Dynamical effects in fission reactions investigated at high energies

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Why still fission?

One of the most interesting and challenging processes in nuclear physics

Fission has implications in many different domains:

- nuclear structure at large deformation
- dynamics of highly excited nuclear matter
- nuclear astrophysics
- production of RIBs and radio-tracers
- energy
- spallation neutron sources

A conceptually complicated process:

- largest scale collective motion in nuclei
- interplay between intrinsic and collective degrees of freedom
- governed by macroscopic and microscopic components in the nuclear potential

A difficult experimental characterization:

- atomic number of fission fragments only at reach in inverse kinematics
- full identification of both fission fragments only achieved very recently

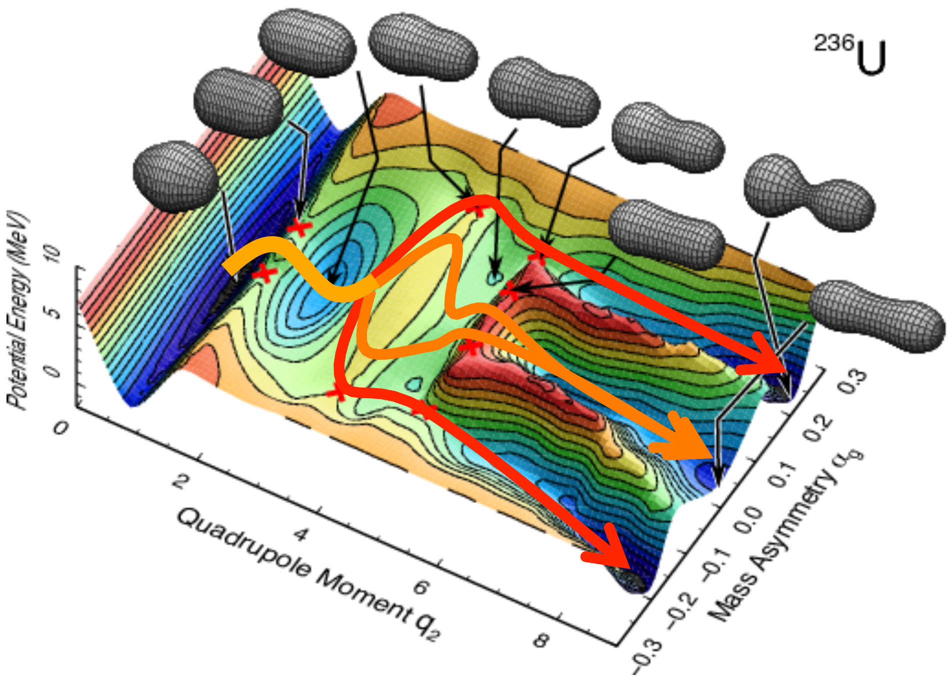
Layout

- ✓ Some basic concepts
- ✓ Experimental approaches
- ✓ Fission studies in inverse kinematics at GSI
  - setups
  - ground-to-saddle dynamics
  - post-saddle dynamics
- ✓ Future perspectives

Static properties

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

- **deformation**: when fission takes place (fission cross section)
- **mass asymmetry**: how fission occurs (fission fragments A, Z and kinetic energy)



Dynamic properties

Coupling between intrinsic (s.p. excitations) and collective (deformation) degrees of freedom: **fission time** and **energy dissipation**

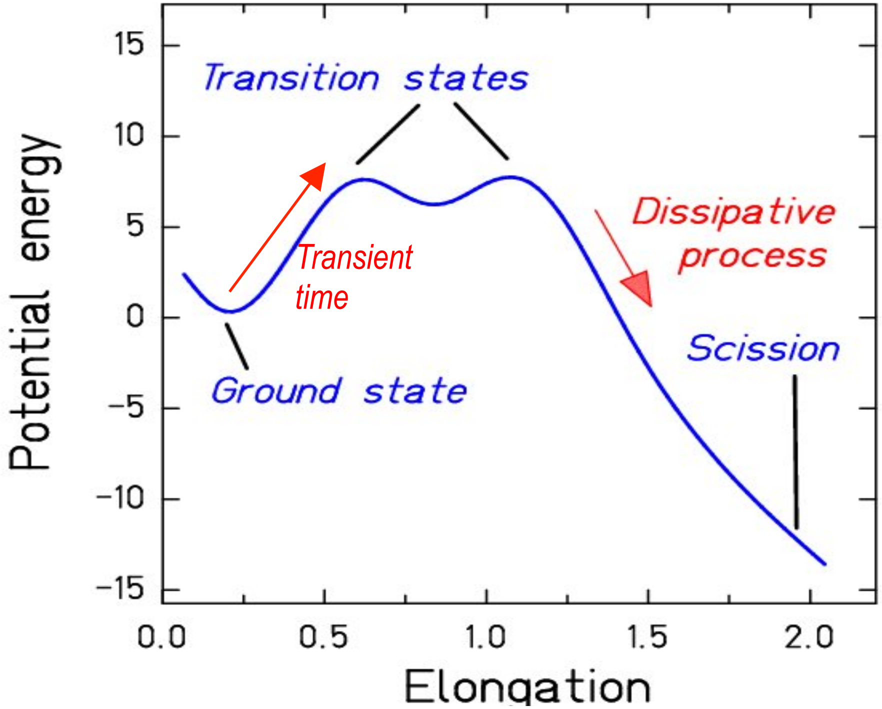
- Transport equations
- dissipation parameter

$$\frac{dv}{dt} = -\frac{1}{m}\frac{\partial V(Q)}{\partial Q} - \beta v - \frac{F(t)}{m}$$

The temperature and deformation dependence of the dissipation parameter under debate

Determination of the fission time: fission clocks

- Pre-scission particle emission (neutrons)
- Fission cross sections
- Crystal blocking techniques



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Determination of the fission time: fission clocks

- Pre-scission particle emission (neutrons)
- Fission cross sections
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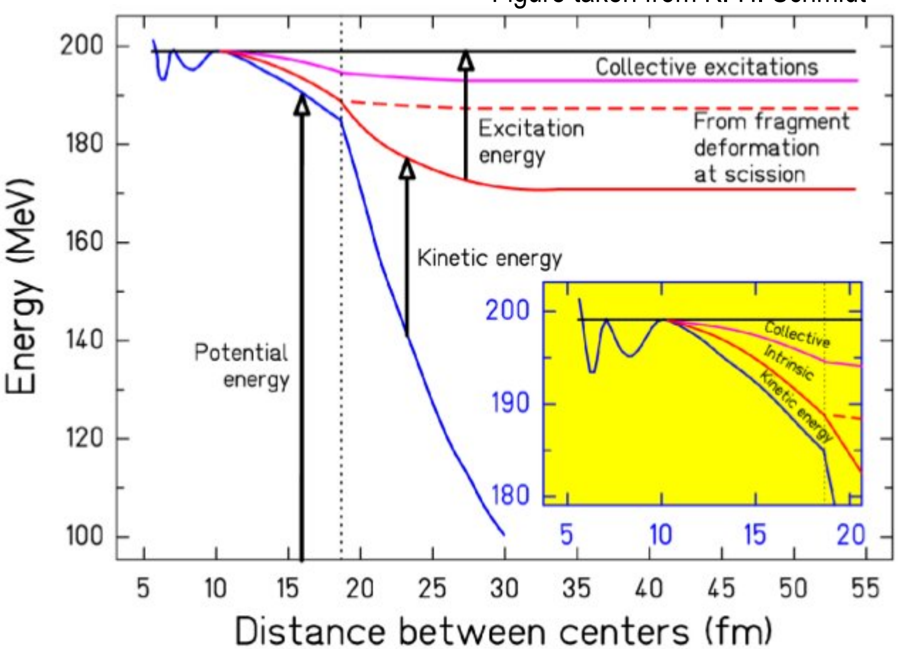
Energy dissipated

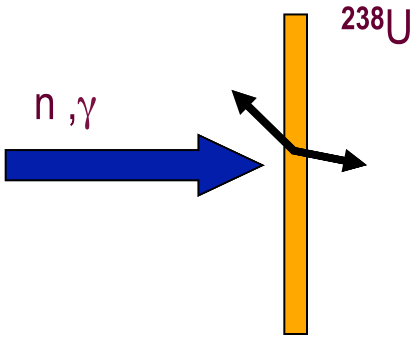
- Odd-even staggering in the fragments
- Pre-scission particle emission (neutrons)
- **TKE, A, Z of the fission fragments**

Figure taken from K.-H. Schmidt



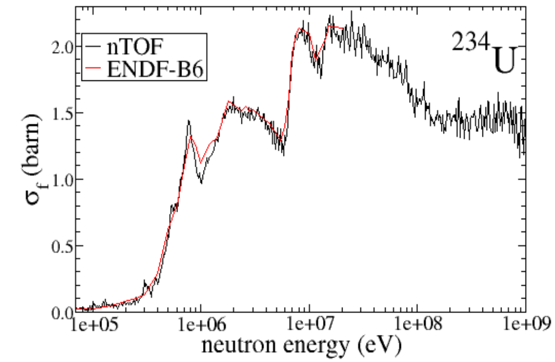
Experimental approaches

Direct kinematics:



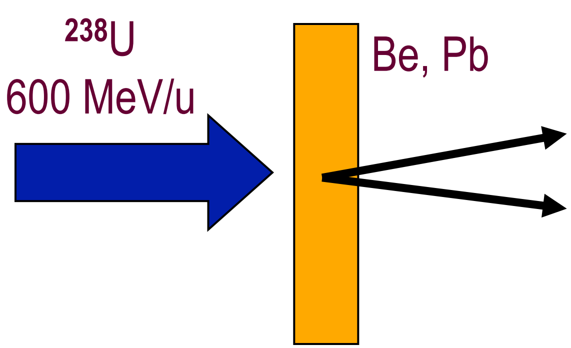
Observables:
- Fission cross sections
- Mass identification of both fragments
- Charge identification of light fragments
- neutrons and lcp in coincidence

Limitations:
- Charge identification of the fragments
- Only stable nuclei



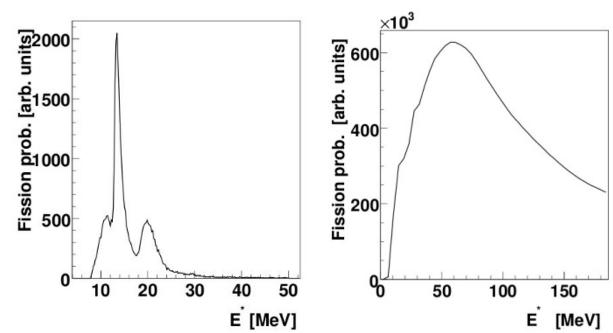
Main experiments:
- ILL, Geel, nTOF, …

Inverse kinematics:



Observables:
- Fission cross sections
- Mass and charge identification of both fragments (recently achieved)
- neutrons and lcp in coincidence

Limitations:
- Initial configuration (A, Z, E*, J)
- Minor actinides

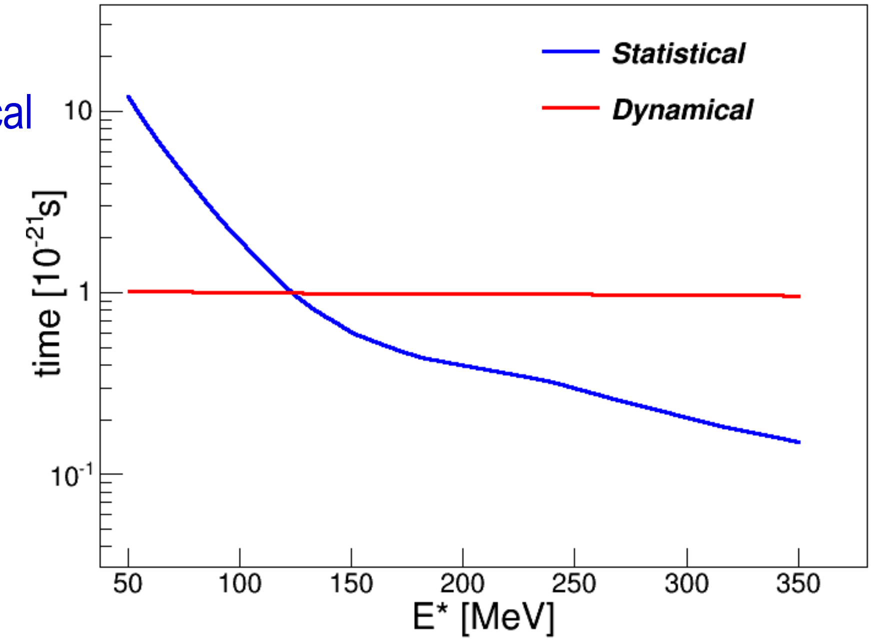


Main experiments:
- GSI, GANIL,RIBF, …

Experimental approaches

✓ Only at sufficiently high excitation energies dynamical effects seems to dominate over typical statistical times

✓ Reactions producing fissioning systems with low angular momentum and moderate deformation also favour the investigation of dynamical effects.



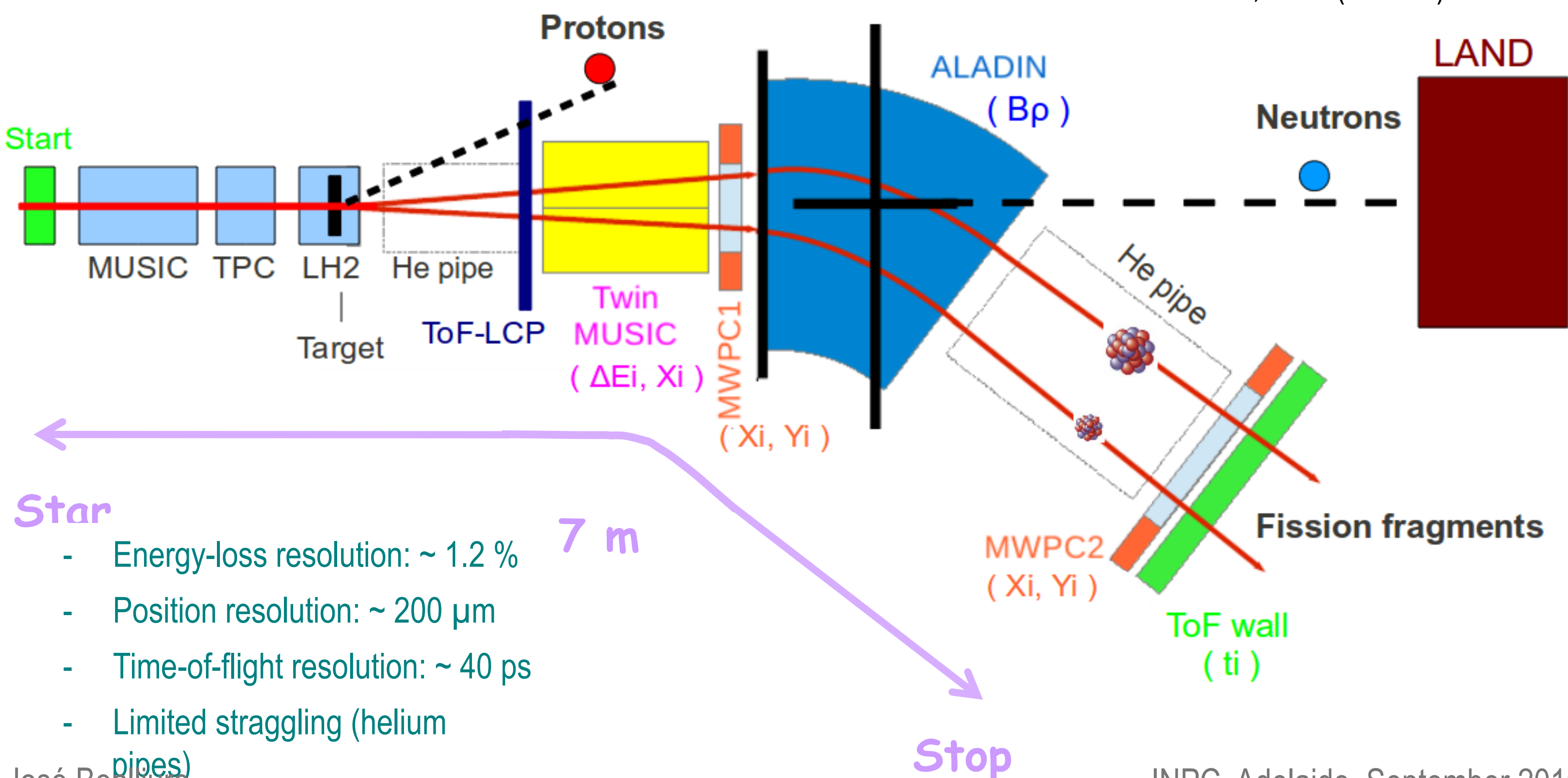
Spallation reactions induced by relativistic protons on low-fissility nuclei led to highly excited remnants with low angular momentum and deformation

