Spallation reactions studies in inverse kinematics at GSI *

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* Work performed in the frame of the HINDAS project

§ **http://www-w2k.gsi.de/charms**

Glossary

- **Fragment separator (FRS)**

  Resolution and acceptance

- **Experimental results – general view**

  Nuclide distributions

- **Experimental results – specific**

  What can we learn from the data?

- **Outlook**

Interest in spallation reactions

- **ADS technology**: Data on high-energy proton-induced reactions in different materials (e.g. spallation target, beam window, construction materials ...)

Nuclear reactions up to 1 GeV have to be known

- Reactions studied at GSI:

Projectile	Target	Energy [*A* GeV]
^{56}Fe	^{1}H	0.3, 0.5, 1.0, 1.5
$^{136,124}Xe$	$^{1,2}H$	0.2, 0.5, 1
^{197}Au	^{1}H	0.8
^{208}Pb	$^{1,2}H$	0.5, 1
^{238}U	$^{1,2}H$	1

Data available at http://www-w2k.gsi.de/charms/data.html

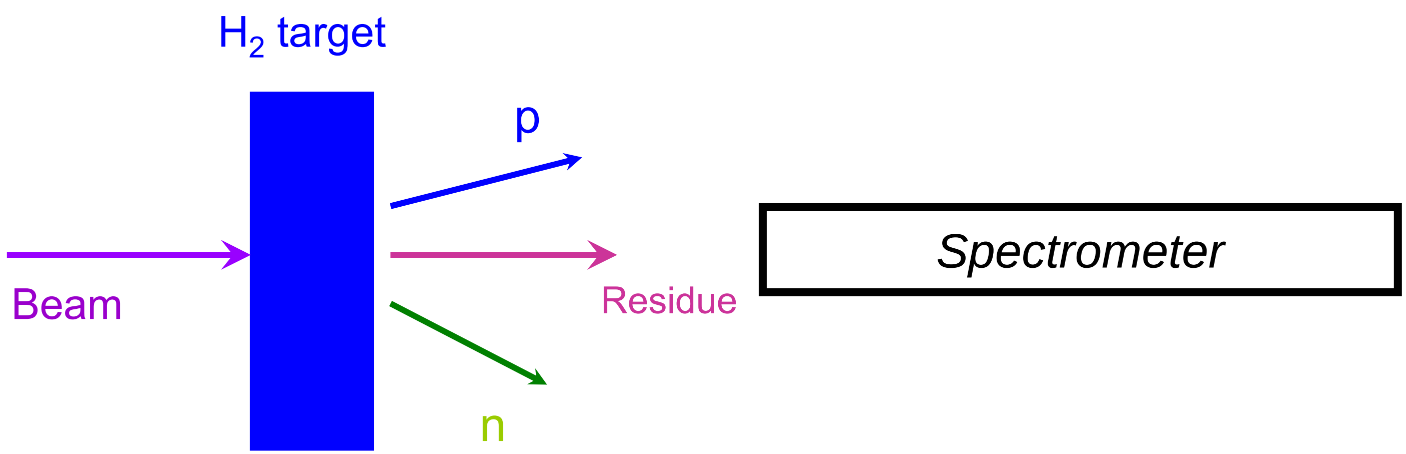
- Excellent basis for model benchmarking

- Also ⇨ **RIB production, neutron sources, astrophysics, space technology**

Inverse kinematics

- **In-flight identifications of heavy reaction products:**

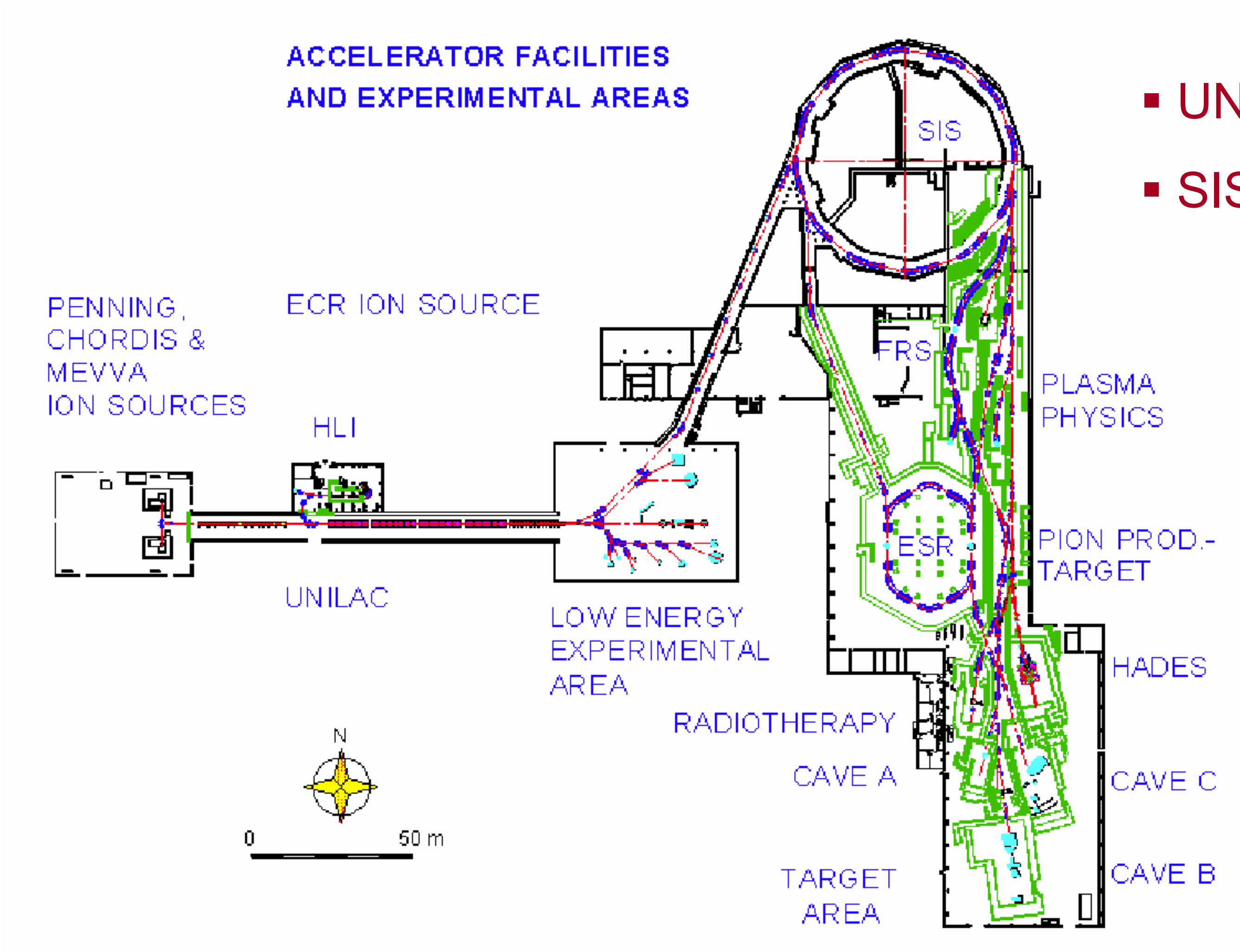
High-energy (~ 1 *A* GeV) heavy-ion beam impinges on liquid-hydrogen target



