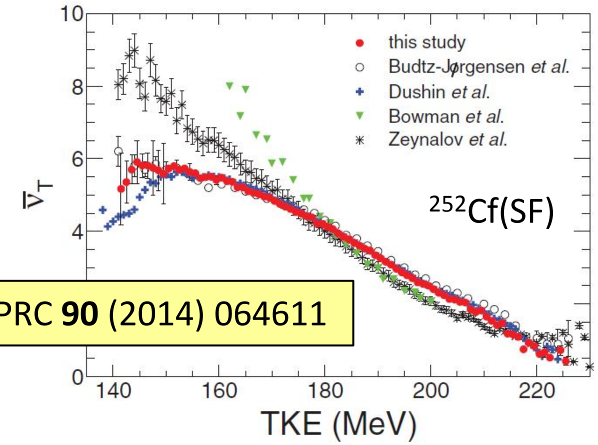
Figure 5.5. The angular anisotropy fitted with Legendre polynomials up to P_4. Strong fluctuations in angular anisotropy as a function of incident neutron energy are seen. The results are compared to data from Refs. [3, 4, 5] where 1.0 correspond to the isotropic case of $^{235}U(n_{th}, f)$.

Strong fluctuations in the angular distributions in ^{234}U(n,f) close to vibrational resonance.
Resonances connected to the so-called *transition states* at the saddle.
Also changes in mass and energy distributions where observed.
May be connected to structure in potential energy landscape (fission barrier heights).

Some challenges

Questions: Where does the excitation energy go?
When does the freeze-out of fragment properties occur?
Do scission neutrons exist?

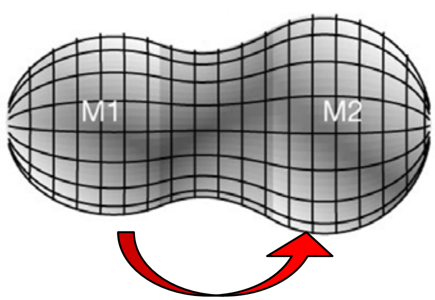
Linked to that: Prompt neutrons?
Isomeric yields?
…



A. Göök et al., PRC **90** (2014) 064611

New theoretical ideas: Energy sorting mechanism based on the constant temperature model

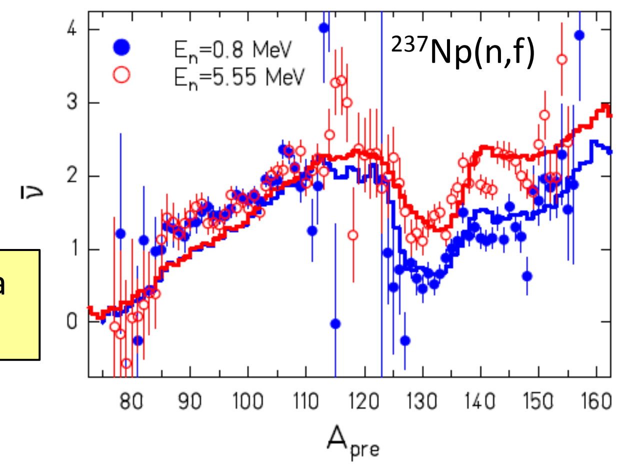
Schmidt and Jurado, PRC 83 (2011) 061601(R)



Excitation energy

GEF code

K.-H. Schmidt et al., Nucl. Data Sheets **131** (2016) 107-221



Needs

Needs: e.g., knowledge of fission yields for various fuel cycle or nucleosynthesis scenarios .

Examples for reactor applications:

- Other fuels and high burn-up …
- Precursors for delayed-neutron emission
- Long-lived fission products (final storage)
- Neutron poisons (neutron absorbers)

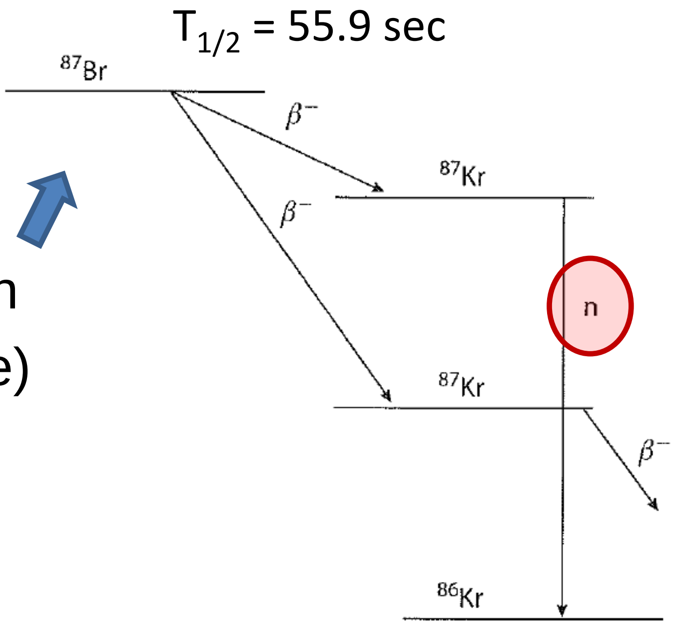


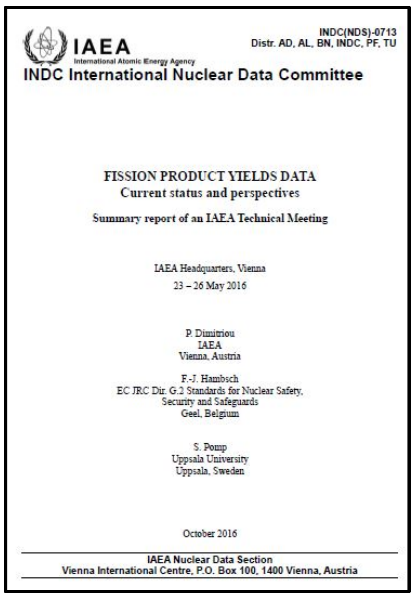
Figure 11.14 Emission of a delayed neutron in ^{87}Br decay.

Figure from Bertulani, Nuclear physics in a nutshell.

Needs II

Needs can only be fulfilled by direct measurements combined with theoretical developments that need guidance from other experimental input (e.g. $\bar{\nu}(A)$).

P. Dimitriou et al, IAEA, INDC(NDS)-0713 (2016)


IAEA
International Atomic Energy Agency
INDC(NDS)-0713
Distr. AD, AL, BN, INDC, PF, TU
INDC International Nuclear Data Committee

FISSION PRODUCT YIELDS DATA
Current status and perspectives
Summary report of an IAEA Technical Meeting

IAEA Headquarters, Vienna
23 – 26 May 2016

P. Dimitriou
IAEA
Vienna, Austria

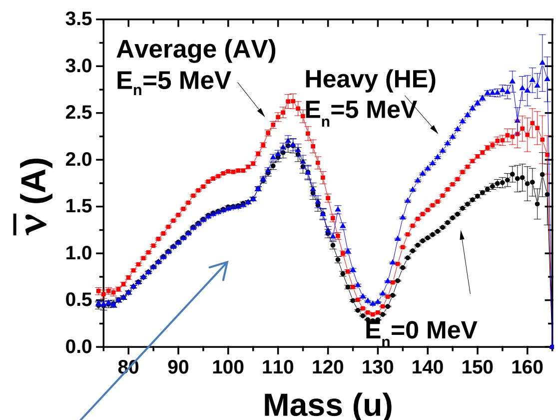
F.-J. Hambsch
EC JRC Dir. G.2 Standards for Nuclear Safety, Security and Safeguards
Geel, Belgium

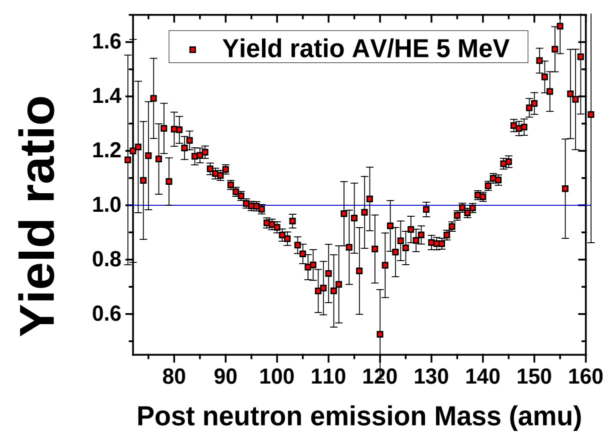
S. Pomp
Uppsala University
Uppsala, Sweden

October 2016

IAEA Nuclear Data Section
Vienna International Centre, P.O. Box 100, 1400 Vienna, Austria

Impact on $\bar{\nu}(A)$ on fission yields in the ^{234}U case:





A. Al-Adili, et al, Phys. Rev. C86 (2012) 054601

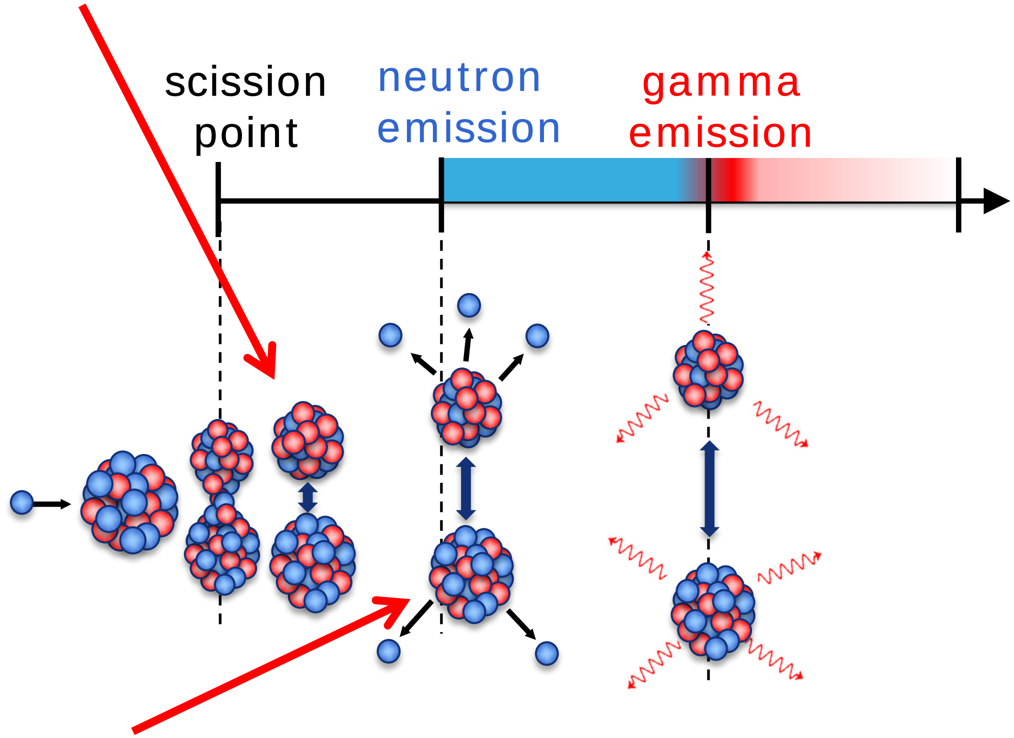
assumption needed in 2E-method ...

Outline

- Some literature sources
- Introduction:
  - Phenomenology, time scale, obserables, challenges, data needs, …
- Fission yields (FY):
  - Definitions, trends, ….
- Overview on model codes
- Overview on experimental methods
- Examples of experimental efforts
  - 2E with FGIC, 2E-2v (VERDI and FALSTAFF), IGISOL and more …

Yields: Definitions I

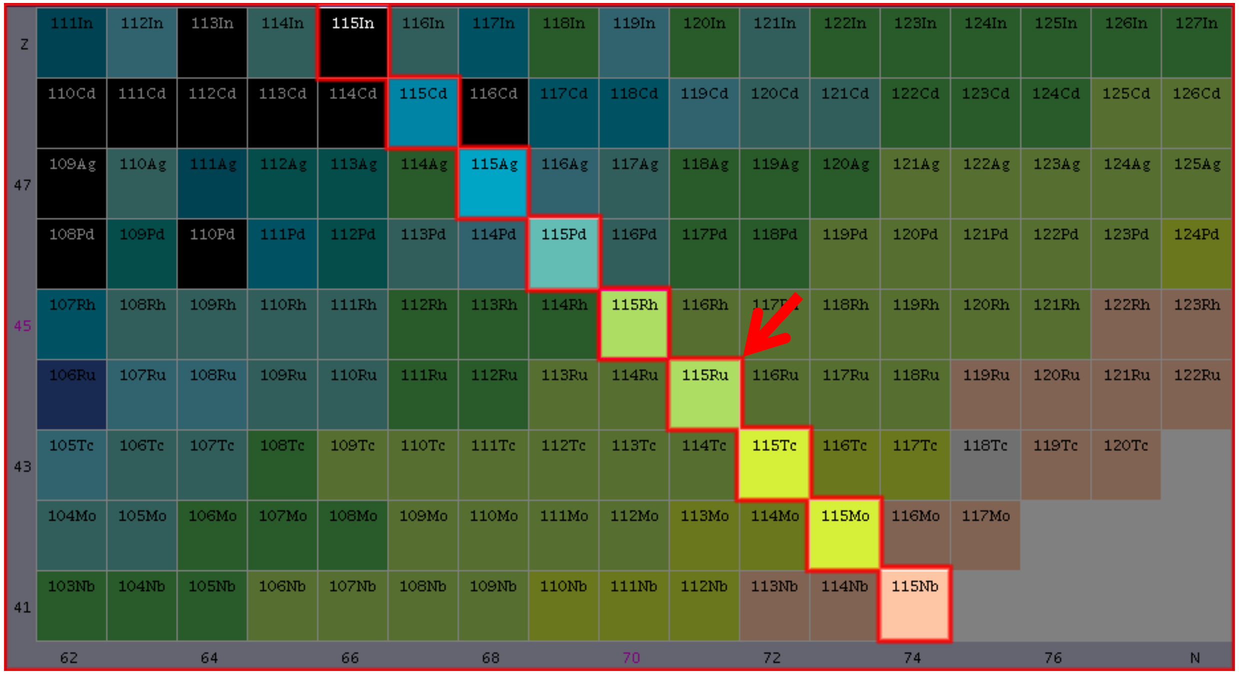
- **Fragment yields**: Yields prior to prompt neutron emission.



- **Product yields:** Yields posterior to prompt neutron emission.

Yields: Definitions II

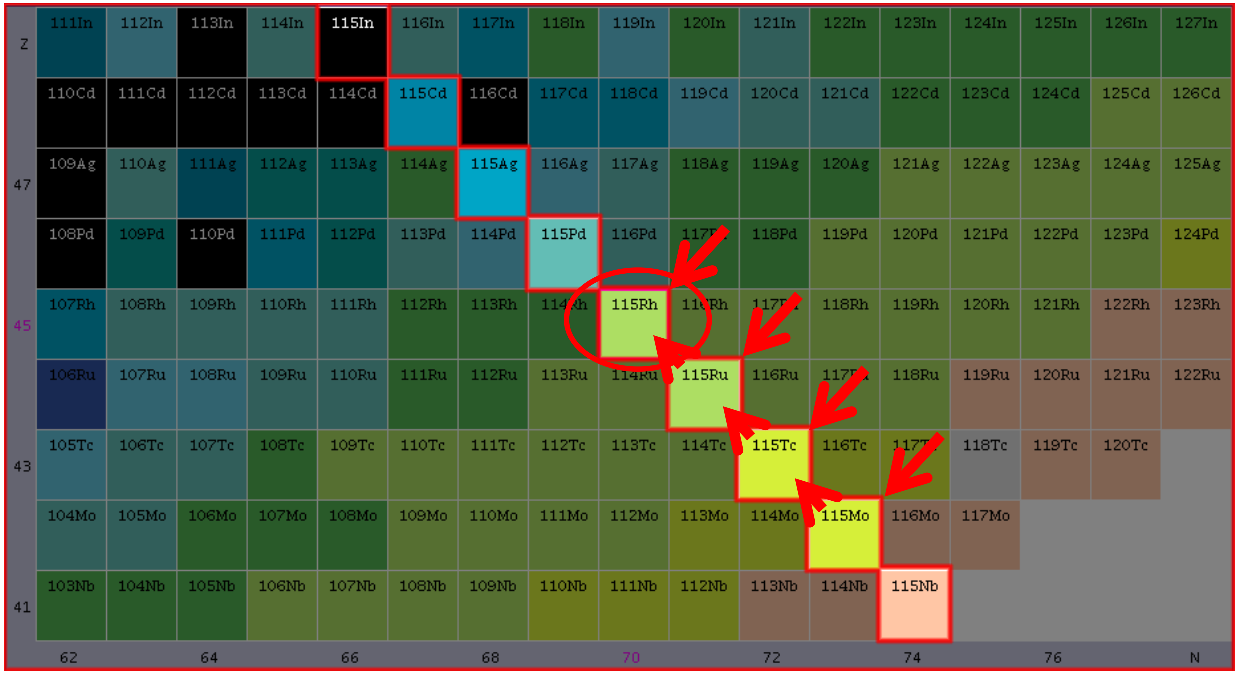
- **Independent fission yields:** number of atoms of a specific nuclide produced directly in the fission process (*i.e.*, not via radioactive decay of precursors).



Source: IAEA-TECDOC-1168 (2000)

Yields: Definitions III

- **Cumulative fission yields**: total number of atoms of a specific nuclide produced (directly and via decay of precursors).



Source: IAEA-TECDOC-1168 (2000)

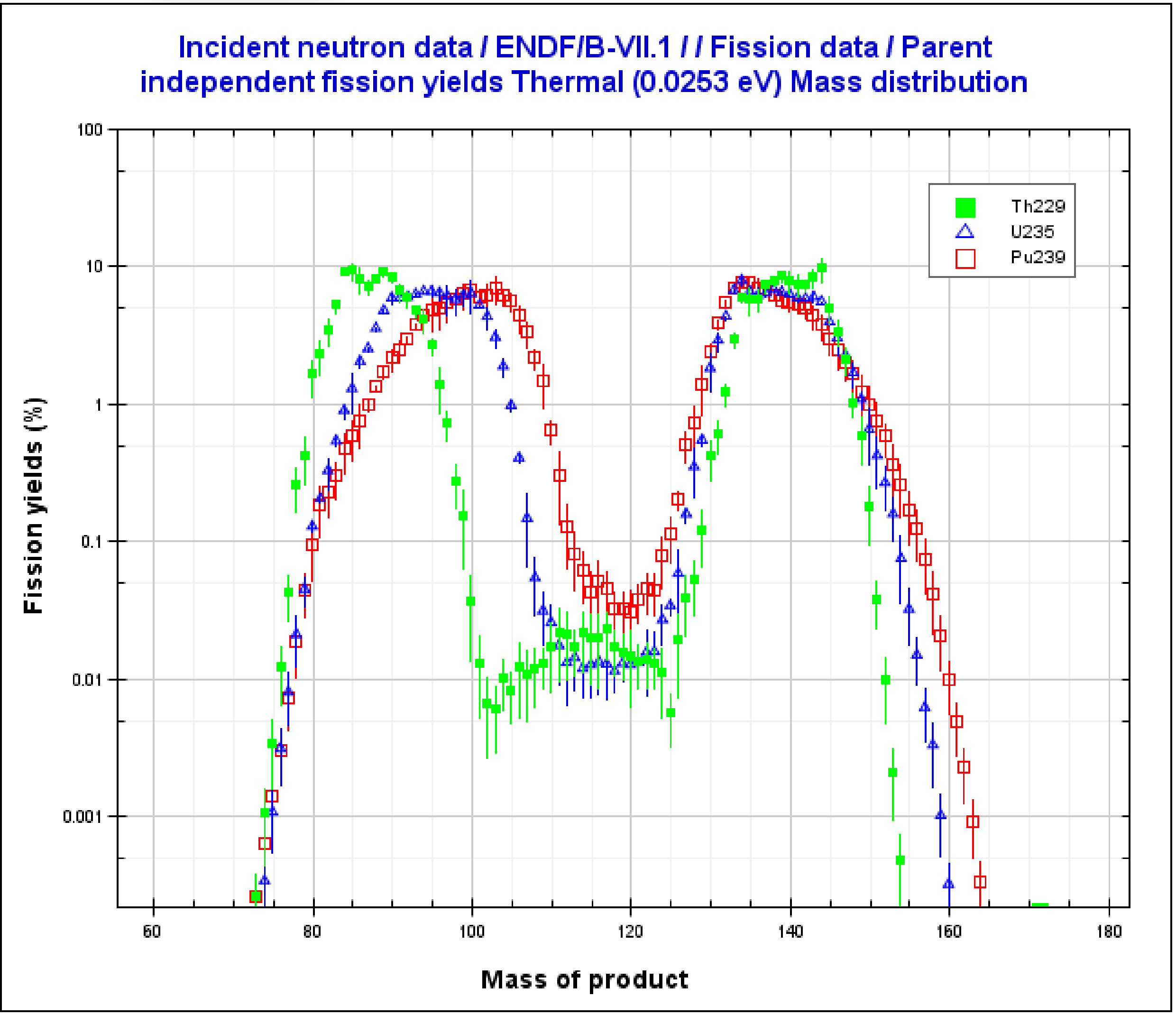
UPPSALA UNIVERSITET

Yields: Definitions III

- **Total chain yields:** defined as the sum of cumulative yield(s) of the last (stable or long-lived) chain member(s).
- **Mass number yields:** defined as the sum of all independent yields of a particular mass chain and are in this way distinguished from chain yields.
- Some of the most modern methods to measure fission yields provide sets of truly independent yields which - at summation - will produce *mass number yields* rather than *chain yields*.