^{208}Pb +p @ 370, 500, 650A MeV

Experiments at GSI

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

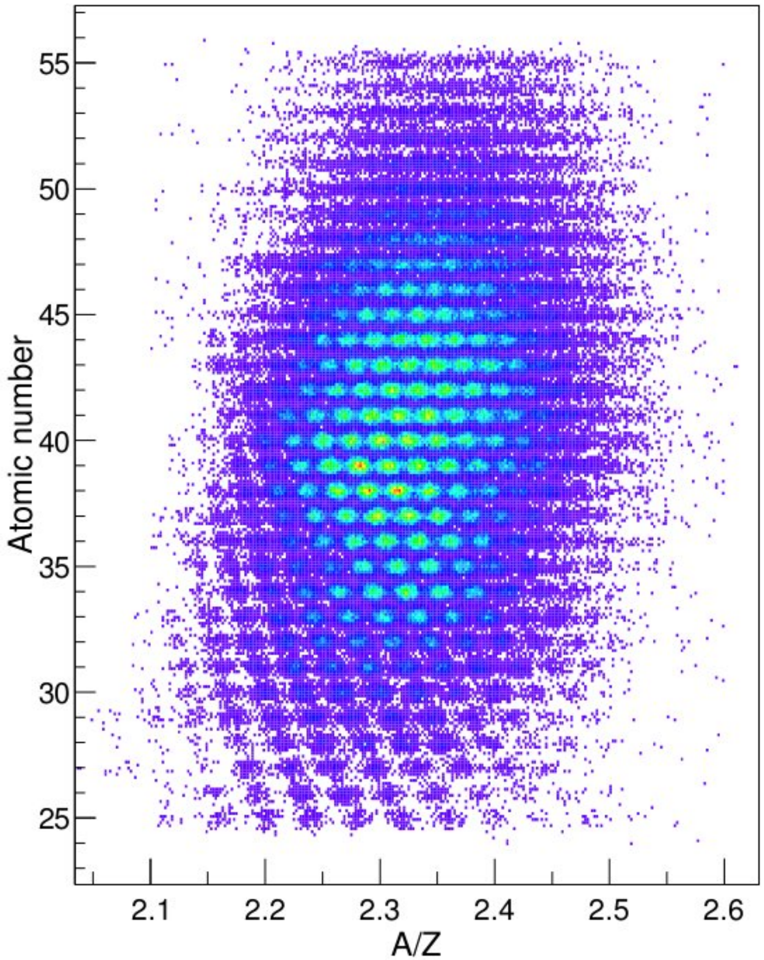
J. Taieb, CEA (France)



- Energy-loss resolution: ~ 1.2 %
- Position resolution: ~ 200 μm
- Time-of-flight resolution: ~ 40 ps
- Limited straggling (helium pipes)

Experiments at GSI

Complete identification of both fission fragments



For the first time both fission fragments were identified in atomic and mass number and their velocities were determined with good accuracy.

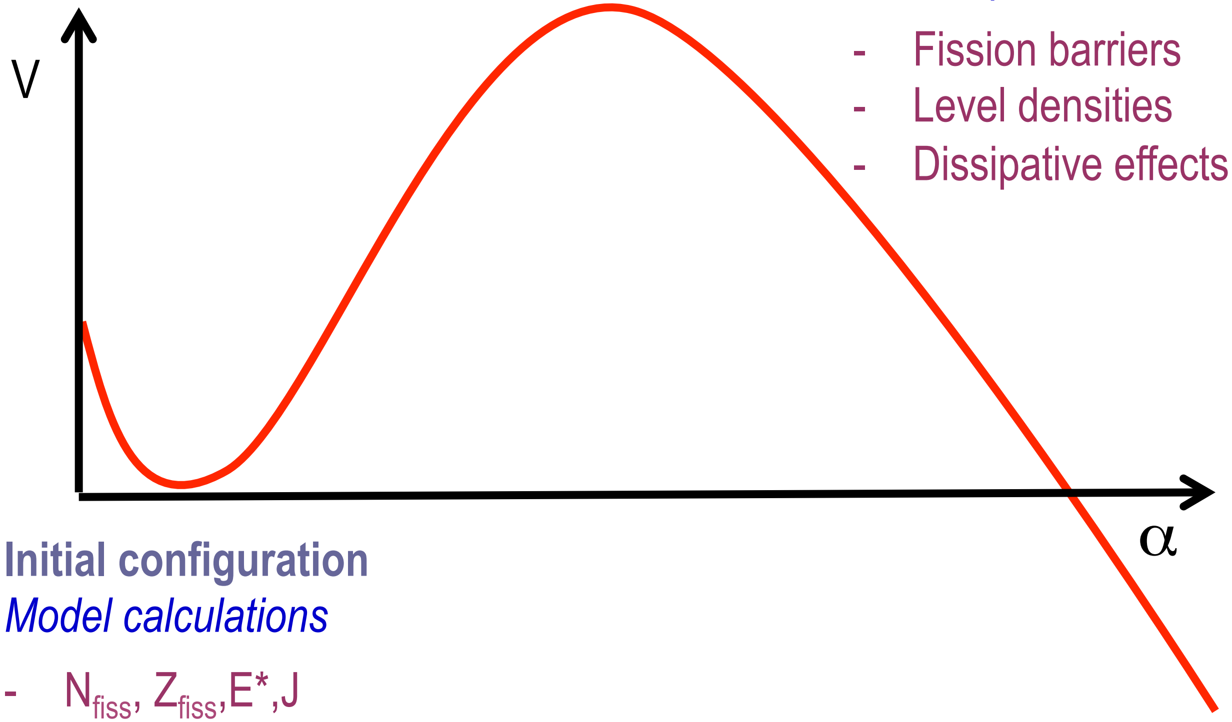
J.L. Rodriguez et al., Phys. Rev. C 91, 064616 (2015)

Fission at high-excitation energy: observables

Experimental information to constrain model calculations

Saddle point configuration
Fission probabilities and charge distributions:

- Fission barriers
- Level densities
- Dissipative effects



Initial configuration
Model calculations

- N_{fiss}, Z_{fiss}, E^*, J
- Energy dependence of shell corrections
- Energy dependence of collective enhancement

Scission point configuration
Isotopic and TKE distributions

- Mass asymmetry
- Energy sharing
- Dissipative effects
- Fragments deformation

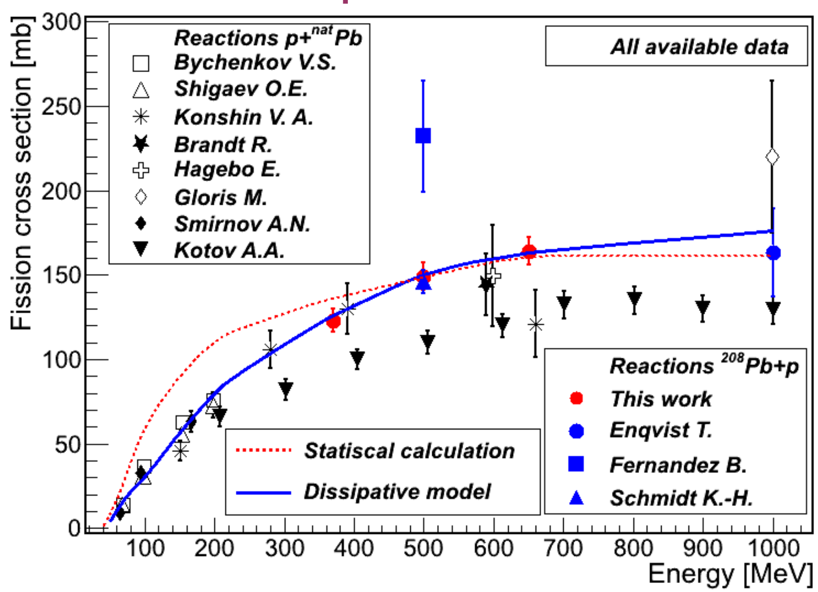
Ground-to-saddle dynamics

Total fission cross sections.

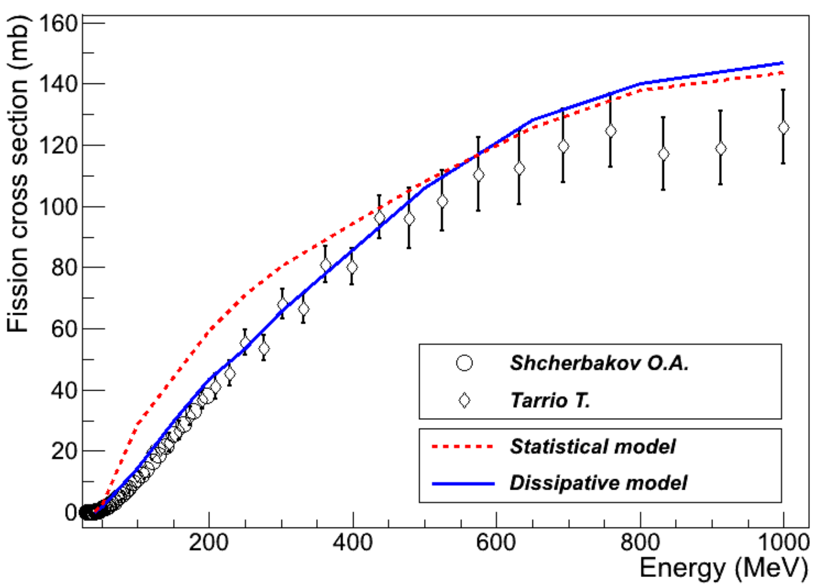
- Measurements on high energy fission were scarce and/or controversial until recently.

- Fission probabilities are defined by the fissioning nucleus (A, Z, E*, J), the fission barrier, level densities and the model used for the fission decay width (nuclear viscosity β).

$p+^{nat,208}Pb$



$n+^{nat}Pb$



- Additional boundaries required to constrain model parameters contributing to the fission width.

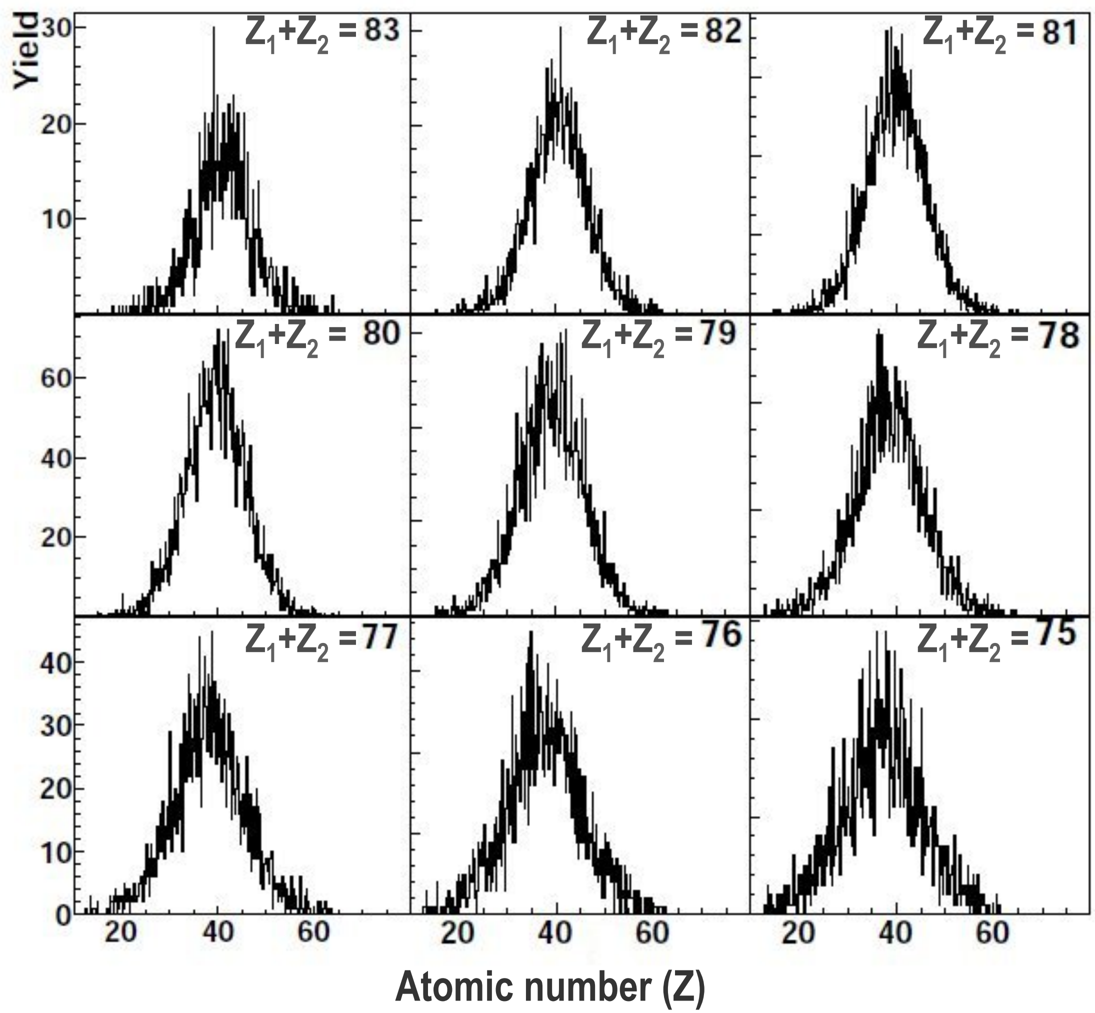
Dissipative model: INCL4.6 + ABLA07

Statistical model: INCL4.6 + Bohr&Wheeler

Ground-to-saddle dynamics

Charge distributions

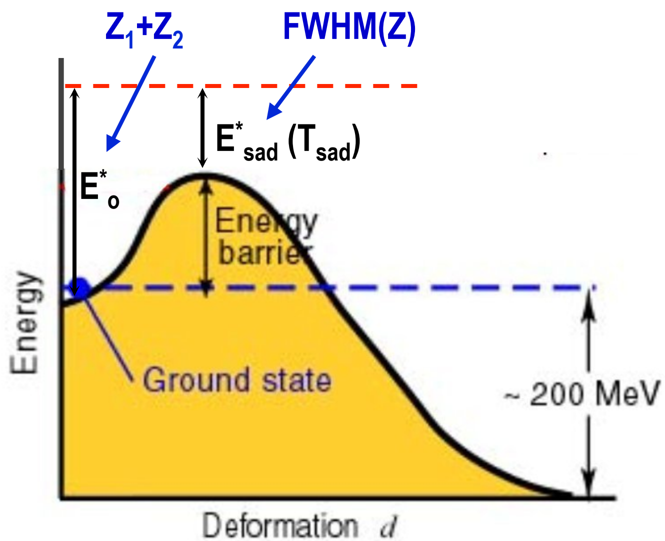
^{208}Pb+p 500 A MeV



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

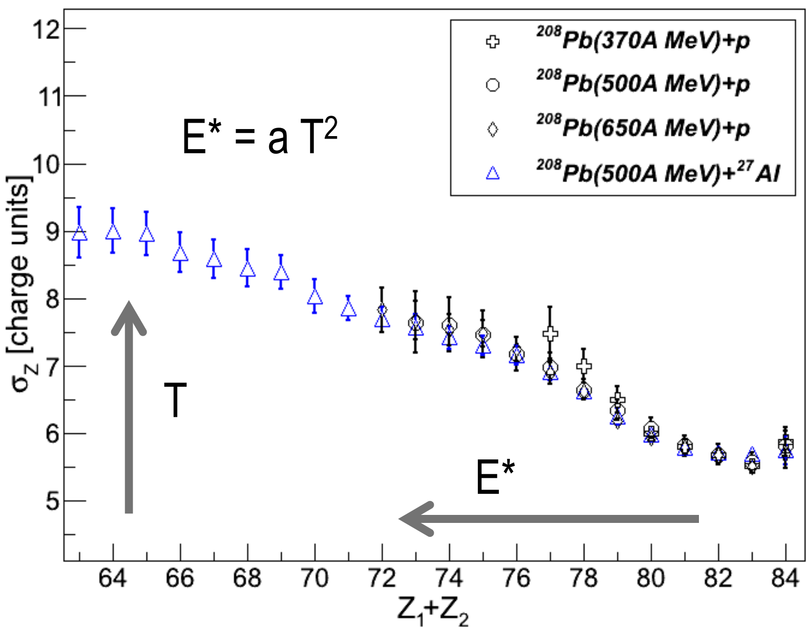
$$FWHM(Z) \propto \frac{Z_{fis}^2 T_{sad}}{d^2V/d\eta^2}$$

