

Systematic study of spallation reactions in inverse kinematics at the FRS

M. Valentina Ricciardi
GSI

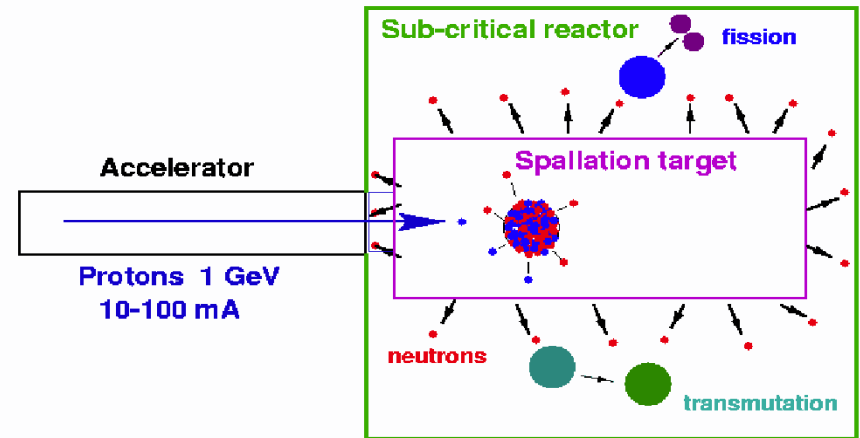
A campaign of measurements and studies started at GSI in 1996
in collaboration with other institutes:

Universidad de Santiago de Compostela, Spain
IPN Orsay, France
CEA Saclay, France
CENBG Bordeaux, France

Motivation

Original motivation: ADS

Need for **precise** evaluation of production **cross sections** and **velocity** for all nuclei produced in a **large range of excitation energies** in many materials



Strategy: limited number of experiments for selected nuclei

Better insight in the reaction mechanisms: fission, fragmentation, multifragmentation, phase-transitions (superfluid-liquid, liquid-gas)

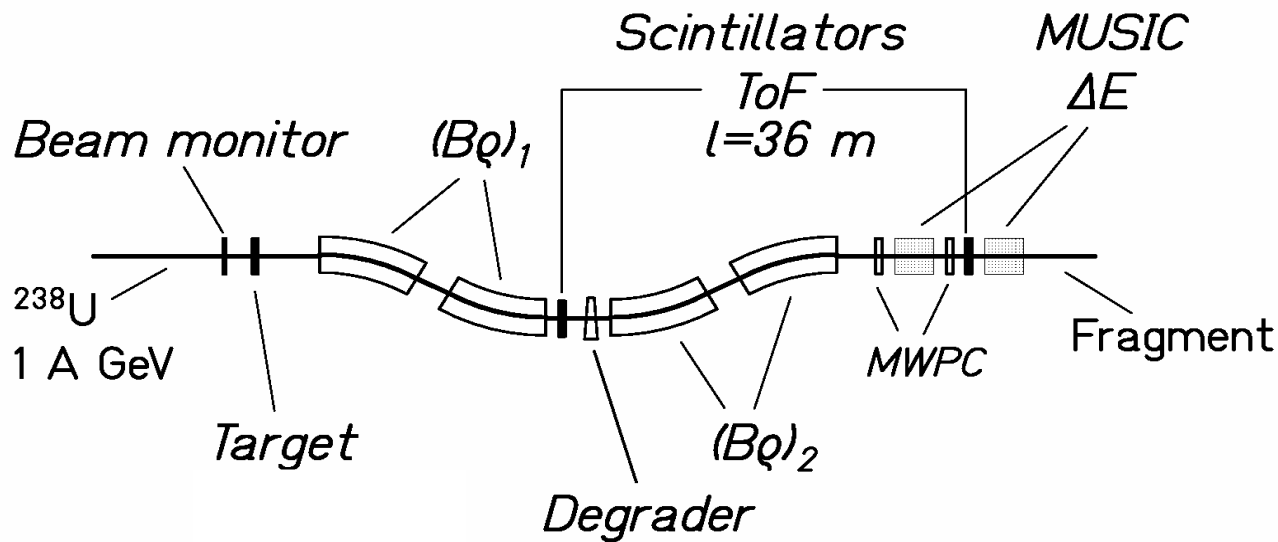


high predictive power of the nuclear-reaction codes (INCL+ABLA, ABRABLA)