- **Advantages:**

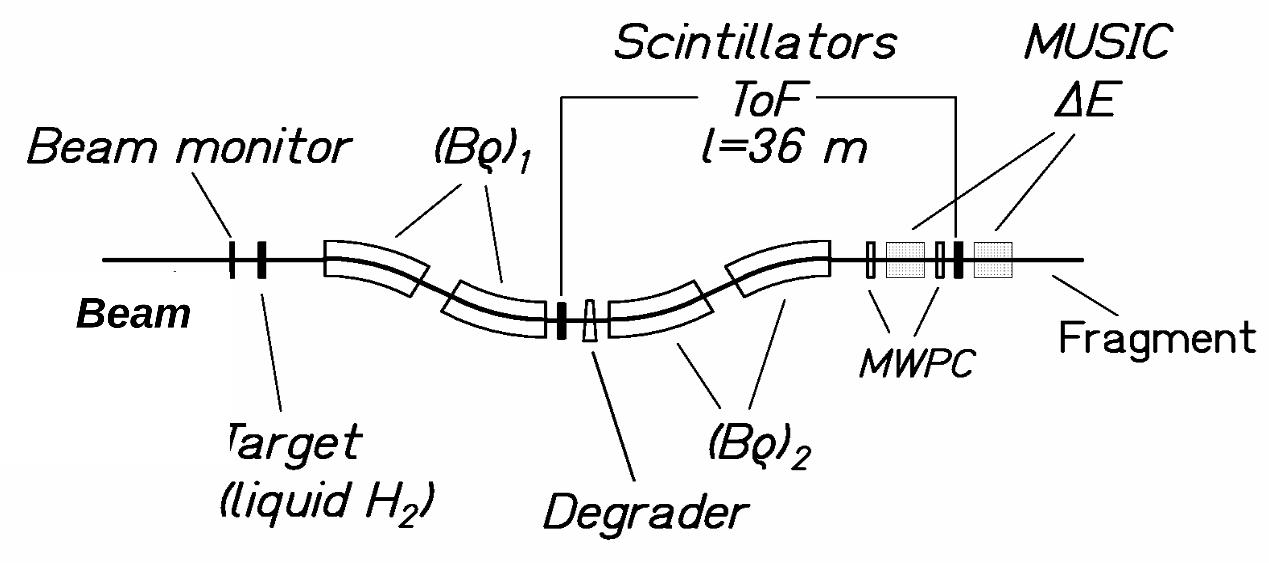
- "All" half-lives
- All isotopes
- Kinematical properties

Experimental facility at GSI



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

Fragment separator (FRS)



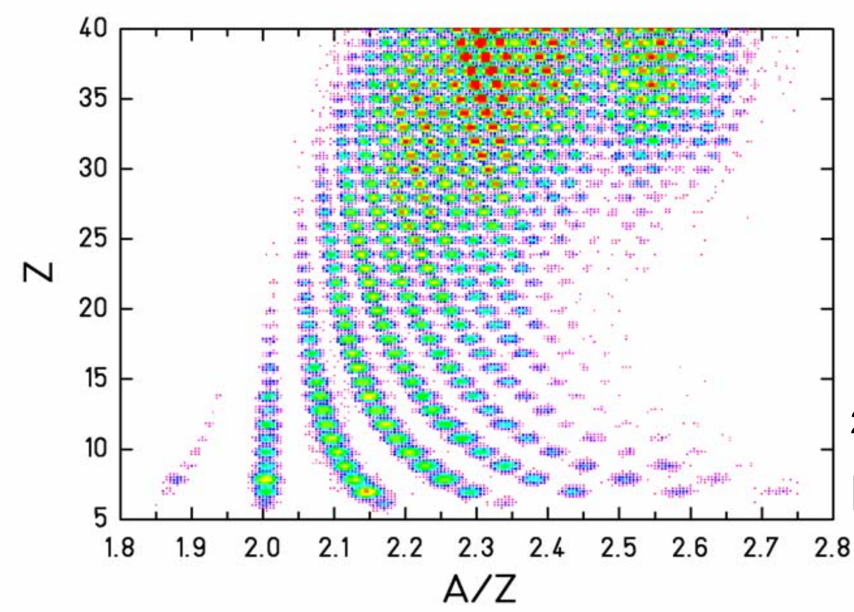
$$B\rho = \frac{m_0 c}{e} \cdot \frac{A}{Z} \cdot \beta \cdot \gamma$$

Θ^{max} = 15 mrad

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

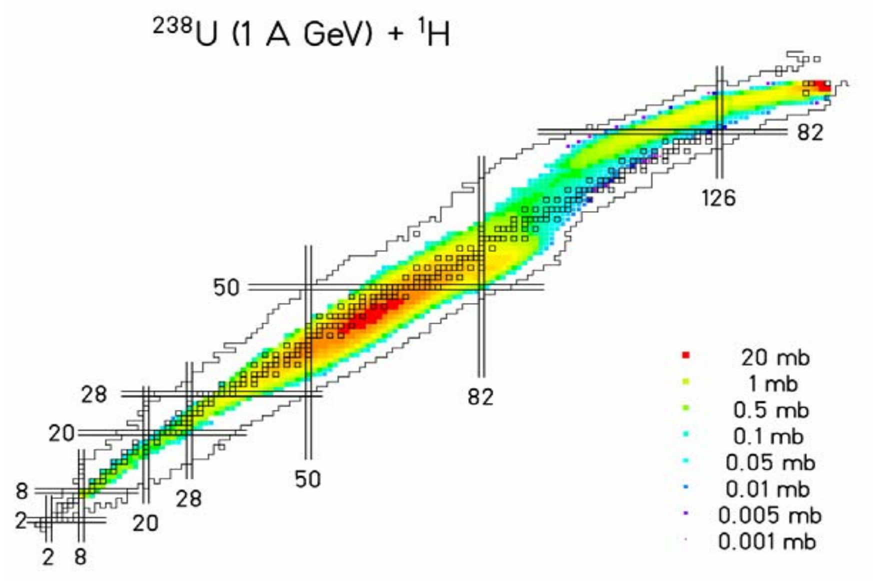
Resolution:

- $\Delta(B\rho)/B\rho \approx 5 \cdot 10^{-4}$
- $\Delta A/A \approx 2.5 \cdot 10^{-3}$
- $\Delta Z/Z \approx 5 \cdot 10^{-3}$
- $\Delta(\beta\gamma)/\beta\gamma = 5 \cdot 10^{-4}$

