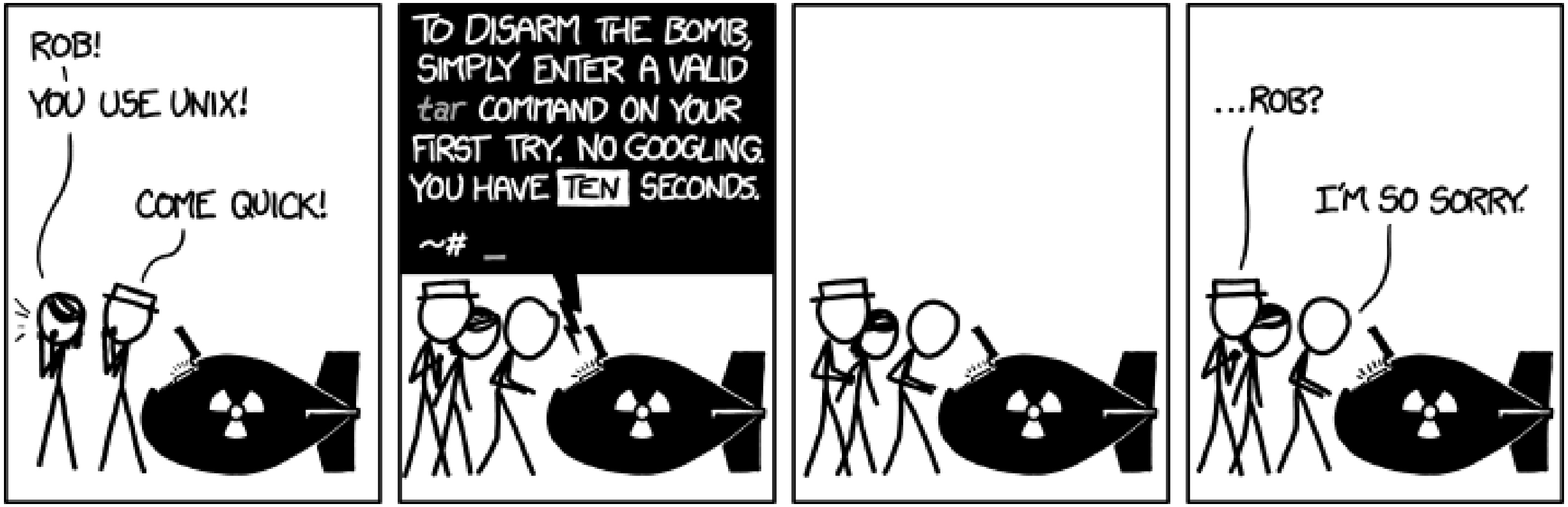
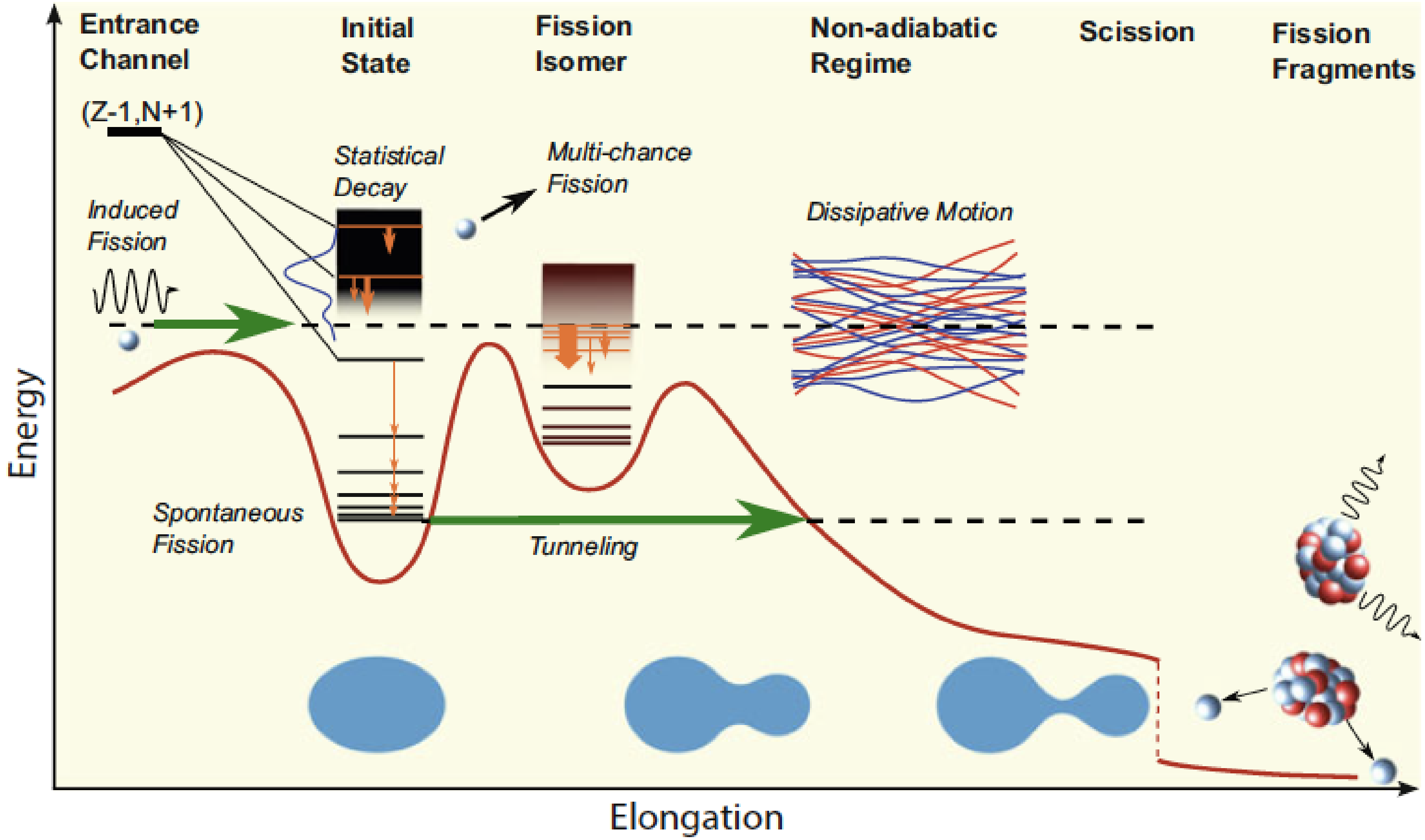
Nuclear Fission
Lecture 2

A. Heinz
Chalmers University of Technology



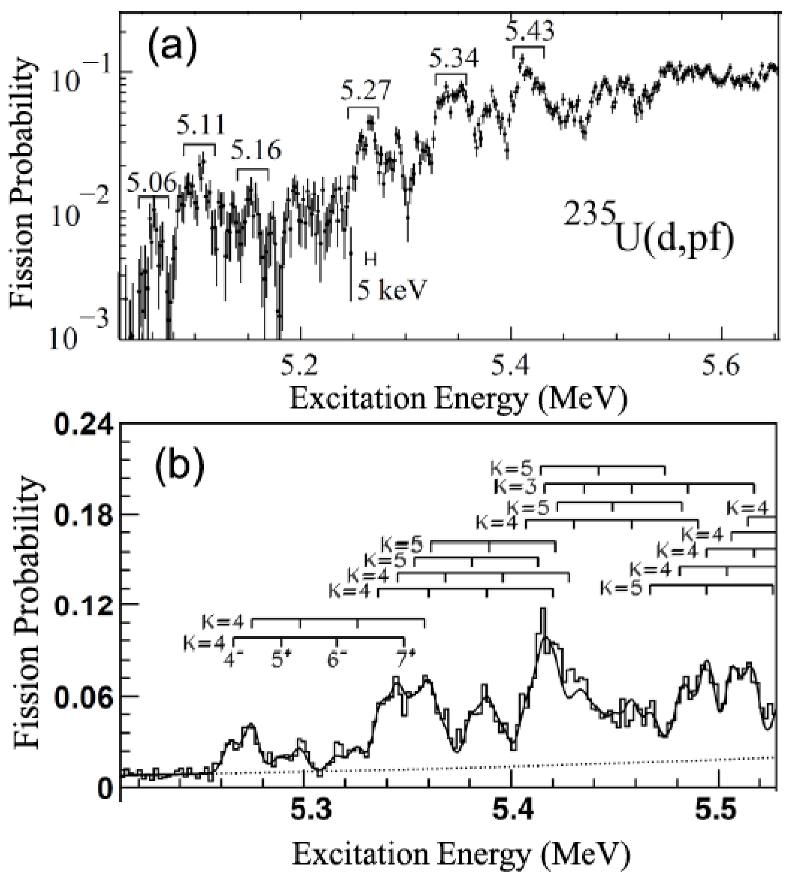
https://xkcd.com1168/

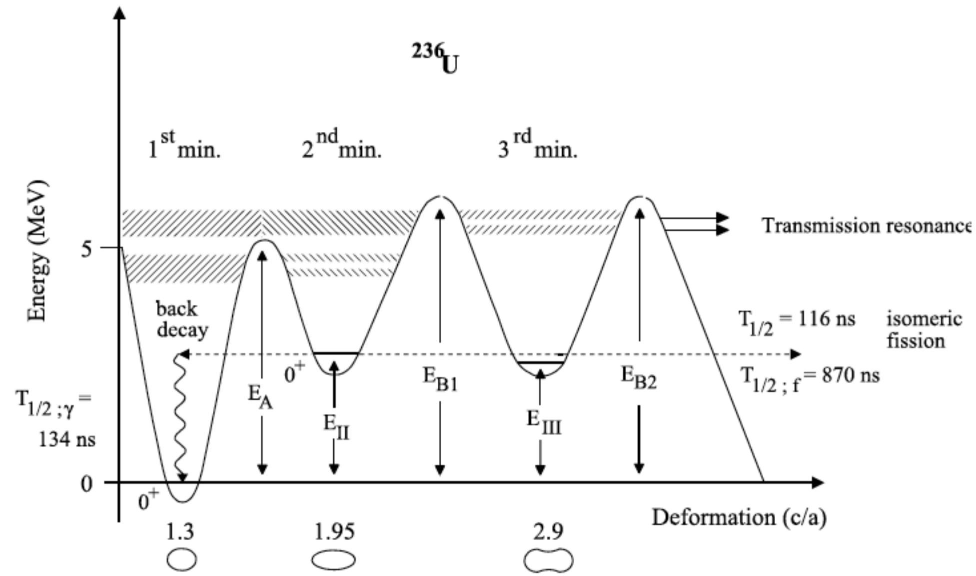
An overview

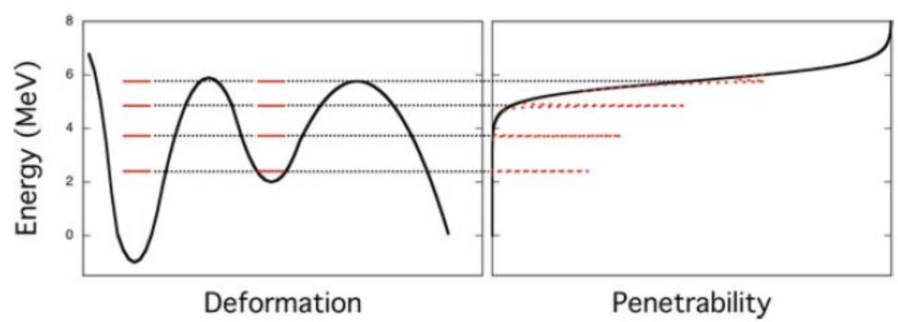


N. Schunck, *Microscopic Theory of Nuclear Fission* in *Handbook of Nuclear Physics*, Springer Nature Singapore (2023)

Fission probabilities







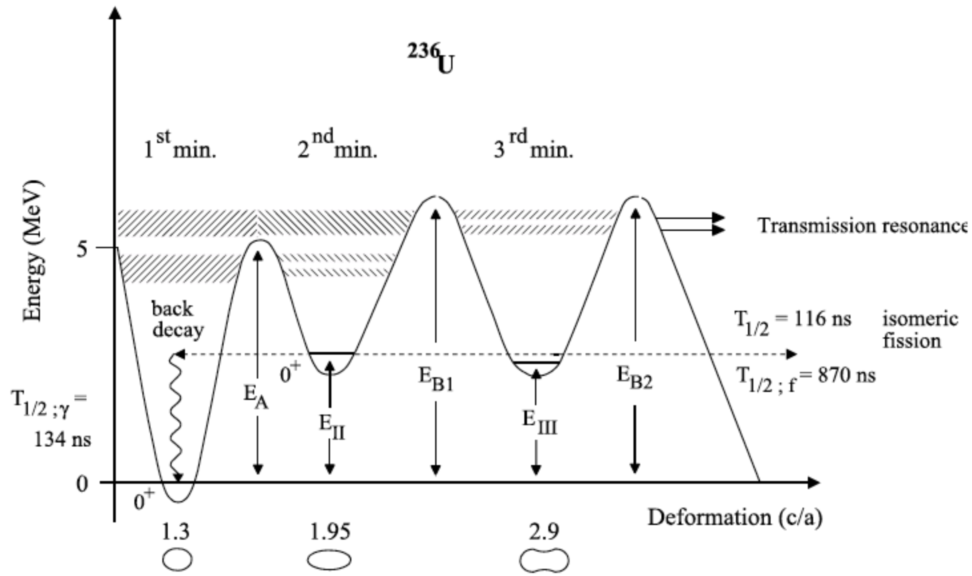
A.N. Andreyev et al., Rep. Prog. Phys. 81, 016301 (2018)