Other applications

Radioactive-beam production, neutron sources, astrophysics, space technologies, biology and medicine

Measurement in inverse kinematics at FRS



$$\Theta^{\max} = 15 \text{ mrad}$$

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

$$\text{ToF} \Rightarrow \beta\gamma$$

$$x_1, x_2 \Rightarrow B\rho$$

$$\Delta E \Rightarrow Z$$

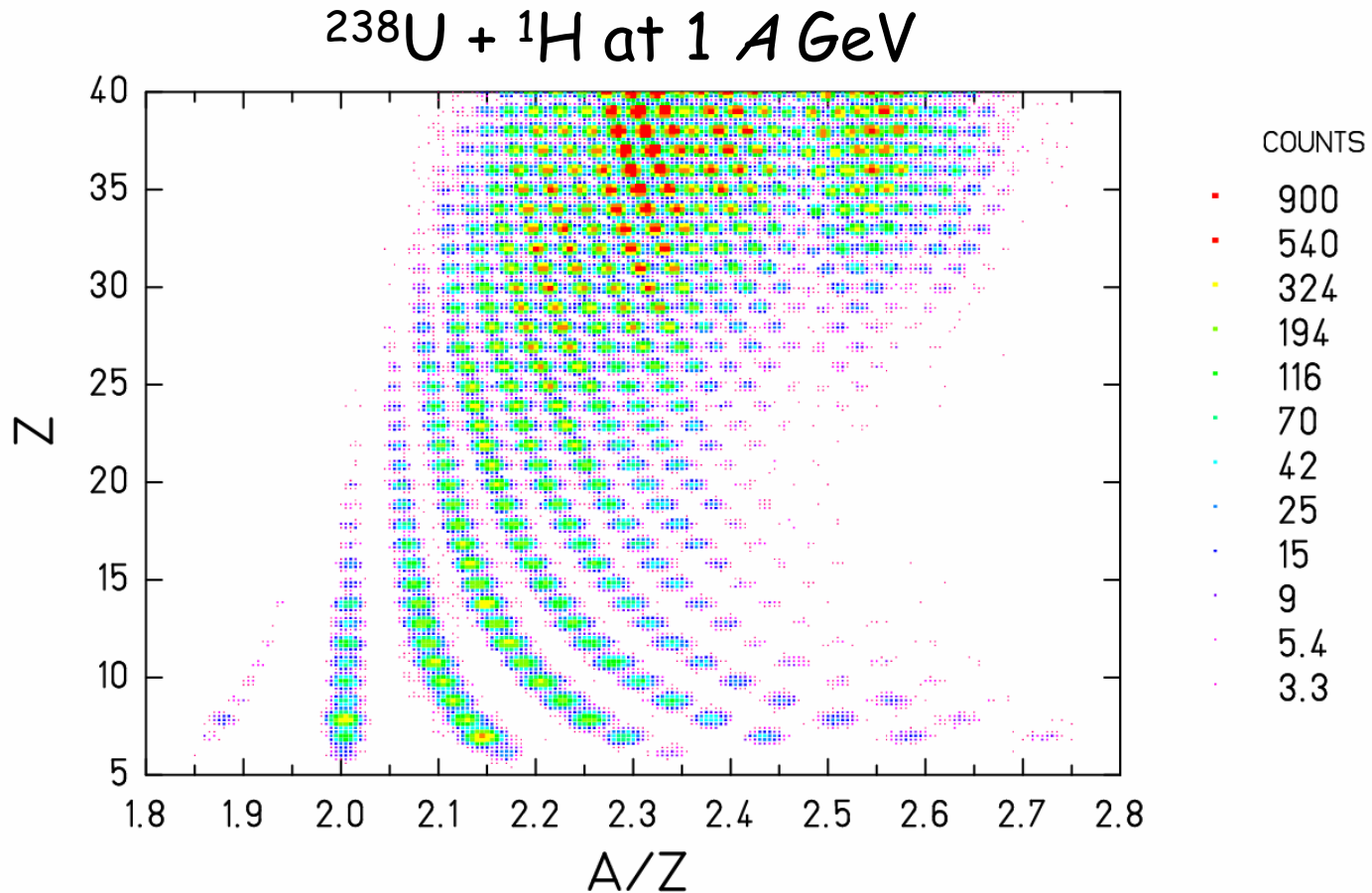
$$\frac{A}{Z} = \frac{e}{m_0 c} \cdot \frac{B\rho}{\beta \cdot \gamma}$$

