Experiments on Fission Dynamics with Relativistic Heavy-ion Beams

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**) PhD thesis on this subject*

- **Experimental tools**
- **Reaction mechanisms**
- **Results**

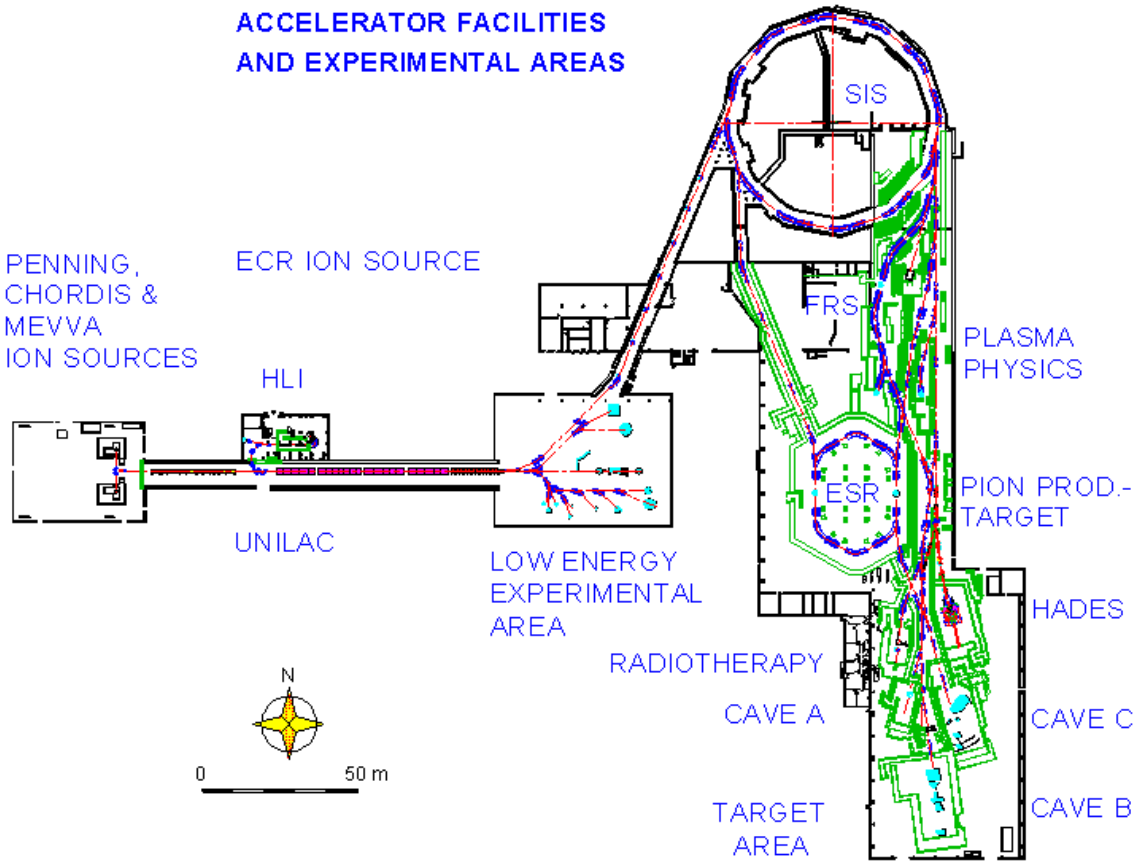
  Multi-modal fission

  Dissipation

  Extremely asymmetric mass splits
- **Prospects**
- **Summary**

Experimental tools

The facilities of GSI



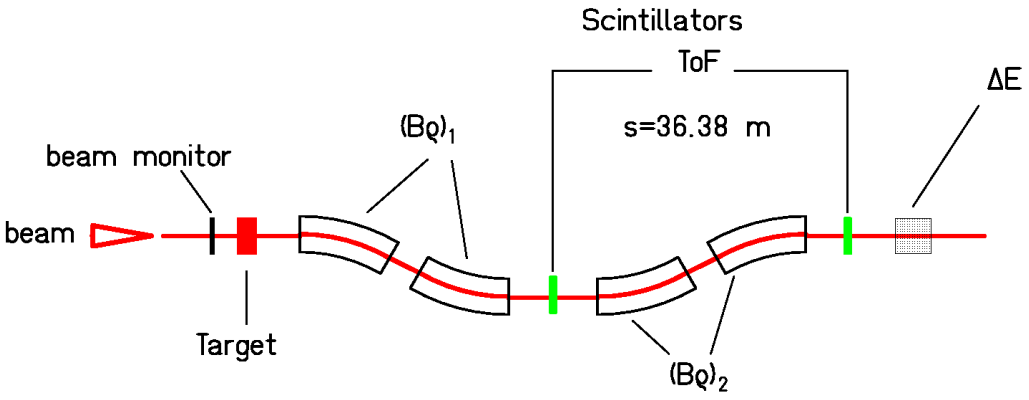
UNILAC: Universal linear accelerator (E ≤ 20 A MeV).

