Basic Research at GSI for the Transmutation of Nuclear Waste*

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* Work performed in the frame of the HINDAS project

Glossary

- **Fragment separator:**

  Resolution and acceptance

- **Experimental results – general view:**

  Velocity distributions.

  Nuclide distributions.

- **Experimental results – specific:**

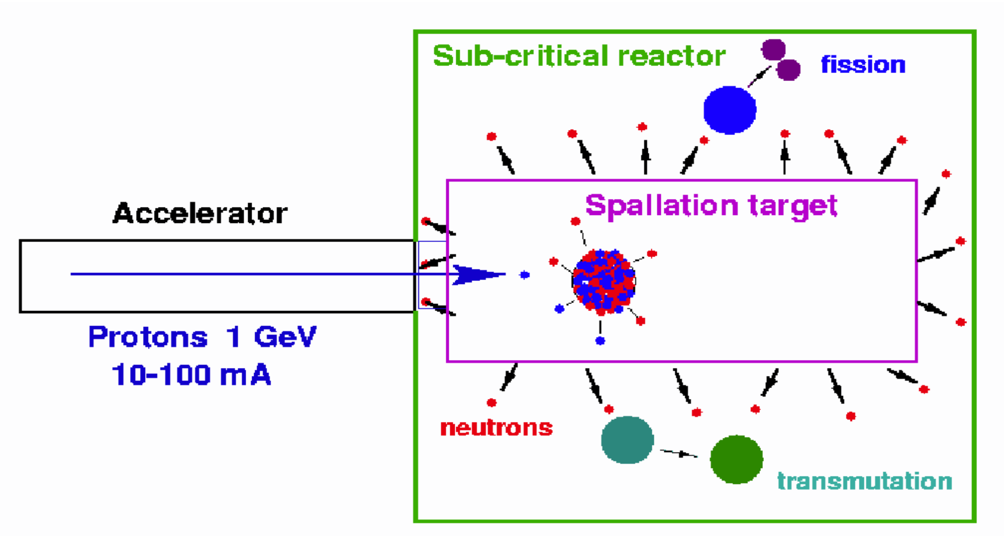
  Dissipation in fission – statistical vs. dynamical

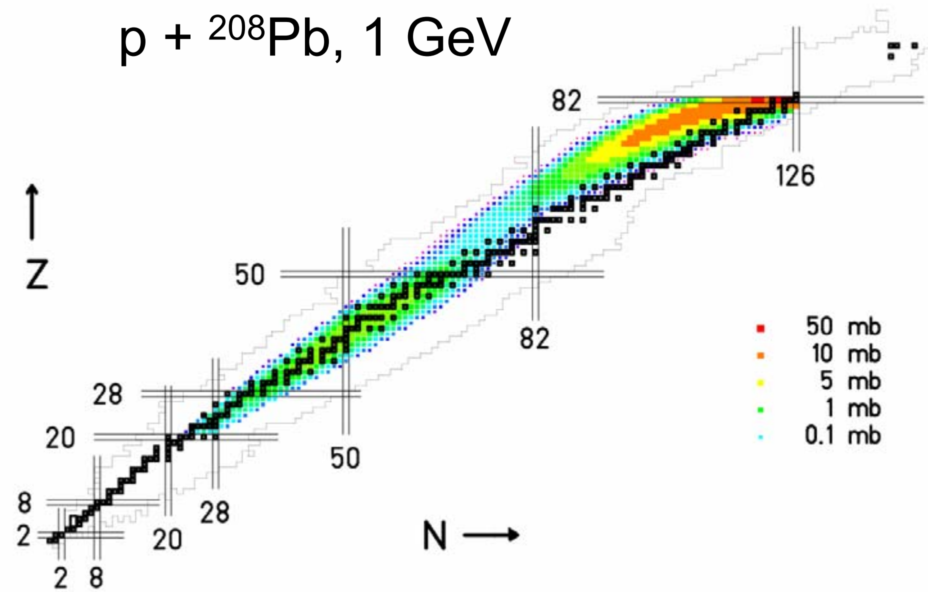
  Thermal instabilities in nuclei – how hot can nucleus be

  Even-odd structure in the final residue yields – restoring the nuclear structure effects at the end of the evaporation chain

- **Outlook.**

Motivation - Hybrid System (ADS)





T. Enqvist et al., NPA686 (01)481

- Yields of spallation neutrons.
- <u>Production of radioactive nuclei by spallation.</u>
- <u>Material damages due to irradiation.</u>

Nuclear reactions up to 1 GeV have to be known!

Nuclear physics at GSI for ADS design

How-to:

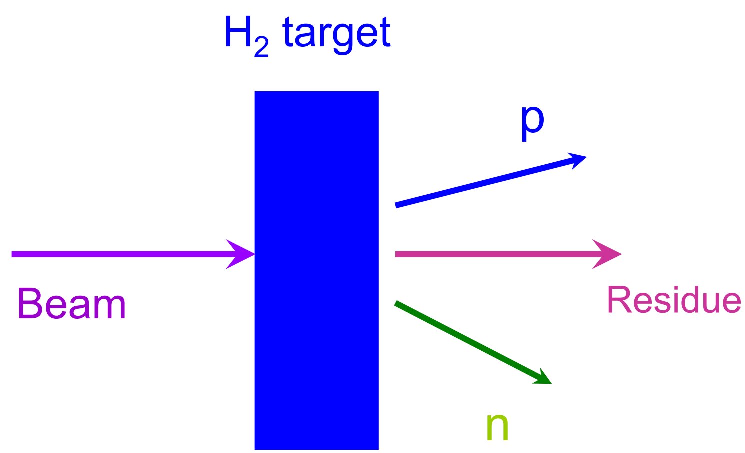
The data on systematic investigation of a few representative systems (Fe, Xe, Au, Pb, U) put important constraints on the models to be improved or developed.

⇨ **Inverse kinematics**

In-flight identifications of heavy reaction products.

Advantage:

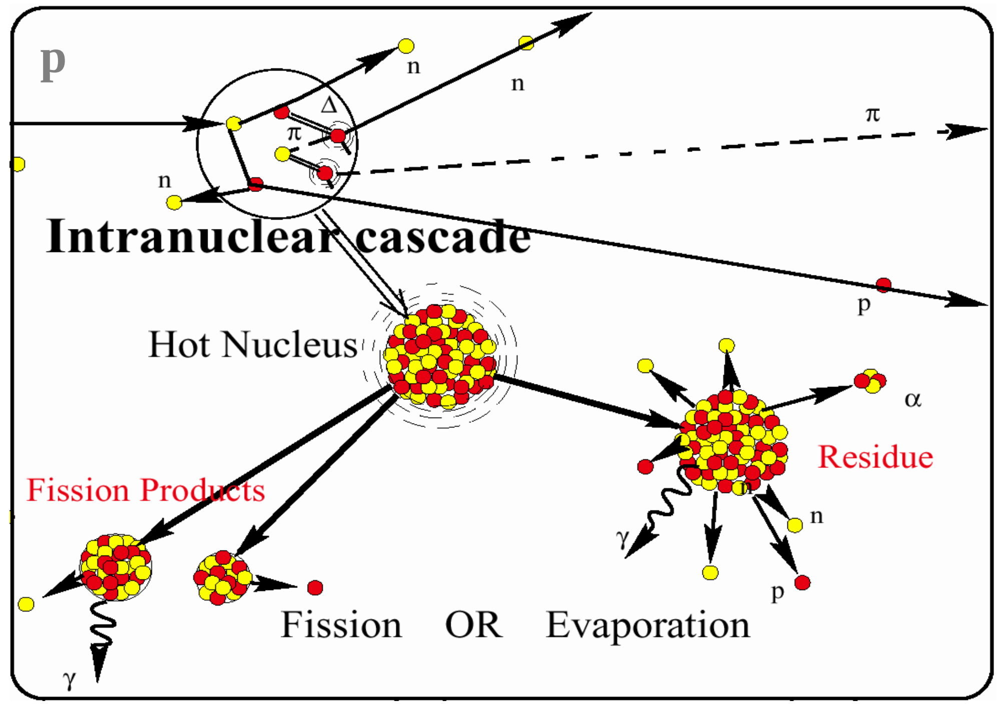
- ❑ all half-lives above 150 ns
- ❑ all isotopes
- ❑ kinematical properties



Nuclear physics at GSI for ADS design

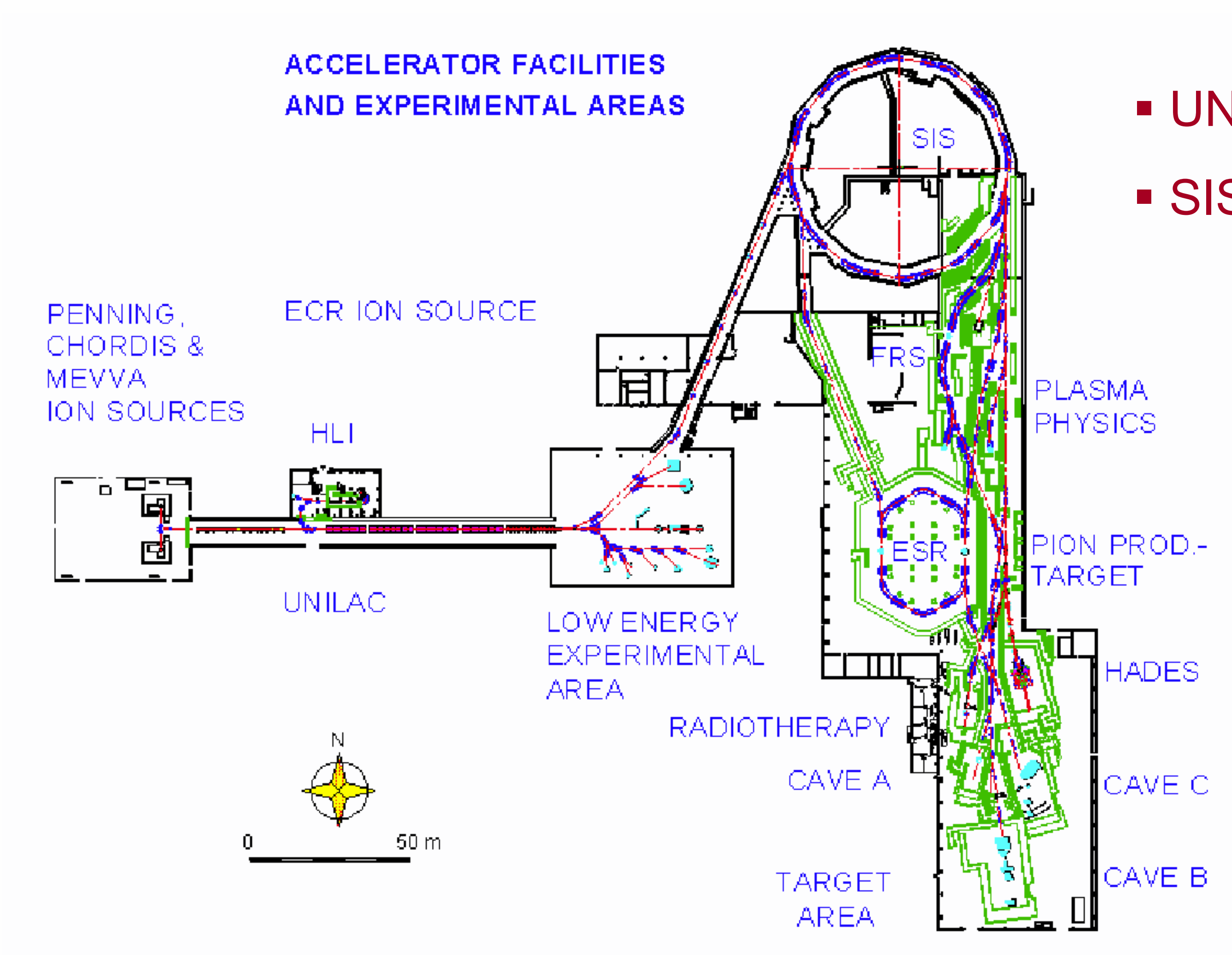
Goal:

Complete understanding and modelling of spallation reactions at 0.2 – 2 *A* GeV.



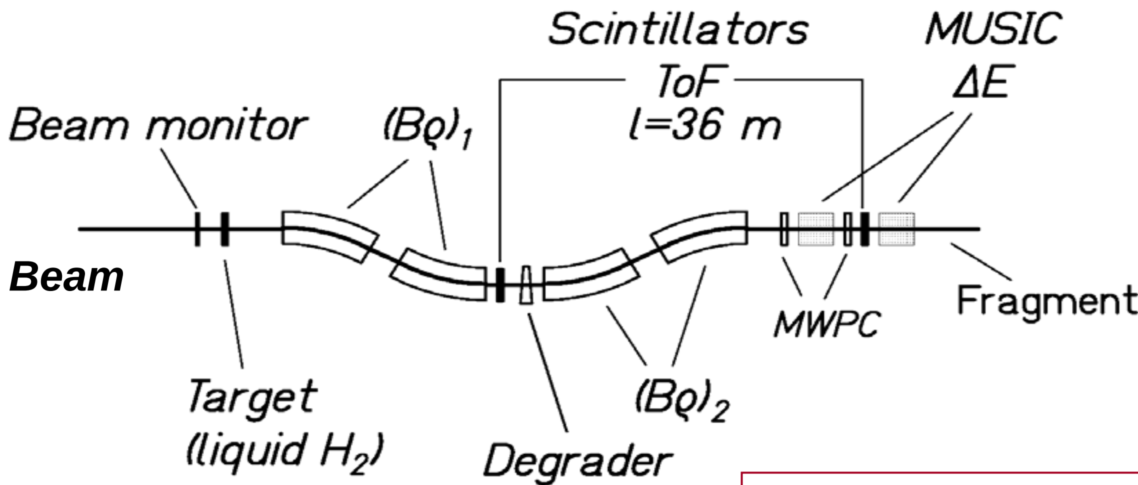
- ⇨ Energy deposition in spallation.
- ⇨ Decay of hot nucleus.