Source: IAEA-TECDOC-1168 (2000)

Trends I



- Light mass peak shifts as compound mass increases
- Heavy mass peak remains centered around A≈140.
- Effect of closed shells (132=50+82)

UPPSALA UNIVERSITET

The model by P. Möller et al. manages to describe the experimental fact that the average mass of the heavy fragment remains roughly stable around A=140.

Open circles: calculation
Filled circles: exp. data

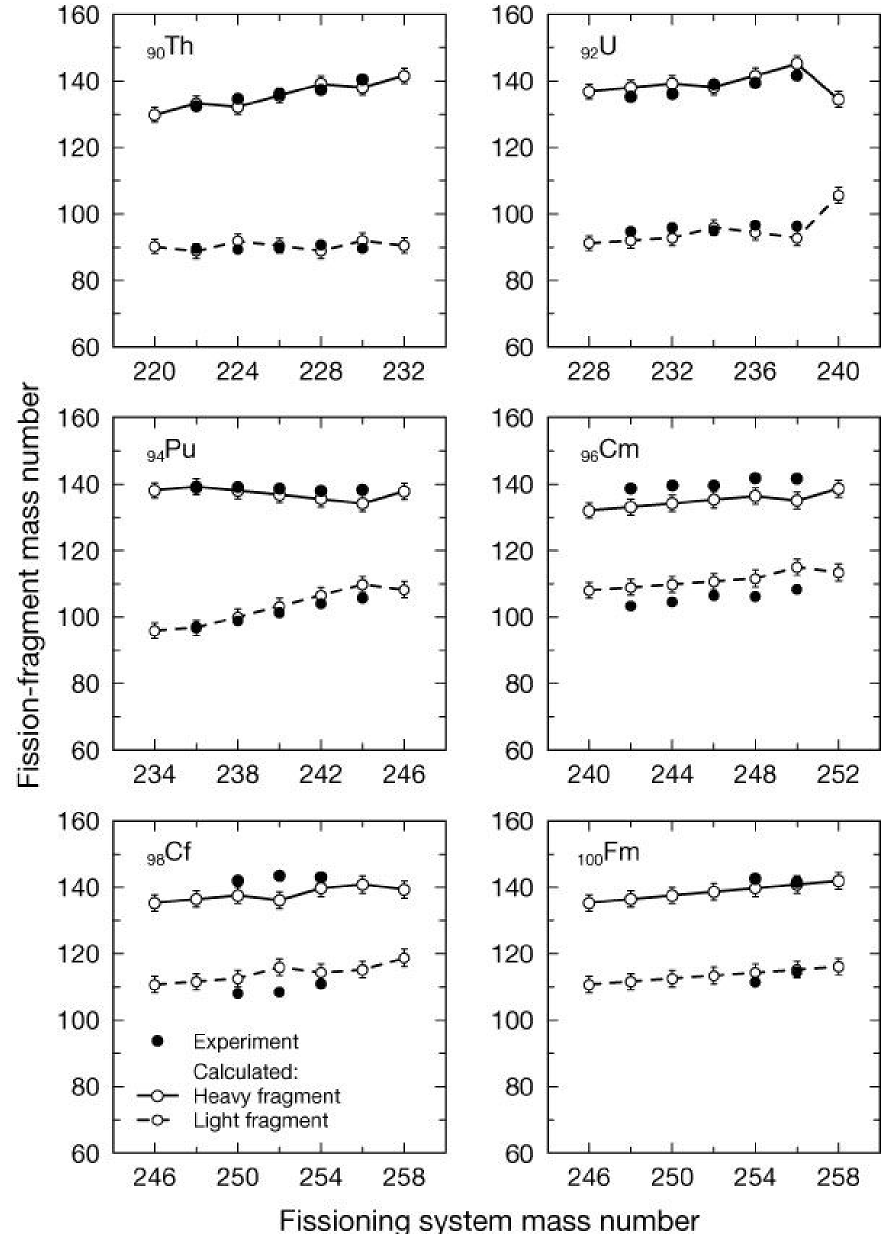
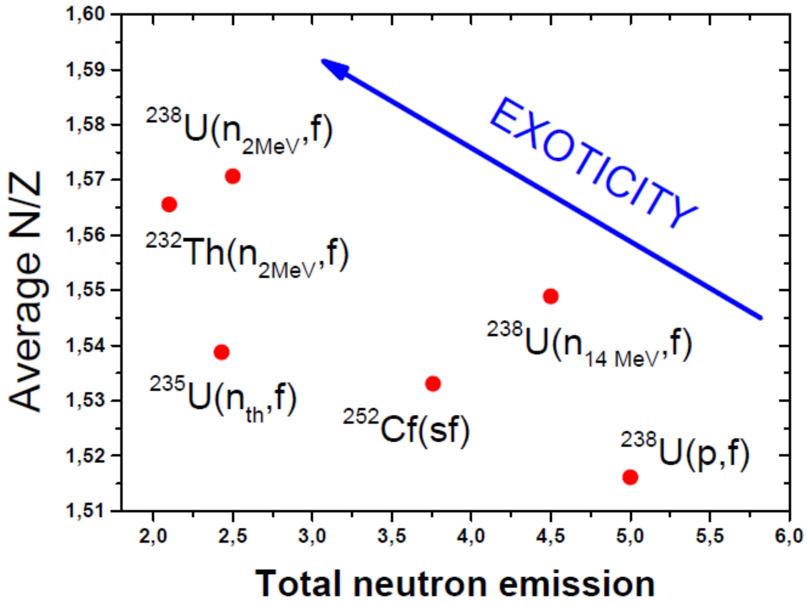
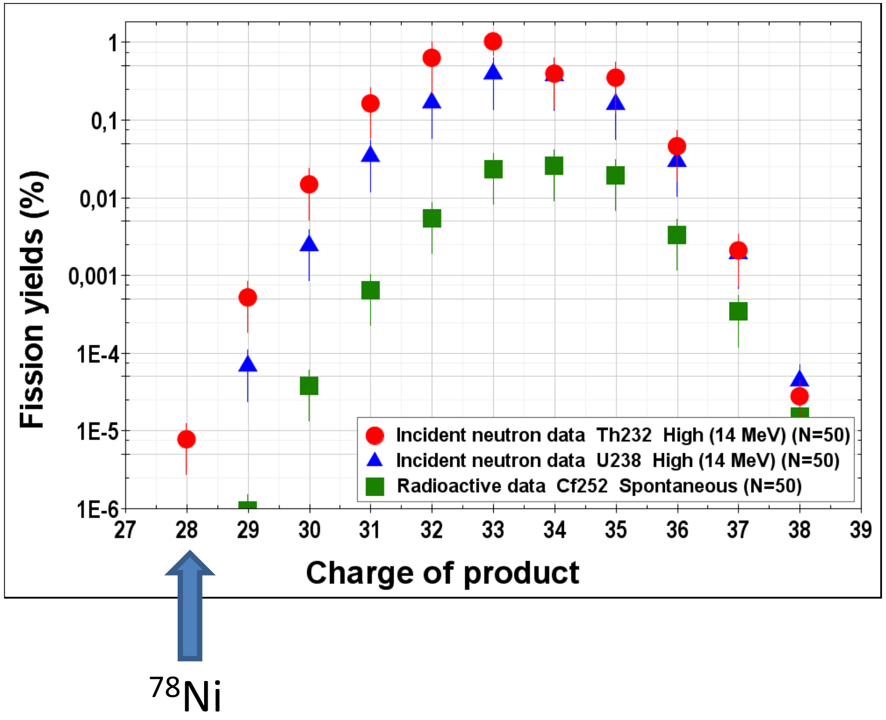


Fig 7 in P. Möller et al., Nature **409** (2001) 785

Trends II

Lighter compound system and fewer prompt neutrons
→ better production rates for exotic, neutron-rich nuclei





Trends III

higher energy of incident neutron →

Yields generally asymmetric

But towards higher energies the symmetric component Increases (and gets wider).

I.e. shell effects less important at high excitation energies.

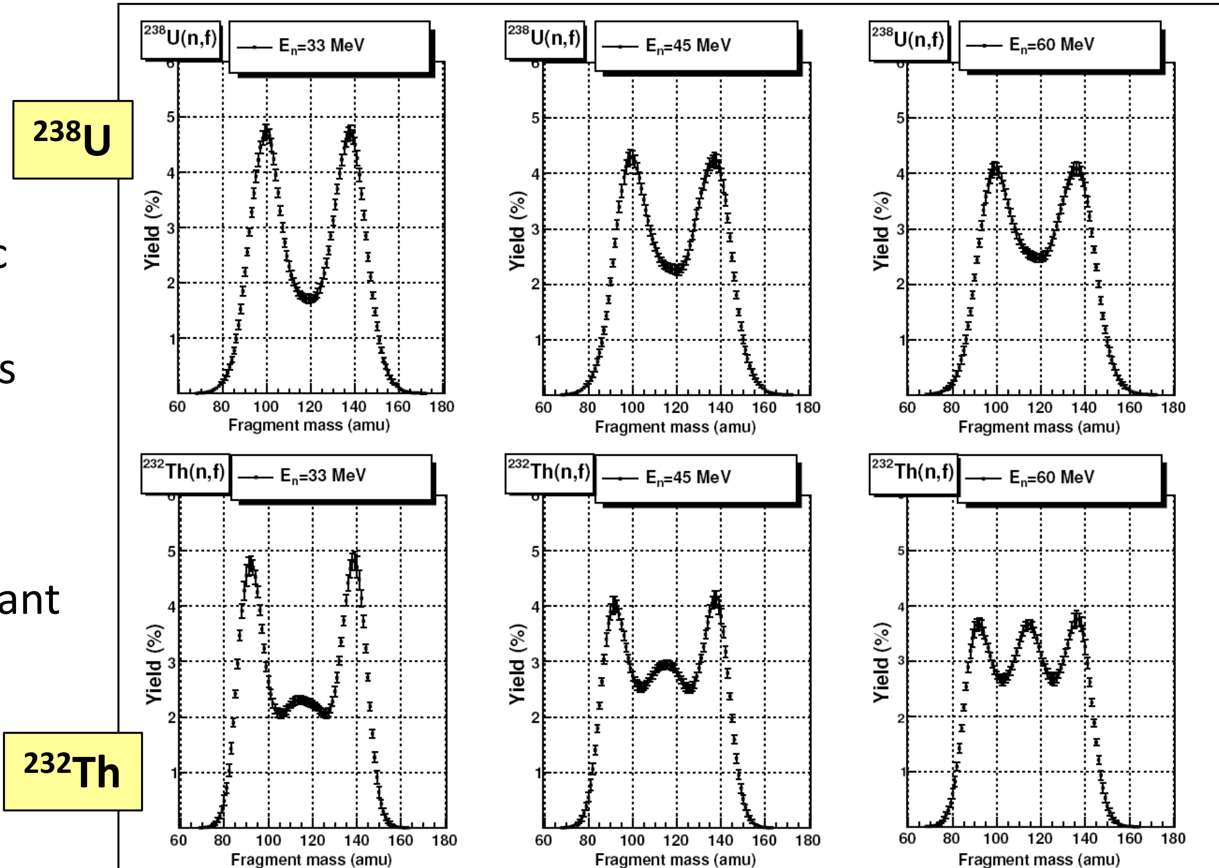


Figure 4.3: Pre-neutron emission fragment mass distributions for neutron-induced fission of ^{238}U (upper row) and ^{232}Th (lower row) at 33, 45 and 60 MeV.

PhD thesis V. Simutkin, Uppsala 2010

Trends IV

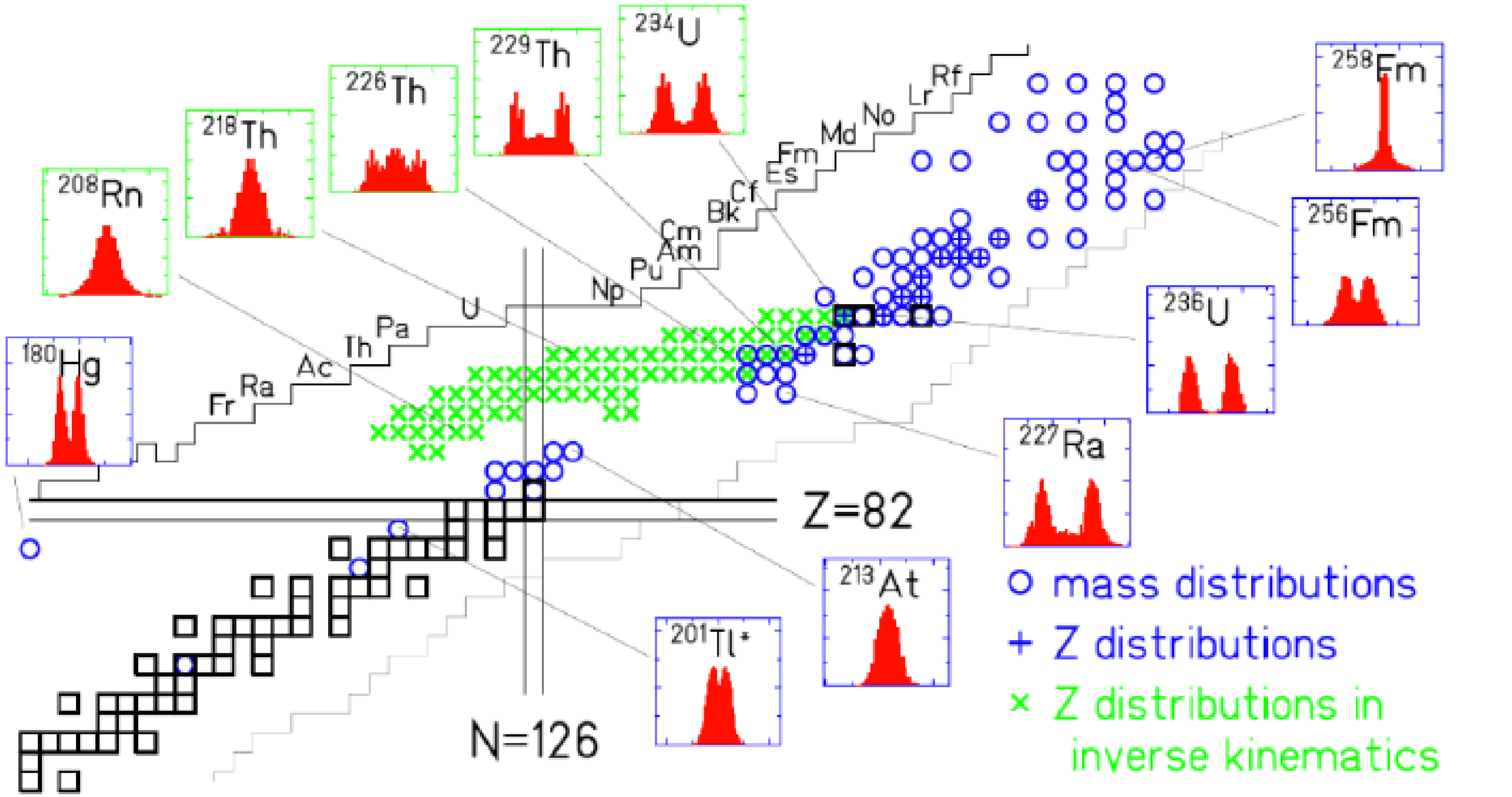


Figure from K.H. Schmidt et al., Nucl. Data Sheets 131 (2016) 107

Outline

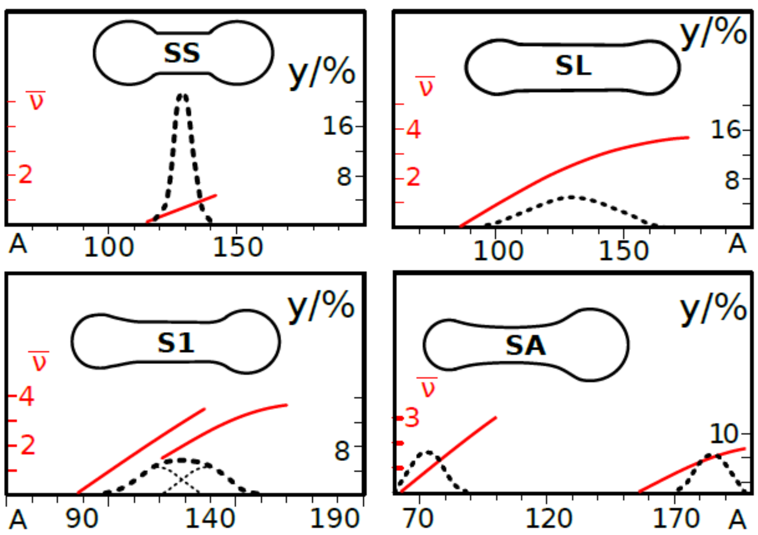
- Some literature sources
- Introduction:
  - Phenomenology, time scale, obserables, challenges, data needs, …
- Fission yields (FY):
  - Definitions, trends, ….
- Overview on model codes
- Overview on experimental methods
- Examples of experimental efforts
  - 2E with FGIC, 2E-2v (VERDI and FALSTAFF), IGISOL and more …

Models I

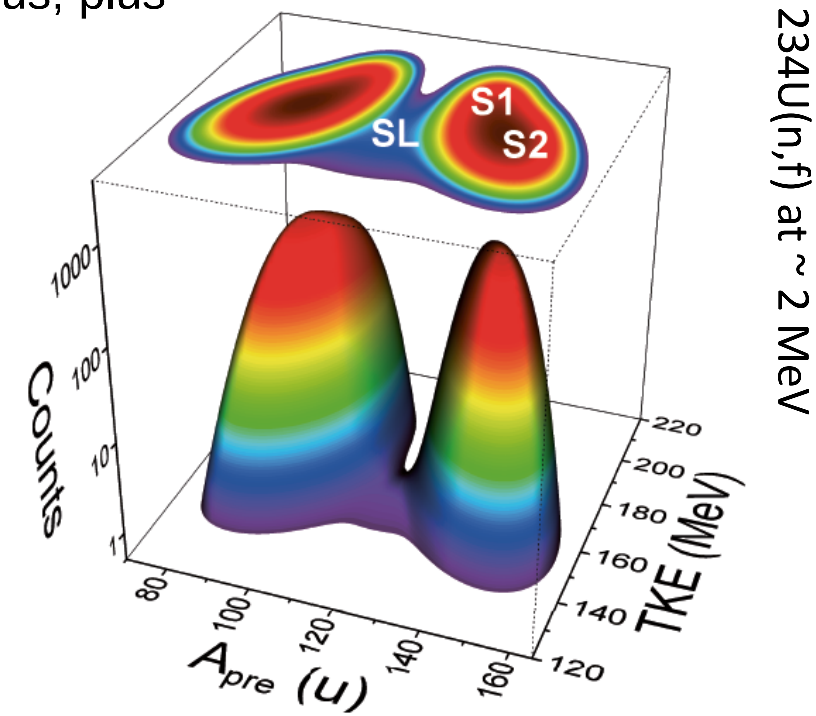
Multi-Modal Random-Neck Rupture Model (Brosa model)

(1) multi-channel fission ("fission modes"); different paths on potential energy landscape, defines shape of fissioning nucleus; plus

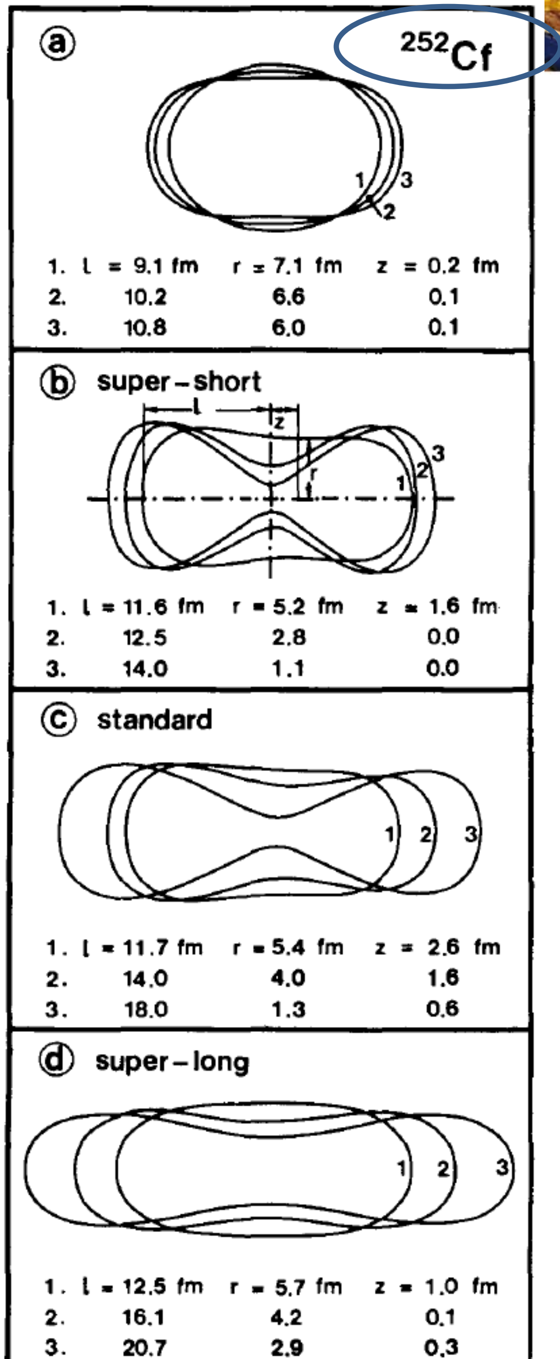
(2) random break-up of the neck.