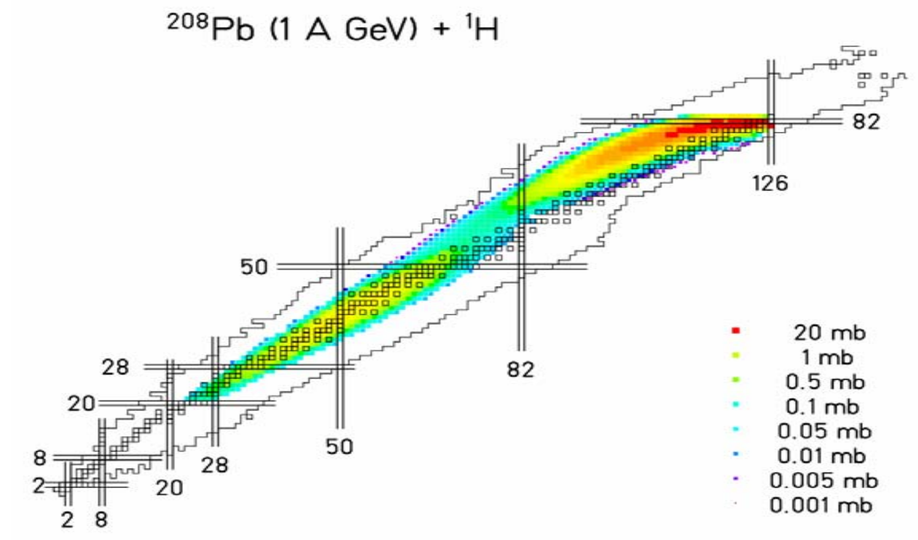


^{238}U+Ti at 1 A GeV
M.V. Ricciardi, PhD

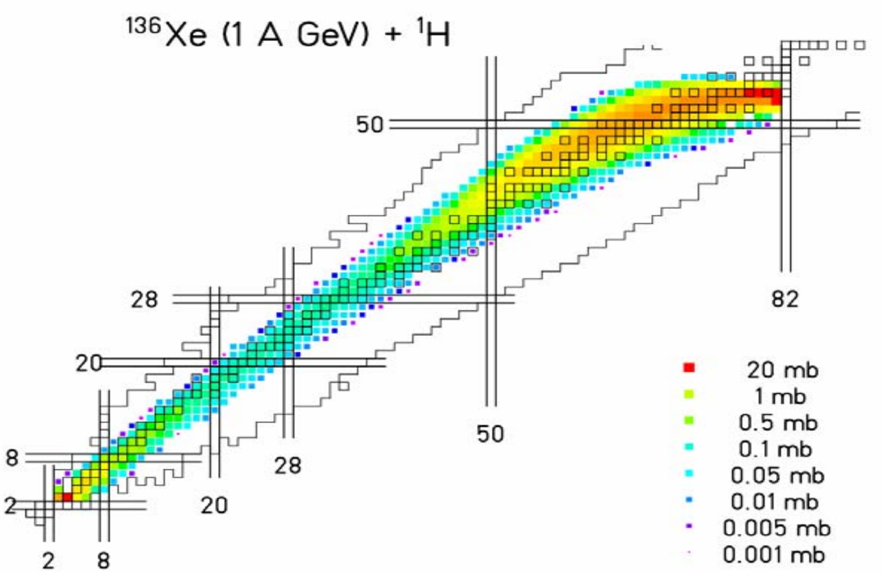
Measured production cross sections



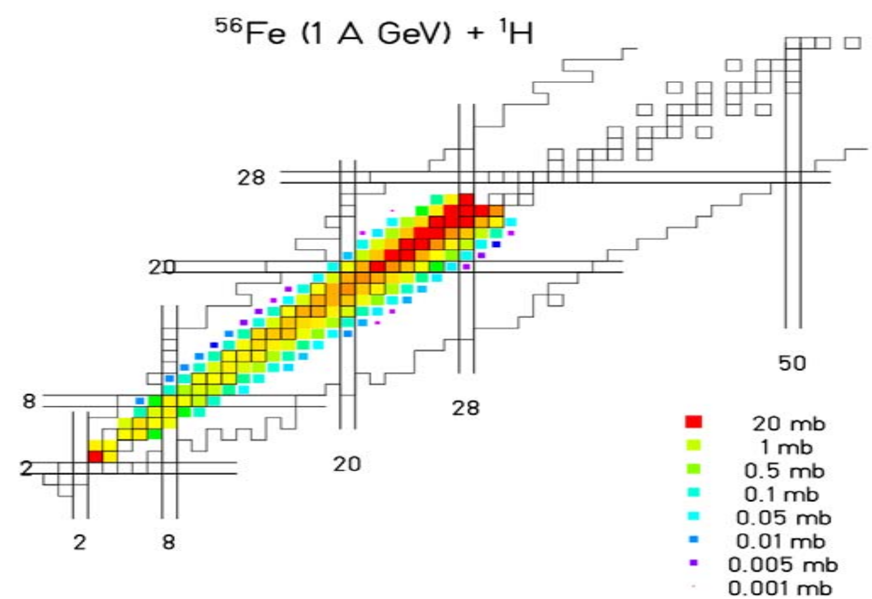
Taieb et al, Bernas et al, Ricciardi PhD



Enqvist et al, Kelić et al



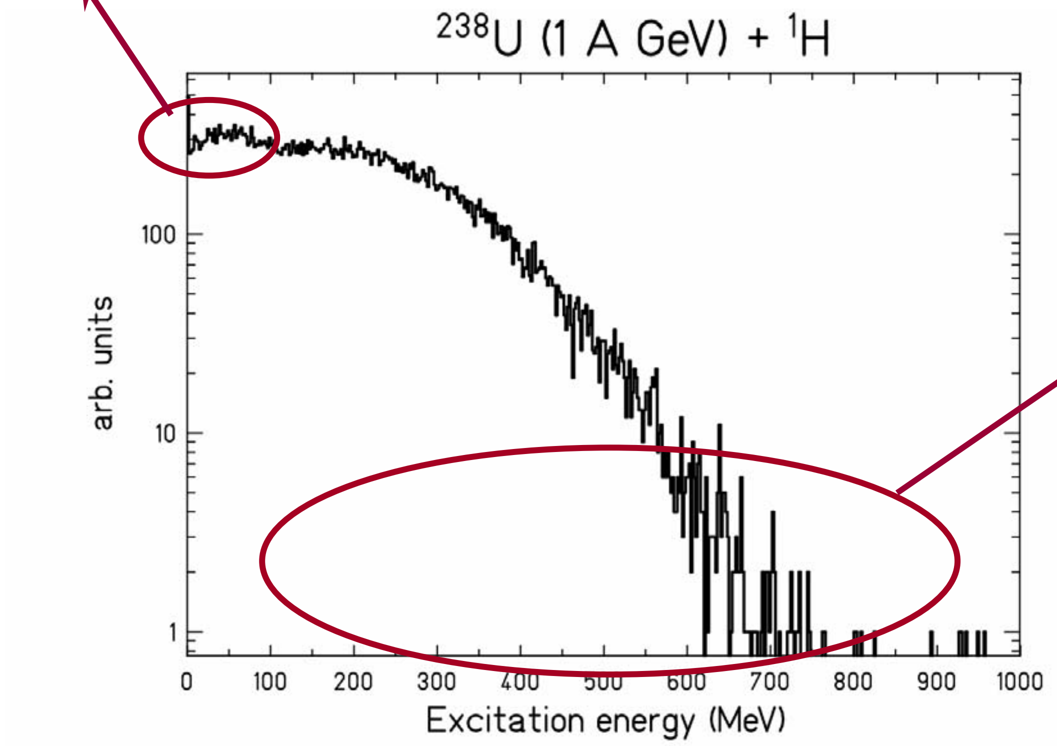
Napolitani PhD



Napolitani PhD, Villagrasa PhD

Need for global models

Pairing correlations, shell effects, collective enhancement in level density

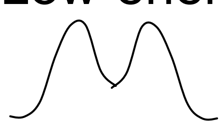


Nucleus behaves more like a drop of honey than like a drop of water

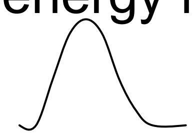
⇨ Viscosity of nuclear matter

Transition

Low-energy fission ⇨ High-energy fission



⇨



⇨ **GSI model ABLA**

Role of dissipation in fission

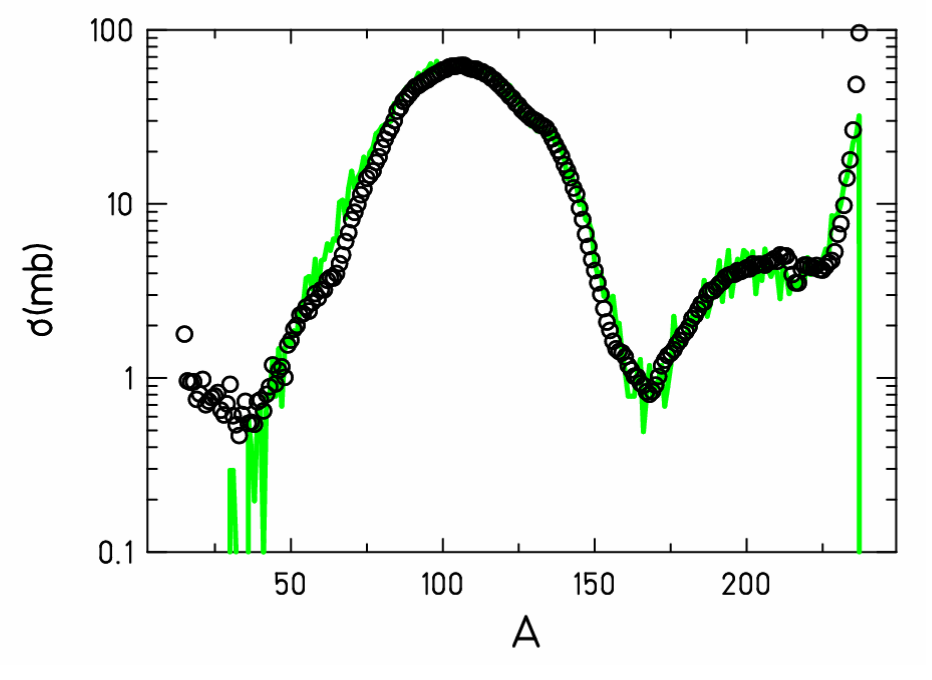
^{238}U + p at 1 *A* GeV; Experiment vs. ABLA calculations