Experimental facility at GSI



- UNILAC : Up to 20 A MeV
- SIS : 50 – 2000 A MeV, up to 10^{11} part/spill

The GSI Fragment Separator



Length $= 72$ m

$(B\rho)_{max} = 18$ Tm

$\Theta^{max} = 15$ mrad

$\Delta p/p = \pm 1.5$ %

$$B\rho = \frac{m_0 c}{e} \cdot \frac{A}{Z} \cdot \beta \cdot \gamma$$

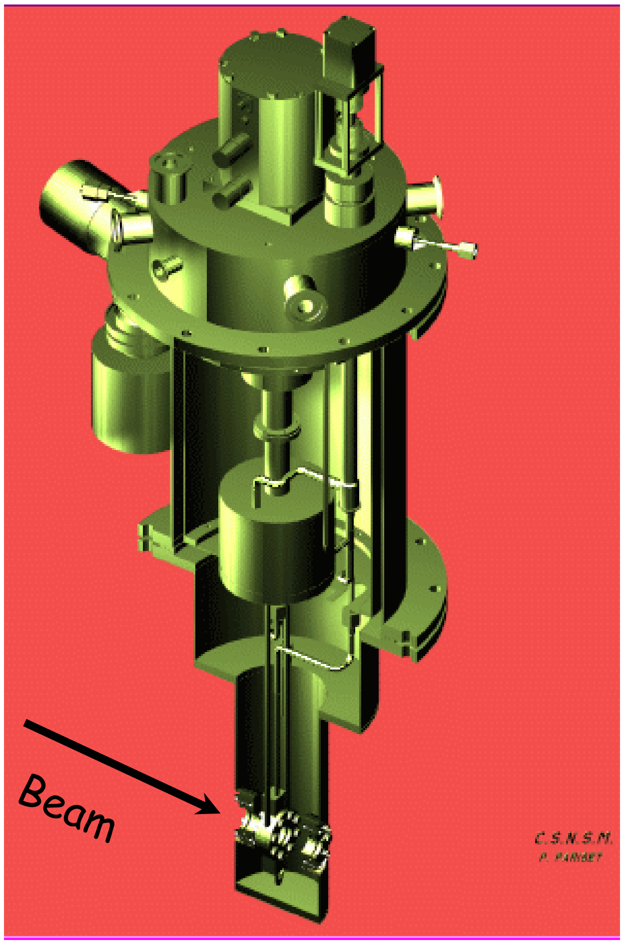
Resolution:

- $\Delta(B\rho)/B\rho \approx 5 \cdot 10^{-4}$
- $\Delta(TOF) \approx 100$ ps
- From TOF $\Rightarrow \Delta(\beta\gamma)/\beta\gamma = 2.5 \cdot 10^{-3}$

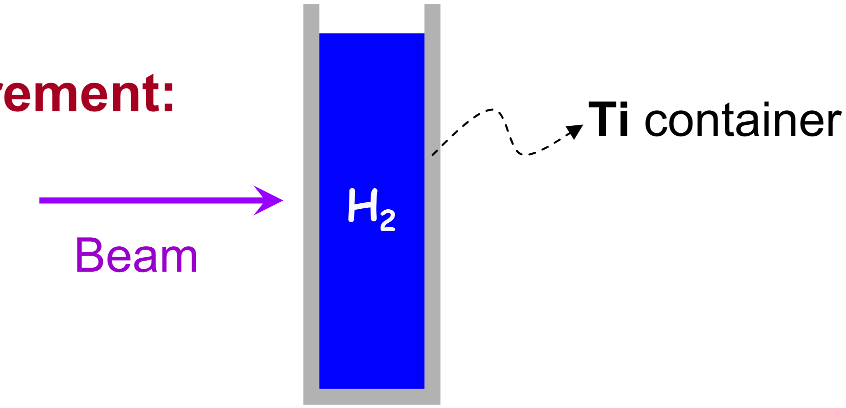
After *A* and *Z* identification $\Delta(\beta\gamma)/\beta\gamma$ is given only by $\Delta(B\rho)/B\rho$.

From $B\rho \Rightarrow \Delta(\beta\gamma)/\beta\gamma \approx 5 \cdot 10^{-4}$

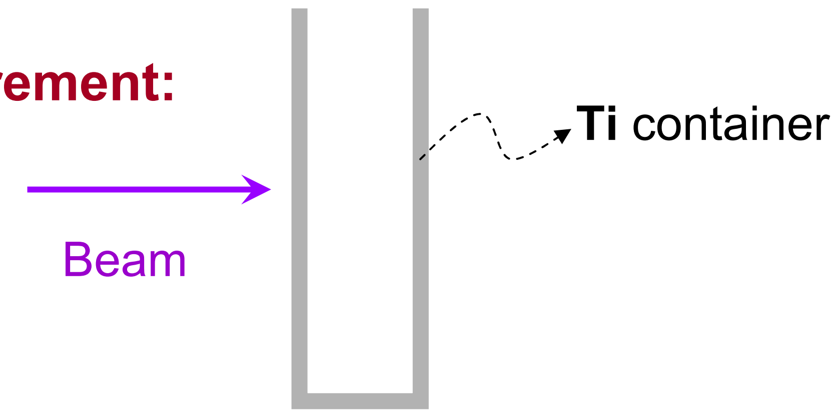
Liquid ^1H and ^2H targets



1st Measurement:



2nd Measurement:

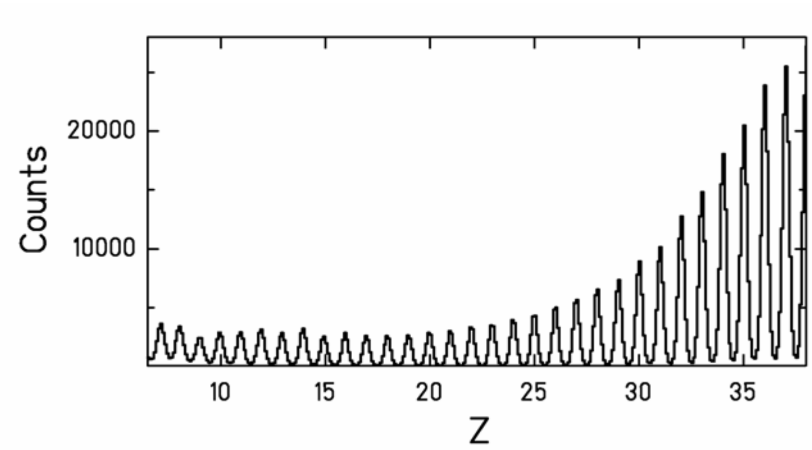


Identification pattern

❑ Charge identification

From energy loss in MUSIC

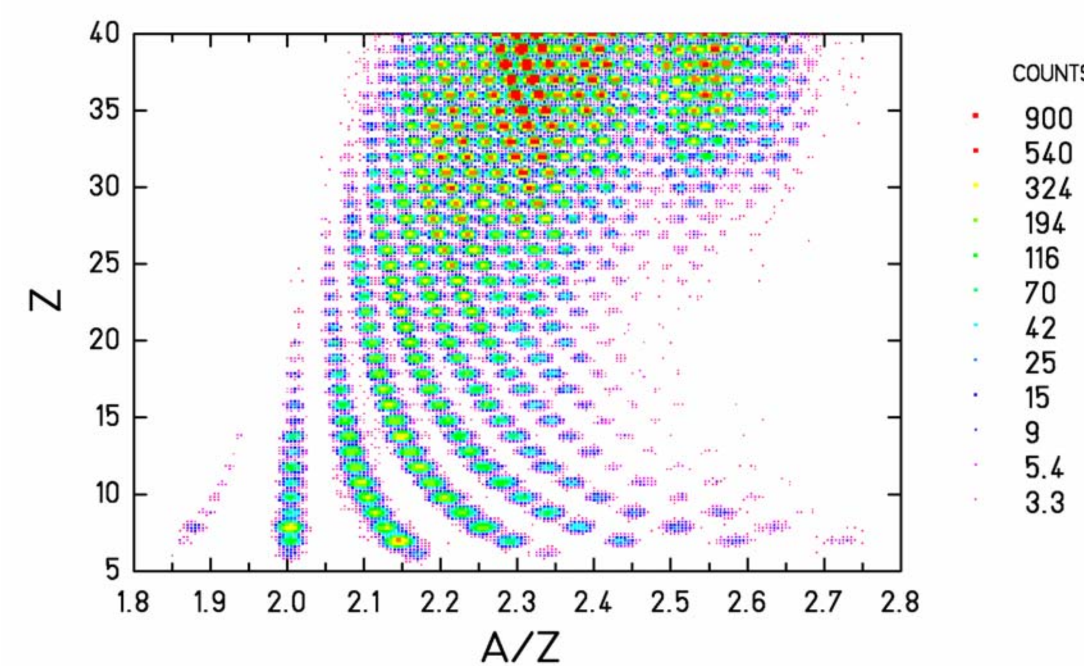
$Z / \Delta Z \approx 200$ for heaviest products