Resolution:

- $\Delta(\beta\gamma)/\beta\gamma \approx 5 \cdot 10^{-4}$
- $\Delta Z \approx 0.4$
- $\Delta A / A \approx 2.5 \cdot 10^{-3}$

Nuclide identification

→ production cross sections for all nuclei ←

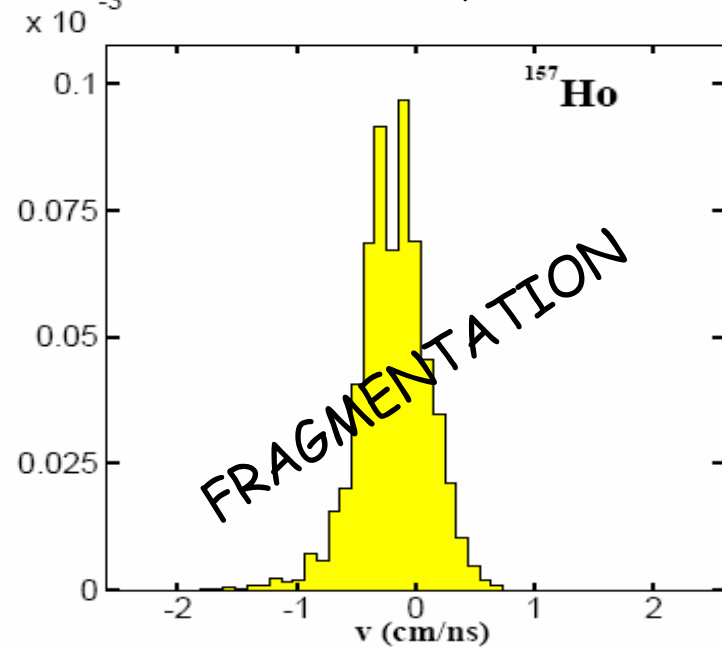
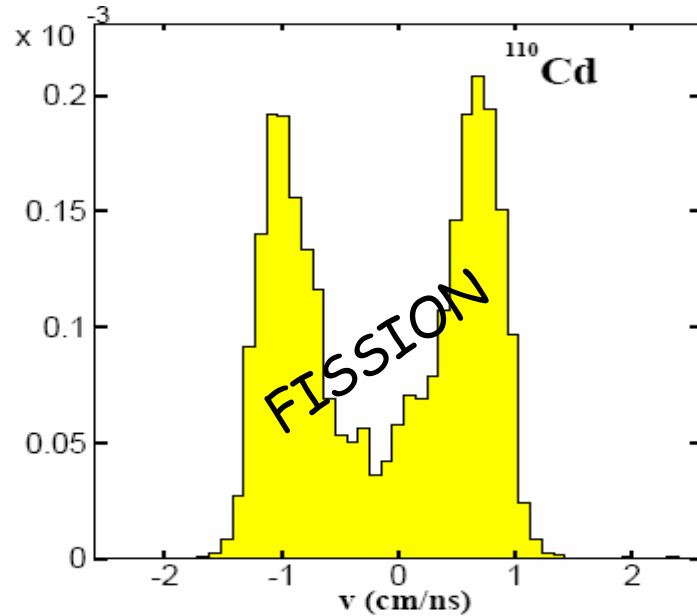


Ricciardi et al, Phys. Rev. C73 (2006) 014607

Velocity distributions

^{238}U (1 AGeV) + ^2H

Pereira, PhD thesis



Limited angular acceptance of FRS together with different kinematical properties of fission and fragmentation residues $\Rightarrow$ reaction mechanism

For each nucleus: production cross section, velocity and production mechanism

Performed experiments

Projectile	Target	Energy [<i>A</i> GeV]
^{56}Fe	$^1,^2\text{H}$, Ti	0.3, 0.5, 0.75, 1, 1.5
$^{136,124}\text{Xe}$	$^1,^2\text{H}$, Ti	0.2, 0.5, 1
^{197}Au	^1H , Ti	0.8
^{208}Pb	$^1,^2\text{H}$, Ti	0.5, 1
^{238}U	$^1,^2\text{H}$, Ti	1

Cross sections and velocity distributions
for more than 10,000 nuclei measured !