η: mass asymmetry



Ground-to-saddle dynamics

Charge distributions



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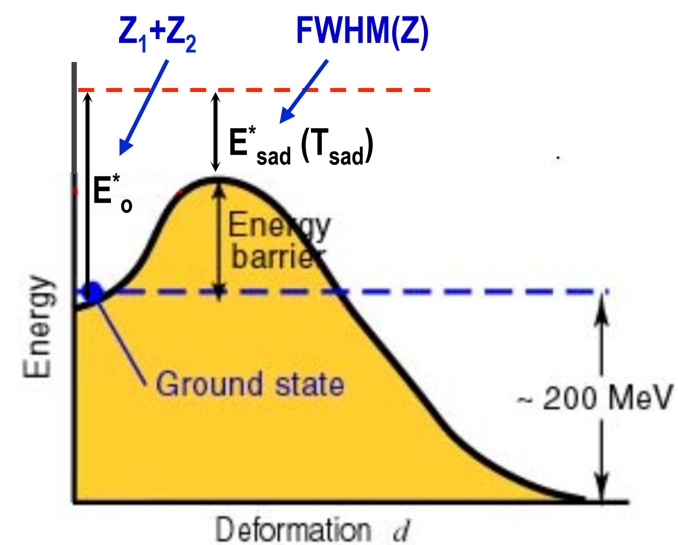
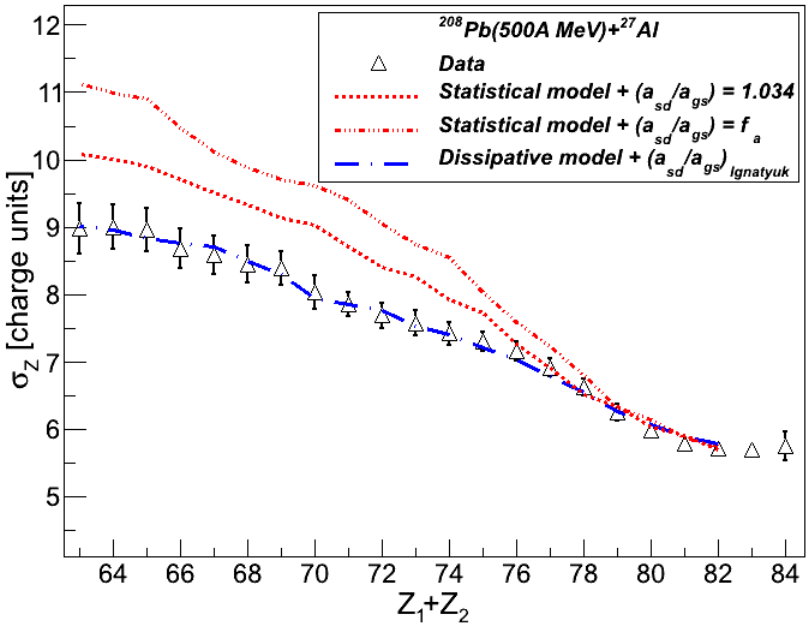
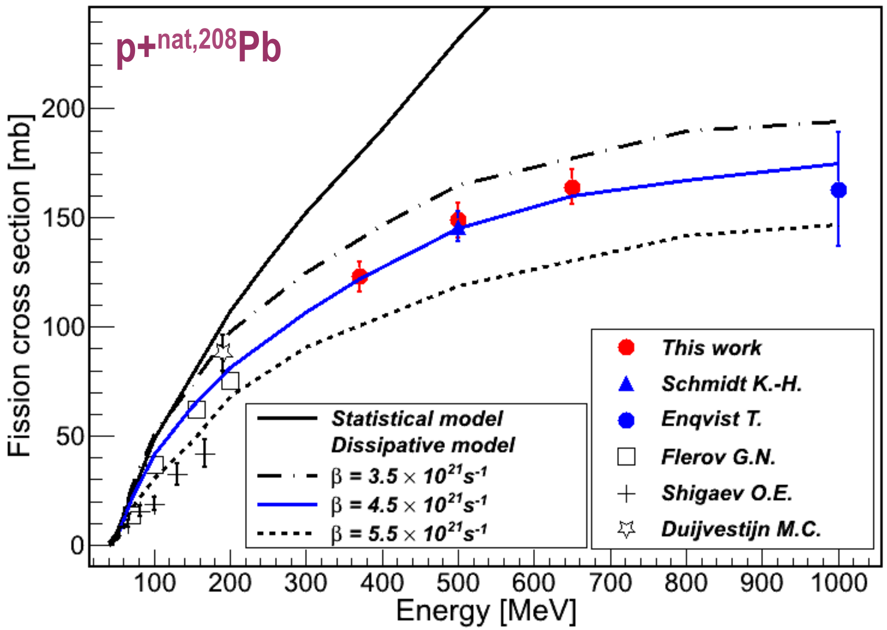


The universal behaviour of the width of the charge distributions confirms that this observable does not depend on the entrance channel of the reactions.

Ground-to-saddle dynamics

Constraining level densities and viscosity parameters





$$\rho(E^*,J) = \rho_{qp}(E^*,J)K_{rot}(E^*,J)K_{vib}(E^*)$$

$$\rho_{qp}(E^*) = \frac{\sqrt{\pi}}{12}\frac{e^S}{a^{1/4}E^{*5/4}}$$

$$S = 2\sqrt{a(E^* + \delta Uk(E^*) + \delta Ph(E^*))}$$

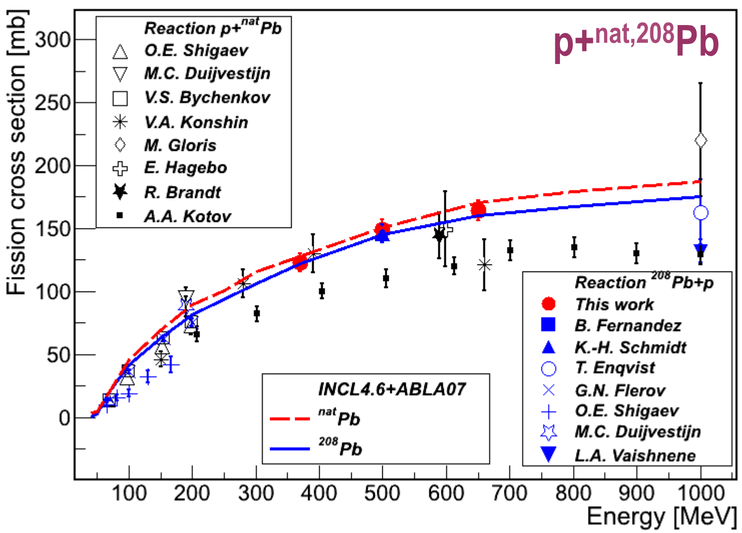
$a = A/8 - A/12$, $a_{sd}/a_{gs} = f_a$

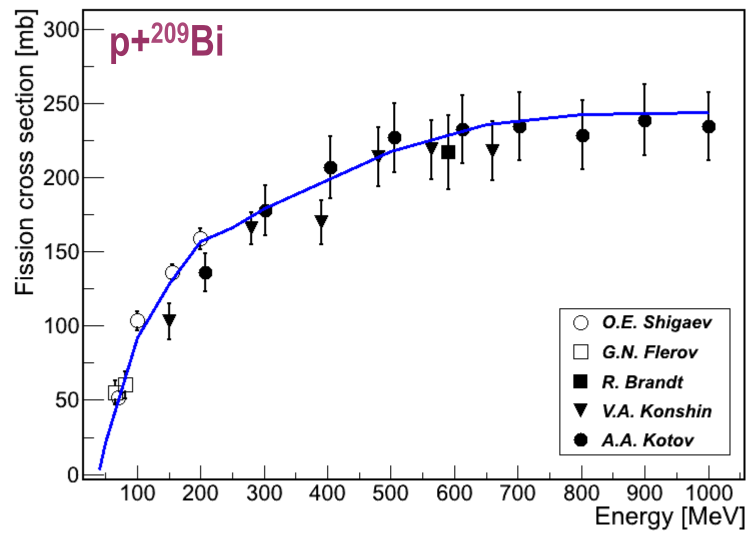
$a(q)_{Ignatyuk} = a_1 A + a_2 B_s(q)$ A.V.. Ignatyuk et al., SJNP (1975)

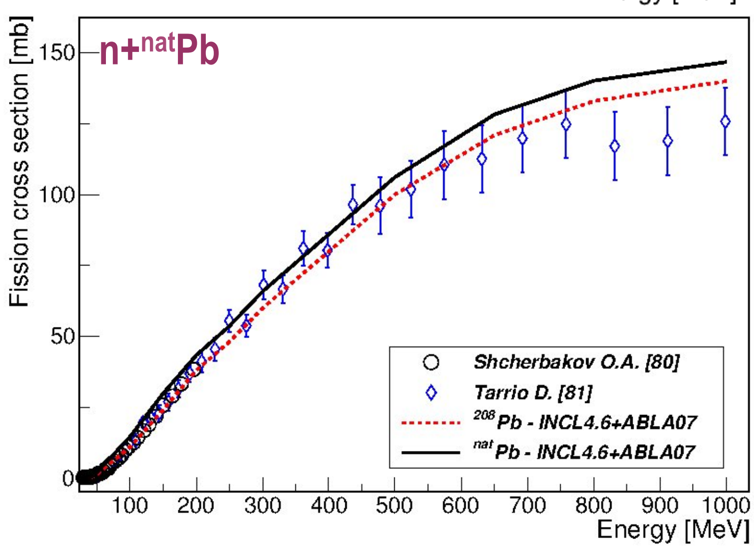
J.L. Rodriguez et al., Phys. Rev. C 92, 044612 (2015)

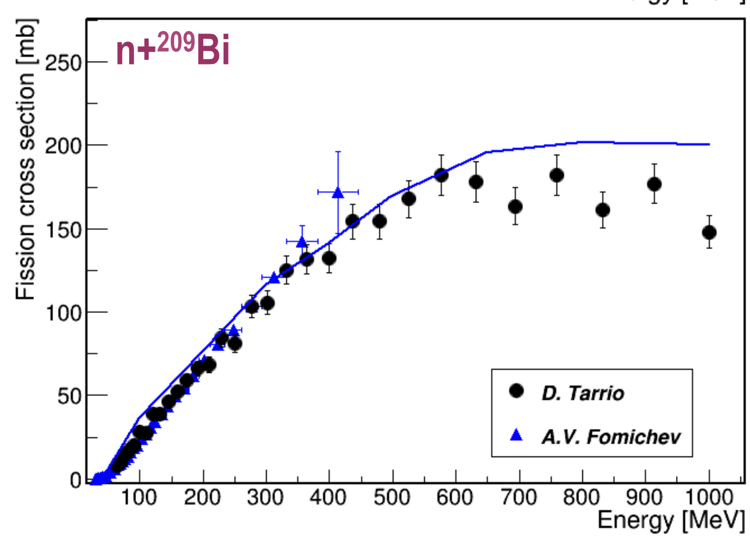
Ground-to-saddle dynamics

Systematic investigation of proton- and neutron-induced fission









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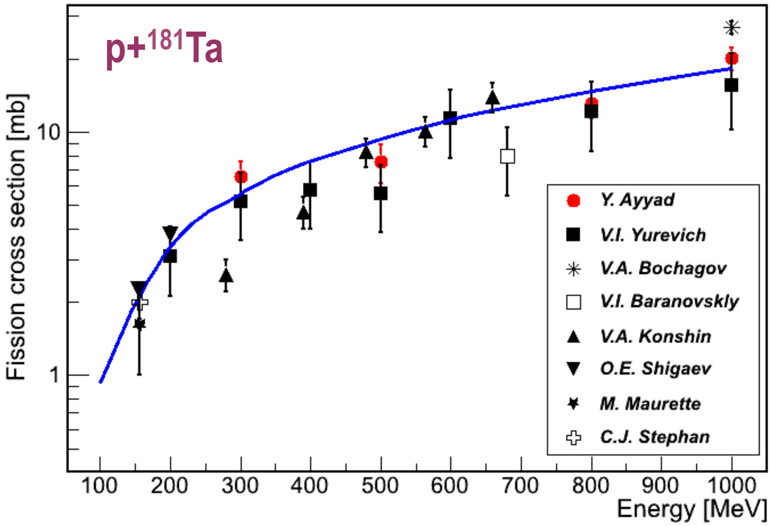
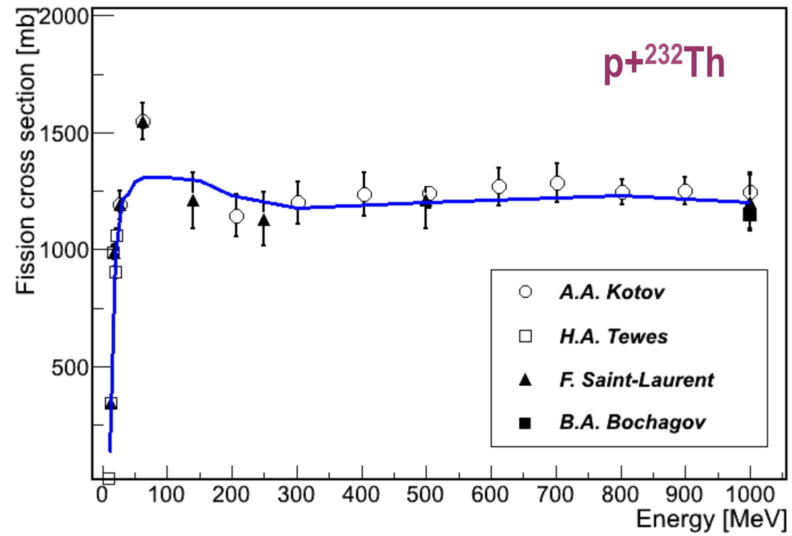
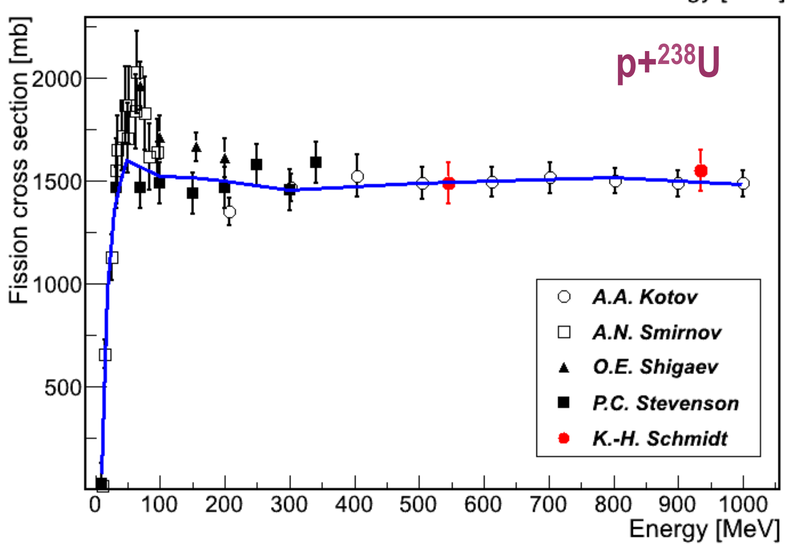
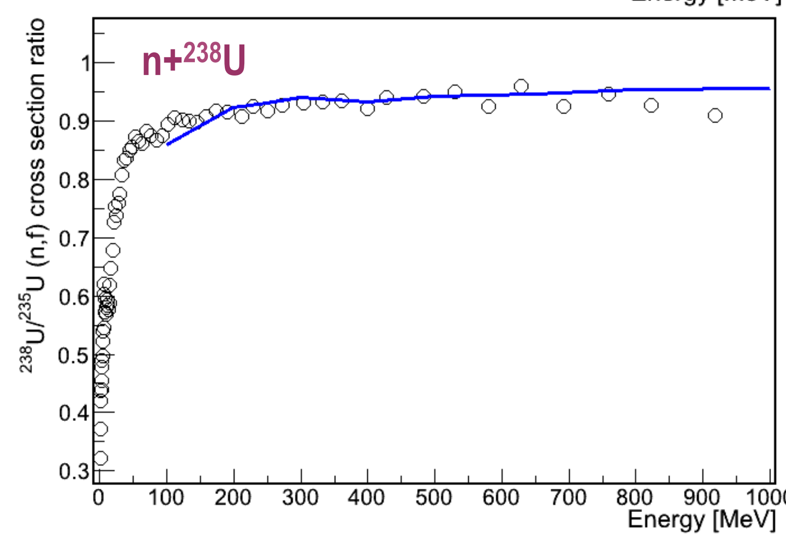


