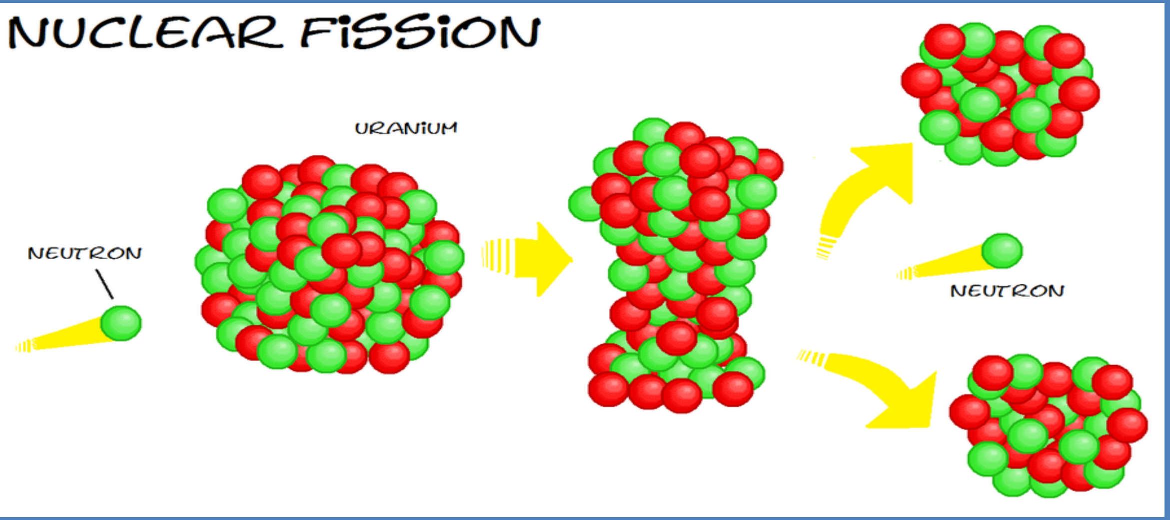
Fission dynamics at high excitation energy investigated with the SOFIA setup at GSI: Results and future perspectives at FAIR

José Luis Rodríguez-Sánchez
University of Santiago de Compostela, Spain
SPhN, IRFU, CEA, France



Why are we investigating the fission process?

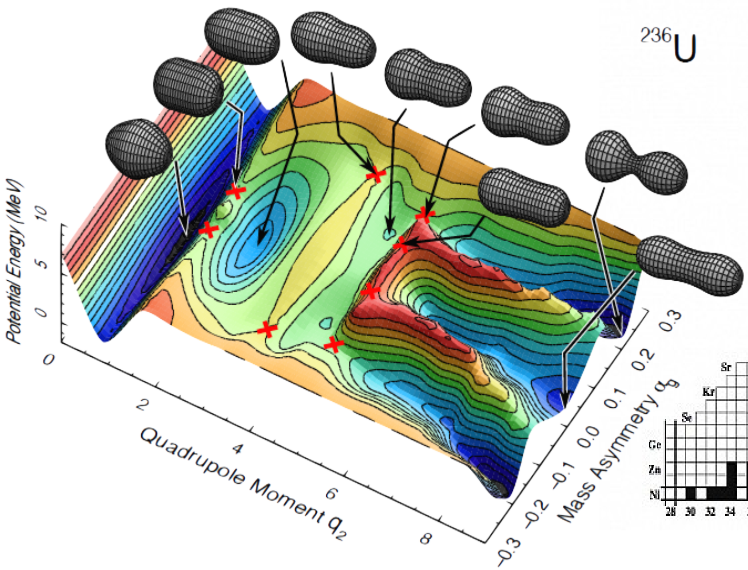
78 years after its discovery, nuclear fission still represents an important challenge for nuclear physics

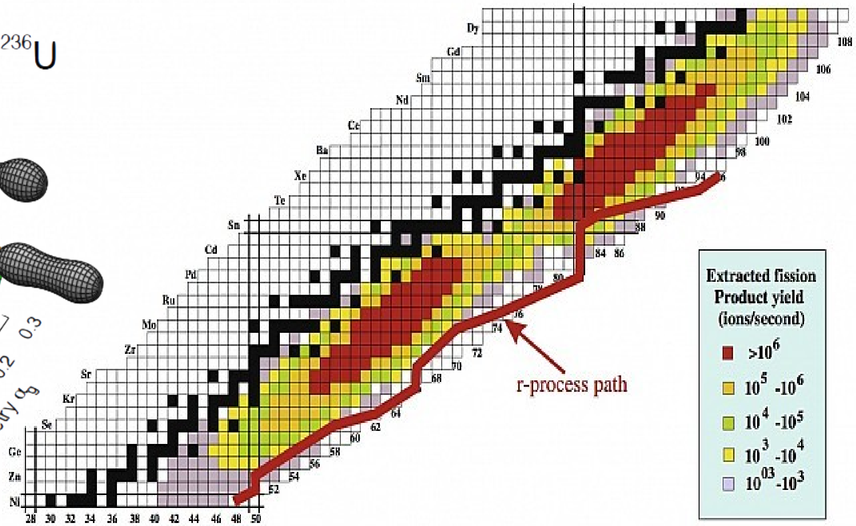
Fission has implications in many different domains:

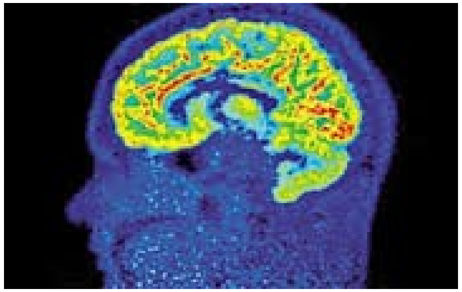
- Nuclear structure at large deformation
- Dynamics of nuclear matter
- Nuclear astrophysics
- Production of Radioactive Ion Beams and medical radio-tracers
- Energy production
- Neutron spallation source

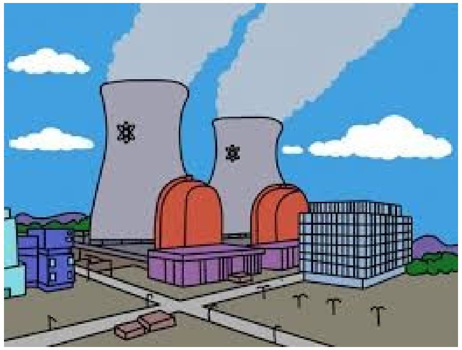
Otto Hahn

Fritz Strassmann









Layout

- Basic concepts
  - What we know about fission
  - Open questions
- Experimental approaches
  - Direct kinematics
  - Inverse kinematics
- Fission experiments at GSI
  - Fragment separator FRS
  - SOFIA setup: Complete identification of both fission fragments
- Fission dynamics from the SOFIA experiment
  - Ground-to-saddle dynamics
  - Saddle to scission dynamics
- Conclusions and future fission experiments at FAIR (Facility for Antiproton and Ion Research)

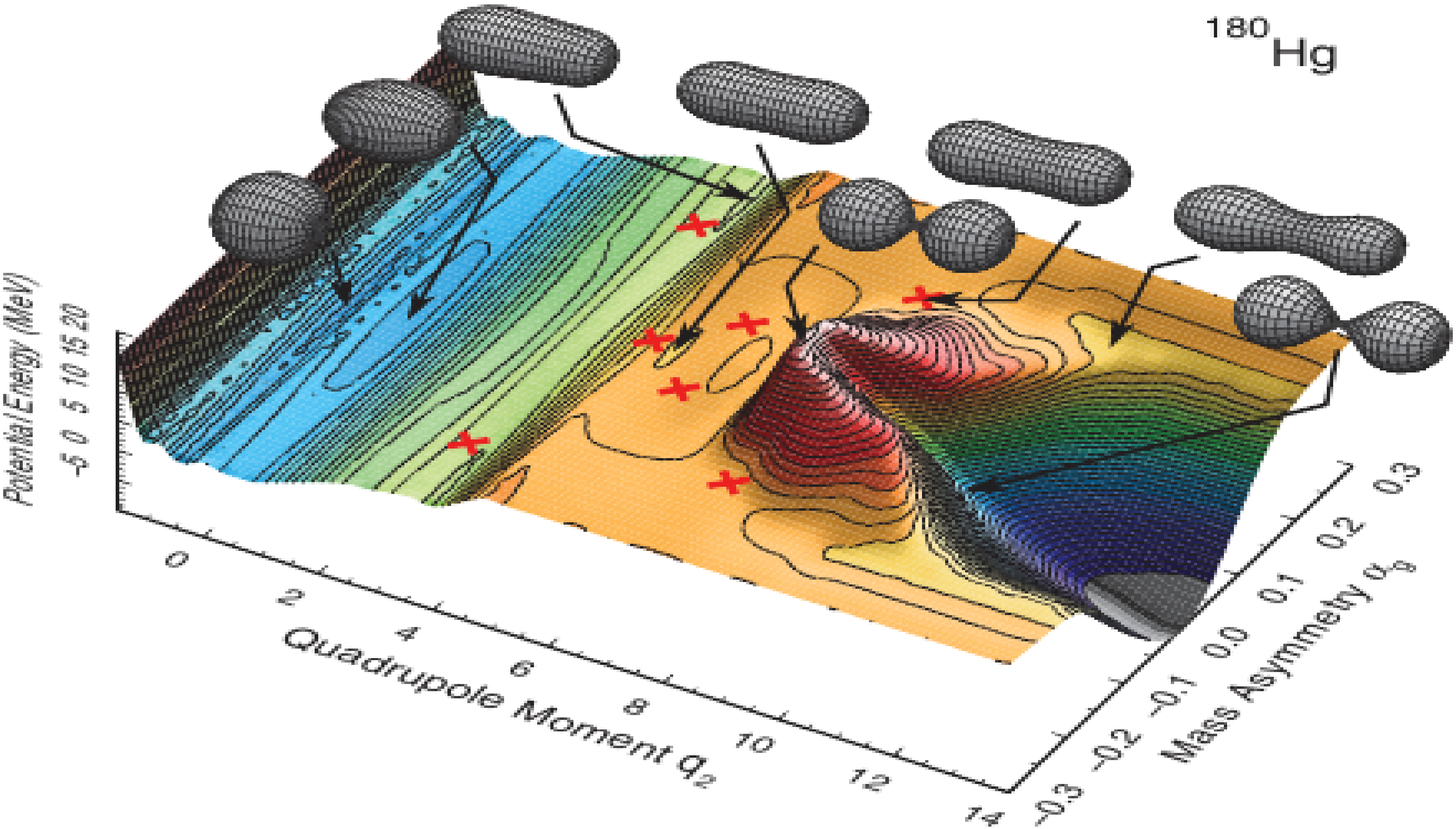
Basic concepts

Static properties

- Governed by the potential energy landscape according to two main degrees of freedom:

elongation: when fission takes place

mass asymmetry: how fission occurs

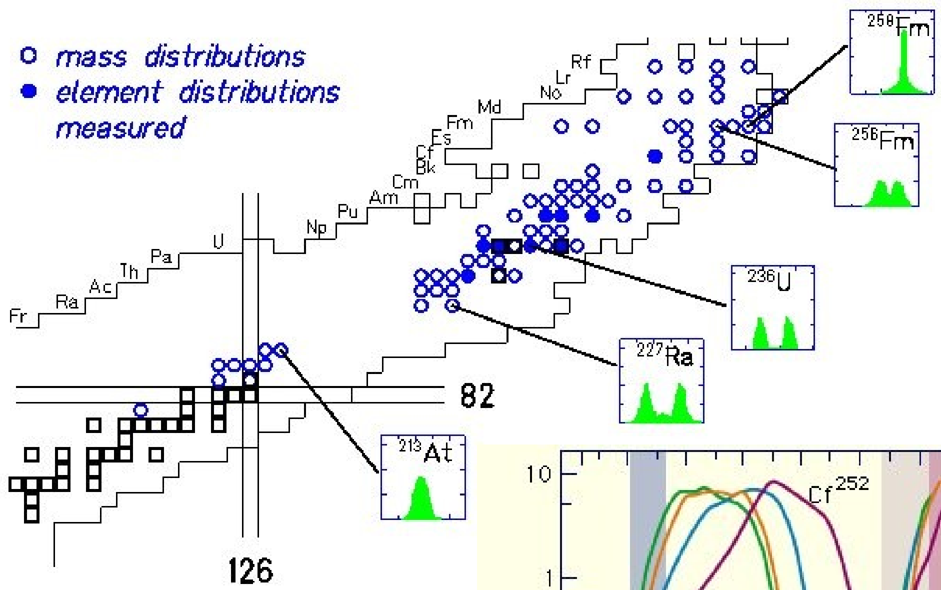


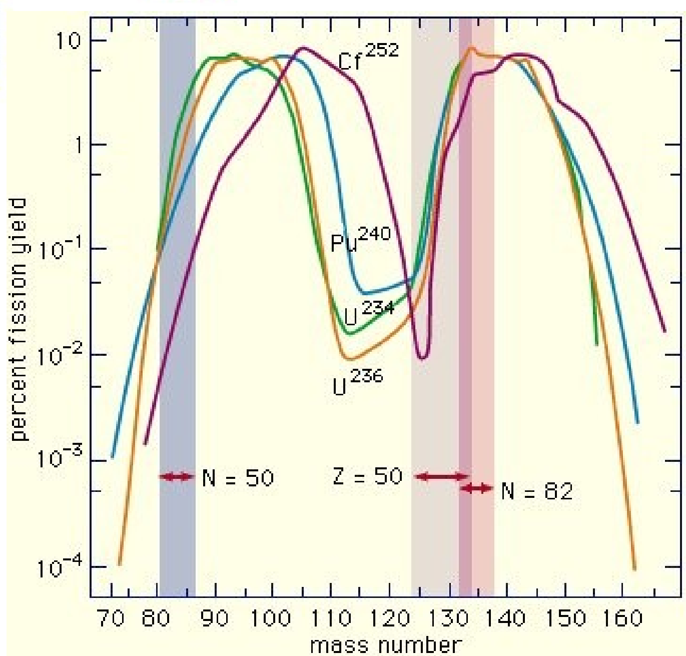
Basic concepts

Static properties

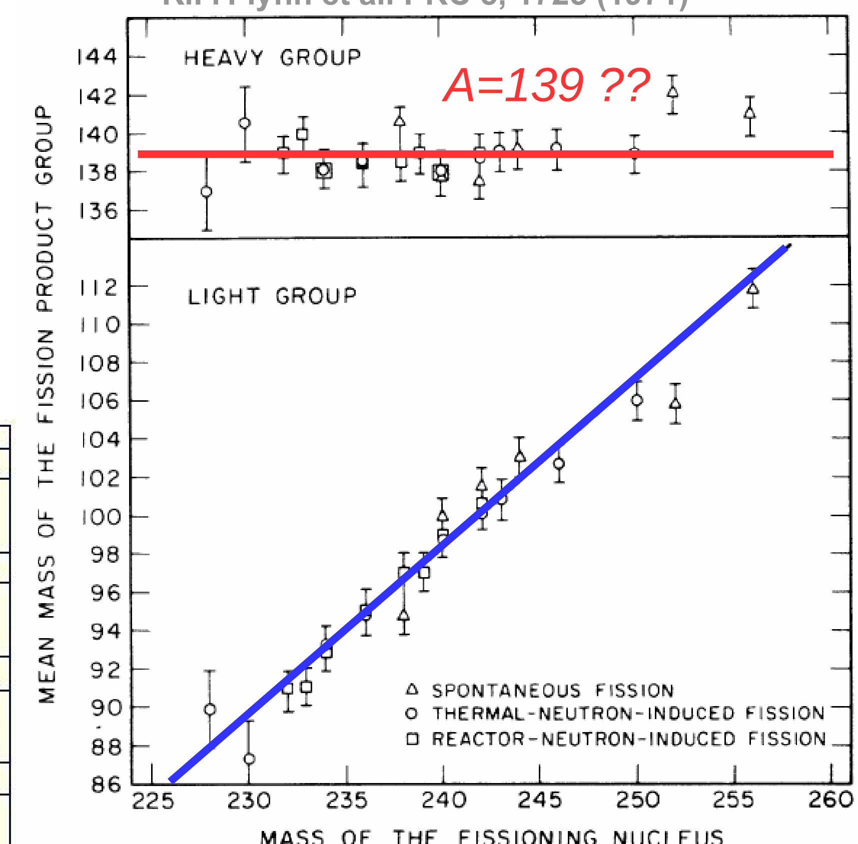
Structural effects manifest in the mass/charge asymmetry degree of freedom:

- Shell closures Z=50 and N=82 were proposed to explain the mass asymmetry in the actinide region





K.F. Flynn et al. PRC 5, 1725 (1971)



Nuclear magic numbers according the single-particle picture:

Z=50 and N = 82

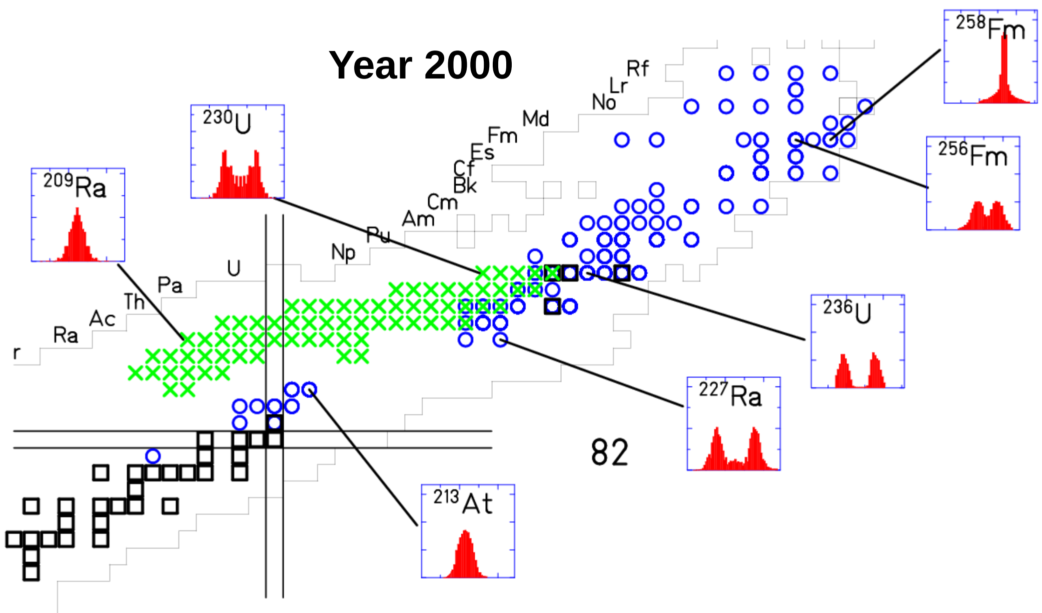
A = 132

Basic concepts

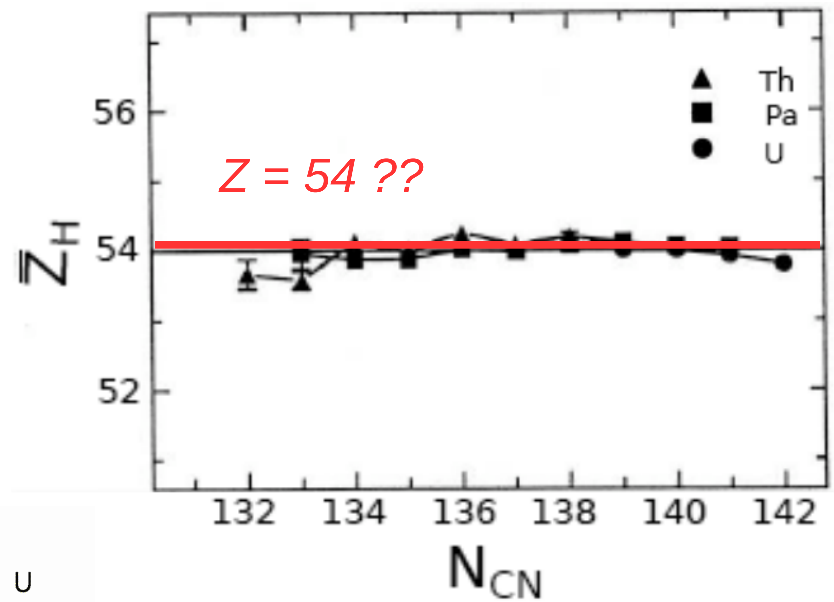
Static properties

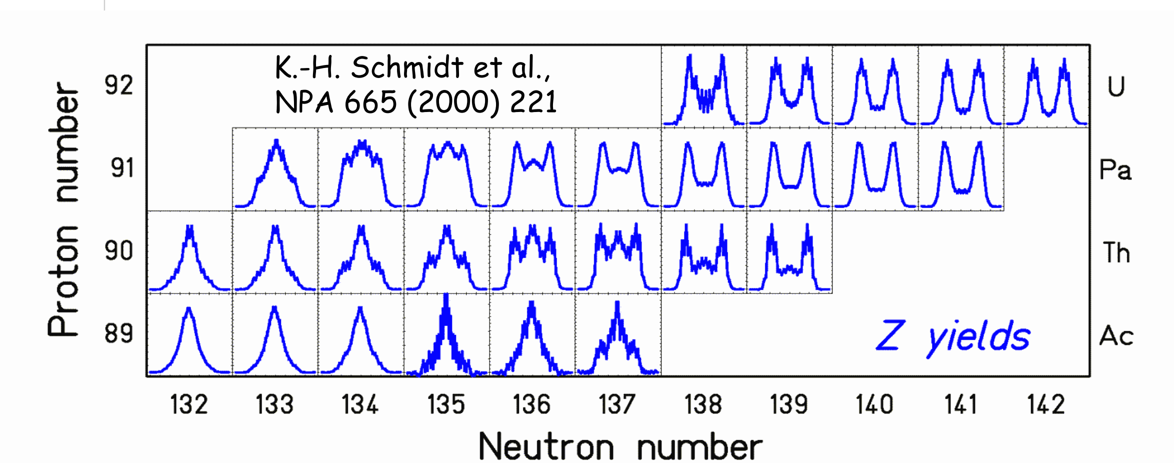
Structural effects manifest in the mass/charge asymmetry degree of freedom:

- Shell closures Z=50 and N=82 were proposed to explain the mass asymmetry in the actinide region



- Charge distributions do not show evidences for the shell closure at Z=50

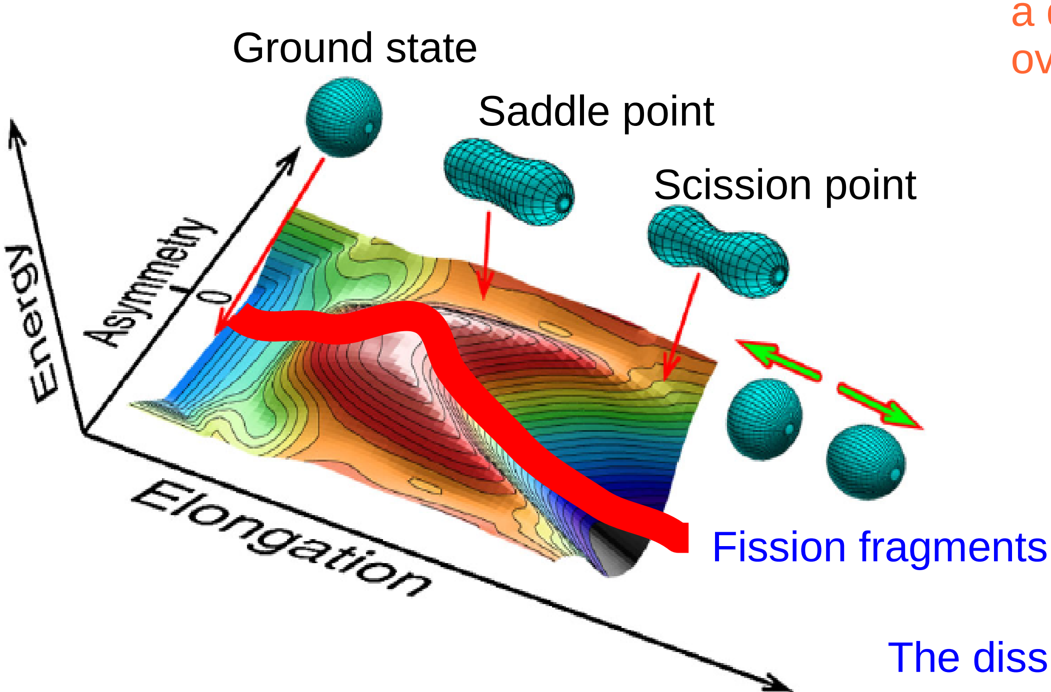




Basic concepts

Dynamical properties

- Time evolution of the fissioning nucleus from the ground state to the scission point
- Governed by the coupling between intrinsic (excitation energy) and collective (motion) degrees of freedom



Ground-to-scission dynamics can be described as a diffusion process of the fission degree of freedom over the fission barrier using transport models:

Fokker-Planck equation

$$\frac{\partial W}{\partial t}=\left[\frac{-\partial}{\partial x}\nu+\frac{\partial}{\partial \nu}\left(\beta\nu-\frac{1}{m}\frac{\partial}{\partial x}U(x)\right)+\frac{\beta kT}{m}\frac{\partial^2}{\partial \nu^2}\right]W$$

Langevin equation

$$\frac{d\nu}{dt}=-\beta\nu-\frac{1}{m}\frac{\partial}{\partial x}U(x)+\frac{F'(t)}{m}$$

The dissipation parameter β quantifies the exchange rate between intrinsic and collective energy and defines the average time (transient time) that the fission system needs to reach the saddle-point deformation

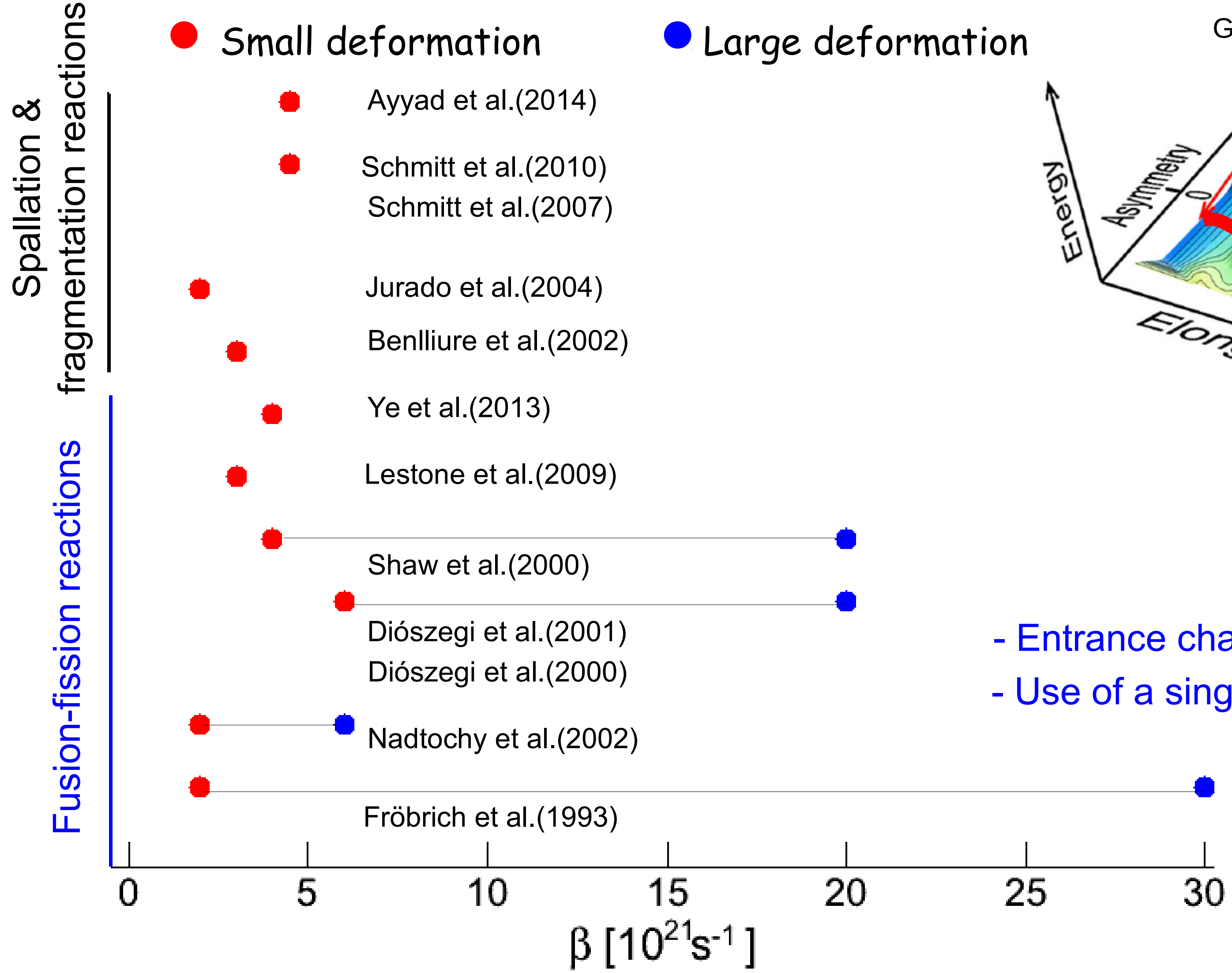
- Observables

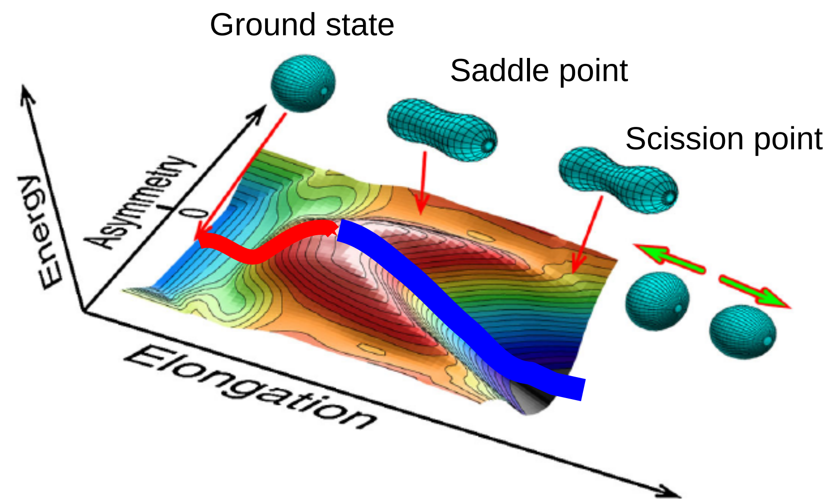
Pre-scission neutron, light charged particles and γ-ray emission are used to prove total fission times, while fission probabilities give access to ground-to-saddle transient effects and the corresponding value of β

Basic concepts

Dynamical properties

Last experimental results of the dissipation parameter



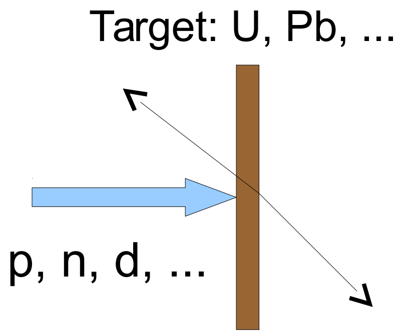


- Entrance channel in fusion-fission reactions
- Use of a single observable

The magnitude and the temperature and deformation dependencies of the dissipation parameter are still under debate

Experimental approaches

Direct kinematics



Main facilities:

- n_ToF, ILL, Geel, ...

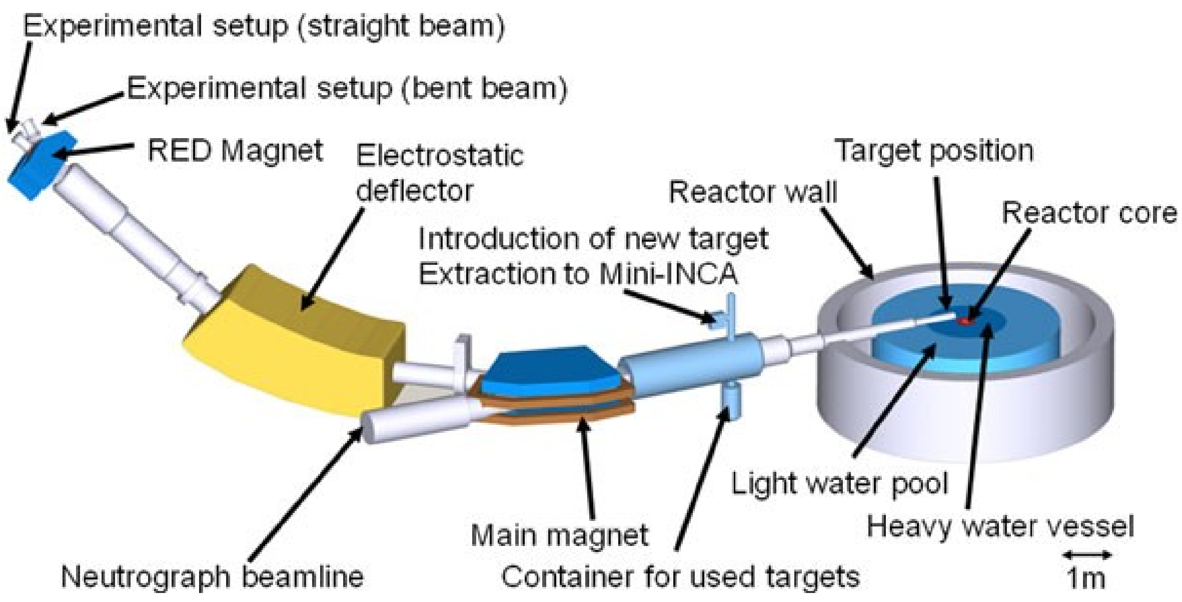
Observables:

- Fission cross sections
- Mass identification of both fragments
- Neutrons and light-charged particles

Limitations:

- Only stable nuclei
- Identification of one of the two fission fragments
- Poor resolution in atomic number

LOHENGRIN fission fragment separator at ILL



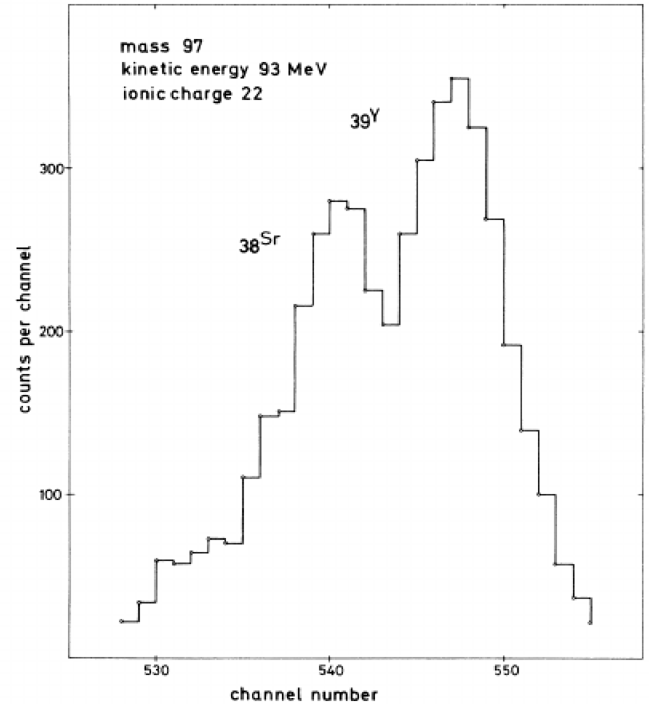
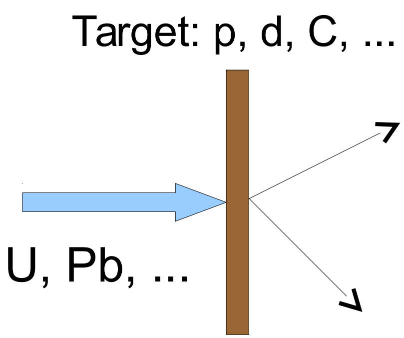


FIG. 1. The signal obtained from a ΔE Si-surface barrier detector irradiated by monoenergetic fission products of mass 97. One can clearly distinguish the peaks due to ^{97}Y and ^{97}Sr. The peak due to ^{97}Rb is still noticeable as a shoulder.

Experimental approaches

Inverse kinematics



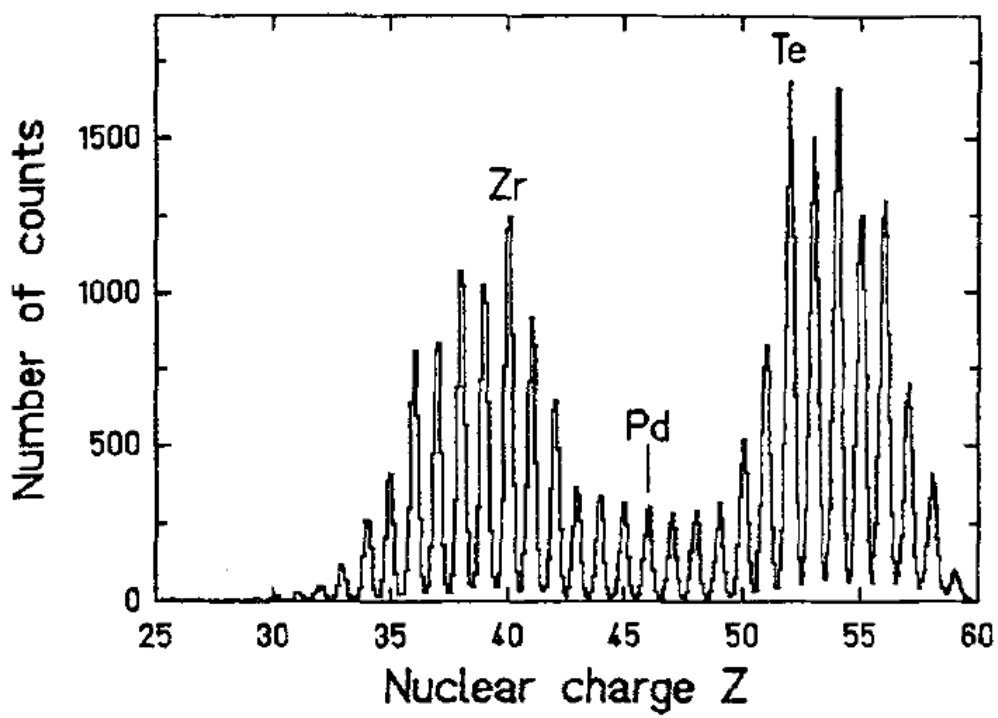
Main facilities:

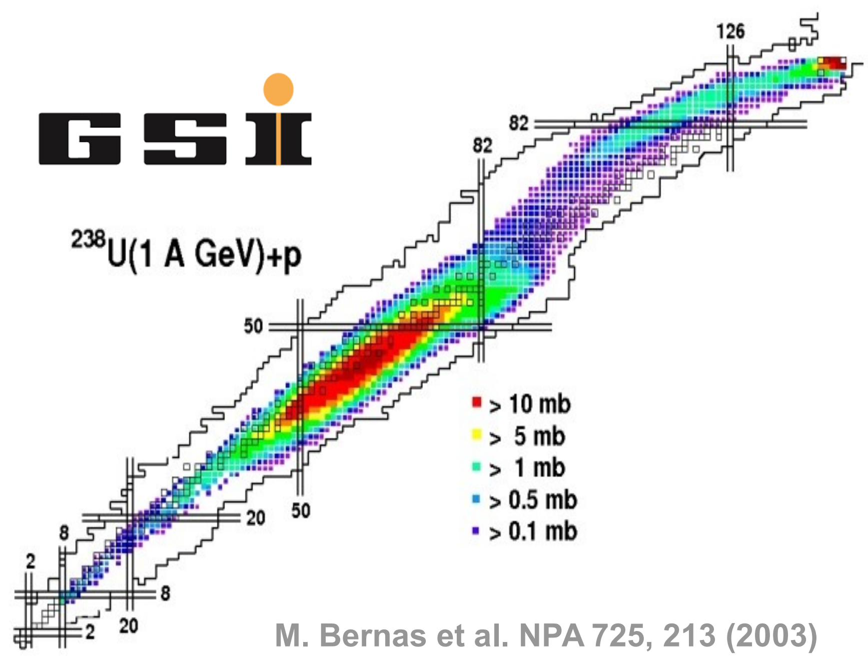
- GSI, GANIL, RIKEN, ...