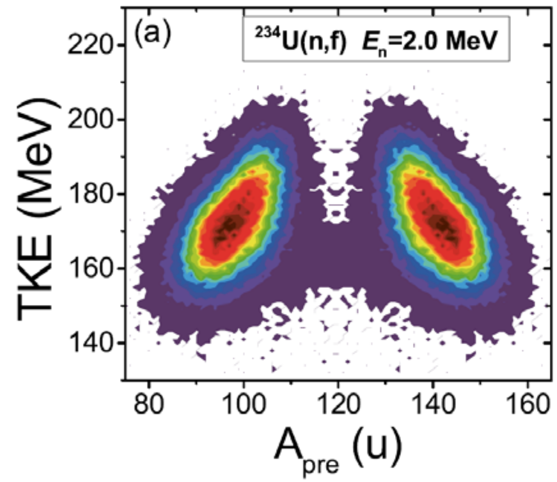
U. Brosa et al., "Nuclear scission", Phys. Rep **197** (1980) 167.

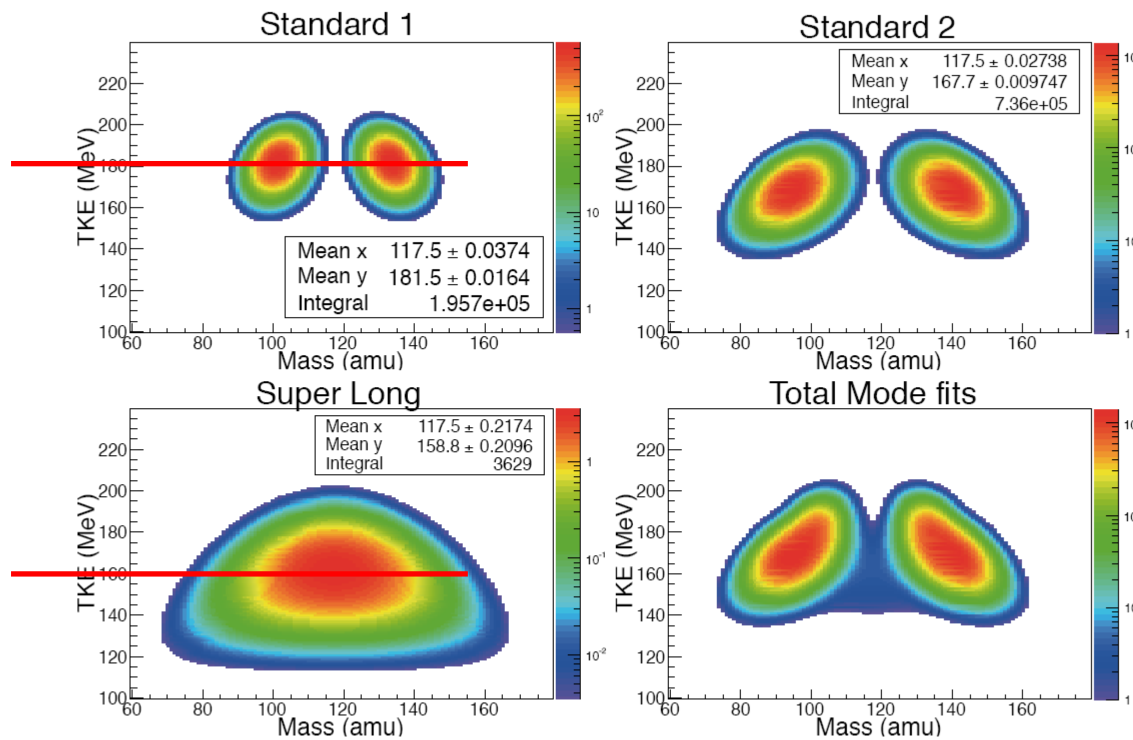


A. Al-Adili, PhD thesis, Uppsala 2013



From: Brosa et al., *Phys. Rep.* **197** (1990) 167





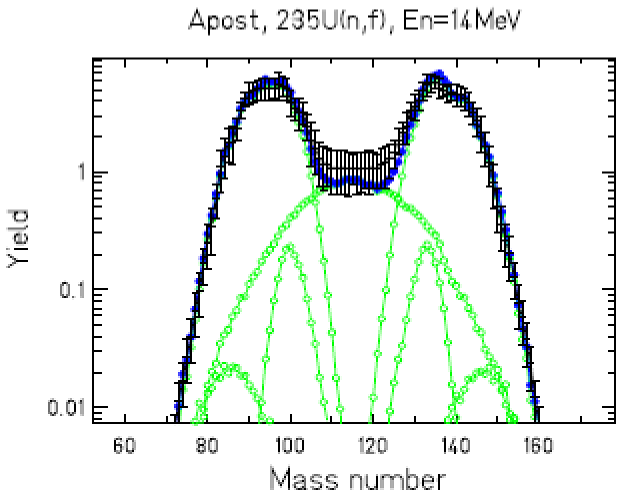
From: Ali Al-Adili, PhD thesis, Uppsala, 2013

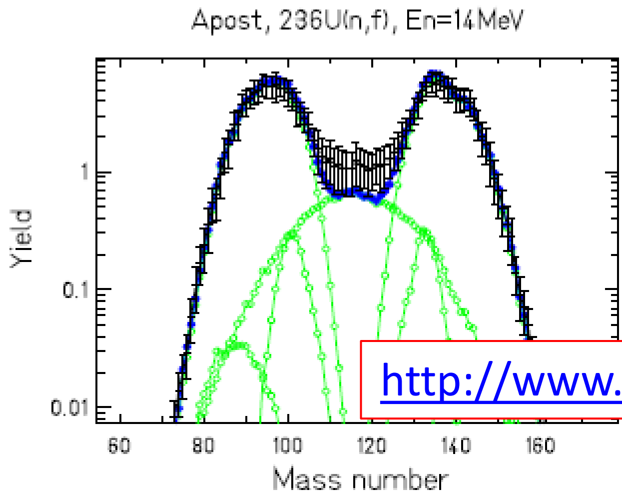
Models II

GEF (General Fission) model

(K.H. Schmidt et al., "General Description of Fission Observables: GEF Model Code", Nucl. Data Sheets 131 (2016) 107)

"The GEF code aims to provide *a* *complete description* including the entrance channel and the de-excitation of the fragments"





http://www.khs-erzhausen.de/GEF.html

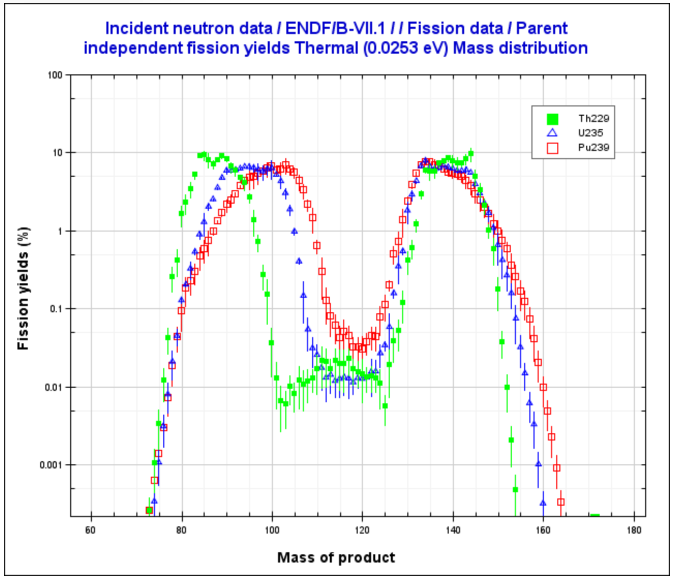
Models III

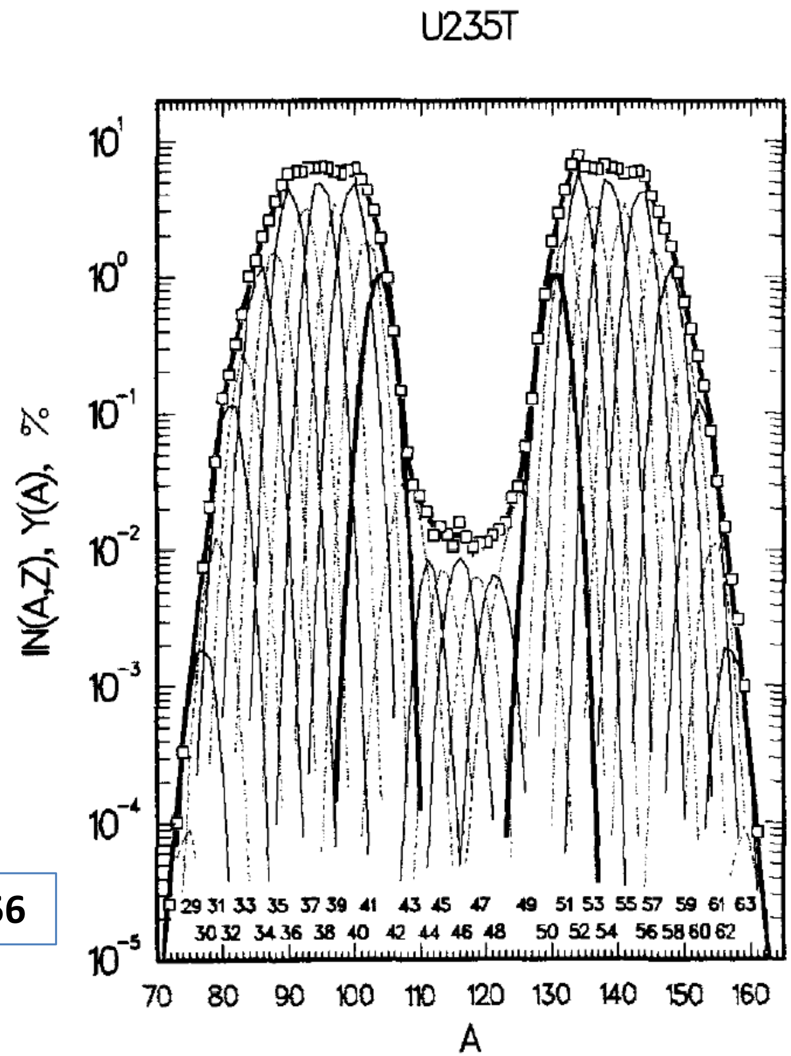
Versions of the Brosa and GEF models are part of TALYS 1.8

Other models often focus on de-excitation (prompt n and γ), e.g.:

- **FREYA** by R. Vogt et al., https://nuclear.llnl.gov/simulation/main.html
  YouTube video: https://www.youtube.com/watch?v=x__MNOqdLpI
- **FIFRELIN** by O. Litaize et al., Eur. Phys. J. A **51** (2015) 1.
- **CGMF** by P. Talou et al., Phys. Rev. C **83** (2011)
- **Point-by-point model** (PbP) by A. Tudora et al., e.g. Ann. Nucl. Energy 33 (2006) 1030.

Wahl systematics I





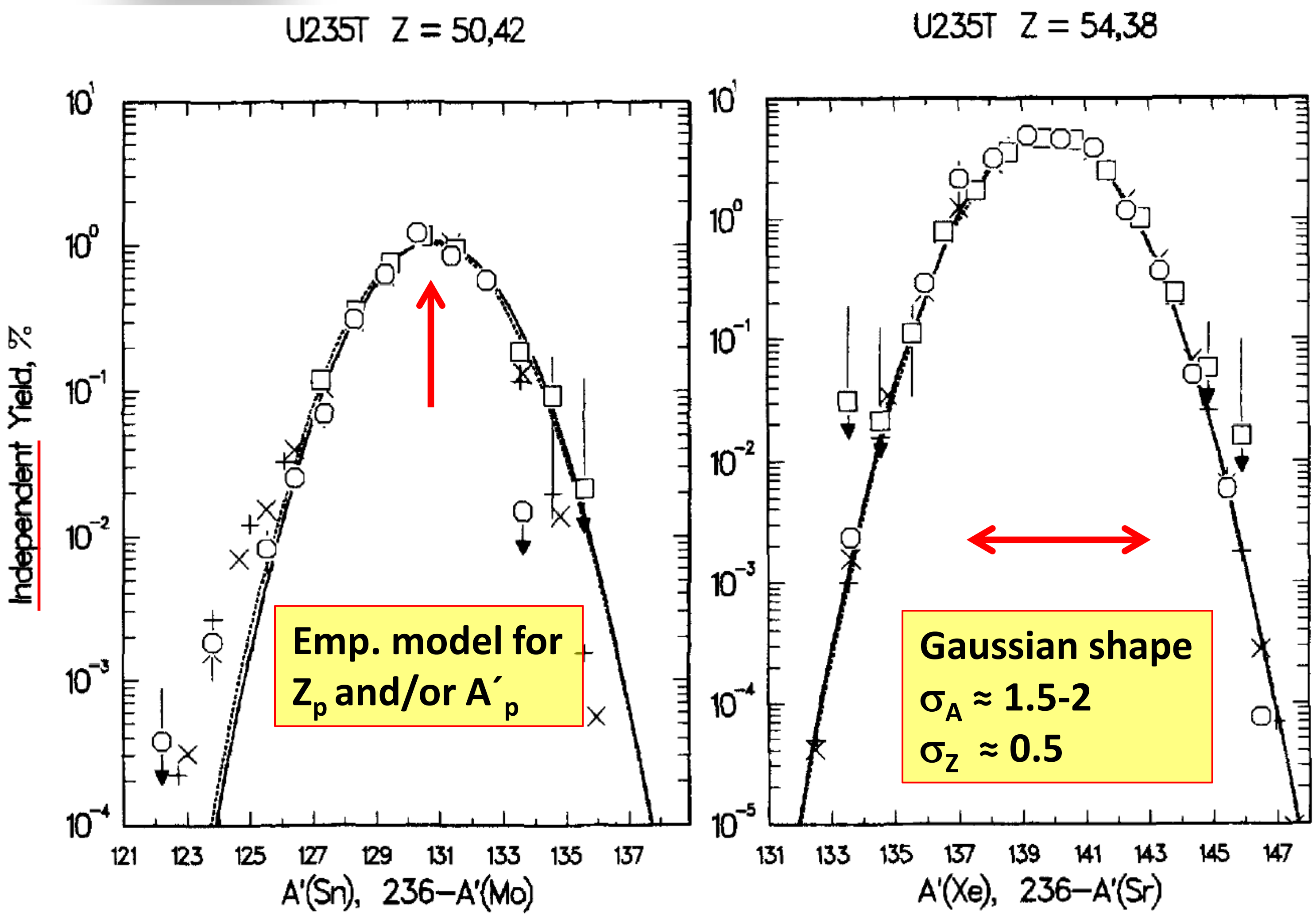
Yields normalized to total yield of 200%.

Review of (at the time) available experimental FY data and development of an empirical model for $^{233}U(n_{th},f)$, $^{235}U(n_{th},f)$, $^{239}Pu(n_{th},f)$, $^{252}Cf(SF)$:

A.C. Wahl, At Data and Nucl Data Tables, 39 (1988) 1-156

Later extension, e.g. A.C.Wahl, *LA-13928* (2002) include, e.g., nubar(A).

Wahl systematics II



Corrections for even-odd effects

A.C. Wahl, At Data and Nucl Data Tables, 39 (1988) 1-156

Outline

- Some literature sources
- Introduction:
  - Phenomenology, time scale, obserables, challenges, data needs, …
- Fission yields (FY):
  - Definitions, trends, ….
- Overview on model codes
- Overview on experimental methods
- Examples of experimental efforts
  - 2E with FGIC, 2E-2v (VERDI and FALSTAFF), IGISOL and more …

Experimental methods I

Stopped fragments:

- Radiochemical separation
  - earliest method; only long-lived products; activity measured from β-decay or γ-decay (with low resolution)
- Mass spectrometry
  - long-lived products only; sample evaporated and mass analyzed; precise technique but difficult to normalize
- γ-ray spectroscopy
  - isotope specific; also short-lived nuclides accessible; can be used with activation technique or fast on-line mass separation
- ISOL method
  - can be combined with Penning trap or γ-ray spectroscopy; can be difficult to normalize

Experimental methods II

Unstopped fragments:

- LOHENGRIN@ILL
  - reactor based
  - mass, charge, and energy are measured
  - only one fragment
  - combined with, e.g., γ-spectroscopy

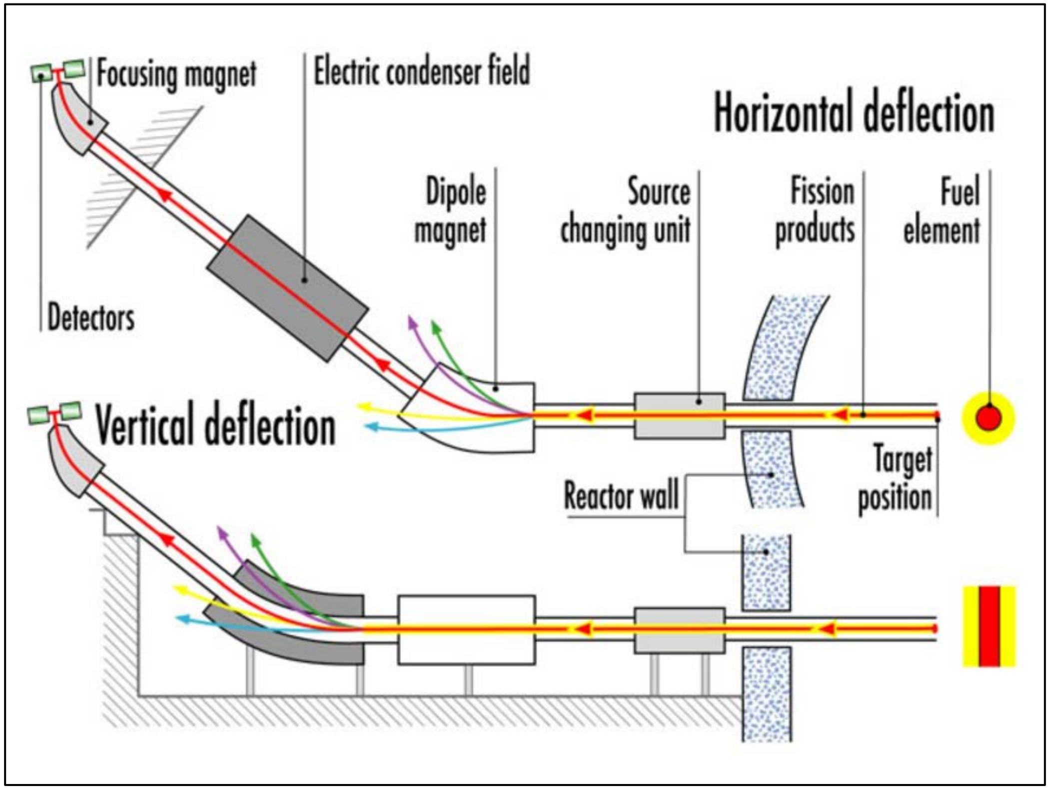


Image from https://www.ill.eu

Experimental methods III

Unstopped fragments:

- Inverse kinematics
  - accelerator based (charged particle induced fission or Coulomb excitation)
  - can access fission of exotic, very short-lived nuclei
  - e.g. SOFIA@GSI (both FF) and VAMOS@GANIL (one FF) →
  - high mass resolution (isotopic yields)