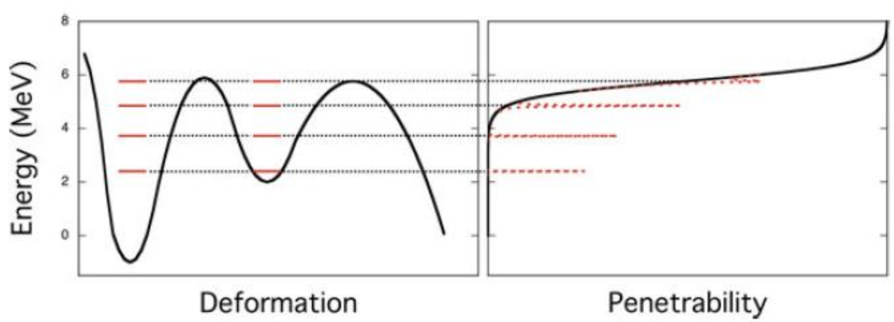
A. and S. Oberstedt, *The Multi-humped fission barrier*, in *Handbook of Nuclear Physics*, Springer, 2023

Fission probabilities

Structures in the fission probability (or cross section) allow to extract **barrier parameters** and to identify **isomeric states** in the 2nd and sometimes 3rd minimum.

Resonances result in higher fission probabilities.

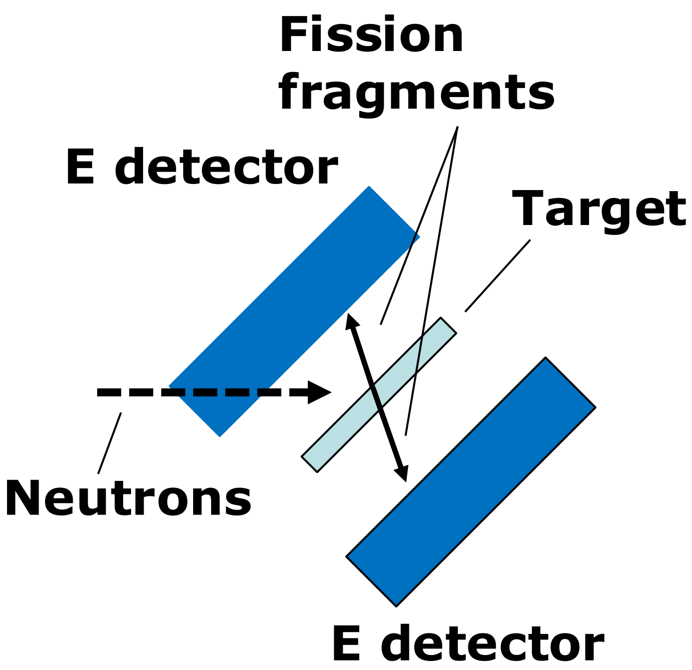




A.N. Andreyev et al., Rep. Prog. Phys. 81, 016301 (2018)

A. and S. Oberstedt, *The Multi-humped fission barrier*, in *Handbook of Nuclear Physics*, Springer, 2023

How to measure fission fragment masses



The double kinetic energy method (2E)

Momentum conservation:

$$\frac{M_1}{M_2} = \frac{E_2}{E_1}$$

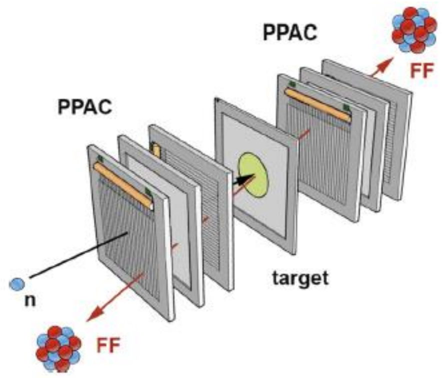
with $M_{1,2}$ as fission fragment masses and $E_{1,2}$ as their kinetic energies. The masses are given by

$$M_{1,2} = M_{CN} \frac{E_{2,1}}{E_1 + E_2}$$

with M_{CN} as the mass of the fissioning compound nucleus.

Advantages: large solid angle coverage is possible, correlations with TKE release.

How to measure fission fragment masses



N. Colonna et al.,
Eur. Phys. J. A. 56, 48 (2020)

The velocity - double kinetic energy (v - 2E) method

Mass of a given fission fragment after neutron evaporation, M_{post}:

$$M_{post} = 2\frac{E \cdot ToF^2}{L^2}$$

with E as kinetic energy of a given fragment and ToF as its time-of-flight. The flight path is given by L.

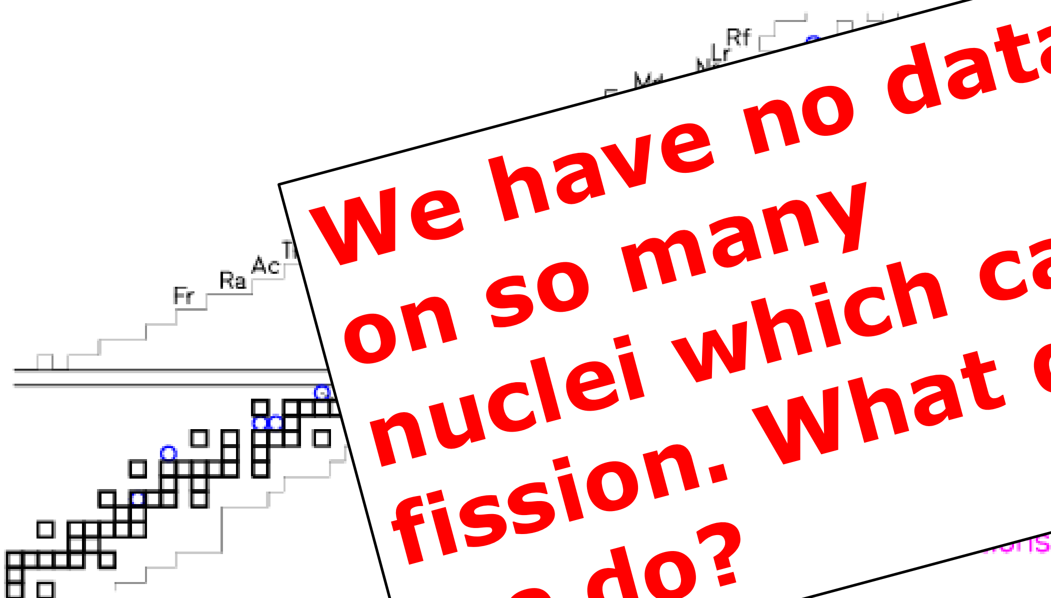
More modern approaches:

Precision mass measurement methods like an MR-ToF* or a Penning trap.

Advantages: much better mass resolution, but more complex.

***Multi-reflection time-of-flight mass spectrograph**

Experimental status around 1995



We have no data on so many nuclei which can fission. What do we do?

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

- **Limited number of isotopes studied due to experimental limitations.**

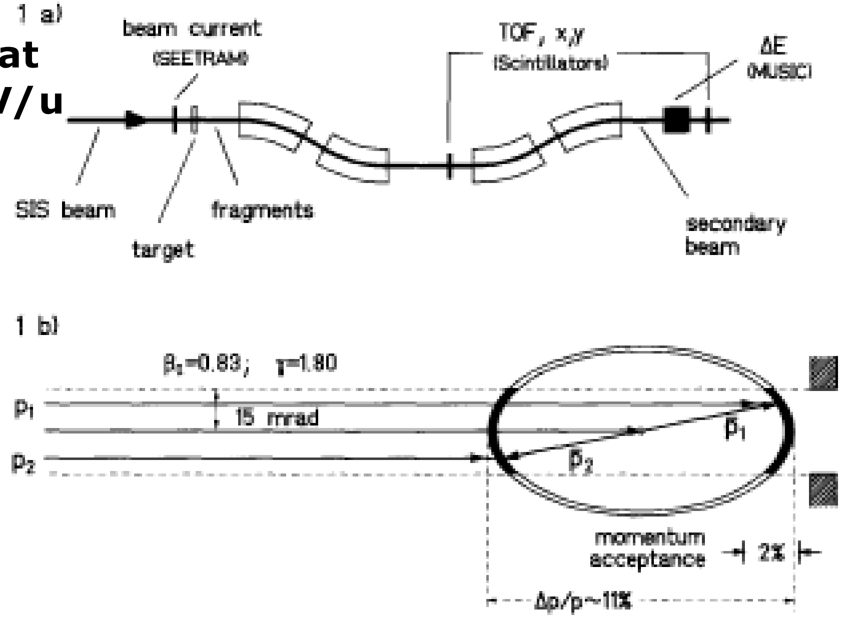
  Three main approaches to induce fission: neutrons, light charged particles, spontaneous fission.

- **Significant changes in the mass (charge) distributions of the fission fragments -> changes in the potential energy surface.**

Disclaimer: we talk here about data at low E* and low angular momentum where nuclear structure effects are observable.

Fission in inverse kinematics: isotopic resolution of fission fragments

^{238}U at 1GeV/u



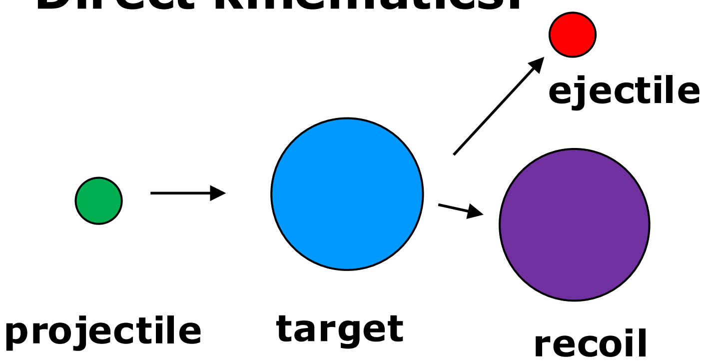
$$\left.\begin{array}{l}\text{Nuclear Charge Z} \Rightarrow \text{ ionization chamber} \\ \text{Bending } \rho \Rightarrow \text{ positions} \\ \text{Velocity } \gamma\beta \Rightarrow \text{ ToF} \\ \text{Magnetic field B} \Rightarrow \text{ Hall probes}\end{array}\right\} \Rightarrow \frac{B\rho \cdot Z}{\gamma\beta} = A$$

M.Bernas et al., Phys. Lett. B 331, 19 (1994)

- **The beam fissions, not the target.**
- **Event-by-event identification of one fission fragment!**
- **Widely used to produce neutron-rich beams.**
- **But: Only for stable primary beams!**

Direct vs. inverse kinematics

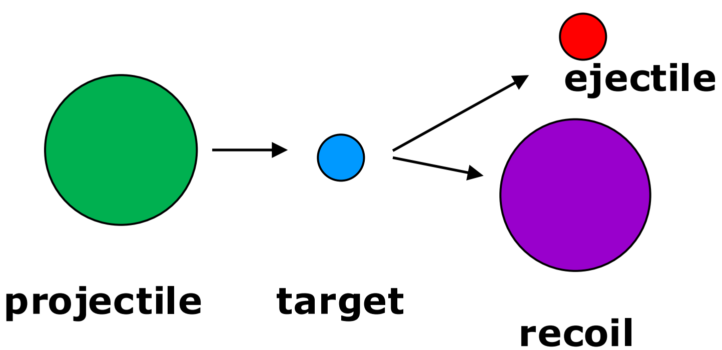
Direct kinematics:



Advantages:
- **High beam intensities.**
- **High angular and energy resolution of the ejectile.**

Disadvantages:
- **Needs stable or long-lived beam and target.**
- **Recoil identification.**
- **Hard to do complete kinematics.**