SIS18: Heavy-ion synchrotron (E ≤ 1 ... 2 A GeV).

FRS: Magnetic spectrometer for separation of radioactive beams.

Experimental tools

The Fragment Separator FRS



Determination of *A*, *Z*, *p* of heavy residues from

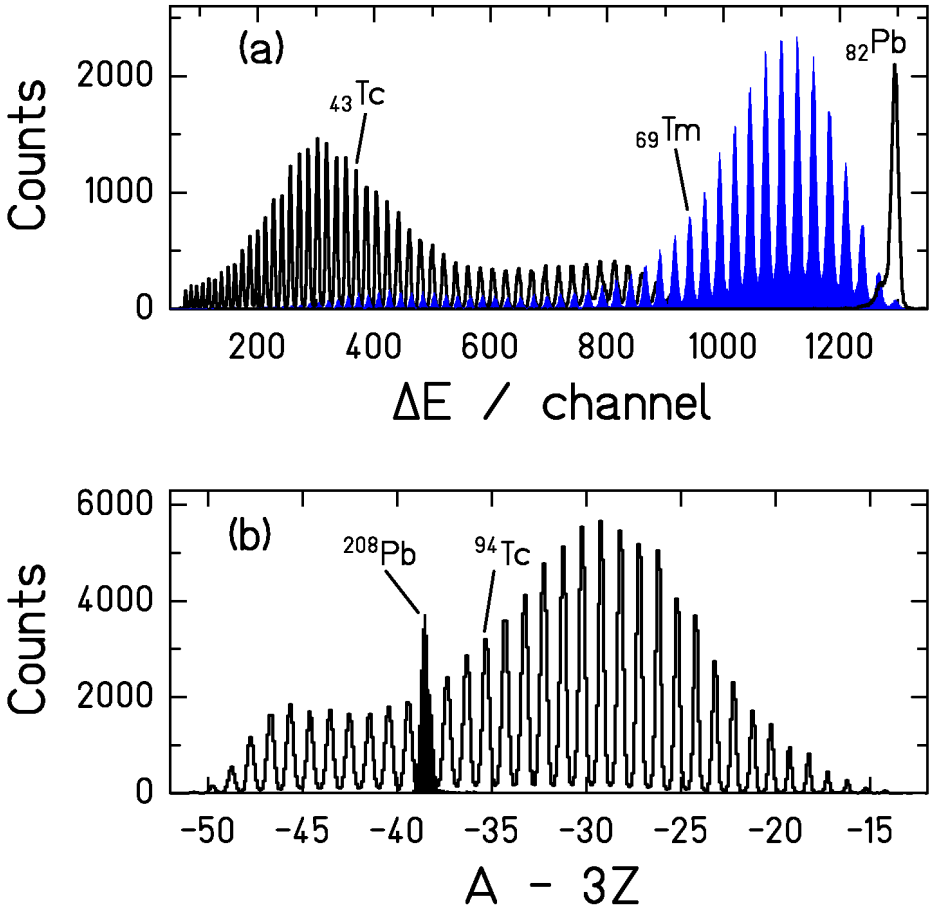
- **magnetic rigidity**
- **time-of-flight**
- **energy loss.**