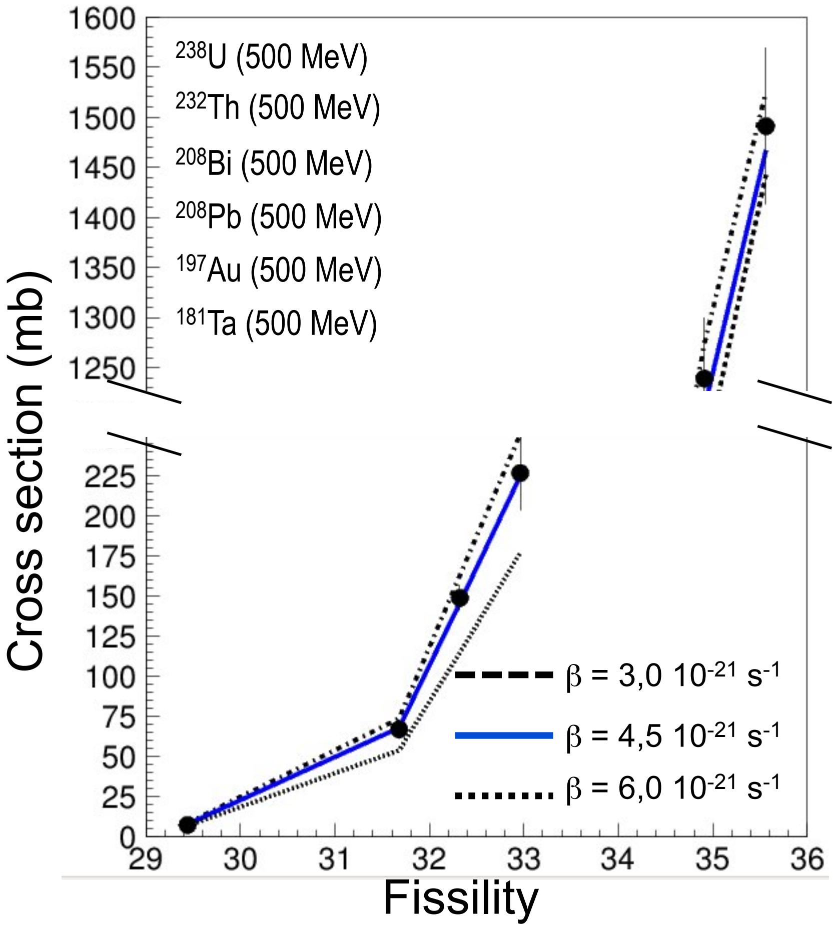


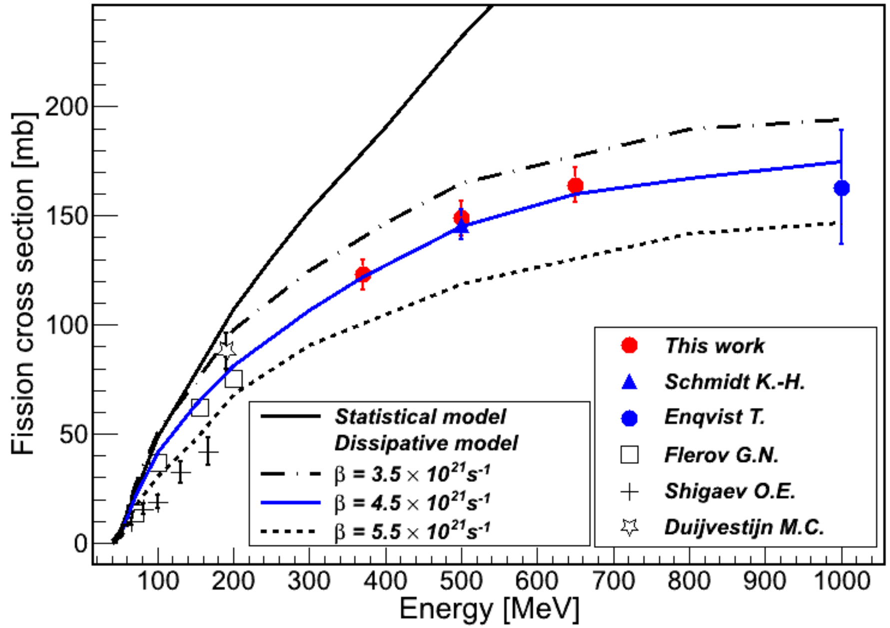




Ground-to-saddle dynamics

Deformation and temperature dependences of the dissipation parameter

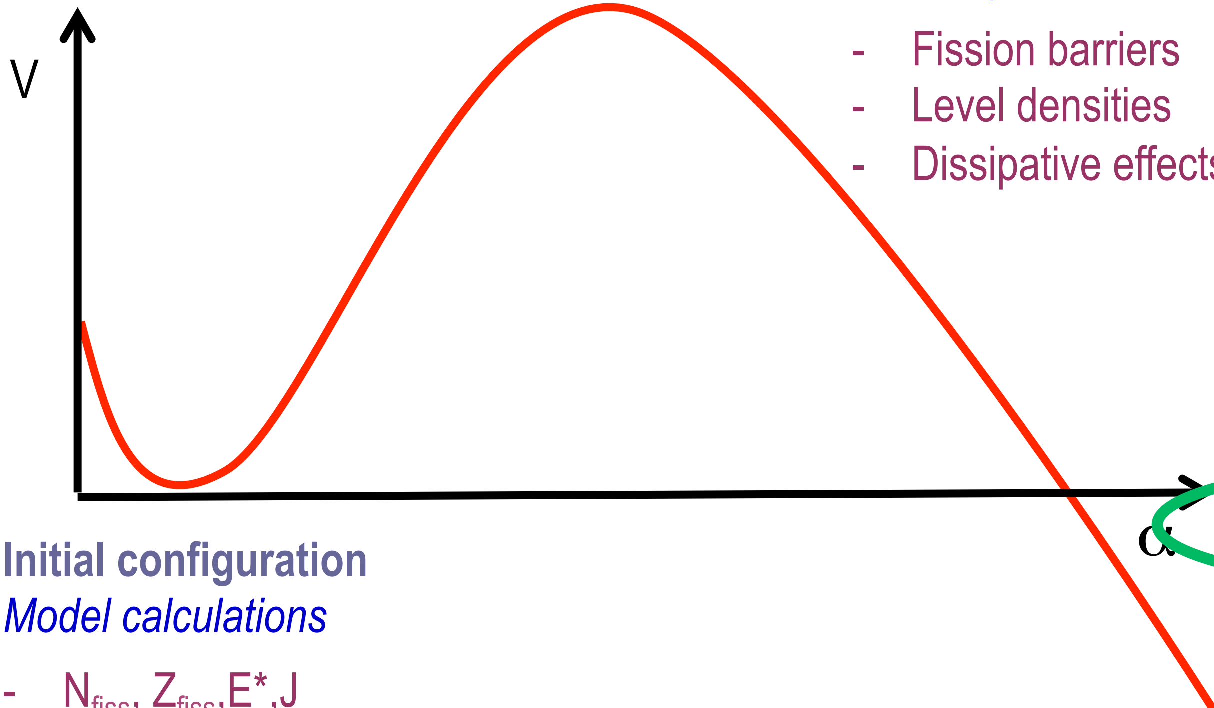




A single value for the viscosity parameter describes fission cross sections over a broad range in fissility and temperature.

Fission at high-excitation energy: observables

Experimental information to constrain model calculations



Saddle point configuration

Fission probabilities and charge distributions:

- Fission barriers
- Level densities
- Dissipative effects

Initial configuration

Model calculations

- N_{fiss}, Z_{fiss}, E^*, J
- Energy dependence of shell corrections
- Energy dependence of collective enhancement

Scission point configuration

Isotopic and TKE distributions

- Mass asymmetry
- Energy sharing
- Dissipative effects
- Fragments deformation

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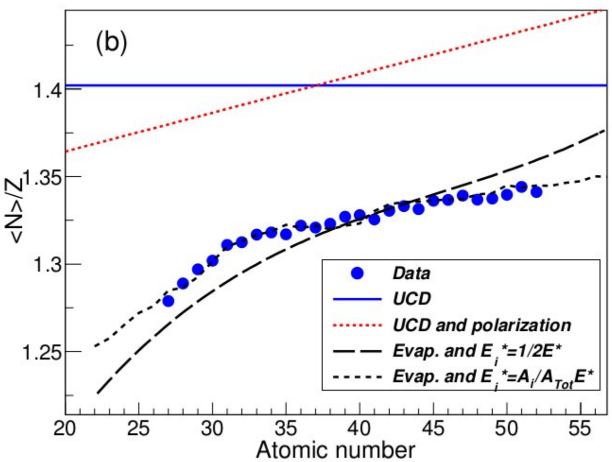
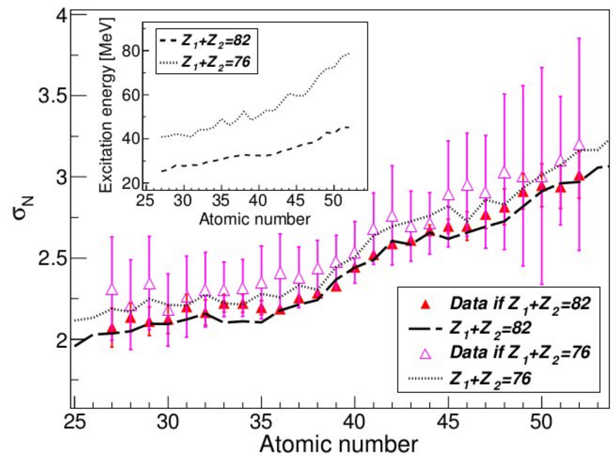
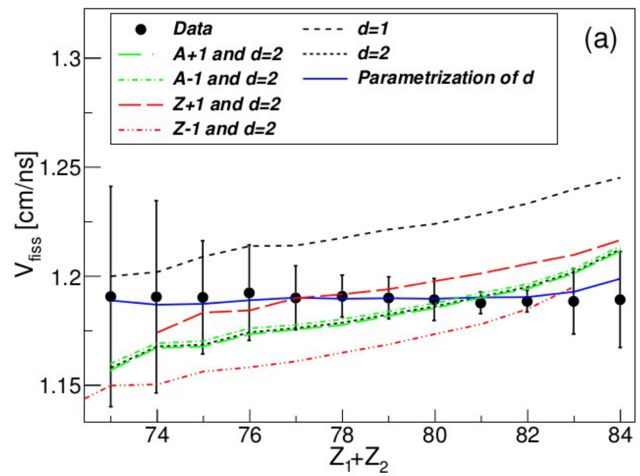
Post-saddle dynamics

Isotopic and TKE distributions of fission fragments: scission point configuration





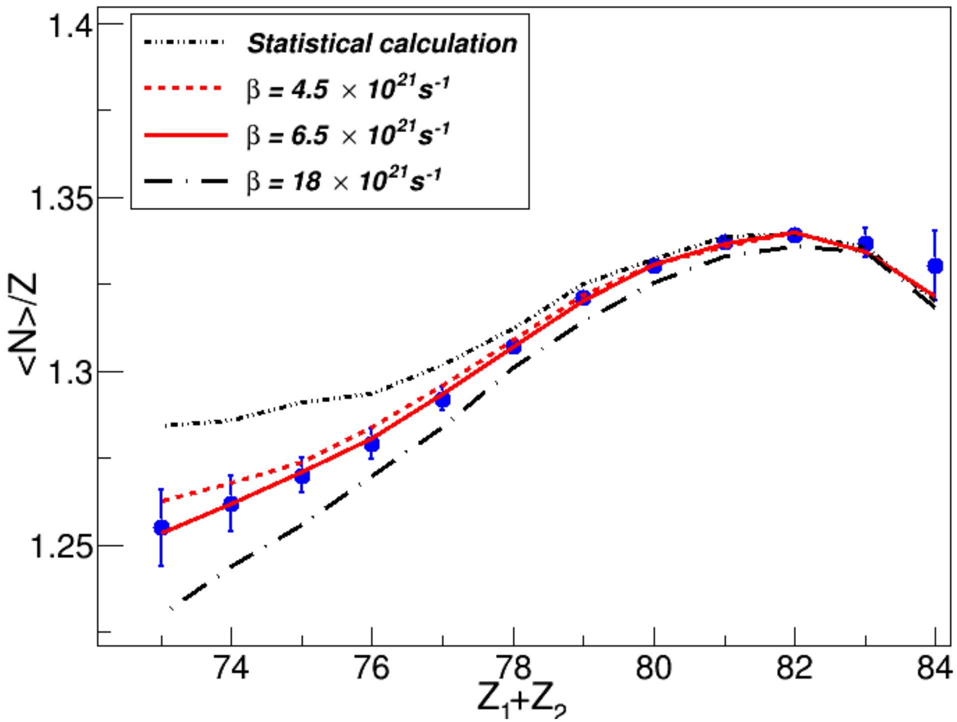


- ✓ The average neutron excess of the final fragments <N>/Z reflects the energy sharing between both fragments.
- ✓ The width of the isotopic distributions depends on the total excitation energy at the scission point.
- ✓ Total kinetic energies determine the deformation of the fragments at the scission point.