❑ Mass identification

From $B\rho$ and $\beta\gamma$

$A / \Delta A \approx 400$

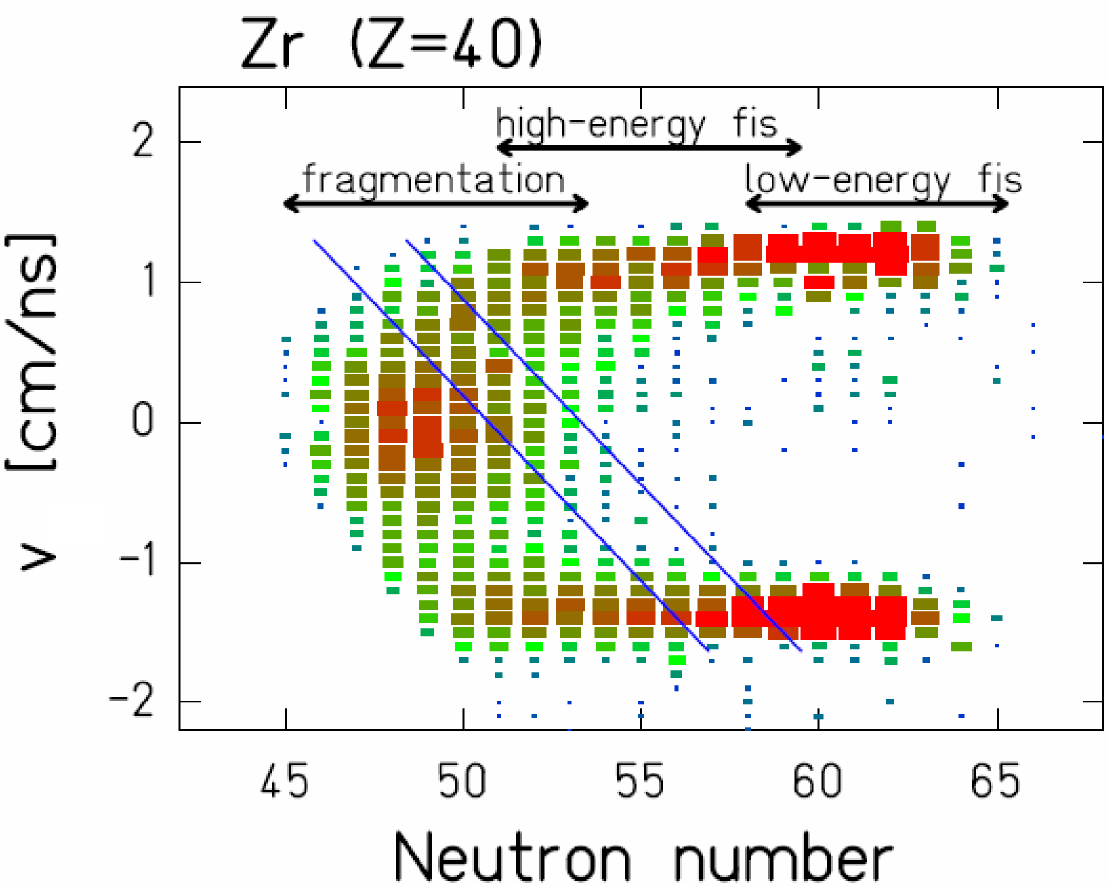


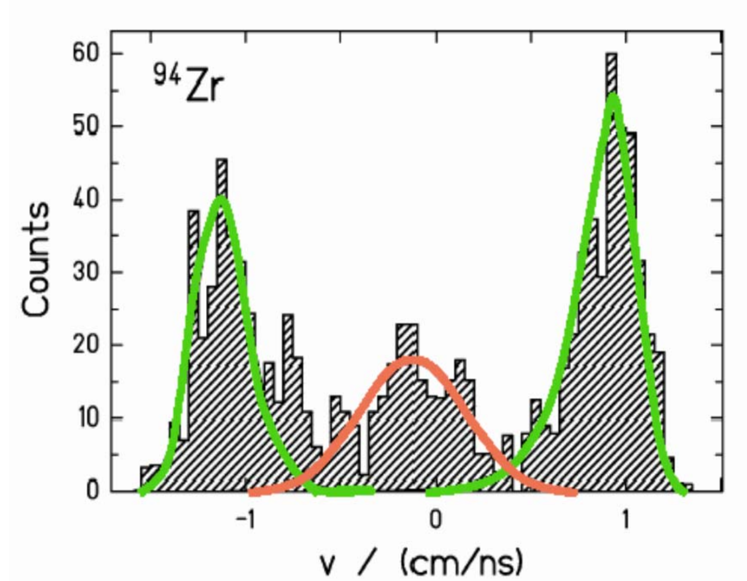
^{238}U+Ti at 1 *A* GeV

M.V. Ricciardi, PhD thesis

Kinematics

$^{238}U + ^{208}Pb$, 1 *A* GeV





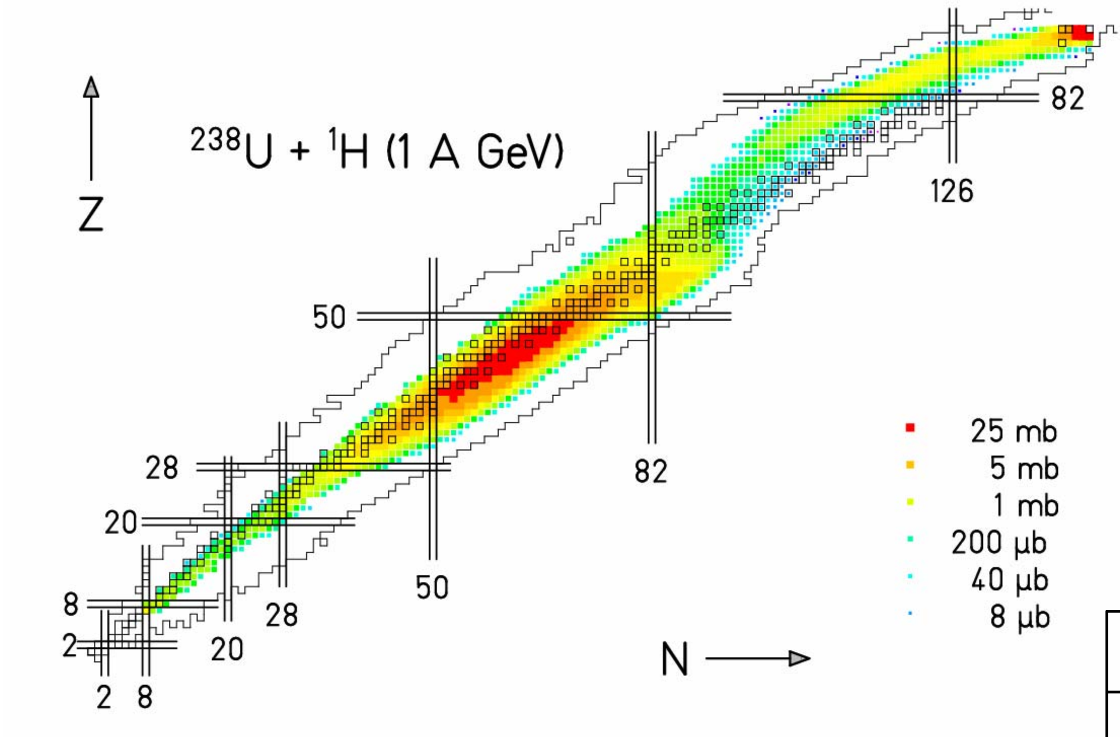
For every nuclide:

✓ Recoil energy

✓ Production mechanism – **fission** / **fragmentation**

T. Enqvist et al, NPA658 (1999), 47.

Production cross sections



J. Taïeb et al., NPA 724 (2003) 413

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

M.V. Ricciardi, PhD thesis

Data accuracy:

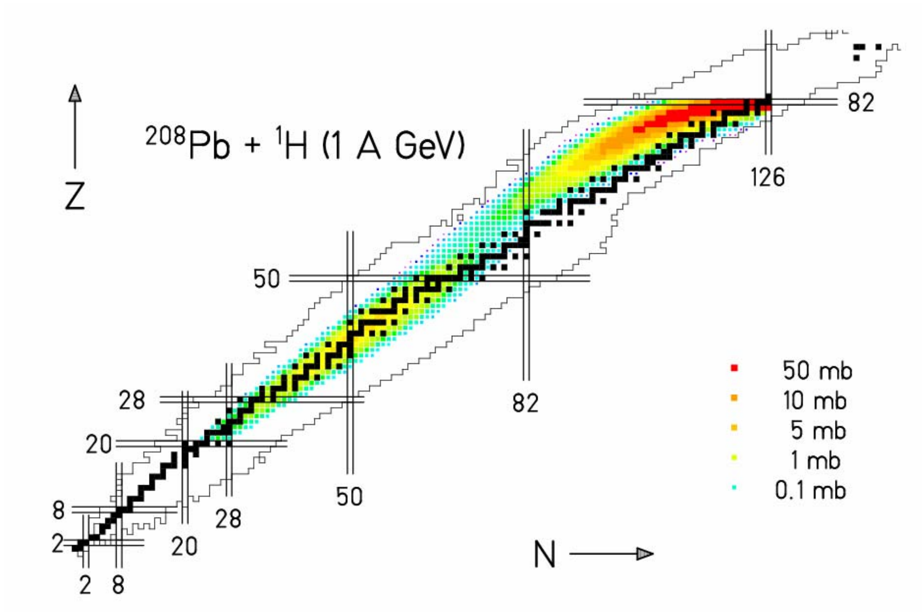
- Statistic – about 3%
- Systematic – 9 - 15 %

Studied systems:

Projectile	Target	Energy [A GeV]
^{56}Fe	^{1}H	0.2 - 1.5
^{136,124}Xe	^{1,2}H, Ti, Pb	0.2, 0.5, 1
^{197}Au	^{1}H	0.8
^{208}Pb	^{1,2}H, Ti	0.5, 1
^{238}U	^{1,2}H, Ti, Pb	1

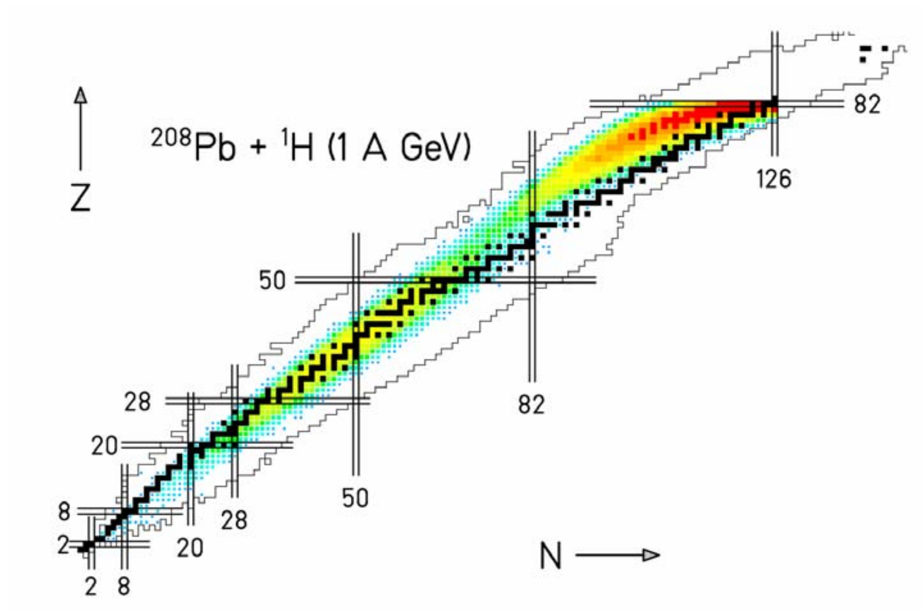
GSI code ABRABLA

- Experiment



T. Enqvist et al., NPA686 (01)481

- ABRABLA calculations



Role of dissipation in fission

❑ Low excitation energies:

- Statistical time scale much longer than the dynamical ⇨

  could "justify" the use of the Bohr-Wheeler transition-state model.