Observables:

- Fission cross sections
- Mass and charge identification of both fragments (recently achieved)
- Neutrons and light-charged particles

P. Armbruster et al. ZPA 355, 191 (1996)

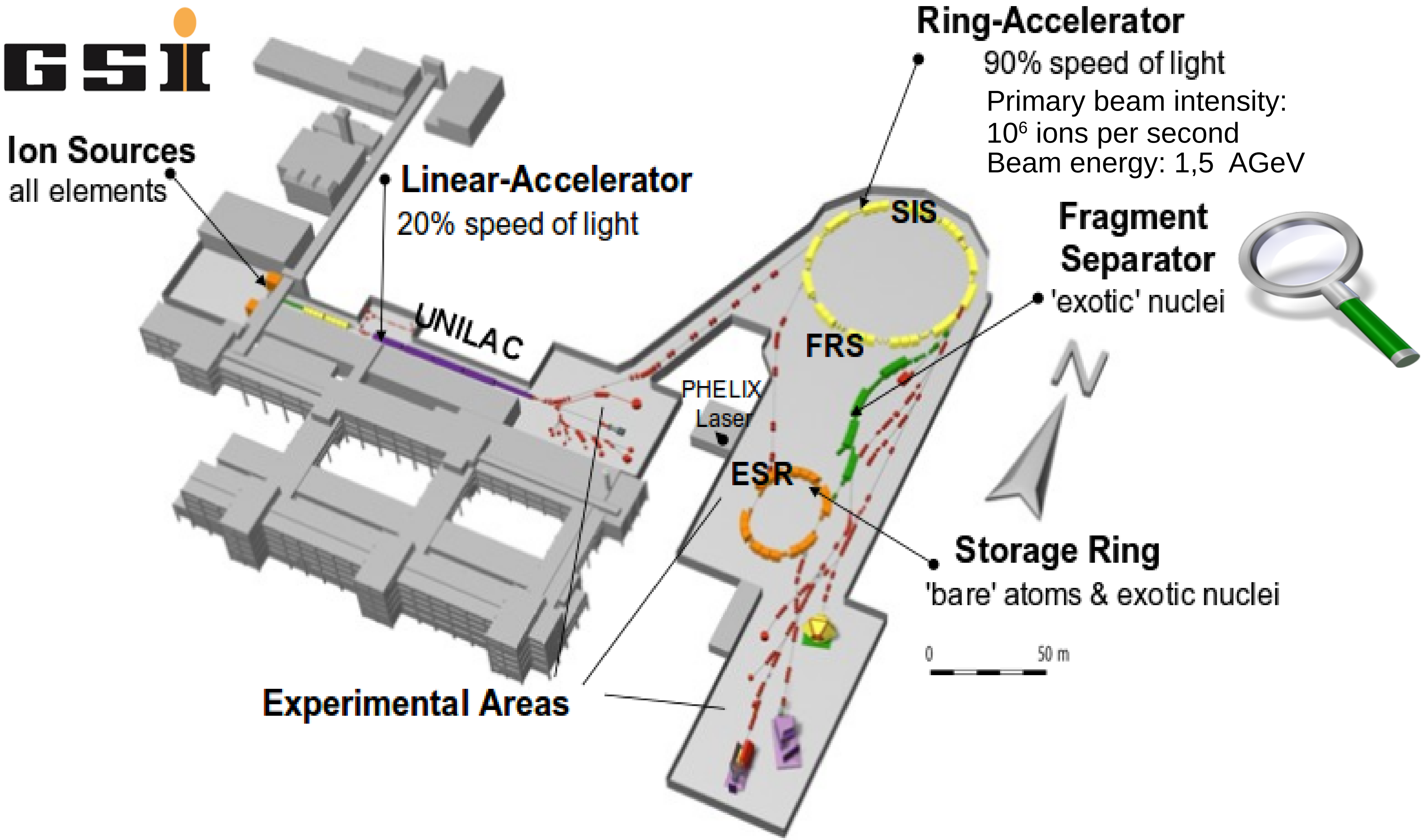




M. Bernas et al. NPA 725, 213 (2003)

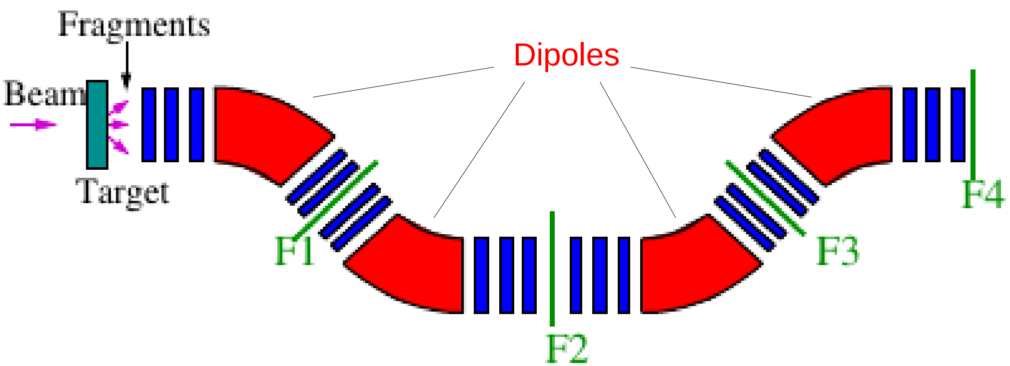
J. Taieb et al. NPA 724, 413 (2003)

Experiments at GSI



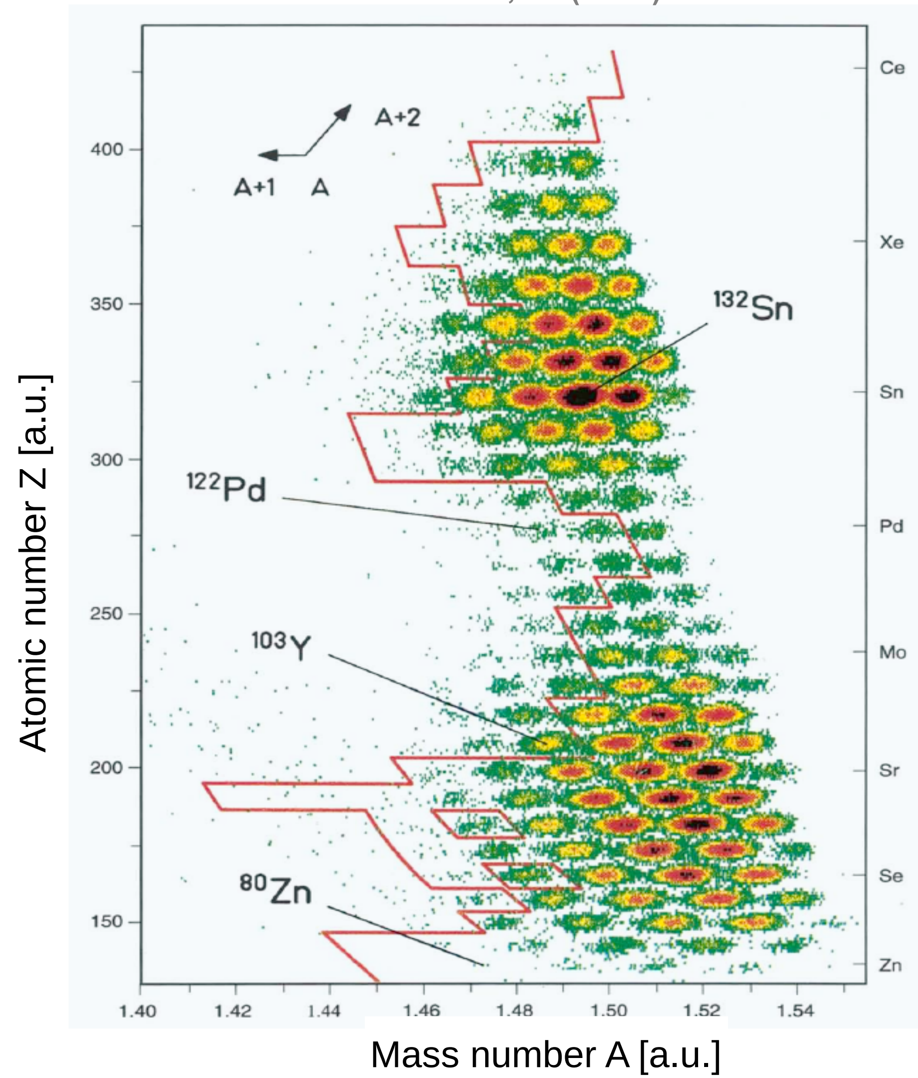
Experiments at GSI: Fragment separator (FRS)

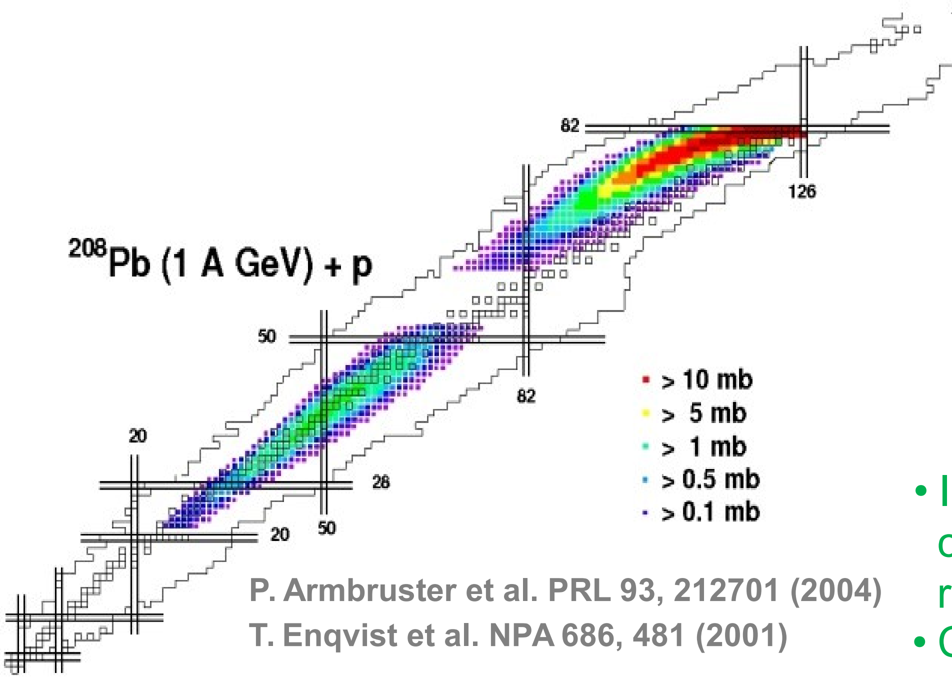
- In-flight identification of fission fragments



- Fission reactions of stable nuclei: ^{238}U, ^{208}Pb, ^{197}Au...
- Full identification in mass and atomic number
  but only for one of the two fission fragments

M. Bernas et al. PLB 331, 19 (1994)



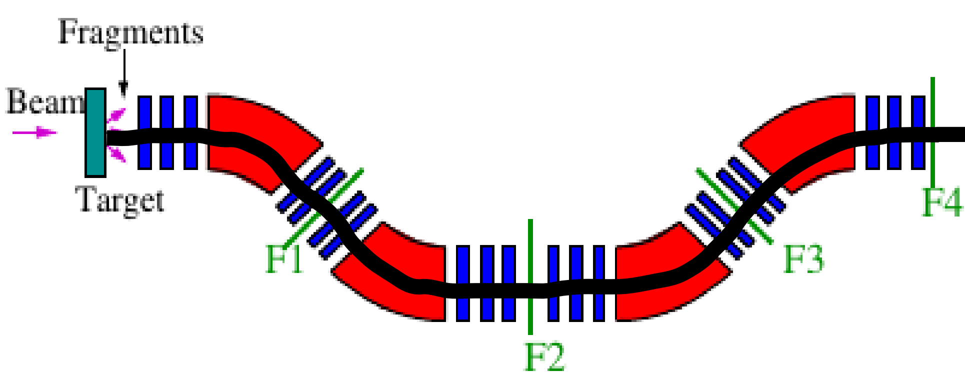


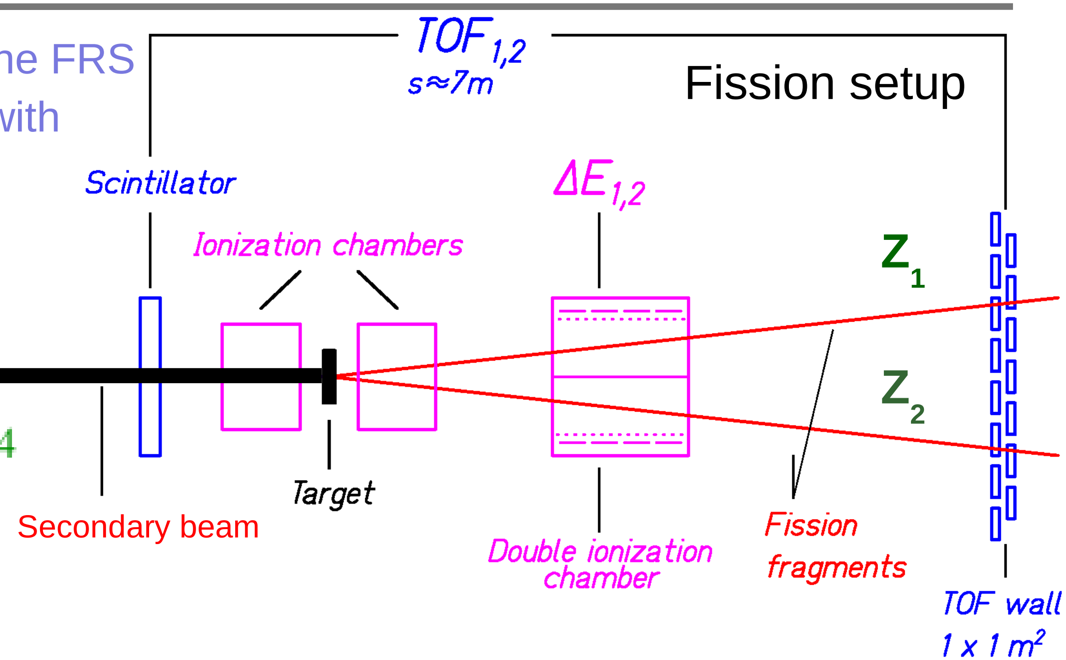
P. Armbruster et al. PRL 93, 212701 (2004)
T. Enqvist et al. NPA 686, 481 (2001)

- Important data to improve the prediction power of model calculations used for the production of exotic nuclei in radioactive-beam facilities
- Characterization of spallation neutron targets

Experiments at GSI: Fragment separator (FRS)

- In-flight identification of secondary beams using the FRS
- Fission reactions of unstable nuclei investigated with a double ionization chamber