J.L. Rodriguez et al., Phys. Rev. C 91, 064616 (2015)

Post-saddle dynamics

Neutron excess of the final fragments: pre-scission neutron emission

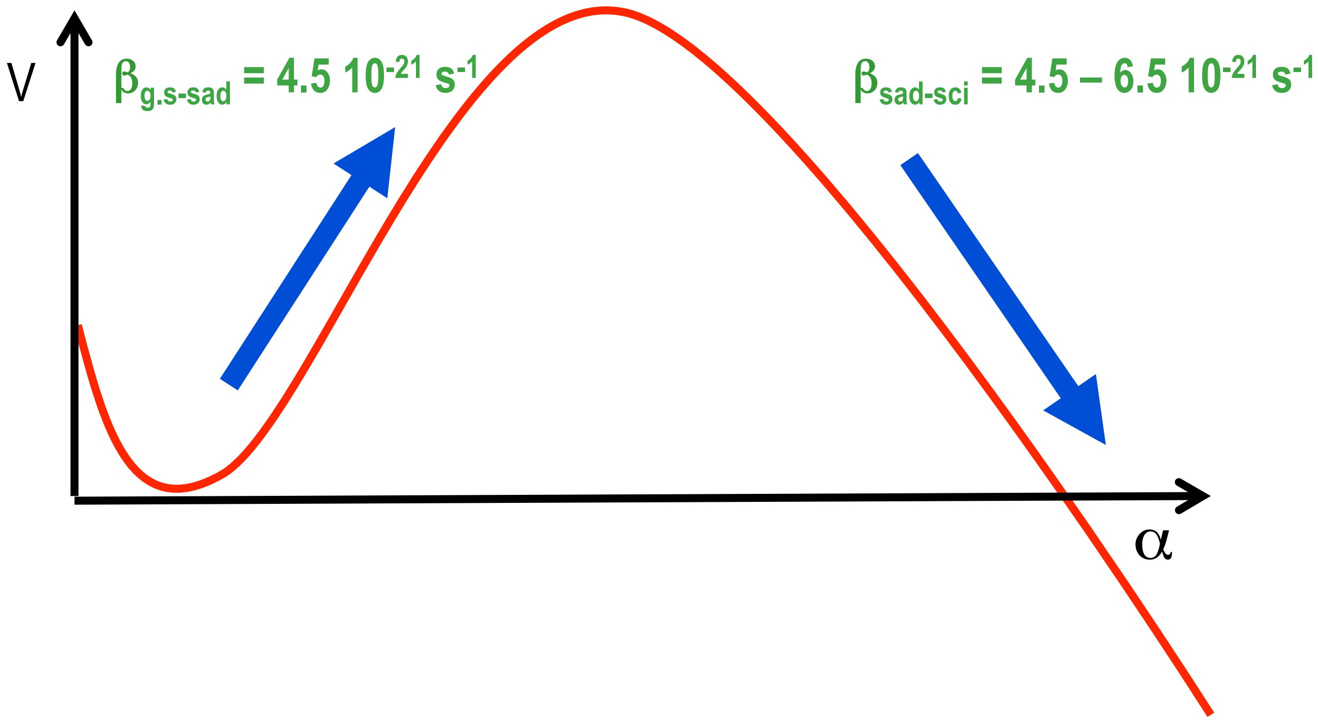


- ✓ The average neutron excess of the final fragments <N>/Z is very sensitive to the saddle-to-scission dynamics.
- ✓ The data can be described with a $\beta_{sad\text{-}sci} = 4.5 - 6.5\ 10^{-21}\ s^{-1}$

J.L. Rodriguez et al., submitted to Phys. Rev. C

Fission dynamics

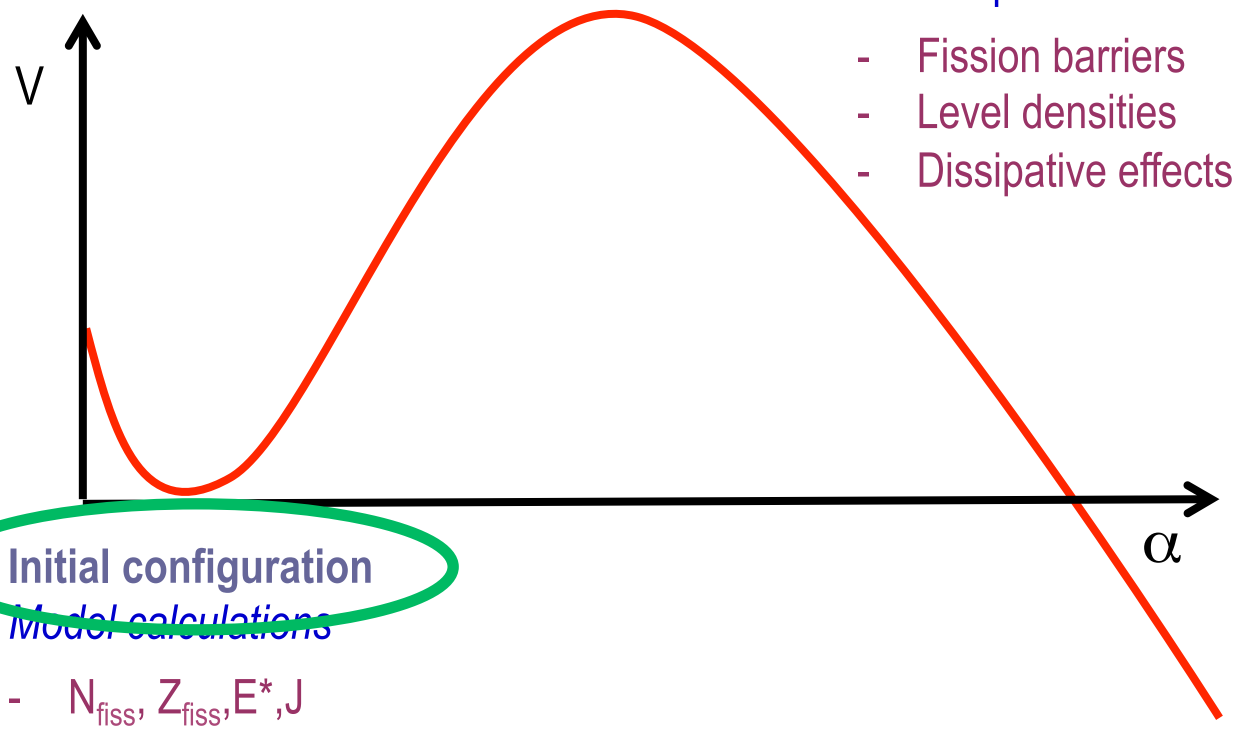
Deformation dependence of the dissipation parameter



No evidences for a deformation-dependent dissipation parameter are observed

Fission at high-excitation energy: observables

Experimental information to constrain model calculations



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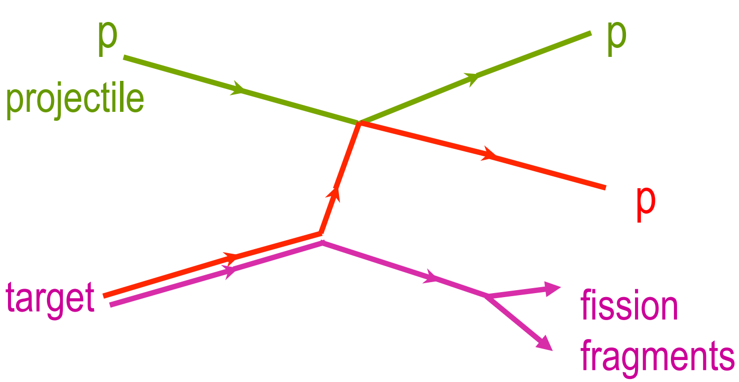
New experimental approaches

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

- High-energy induced fission under well defined initial conditions

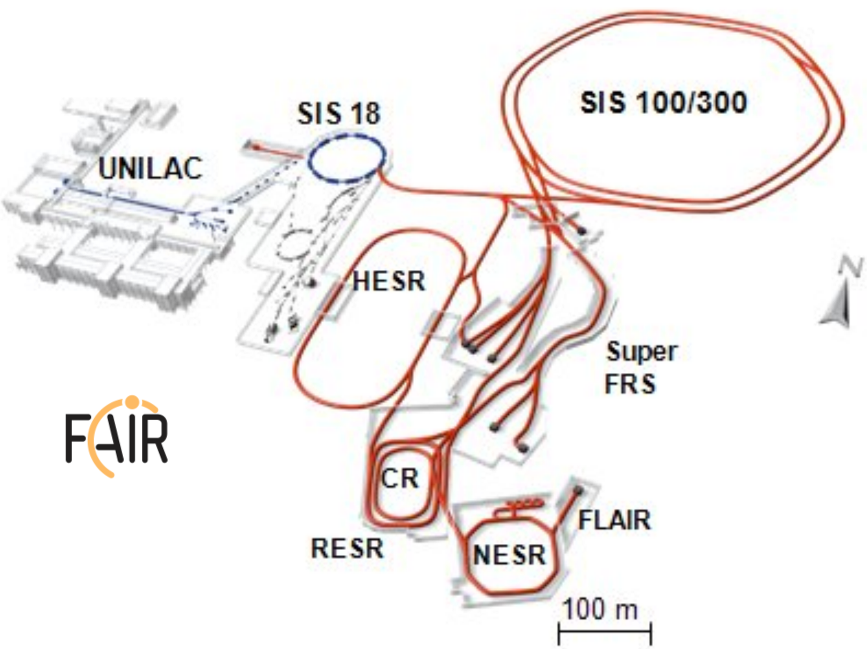


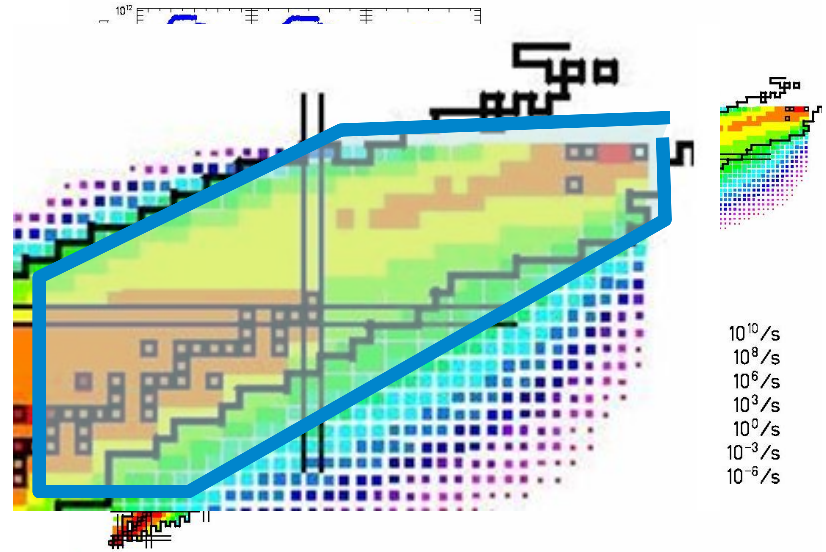
- ✓ Well defined kinematical conditions
  - Momentum and excitation energy of the recoiling nucleus
- ✓ Relatively large cross sections
  - 10 – 50 mb
- ✓ Large range in excitation energy
  - up to 60 MeV (maybe more)
- ✓ Possibility to use unstable nuclei
  - inverse kinematics

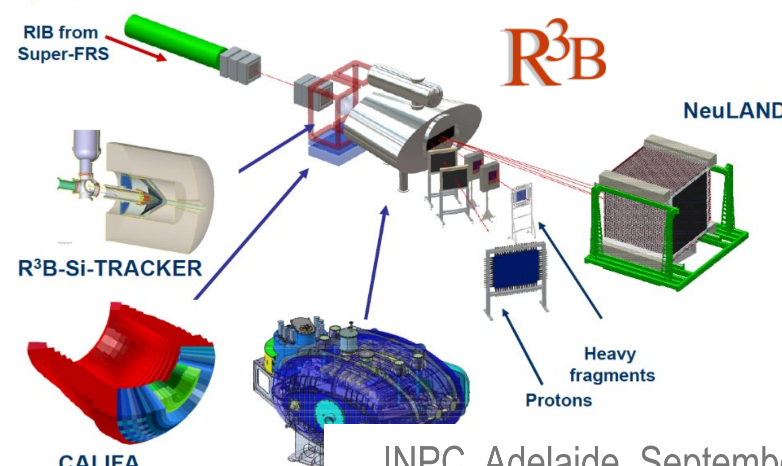
New experimental approaches

(p,2p) and (p,pn) quasi-free scattering: experimental requirements

- Secondary beams
- Inverse kinematics







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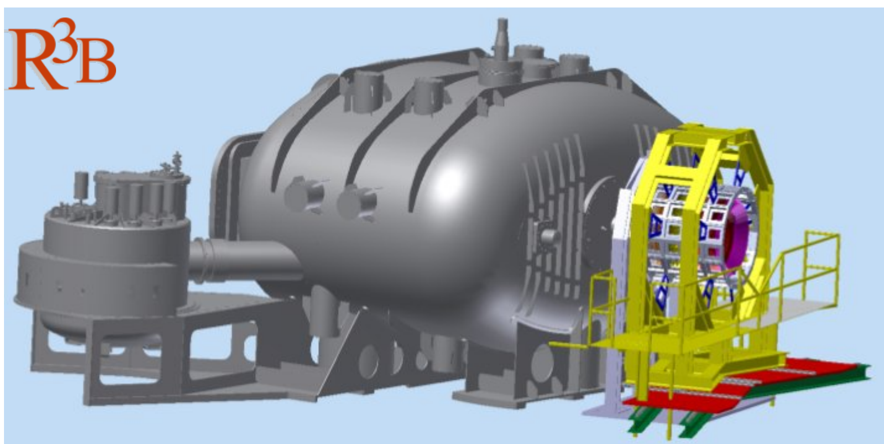
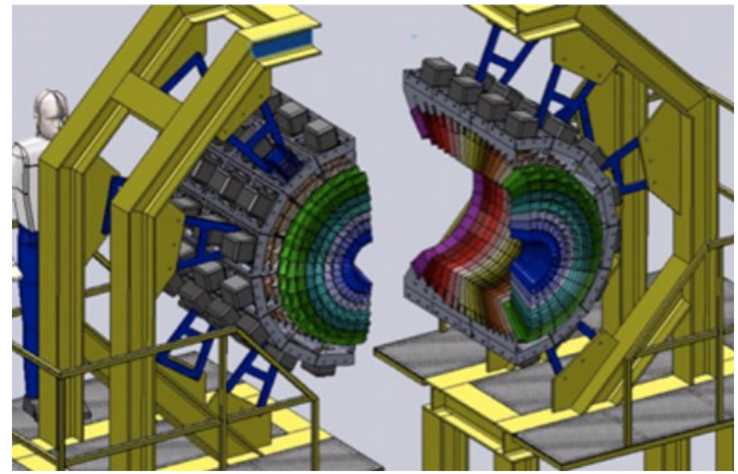
New experimental approaches

(p,2p) and (p,pn) quasi-free scattering: experimental requirements

- Large acceptance for protons
- Good 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 $E\gamma$=15MeV
- γ-ray sum energy resolution < 10%
- energy range for protons: up to 700 MeV
- proton energy resolution < 1 % (stopped)
  < 7% (punch through)