Used for

- **identification of reaction products**
- **separation of secondary beams**

Experimental tools

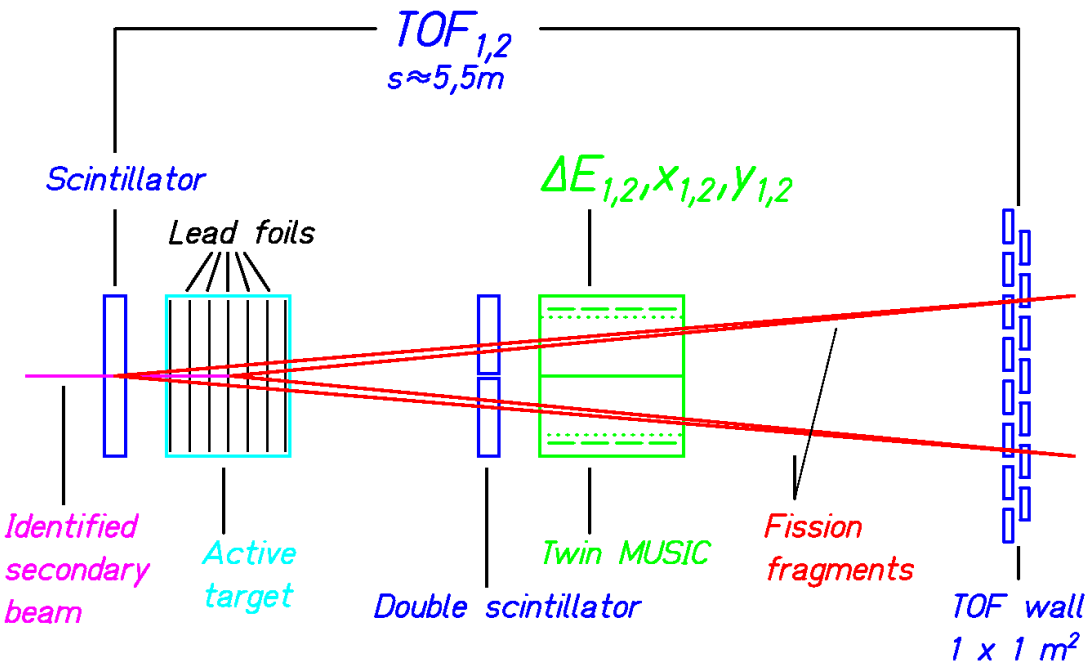
Resolution in *A* and *Z*



Unambiguous identification of all heavy reaction products

Experimental tools

Large-acceptance fission set-up



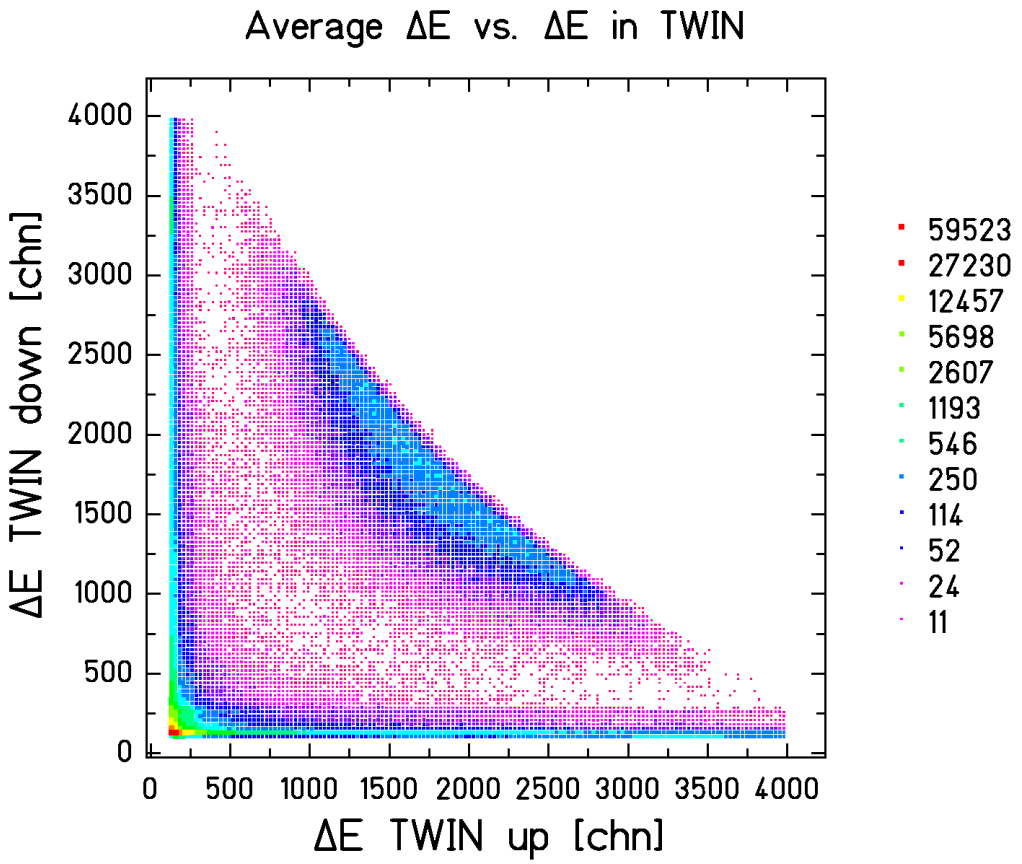
Almost 100% detection efficiency.

Determination of Z_1, Z_2, TKE from

- ΔE_1, ΔE_2
- ToF
- **angles.**

Experimental tools

Raw data of TWIN ionisation chamber



Mechanisms to induce fission

- **Electromagnetic excitations (GDR -> $E^* \approx 11$ MeV)**
    - Number of protons is preserved!