Data accuracy:

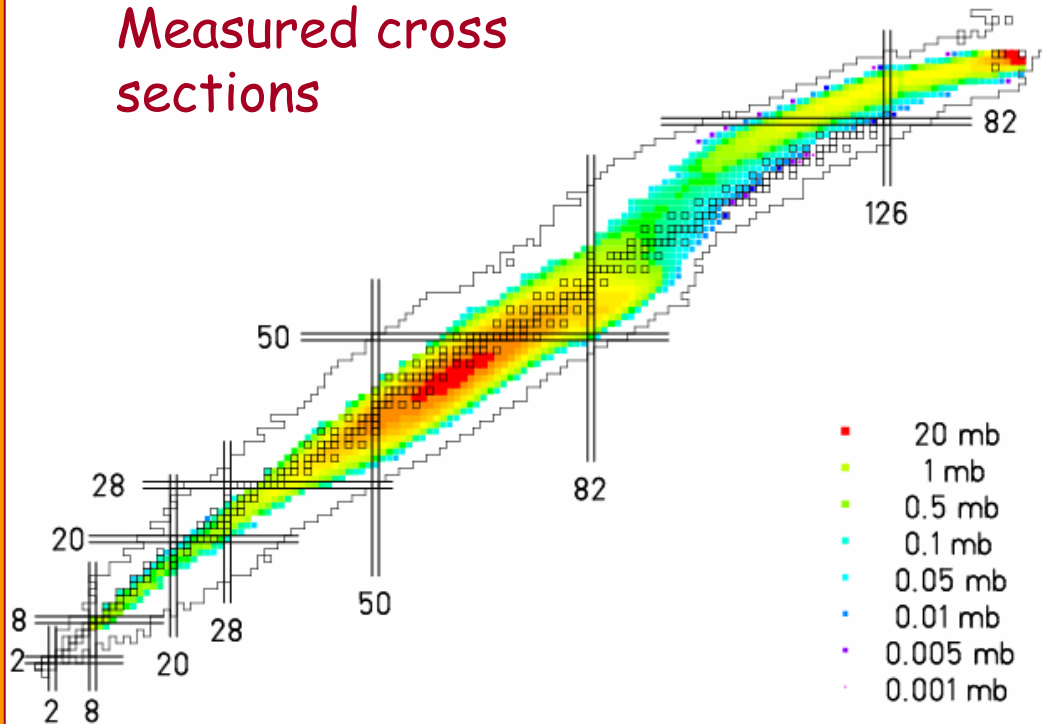
Statistic: below 3%

Systematic: 9 - 15 %

Data available at: www.gsi.de/charms/data.htm

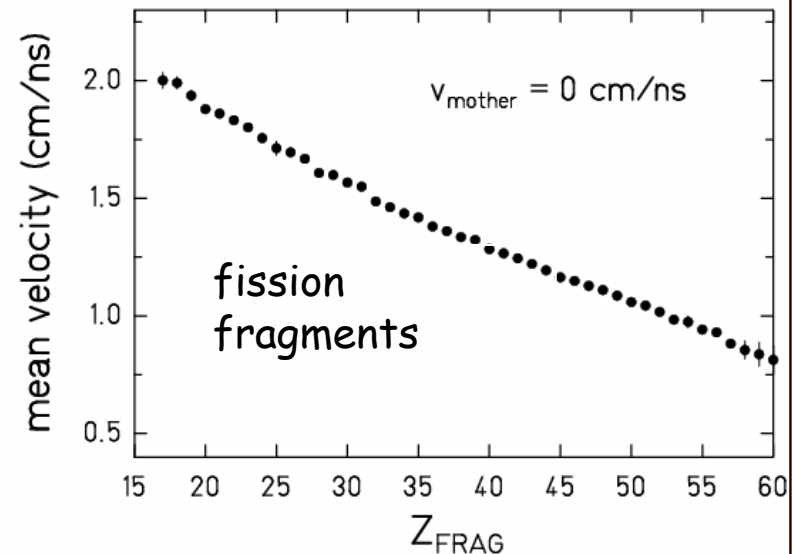
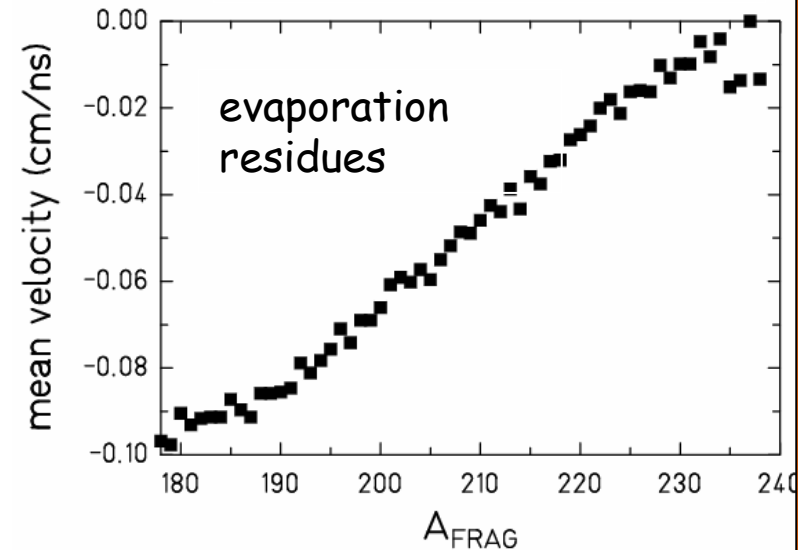
Example: 1 A GeV ^{238}U on ^1H