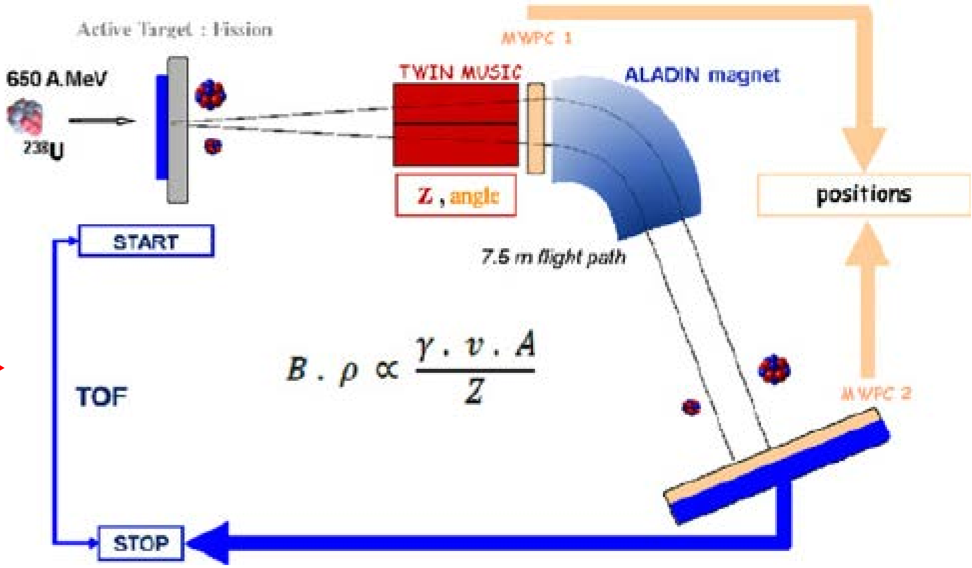
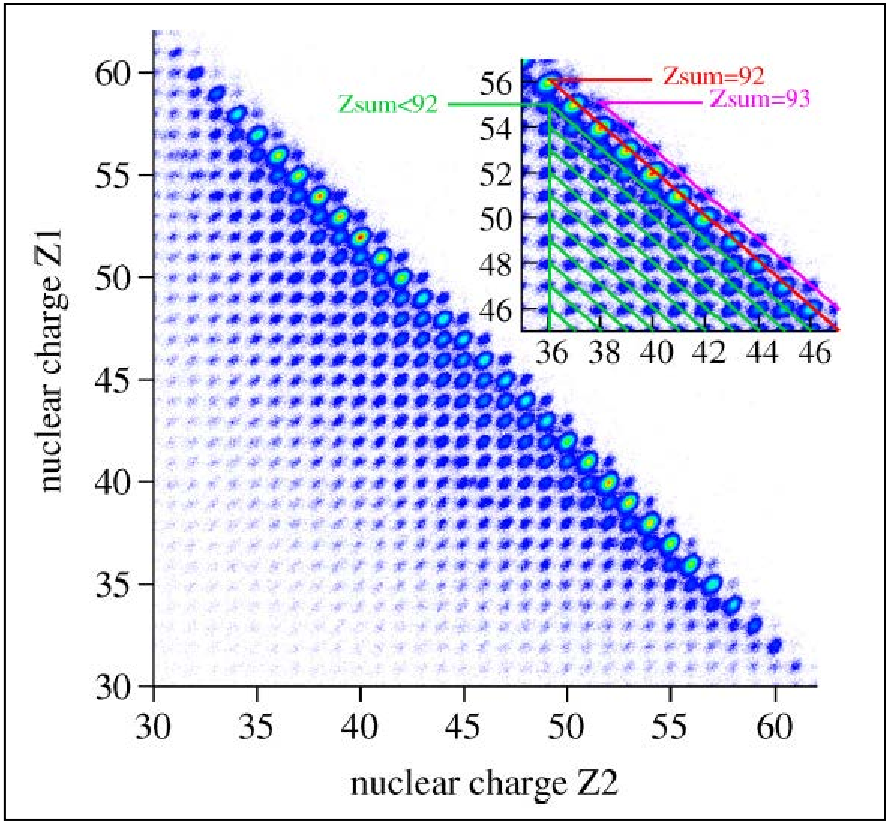


Figure: E. Pellereau et al., EPJ Web of Conf. **62**, 06005 (2013)

Latest results from GSI

E. Pellereau et al. Phys. Rev. C 2017



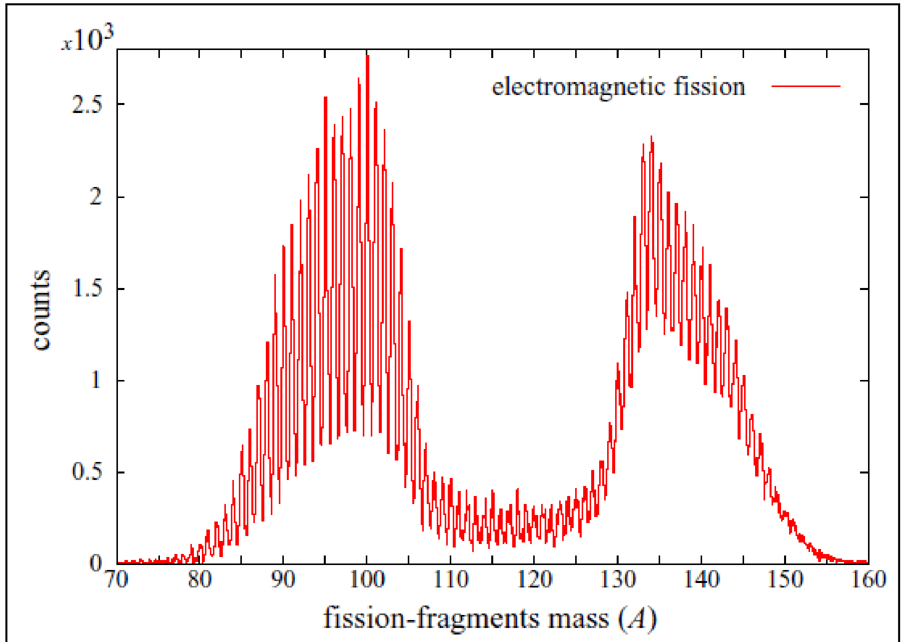


FIG. 11. Fission-fragment mass distribution for electromagnetically induced fission of ^{238}U.

Charges of correlated fission products from ^{238}U

Experimental methods IV

Unstopped fragments:

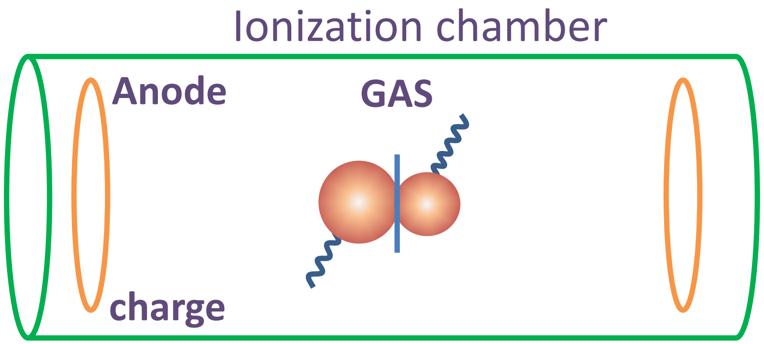
Experiments with (high-energy) neutron beams

- More “small scale”, flexible experiments
  - 2E method and 2v method
  - 2E-2v method
- Need for suitable targets (sizeable amounts)

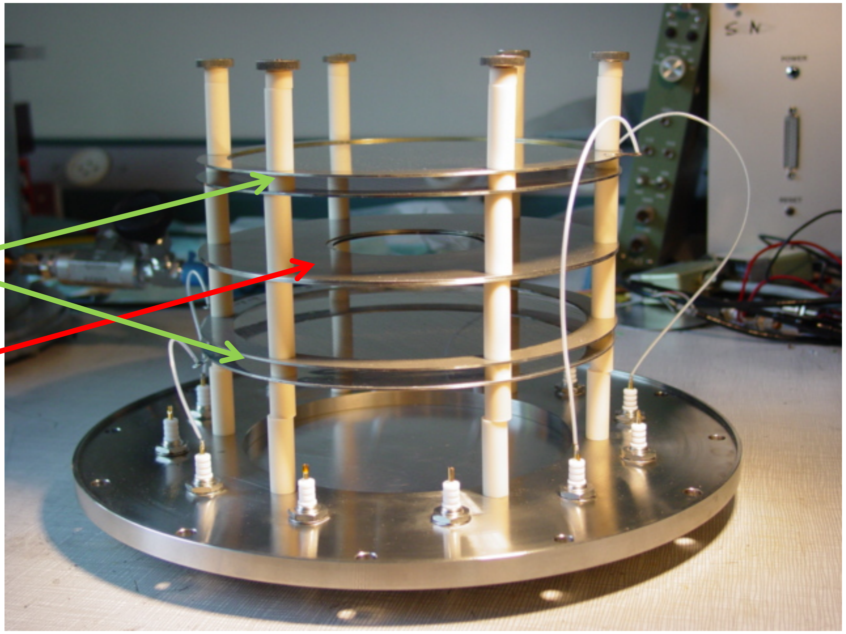
2E-method

Measurement: e.g. with Frisch-Grid Ionization Chamber:

(see, e.g., PhD thesis Ali Al-Adili, Uppsala 2013)



Inside of a FGIC:



Frisch-Grids and Anodes

Target (Cathode, backing)

Typical mass resolution: 4-6 u

2E-method

- If the kinetic energies E_1^{pre} and E_2^{pre} of the *two* fission fragments are measured, the fragment masses can be obtained from momentum conservation (in the c.m. system).

$$\boldsymbol{m_{1,2}^{pre} = m_{CN} \cdot \frac{E_{2,1}^{pre}}{E_1^{pre} + E_2^{pre}}}$$

Problem:

Measured: E^{post} $\longrightarrow$ need to make an assumption on the energy change due to neutron emission.

UPPSALA UNIVERSITET

2E-method

Use iterative procedure assuming kinetic energy scales with mass of fragment/product to get better value for the fragments energy:

neutron multiplicity as function of fragment mass (input from some model)

$$m_{1,2}^{post}(i+1) = m_{1,2}^{pre}(i) - \nu_{1,2}\left(m_{1,2}^{pre}\right)$$

$$E_{1,2}^{pre}(i+1) = E_{1,2}^{post} \cdot \left(\frac{m_{1,2}^{pre}(i)}{m_{1,2}^{post}(i+1)} \right)$$

$$m_{1,2}^{pre}(i+1) = m_{CN} \cdot \frac{E_{2,1}^{pre}(i+1)}{E_{1}^{pre}(i+1) + E_{2}^{pre}(i+1)}$$

Do until changes are small

2v-method

- Similar to the previous method but instead of the energies, velocities are measured.
- Assuming we have the fragment (pre neutron-emission) velocities, momentum conservation gives:

$$m_{1,2}^{pre} = m_{CN} \cdot \frac{\mathbf{v}_{2,1}^{pre}}{\mathbf{v}_1^{pre} + \mathbf{v}_2^{pre}}$$

How to? Use, e.g. PPACs (Parallel Plate Avalanche Chambers) as start and stop detectors.

And same problem again:

Measured: v^{post} $\longrightarrow$ need to assume that velocity is unchanged by neutron emission and use an iterative procedure …

2E-2v-method I

Measurement of energy and velocity of both products.

Product masses are readily obtained:

$$m_{1,2}^{post} = \frac{2 \cdot E_{1,2}^{post}}{\left(\mathrm{v}_{1,2}^{post}\right)^2}$$

Like in 2v-method: assuming that, on average, velocities are unchanged by neutron emission, pre neutron-emission masses are obtained (momentum conservation):

$$m_{1,2}^{pre} = m_{CN} \cdot \frac{\mathrm{v}_{2,1}^{pre}}{\mathrm{v}_1^{pre} + \mathrm{v}_2^{pre}}$$

2E-2v-method II

Now comes *the thing*:

$\bar{\text{v}}(\boldsymbol{m}^{\boldsymbol{pre}})$ can be obtained:

$$\mathbf{v}_{1,2} = \frac{\boldsymbol{m}_{1,2}^{\boldsymbol{pre}} - \boldsymbol{m}_{1,2}^{\boldsymbol{post}}}{\boldsymbol{m}_{\mathbf{n}}}$$

(event-by-event)

and also:

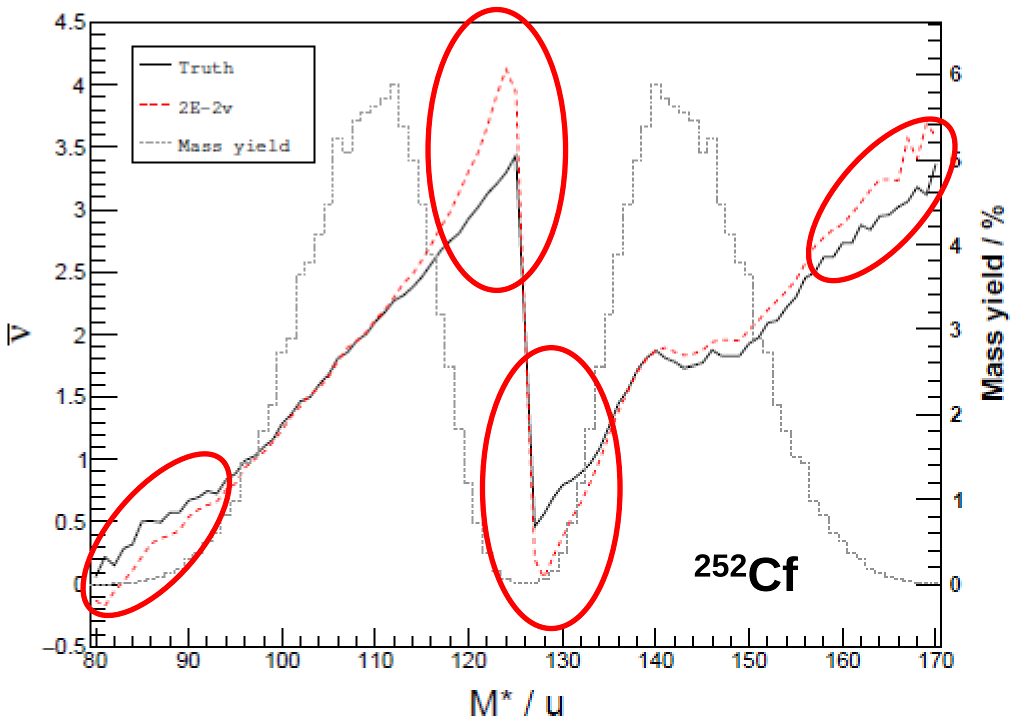
$$\boldsymbol{E}_{1,2}^{\boldsymbol{pre}} = \frac{1}{2}\,\boldsymbol{m}_{1,2}^{\boldsymbol{pre}}\left(\mathbf{v}_{1,2}^{\boldsymbol{post}}\right)^{2}$$

This works rather well but …

2E-2v-method III

However:

the “unchanged velocity” assumption leads to a width of the m^{pre} uncertainty of about 0.8 u and a bias ….



K. Jansson et al., arXiv:1709.07443

Simulation with “perfect” experimental resolution
(pseudo-data from GEF code)

Good news:
this can be correct for.

2E-2v-method IV

K. Jansson et al., arXiv:1709.07443

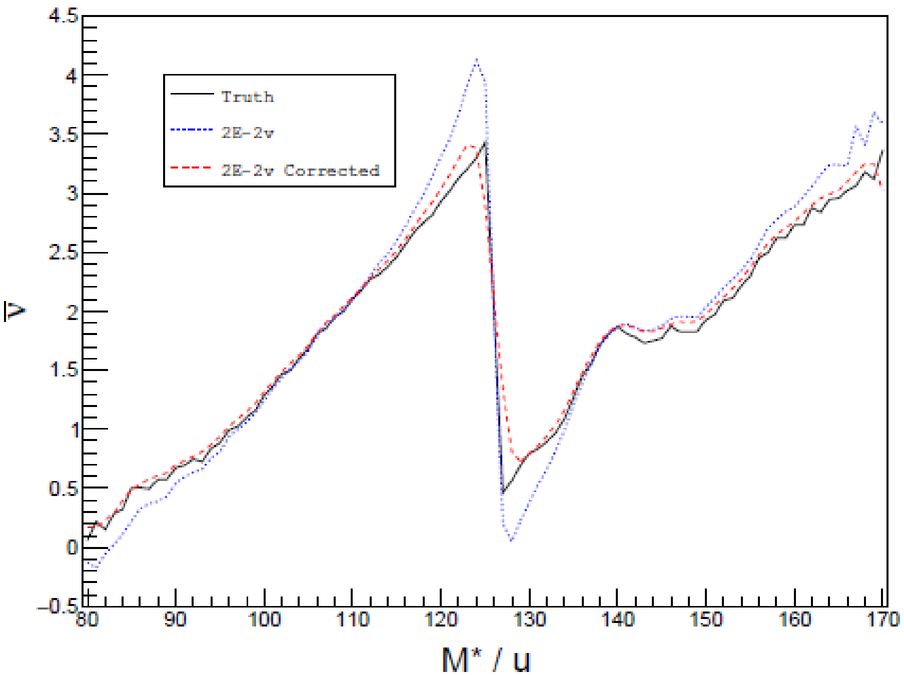


FIG. 4. (Color online) The corrected $\bar{\nu}(M^{\text{pre}})$ from ^{252}Cf(sf) shows signs of smearing, but reproduces the synthetic data well apart from that. The 'true' $\bar{\nu}(M^{\text{pre}})$ and the uncorrected $\bar{\nu}(M^{\text{pre}})$ are shown as references.

Conclusion:

The 2E-2v method is well-suited to measure m^{post} and m^{pre} with good resolution (about 1u).

Hence: very good way to obtain neutron multiplicity as function of fragment mass.

UPPSALA UNIVERSITET

Outline

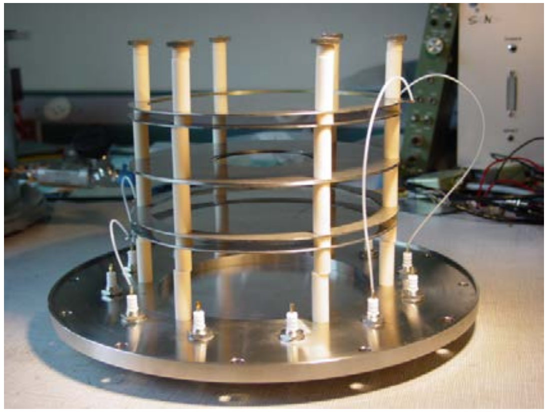
- Some literature sources
- Introduction:
  - Phenomenology, time scale, obserables, challenges, data needs, …
- Fission yields (FY):
  - Definitions, trends, ….
- Overview on model codes
- Overview on experimental methods
- Examples of experimental efforts
  - 2E with FGIC, 2E-2v (VERDI and FALSTAFF), IGISOL and more …

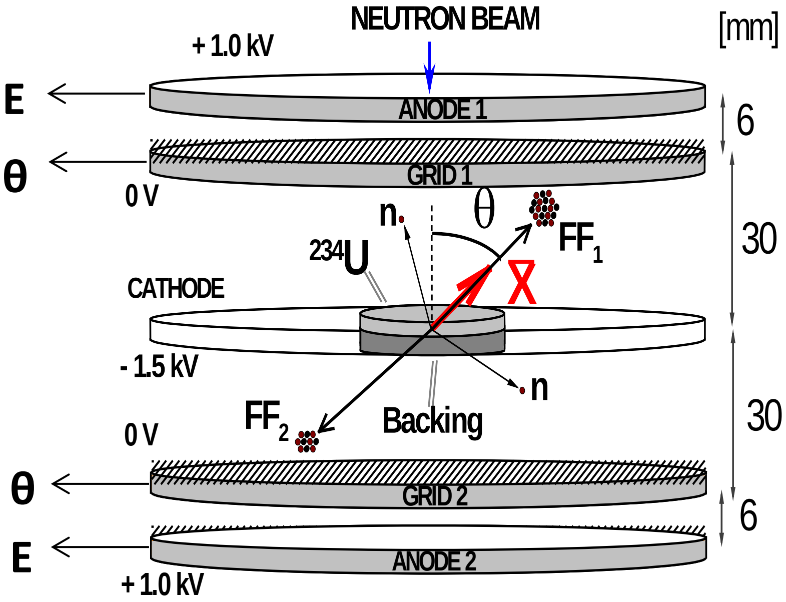
Outline

- Some literature sources
- Introduction:
  - Phenomenology, time scale, obserables, challenges, data needs, …
- Fission yields (FY):
  - Definitions, trends, ….
- Overview on model codes
- Overview on experimental methods
- Examples of experimental efforts
  - 2E with FGIC, 2E-2v (VERDI and FALSTAFF), IGISOL

FY using the 2-E method

FGIC
(Frisch-Grid Ionization Chamber)





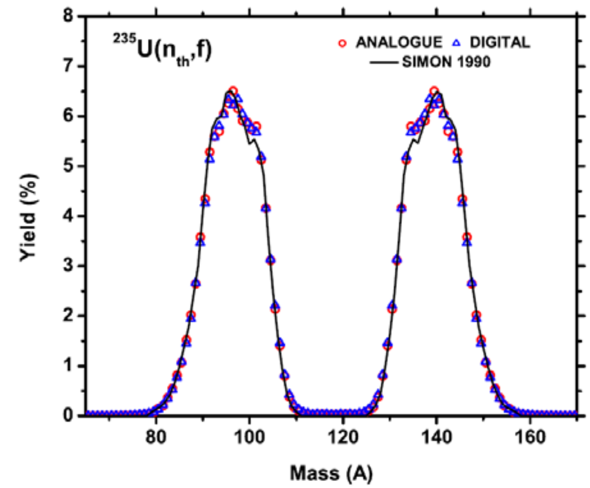
- ◎ ~4π geometrical efficiency.
- ◎ Very simple operation/analysis based on conservation of momentum and mass.
- ◎ Poor mass resolution (4-6 u).
- ◎ Assumption on neutron emission needed.