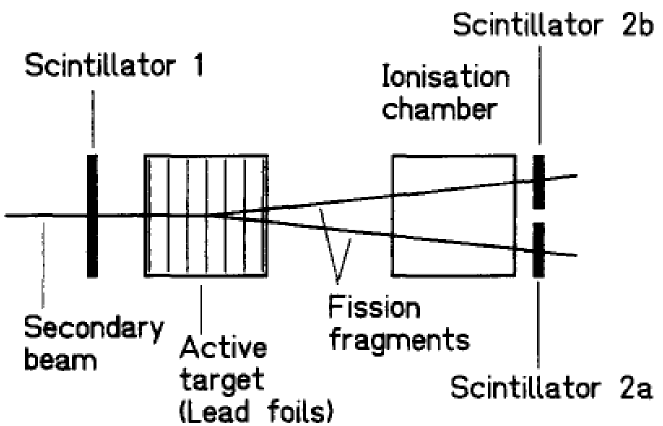
Inverse kinematics:

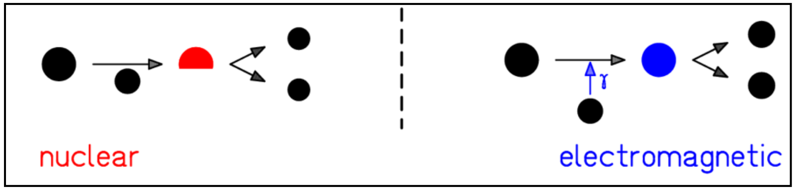


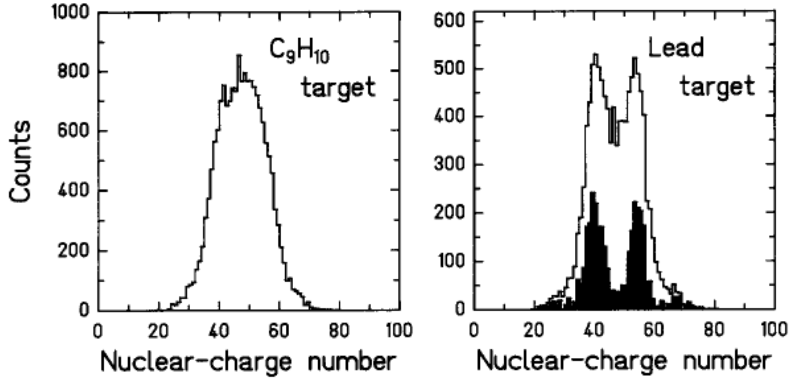
Advantages:
- **Works with short lived beams.**
- **Recoils identification.**
- **Possible to do complete kinematics.**

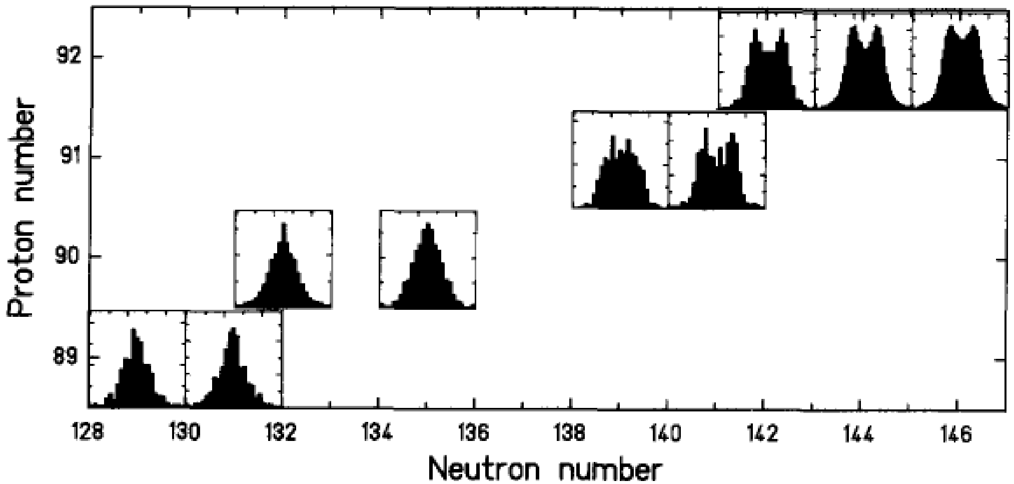
Disadvantages:
- **Energy and angular resolution of the ejectile.**
- **Low beam intensities.**

Fission of radioactive beams in inverse kinematics (first attempt)





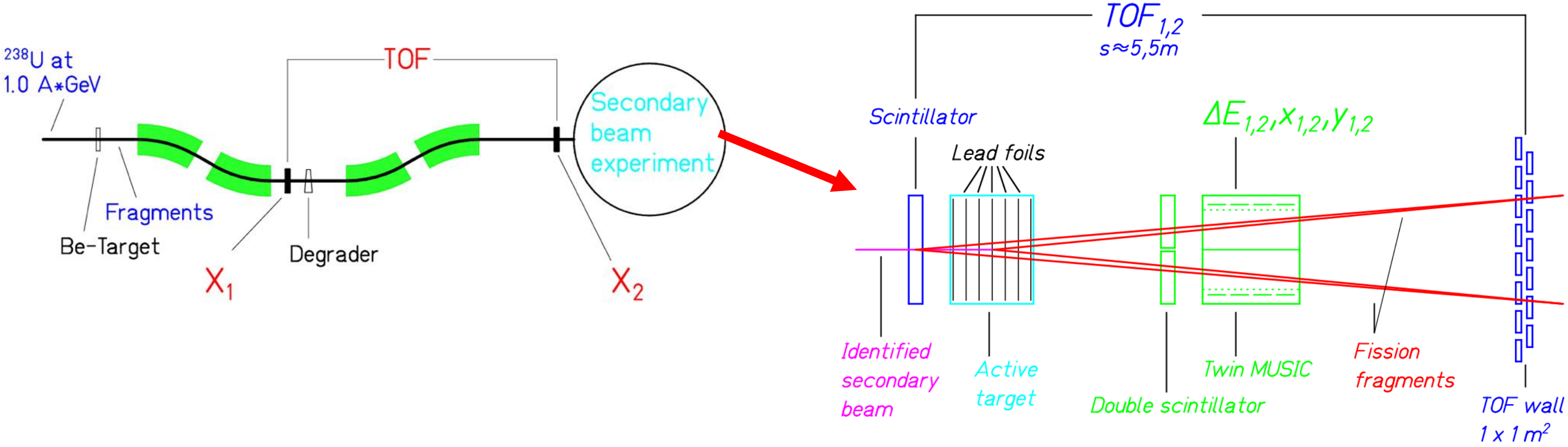




K.-H. Schmidt, A. Heinz, et al., Phys. Lett. B 325, 330 (1994)

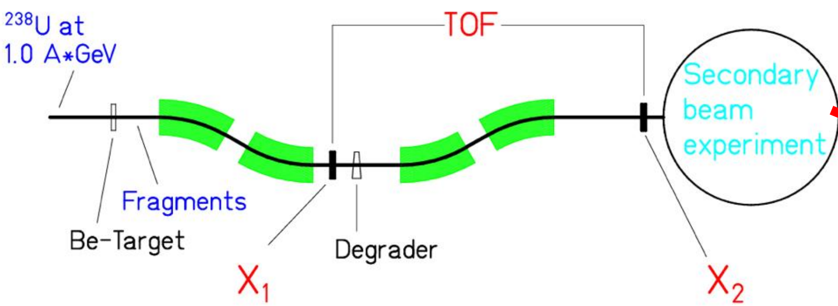
Use radioactive (secondary) beams in inverse kinematics at relativistic energies (about 500 MeV/u)

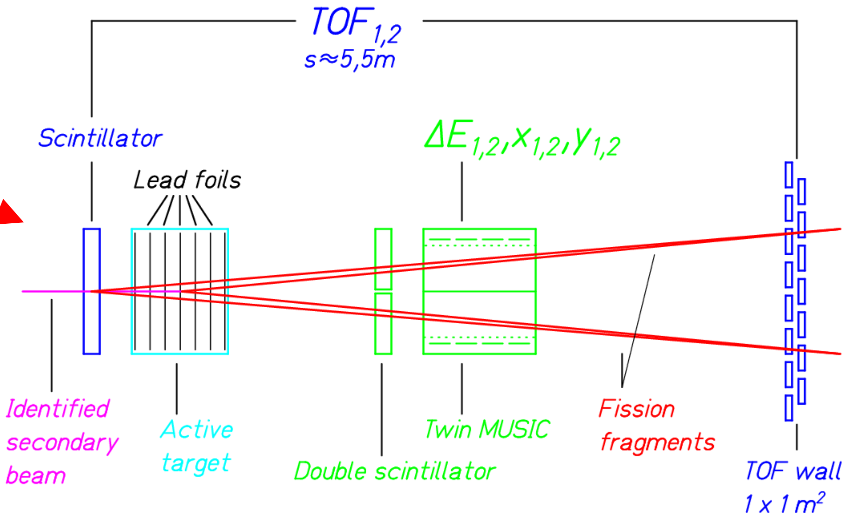
The third attempt

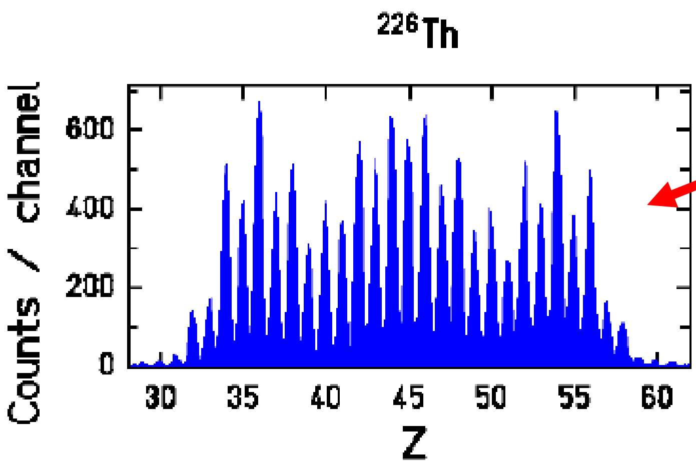


K-H. Schmidt et al., Nucl. Phys. A 665, 221 (2000)

The third attempt

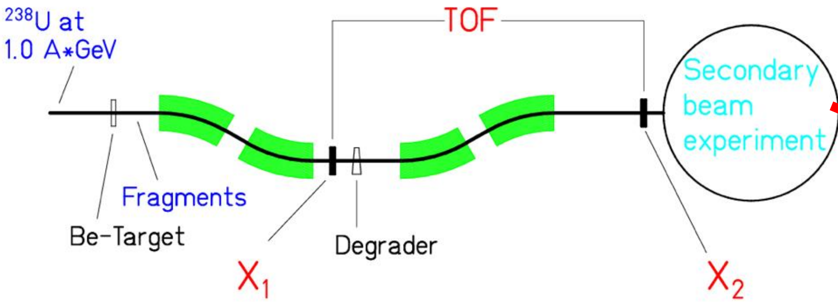


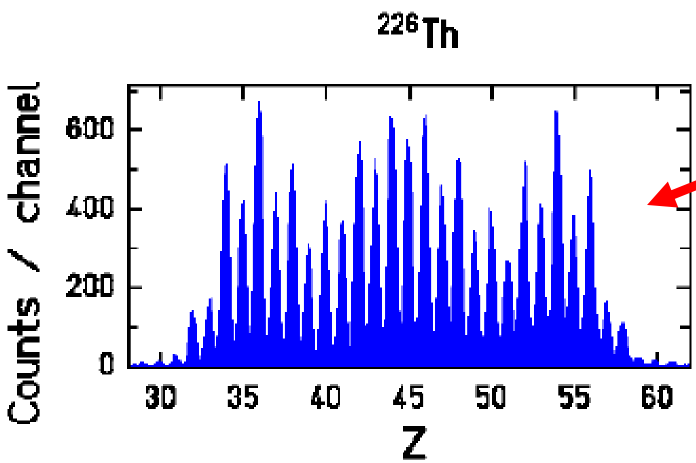


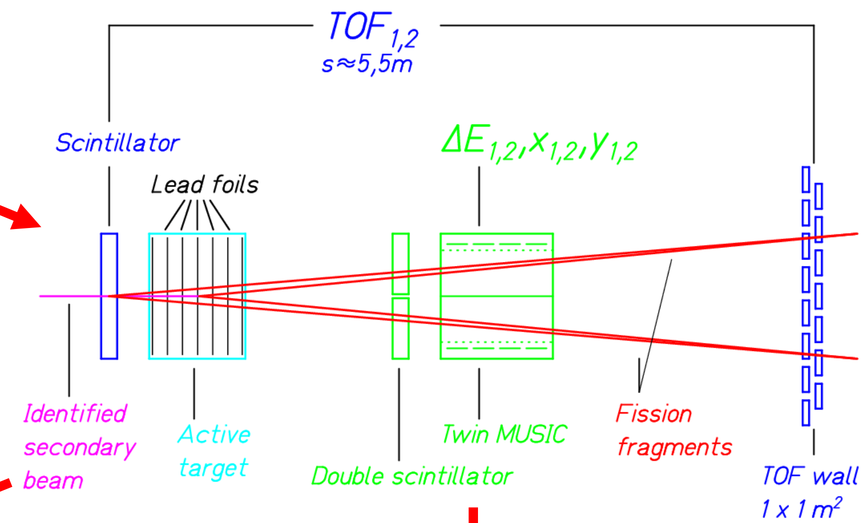


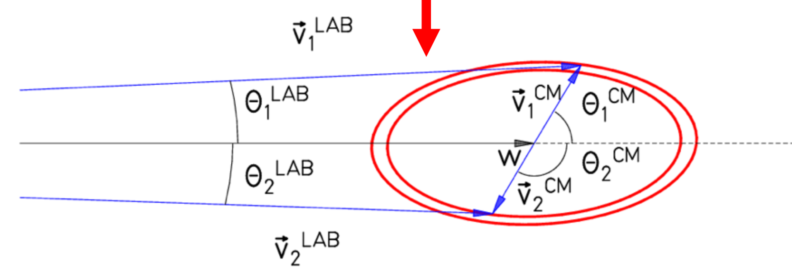
K-H. Schmidt et al., Nucl. Phys. A 665, 221 (2000)