EXP: σ_{fiss} = 1.53 ± 0.2 b

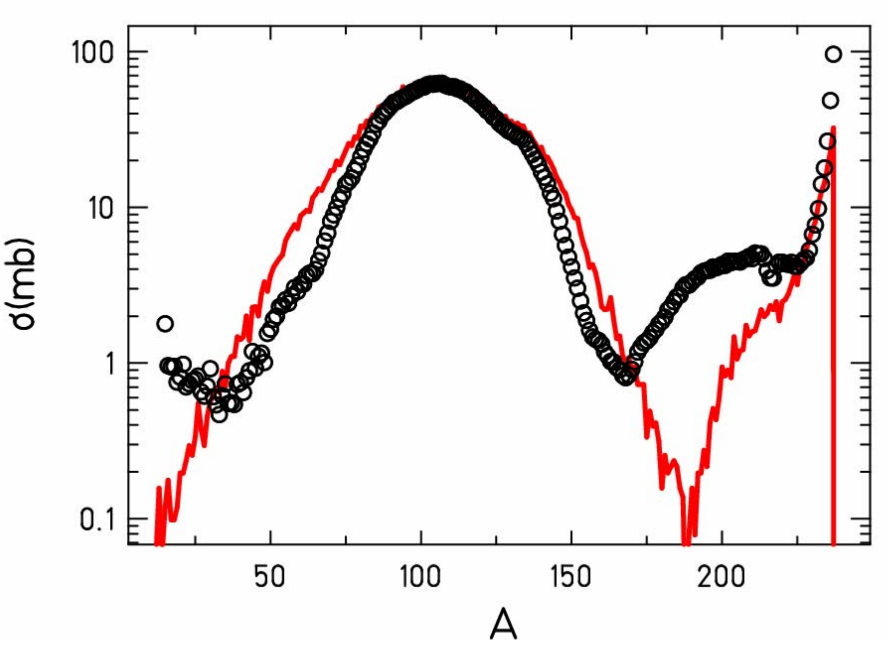
DM: σ_{fiss} = 1.52 b

TSM: σ_{fiss} = 1.73 b

Dynamical model

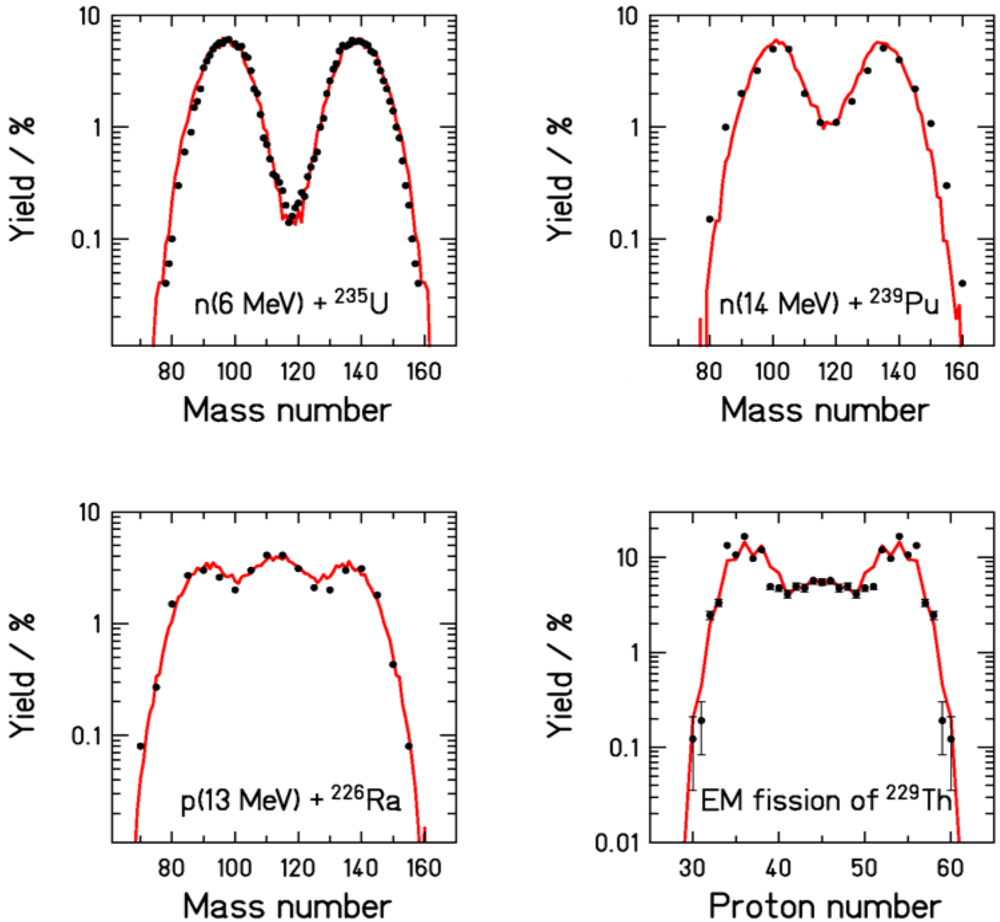


Transition-state model



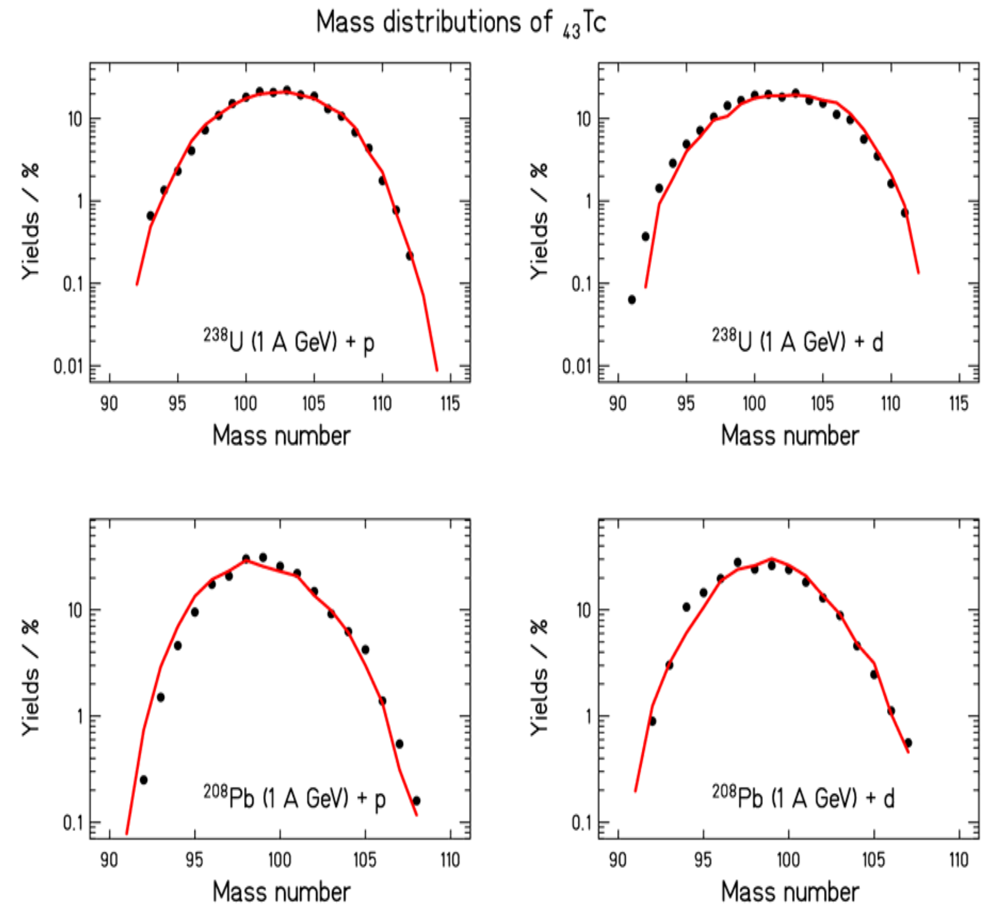
A- and Z-distributions in fission

Low-energy fission:



Data: Sträde et al, Perry et al, Gindler et al, Schmidt et al

High-energy fission:



Data: Bernas et al, Pereira et al, Enqvist et al

Outlook

- Coincidence measurement of heavy residues, light charged particles and neutrons with ^{56}Fe at large-acceptance magnet ALADIN at GSI
  - ⇨ **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