Measured cross sections



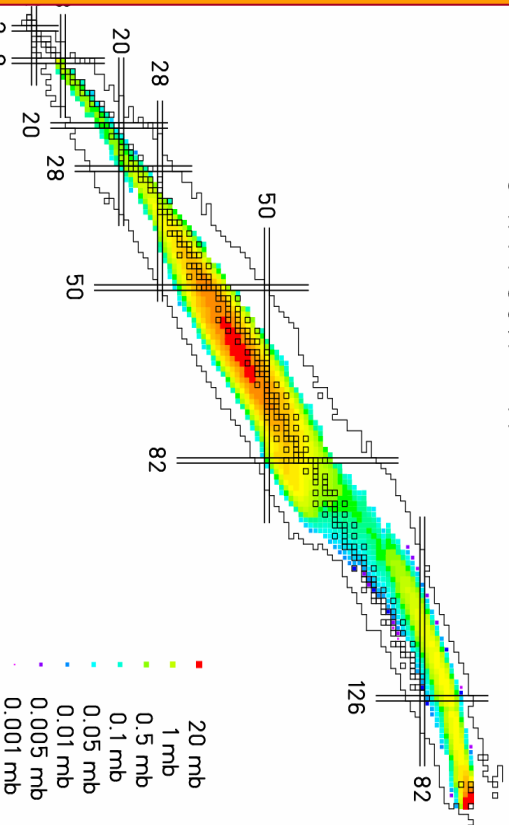
Taieb et al., NPA 724 (2003) 413
Ricciardi et al., PRC 73 (2006) 014607
Bernas et al., NPA 765 (2006) 197
Bernas et al., NPA 725 (2003) 213
Armbruster et al., PRL 93 (2004) 212701