The third attempt







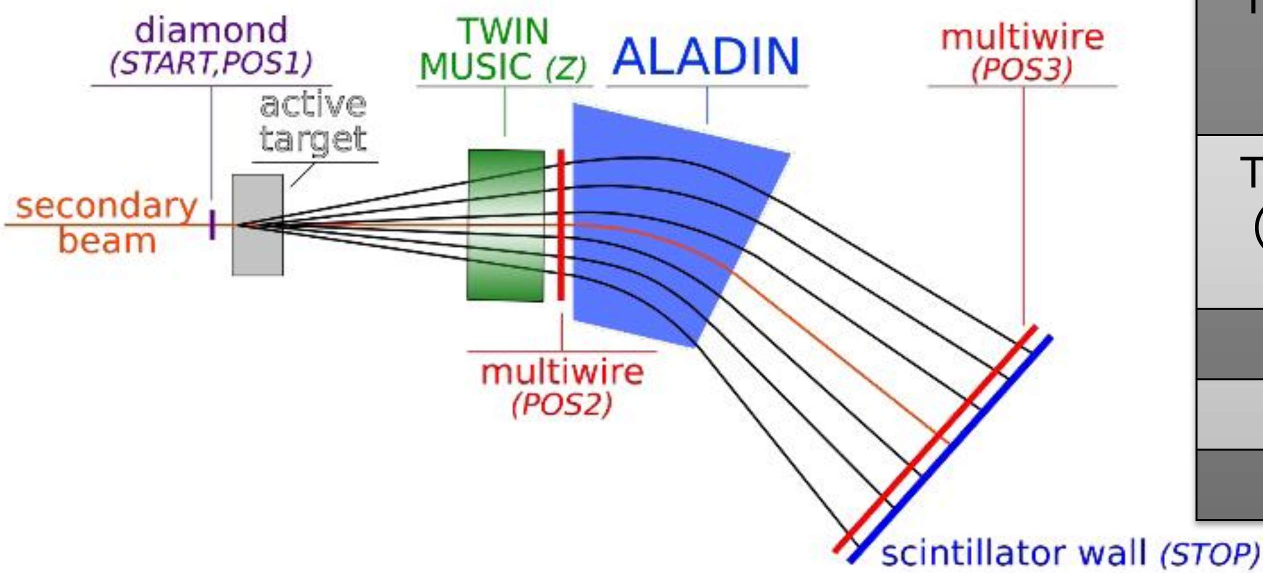


Total Kinetic Energy (TKE)

K-H. Schmidt et al., Nucl. Phys. A 665, 221 (2000)

C. Böckstiegel et al., Phys. Lett B 398, 259 (1997)

SOFIA – Set-up



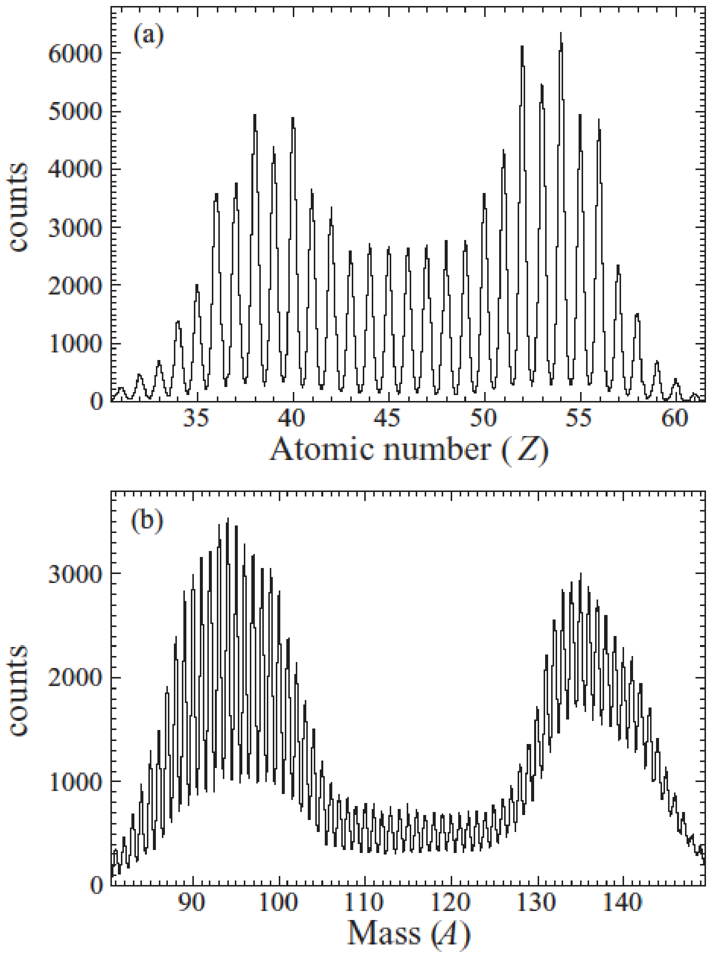
Detector	Resolution (FWHM)
Twin MUSIC (energy)	< 1 % (0.2 in charge units)
Twin MUSIC (position & angle)	≈ 60 μm ≈ 0.1 mrad
MWPC 1	≈ 200 μm
MWPC 2	≈ 300 μm
ToF wall	≈ 40 ps

Major improvement: masses and charges of the fission fragments!

Major challenge: straggling → mass, total kinetic energy resolution.

G. Boutoux et al.

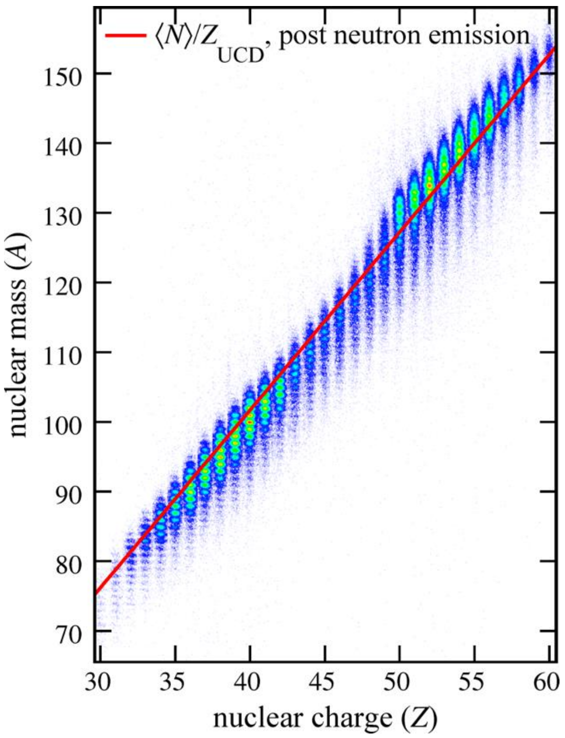
Charge and mass resolution



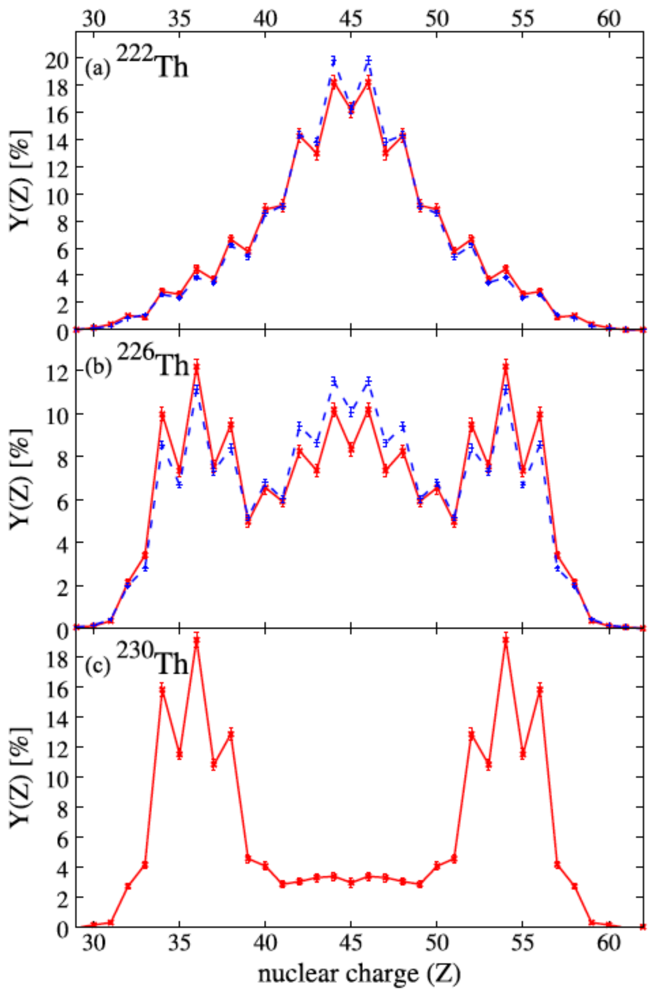
Isotopic resolution!