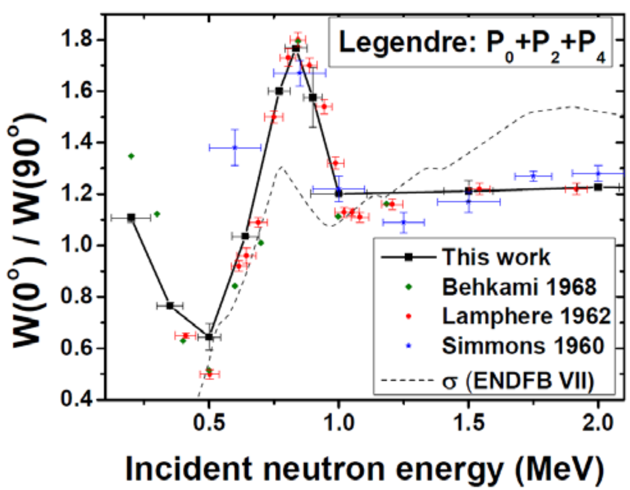
UPPSALA UNIVERSITET

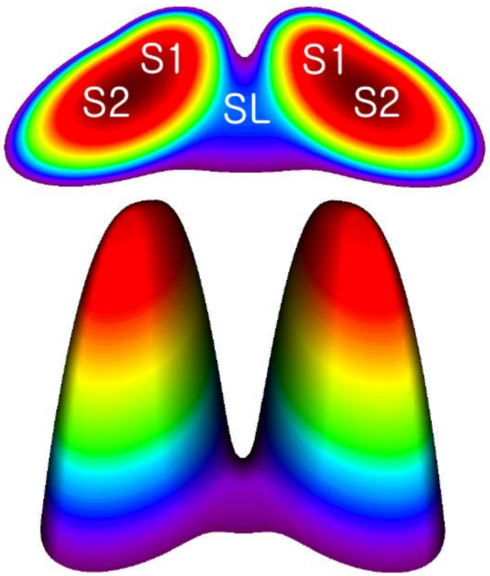
FY using the 2-E method

Selected results

- ◎ Angular distributions
- ◎ Mass yields
- ◎ TKE distributions
- ◎ Fission mode parameterizations



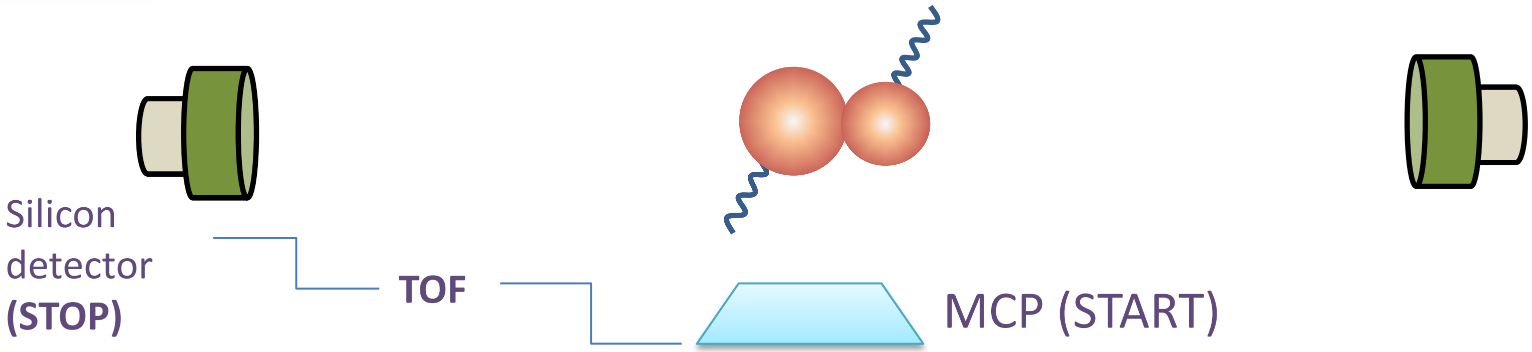




A. Al-Adili et al.,
Phys. Rev. C **93**, 034603, (2016)

2E-2v with VERDI

(VElocity foR Direct particle Identification)



Energy

2 arrays of 16 Si detectors,

Velocity (Time-of-Flight)

Start: Electrons emitted from target detected by Micro Channel Plate (MCP)

Stop: Si detector

2E-2v with VERDI

- Good mass resolution (1-2 u)
- No assumption on neutron emission needed. -> v(A) as bonus!
- Rather complicated/folded analysis.
- <1% geometrical efficiency.

FALSTAFF

(Four arm cLover for the Study of Actinide Fission Fragments)

Slide courtesy Diane Doré

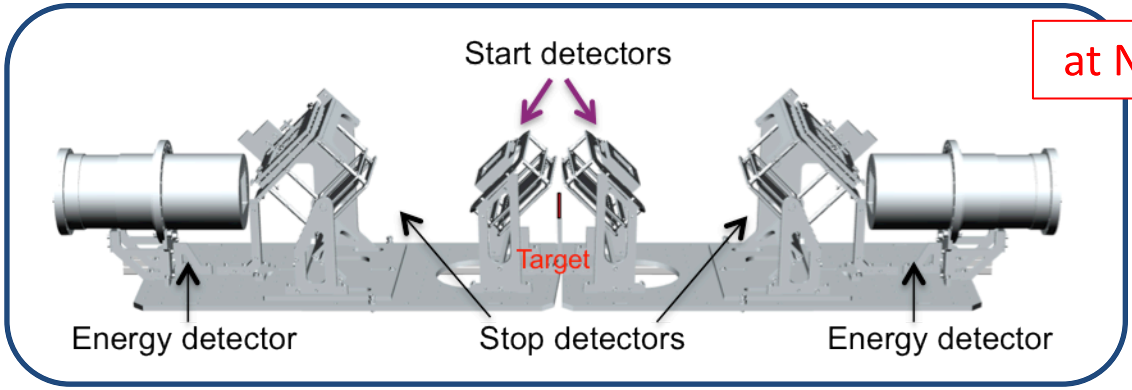
- Spectrometer for fission fragment detection in coincidence
  - Kinetic energy
  - Masses BEFORE and AFTER evaporation (-> $\overline{\nu}$(A))
  - Charge

- Mass **before** evaporation → 2V method
  TOF : *Good time resolution (σ) <150 ps*

- Mass **after** evaporation → EV method
  Energy & TOF
  - *Good energy resolution (~1%)*
  - *Charge identification (dE profile)*

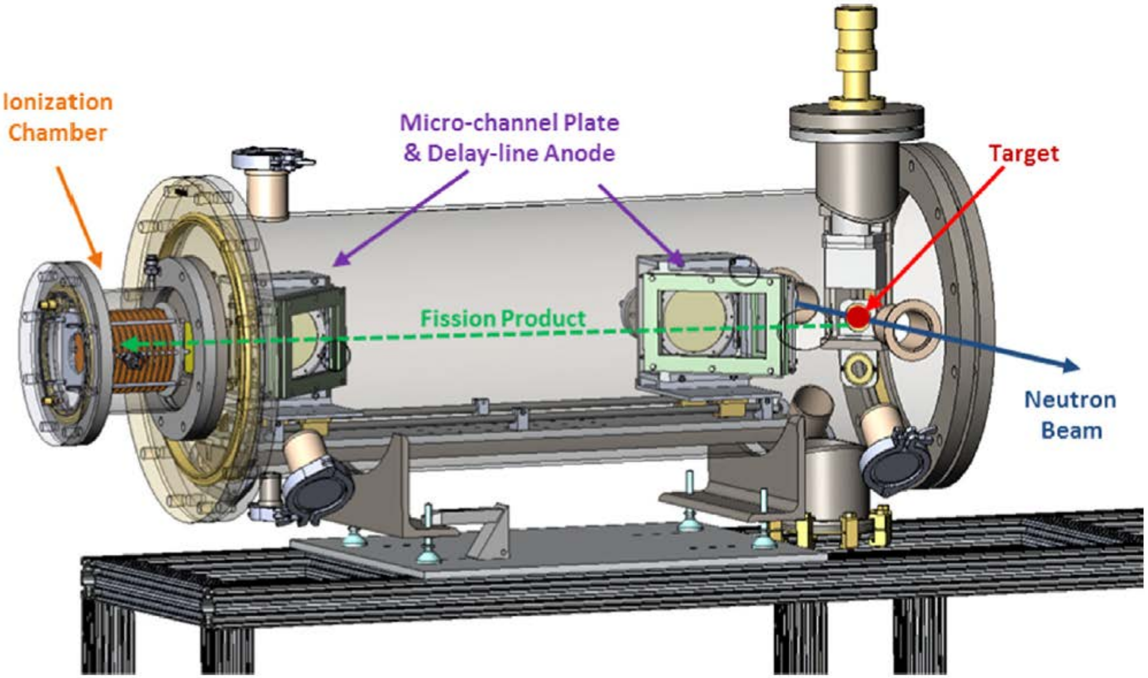
- ***Large solid angle (~1% of 4π)***
- ***Good position resolution (1.2 mm)***

at NFS in 2018



Similar efforts

- SPIDER (LANL); Meierbachtol et al., NIM A **788** (2015) 59



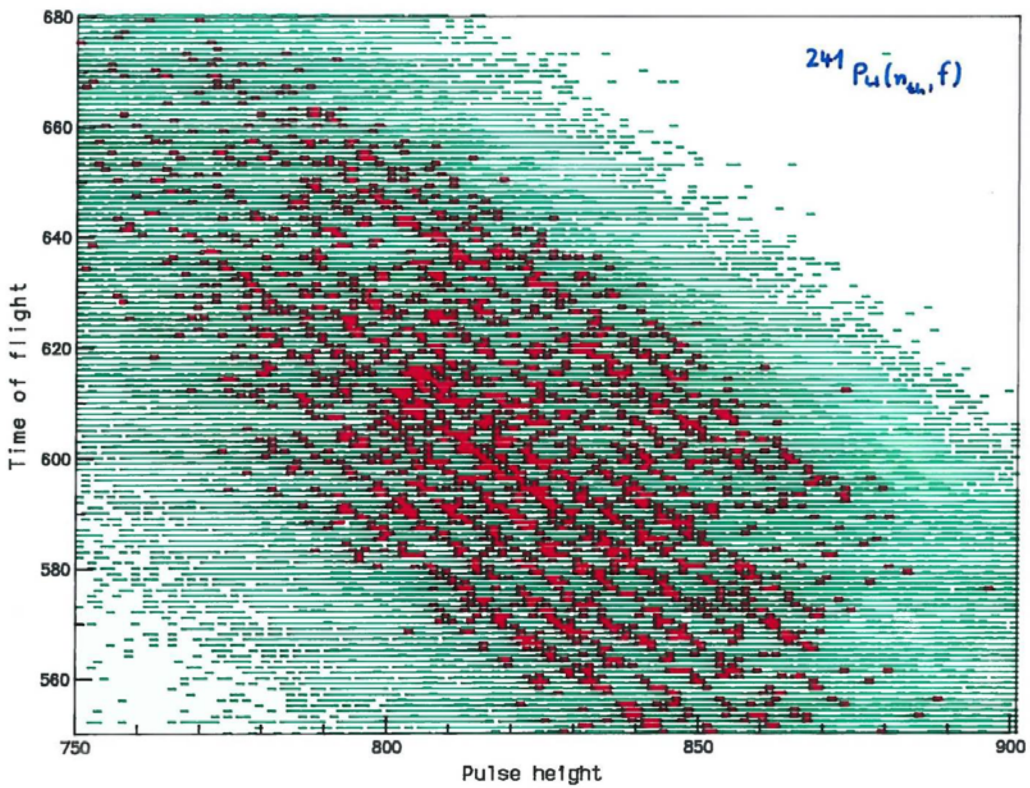
- STEFF (Univ. Manchester); http://t2.lanl.gov/fiesta2014/presentations/Smith.pdf

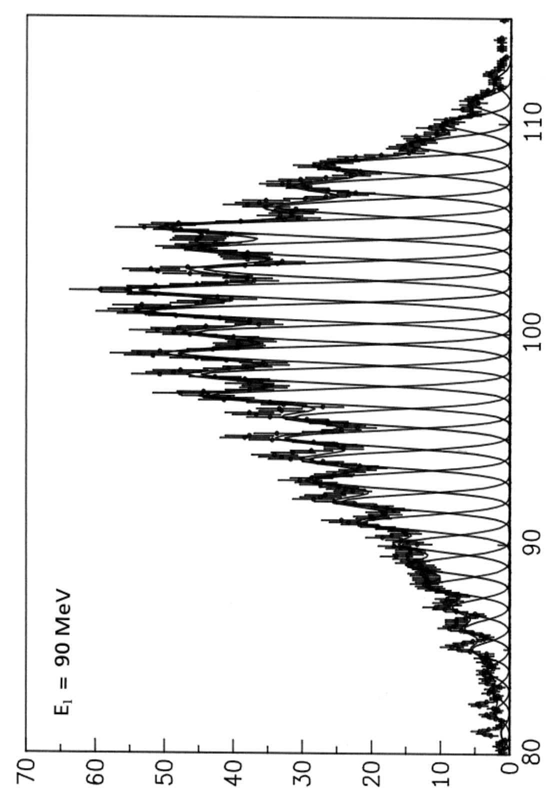
COSI VAN TUTTE

A. Oed et al. NIM **219** (1984) 569

E-v method, i.e. one fragment measured → post-masses only

(n_{th},f); time resolution : 100 ps; masses resolved: $\Delta m/m = 0.6\%$

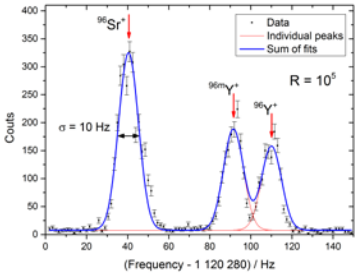


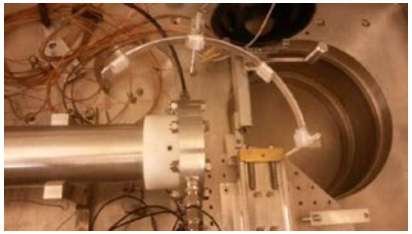


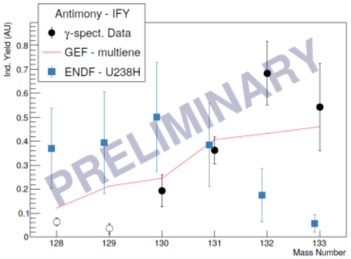
Figures courtesy P. Schillebeeckx (PhD thesis)

IGISOL

- Basic idea and motivations
- IGISOL and JYFLTRAP
- Proton data
- The neutron source
- First experimental results
- Extraction of FF angular momenta
- Summary and outlook







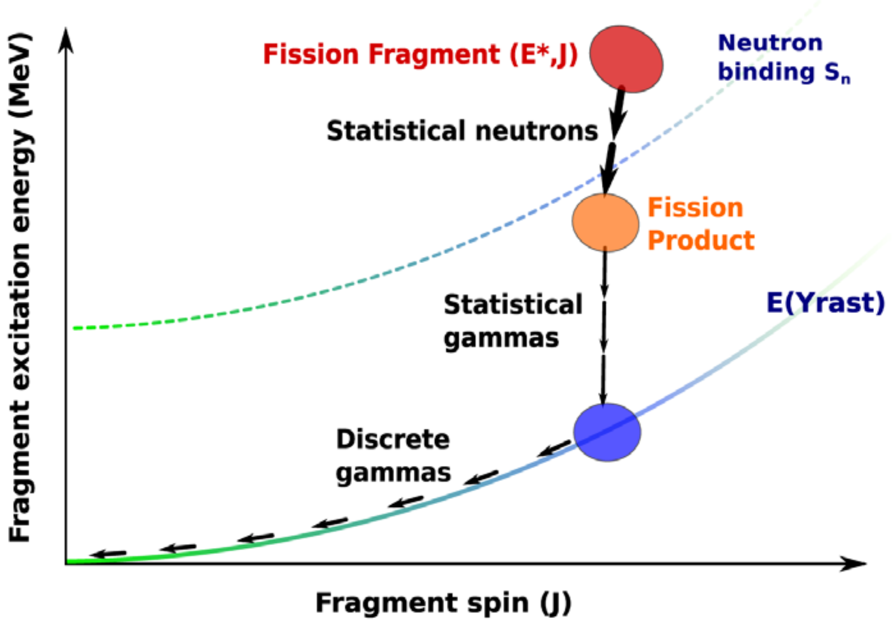
UPPSALA UNIVERSITET

FY and IYR at IGISOL

- Combine **Isotope Separation OnLine technique** with mass-resolving power of a **Penning trap** to obtain FY and even IYR.

- Data on *isotopic yields* and *independent yields* are scarce (and hard to obtain)

- **Isomeric yields ratios** (IYR) can provide knowledge on *spin distributions* in various fissioning systems and can probe, e.g., *dependence on fission modes, fissioning system, excitation energy.*



Further motivation and goals

- IYR are relevant for *anti-neutrino spectra* from reactors …

[A. A. Sonzogni, et al. Phys. Rev. Lett. 116:132502 (2016)]

- … and are relevant in the *r-process*

  (in cases where the isomer is not in thermal equilibrium with the ground state)

And on the "fission side":

- Can we gain insight in the *energy dependence* on IYR?
- Possibility/goal to study *various entrance channels*:
  - > (p,f), (n,f) and (SF)

Why Penning traps

- Possibility to measure isotopic yields and isomeric ratios for various systems, entrance channels, excitation energies
- The method is *fast* (order of 100 ms) and based on *direct ion counting* (no need for γ-decay schemes)
- Routinely a *mass resolution <1 MeV* is achieved
- The *Phase-Imaging Ion-Cyclotron-Resonance* technique will allow for *resolving mass difference of about 50 keV* and a precision in mass measurements on the 10 keV scale

  [S. Eliseev et al., Phys. Rev. Lett. **110**, 082501 (2013)]
- Thus *a large range of isomers*, covering, e.g., various fission modes, may be studied

UPPSALA UNIVERSITET

Examples of possibilities …

Below is part of a tentative list of isomers that can with PI-ICR technique at JYFLTRAP.

Technique was recently successfully tested.

JYFL Accelerator News, Vol. 25, No 2. (2017)
http://users.jyu.fi/~pheikkin/Newsletter/Newsletter.pdf

Isotope	Isomer excitation energy (keV)	GS spin	GS half-life	Isomer spin	Isomer half-life
^{82}As	132.1(2)	2-	19.1(5) s	5-	13.6 s
^{83}Se	228.92(7)	9/2^{+}	22.25(4) min	½-	22.3 min
^{84}Br	310(100)	2-	31.76(8) min	6-	6.0 min
^{90}Rb	106.90(3)	0-	158(5) s	3-	258 s
^{97}Y	667.52(23)	½-	3.75(3) s	9/2^{+}	1.17 s
^{99}Nb	365.27(8)	9/2^{+}	15.0(2) s	½-	2.5 min
^{102}Tc	20(10)	1+	5.28(15) s	(4,5)	4.35 min
^{108}Rh	115(18)	1+	16.8(5) s	5+	6.0 min

……

UPPSALA UNIVERSITET

IGISOL and JYFLTRAP @JYFL

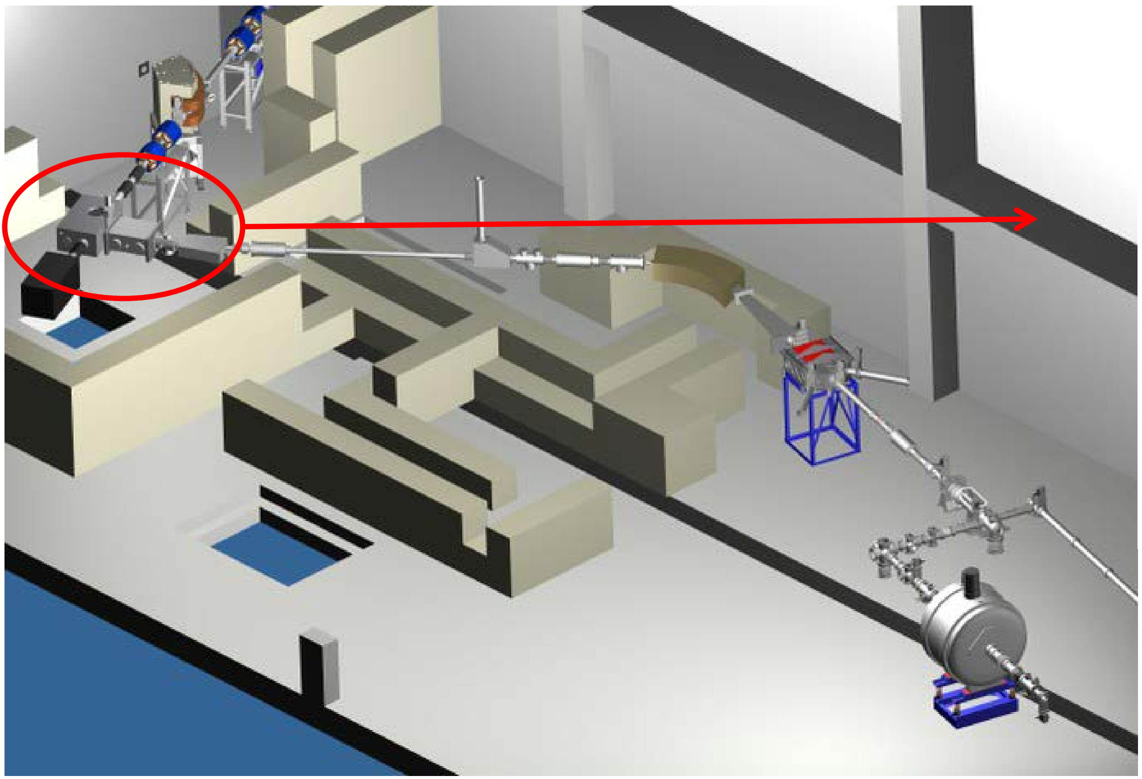
MCC30/15 Cyclotron
p: 18 – 30 MeV @ 100 μA
D: 9 – 15 MeV @ 50 μA

