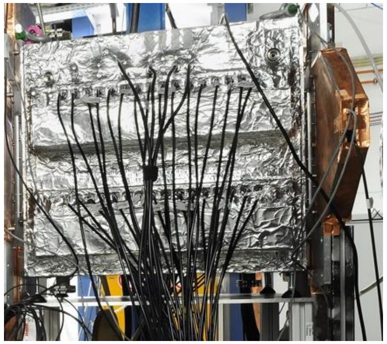
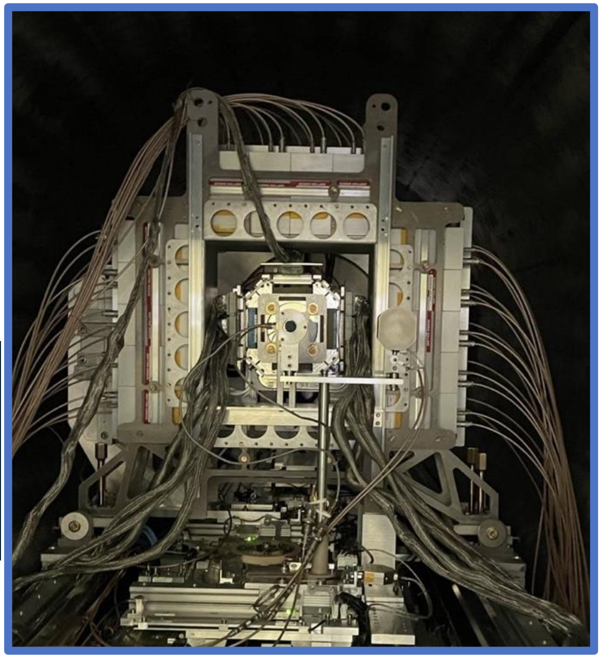
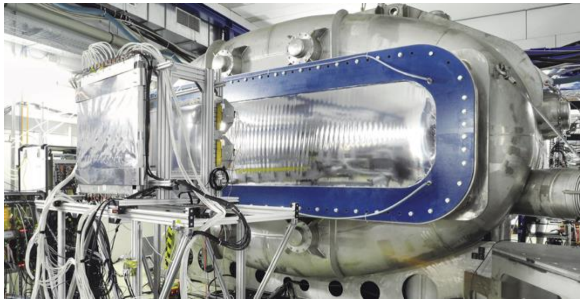
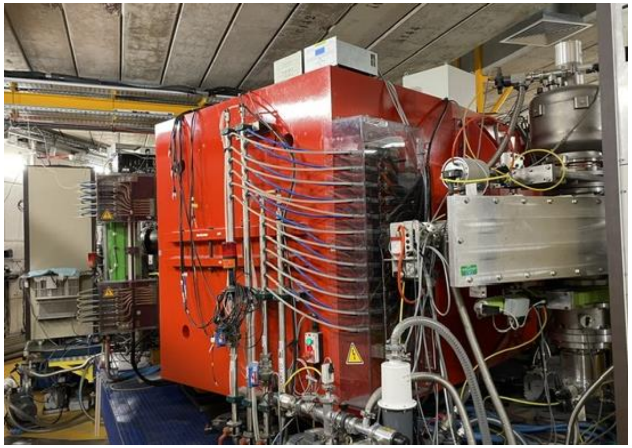
Fission in inverse kinematics – history, status and outlook

A. Heinz
Chalmers University of Technology

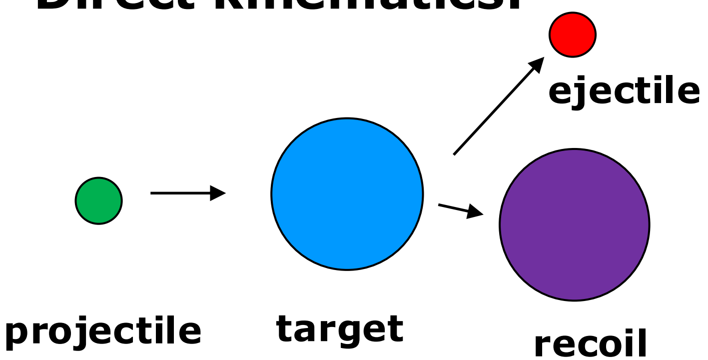





Knut och Alice Wallenbergs Stiftelse

Vetenskapsrådet

Direct vs. inverse kinematics

Direct kinematics:

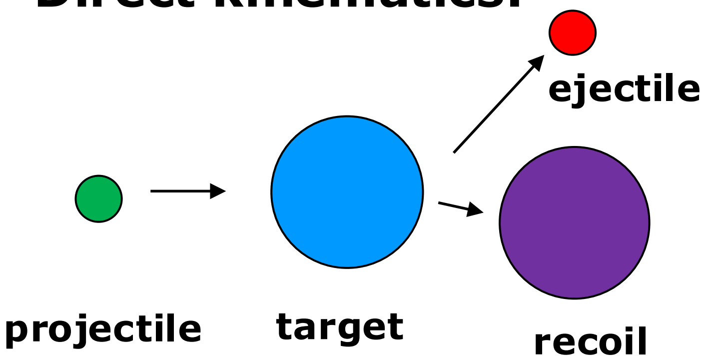


Advantages:
- High beam intensities.
- High angular and energy resolution of the ejectile.

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

Direct vs. inverse kinematics

Direct kinematics:



Advantages:
- High beam intensities.
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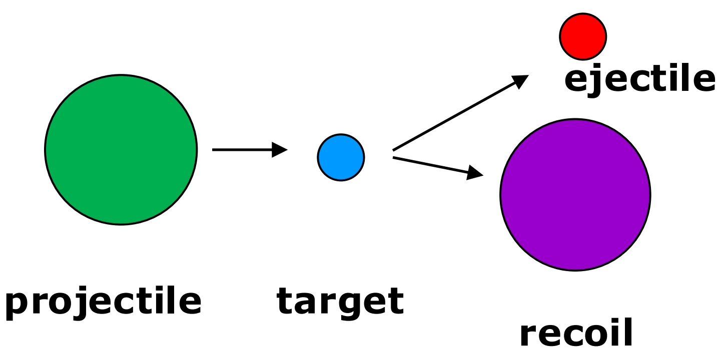
Inverse kinematics:

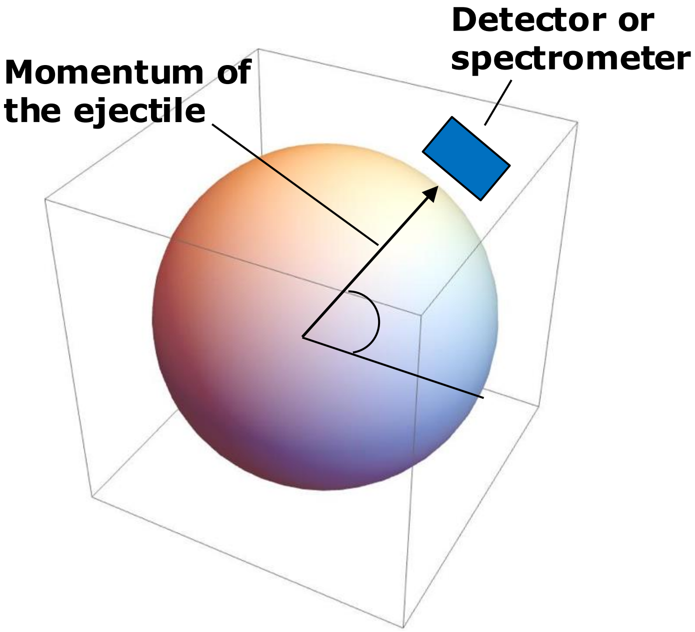


Advantages:
- Works with short lived beams.
- Recoils identification.
- Possible to do complete kinematics.

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

Kinematics

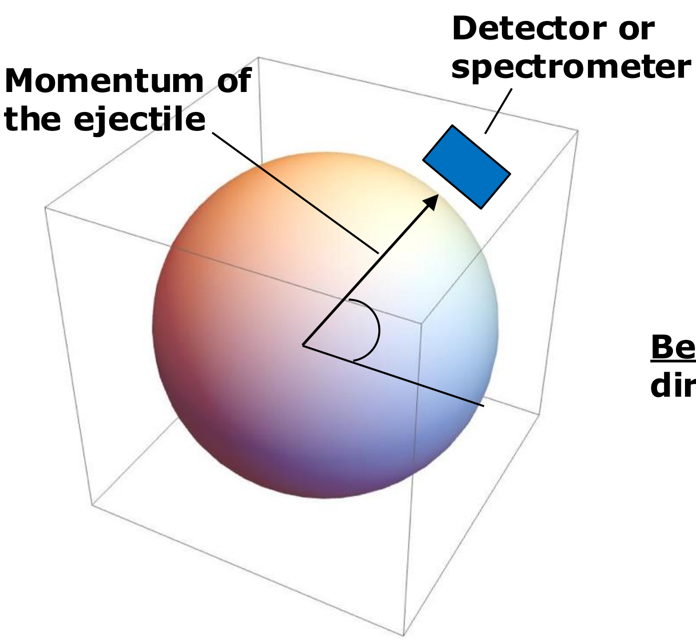
Direct kinematics:



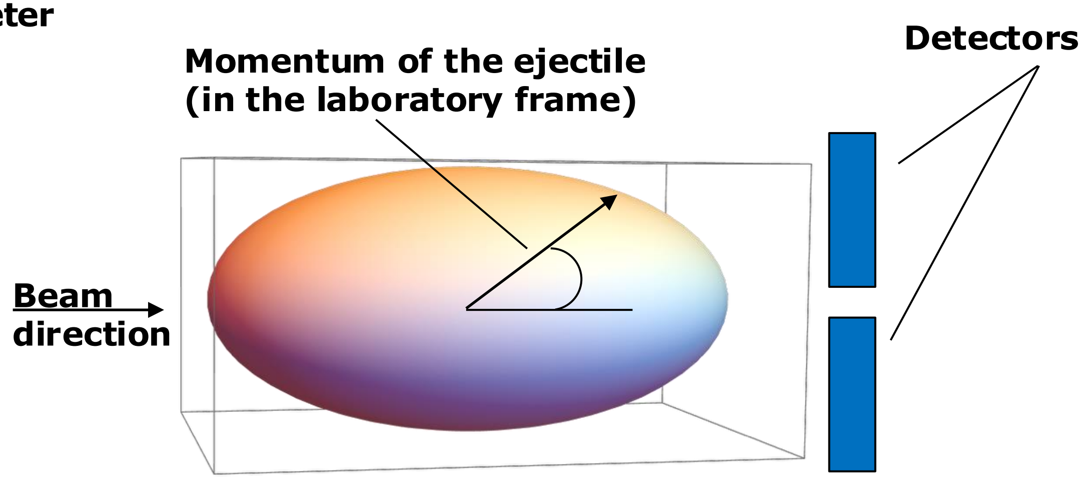
- Possible to get very good energy and angular resolution.
- Hard to cover 4π.