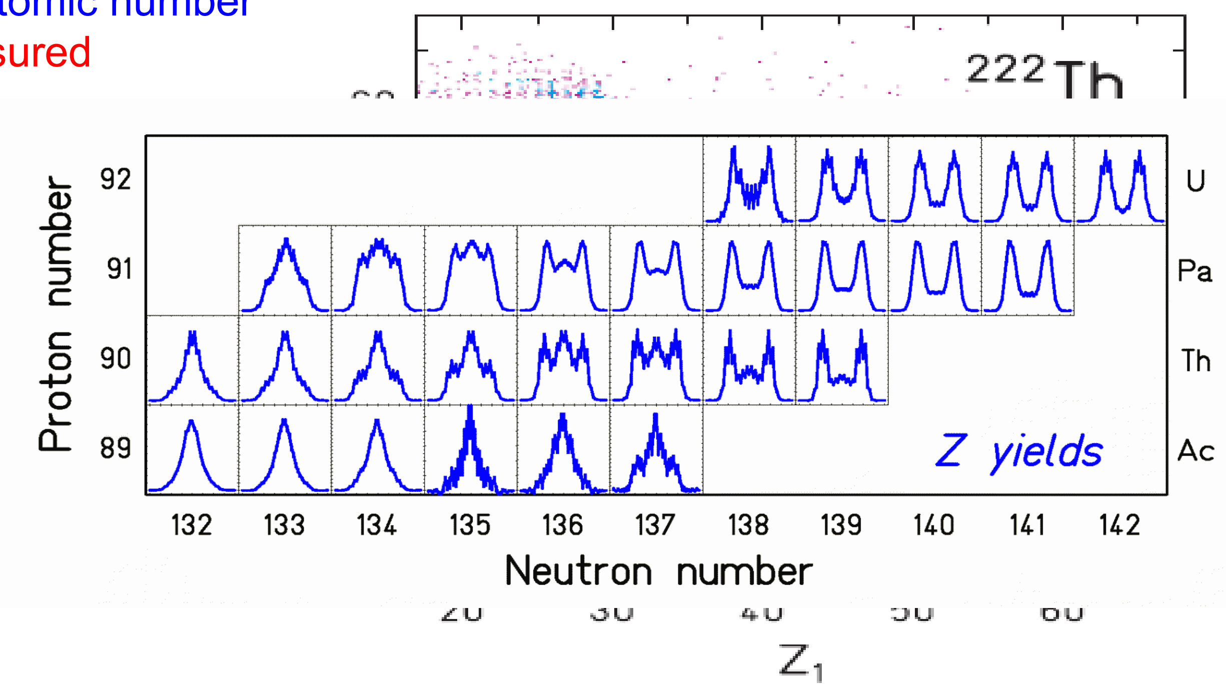




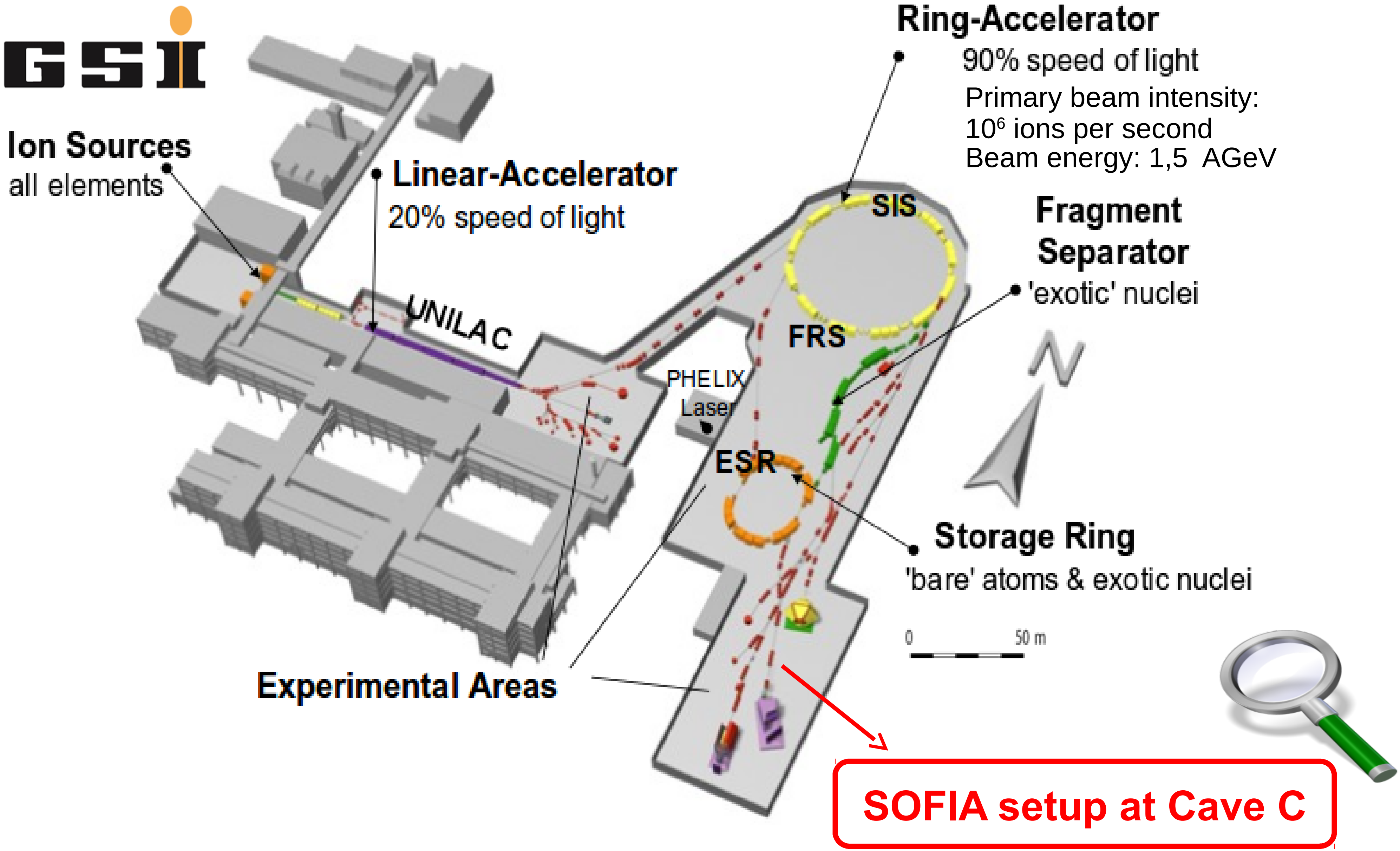
- Detection of both fission fragments in atomic number but their mass numbers were not measured

K.-H. Schmidt et al. NPA 665, 221 (2000)
C. Böckstiegel et al. NPA 802, 12 (2008)

- Important for the investigation of shell effects in fission



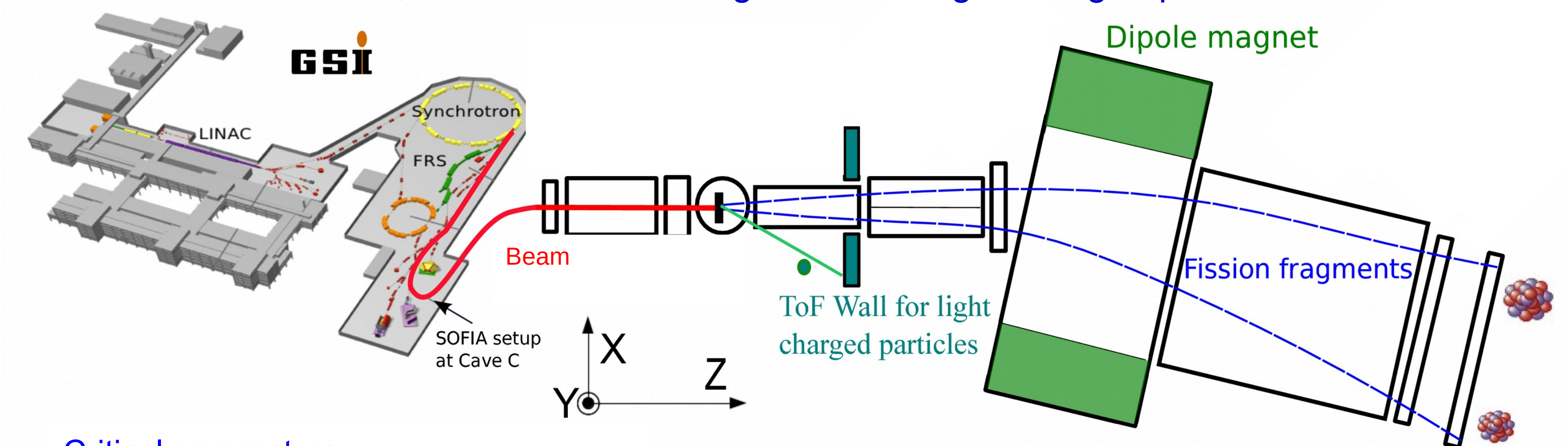
Experiments at GSI: SOFIA



SOFIA: experimental setup

SOFIA (Studies On FIssion with Aladin) J. Taieb et al., CEA (France)

Full identification in A, Z of both fission fragments and light-charged particles

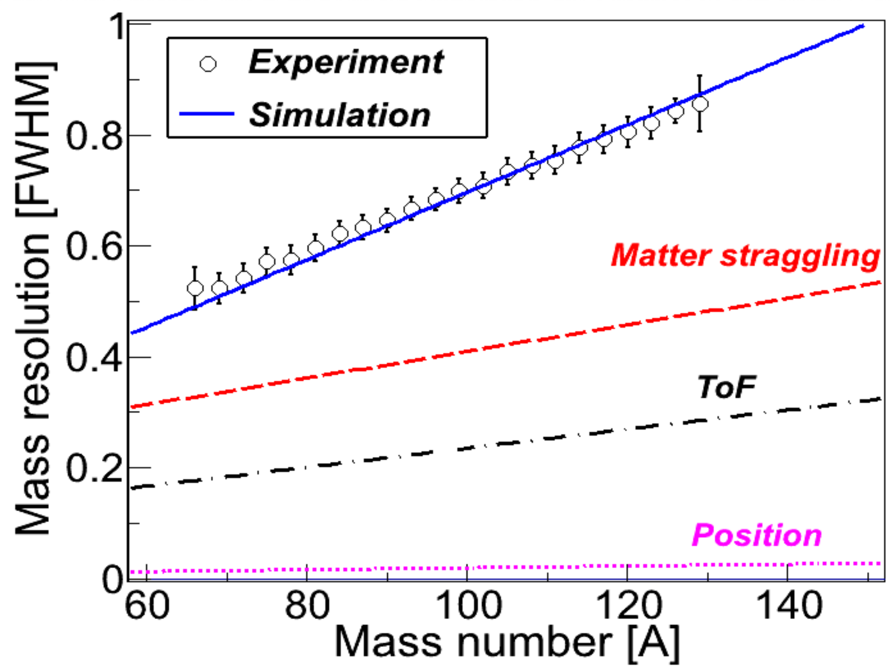


Critical paremeters:

- Energy-loss resolution ~ 1.2 %
- Large acceptance dipole magnet
- Position resolution ~ 250 μm
- Time-of-flight resolution ~ 40 ps
- Limited straggling (helium gas)

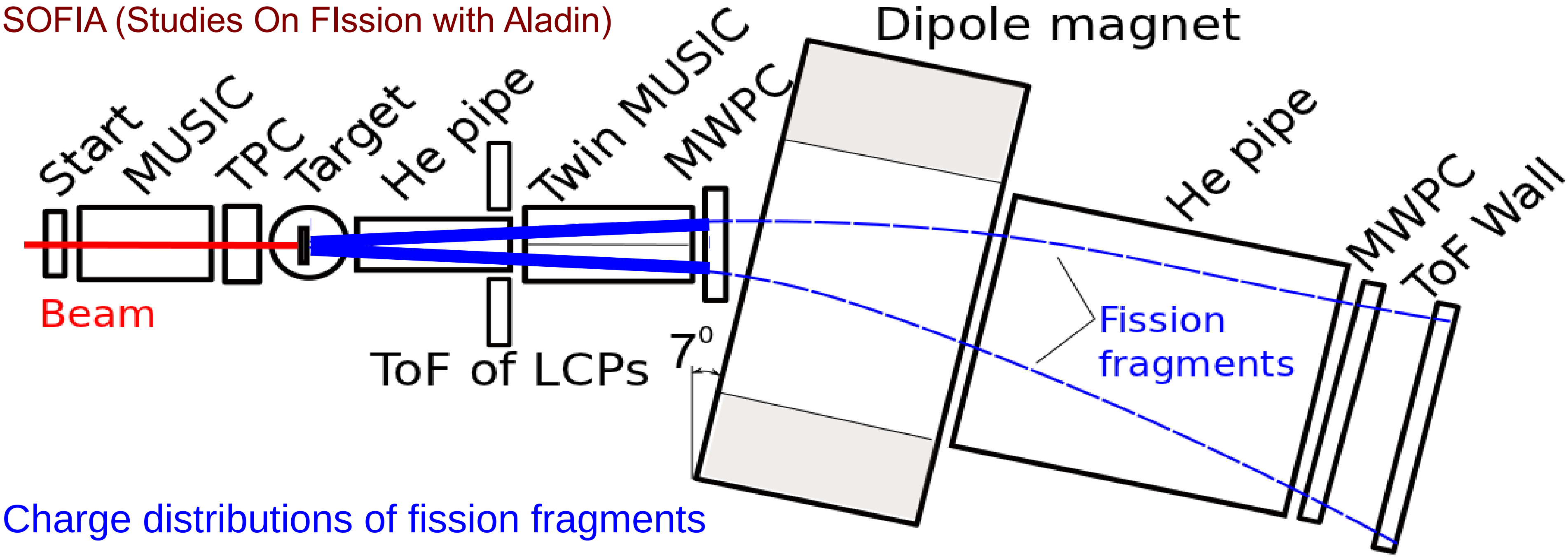
Reactions:

- Coulomb induced fission (static properties)
- Spallation induced fission (dynamical properties)



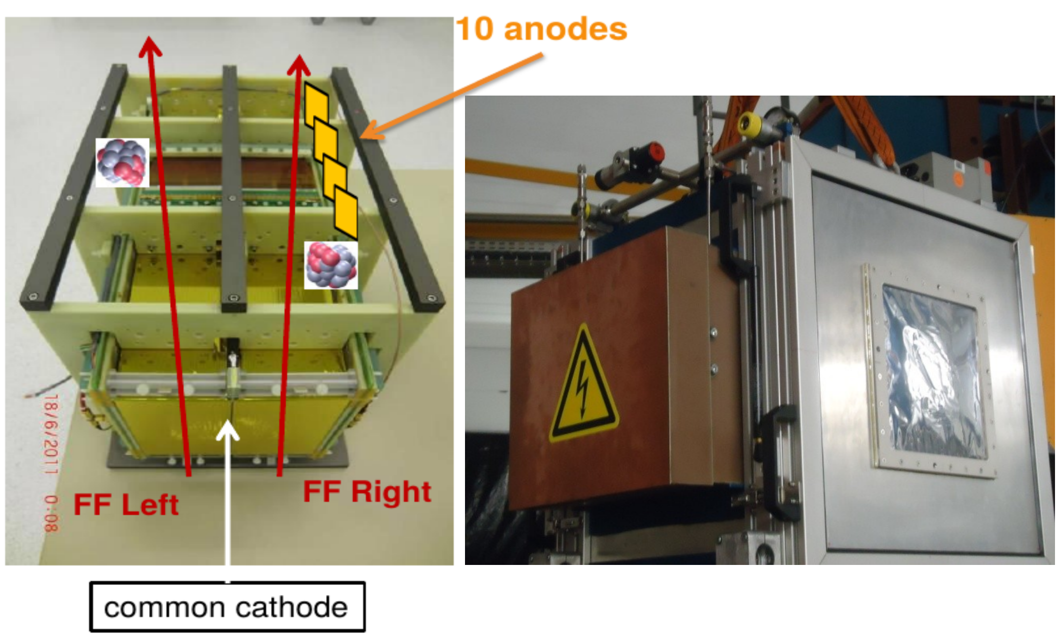
SOFIA: experimental setup

SOFIA (Studies On FIssion with Aladin)

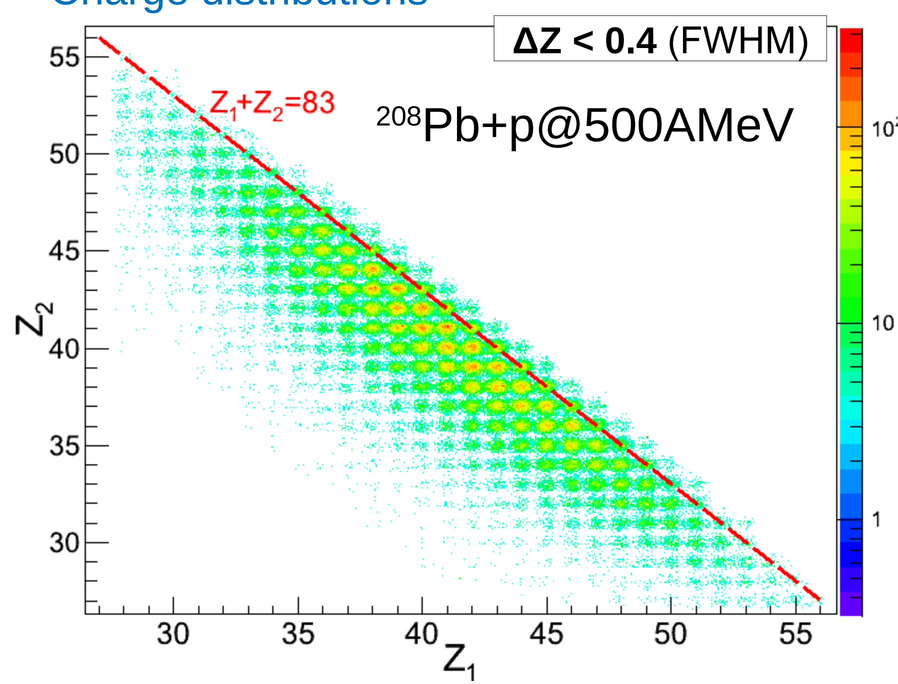


Charge distributions of fission fragments

Identification in a double ionization chamber

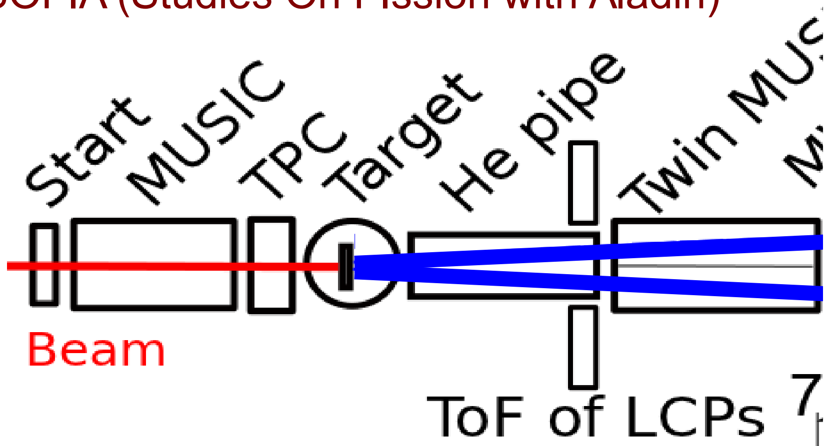


Charge distributions



SOFIA: experimental setup

SOFIA (Studies On FIssion with Aladin)

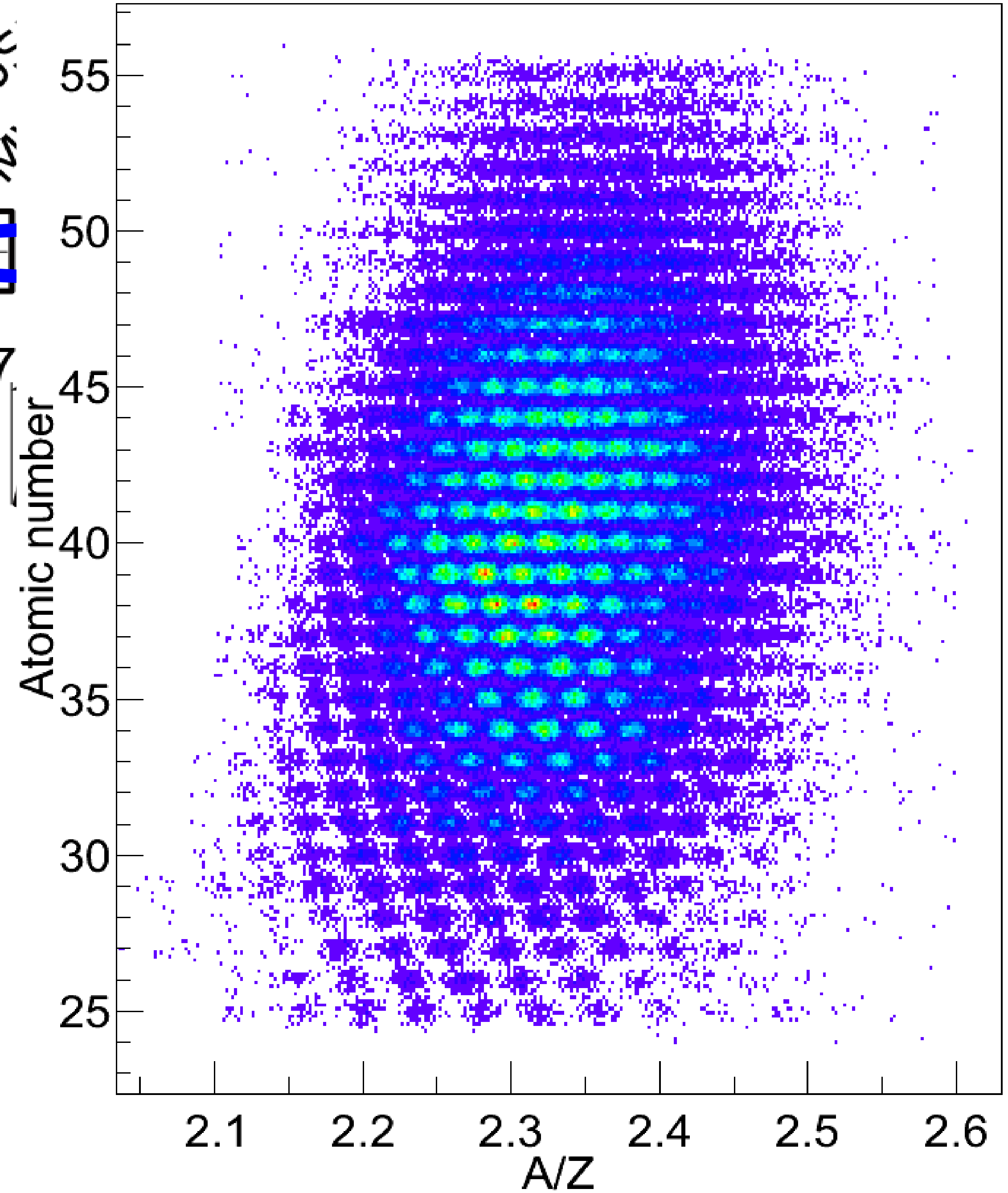


Mass distributions of fission fragments

In-flight mass identification of both fission fragments using the magnetic ridigity and the time of flight