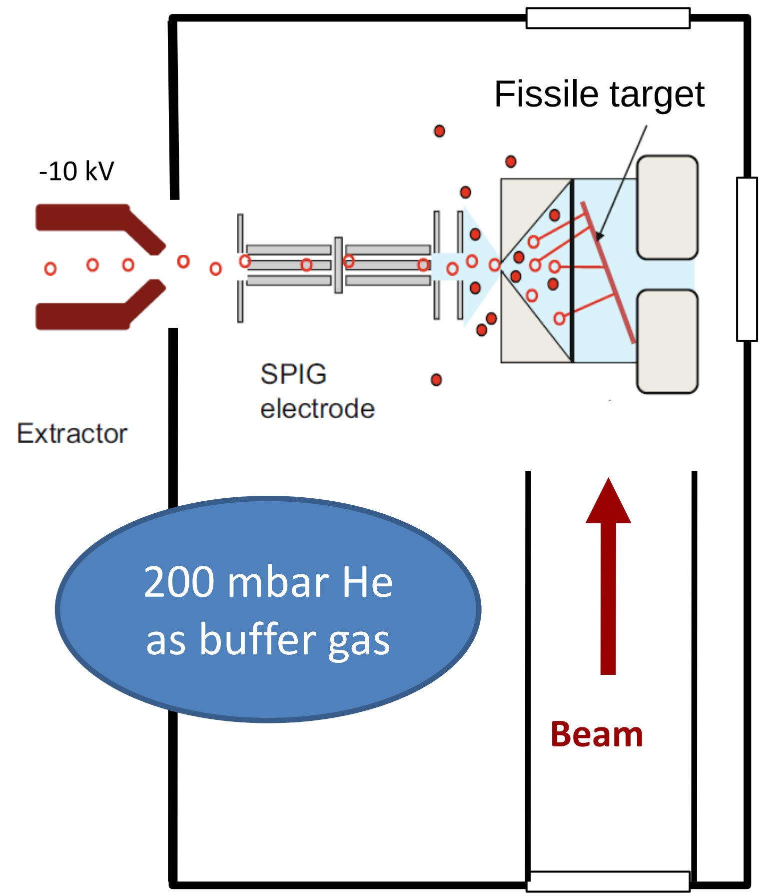
Also possible to use **K-130 cyclotron**,
Could give ~ 4000 hrs/yr

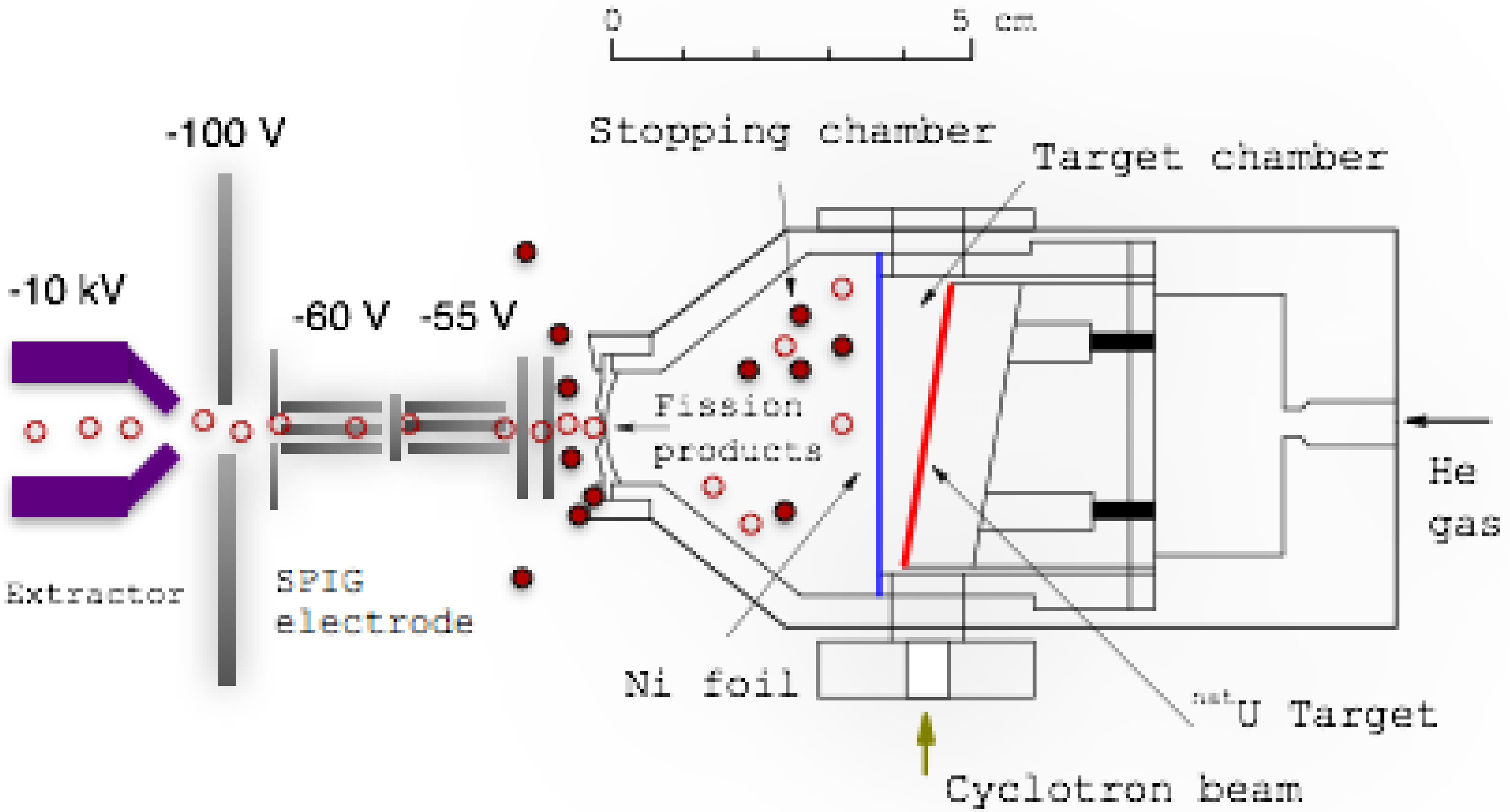
IGISOL = Ion Guide Isotope Separation OnLine

JYFLTRAP = JYväskylä physics Laboratory penning TRAP

Fission chamber and ion guide



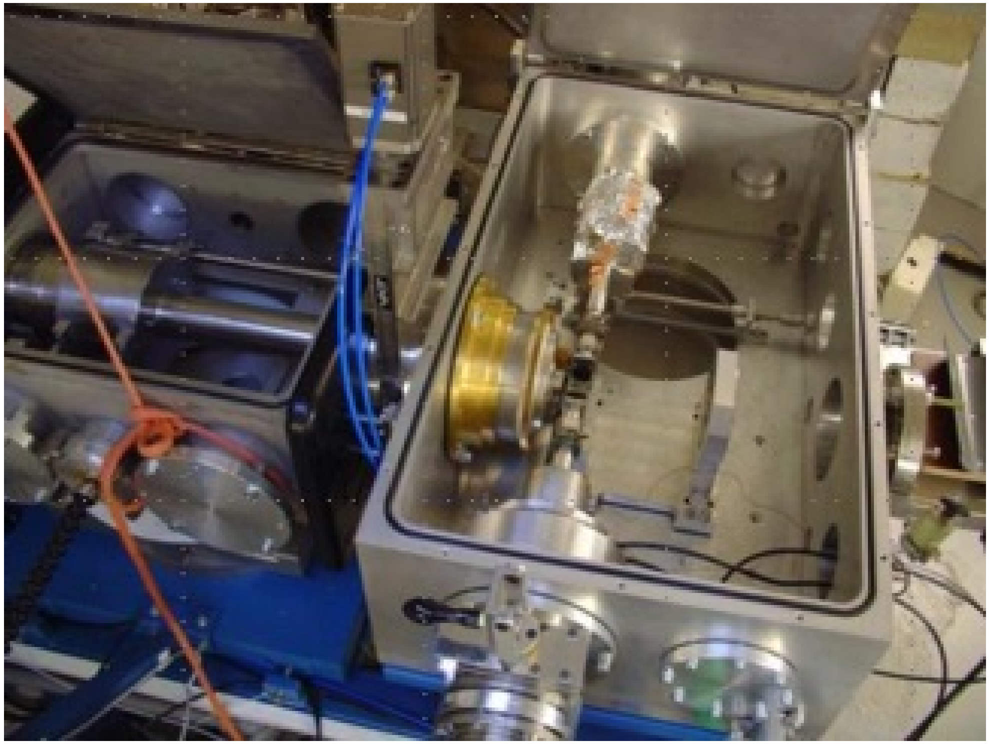



0
5 cm
-100 V
-10 kV
-60 V
-55 V
Stopping chamber
Target chamber
Fission
products
He
gas
Extractor
SPIG
electrode
Ni foil
^{nat}U Target
Cyclotron beam

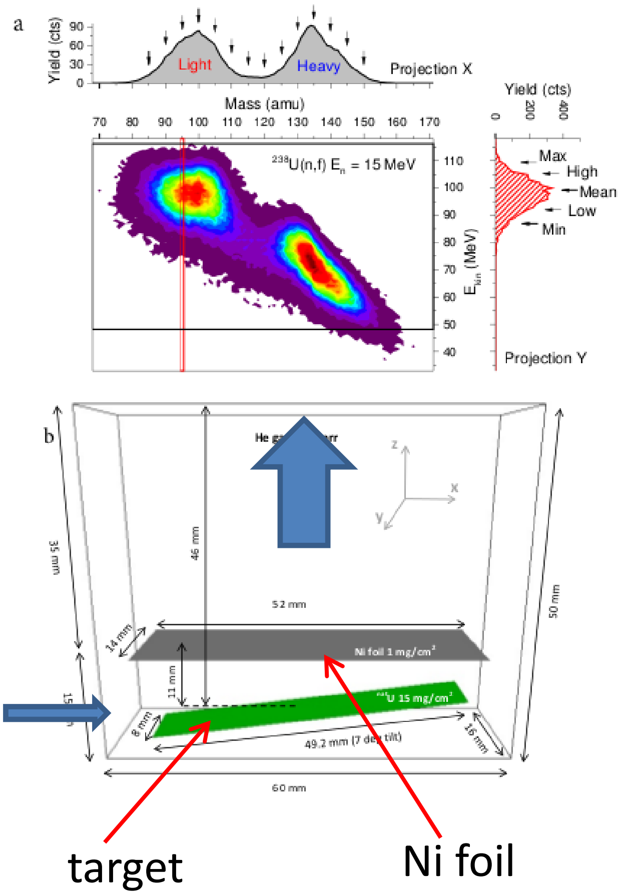
More on the fission chamber

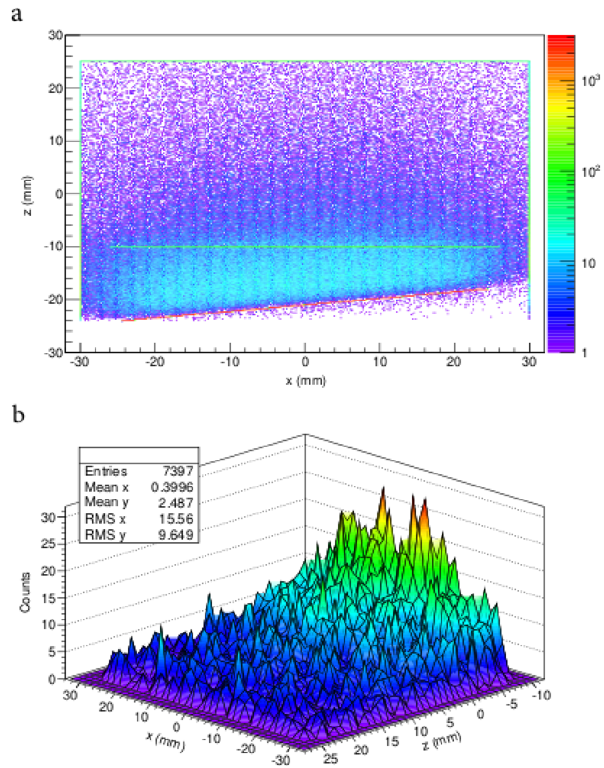
- Chemistry can matter
  - probability of 1^+ charge state?

1+/2+	^{132}Sn	1.19	±	0.17
	^{132}Sb	2.78	±	0.42



Simulations …





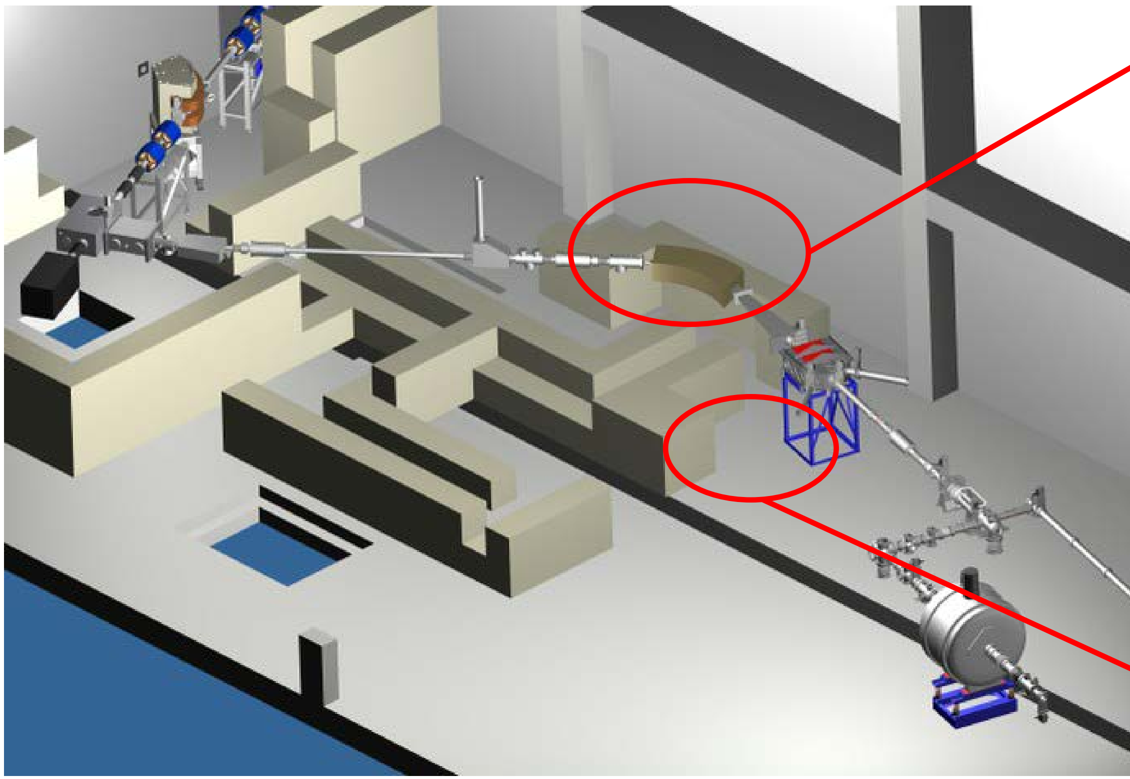
Simulations of mass- and energy dependence of fission product extraction efficiencies.

As input to the simulations realistic fission data were used (**GEF code**).

Dependence of stopping efficiency on mass and energy is found to be small compared to other systematic uncertainties.

A. Al-Adili et al., EPJ **A** (2015) 51:59, K. Jansson et al., submitted to EPJ A

First mass separation



Dipole magnet

Mass resolving power

M/ΔM=500

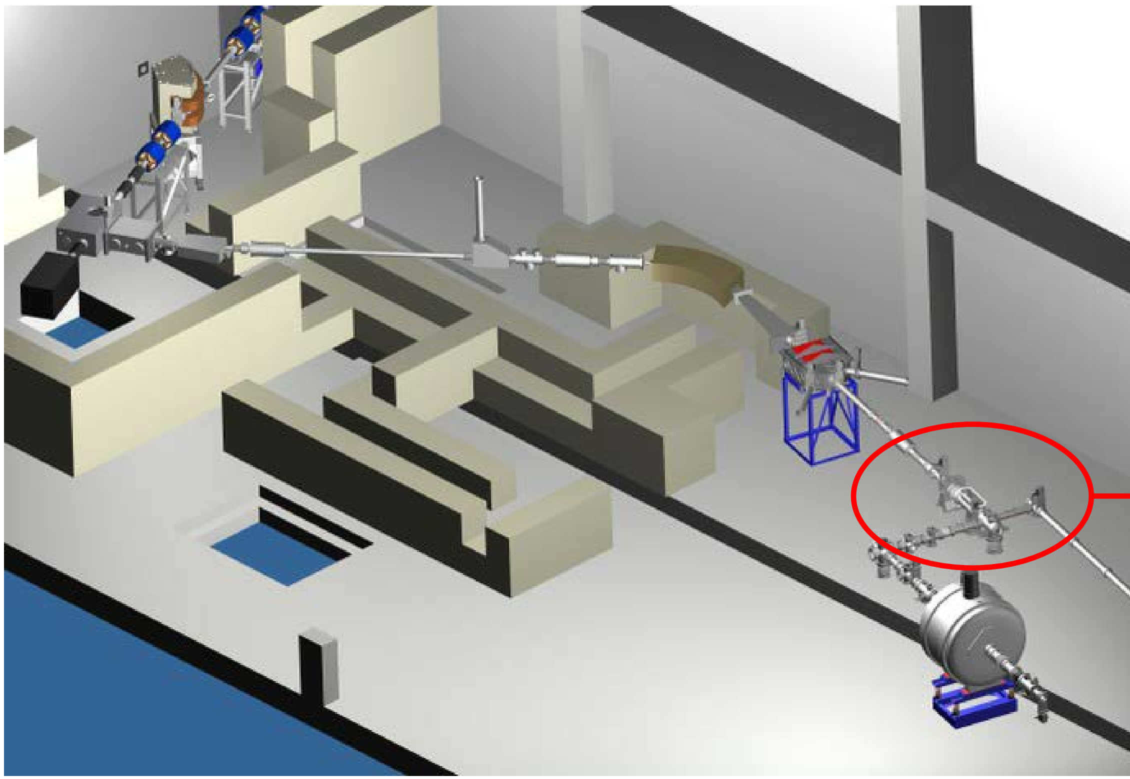
γ spectroscopy station

(missing in figure)

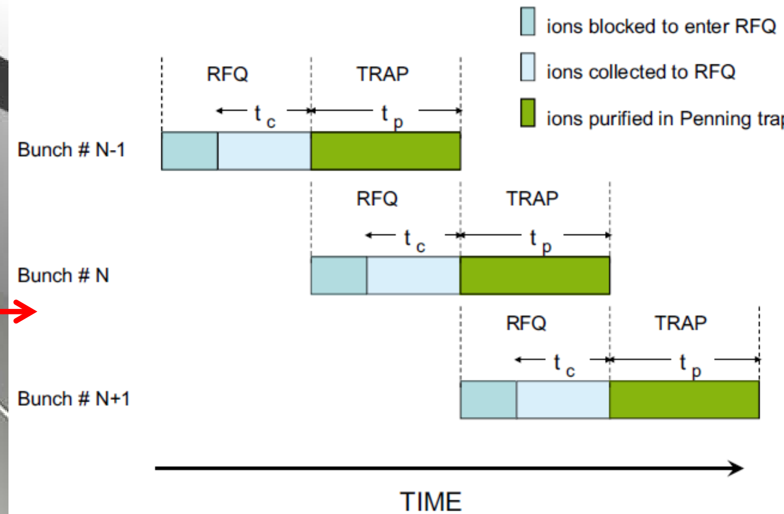
Ge detector in coincidence with β counter

UPPSALA UNIVERSITET

RFQ-cooler and buncher

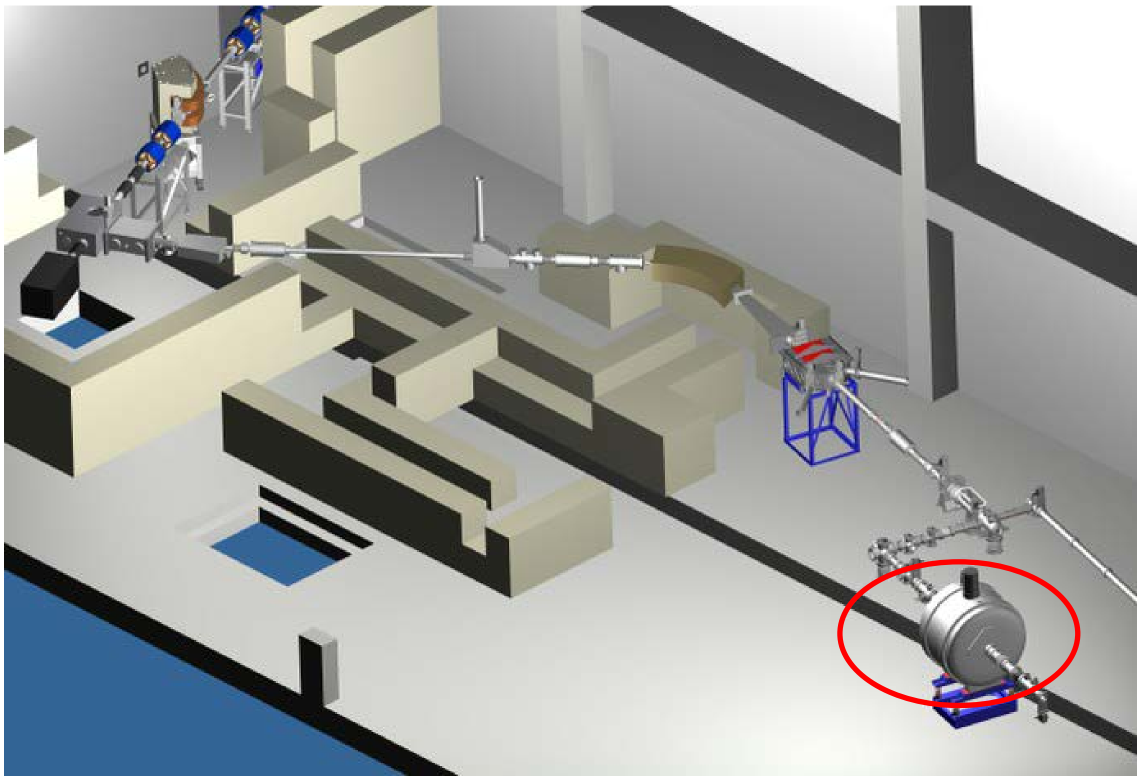


Ions are collected and then released towards the trap



H. Penttilä et al.,
Eur. Phys. J. A **44**, 147–168 (2010)

Two stage Penning trap



Mass resolv. power M/ΔM > 10^5
Resolve isomers 0.5 MeV apart
(and better …)