Kinematics

Direct kinematics:



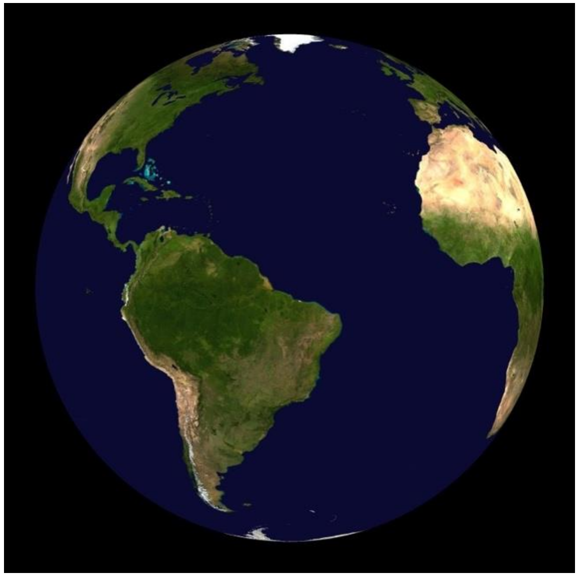
Inverse kinematics:



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

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

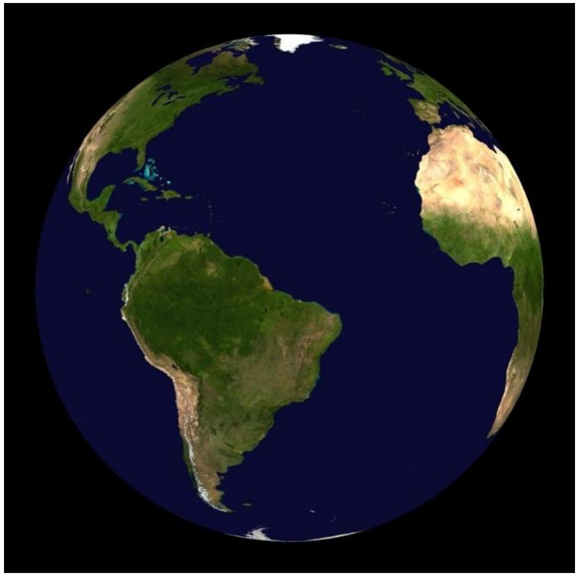
A problem known from geography



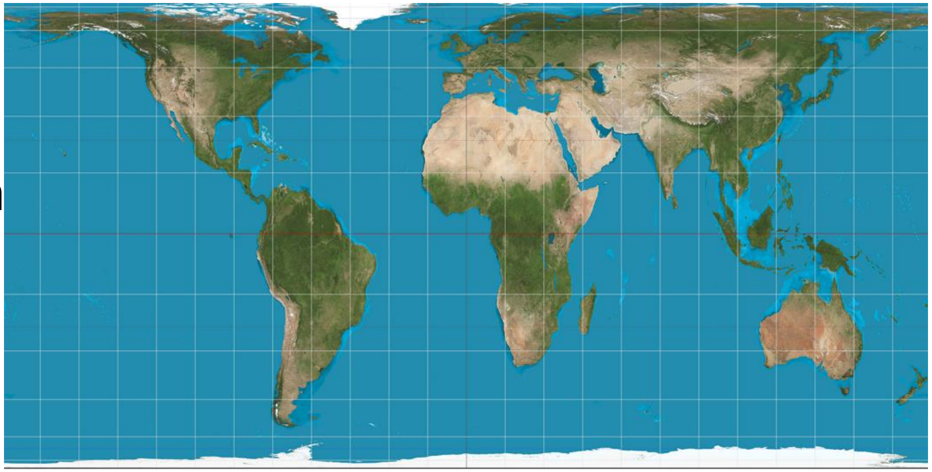
Projection →

Images from Wikipedia

A problem known from geography

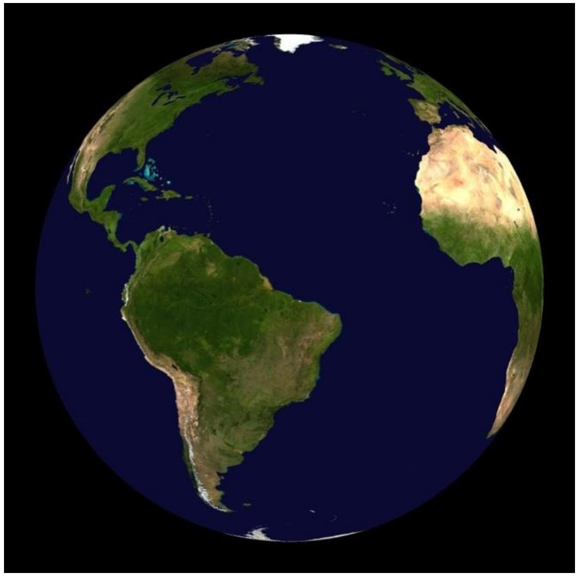


Projection

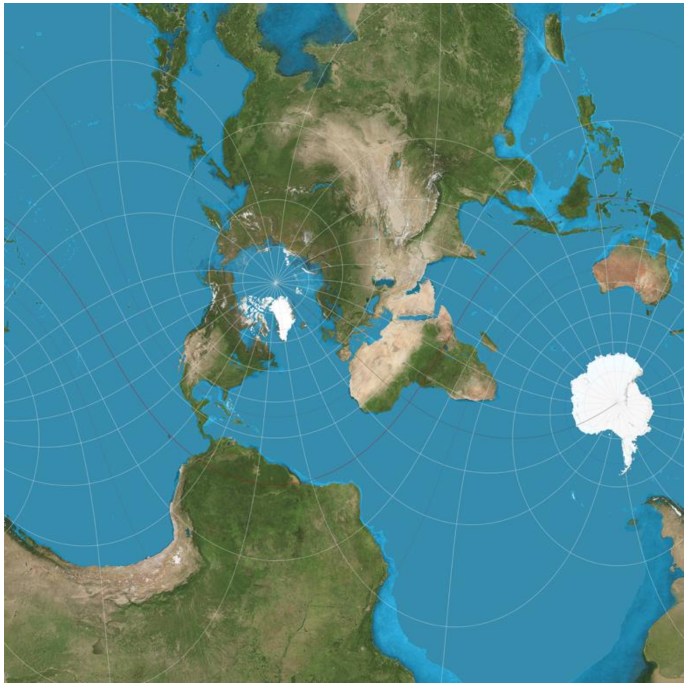


Images from Wikipedia

A problem known from geography

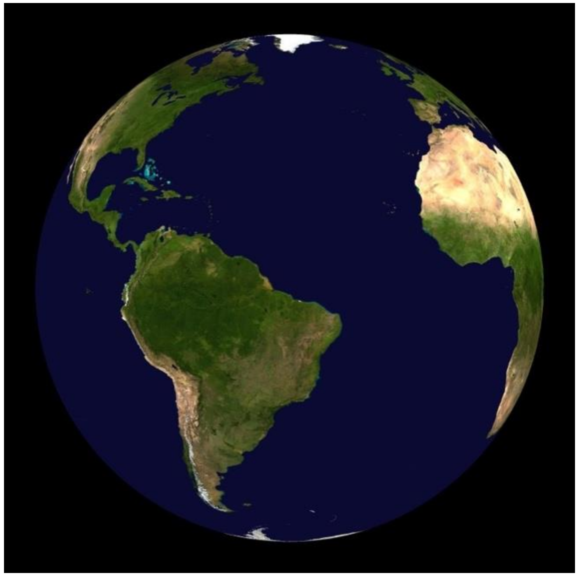


Projection →

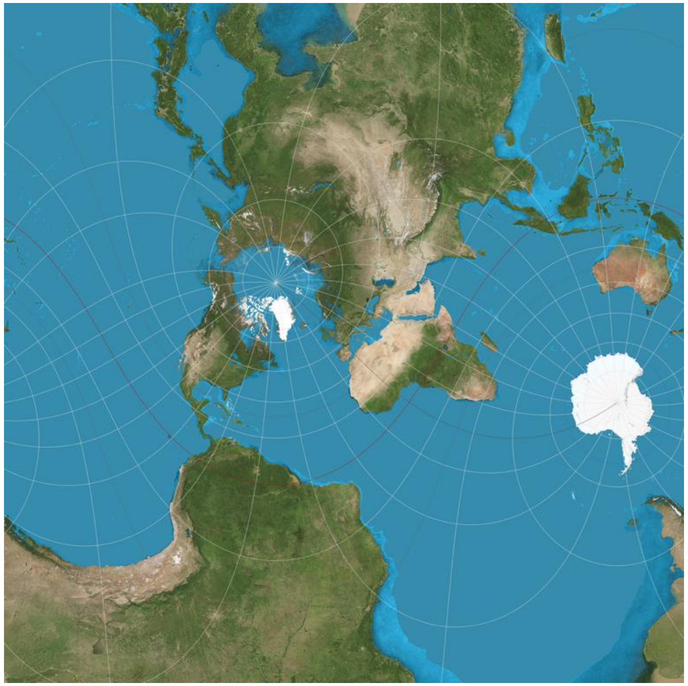


Images from Wikipedia

A problem known from geography



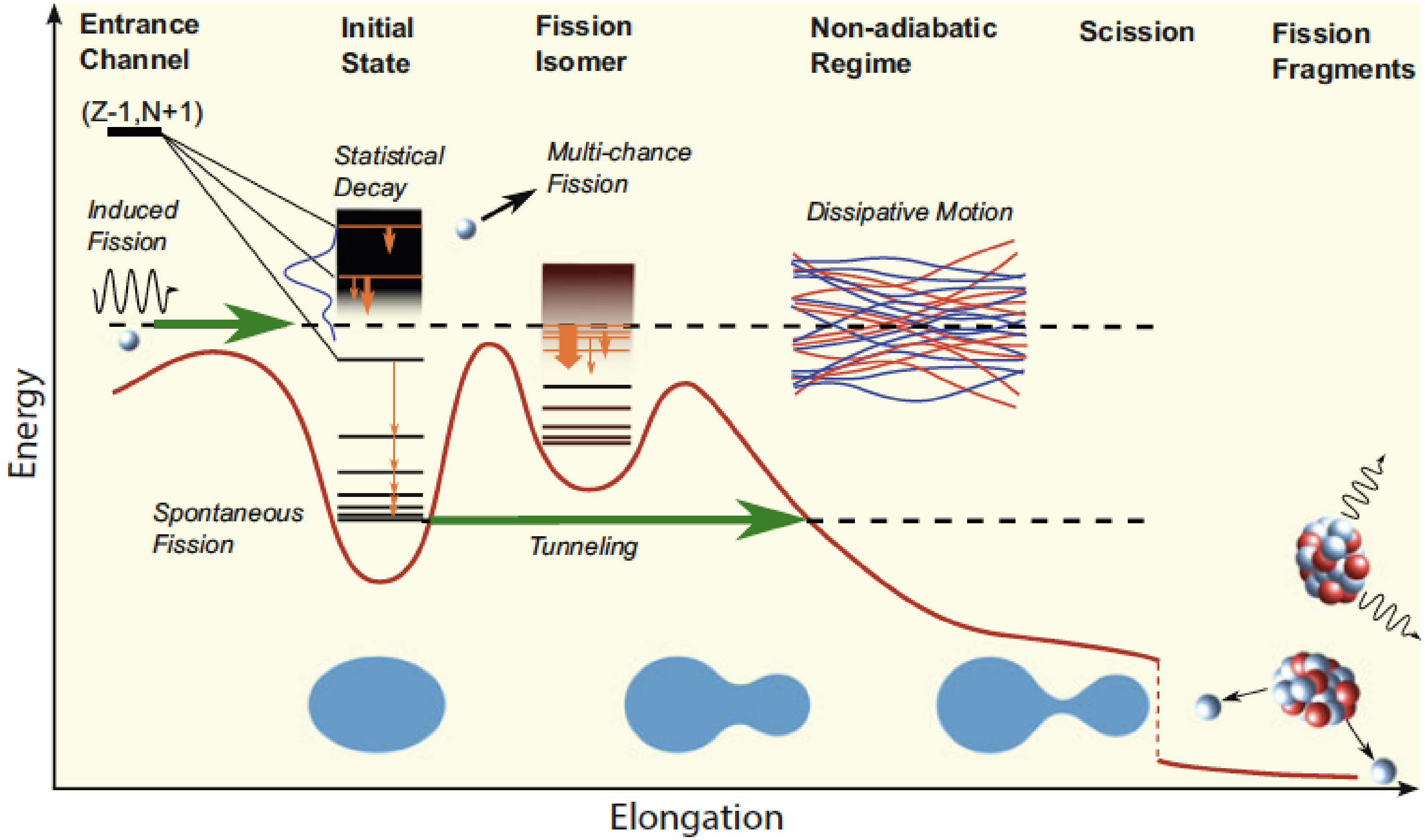
Projection →



The "solution" for inverse kinematics: don't project on 2D
→ listen to the talk of Maria Vittoria.

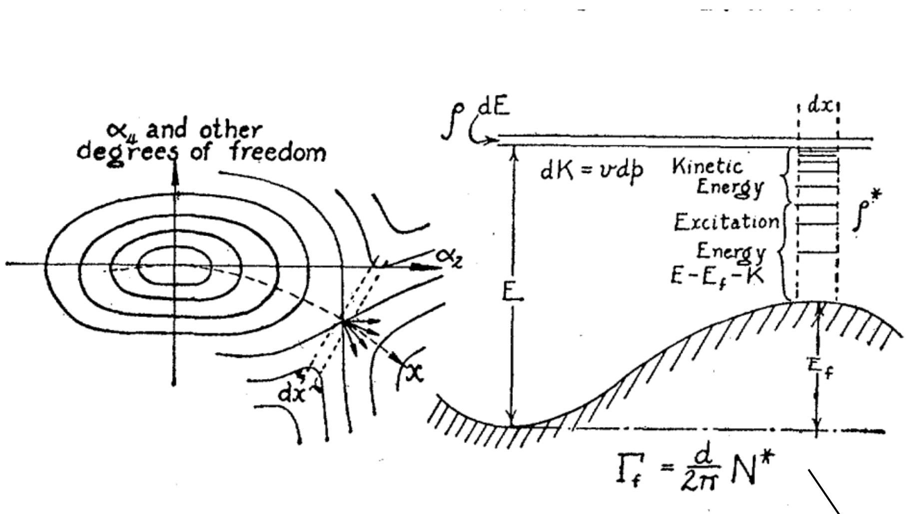
Images from Wikipedia

Nuclear fission



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

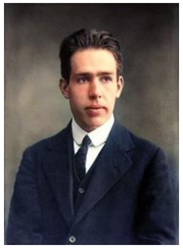
Potential Energy Surface




Disintegration of Uranium by Neutrons: a New Type of Nuclear Reaction