^{238}U

E. Pellerau et al.,
Phys. Rev. C 95,
054603 (2017)



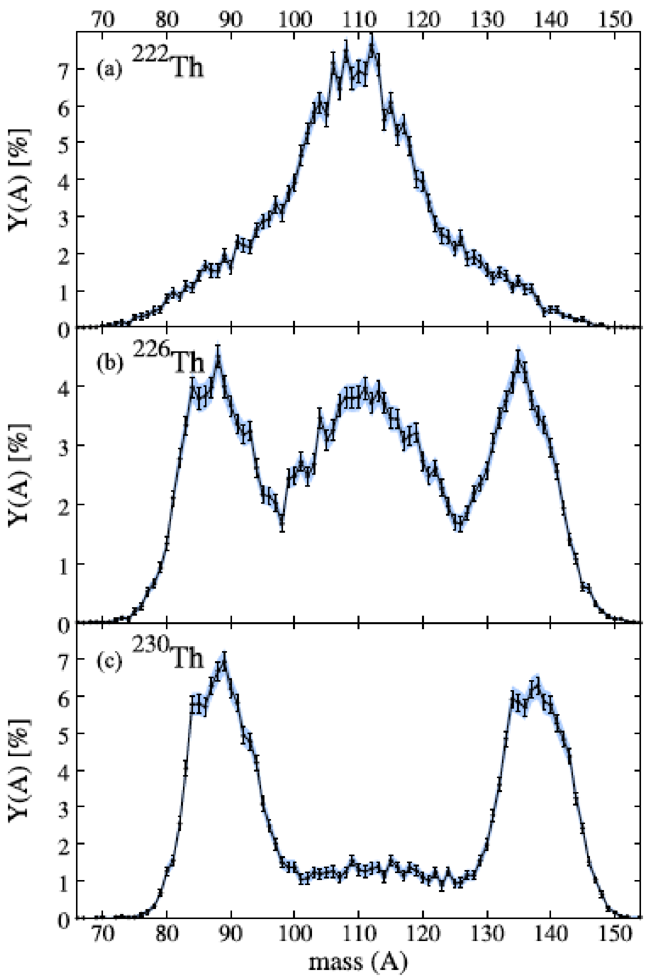
Charge yields vs. mass yields



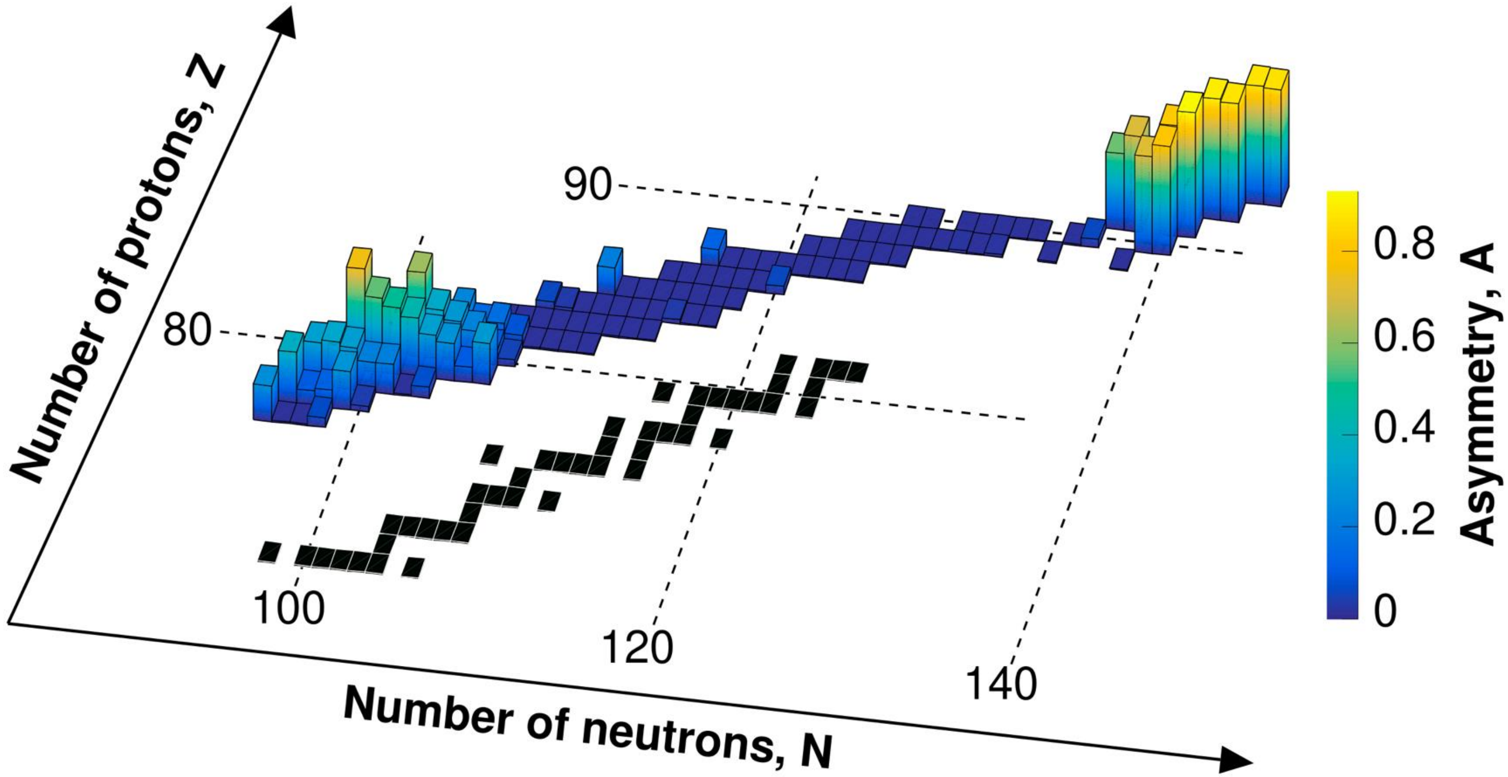
Post-evaporation yields:

Mass yields are affected by neutron evaporation.

A. Chatillon et al., Phys. Rev. C 99, 054628 (2019)

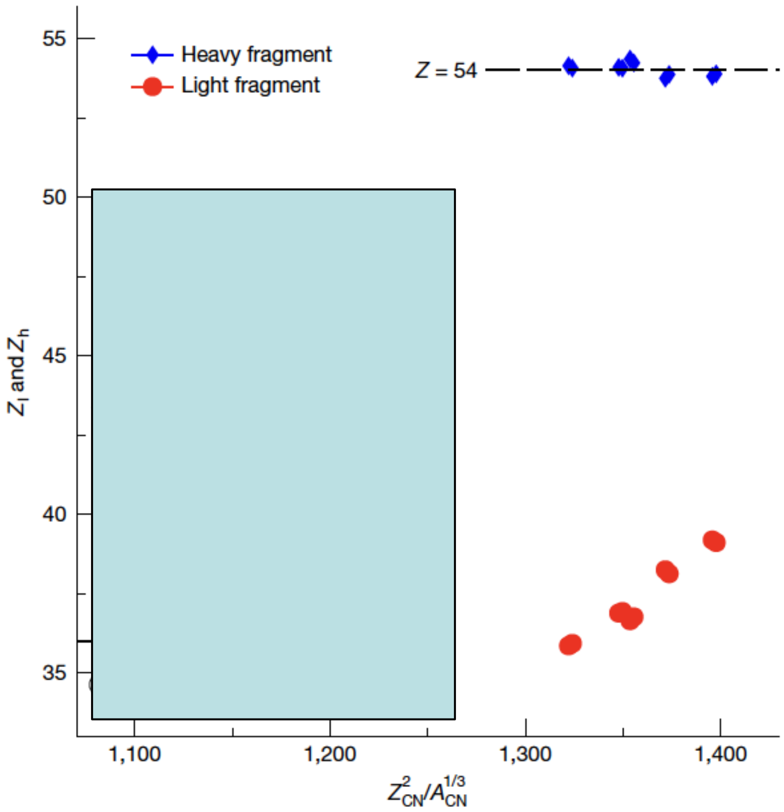


Asymmetric fission



P. Morfouace et al., Nature 641, 339 (2025)

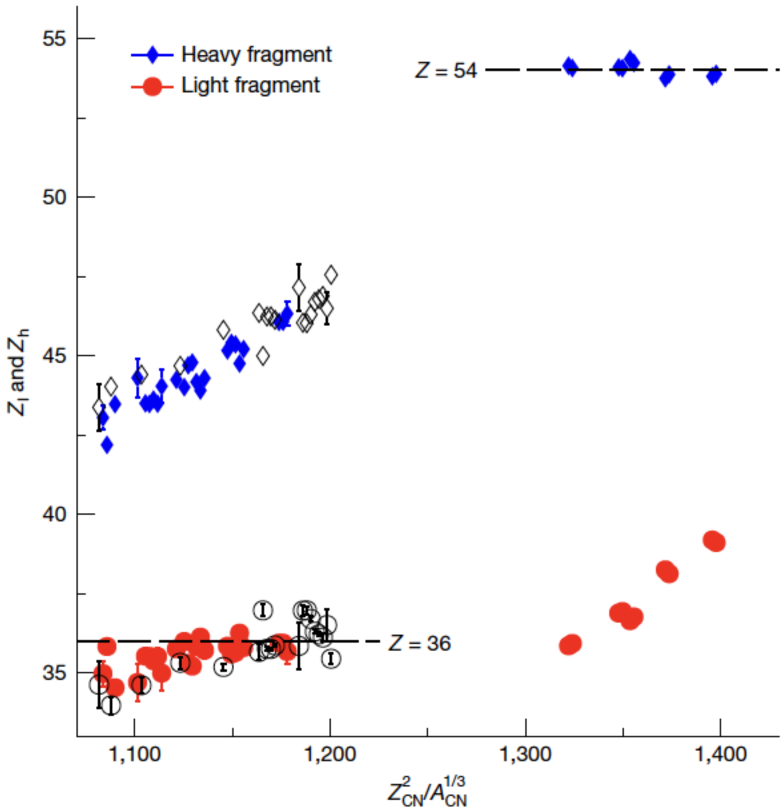
Asymmetric fission



⇒ **Looks like the Z of the heavy fragment is always constant.**

P. Morfouace et al., Nature 641, 339 (2025)

Asymmetric fission

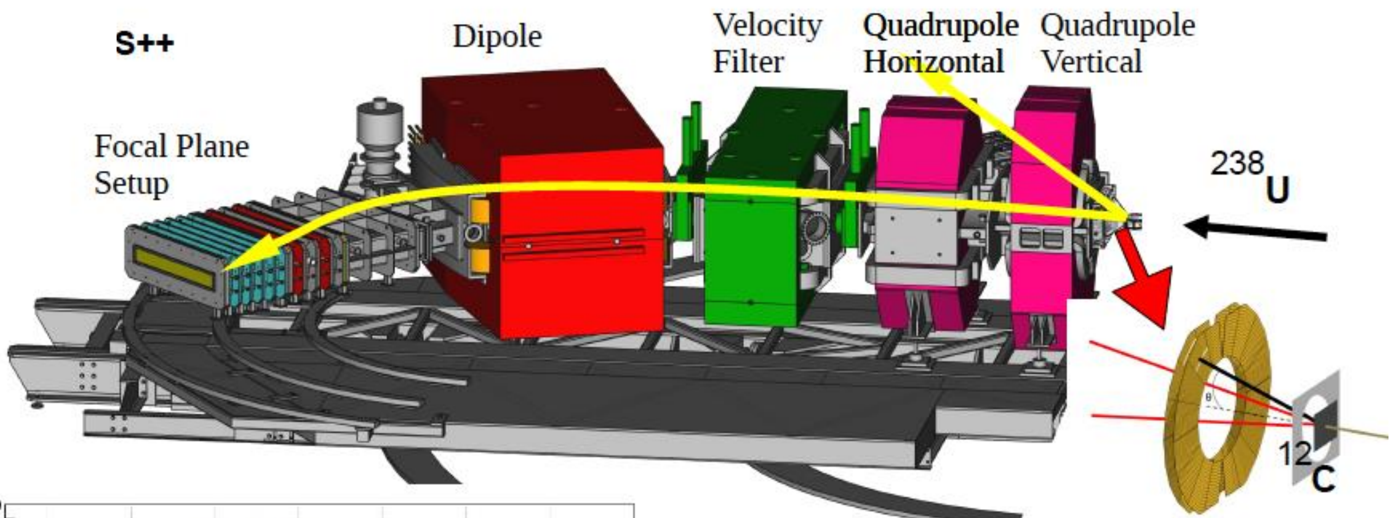


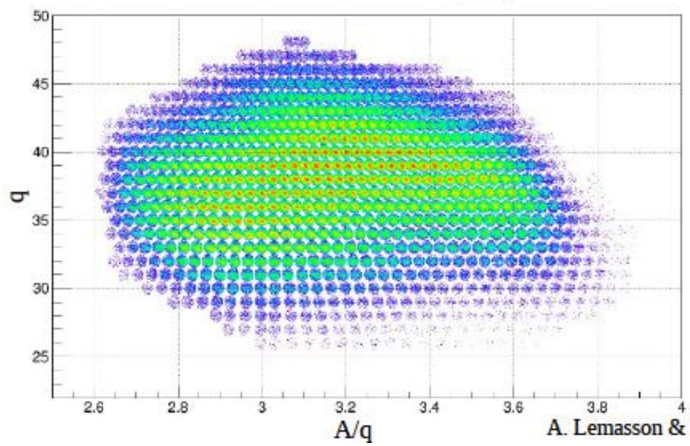
⇒ **(Deformed) Proton shells are responsible for the observed behavior.**

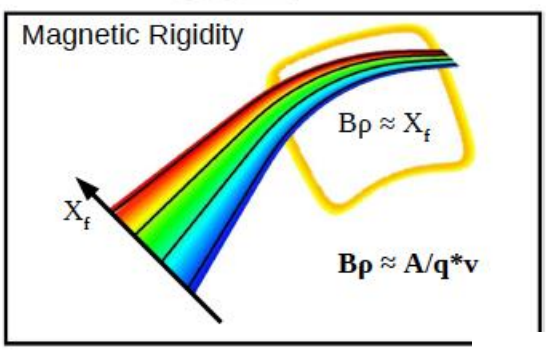
P. Morfouace et al., Nature 641, 339 (2025)