  - ⇨ **Aiming for a kinematically complete fission experiment**

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

Collaborations

GSI

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

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CEA-Saclay

A. Boudard, L. Donadille, J.-E. Ducret, B. Fernandez, R. Legran, S. Leray, C. Villagrasa, C. Volant, W. Wlazło

University Santiago de Compostela

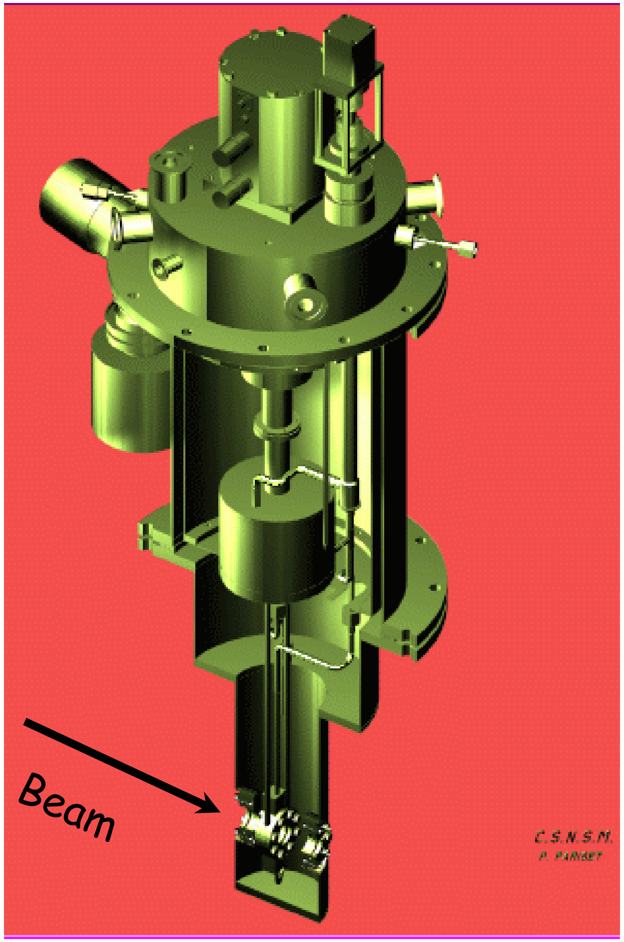
J. Benlliure, E. Casarejos, M. Fernandez, J. Pereira

13 PhD

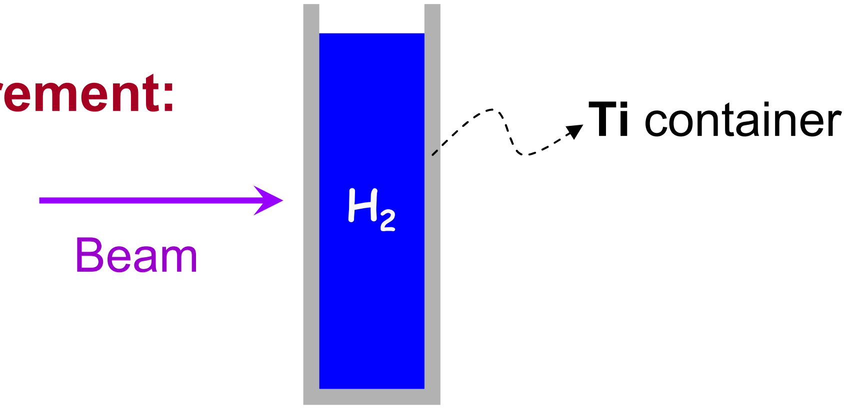
CENBG-Bordeaux

S. Czajkowski, M. Pravikoff

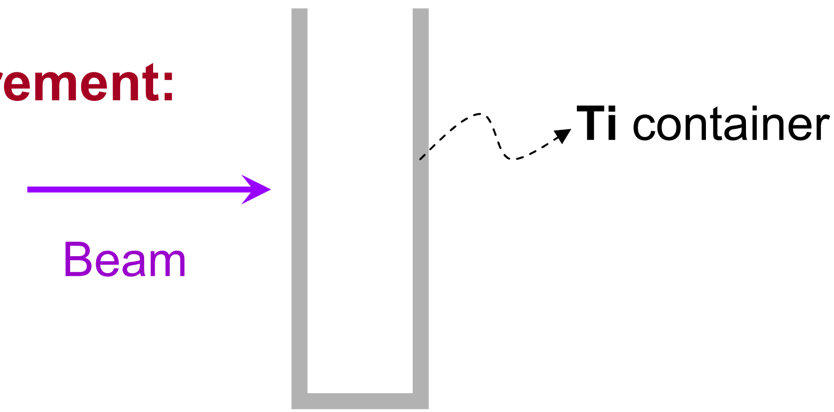
Liquid ^1H and ^2H targets



1^{st} Measurement:



2^{nd} Measurement:

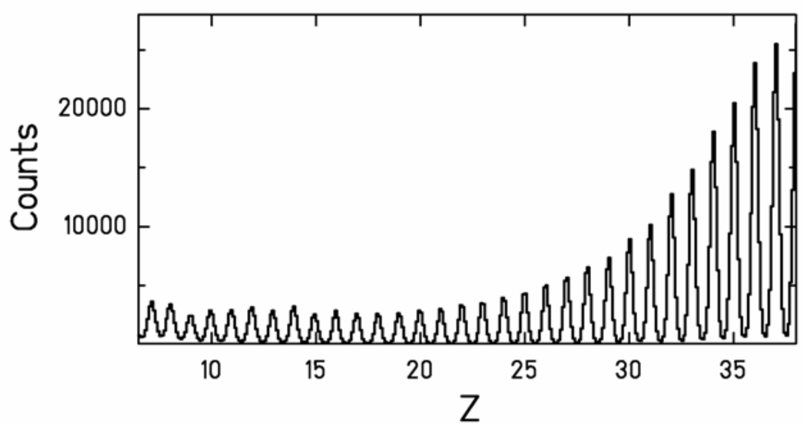


Identification pattern

❑ **Charge identification**

From energy loss in MUSIC

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

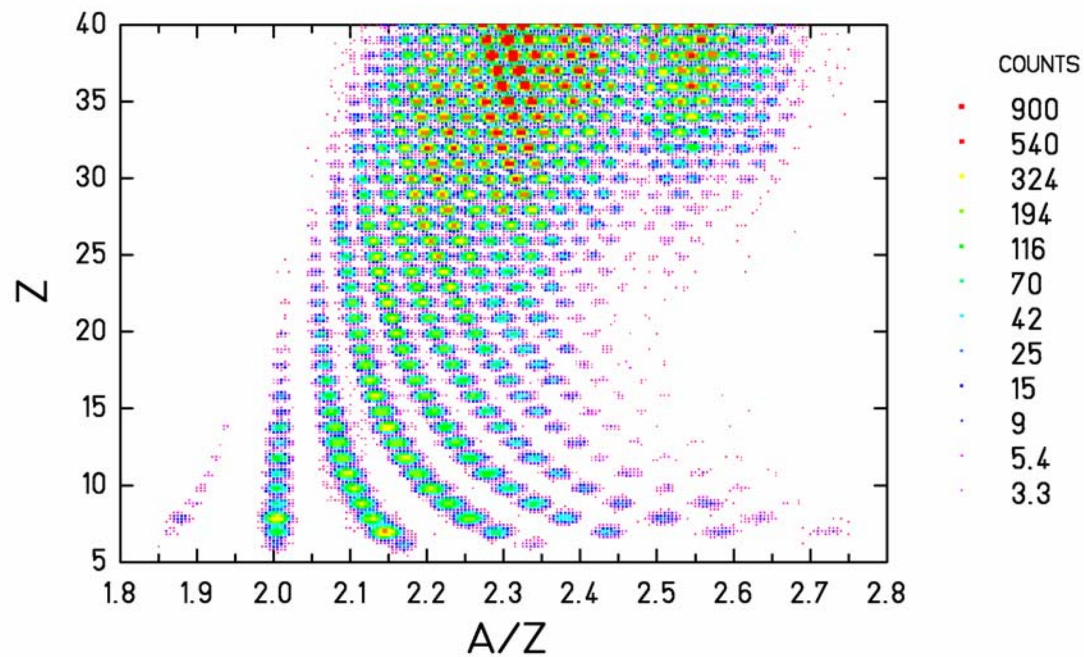


^{238}U+Ti at 1 *A* GeV
M.V. Ricciardi, PhD thesis

❑ **Mass identification**

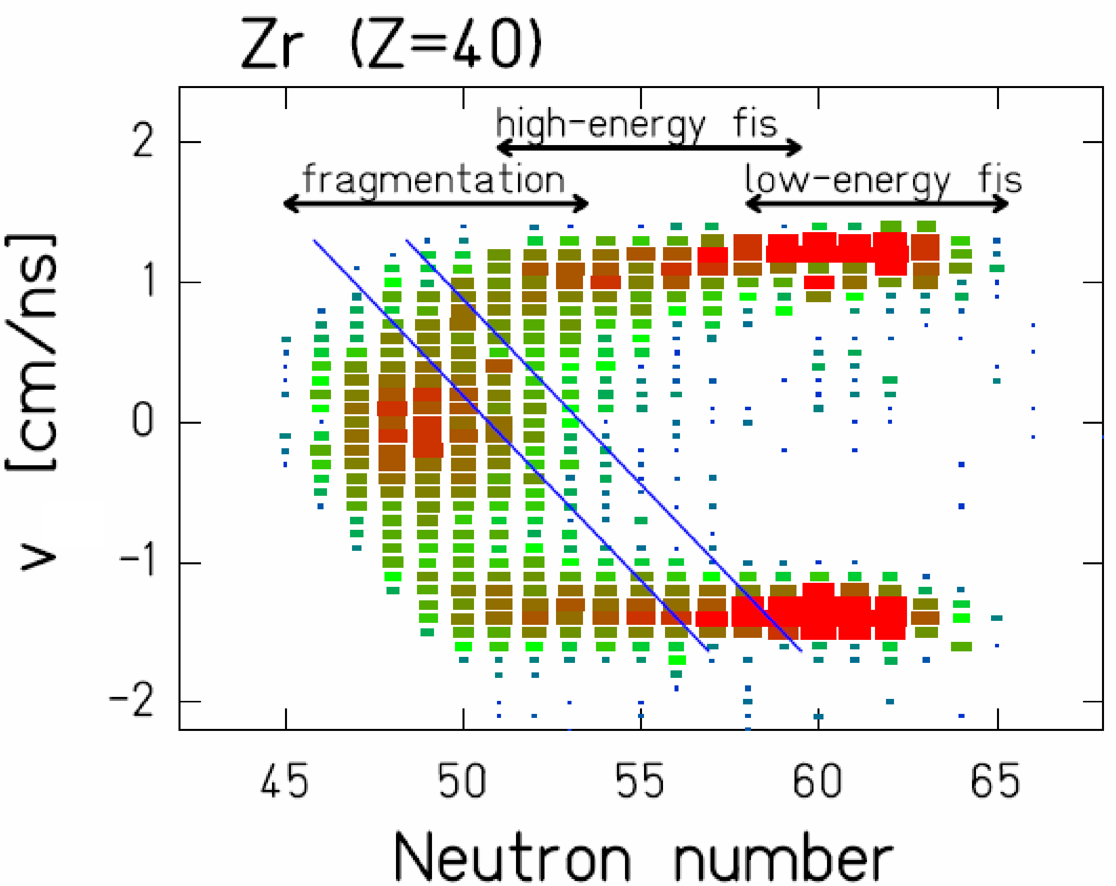
From $B\rho$ and $\beta\gamma$

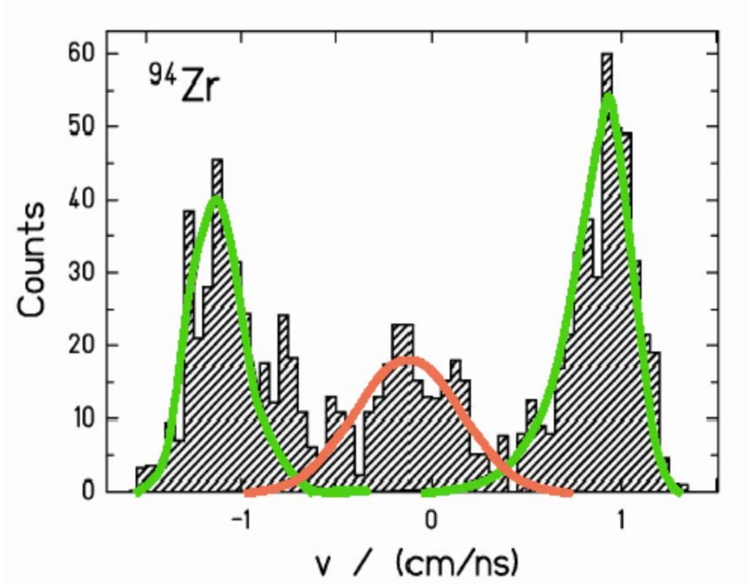
$A / \Delta A \approx 400$



Kinematics

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





For every nuclide:

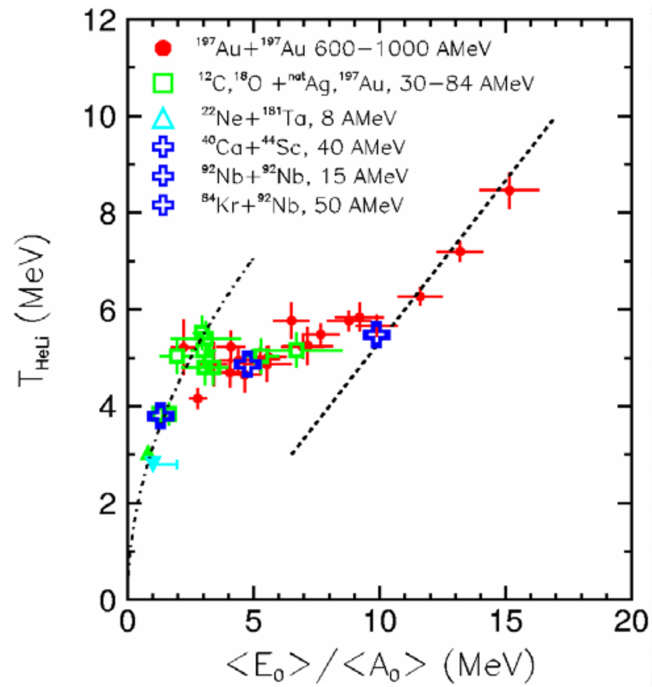
✓ Recoil energy

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

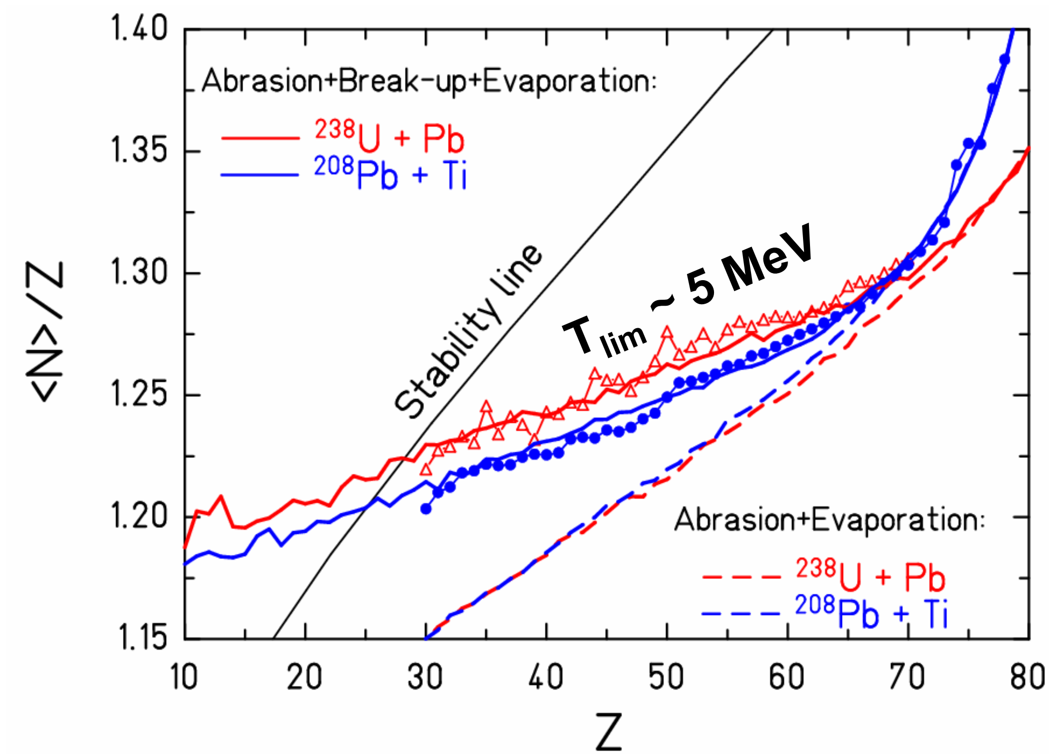
T. Enqvist et al, NPA658 (1999), 47.

Thermal instabilities

❑ ALADIN - 4π experiments, only light products



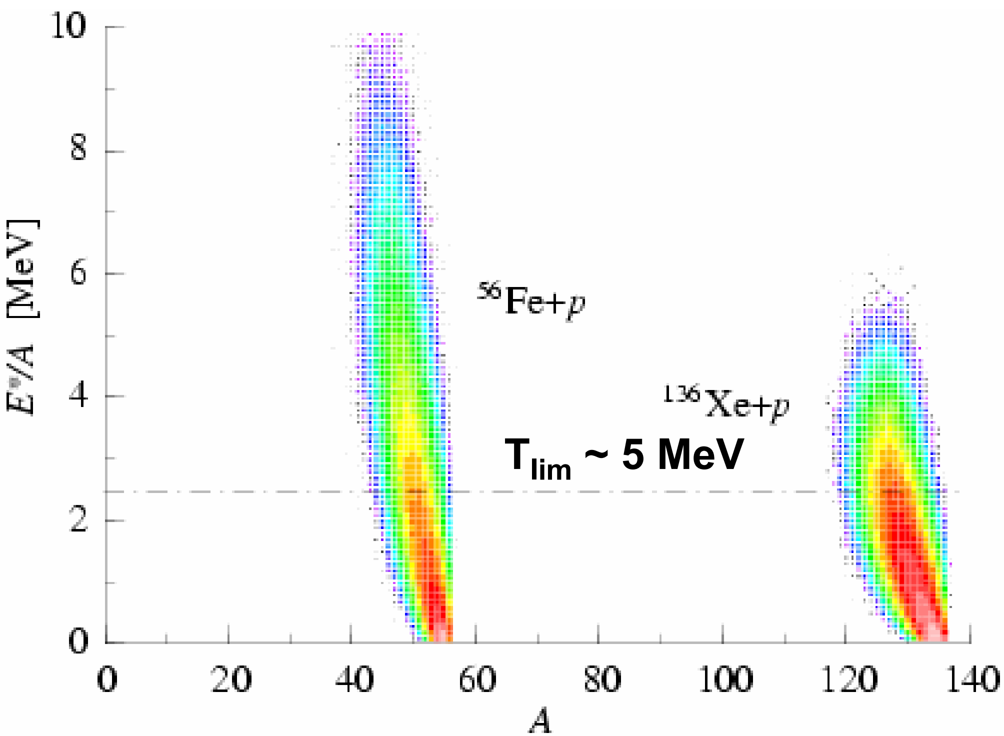
❑ FRS - Thermometry extended to heavy products (K.-H. Schmidt et al, NPA 710 (02) 157)