On bombarding uranium with neutrons, Fermi and collaborators[1] found that at least four radioactive substances were produced, to two of which atomic numbers larger than 92 were ascribed. Further investigations[2] demonstrated the existence of at least

Meitner, O. Frisch, Nature 143, 239 (1939)




SEPTEMBER 1, 1939 PHYSICAL REVIEW VOLUME 56

The Mechanism of Nuclear Fission

NIELS BOHR
University of Copenhagen, Copenhagen, Denmark, and The Institute for Advanced Study, Princeton, New Jersey

AND

JOHN ARCHIBALD WHEELER
Princeton University, Princeton, New Jersey

(Received June 28, 1939)

The potential energy surface and the relation to the level density, i.e. available phase space, above it.

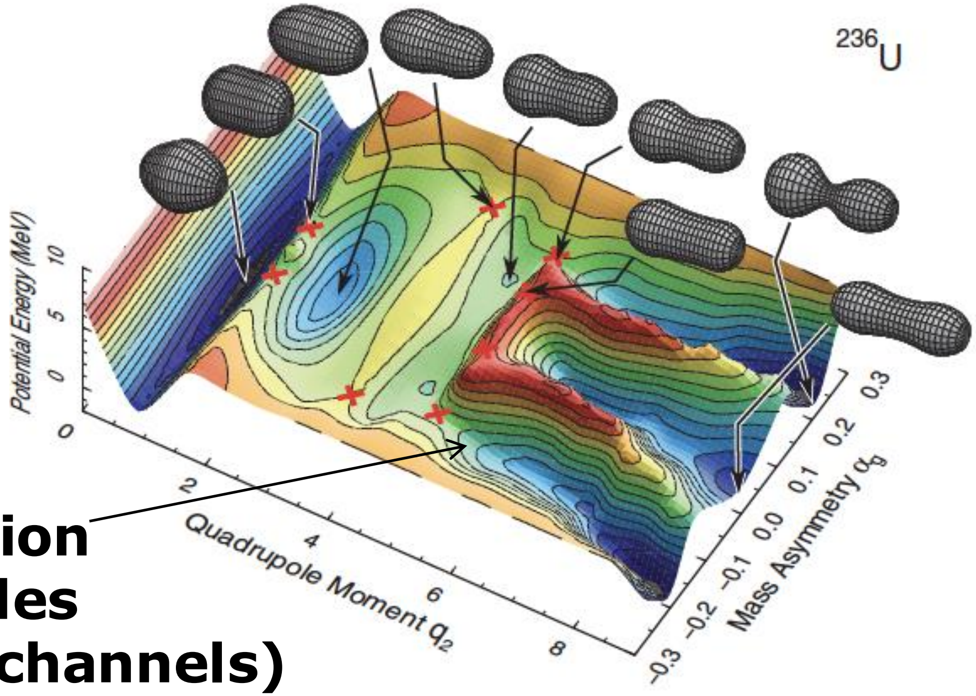
Fission modes

Valleys and passes in the potential energy surface.

⇒ **Fission modes characterized by:**
  ⇒ **asymmetry and**
  ⇒ **deformation at scission.**

⇒ **Experimental signatures:**
  ⇒ **Fission fragment mass and charge distributions.**
  ⇒ **Total kinetic energy release.**

⇒ **Mapping of the potential energy surface with data.**

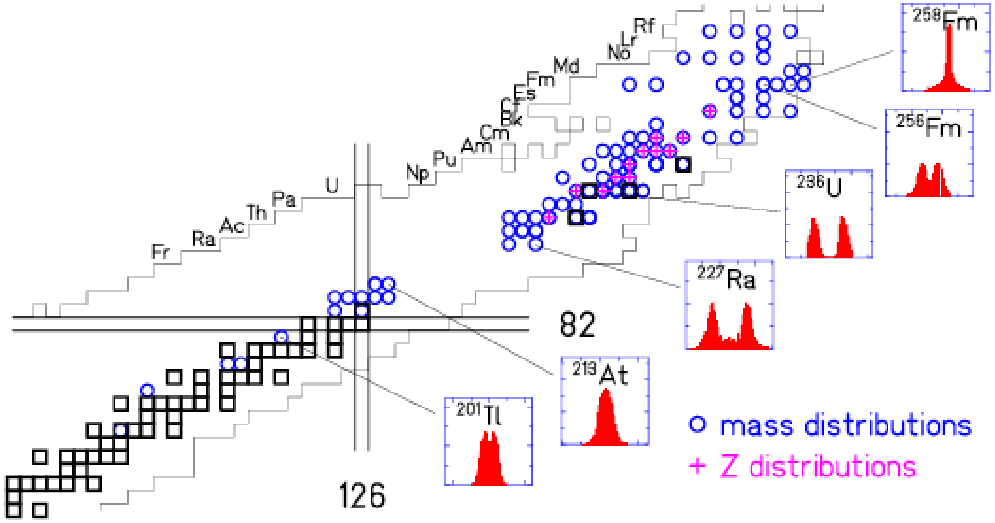


Fission modes (or channels)

T. Ichikawa et al., Phys. Rev. C 86, 024610 (2012)

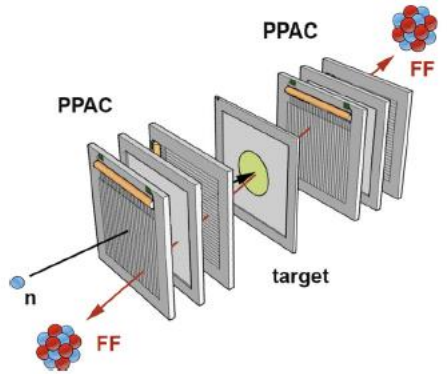
The available phase space is the key to understand the fission fragment yields.