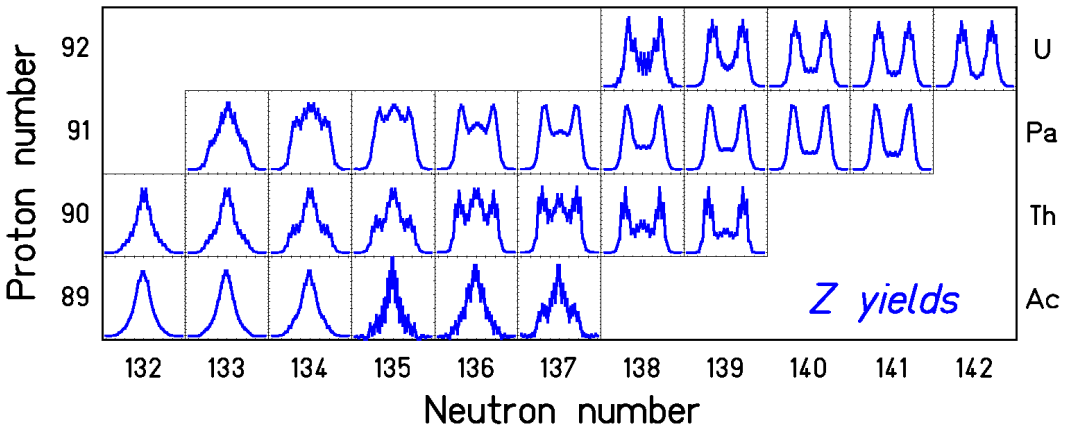
- **Peripheral nuclear collisions (Abrasion)**

  ($E^* \approx 27$ MeV $\times \Delta A$)
    - Loss of several nucleons.
    - High excitation energies.
    - Small shape distortions.
    - Low angular momentum (10 to 20 h).

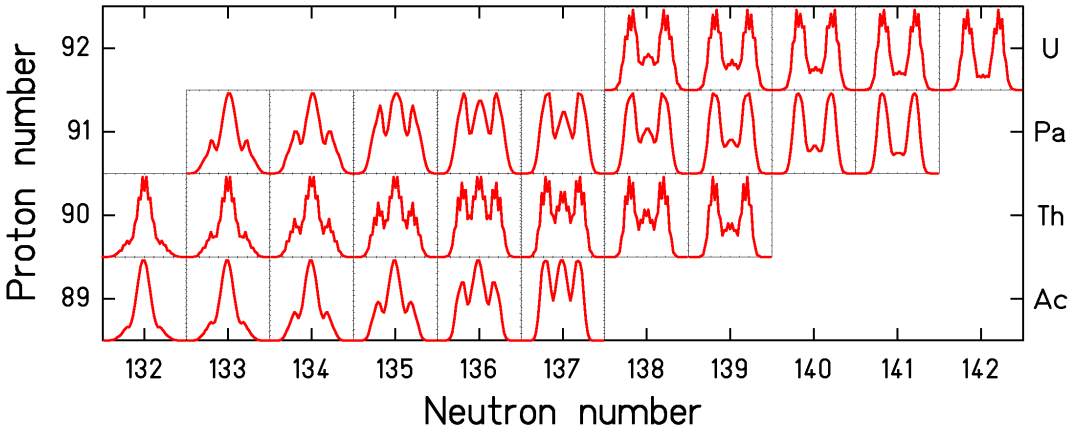
Results on multi-modal fission

Element distributions (E* ≈ 11 MeV)

Measured:

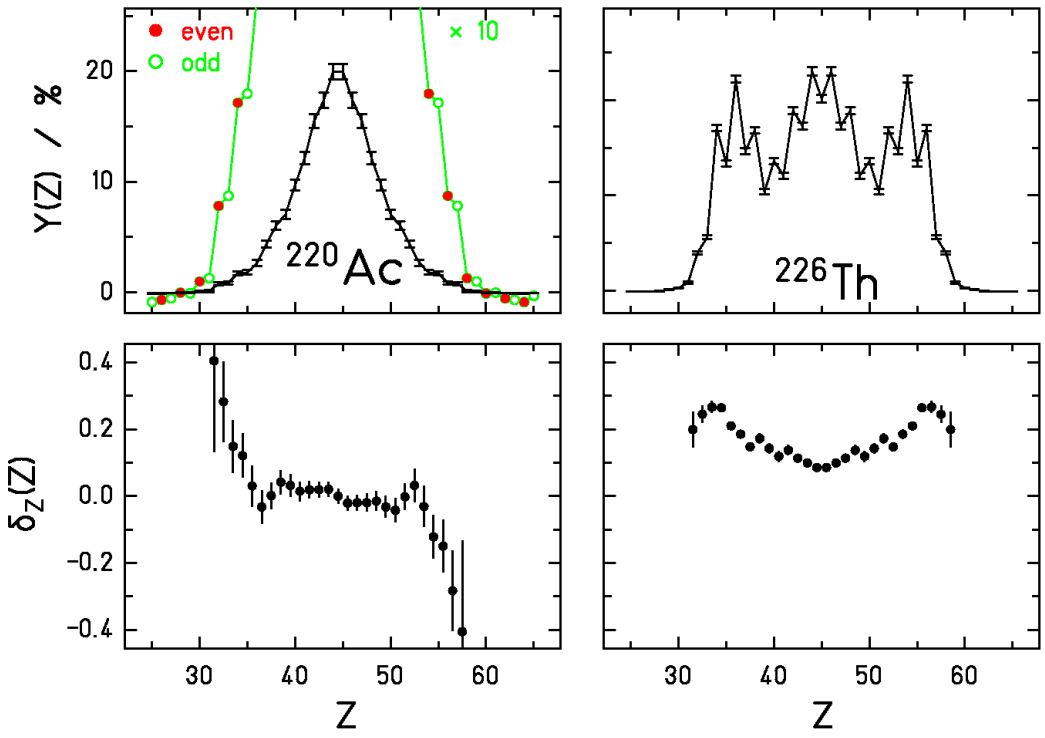


Model calculation:



Results on dissipation in a cold nuclear system

Pair breaking in fission (E* ≈ 11 MeV)



($\delta_Z(Z)$ = local even-odd effect)

Even-odd effect for odd-Z fissioning nucleus ($_{89}$Ac)

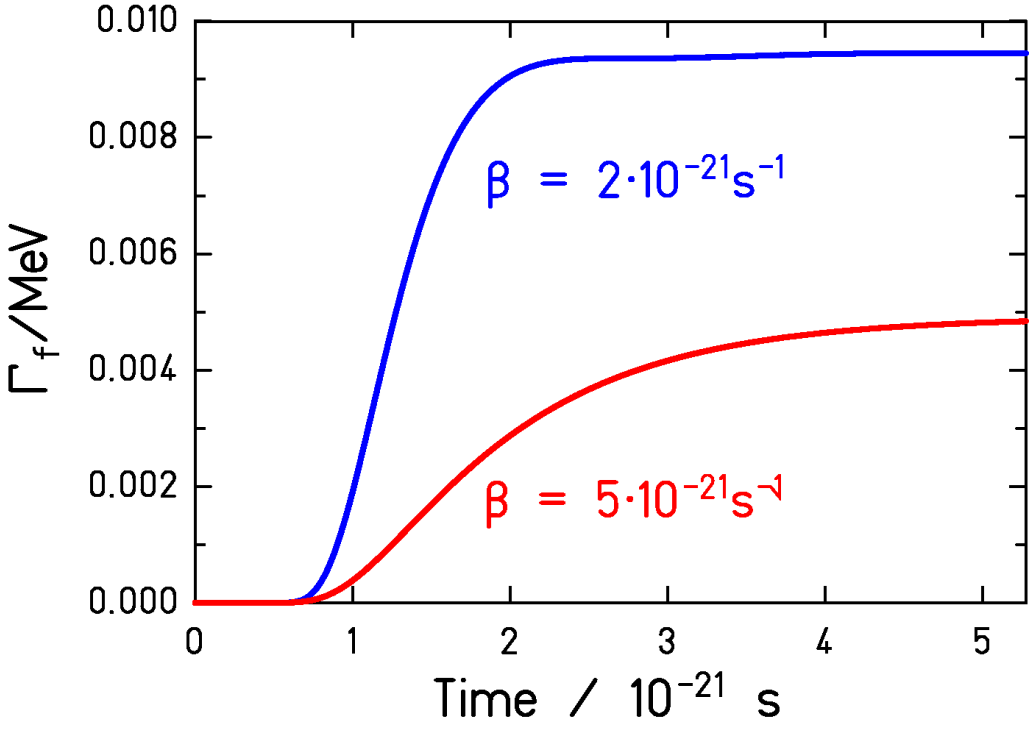
Even-odd effect at symmetry for even-Z nucleus ($_{90}$Th)