Cyclotron frequency
Each nuclide/isomer is Identified by its unique frequency in the Penning trap

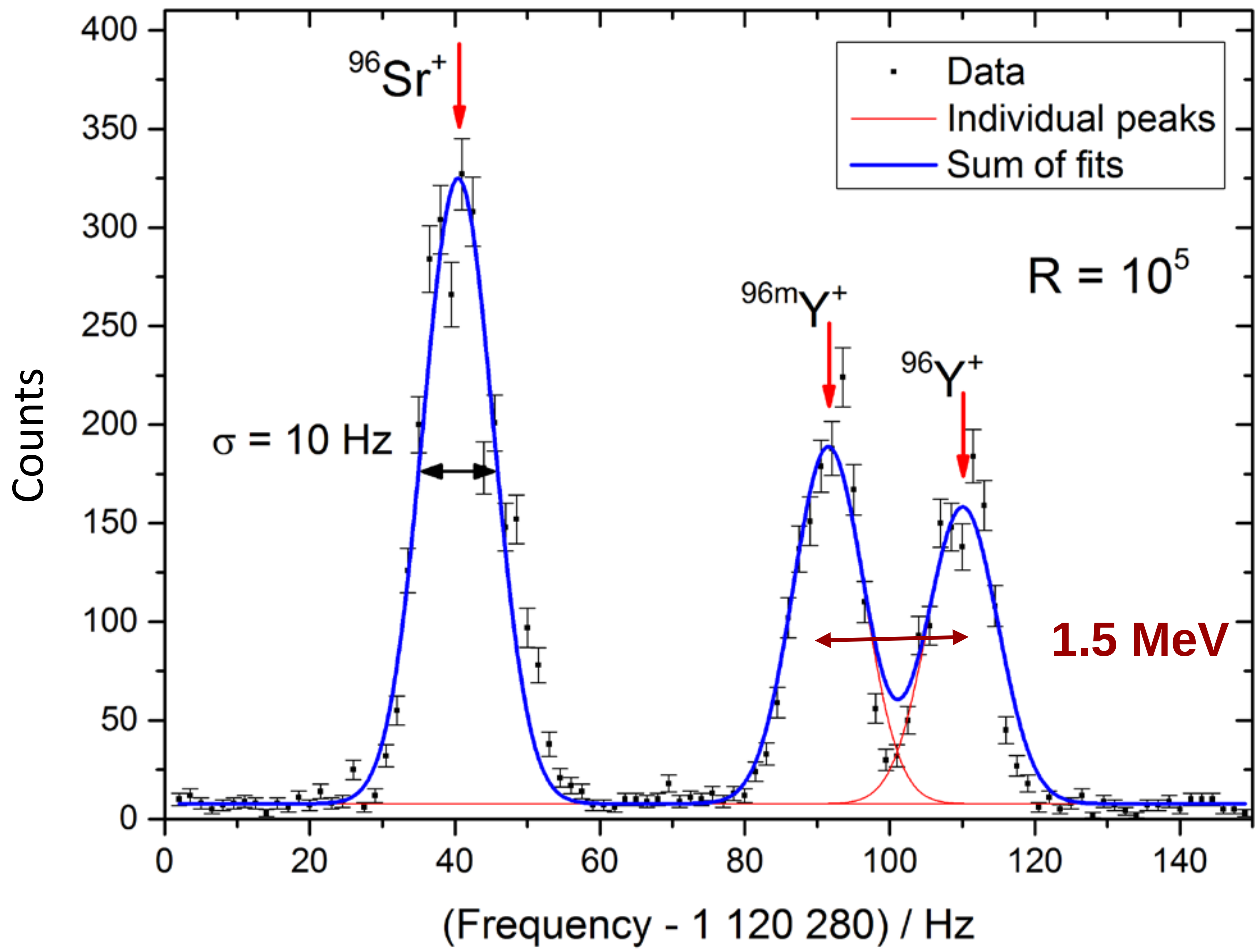
$$f_c = \frac{1}{2\pi}\frac{q}{m}B$$

Detector chamber
Multi-channel plate (MCP) counts all ions at given cyclotron frequency

Total time from production to detection ~300 ms

UPPSALA UNIVERSITET

How it then can look …

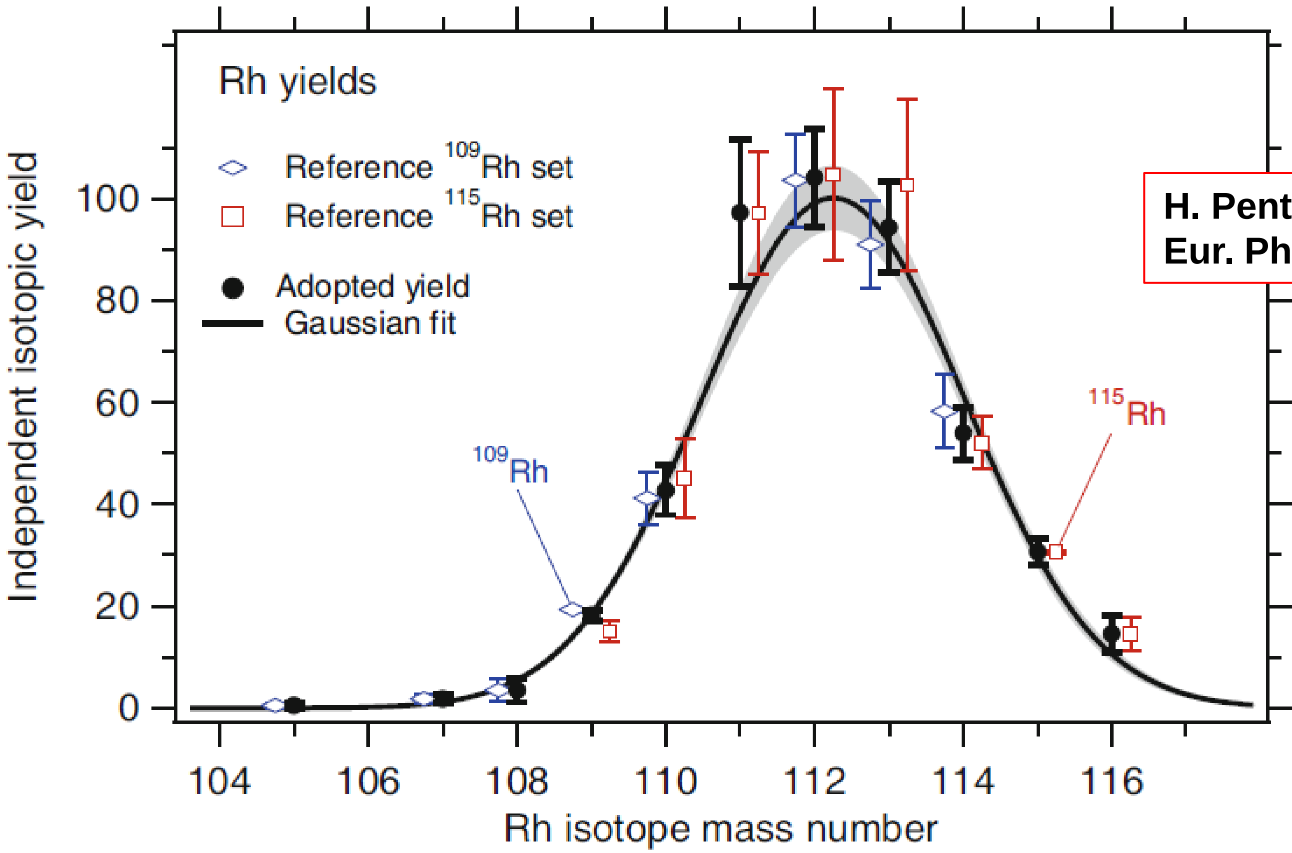


H. Penttilä et al., Eur. Phys. J. A **44**, 147–168 (2010)

UPPSALA UNIVERSITET

Done: IFY from (p,f) at 25 and 50 MeV

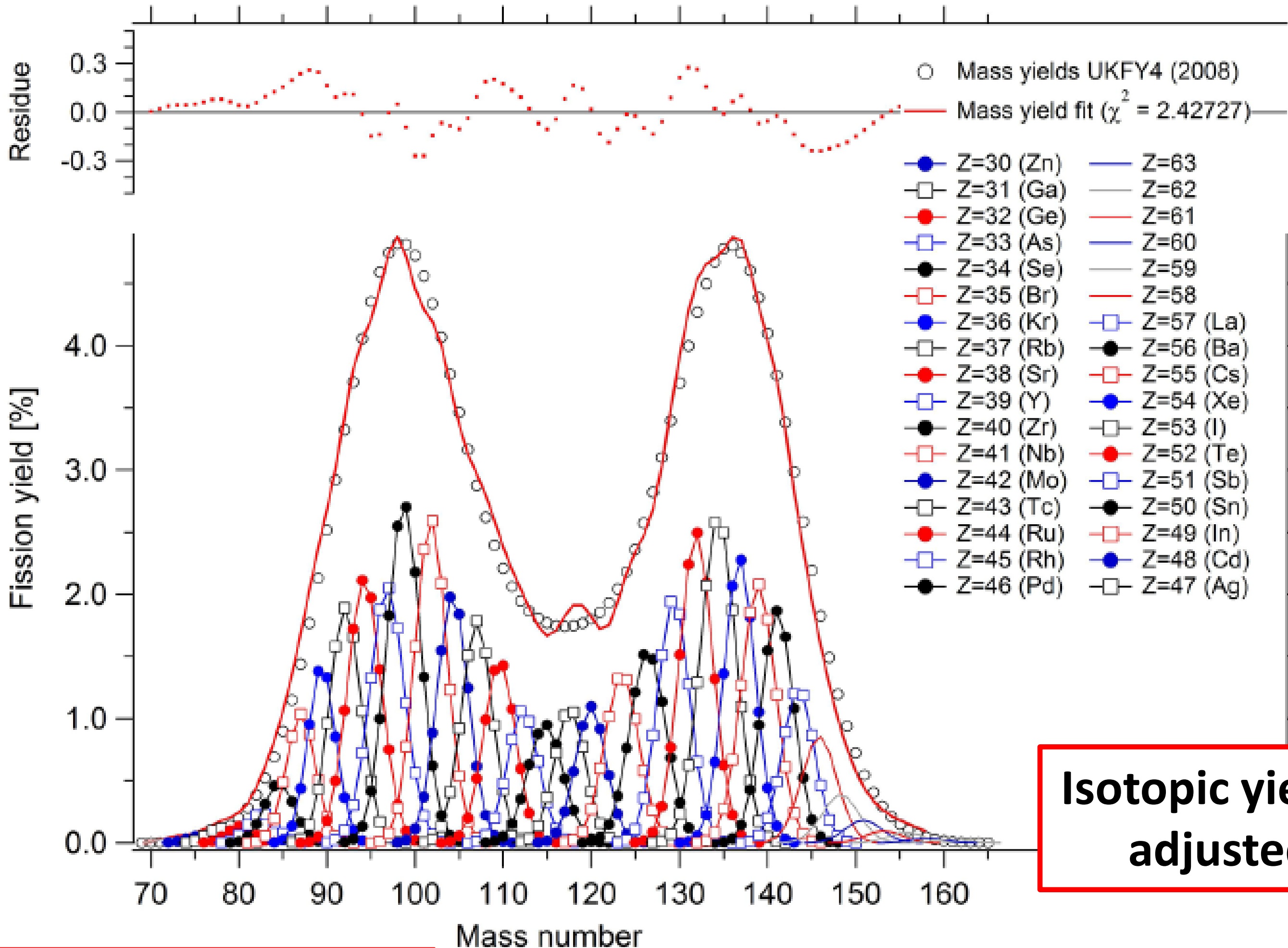
A number of measurements for p+^{nat}U and p+^{232}Th have been performed



H. Penttilä et al.,
Eur. Phys. J. A (2016) 52: 104

Example Rhodium: measured with two different reference points

IFY for $^{nat}U(p,f)$ at 25 MeV



Isotopic yield distributions adjusted to UKFY4.1

H. Penttilä et al.,
Eur. Phys. J. A (2016) 52: 104

UPPSALA UNIVERSITET

IYR in (p,f)

Performed:

- First direct measurement of IYR by direct ion counting.in (p,f)
- Several isomeric pairs in ^{238}U(p,f) and Th(p,f) measured for the first time.

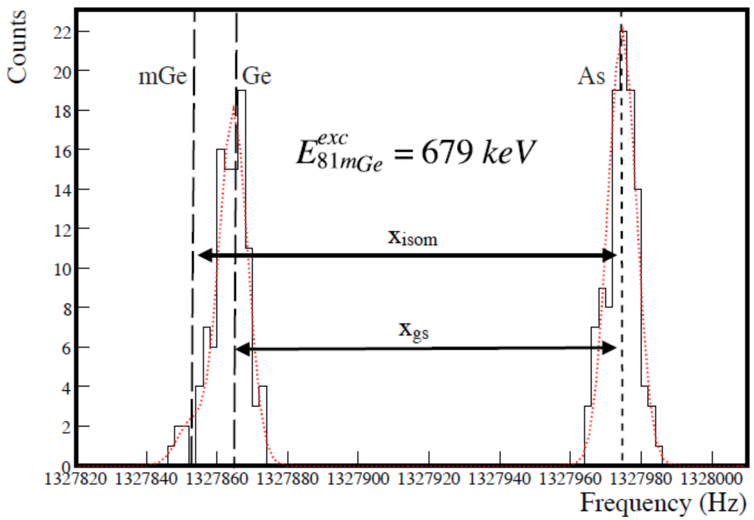
V. Rakopoulos et al., ND2016 proceedings
V. Rakopoulos et al., manuscript with new data from 2016 in preparation

Six isomers studied

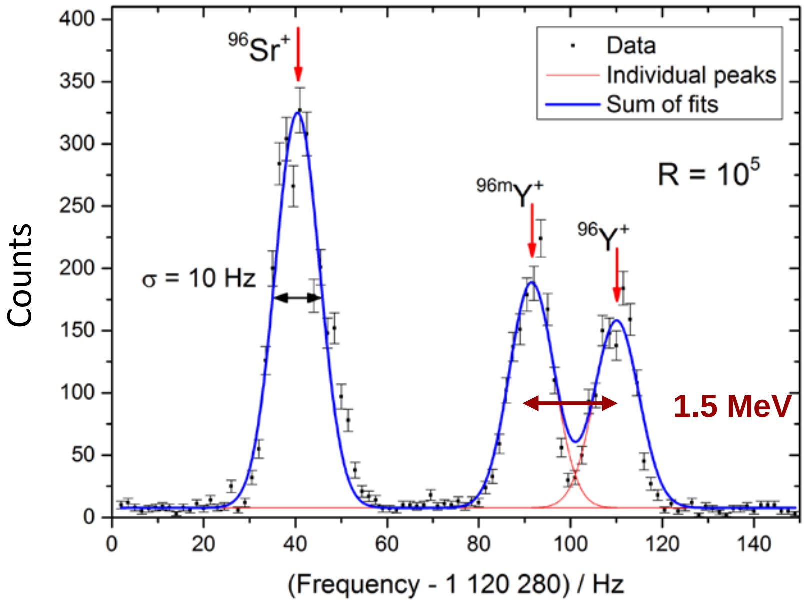
TABLE I. Information for the nuclides presented in this work. All data are retrieved from [47].

	Ground State		Isomeric State			
Nuclide	Spin	$\tau_{1/2}$ (s)	E_{exc} (keV)	Spin	$\tau_{1/2}$ (s)	Decay Mode
^{81}Ge	$9/2^+$	7.6	679	$1/2^+$	7.6	β^-=100%%
^{96}Y	0^-	5.34	1140	8^+	9.6	β^-=100%
^{97}Y	$1/2^-$	3.75	667	$9/2^+$	1.17	β^->99.3%, IT<0.7%
^{128}Sn	0^+	3544	2091	7^-	6.5	IT=100%
^{129}Sb	$7/2^+$	15840	1851	$19/2^-$	1062	β^-=85%, IT=15%
^{130}Sn	0^+	223.2	1946	7^-	102	β^-=100%

Example:
the toughest case, ^{81}Ge

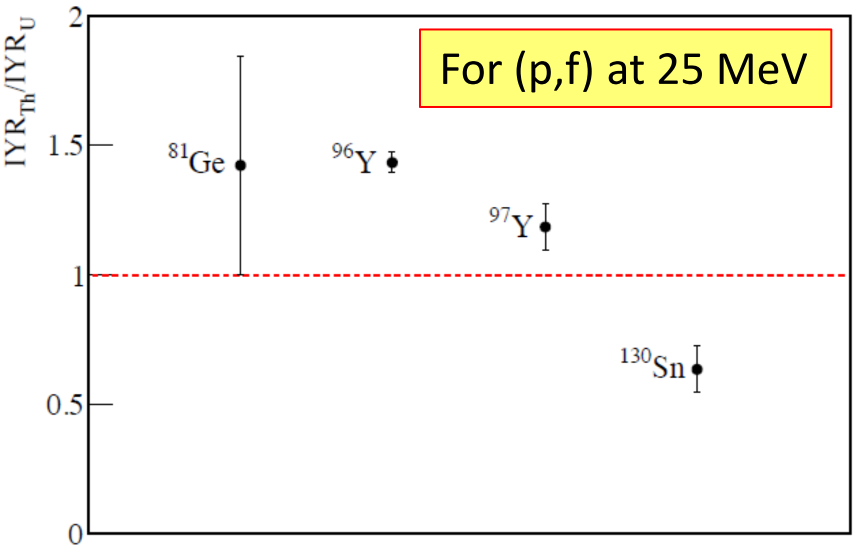


Isomeric yield ratios



$$\text{Ratio} = \frac{\text{Yield}(^{96m}\text{Y})}{\text{Yield}(^{96}\text{Y})+\text{Yield}(^{96m}\text{Y})}$$

Question:
Is there a dependence on the *initial system* or the *fission mode* for some isomeric yield ratios?



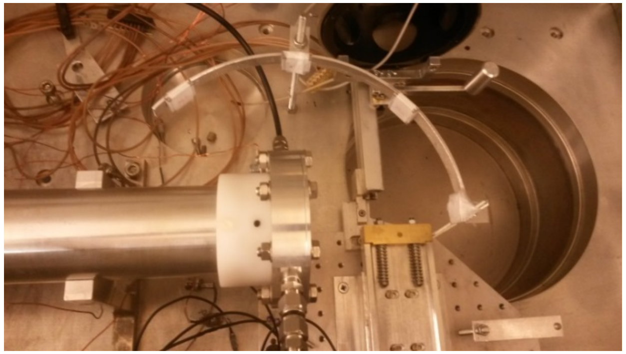
V. Rakopoulos, **preliminary results**

Now let's go to (n,f)

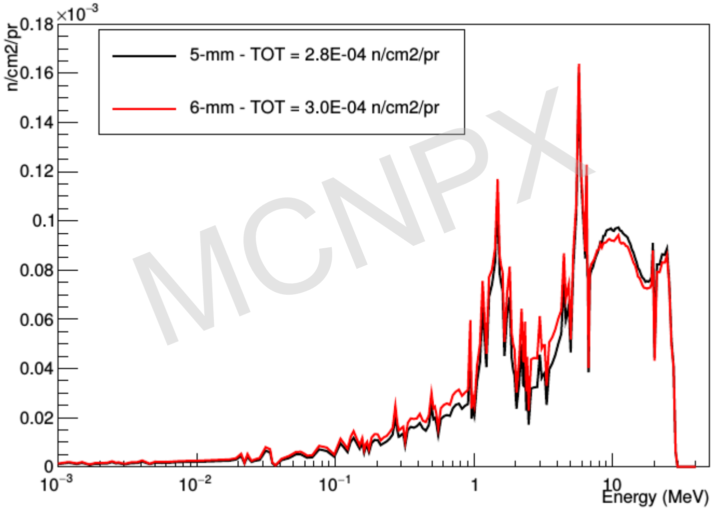
First we need a neutron source

Use Be(p,xn).
Thick target.
"White" neutron spectrum

The results show that a total neutron flux between 2 and 5×10^{12} n/sr/s at an incoming proton current of 100 µA can be achieved with this setup. Of these, between 2 and 3×10^{12} n/sr/s are fast neutrons ($E_n > 1$ MeV) [14]. Both these numbers fulfil the design goal in terms of total and fast neutron flux and allow neutron-induced fission studies at IGISOL-JYFLTRAP.