Experimental status around 1995



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

Schematic layout of an experiment (n_TOF):

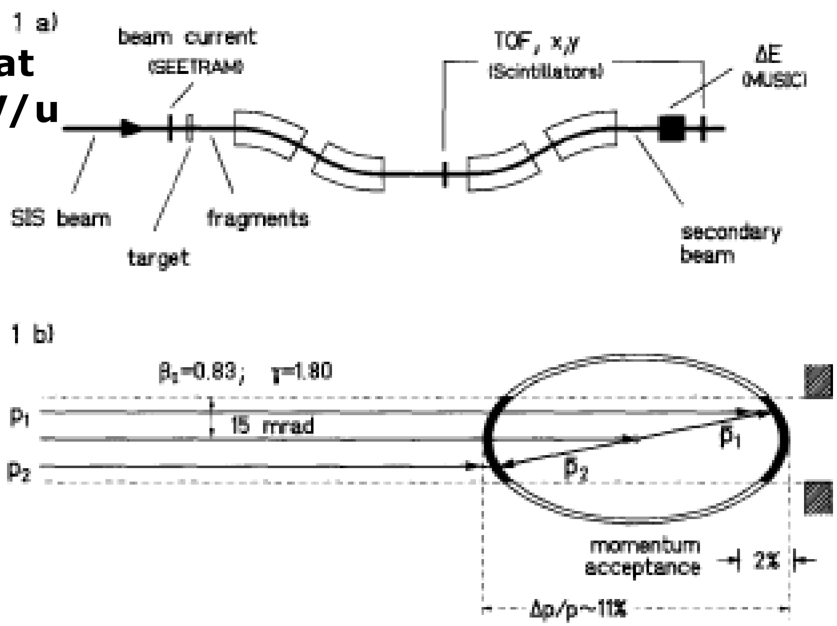


N. Colonna et al.,
Eur. Phys. J. A. 56, 48 (2020)

- **Limited number of isotopes studied mostly in direct kinematics.**
- **Three main approaches to induce fission: neutrons, light charged particles, spontaneous fission.**
- **Challenging to identify fission fragments in A and Z.**

Fission in inverse kinematics: isotopic resolution of fission fragments

^{238}U at 1GeV/u



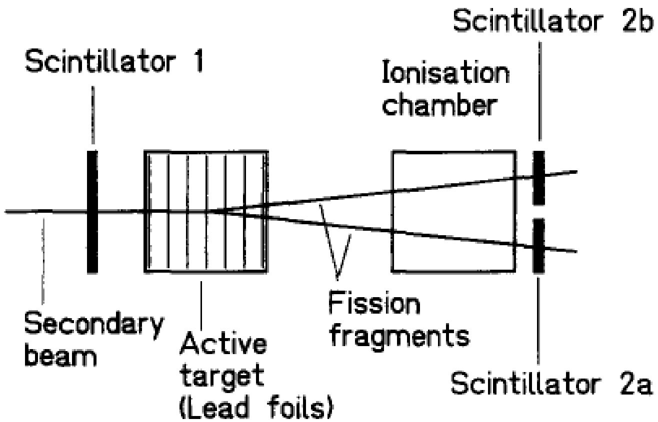
$$\left.\begin{array}{l} \text{Nuclear Charge Z} \Rightarrow \text{ ionization chamber} \\ \text{Bending } \rho \Rightarrow \text{ positions} \\ \text{Velocity } \gamma\beta \Rightarrow \text{ ToF} \\ \text{Magnetic field B} \Rightarrow \text{ Hall probes} \end{array}\right\} \Rightarrow \frac{B\rho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

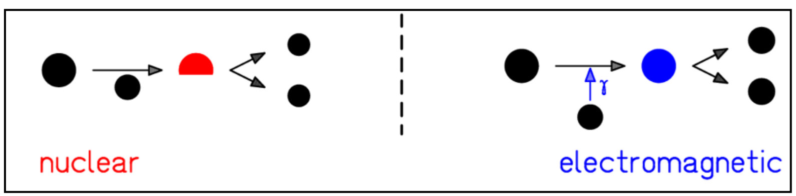
- **The beam fissions, not the target.**
- **Event-by-event identification of one fission fragment!**
- **Only for stable beams!**
- **Widely used to produce neutron-rich beams.**

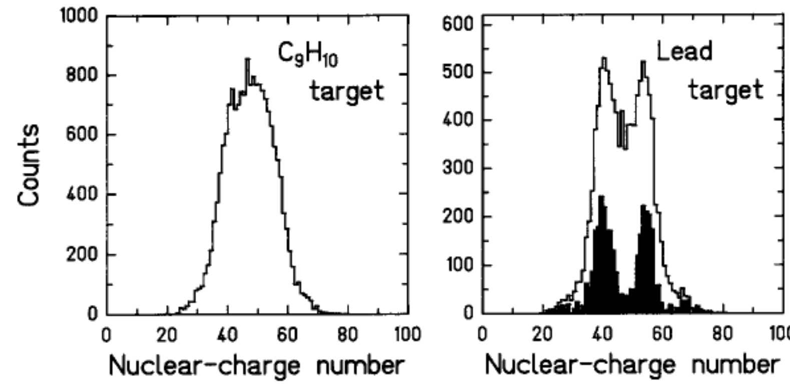
M.Bernas et al., Phys. Lett. B 331, 19 (1994)

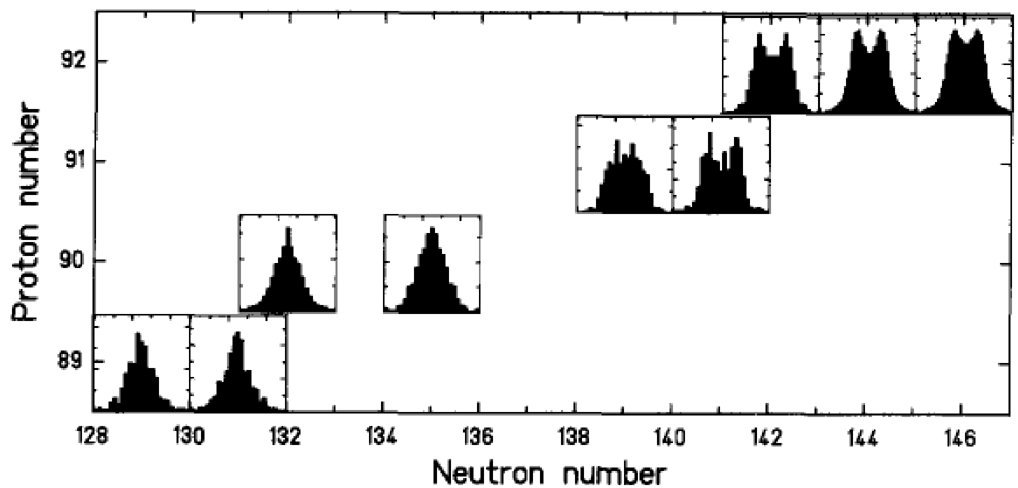
Talk of S. Pietri

Fission of radioactive beams in inverse kinematics (first attempt)





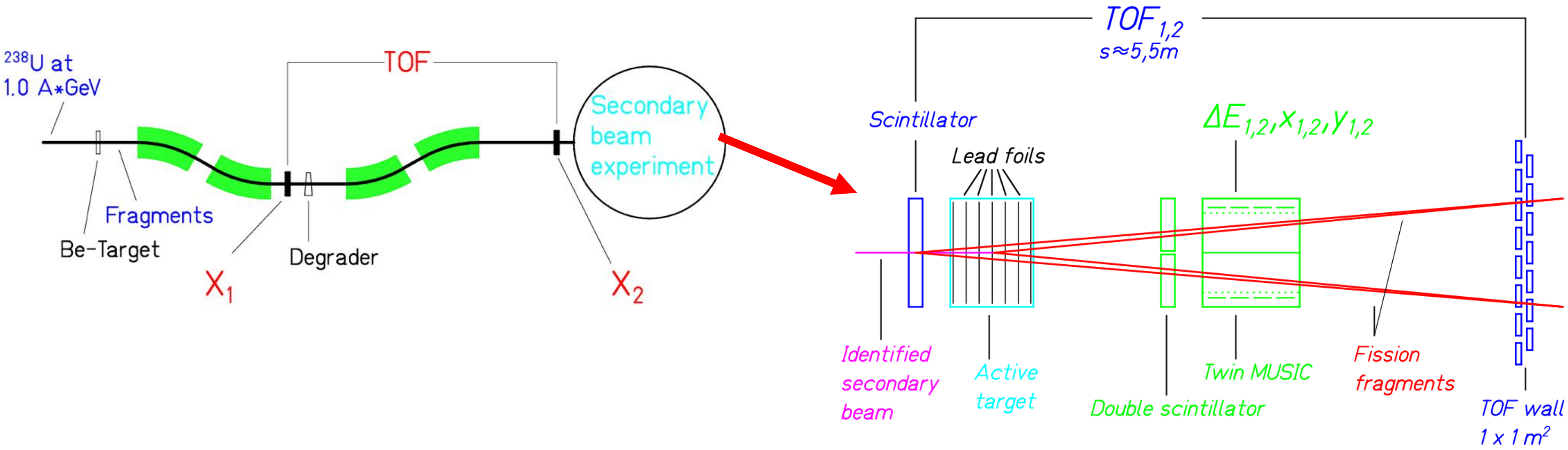




K.-H. Schmidt, A. Heinz, et al., Phys. Lett. B 325, 330 (1994)