Strong increase of even-odd effect in asymmetric fission

Interpretation: Nucl. Phys. A 634 (1998) 89,
Nucl. Phys. A 678 (2000) 215

Results on dissipation in a cold nuclear system

Time-dependent flow over the fission barrier

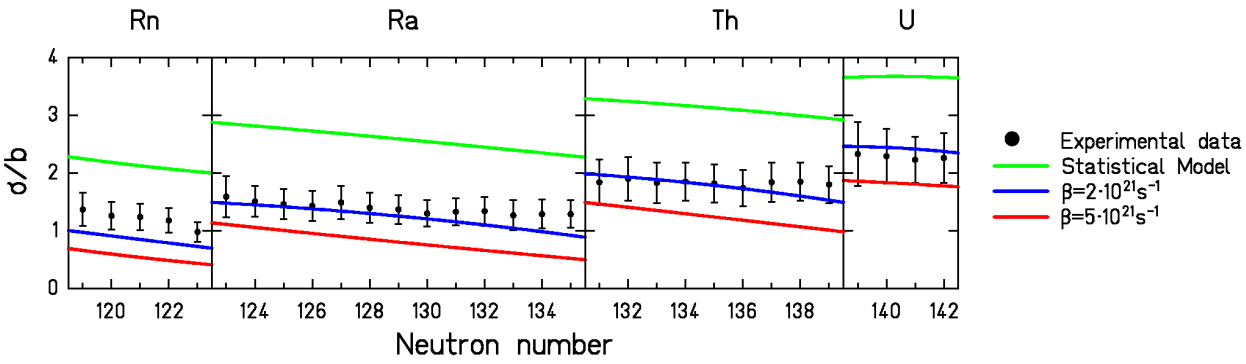


An example for the solution of the Fokker-Planck equation used in the nuclear-reaction code.

Results on dissipation in a heated nuclear system

Signatures of dissipation in fission:

1. Total fission cross sections



Systematic overview with different secondary beams

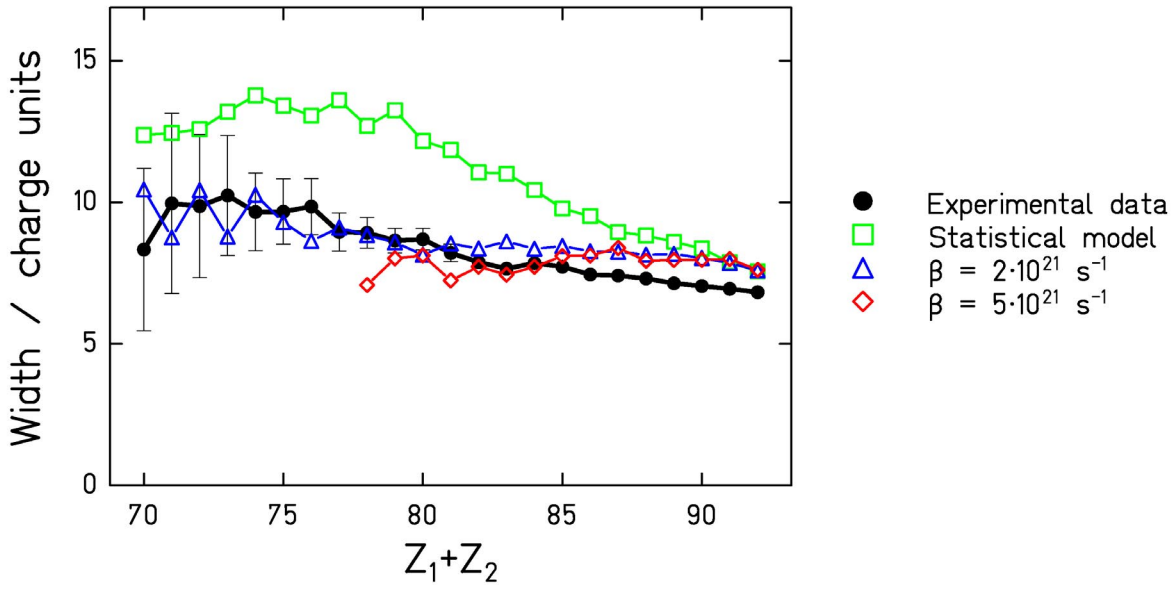
Evidence for dissipative hindrance of fission:

$$\beta = 2\ 10^{21}\ s^{-1}$$

Results on dissipation in a heated nuclear system

Signatures of dissipation in fission:

2. Widths of element distributions



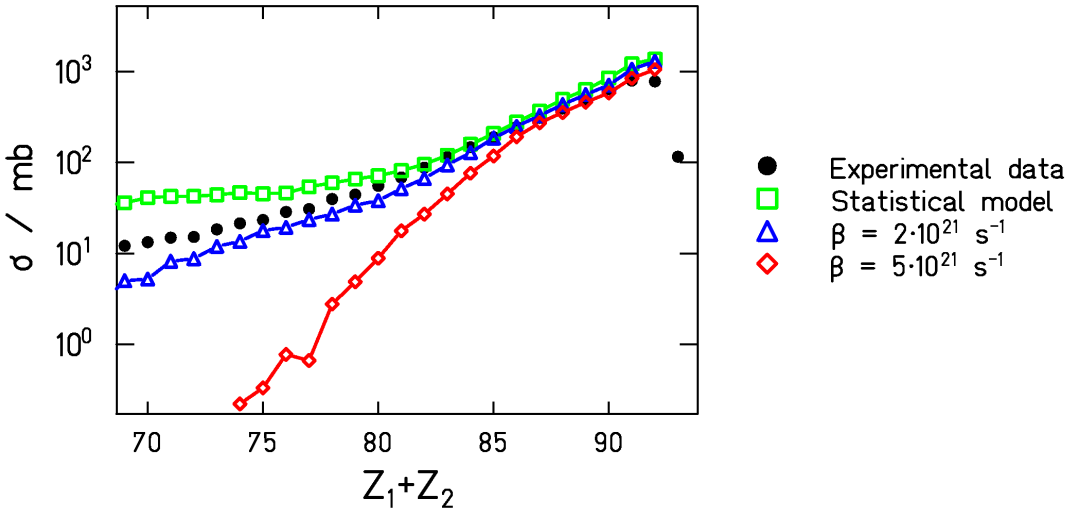
Fission of ^{238}U (1 A GeV) in a plastic target.