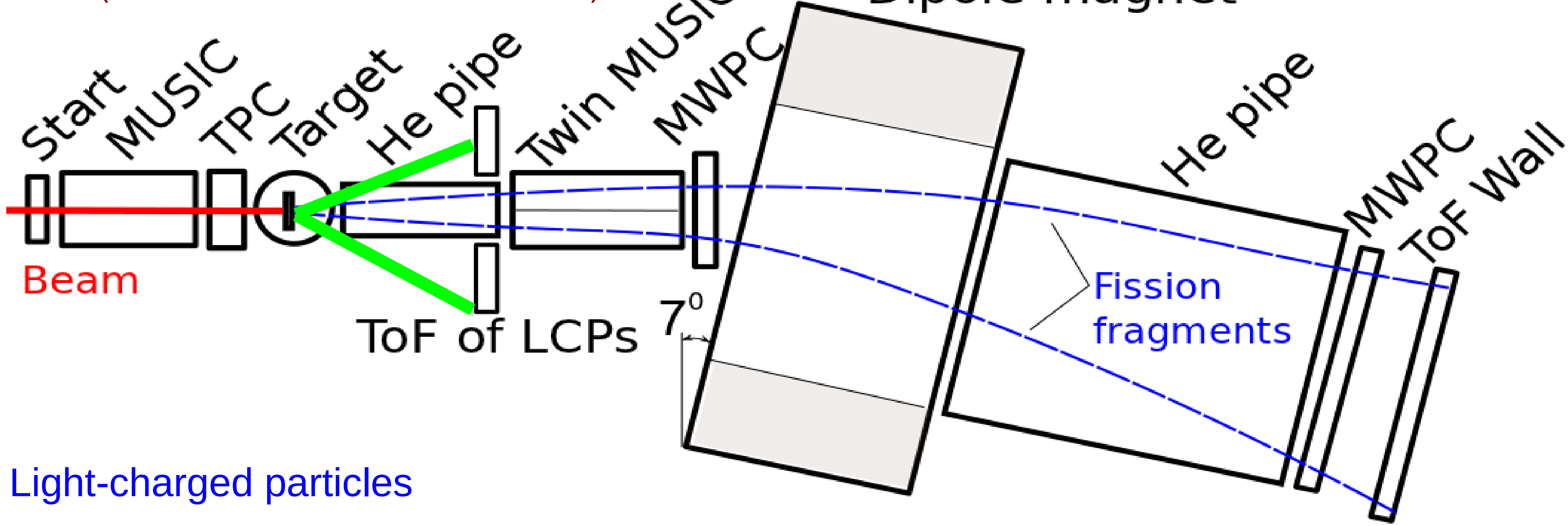
$$A = \frac{Z B \rho}{\beta \gamma}$$

Bρ: dipole magnet and tracking
βγ: time of flight

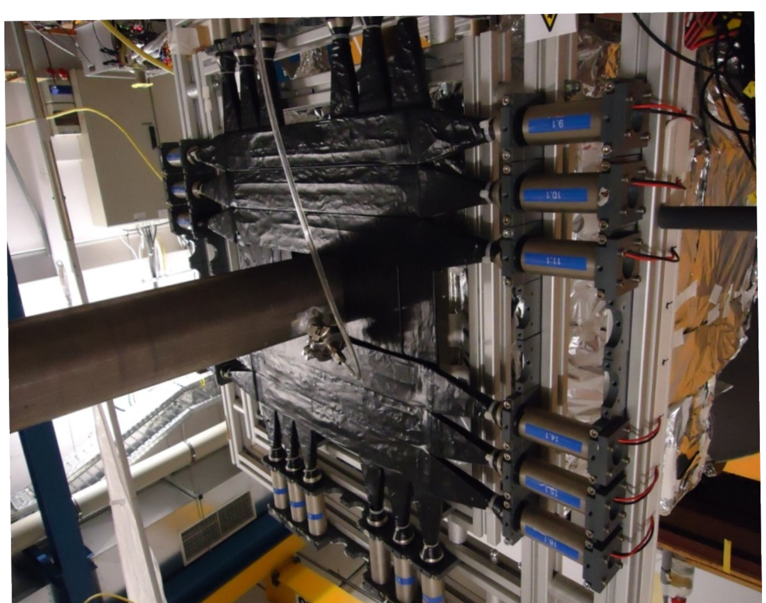


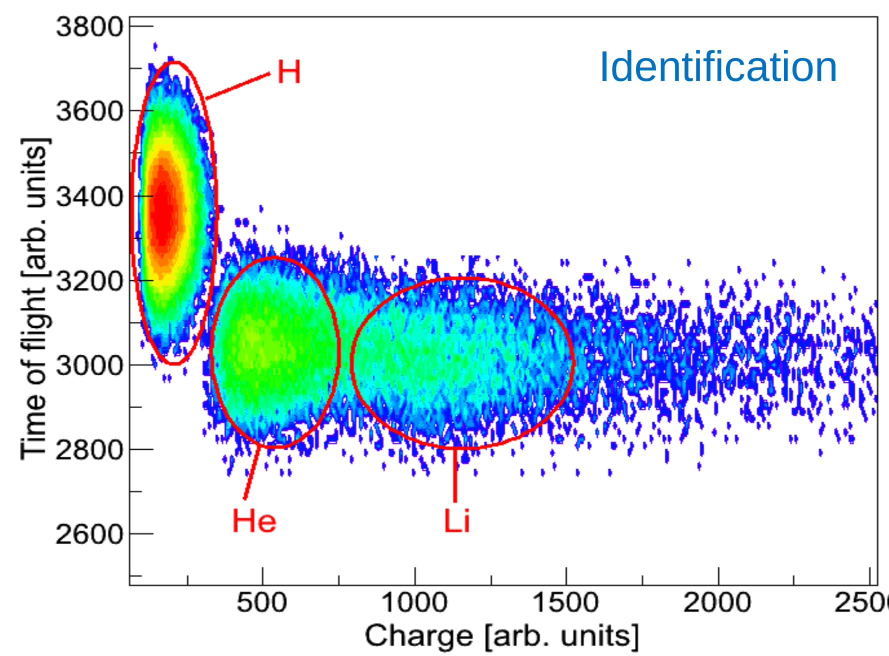
SOFIA: experimental setup

SOFIA (Studies On FIssion with Aladin)



Light-charged particles

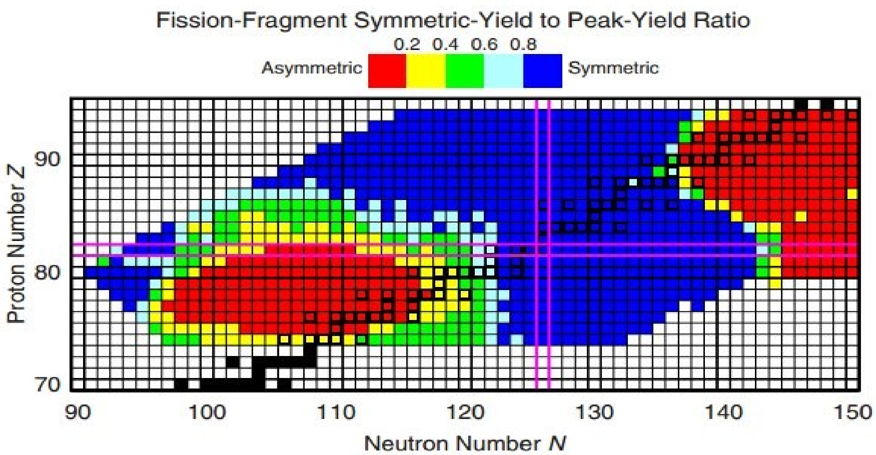


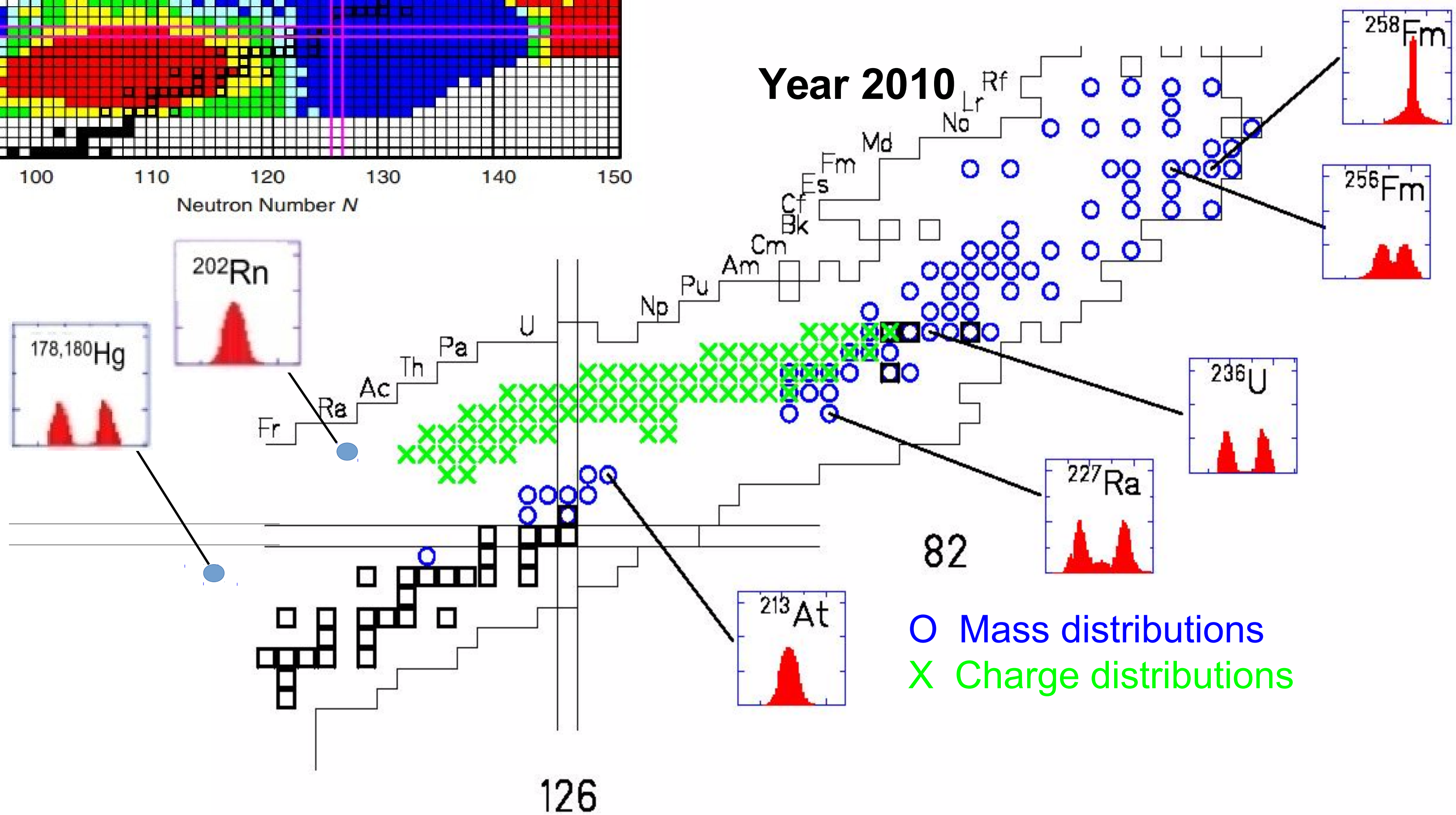


SOFIA: Coulomb-induced fission

Static properties

Mass/charge asymmetry dregree of freedom





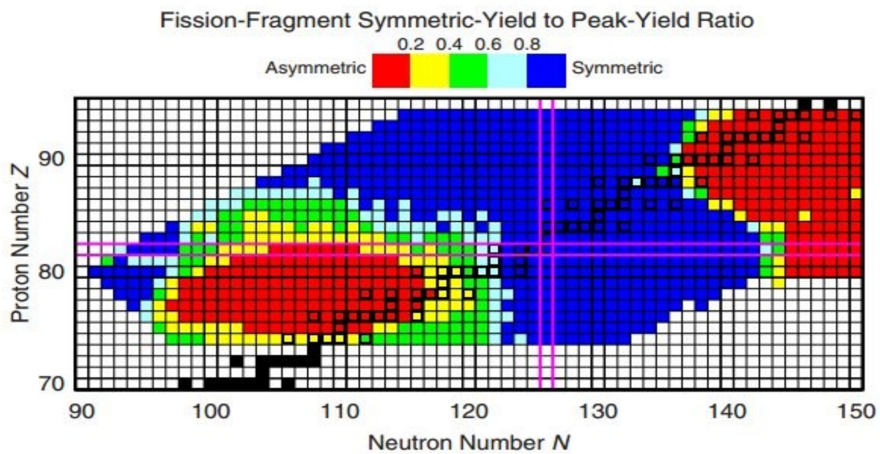
SOFIA: Coulomb-induced fission

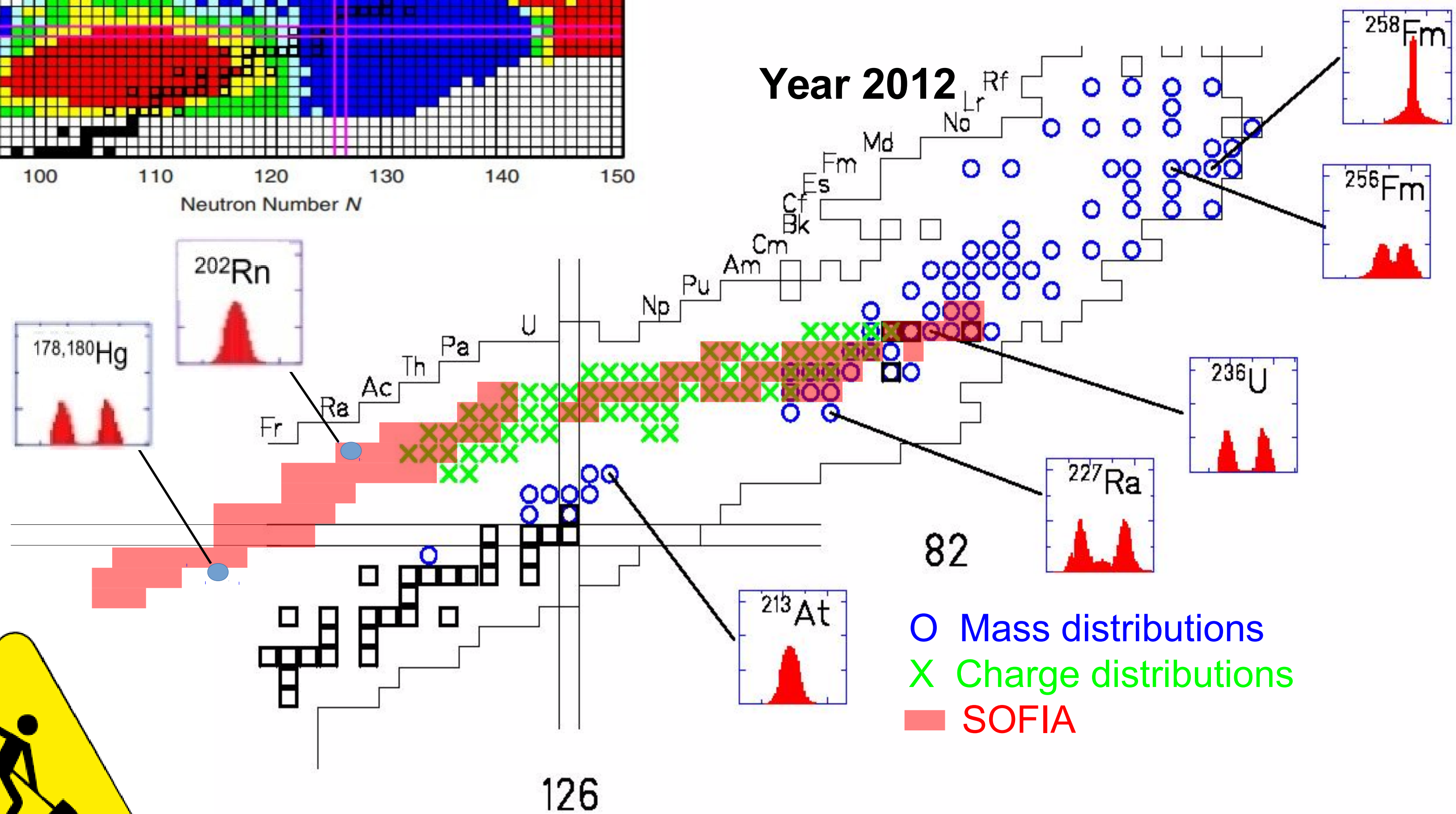
Static properties

Mass/charge asymmetry dregree of freedom

Measurement of the charge and mass distributions from uranium to mercury

J. Taieb et al., CEA (France)

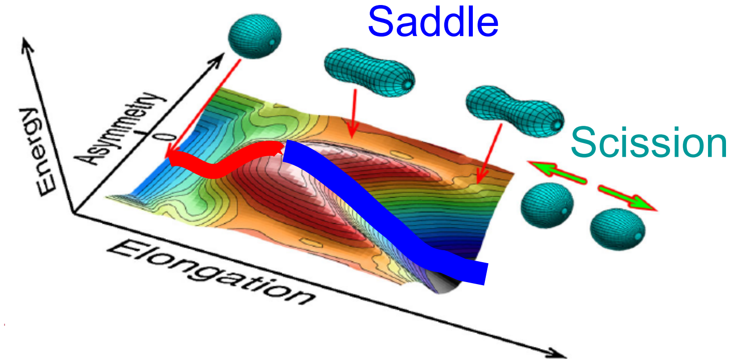




SOFIA: Spallation-induced fission

Dynamical properties

- Fission competes with other deexcitation channels like the evaporation of particles and γ-ray