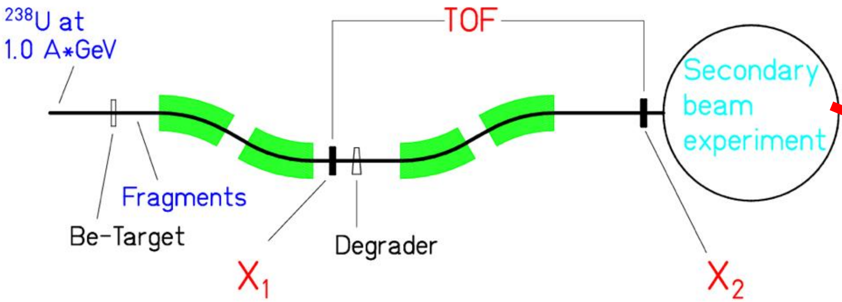
Use radioactive (secondary) beams in inverse kinematics at relativistic energies (about 500 MeV/u)

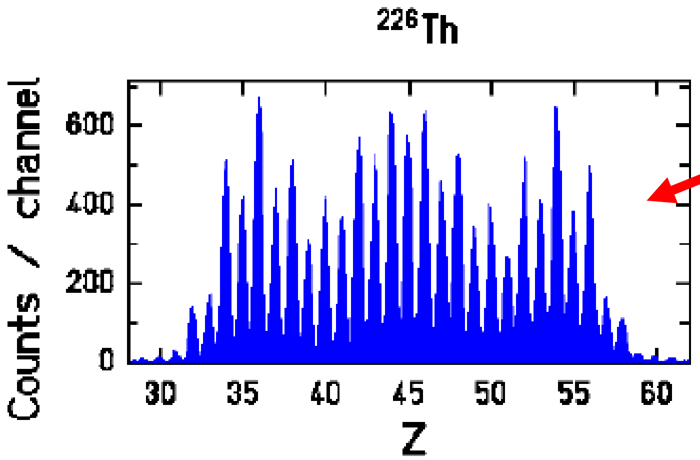
The third attempt

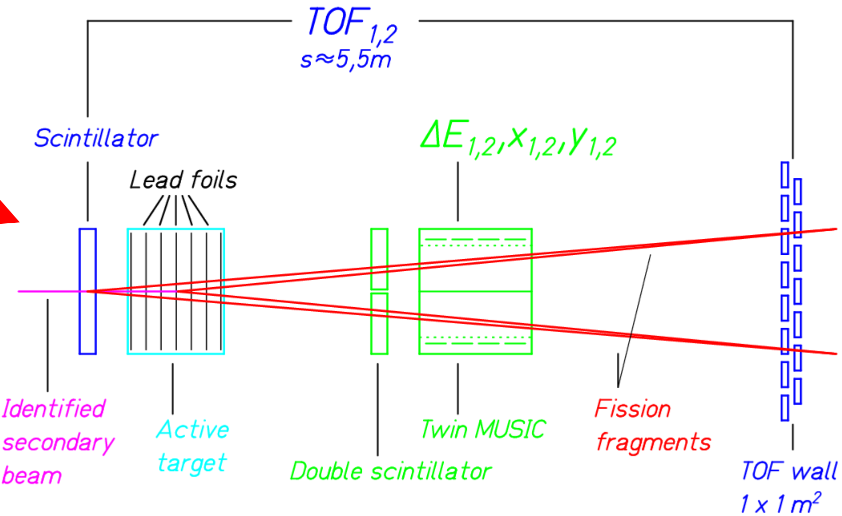


K-H. Schmidt et al., Nucl. Phys. A 665, 221 (2000)

The third attempt







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

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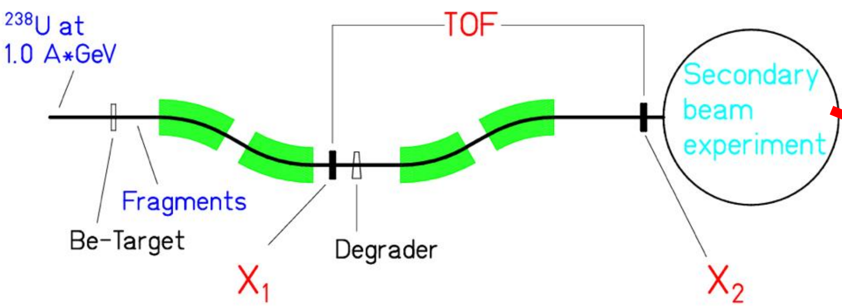
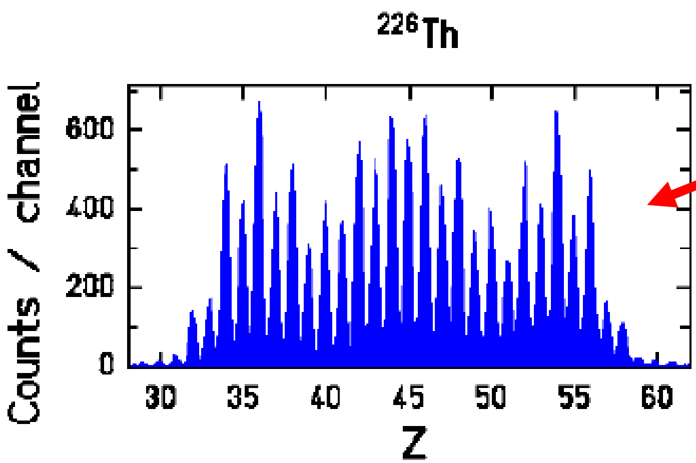
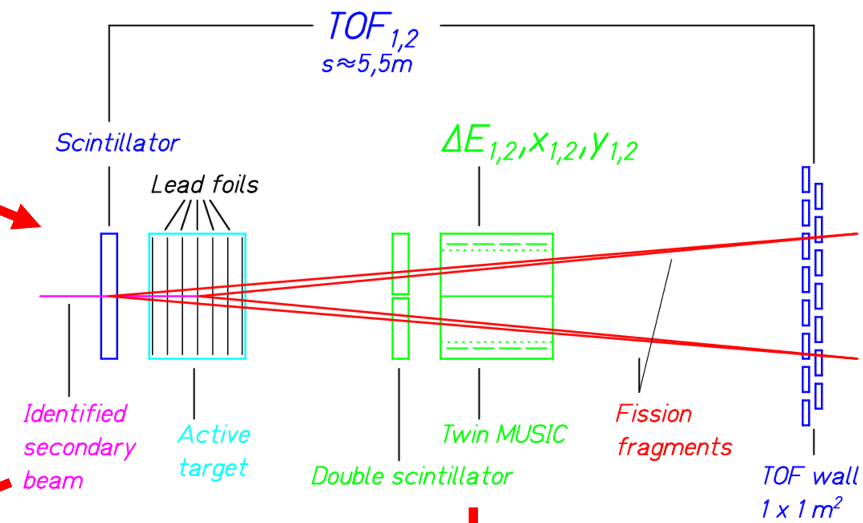
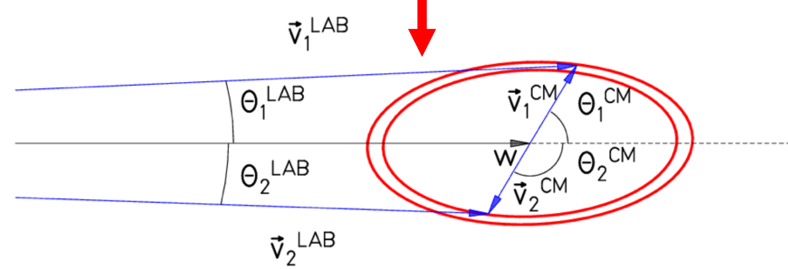




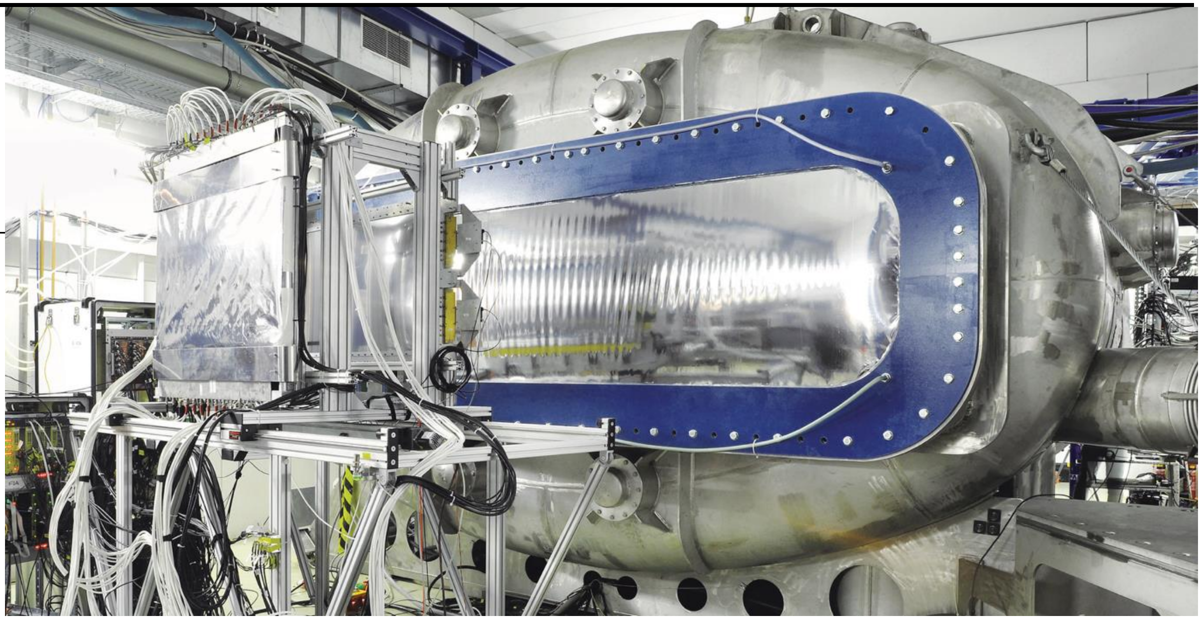




Total Kinetic Energy (TKE)