❑ High excitation energies:

- Dynamical time scale comparable to the statistical ⇨

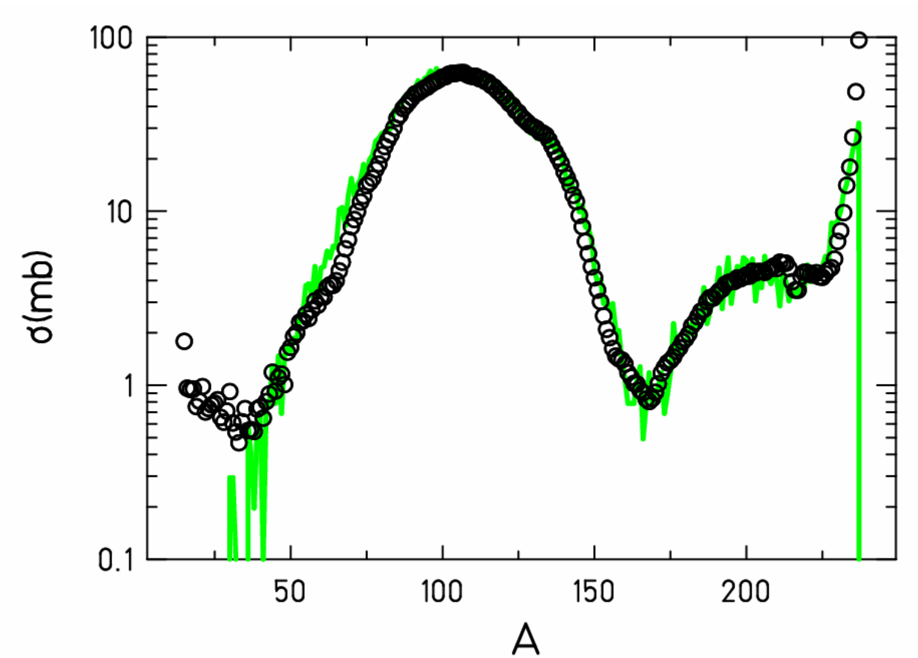
  fission has to be treated as a dynamical process.

Proper description of fission is important for the evaporation – fission competition in spallation reactions.

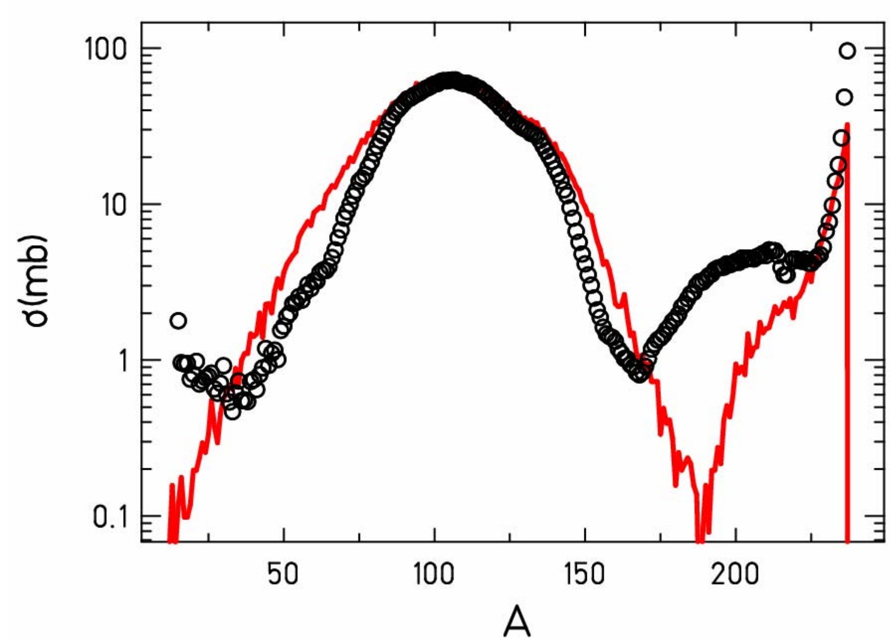
Role of dissipation in fission

^{238}U + p at 1 *A* GeV; Experiment vs. ABRABLA calculations

Dynamical model



Transition-state model



Exp. data:
J. Taïeb et al., NPA 724 (2003) 413
M. Bernas et al., NPA 725 (2003) 213
M.V. Ricciardi, PhD thesis