Characterization of Be(p,xn) neutron field with activation plates.

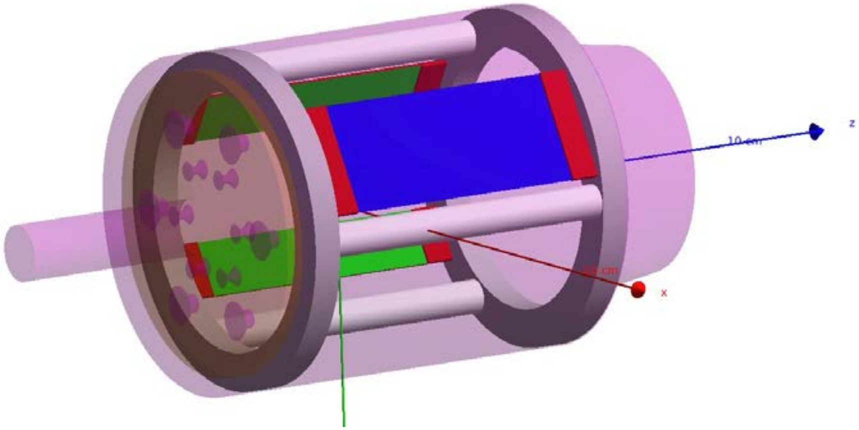


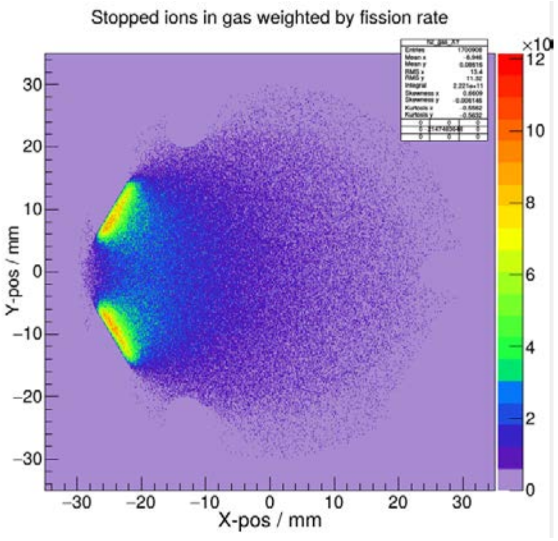
A. Solders et al., NDS **119** (2014) 338.
A. Mattera et al., EPJ A **53** (2017) 173.

Challenge: efficiency and normalization

(need for simulations and measurements)

Up to six normal targets (one in each hexagon side holder), or one big (5x2 cm) foil pressed against the chamber wall.





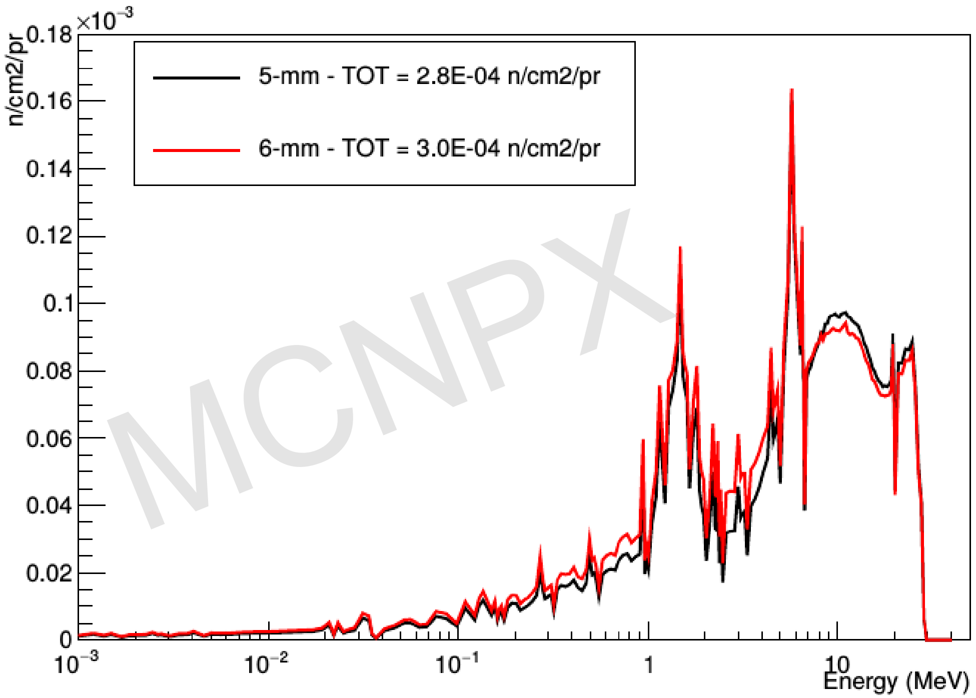
Extensive simulations of stopping efficiency:

- Neutron field from MCNPX
- Ions sampled from GEF
- Transport with Geant4

The “only” thing missing: *charge state distributions*.

Measurements with implantation foils currently under analysis. Use of **Cf-252 source** planned.

Energy distribution and multi-chance



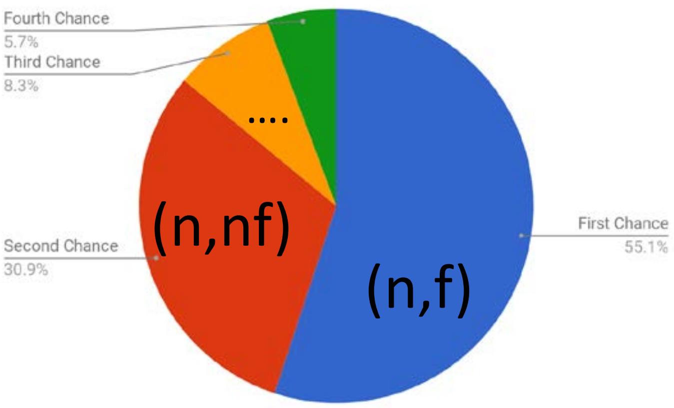
^{nat}U target:

average energy (weighed with XS):

~ 12.4±8.8 MeV

(97 ± 1) % of fissions from ^{238}U

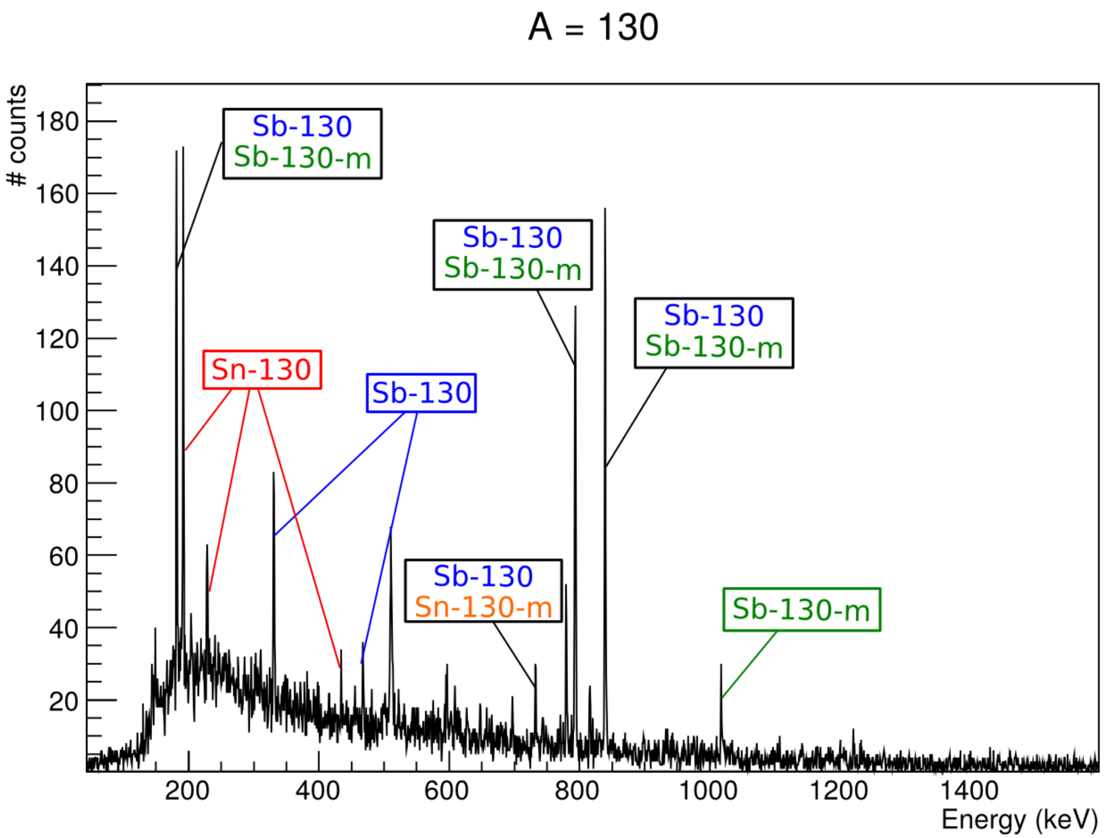
Multi-chance fission open



(based on GEF)

UPPSALA UNIVERSITET

In the (n,f) case we could not *yet* go …

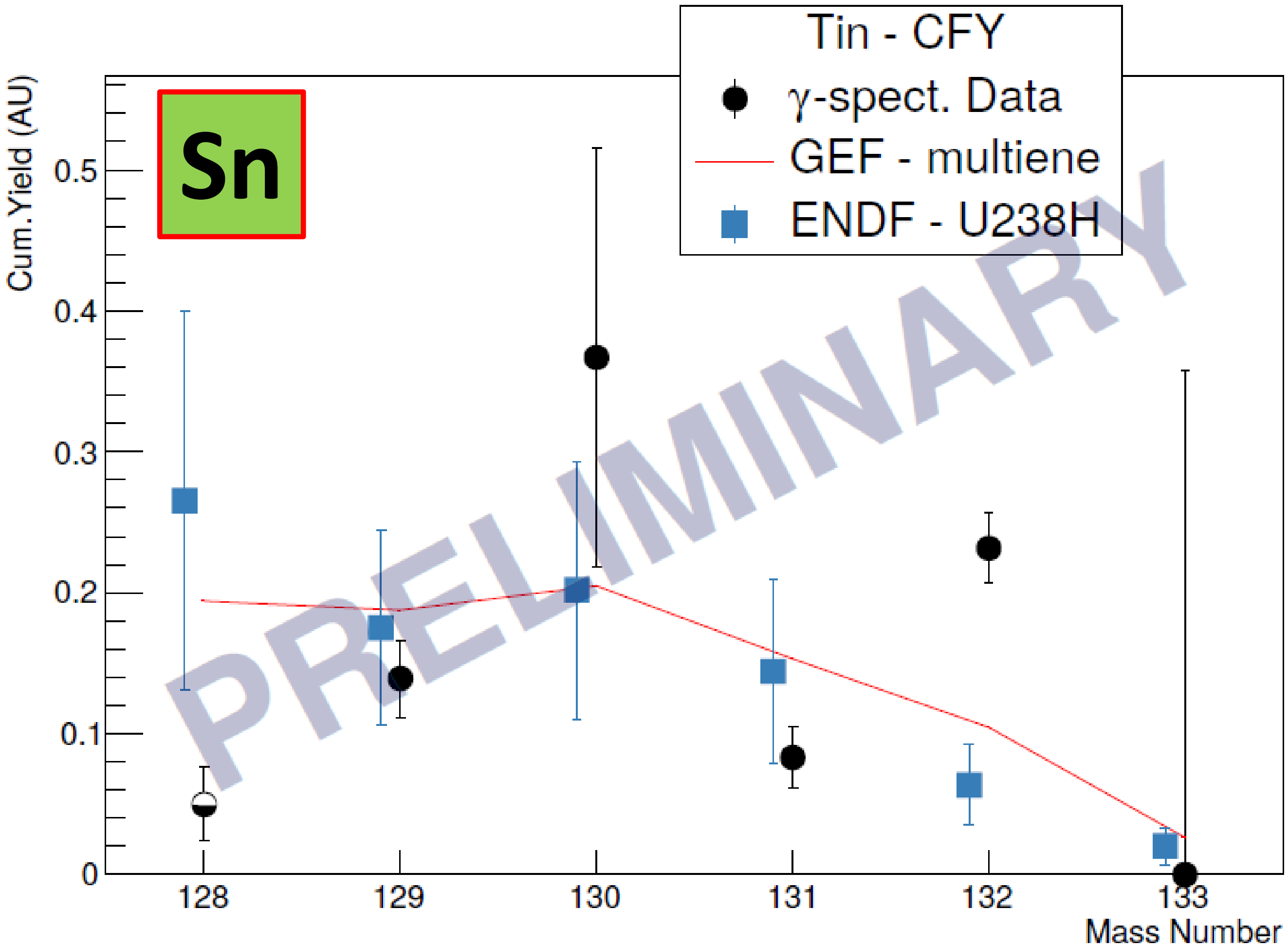


… all the way to the trap in this run (too low proton current).

Results presented here are based on **γ-spectroscopy** (with β coincidence) after the analyzing magnet.

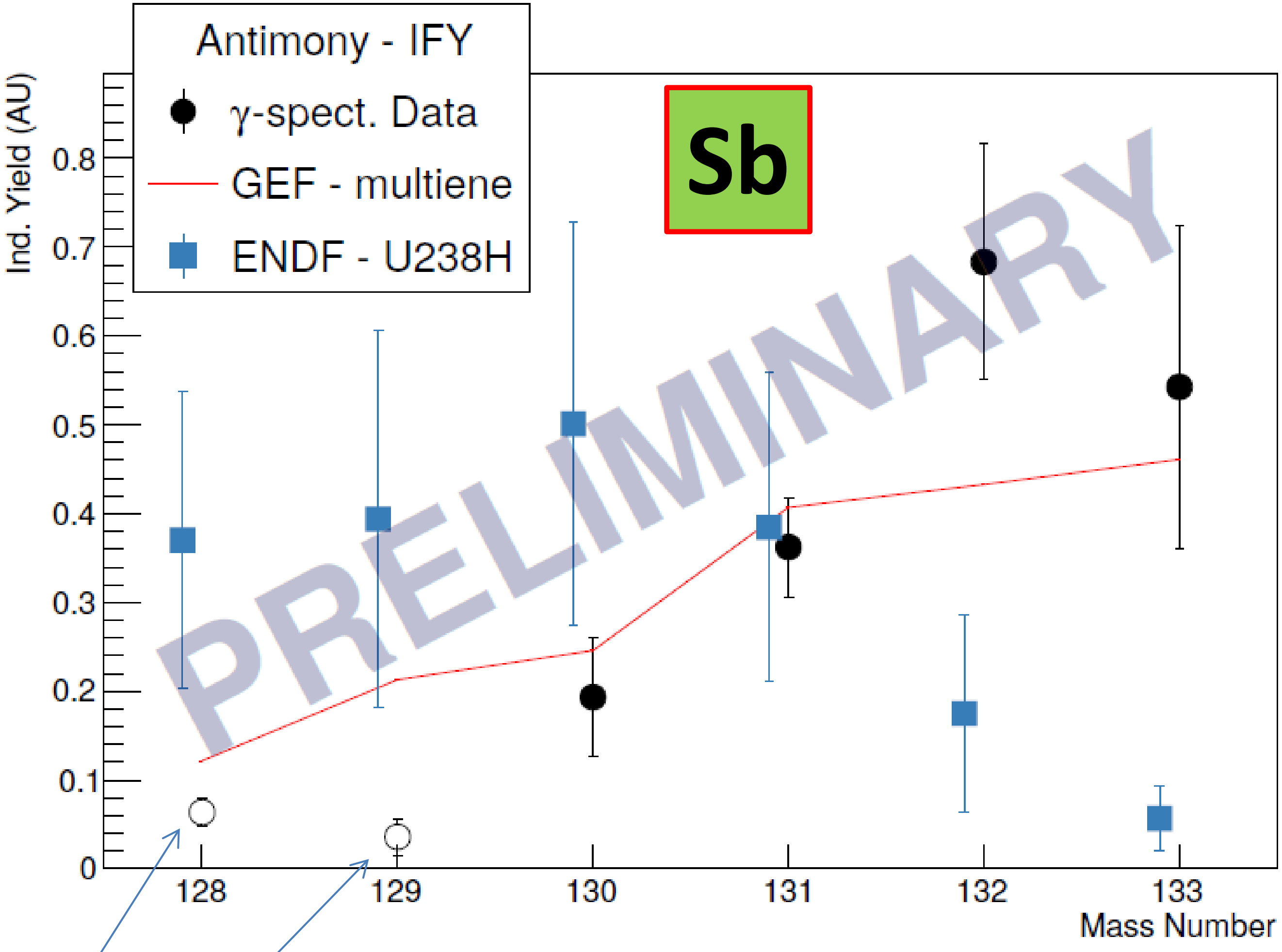
Six magnet settings:
masses **128 – 133** studied.
Data were collected during 2h each.

Sn isotopes - CFY



Relative *cumulative* yields.

Sb isotopes - IFY



Relative *independent* yields.

Only the isomer

Measured IYR

There are 5 nuclides where we see both isom & GS
→ we can extract the IYR

	Sn-m	Sn	Sb-m	Sb
A = 128	IT: 100 %			
A = 129				
A = 130				
A = 131				
A = 132				
A = 133				

	J^{Π}_{is}	J^{Π}_{GS}	E^*_{is} (keV)
^{129}Sn	$(11/2)^-$	$(3/2)^+$	35.15(5)
^{130}Sn	7^-	0^+	1946.88(10)
^{131}Sn	$(11/2)^-$	$(3/2)^+$	65.1(3)
^{130}Sb	$(4,5)^+$	8^-	4.80(20)
^{132}Sb	8^-	4^+	200(30)

UPPSALA UNIVERSITET

Results (also still preliminary)

There are 5 nuclides for which we can extract both isom & GS
→ we can extract the IYR

	Sn-m	Sn	Sb-m	Sb
A = 128	IT: 100 %			
A = 129				
A = 130				
A = 131				
A = 132				
A = 133				

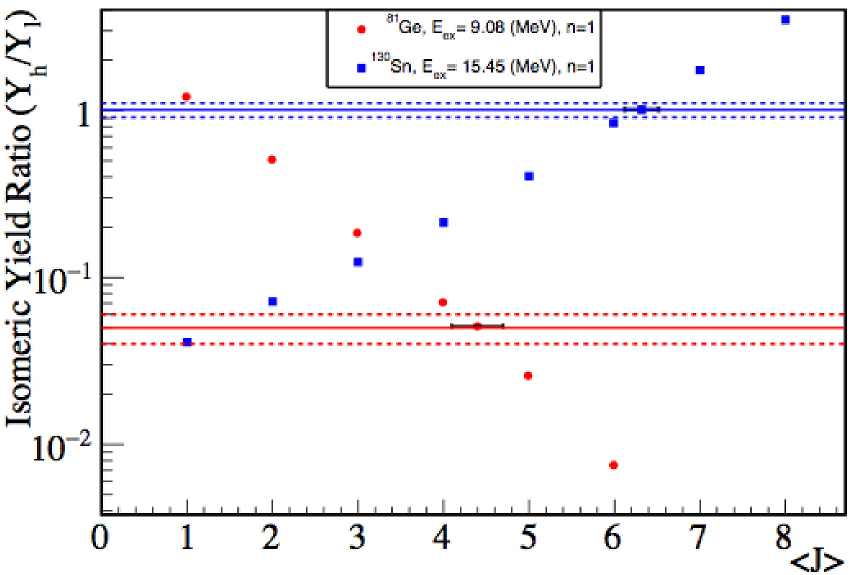
Table 2: IYRs measured in this experiment, compared to evaluated data libraries for fission of ^{238}U induced by 14 MeV neutrons (^{238}U(n$_H$,f)) and to a GEF calculation with a realistic incoming neutron spectrum. IYRs are reported as $Y_{is}/(Y_{is}+Y_{GS})$. The values reported are cumulative IYRs and independent IYRs for Sn and Sb, respectively.

	This work	GEF	ENDF B-VII.1	JENDL
→ ^{129}Sn	**0.37 ± 0.13**	0.63	0.15 ± 0.12	0.68 ± 0.43
^{130}Sn	**0.64 ± 0.48**	0.49	0.48 ± 0.49	0.70 ± 0.46
→ ^{131}Sn	**0.43 ± 0.19**	0.69	0.48 ± 0.45	0.81 ± 0.51
^{130}Sb	**0.81 ± 0.43**	0.68	0.43 ± 0.41	0.43 ± 0.28
^{132}Sb	**0.25 ± 0.10**	0.49	0.61 ± 0.41	0.61 ± 0.20

UPPSALA UNIVERSITET

Deduce FF spin using TALYS for de-exciation

Based on an assumption of emitted neutrons, TALYS is used to predict the IYR for different initial FF spins. The obtained dependence can be compared with the experimental value.



The trend of the curve depends on the spin difference between the ground state and the metastable state.

For the ^{81}Ge case $J_{g.s.}=9/2^+$ & $J_m=1/2^+$, while for the ^{130}Sn case $J_{g.s.}=0^+$ & $J_m=7^-$.

See V. Rakopoulos et al., ND2016 proceedings

UPPSALA
UNIVERSITET

Ackowledgements

Thanks to the nuclear reactions team in Uppsala,
in particular

Ali Al-Adili, Kaj Jansson, Andrea Mattera, and
Vasileios Rakopoulos

for providing material for this lecture.