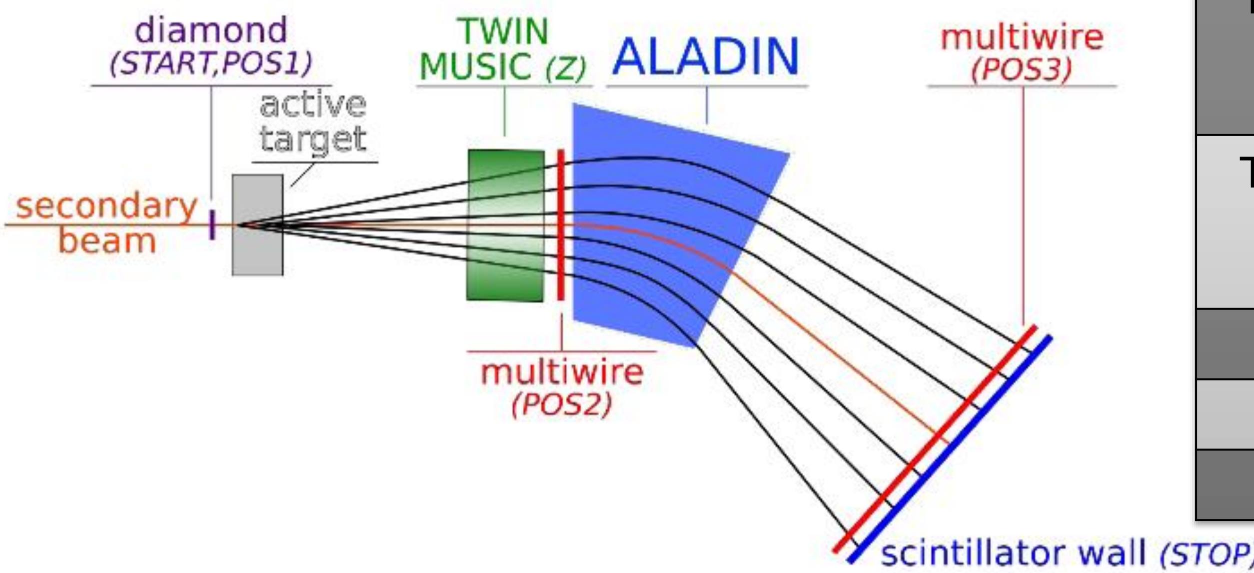
K-H. Schmidt et al., Nucl. Phys. A 665, 221 (2000)

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



Goal:
Measure A and Z of both fission fragments in coincidence for fission of radioactive beams.
Method:
Add a large dipole magnet to the setup.
Disadvantage:
No measurement of E* before fission.

SOFIA – Set-up



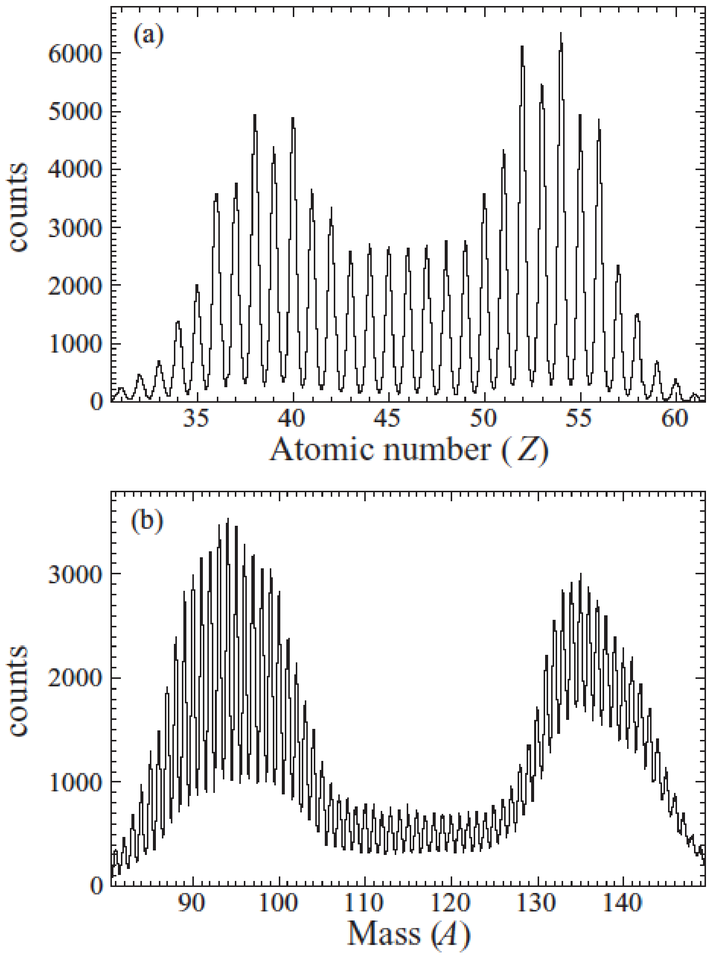
Detector	Resolution (FWHM)
Twin MUSIC (energy)	< 1 % (0.2 in charge units)
Twin MUSIC (position & angle)	≈ 60 μm ≈ 0.1 mrad
MWPC 1	≈ 200 μm
MWPC 2	≈ 300 μm
ToF wall	≈ 40 ps

Major improvement: masses and charges of the fission fragments!

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

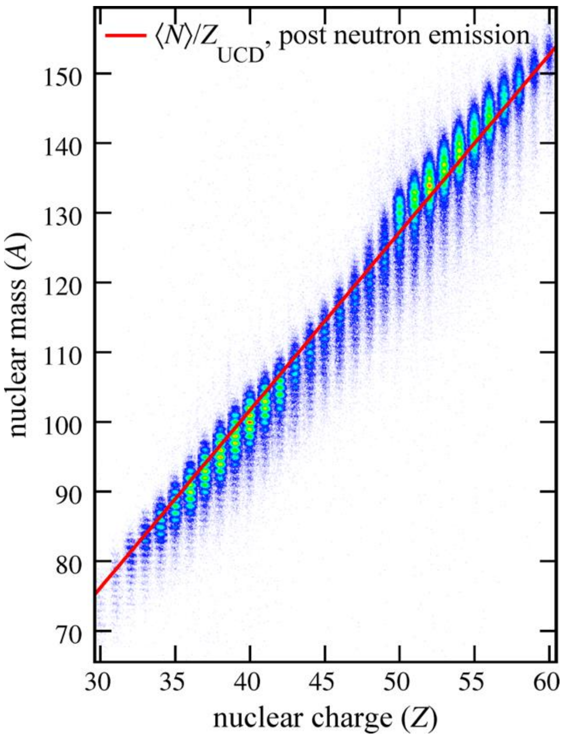
G. Boutoux et al.

Charge and mass resolution



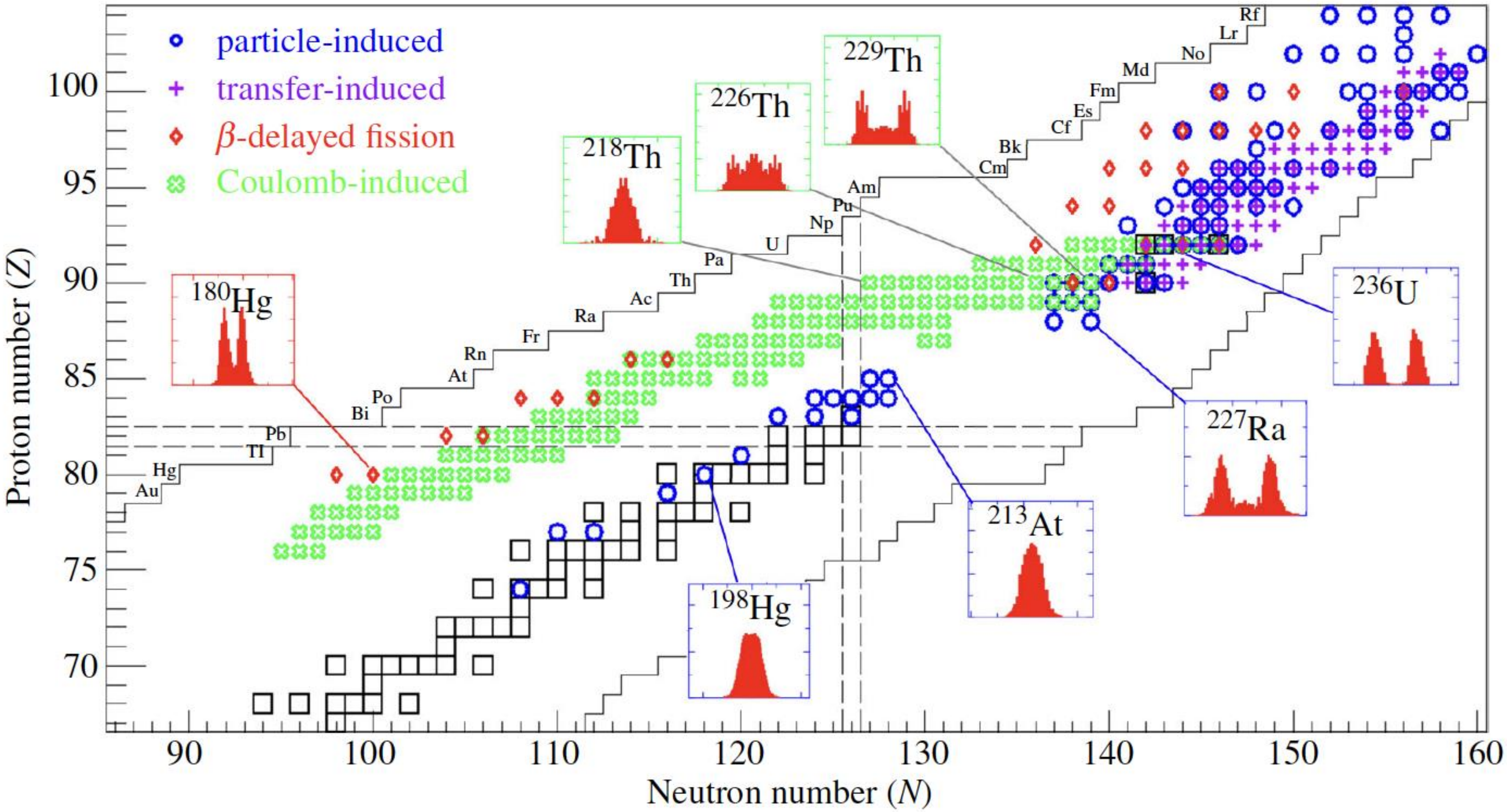
It works!