Again:
Evidence for dissipative hindrance of fission

Results on dissipation in a heated nuclear system

Signatures of dissipation in fission:

3. Partial fission cross sections



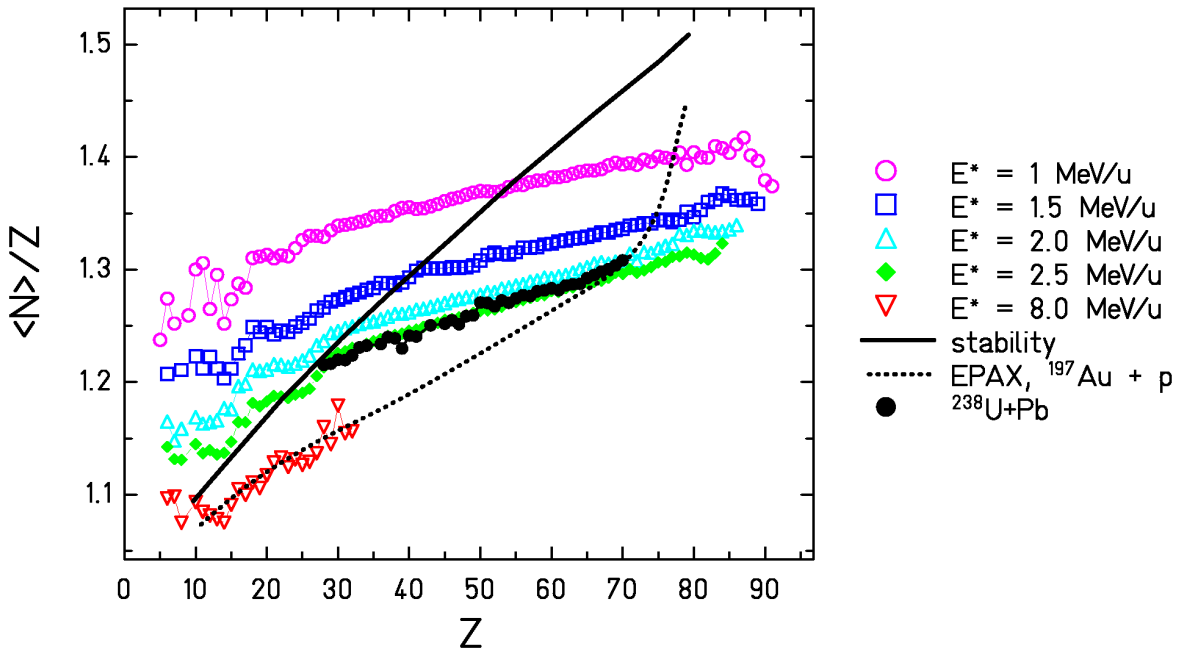
Fission of ^{238}U (1 A GeV) in a plastic target.