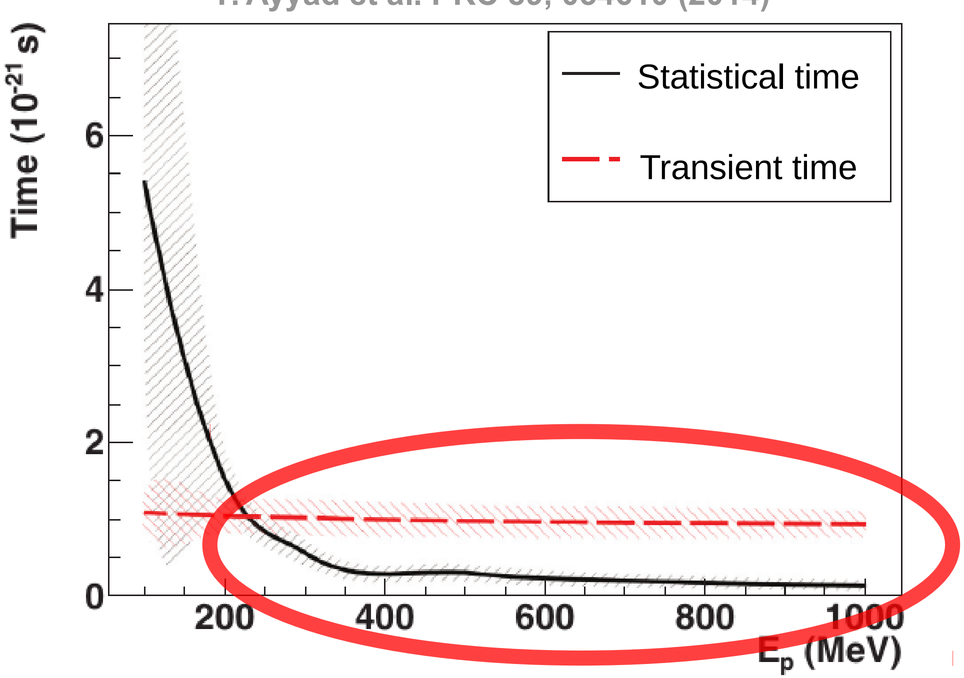


- Dinamical effects only appear at high excitation energies

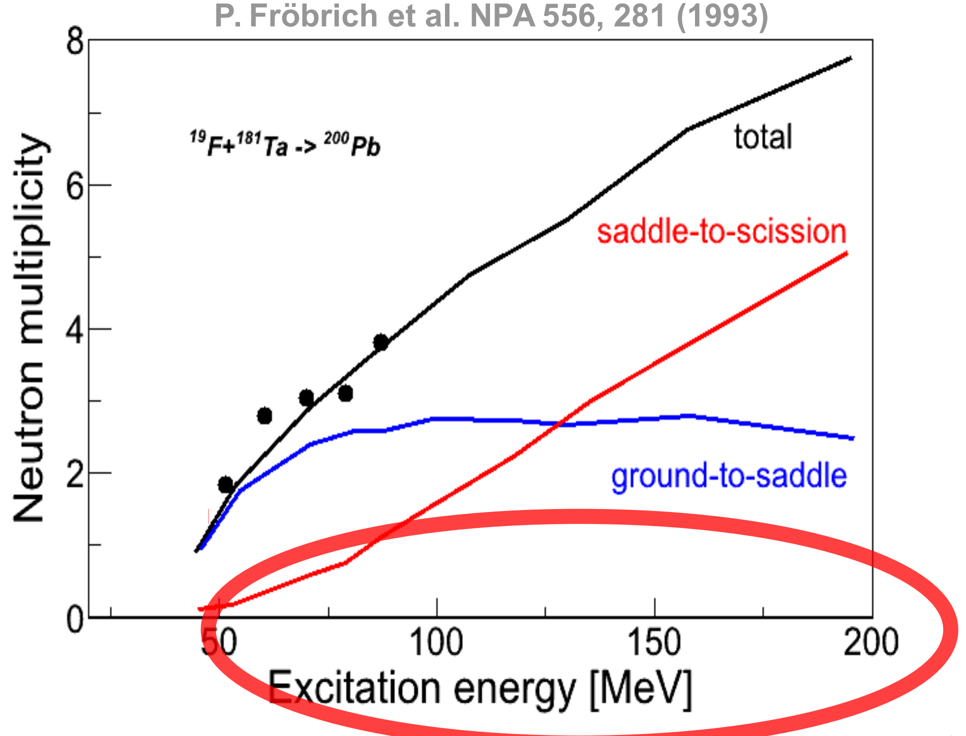
Ground-to-saddle: The time needed by the fissioning system to reach the saddle point (transient time) must be longer than the statistical time for the evaporation of particles

Saddle-to-scission: We need that the fissioning system evaporates particles beyond the saddle point

Y. Ayyad et al. PRC 89, 054610 (2014)



P. Fröbrich et al. NPA 556, 281 (1993)



SOFIA: Spallation-induced fission

Dynamical properties

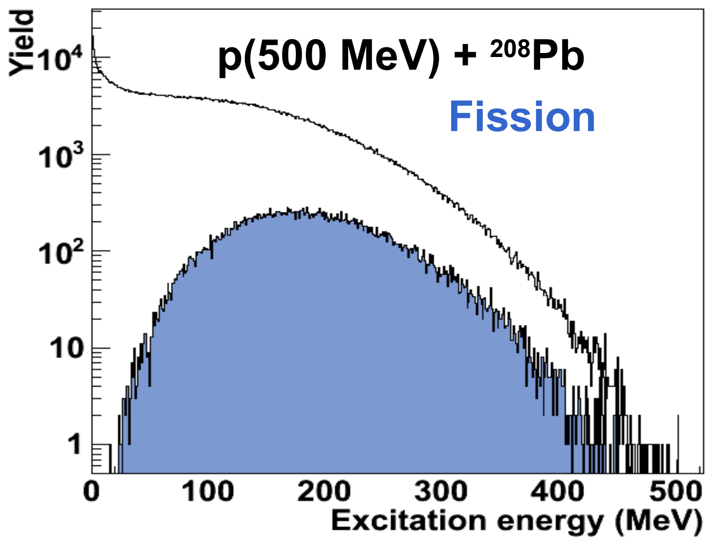
Why spallation reactions on lead

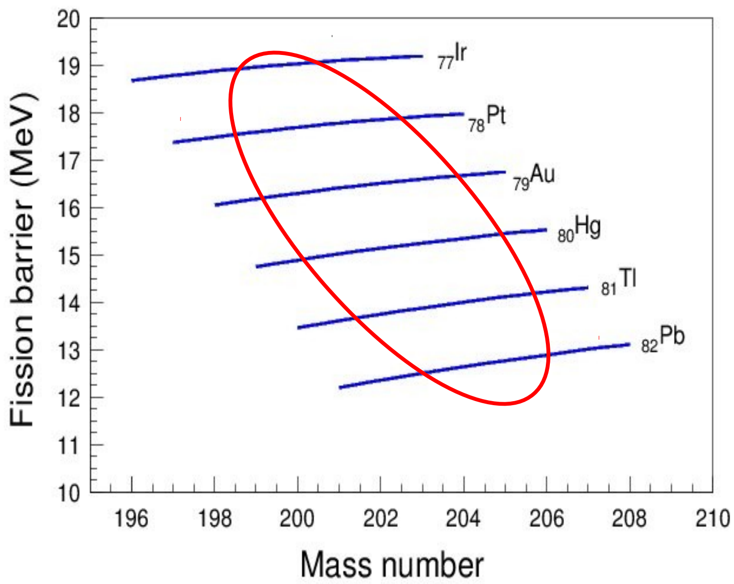
Spallation reactions induced by relativistic protons on nuclei of ^{208}**Pb** led to compound systems with:

- High excitation energy (E* > 100 MeV)

- Low angular momentum (L ~ 5 ħ)

- Small initial deformations





SOFIA: Spallation-induced fission

Dynamical properties

Saddle-point configuration

Fission probabilities and

charge distributions

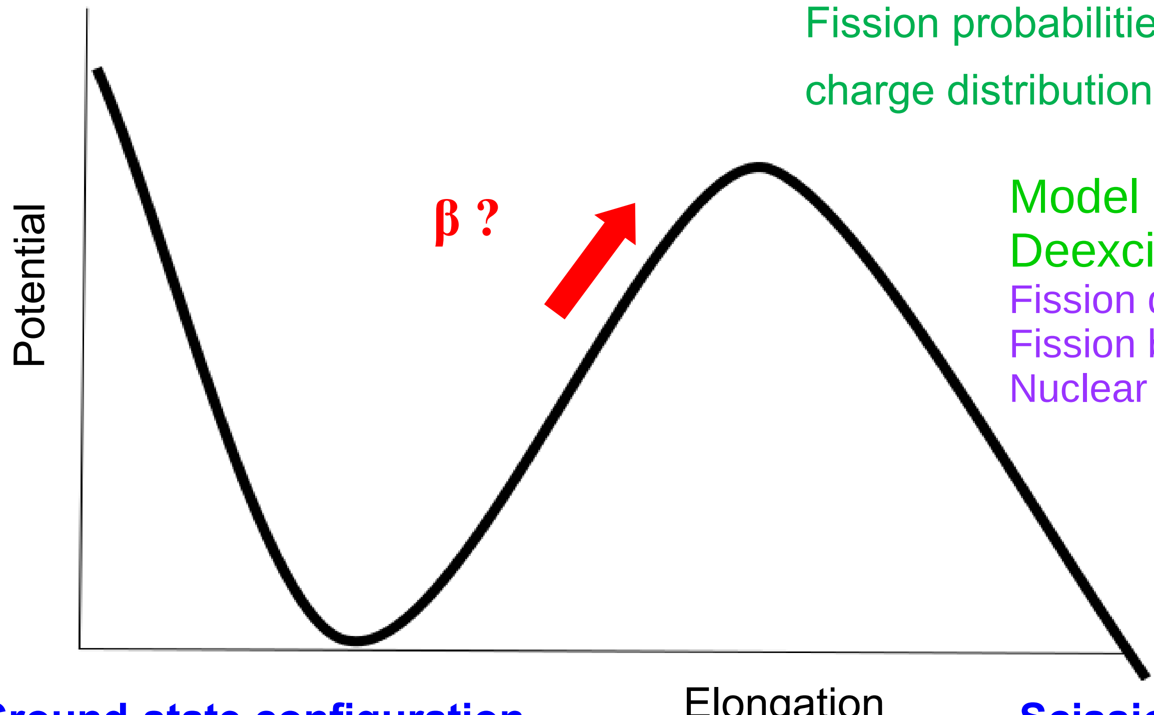
Model Calculations

Deexcitation code ABLA07

Fission dynamics: solution of the FPE

Fission barriers: Liquid-drop model + shell corrections

Nuclear level densities: Ignatyuk’s parametrization



Ground-state configuration

Model calculations

Intranuclear Cascade Code (INCL)

N_{fiss}, Z_{fiss}, E*,J

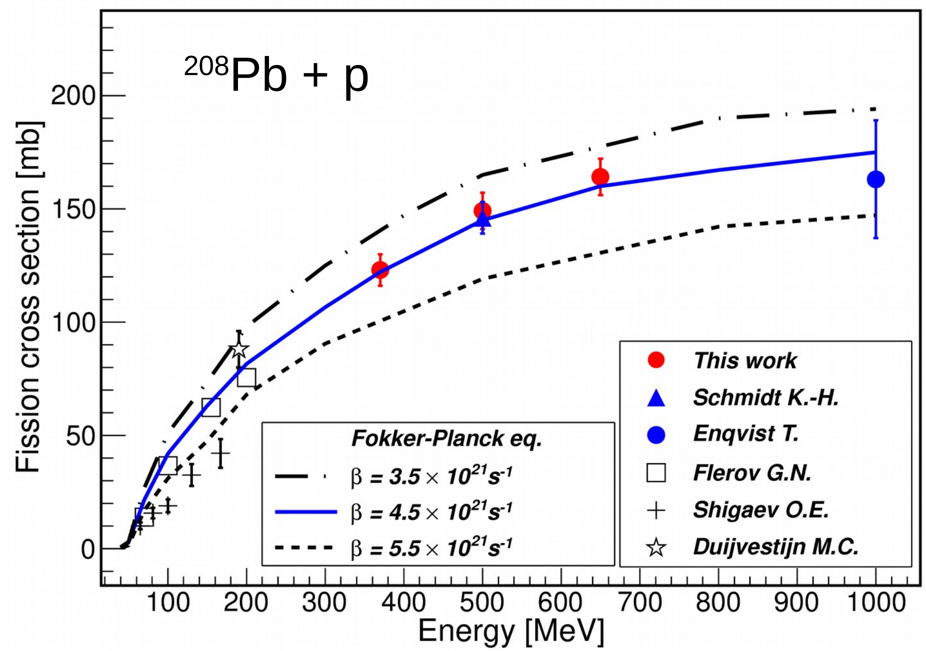
Scission-point configuration

SOFIA: Spallation-induced fission

Presaddle dynamics

Fssion cross sections as a function of the proton kinetic energy

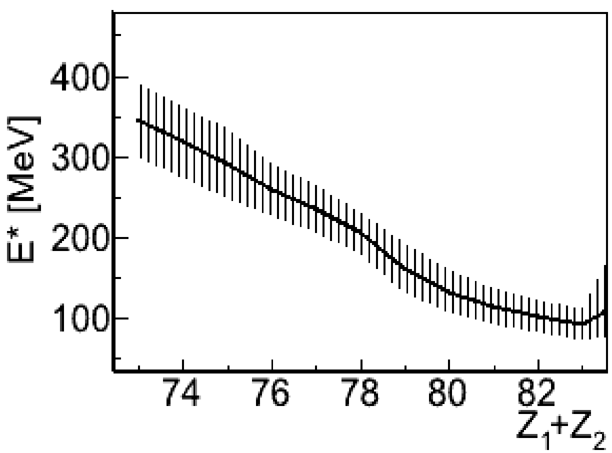
- Sensitivity to nuclear dissipation $\beta = 4.5 \times 10^{21} s^{-1}$

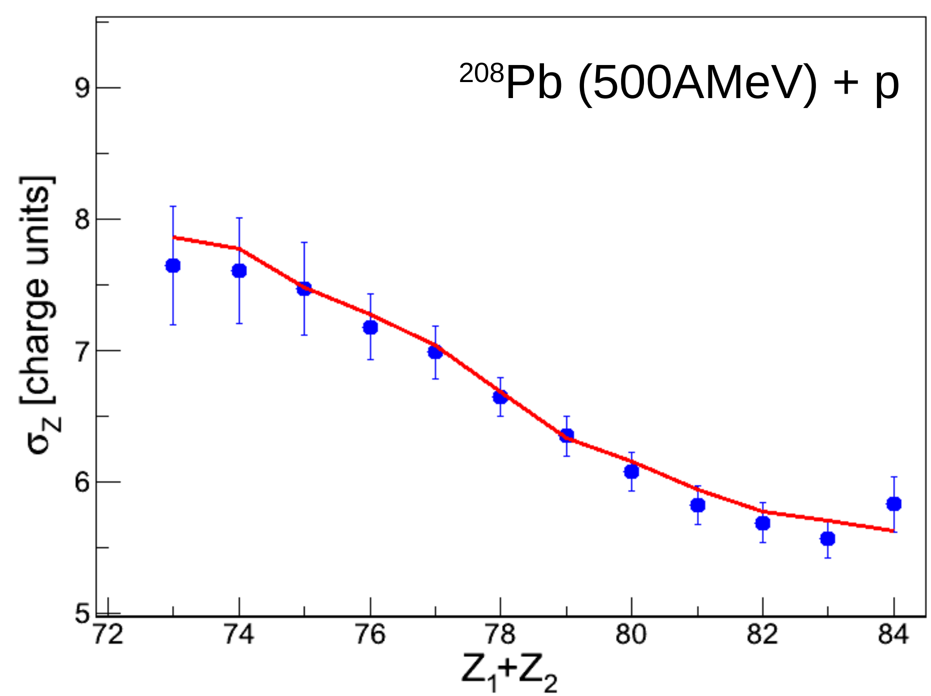


The width of the charge distributions is sensitive to the temperature of the fissioning system at saddle

$$\sigma(Z) \propto \frac{Z_{fis}^2 T_{sad}}{d^2V/d\eta^2}$$

η: mass asymmetry





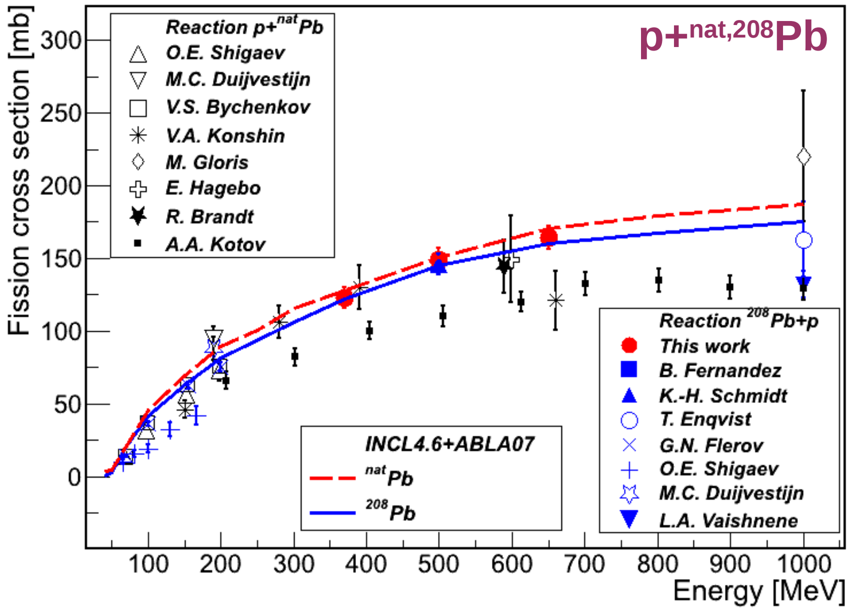
- The calculation for the charge distributions is consistent with a no dependence on temperature

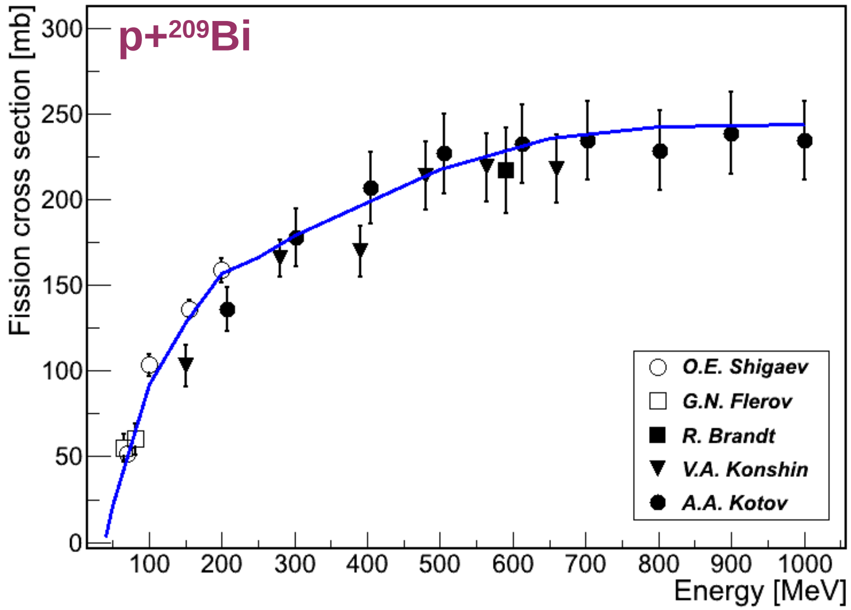
Conclusions in agreement with previous works

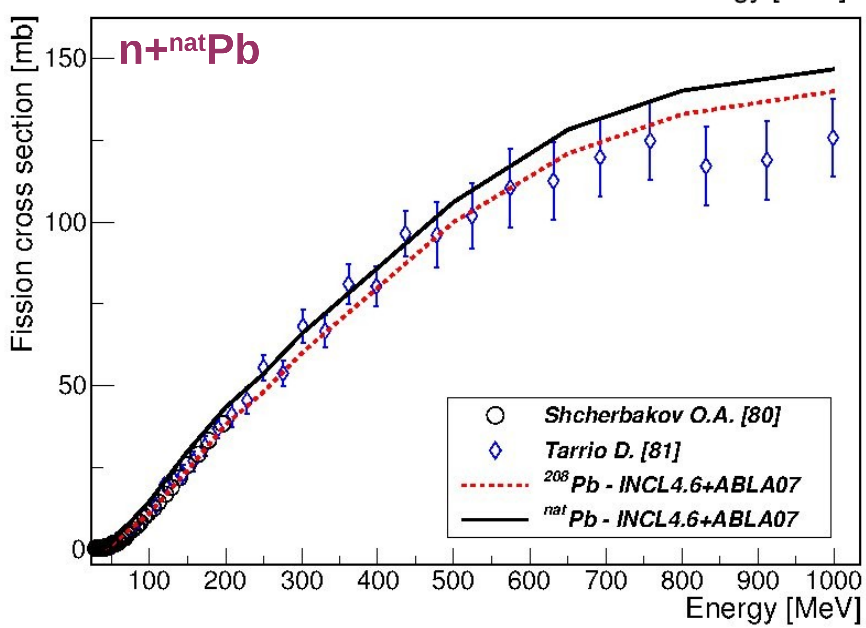
B. Jurado et al. PRL 93, 072501 (2004)
C. Schmitt et al. PRL 99, 042701 (2007)