^{238}U



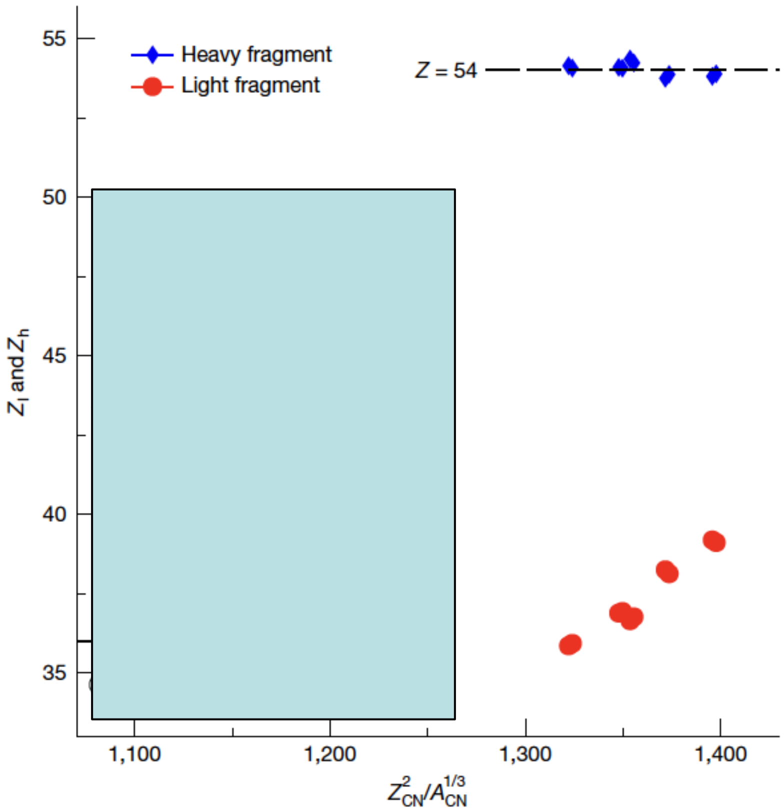
E. Pellerau et al., Phys. Rev. C 95, 054603 (2017)