Again:
Evidence for dissipative hindrance of fission

$$\beta = 2\ 10^{21}\ s^{-1}$$

Results on temperature limit for sequential decay

Freeze-out temperature after break-up

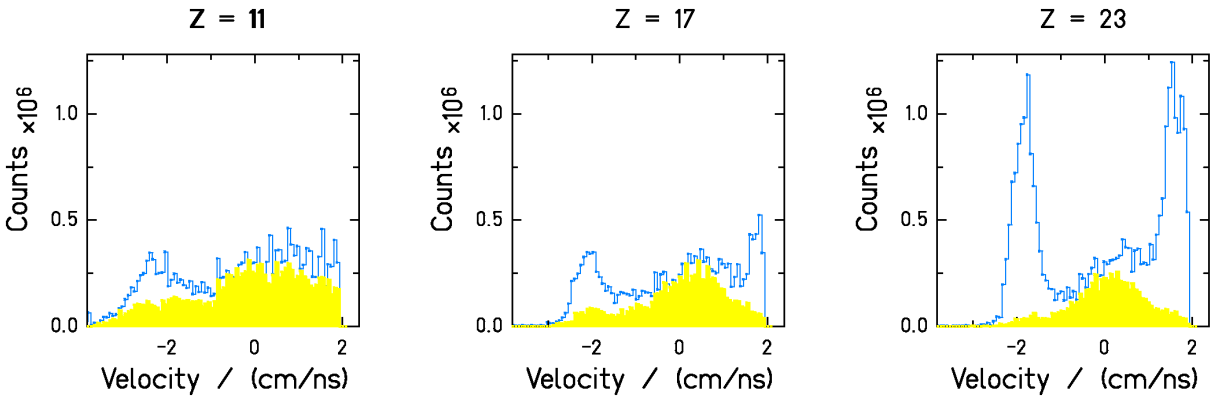


Comparison of <N/Z> ratio with SMM calculations

- **E* = 2.5 MeV/u (corresponding to T = 5 MeV) at freeze-out**
- **Indication that fission is prohibited for T > 5 MeV by thermal instability!**

Result on extremely asymmetric fission

Very light fission products



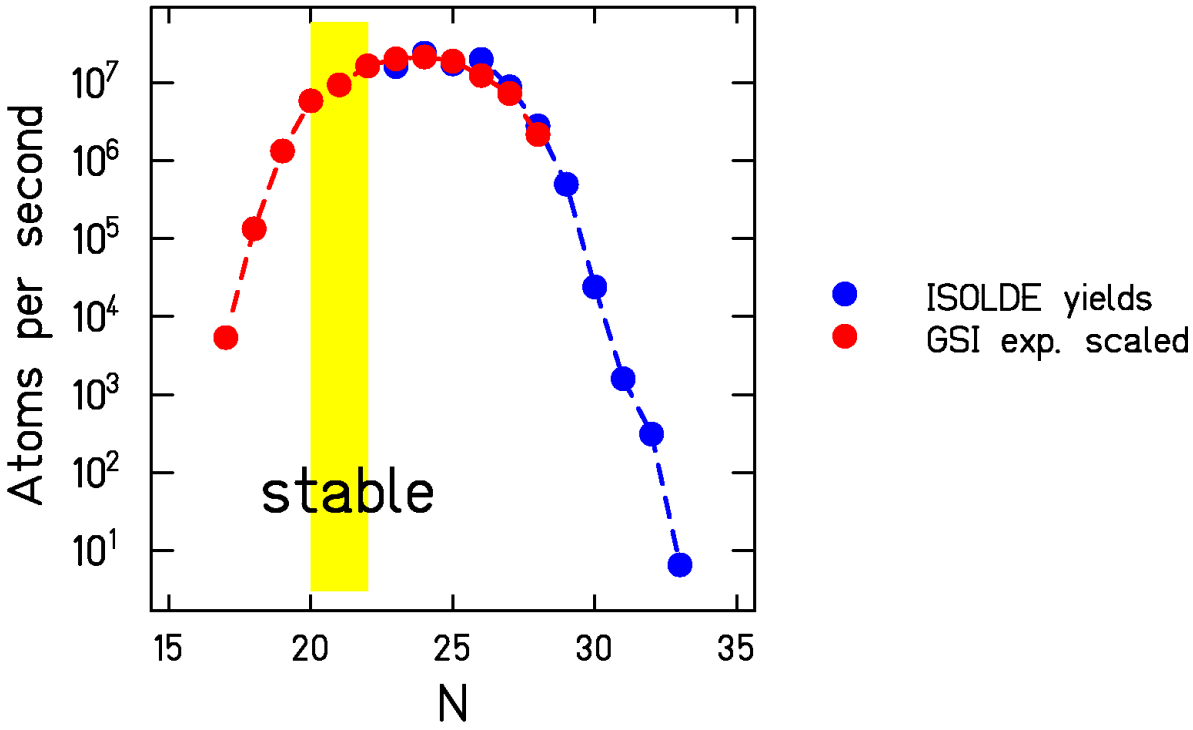
Residue production by ^{238}U (1 A GeV) + Ti (yellow)

and ^{238}U (1 A GeV) + H (blue)

Fission reaches down to Z = 11!

Result on extremely asymmetric fission

Potassium production



ISOLDE yields (spallation of U by 600 MeV protons)

fit to

fission residues in 238U (1 A GeV) + hydrogen.

<u>Light nuclei produced by spallation of U at ISOLDE are fission products!</u>

Conclusion

New possibilities for fission studies by

- **Secondary beams**
- **Inverse kinematics**

Results:

- **General variation of fission channels**
- **Detailed study of pair breaking as a signature for dissipation in cold nuclei**
- **New experimental signatures for dissipation in highly excited nuclei**
- **Limiting temperature for fission due to thermal instability**
- **Extremely asymmetric fission measured**