EXP: σ_{fiss} = 1.53 ± 0.2 b

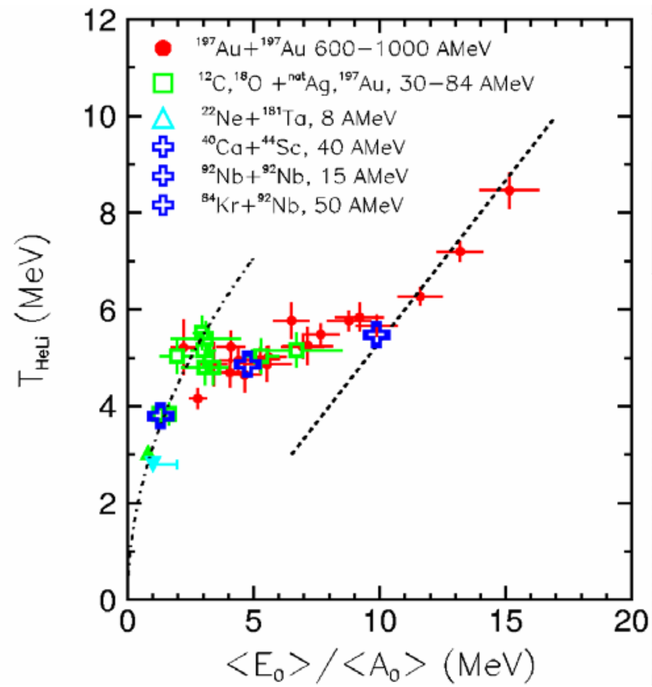
DM: σ_{fiss} = 1.52 b

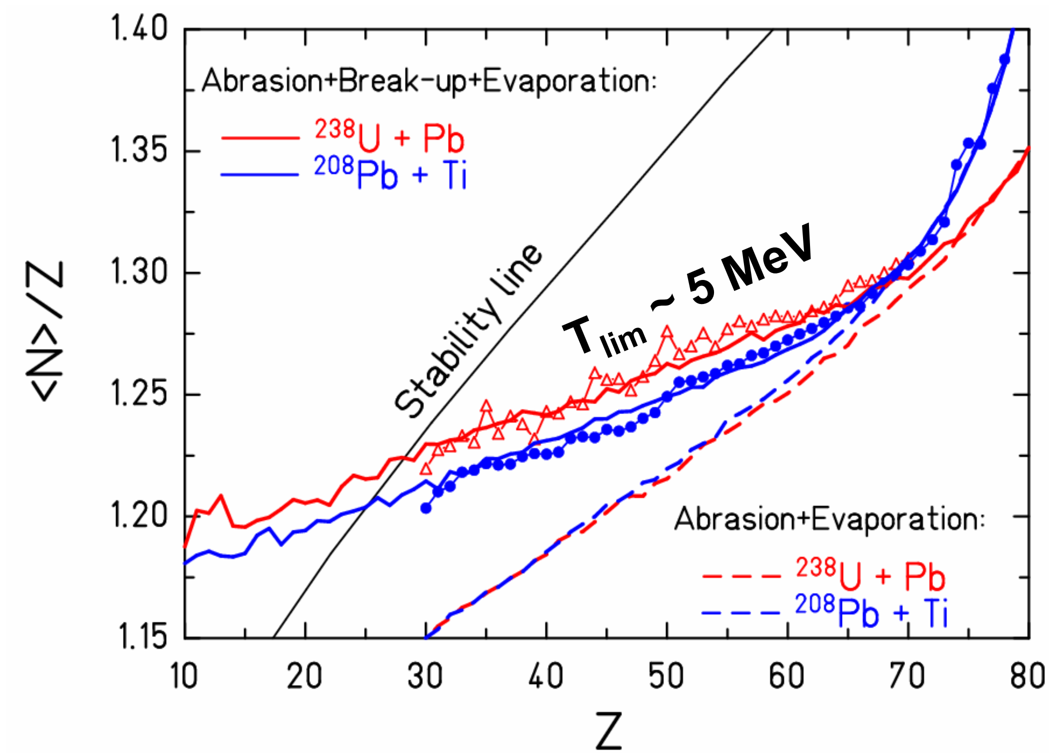
TSM: σ_{fiss} = 1.73 b

Thermal instabilities

❑ ALADIN - 4π experiments, only light products

❑ FRS - Thermometry extended to heavy products (K.-H. Schmidt et al, NPA 710 (02) 157)

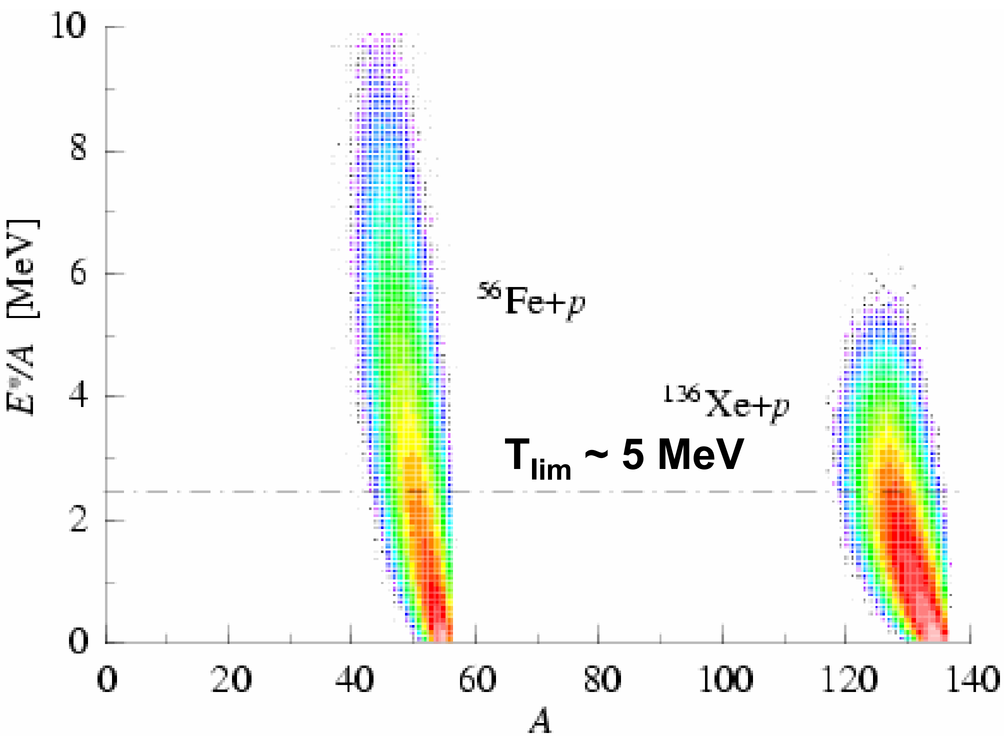


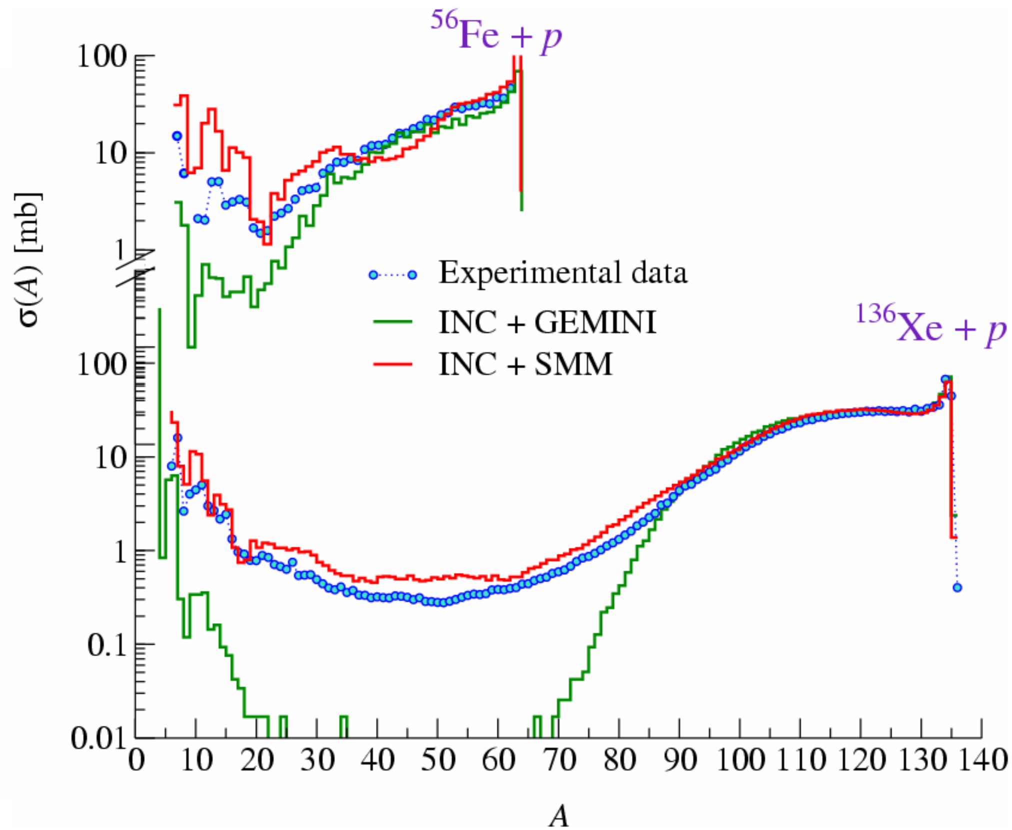


✓ **Unique picture ⇨ maximum temperature of ~ 5 MeV above which compound system can not survive as an entity.**