Multi-nucleon transfer-induced fission at VAMOS++

Very high resolution for one of the fission fragments



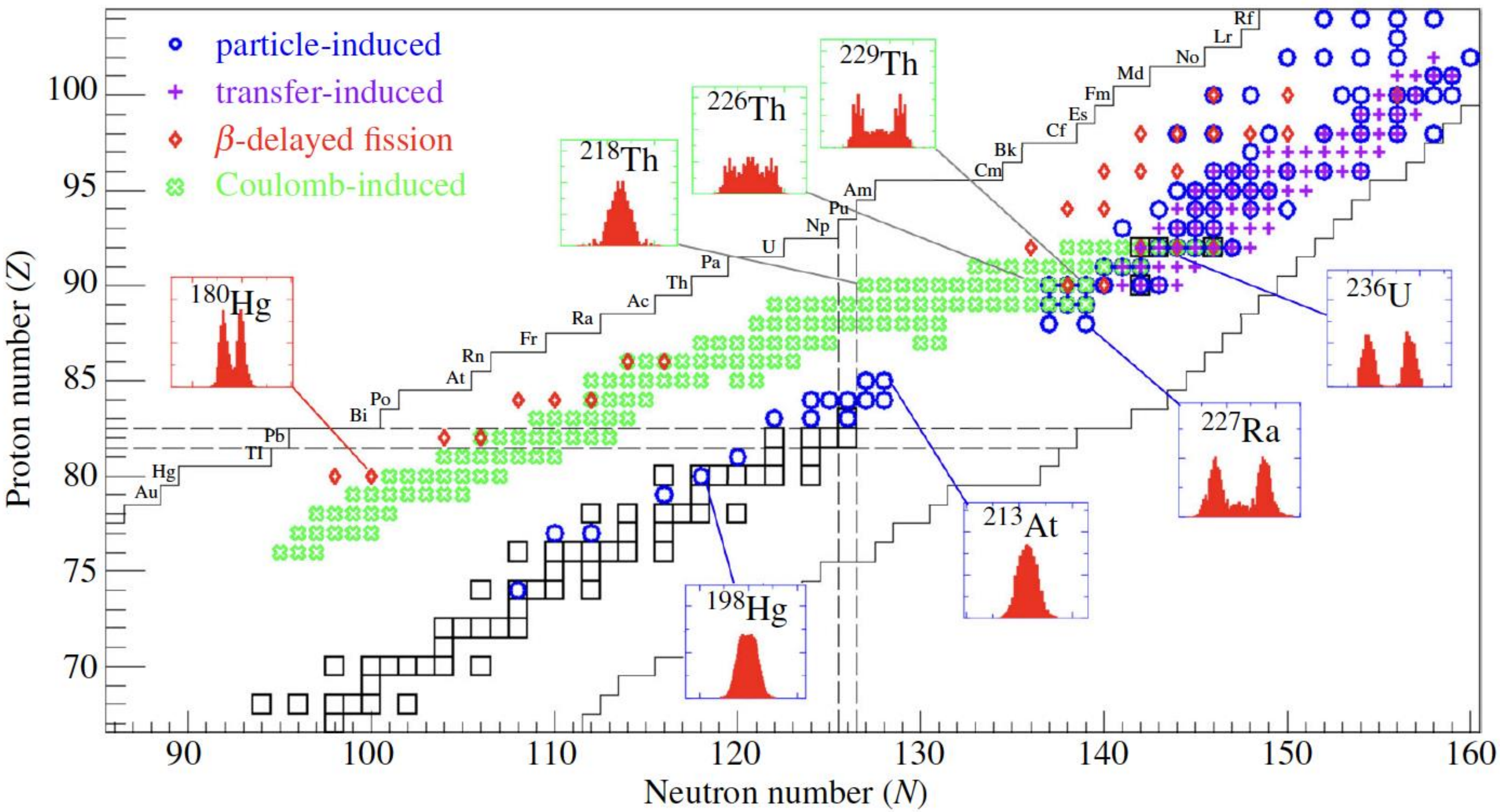




A. Lemasson & M. Rejmund, NIMA 1054, 168407 (2023)

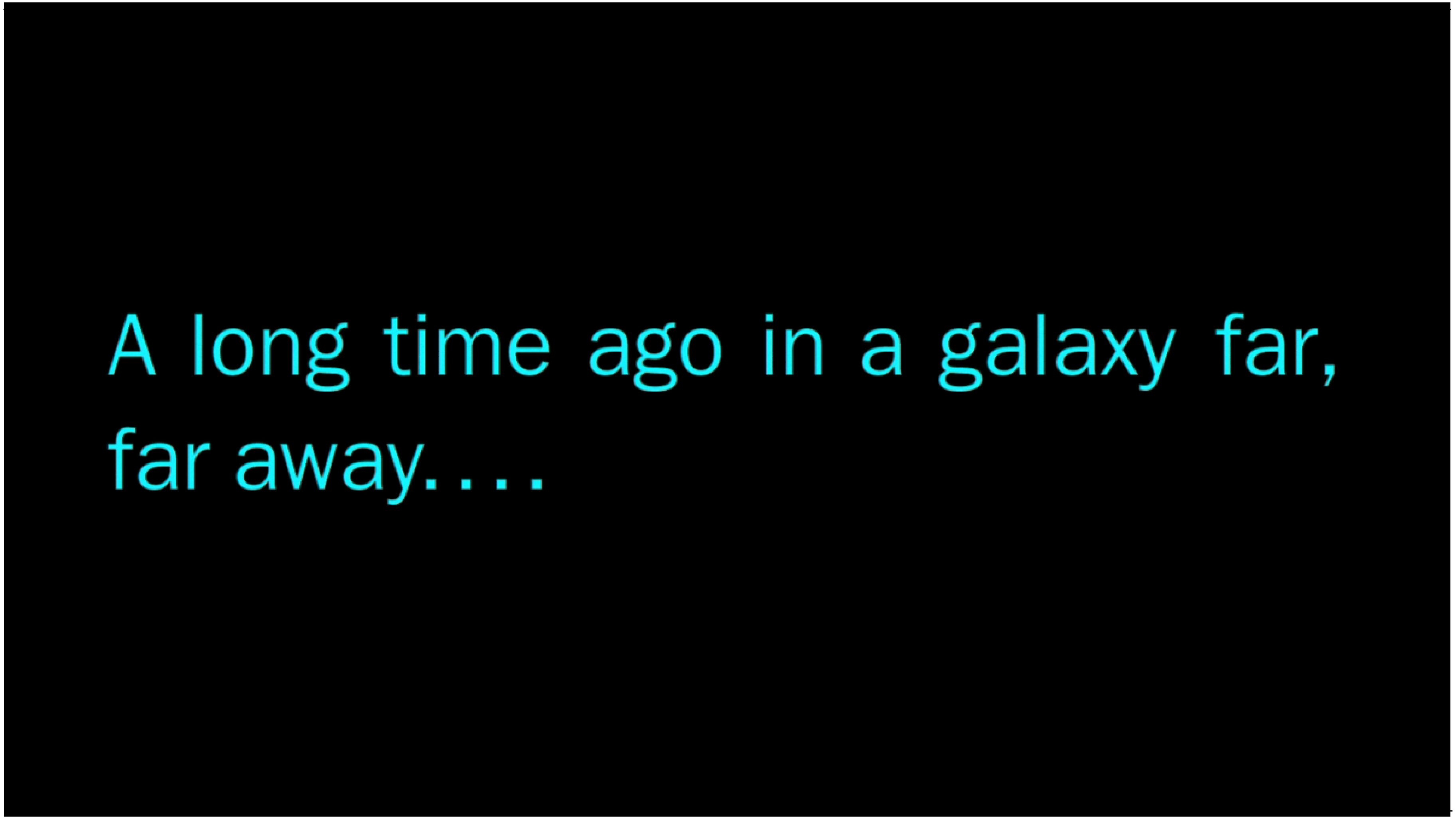
Slide from a presentation of D. Ramos

Status in 2023



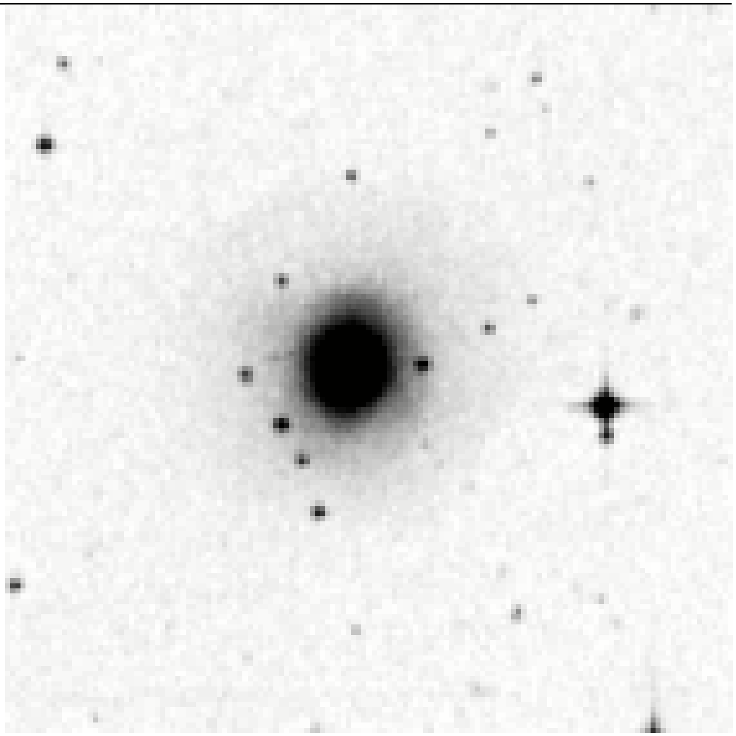
T. Aumann et al., Phil. Trans. R. Soc. A 382, 20230121 (2024)

Something interesting happened...



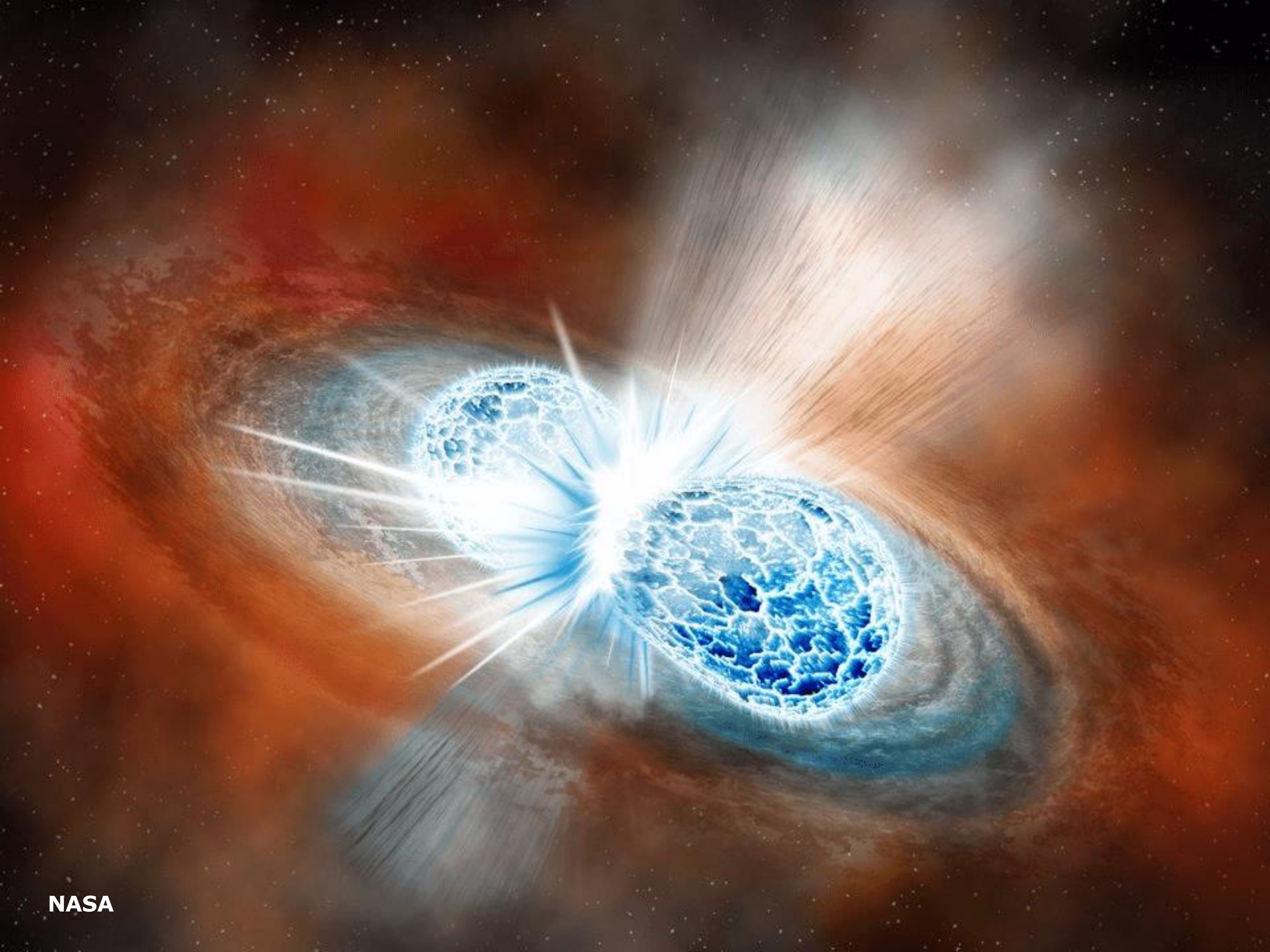
...to be more precise...