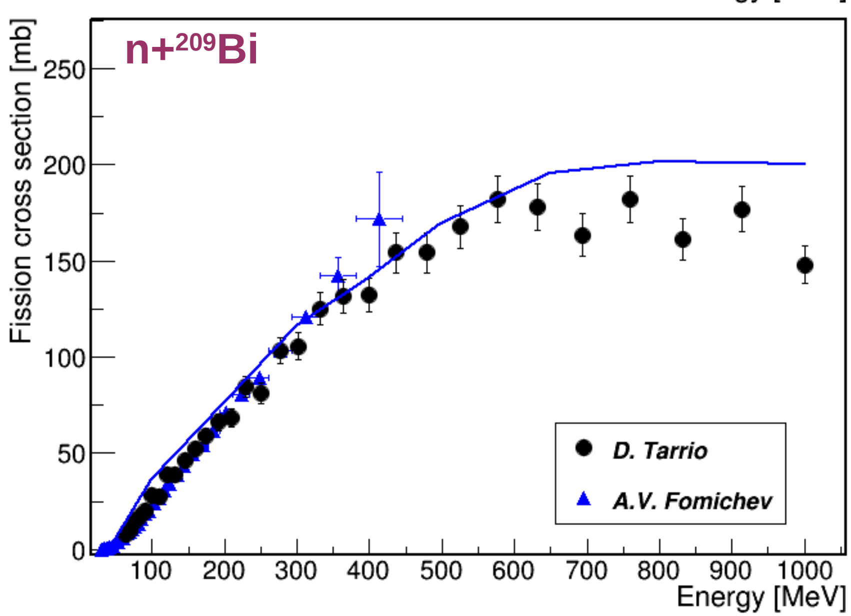
SOFIA: Spallation-induced fission

Systematic investigation of proton- and neutron-induced fission



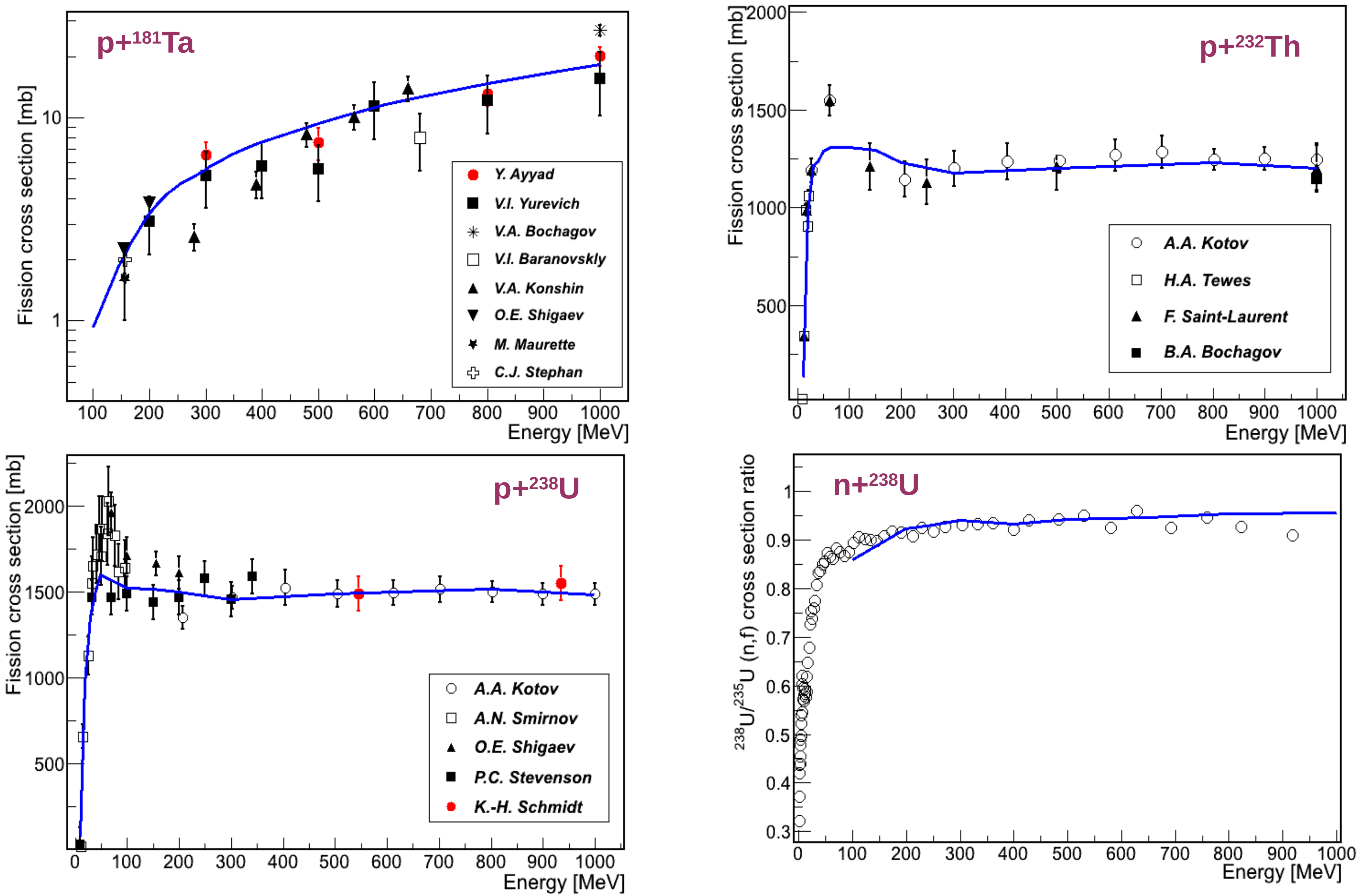






SOFIA: Spallation-induced fission

Systematic investigation of proton- and neutron-induced fission



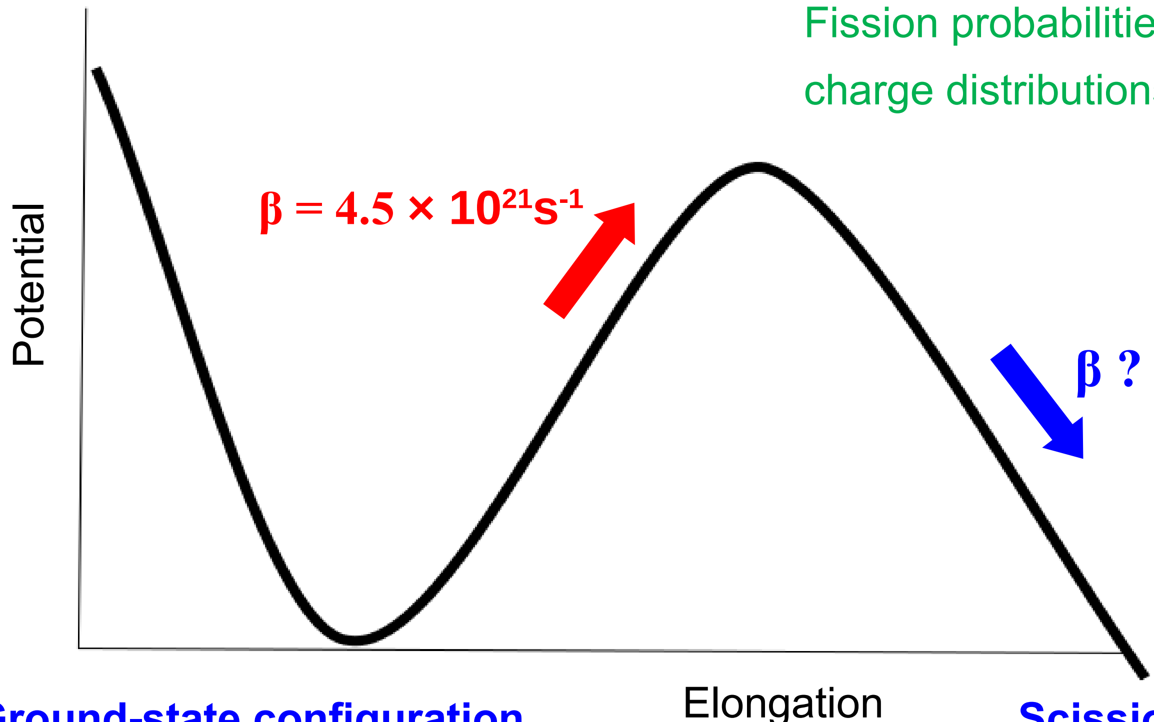
SOFIA: Spallation-induced fission

Dynamical properties

Saddle-point configuration

Fission probabilities and

charge distributions



Ground-state configuration

Model calculations

Intranuclear Cascade Code (INCL)

N_{fiss}, Z_{fiss}, E*,J

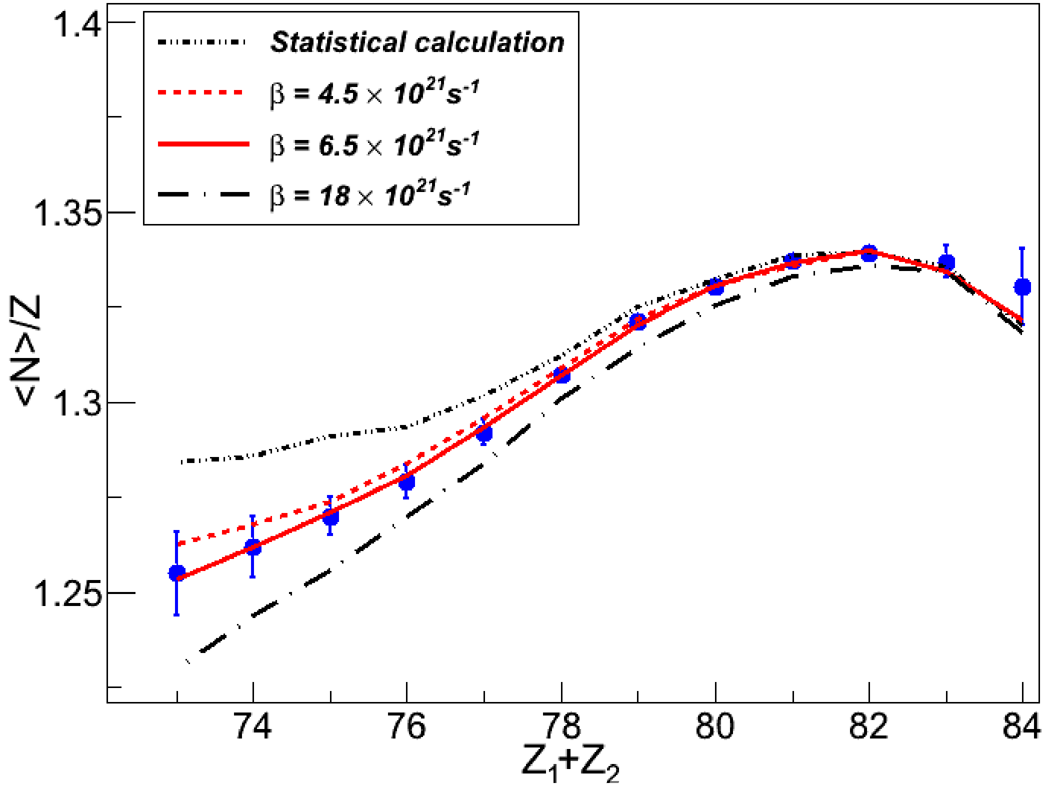
Scission-point configuration

Isotopic distributions of fission fragments

SOFIA: Spallation-induced fission

Postsaddle dynamics

Neutron excess of the fission fragments as a function of the fissioning system



This observable also depends on the evaporation of neutrons between the saddle and the scission point

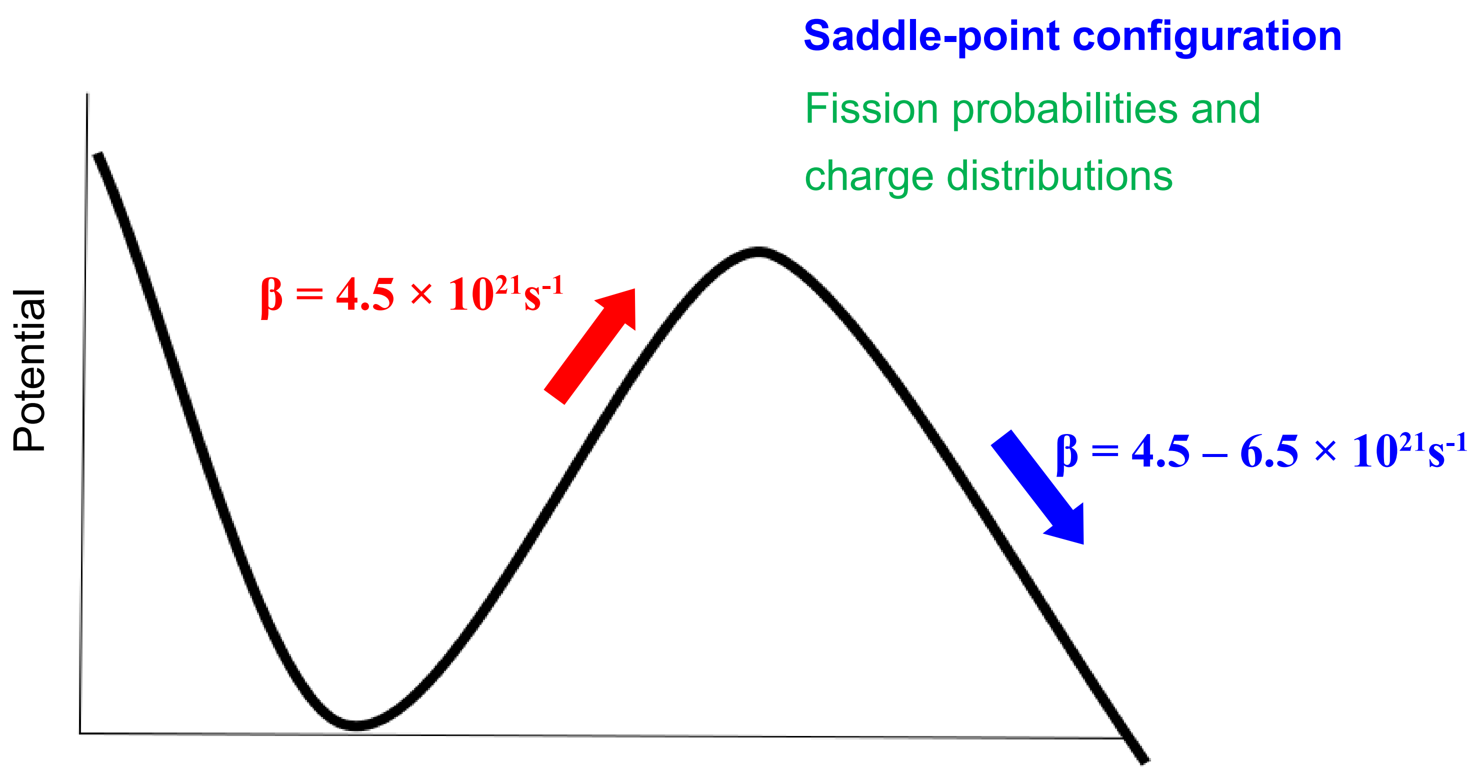
Excellent accuracy thanks to the good resolution in atomic and mass number of the fission fragments

The neutron excess allows us to constrain the dissipation parameter with more precision

β between **4.5 and 6.5 × $10^{21}s^{-1}$**

SOFIA: Spallation-induced fission

Dynamical properties



Ground-state configuration

Model calculations

Intranuclear Cascade Code (INCL)

N_{fiss}, Z_{fiss}, E^*,J

Scission-point configuration

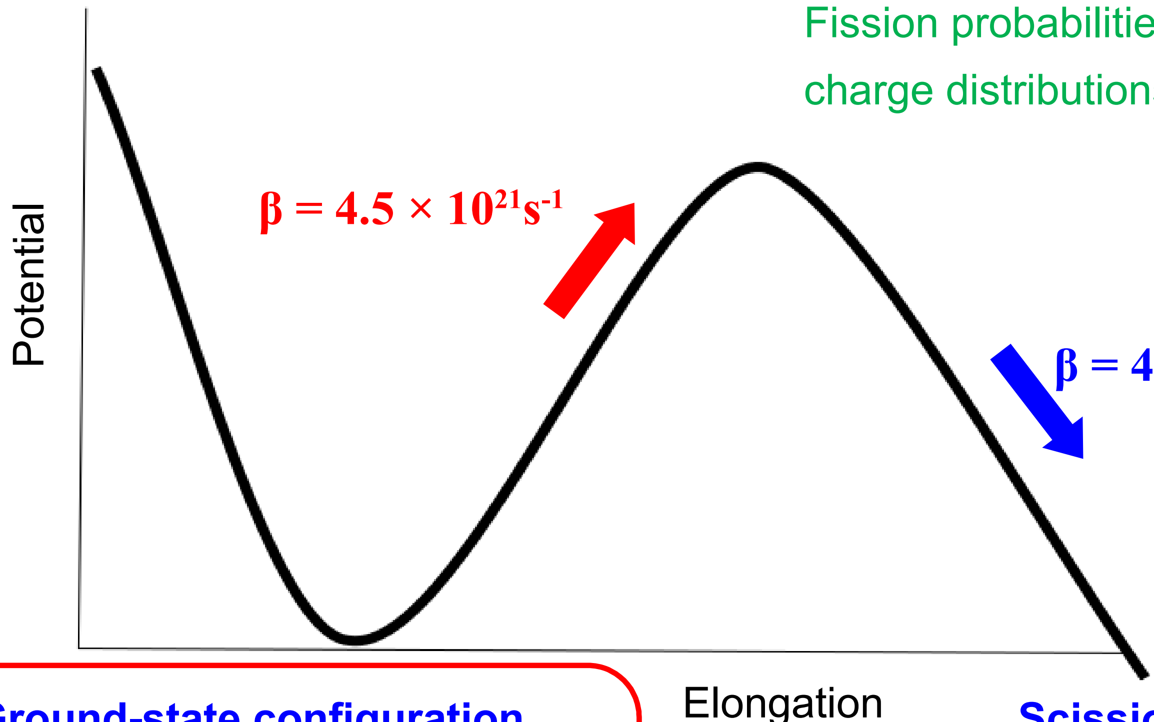
Isotopic distributions of fission fragments

Future opportunities with R3B@FAIR

Dynamical properties

Saddle-point configuration

Fission probabilities and
charge distributions



Ground-state configuration

Model calculations

Intranuclear Cascade Code (INCL)