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New experimental approaches

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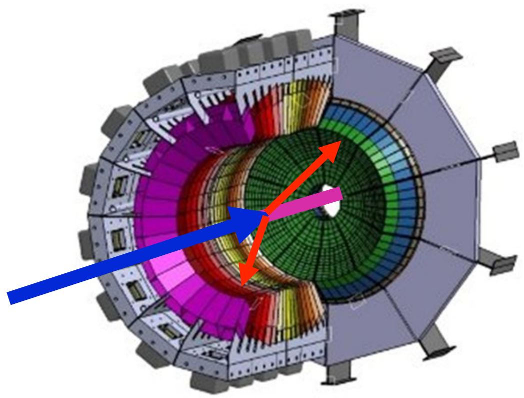
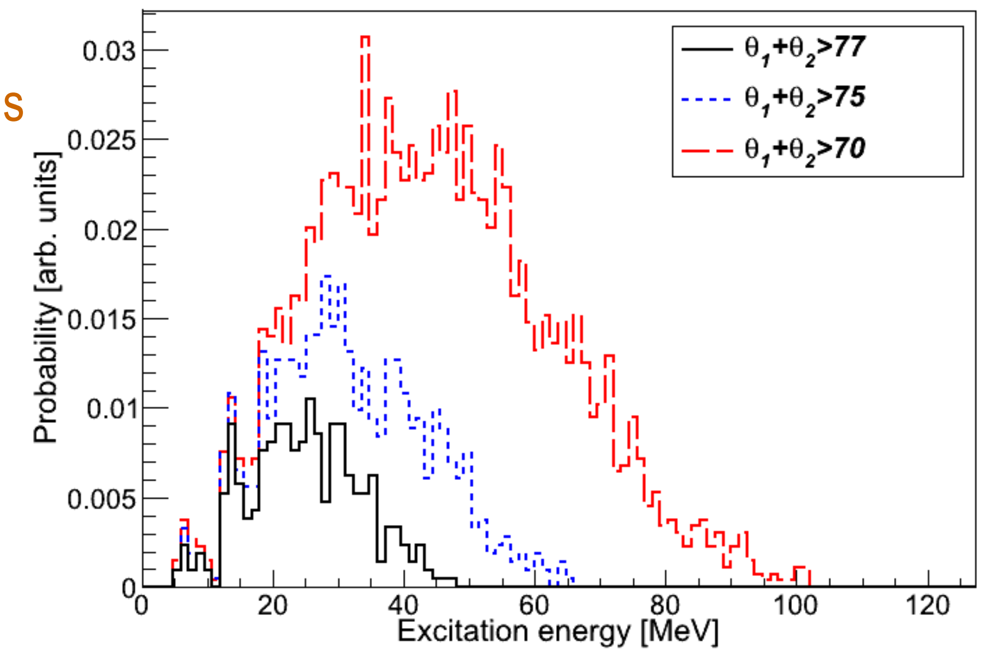
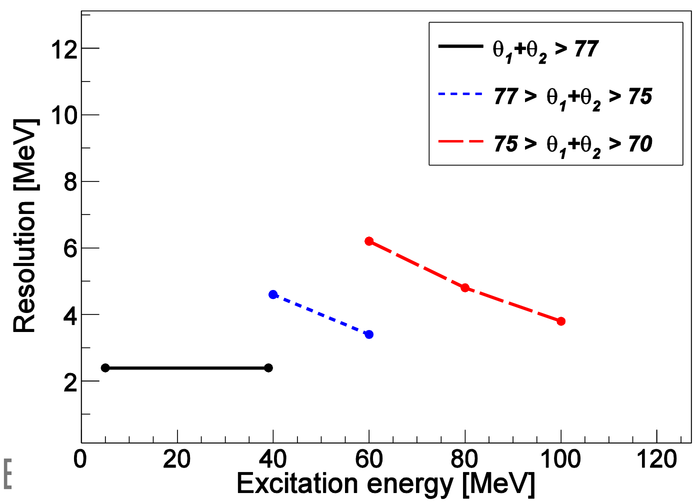






- ✓ Excitation energies up to 60 – 80 MeV
- ✓ Expected resolution in invariant mass (excitation energy) for (p,2p) reactions between 1.5 and 2.5 MeV
- ✓ Isotopic identification of light-residues up to Z=5

Conclusions

✓ Despite its apparent simplicity, fission is still an exciting and challenging mechanism because it addresses many open fundamental questions and it is very relevant for applications.

✓ Recent progress in experimental techniques has also motivated important advances in theory.

✓ Many of the experimental limitations for investigating fission have been overcome using inverse kinematics, providing full characterization of the fission fragments (A, Z, TKE).

✓ In particular we have investigated the dynamics of fission at high excitation energy giving access to coupling times between intrinsic and collective degrees of freedom through transport models.

- Pre- and post-saddle fission dynamics can be described with a dissipation β=4.5 10^{-21} s^{-1}
- No evidences for temperature or deformation dependences in dissipation are observed

✓ We propose to use (p,2p) and (p,pn) reactions to better controll the initial conditions of the fissioning nuclei and investigate the excitation energy dependence of some relevant parameters such as shell effects or collective enhancement in level densities.

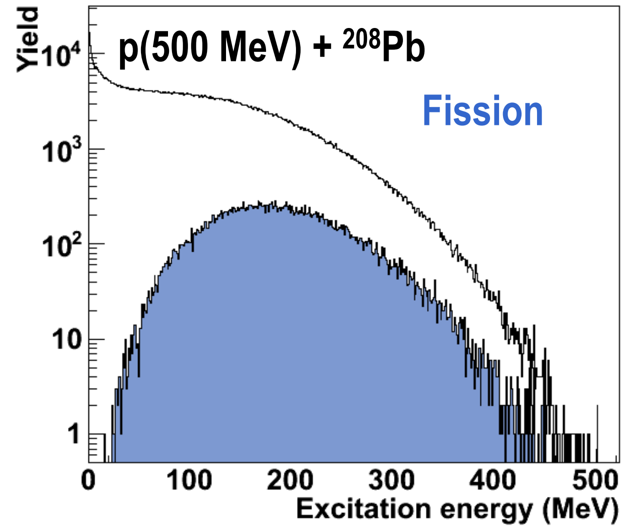
Collaborators & sponsors

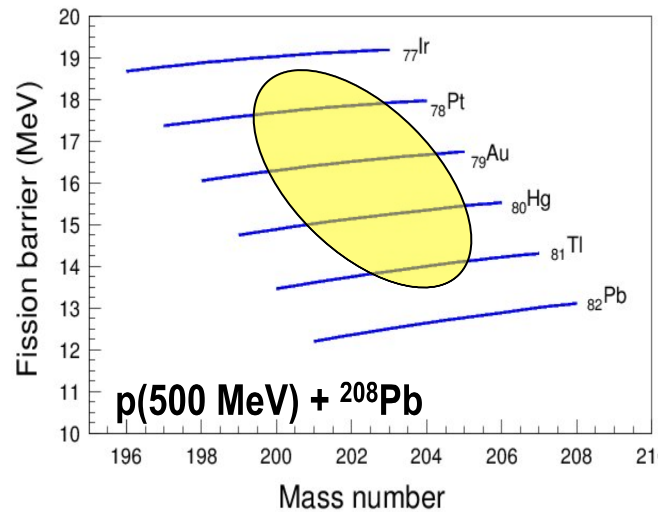
H. Alvarez, L. Audouin, **Y. Ayyad**, G. Belier, A. Boudard, **B. Jurado**, E. Casarejos, A. Chatillon, D. Cortina-Gil, F. Farget, A. Heinz, T. Gorinet, A. Kelic, B. Laurent, S. Leray, J.F. Martin, C. Paradela, E. Pellereau, D. Pérez, B. Pietras, D. Ramos, **J.L. Rodríguez-Sánchez**, C. Rodríguez-Tajes, D. Rosi, **K.-H. Schmidt**, H. Simon, **J. Taieb**, L. Tassan-Got, J. Vargas, C. Volant

Fission of low-fissility highly-excited nuclei

✓ Spallation reactions induced by relativistic protons on low-fissility nuclei (^{208}**Pb**,^{181}**Ta**) led to highly excited remnants with low angular momentum and deformation

✓ The low fissility of those remnants limits fission to relatively large excitation energy (~ 200 MeV)





Present challenges: structural effects

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

- Shell closures Z=50 and N=82,86 were used to explain the mass asymmetry in the actinide region
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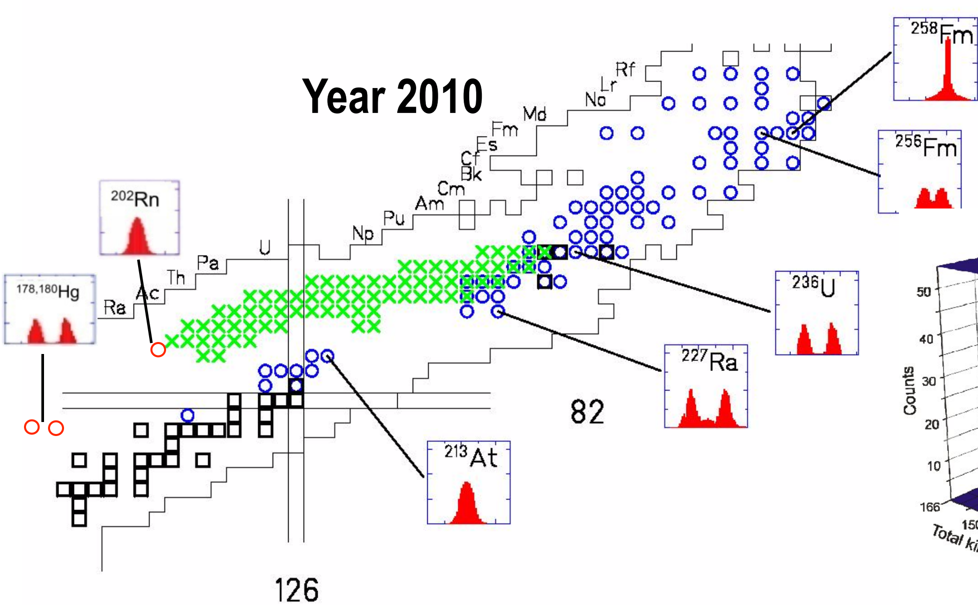
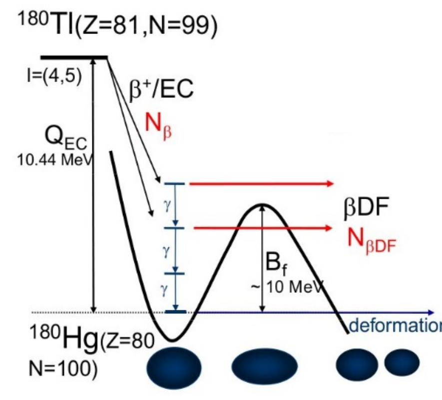
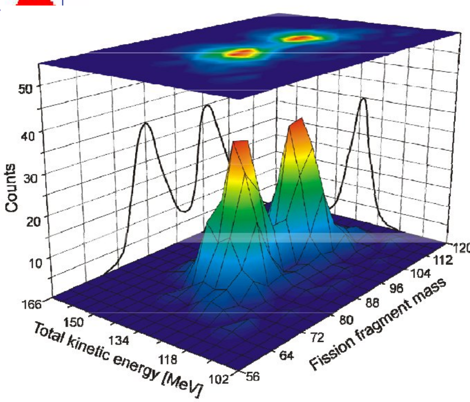


Mass distributions in β-delayed fission of subactinides





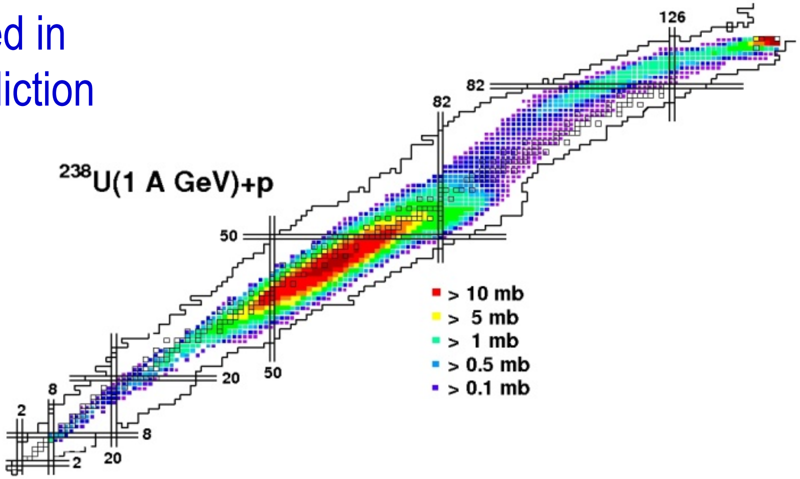
330 fission events were identified and the mass of the fragments determined from energy loss measurements using two silicon detectors

A. Andreyev et al. PRL (2010)

Proton-induced fission at relativistic energies

✓ Spallation reactions induced by relativistic protons on ^{208}**Pb** and ^{181}**Ta** are also of interest for the characterization of spallation neutron targets.

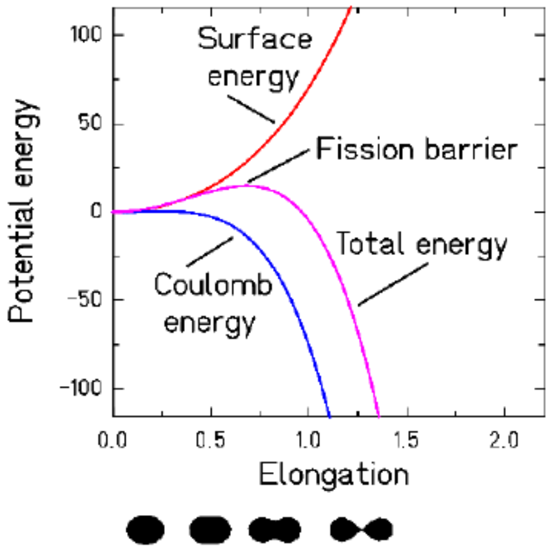
✓ The characterization of the residual nuclei produced in proton on ^{238}**U** reactions is also important for the prediction of the yields produced in radioactive-beam facilities.



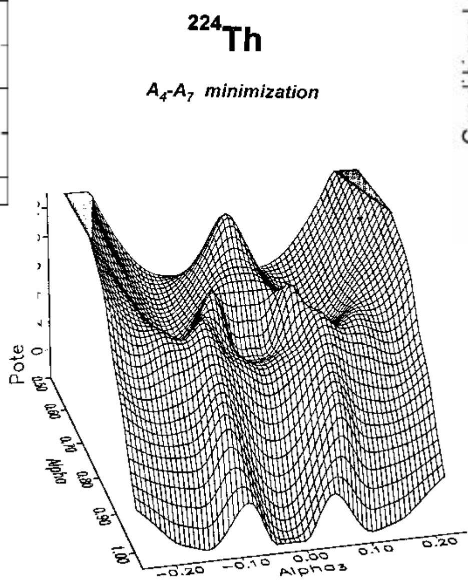
Few basic concepts

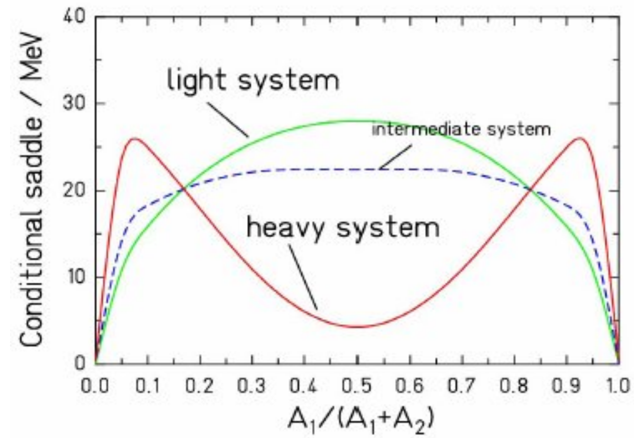
At low energies fission is governed by the potential energy landscape according to two main degrees of freedom:

- **deformation**: when fission takes place
- **mass asymmetry**: how fission occurs