Thermal instabilities

P. Napolitani, PhD thesis, PRC accepted

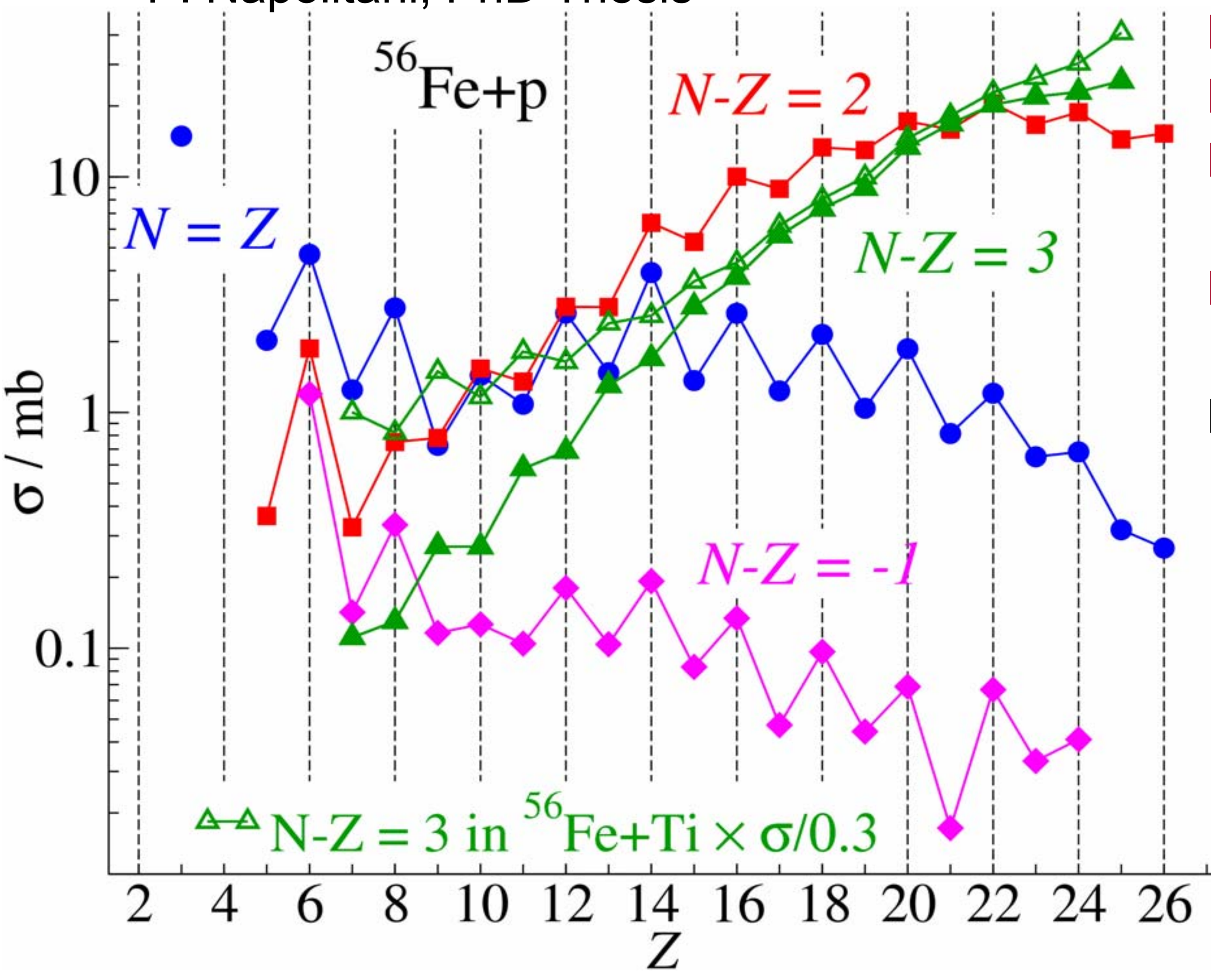




✓ **Have to be considered in order to describe the production of light residues, especially in p-induced reactions on lower-mass targets.**

Even-odd staggering in the final residue yields

P. Napolitani, PhD Thesis



- **Even *A*** : even *Z* favoured
- **Odd *A*, p rich**: even *Z* favoured
- **Odd *A*, n rich**: odd *Z* favoured (20%)
- ***N=Z***: huge staggering >50%!

- Number of excited levels of the mother that could decay into the daughter determines the probability of a channel (M.V. Ricciardi et al, NPA 733 (04) 299).

✓ **Restoring of the nuclear structure in the very last steps of the evaporation.**

Outlook

- Energy dependence of proton-induced spallation of ^{136}Xe (0.2 ... 1 *A* GeV) at FRS. (Data partly analysed, further analysis in progress).
  ⇨ **Modelling of spallation in a thick target.**

- Coincidence measurement of heavy residues, light charged particles and neutrons with ^{56}Fe at ALADIN. (Experiment in preparation).
  ⇨ **Investigation of the decay of highly excited heavy nuclei.**

- Full identification of both fission fragments, simultaneous measurement of neutrons, light charged particles and gammas with new R3B magnetic spectrometer. (Preparative studies).
  ⇨ **Aiming for a kinematically complete fission experiment.**

Summary

❑ **Experimental goal:**

Full coverage of yields and velocities of heavy residues, neutrons and light charged particles.

❑ **Status:**

- Most complete set of relevant data measured (~ 1000 isotopes /system, previously: ~ 20).
- 2nd generation experiment in preparation.

❑ **New information on critical topics:**

- Dissipative hindrance of fission (B. Jurado et al, PRL 93 (2004) 072501).
- Thermal instabilities in nuclei (K.-H. Schmidt et al, NPA 710 (2002) 157).
- Even-odd staggering in residue yields (M.V. Ricciardi et al, NPA 733 (2004) 299).

http://www-w2k.gsi.de/kschmidt

Collaborations

GSI

P. Armbruster, T. Enqvist, K. Helariutta, V. Henzl, D. Henzlova, B. Jurado, A. Kelić, M. V. Ricciardi, K.-H. Schmidt, C. Schmitt, F. Vives, O. Yordanov

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