Status in 2023



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

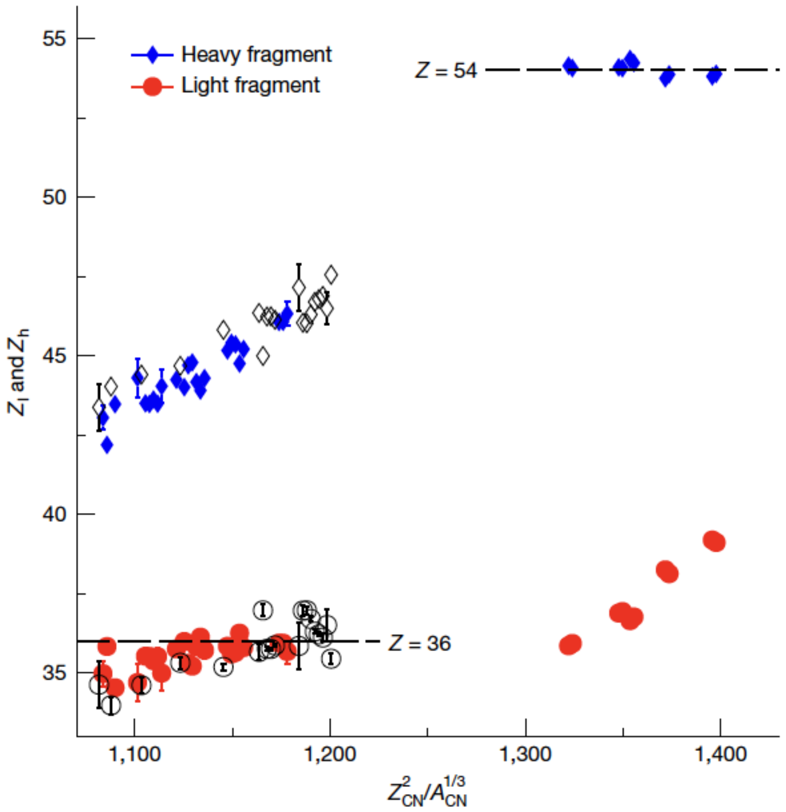
Asymmetric fission



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

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

Asymmetric fission

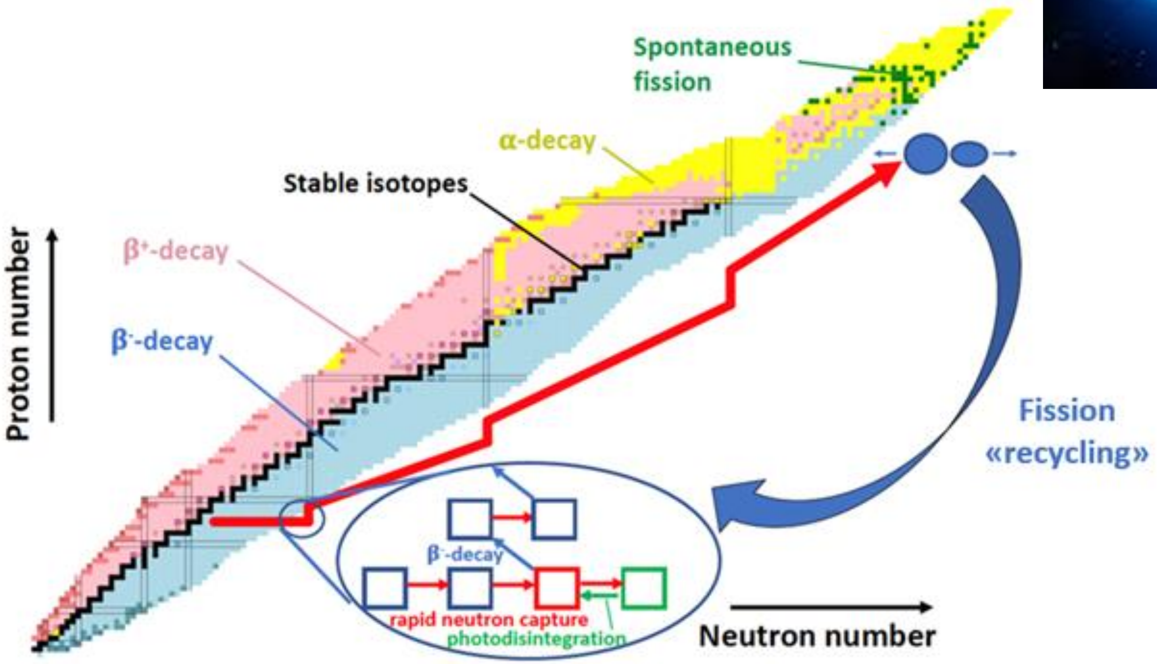


⇒ **(Deformed) Proton shells are responsible for the observed behavior.**

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

Fission and nucleosynthesis

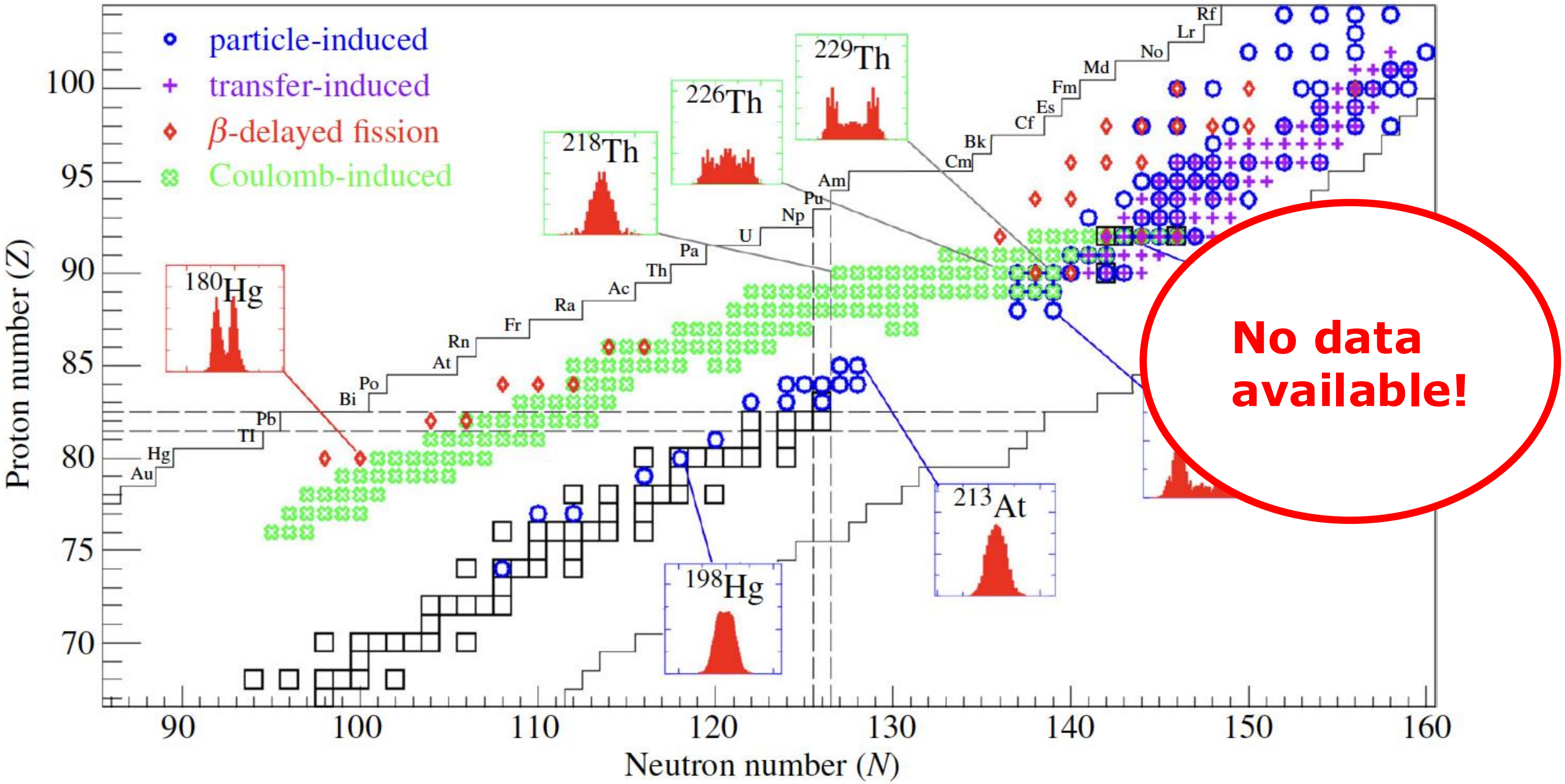
ESO/Univ. Warwick, Mark Garlick



- **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.

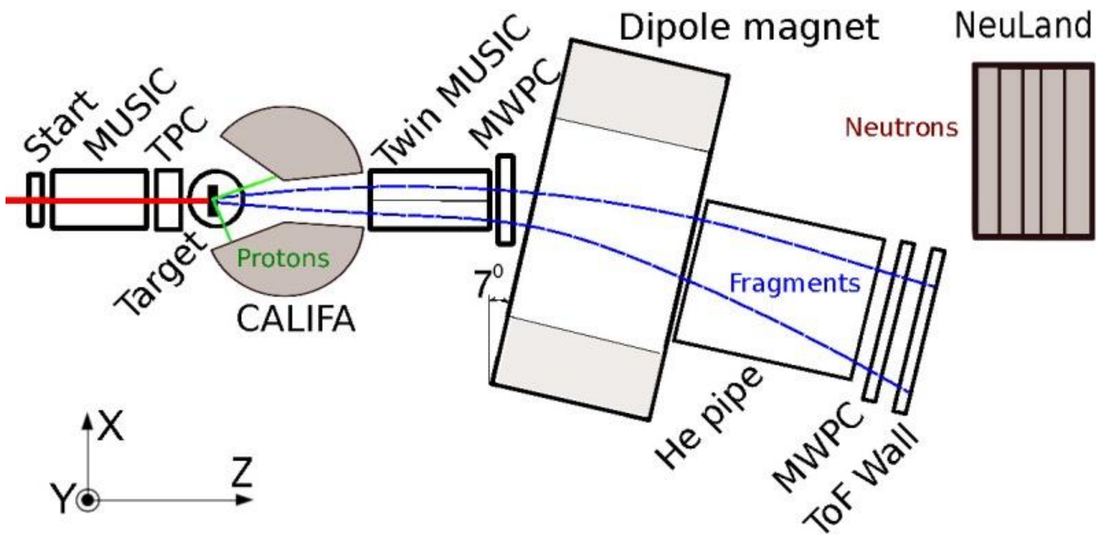
What now?



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.

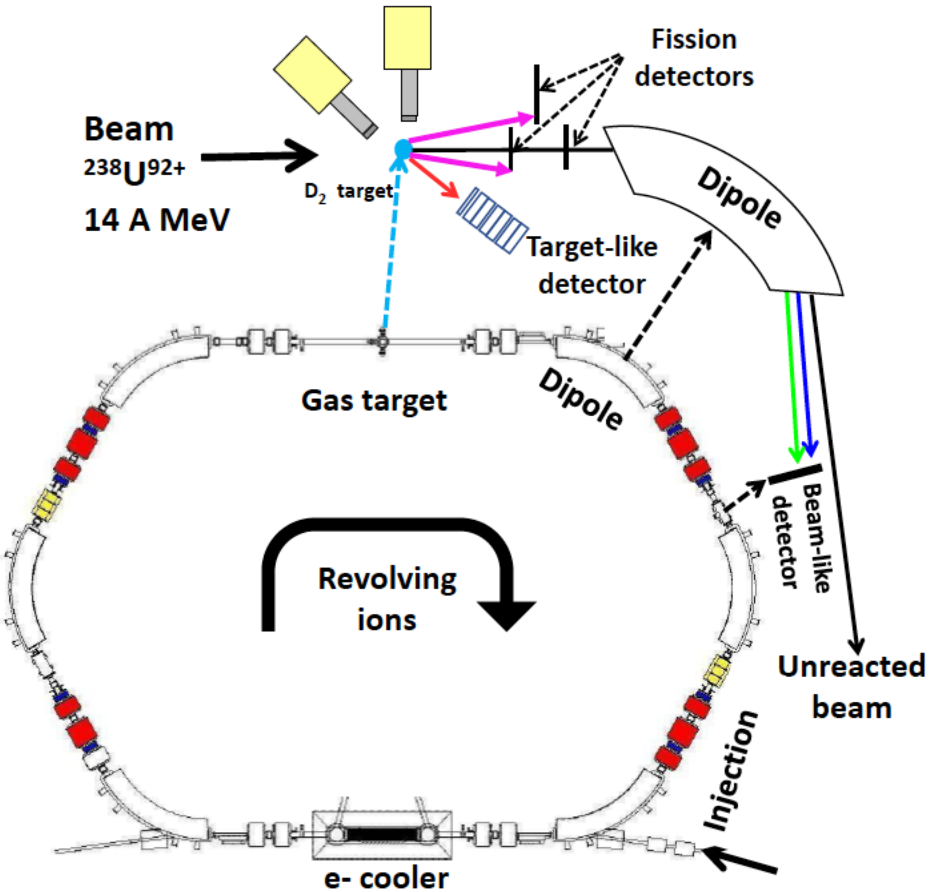


J. Taieb et al.

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.**

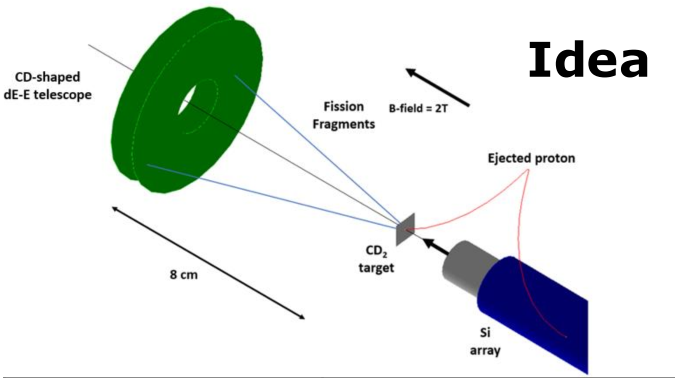
Fission in storage rings



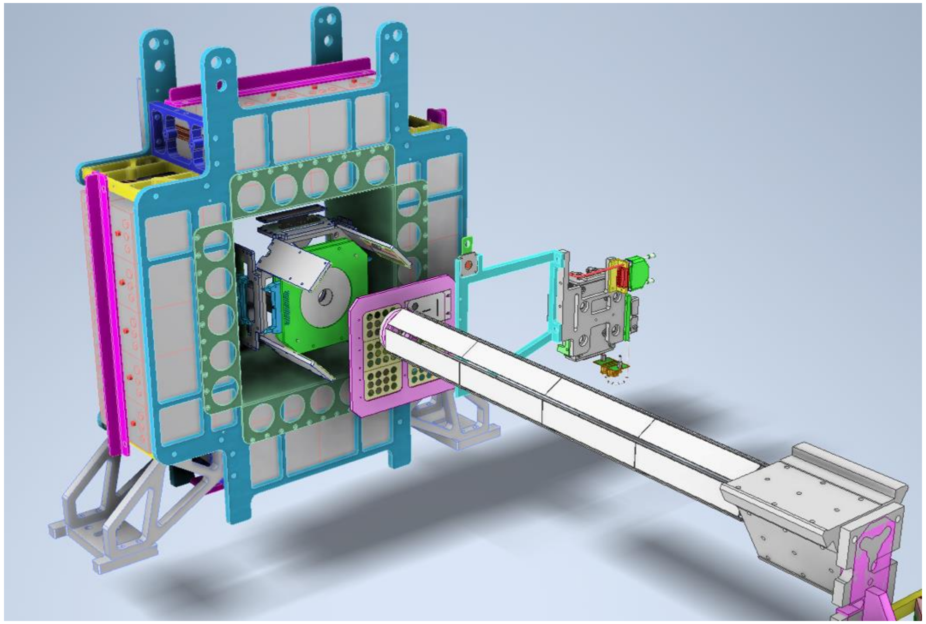
- **Proof-of-principle experiment in the ESR at GSI in Summer 2024.**
- **Tin target => very "clean" conditions.**
- **Measure excitation energy and fission fragment masses.**
- **Measure all competing decay channels simultaneously.**

B. Jurado et al.

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.
⇒ Talk of Maria Vittoria!

What do we need?

- **A and Z of fission fragments.**
- **Total kinetic energy released.**
- **Neutron energies and multiplicities.**
- **Excitation energies.**
- **Gamma-ray multiplicities and energies**
- **…**

But most importantly: the ability to correlate as many of those observables as possible!

Conclusions

- **Inverse kinematics comes with advantages and challenges.**

- **For radioactive beam experiments we have (often) no alternative.**

- **Fission studies in inverse kinematics are (one) way to extend the scope of fission studies.**

- **Different (complementary) experimental approaches have improved our understanding of fission! More is to come!**

Thank you for your attention!