- Fission cross sections
- Excitation energy





- Mass and charge distributions of fragments
- Kinetic energies

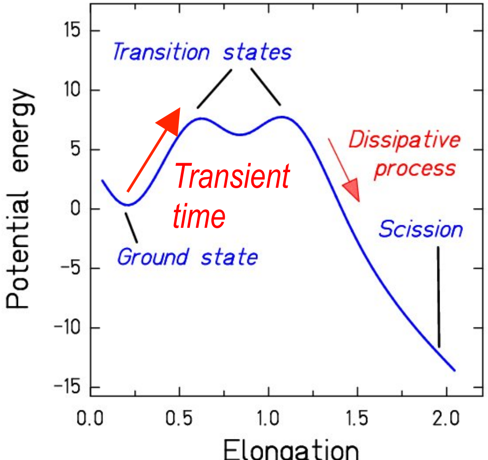
Few basic concepts

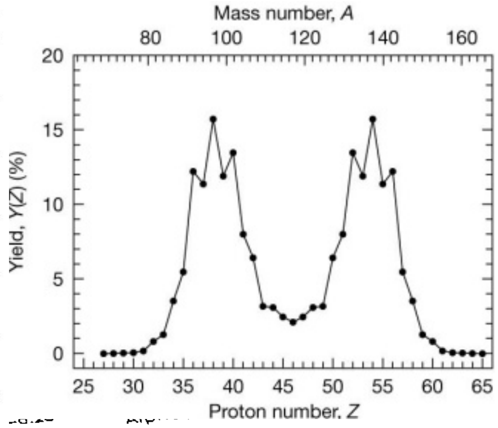
At low energies fission is governed by the potential energy landscape according to two main degrees of freedom:

- **deformation**: when fission takes place
- **mass asymmetry**: how fission occurs

Coupling between intrinsic and collective degrees of freedom also manifest as a dissipative process:

- **saddle-to-scission** energy dissipation: pair breaking
- **ground-to-saddle** transient effects at high excitation energy: fission delay





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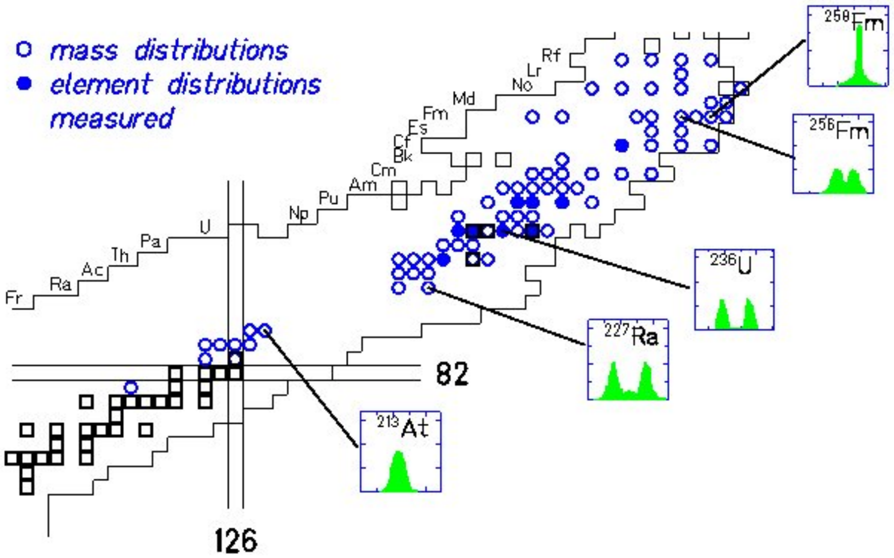

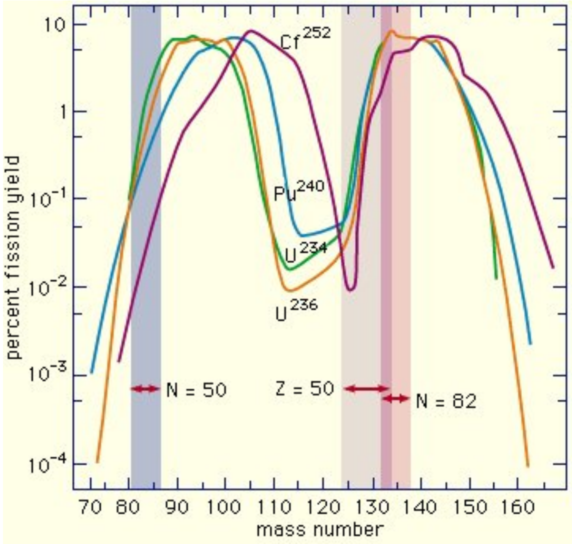

Mostly mass distributions were at reach experimentally

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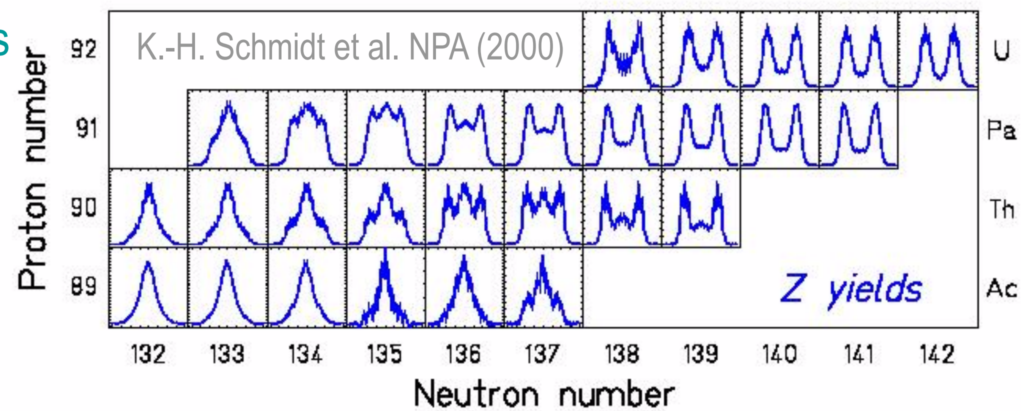

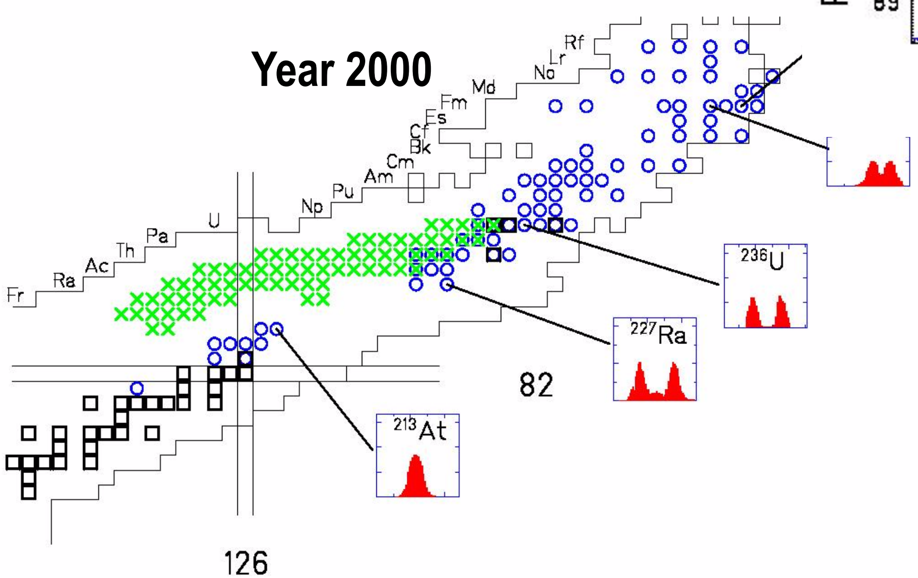

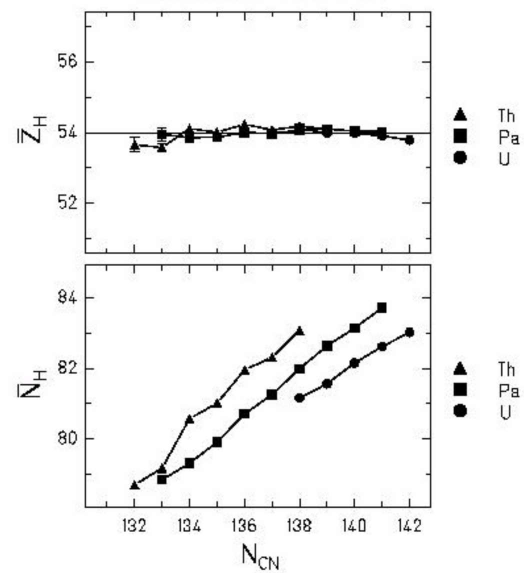

Charge distributions were measured in inverse kinematics

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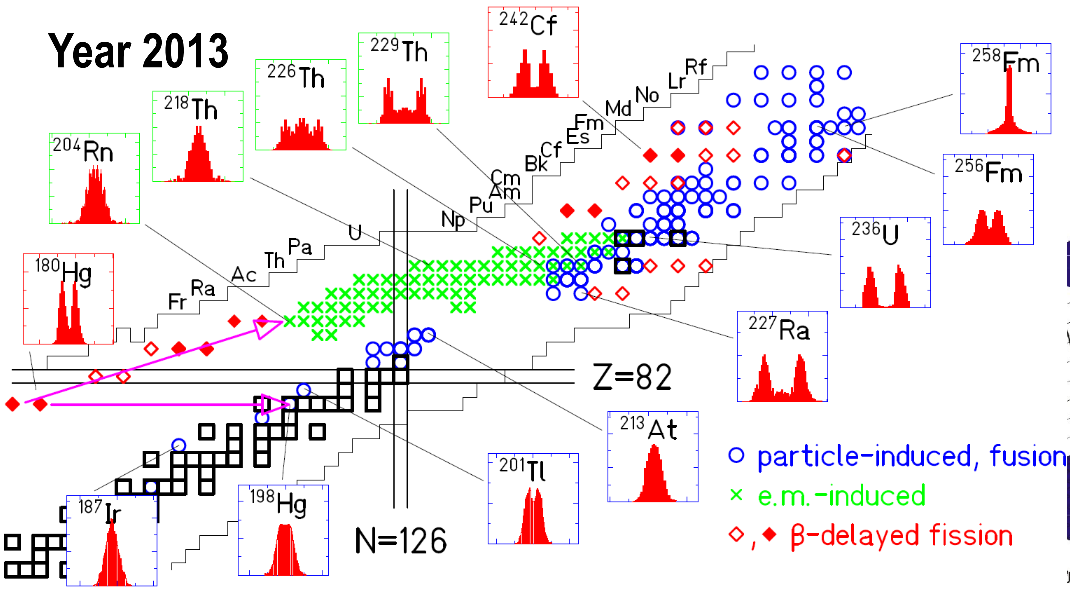

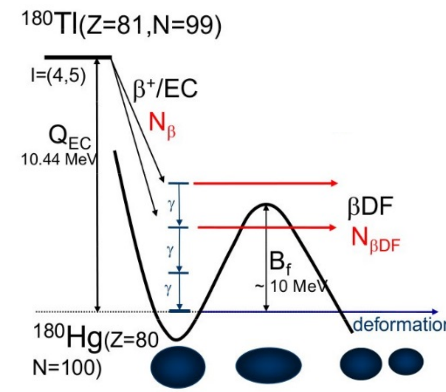

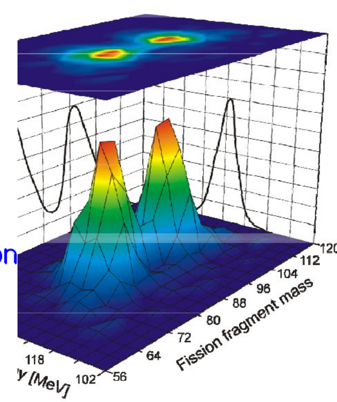

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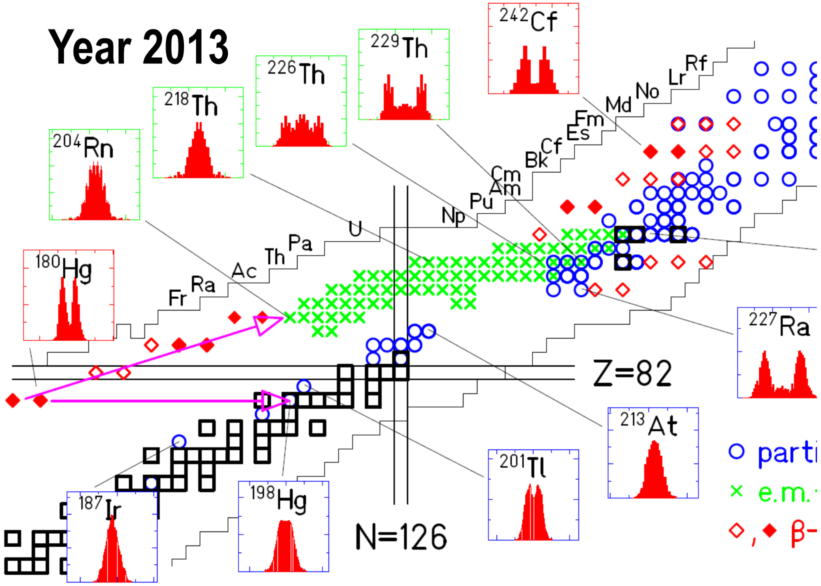
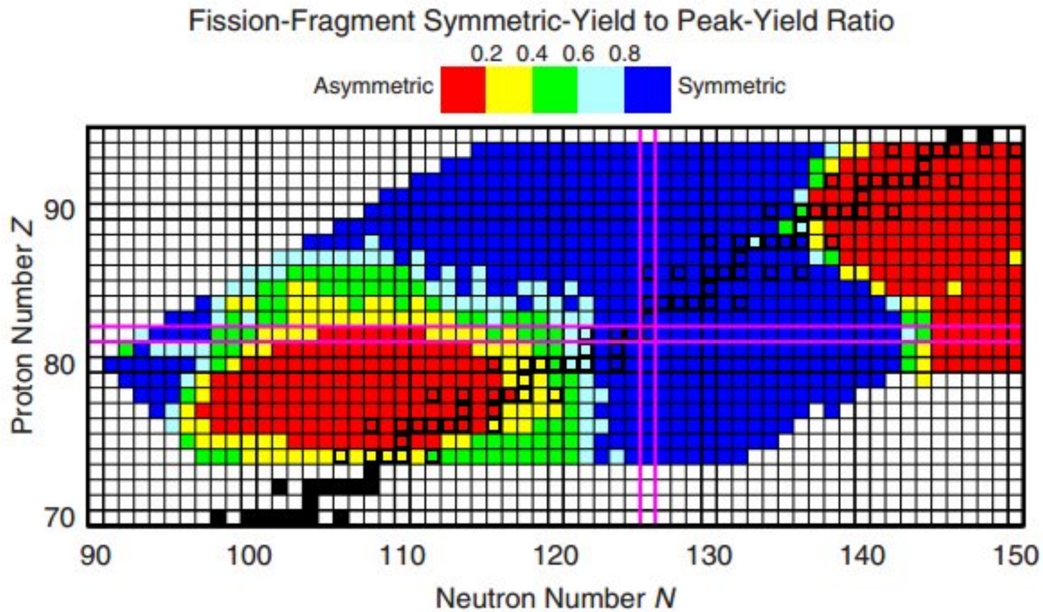




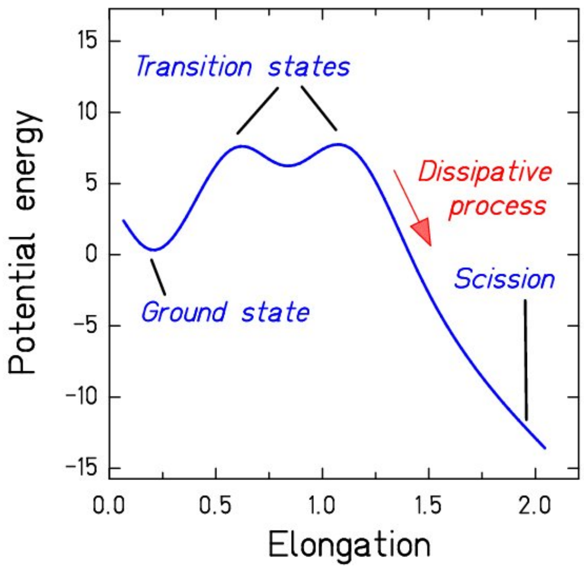
P. Moller and J. Randrup PRC 91, 044316 (2015)