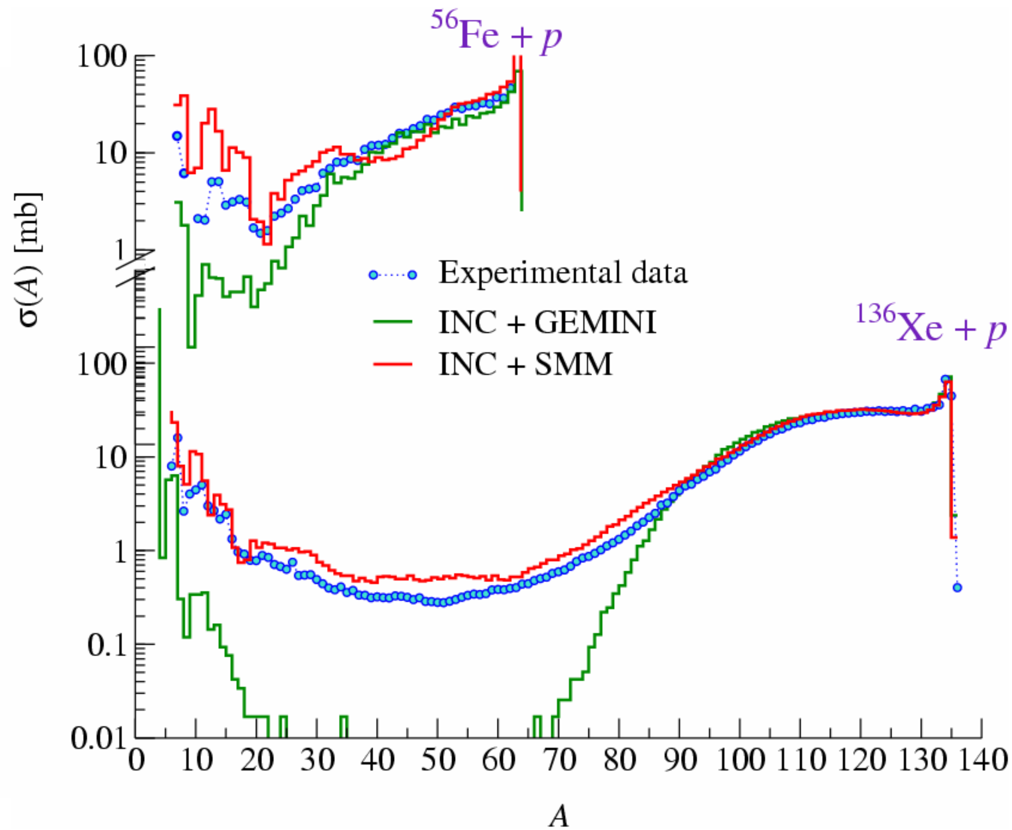


✓ **Unique picture ⇨ maximum temperature of ~ 5 MeV above which compound system can not survive as an entity.**

Thermal instabilities

P. Napolitani, PhD thesis, PRC accepted

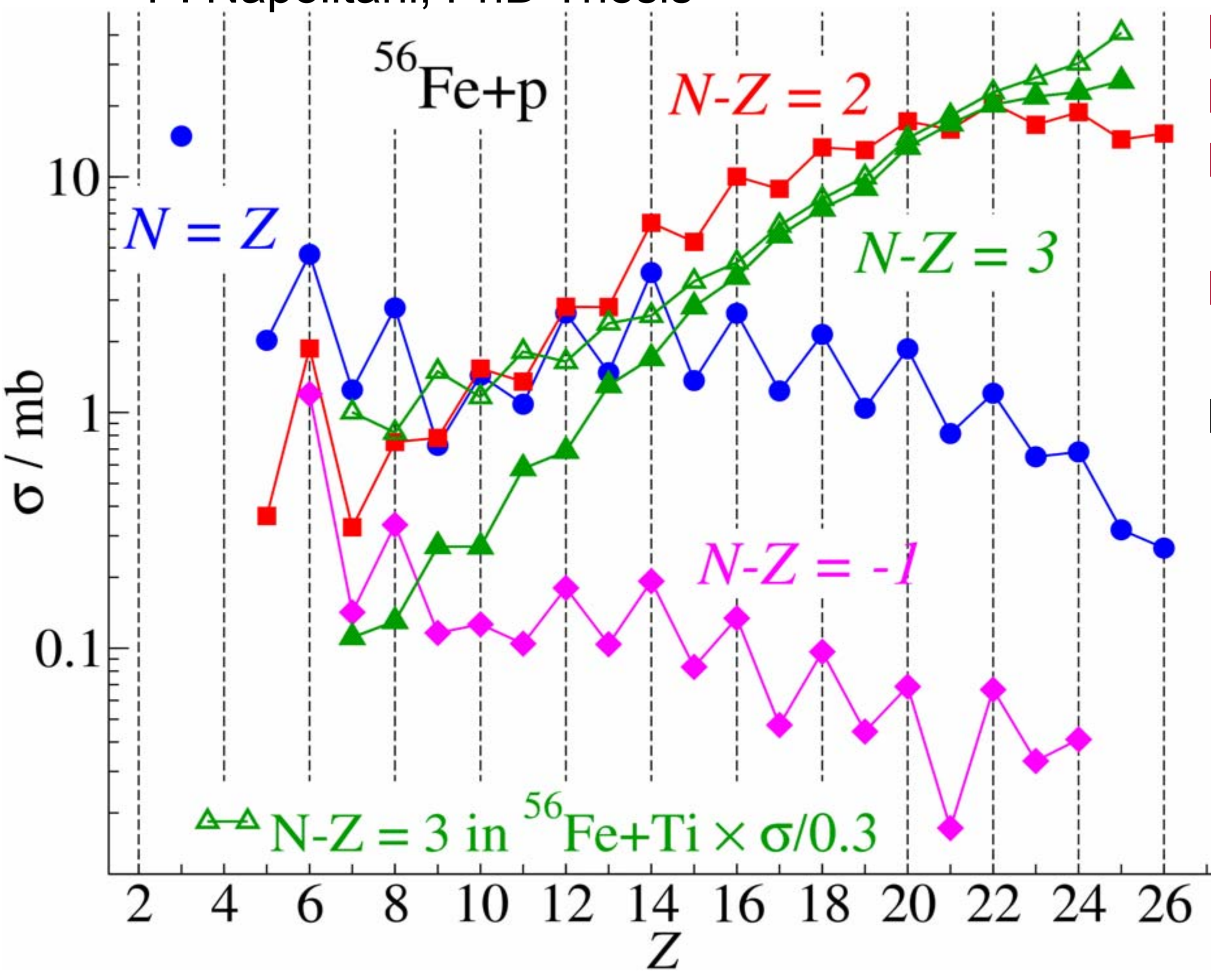




✓ **Have to be considered in order to describe the production of light residues, especially in p-induced reactions on lower-mass targets.**

Even-odd staggering in the final residue yields

P. Napolitani, PhD Thesis



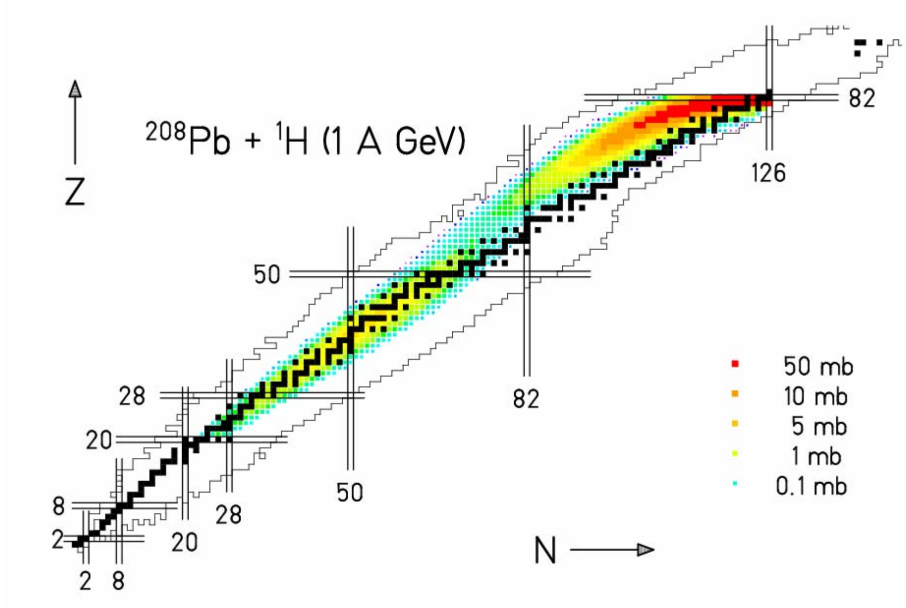
- **Even *A*** : even *Z* favoured
- **Odd *A*, p rich**: even *Z* favoured
- **Odd *A*, n rich**: odd *Z* favoured (20%)
- ***N=Z***: huge staggering >50%!

- 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.**

GSI code ABRABLA

- Experiment



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

- ABRABLA calculations