... about 142 million years ago in a Galaxy called NGC 4993 some 43.8 (+2.9/- 6.9) Mpc (≈1.4 x 10^{24} m) away.



Pretty much an average galaxy. In the NASA/IPAC Extragalactic Database one can find 453 references on it. The first was in 1888, but 396 (87%) of those were published after 2016...

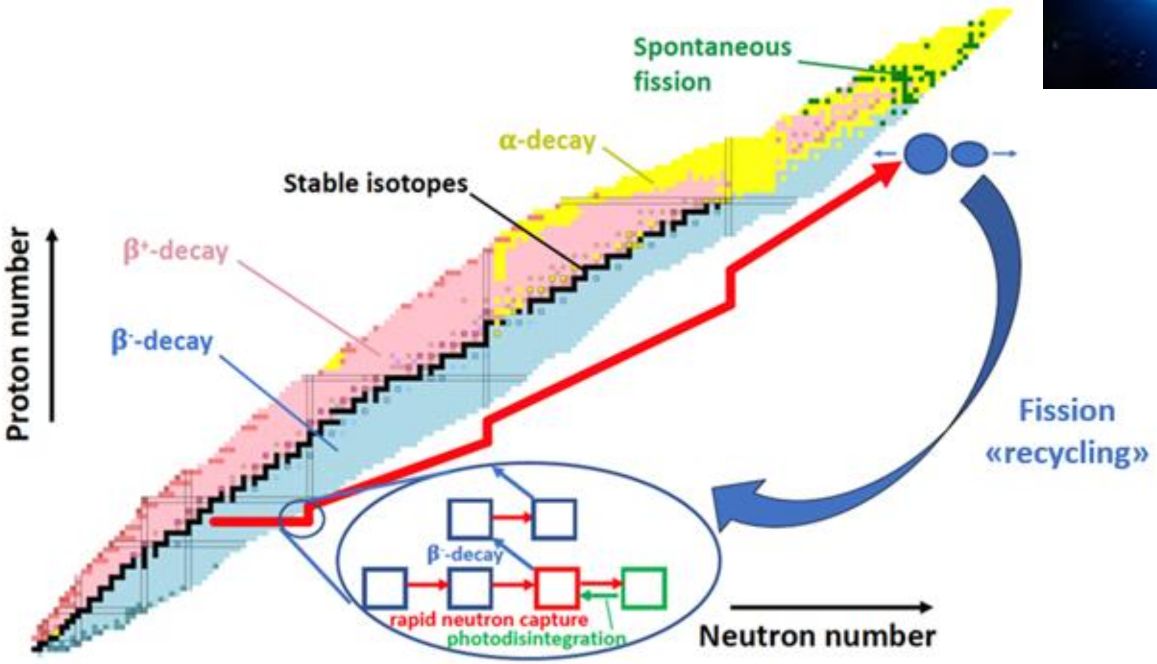
... what happened?



NASA

Fission and nucleosynthesis

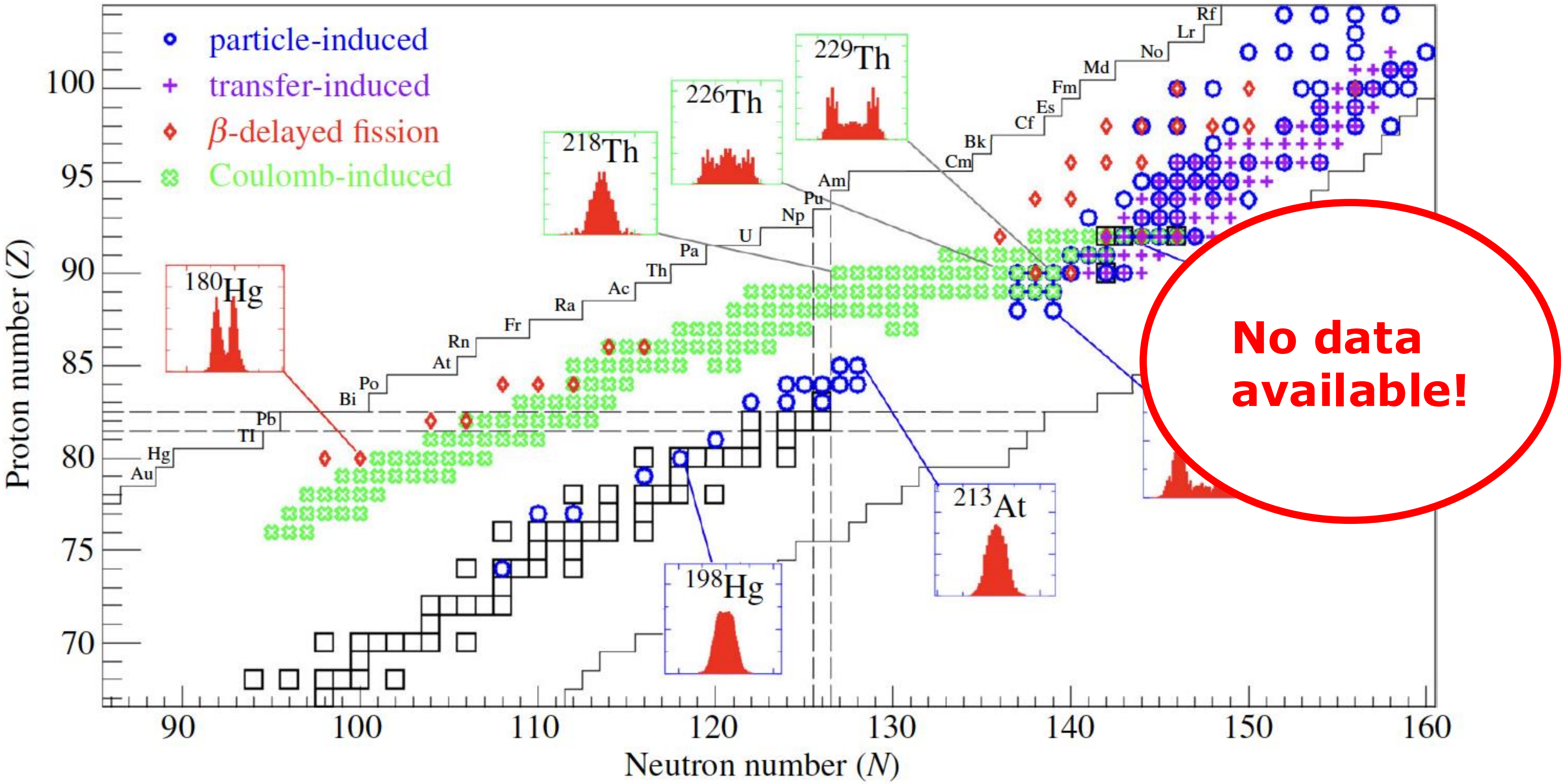
ESO/Univ. Warwick, Mark Garlick



- **Open questions:**
  - **Fission probability of n-rich nuclei?**
  - **What is the role of fission recycling in the r-process?**

Fission determines the mass limit of the nuclei which can be produced in the astrophysical r-process.

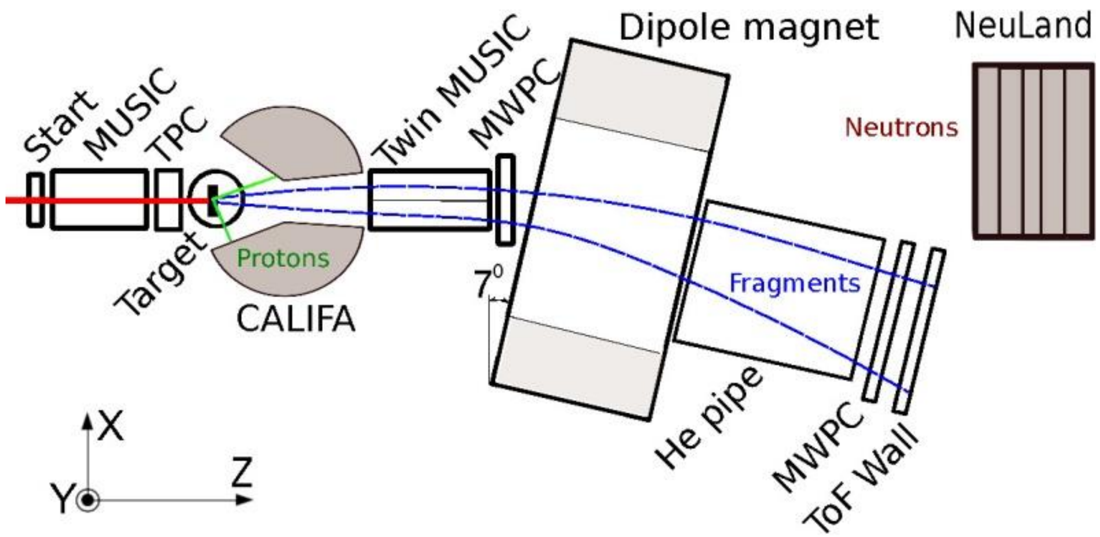
What now?



T. Aumann et al., Phyl Trans. R. Soc. A 382, 20230121 (2024)

Fission after quasi-elastic scattering

Reaction:
(p,2pF) using a liquid H_2 target; relativistic energies.



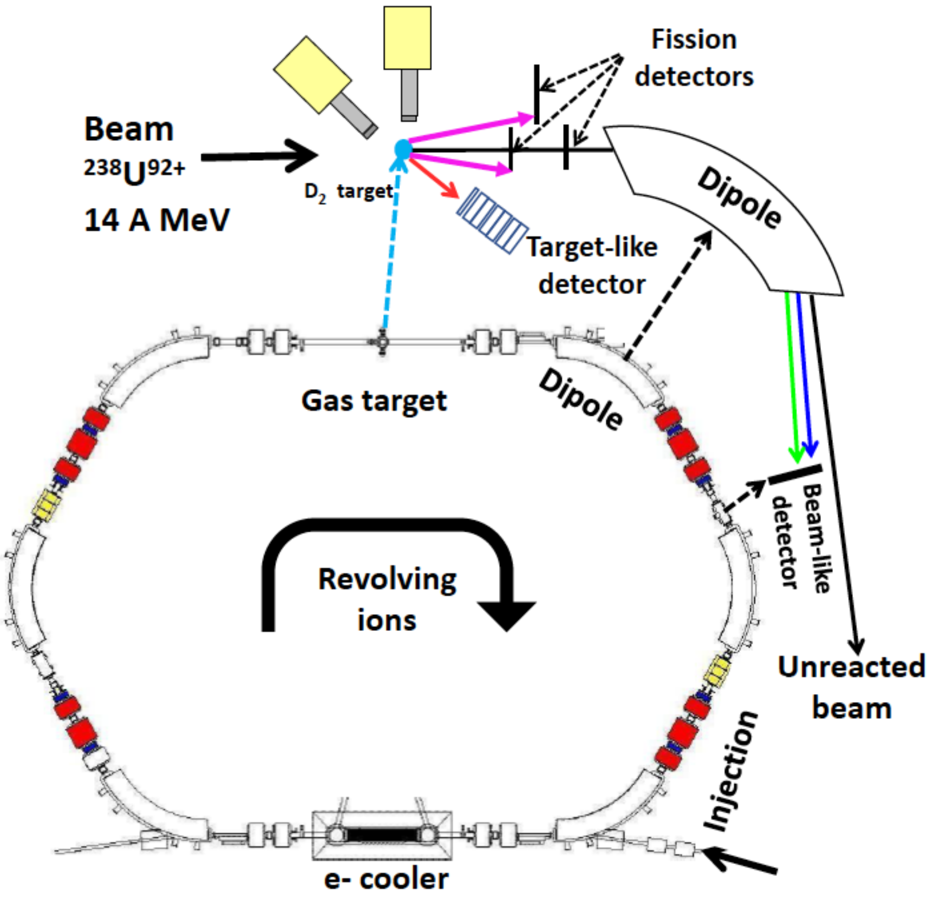
J. Taieb et al.

Advantage:
Measure fission observables (masses, charges of fission fragments, total kinetic energy release) as function of the excitation energy E*.