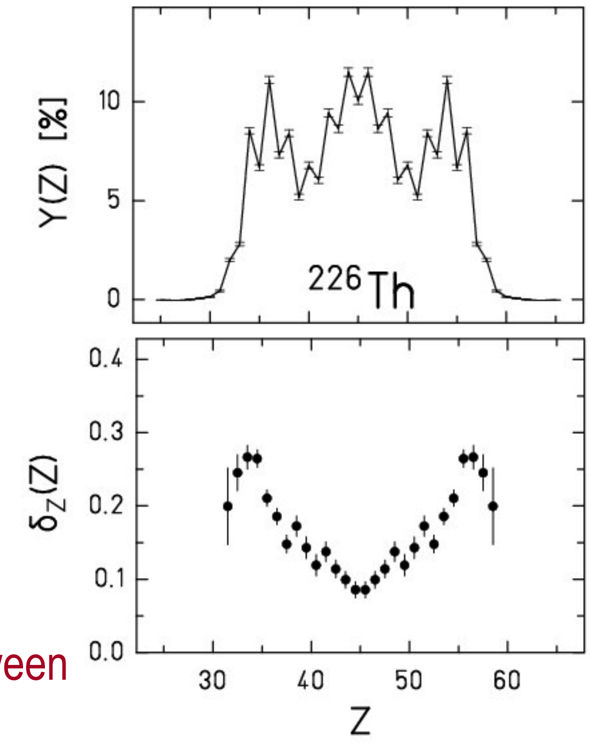
Present challenges: saddle-to-scission dynamics

Saddle-to-scission coupling between intrinsic and collective degrees of freedom:

- Pair breaking in low-energy even fissioning systems is considered as a probe of energy transfer between potential-deformation energy and intrinsic excitations understood as a dissipative process

- However, the magnitude of the even-odd staggering also depends on the asymmetry of the process





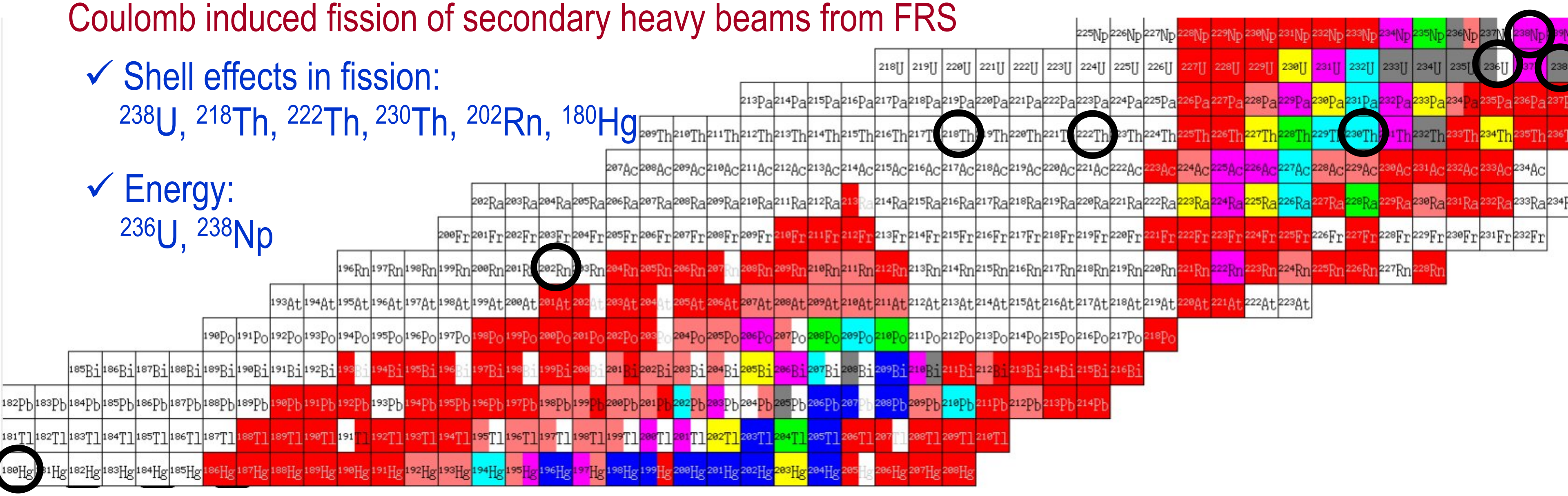
The relation between even-odd staggering in fission fragments, energy dissipation and energy sorting between the nascent fragments is still under debate

Fission studies at GSI

SOFIA phase 1: August/September 2012

Coulomb induced fission of secondary heavy beams from FRS

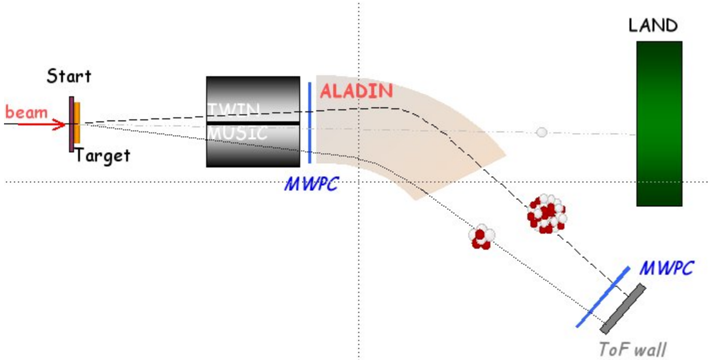
- ✓ Shell effects in fission:
  ^{238}U, ^{218}Th, ^{222}Th, ^{230}Th, ^{202}Rn, ^{180}Hg
- ✓ Energy:
  ^{236}U, ^{238}Np



Proton induced fission on ^{208}Pb

- ✓ Fission dynamics at high excitation energy
- ✓ Spallation sources: contribution to the ANDES EU project (GSI, USC, CEA)

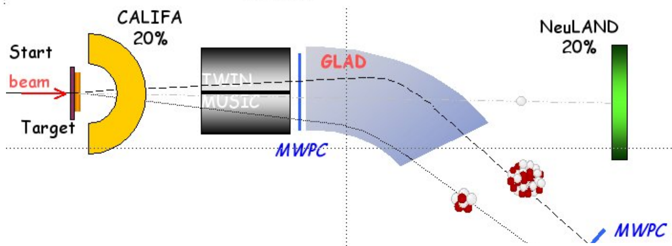
Fission studies at FAIR



SOFIA @ GSI

- fission fragments Z, A
- TKE

2012

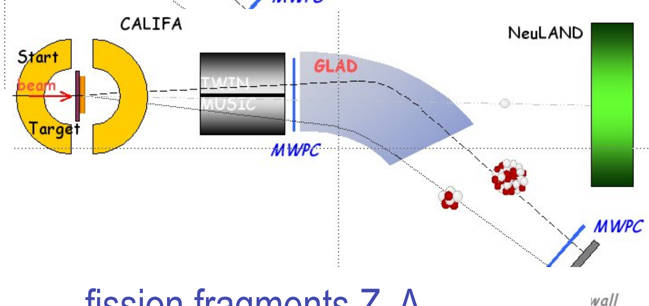


SOFIA pre-R3B

- fission fragments Z, A
- TKE
- neutrons
- gammas

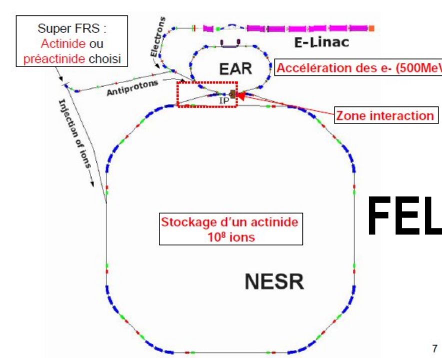
2015 ?

SOFIA @ R3B



- fission fragments Z, A
- TKE
- neutrons
- gammas
- excitation energy ~ 5 MeV

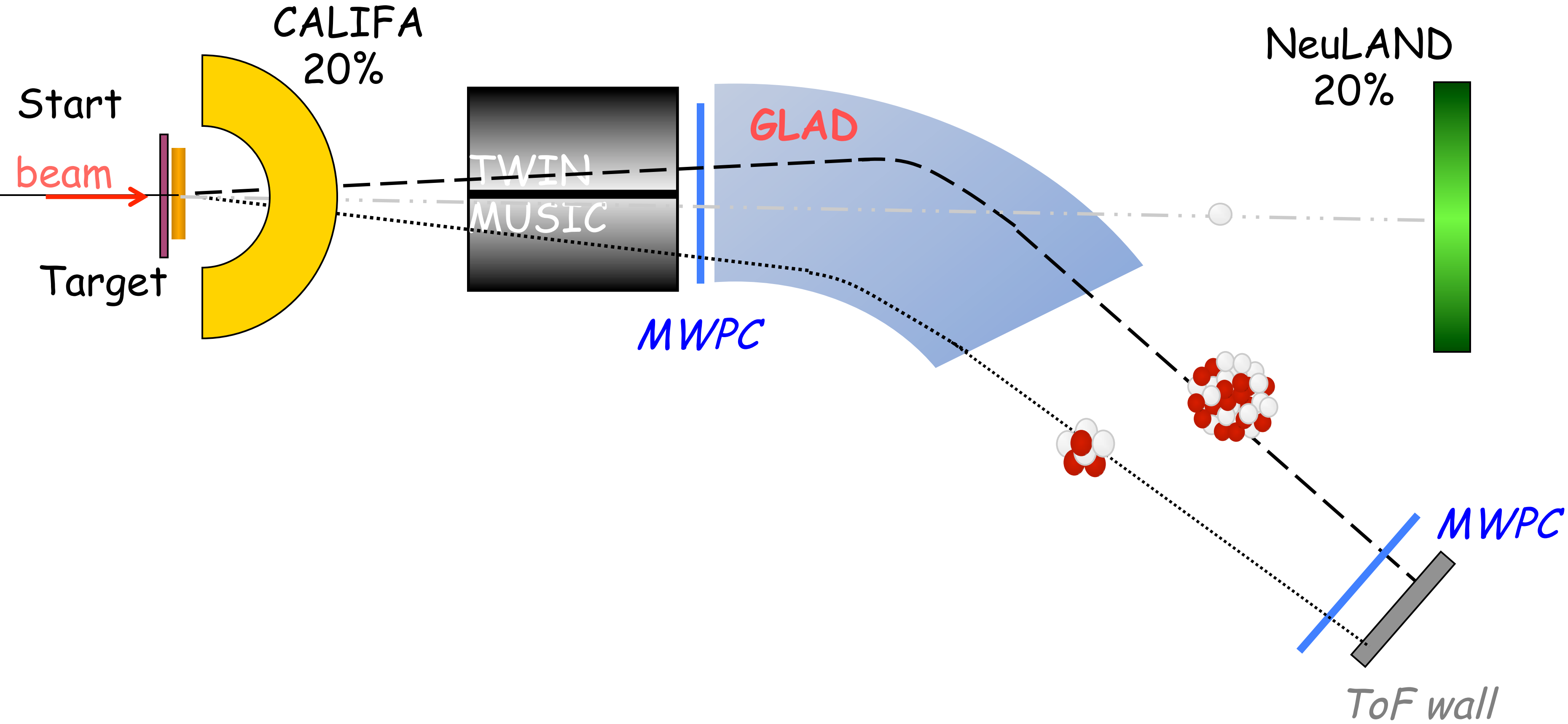
2018 ?



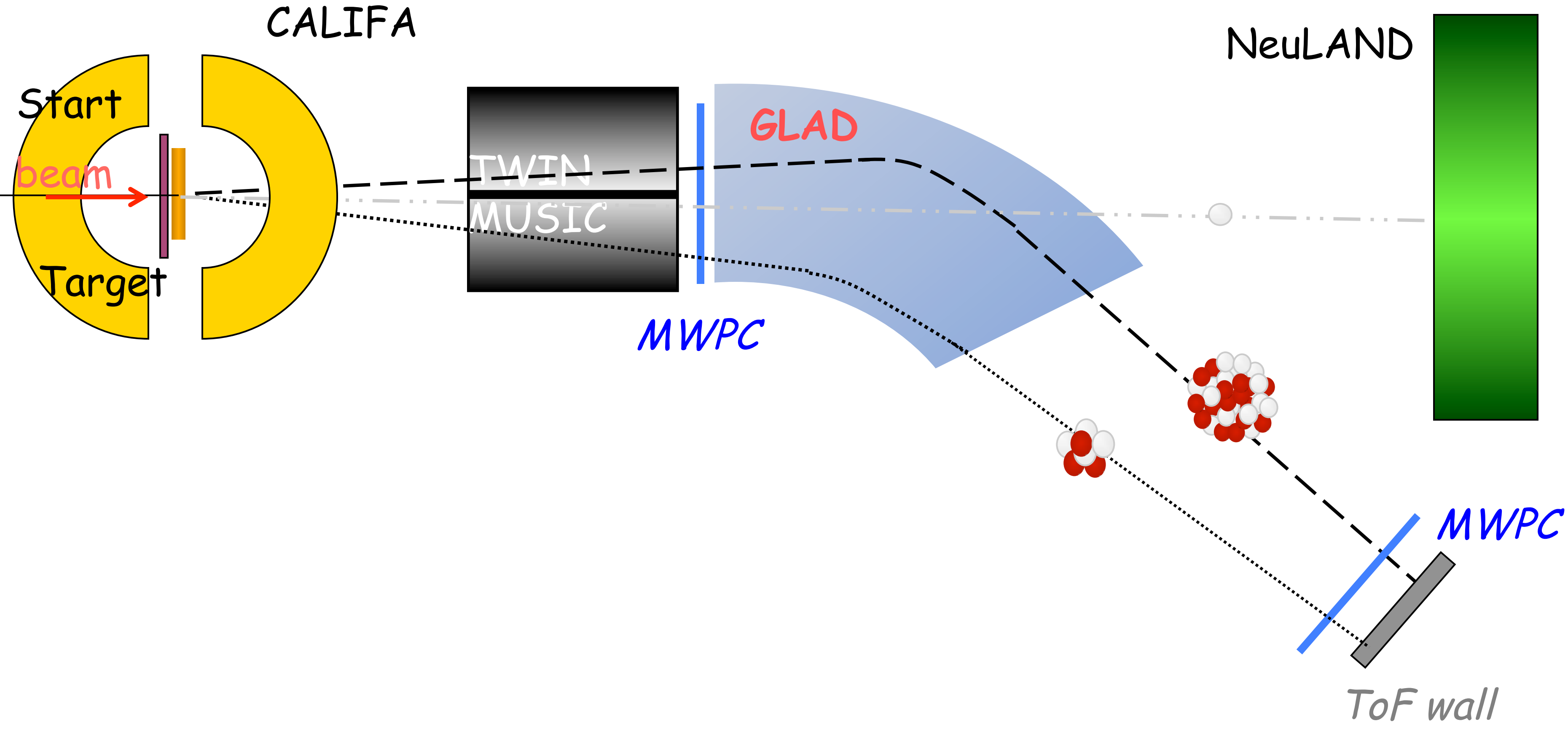
FELISe

- fission fragments Z, A
- TKE
- neutrons
- gammas
- excitation energy ~ 100 KeV

????



CALIFA
20%
Start
beam
Target
TWIN
MUSIC
MWPC
GLAD
NeuLAND
20%
MWPC
ToF wall


CALIFA
Start
beam
Target
TWIN
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GLAD
NeuLAND
MWPC
ToF wall

Motivation

Spallation targets

Lead-bismuth eutetic and tungsten-tantalum are the main candidates for liquid or solid spallation targets for neutron production:

- large neutron excess
- optimum heat dissipation
- limited radiation damages

Although the most important nuclides from a radiological view point are spallation residues (^{207}Bi, ^{208}Po,^{209}Po, ^{204}Tl, …), gaseous fission residues (Kr or Xe) are also very relevant because of their volatility