N_{fiss}, Z_{fiss}, E^*,J

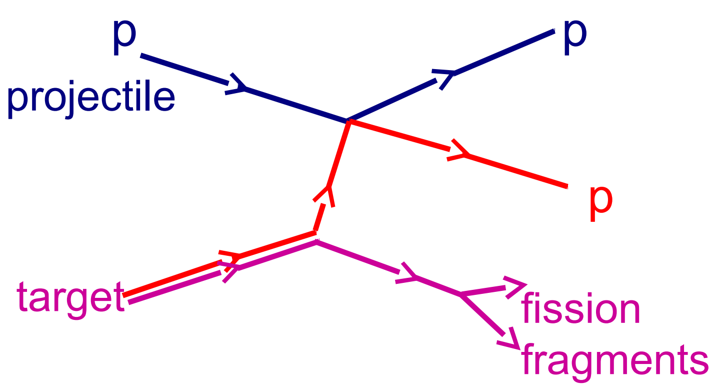
Scission-point configuration

Isotopic distributions of fission fragments

Future opportunities with R3B@FAIR

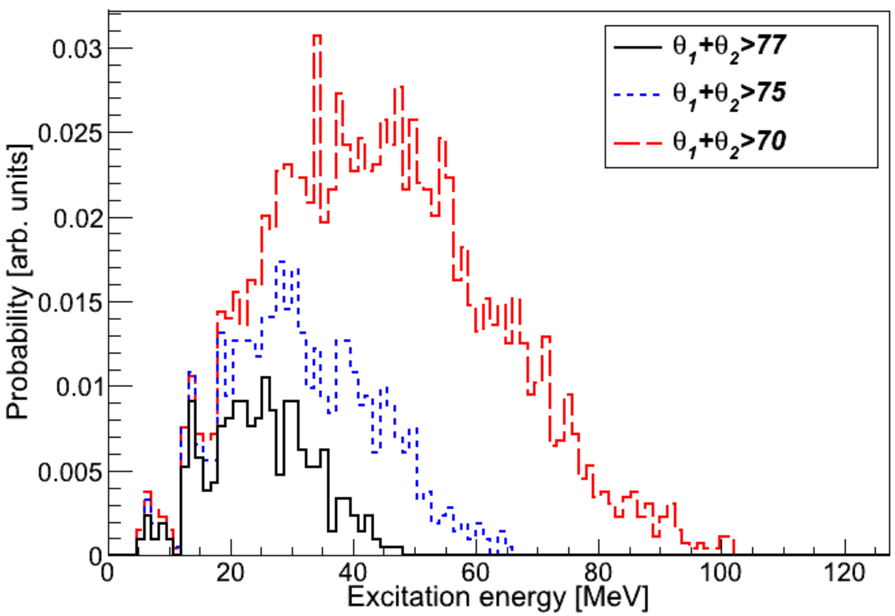
(p,2p) quasi-free scattering (~ 500A MeV)

High-energy induced fission under well defined initial conditions



Relatively large cross sections
- 10 – 50 mb

Possibility to use unstable nuclei
- inverse kinematics



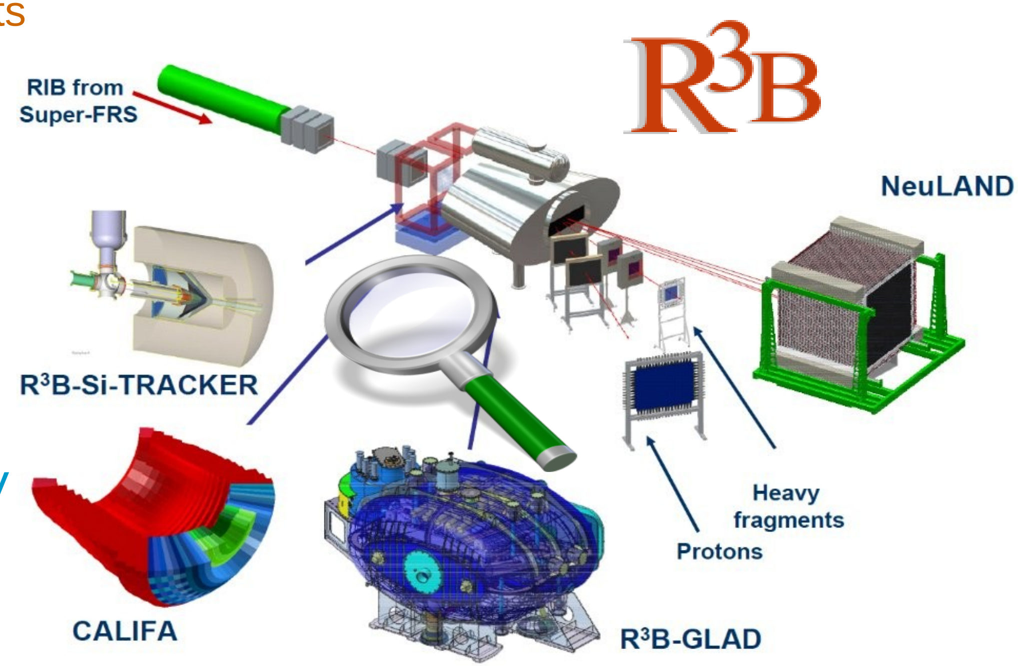
Well defined conditions of the fissioning systems
- Angular momentum around zero
- Excitation energy of the fissioning nucleus obtained from the mass invariant

Large range in excitation energy
- up to 70 MeV (maybe more)

Future opportunities with R3B@FAIR

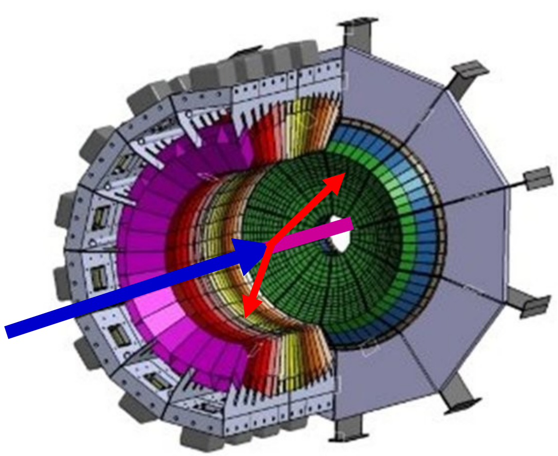
(p,2p) quasi-free scattering (~ 500A MeV): Experimental requirements

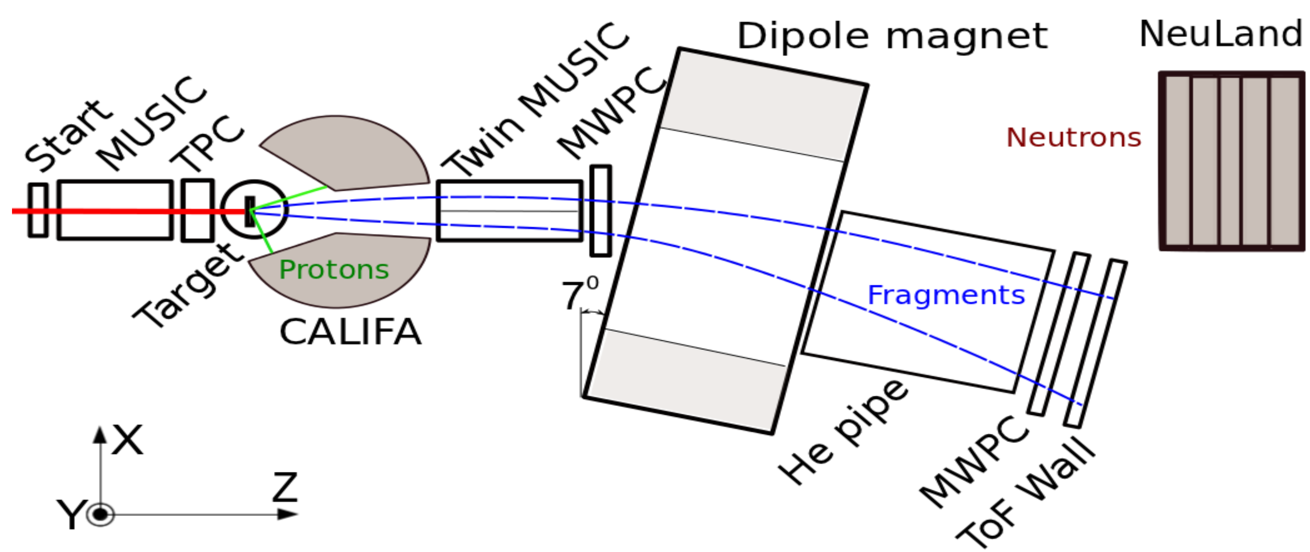
- Large acceptance for protons and fission fragments
- Good kinetic-energy resolution for protons



✓ Silicon tracker
  - Angular resolution ~ 1 mrad
  - Proton detection efficiency ~ 95%

✓ CALIFA
  - γ-ray energy resolution 5 % at 1 MeV
  - photopeak efficiency: 40% for Eγ=15MeV
  - energy range for protons: up to 700 MeV
  - proton energy resolution < 1 % (stopped)
    < 7% (punch through)

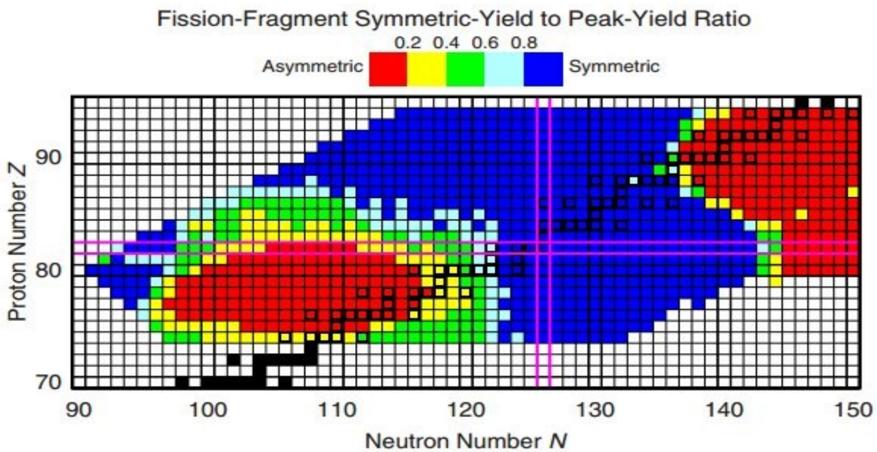




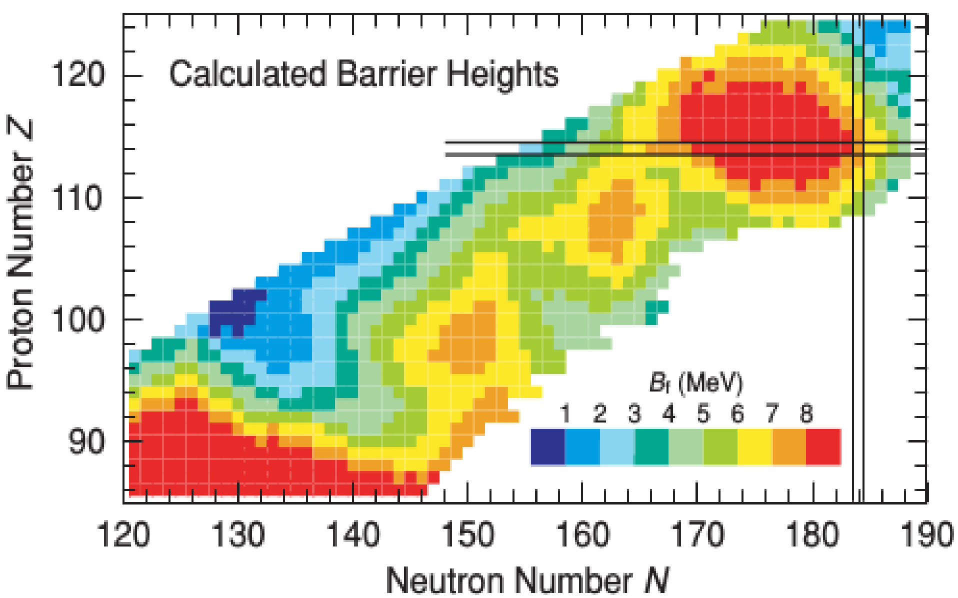
Future opportunities with R3B@FAIR

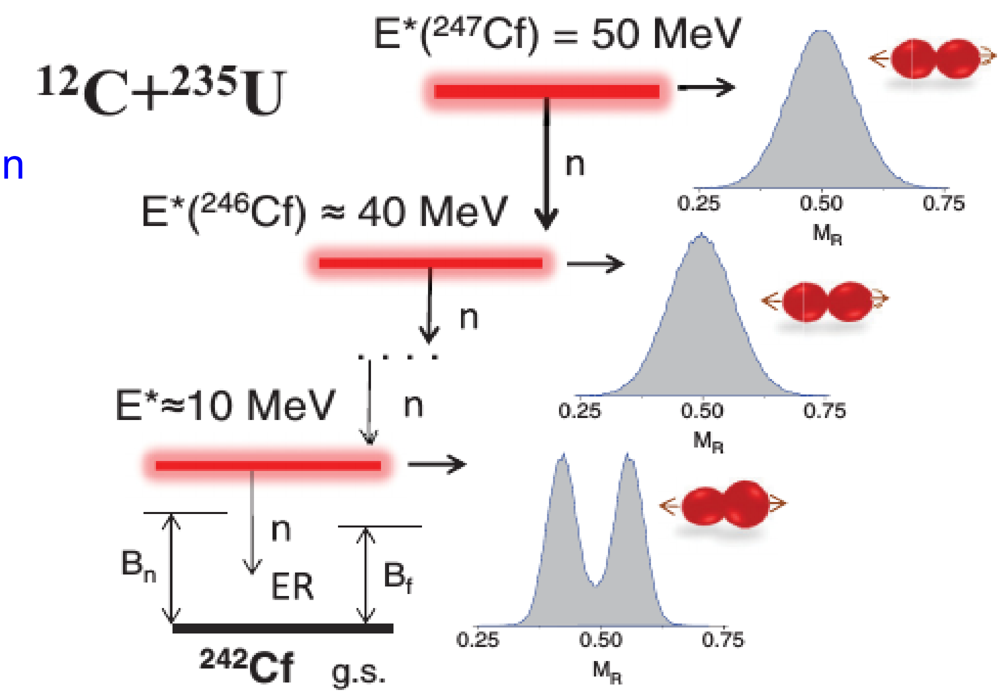
Proposals:

- Mass asymmetry transitions in fission
- Temperature dependence of shell effects in fission



P. Möller et al. PRC 79, 064304 (2009)





- Temperature dependence of collective effects in nuclear level densities
- Fission barries
- Dissipative effects

Conclusions

Many of the experimental limitations for investigating fission have been overcome by using the inverse kinematics, providing a complete characterization of the fission Fragments (A,Z,TKE) together with the light-charged particles

Partial fission cross sections and widths of the charge distributions were used to constrain the value of the **ground-to-saddle dissipation parameter**, obtaining a value of **4.5 × $10^{21}s^{-1}$**

Neutron excess of the fission fragments provides us a constraint for the value of the **saddle-to-scission dissipation parameter**, obtaining a value between **4.5 and 6.5 × $10^{21}s^{-1}$**

These results do not reveal any dependence of the dissipation parameter on deformation or temperature

Future experiments using **(p,2p) quasi-free scattering** could be used to investigate:

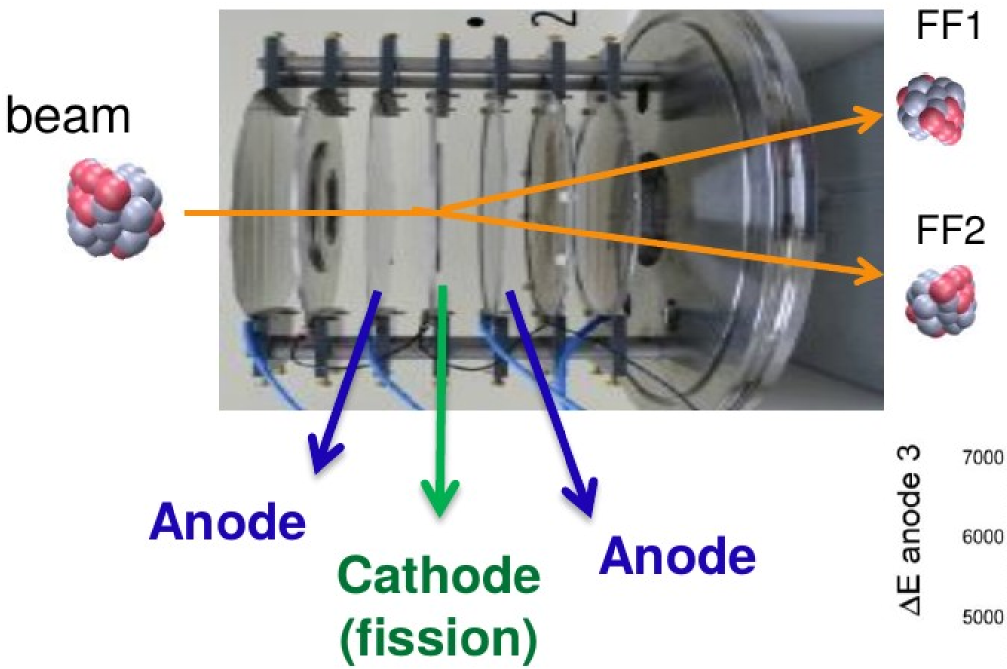
- fission barriers
- collective effects in nuclear level densities
- energy dependence of the structural effects observed in fission
- mass asymmetry transitions in fission

Thank you for your attention !!

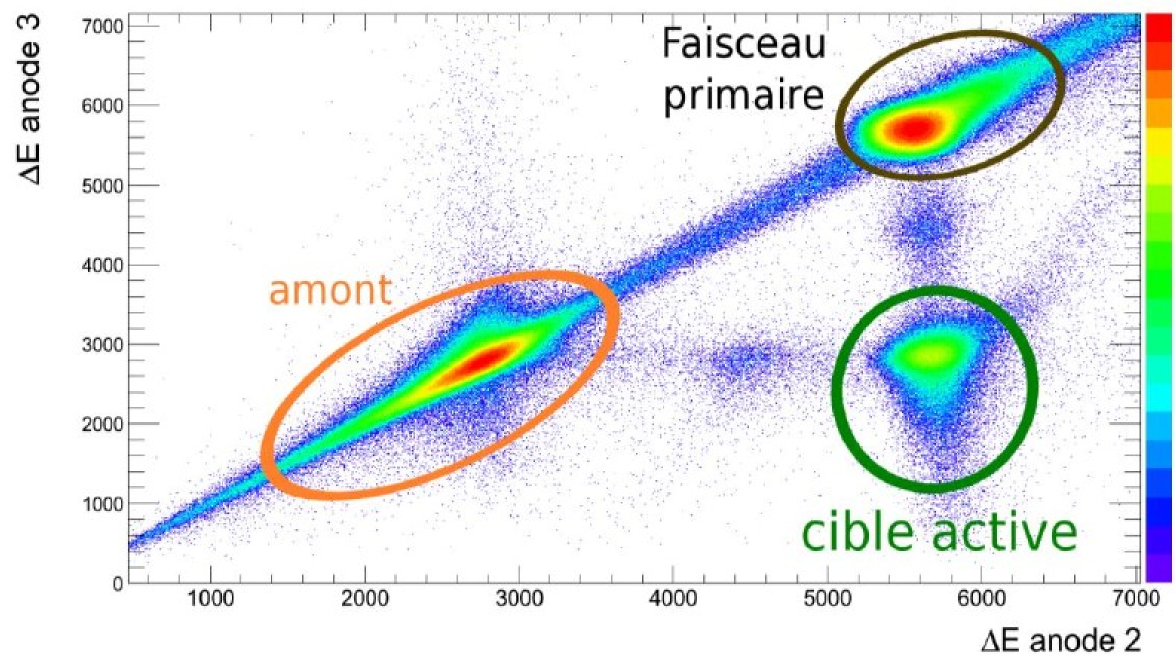
SOFIA: Coulomb-induced fission

Active target

Stack of ionisation chambers



$$\Delta E(FF1) + \Delta E(FF2) \approx \frac{\Delta E(^{238}U)}{2}$$



- ❑ **Fission in the cathodes**
- ❑ **Anodes : provide ΔE**

Courtesy : Julien Taieb