Challenges:

- **Background from delta-electrons.**
- **Lower cross sections.**
- **Limited E* resolution.**

Fission in storage rings

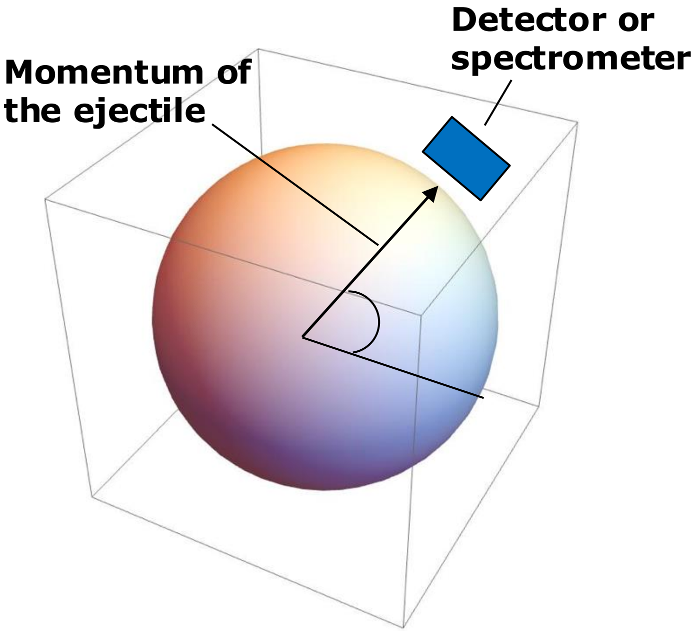


- **Proof-of-principle experiment in the ESR at GSI in Summer 2024.**
- **Tin target => very "clean" conditions.**
- **Measure excitation energy and fission fragment masses.**
- **Measure all competing decay channels simultaneously.**

B. Jurado et al.

Kinematics

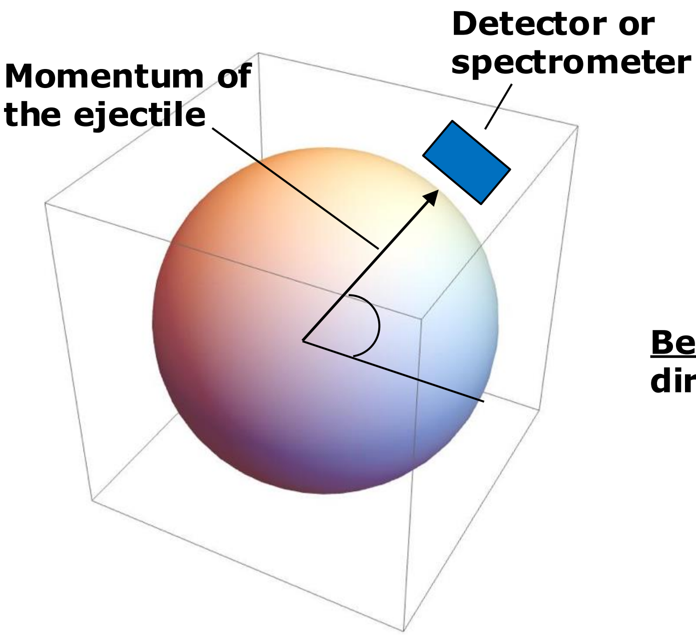
Direct kinematics:



- Possible to get very good energy and angular resolution.
- Hard to cover 4π.

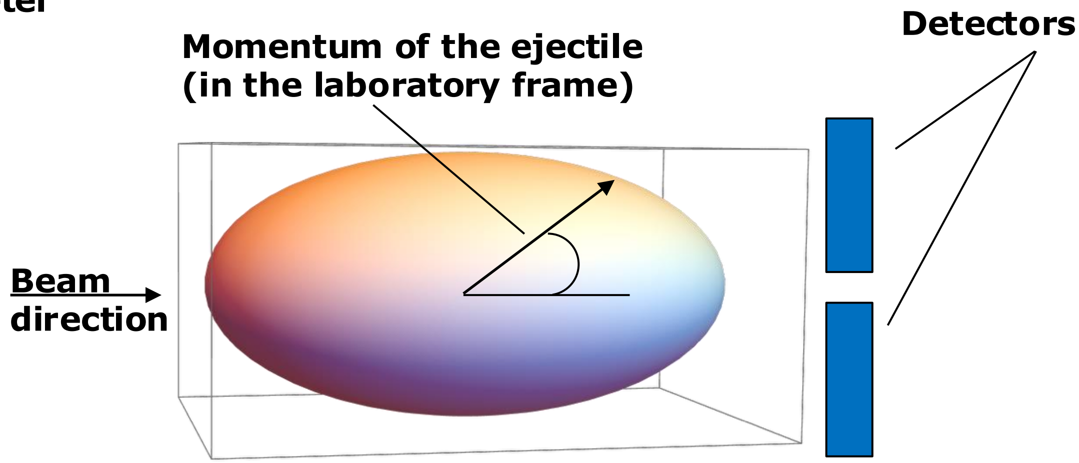
Kinematics

Direct kinematics:



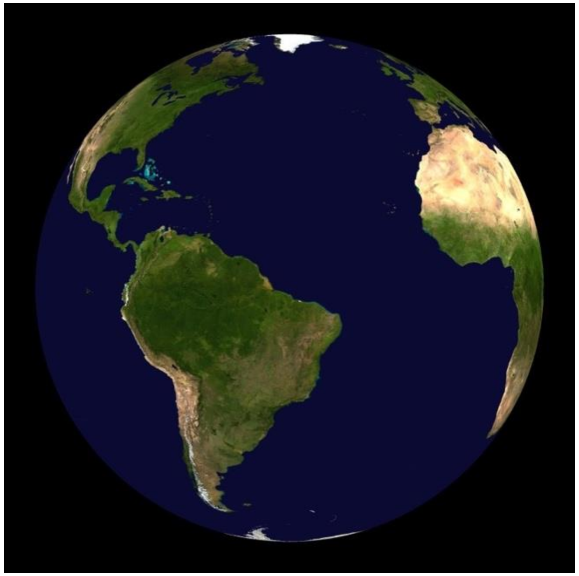
- Possible to get very good **energy and angular resolution**.
- Hard to cover **4π**.

Inverse kinematics:

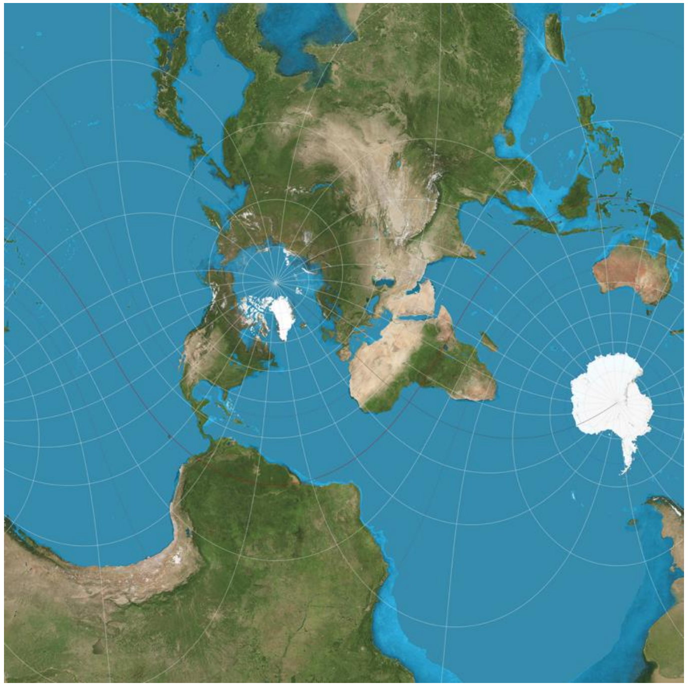


- Possible to get very good **solid angle coverage**.
- **Limited energy and angular resolution.**

A problem known from geography

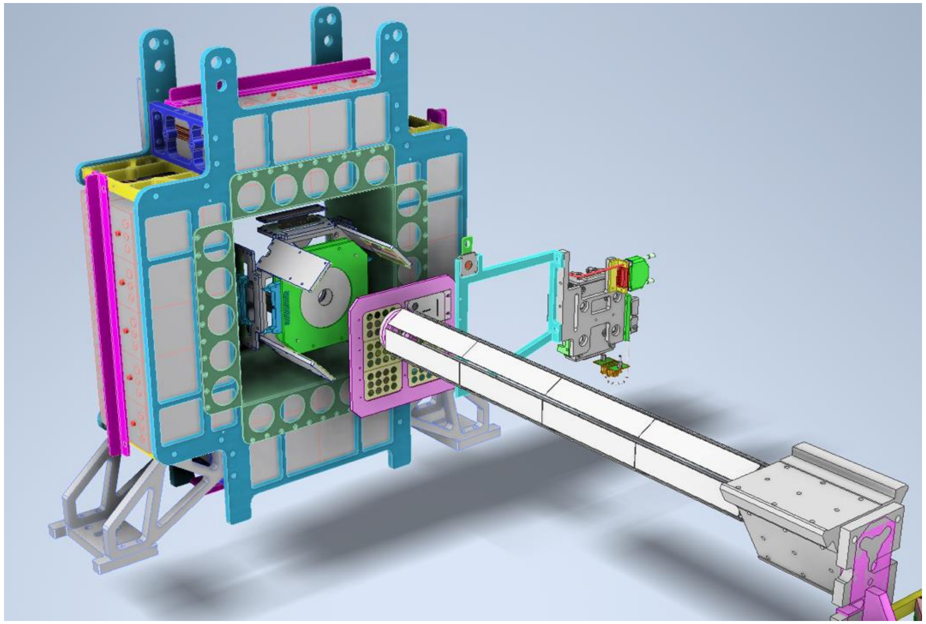


Projection



Images from Wikipedia

Fission using the ISOLDE Solenoidal Spectrometer (ISS)

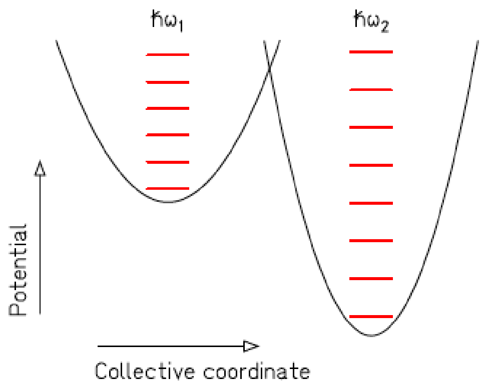


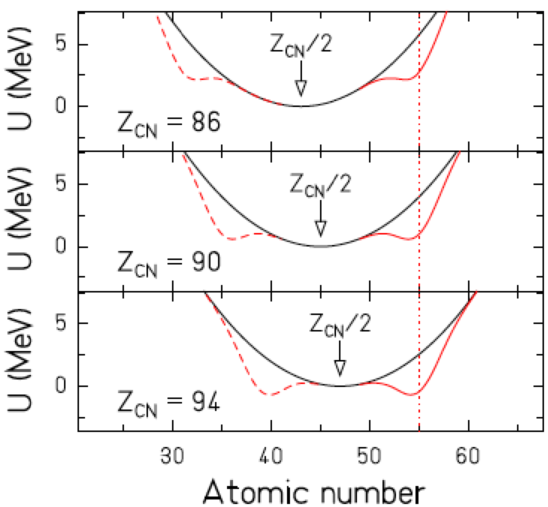
Measured quantities	Observables
Back-scattered protons	E^*, P_f
Fission fragments (FFs)	P_f
Deuterons (for normalisation)	σ_f
γ-rays from FFs	Total E_γ, (m_γ)

Exploit the (d,pF) surrogate reaction with a radioactive beam.

Target: CD_2

The GEneral Fission (GEF) Model





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

GEF is a semi-classical model.

Key assumption:

Shell effects of the fission fragments manifest already at the fission barrier.

➔ The level density gives the yield in a given fission channel.

GEF allows to calculate most fissioning nuclei, fast, and many fission observables.

It has predictive power, i.e. it is not just a fit.

Code available at:

www.khschmidts-nuclear-web.eu, www.cenbg.in2p3.fr/GEF or from the Nuclear-Data Bank of NEA.

for Windows and Linux.

Summary

Fission is driven by a macroscopic component: the competition between the surface and the Coulomb term.

The fission barrier is a simplification – the potential energy surface (PES) is a better description.

Level densities are needed to understand the available phase space.

The influence of shell and pairing on the potential energy surface.

Fission observables: probabilities, fission fragment masses and total kinetic energy release, neutron multiplicities, …

Significant experimental progress by using inverse kinematics.

More to come!

GEF is a powerful and easy to use semi-empiric model.

Books

Nuclear Fission, R. Vandenbosch, J.R. Huizenga

The Nuclear Fission Process, C. Wagemans (Ed.)

Chapters on nuclear fission in *Handbook of Nuclear Physics*, I. Tanihata, H. Toki, E. Kajino (Eds.)

An Introduction to Nuclear Fission, W. Younes, W.D. Loveland

Nuclear Fission, P. Talou, R. Vogt (Eds.)