Measured velocities



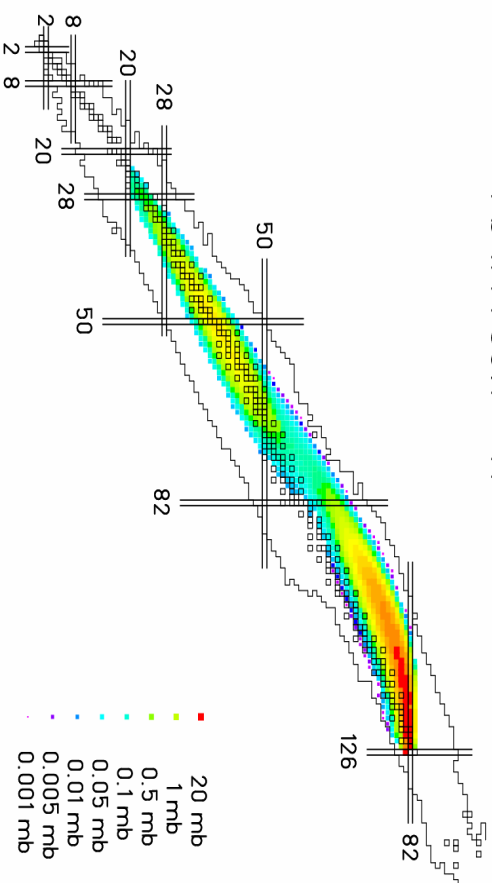
Other examples

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



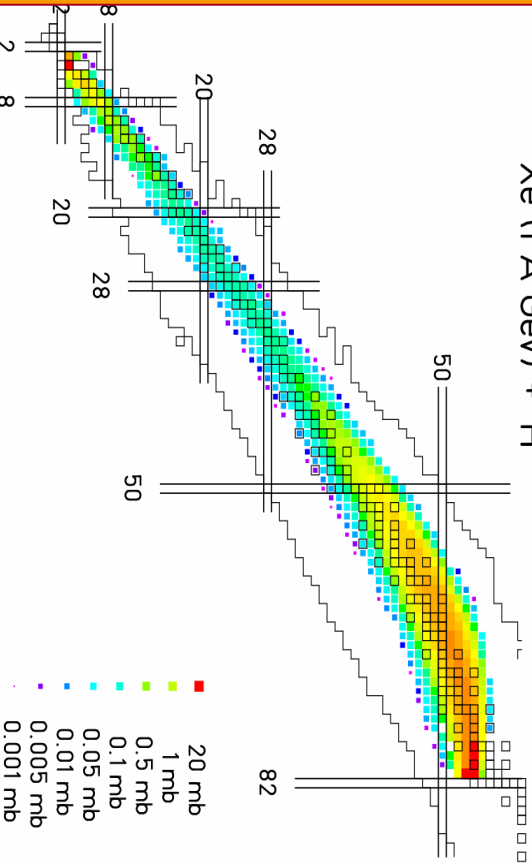
Taieb et al, Bernas et al,
Ricciardi et al

^{208}Pb (1 A GeV) + ^1H



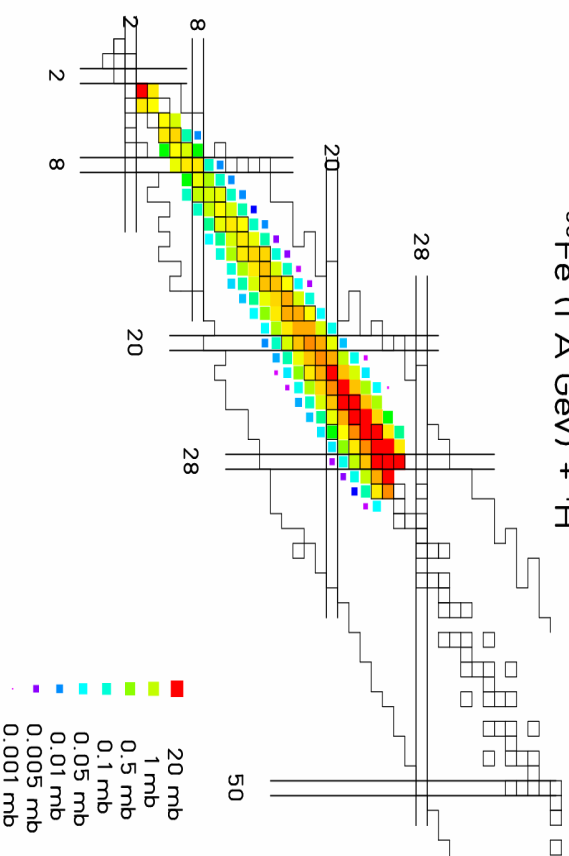
Enqvist et al, Kelić et al

^{136}Xe (1 A GeV) + ^1H



Napolitani PhD

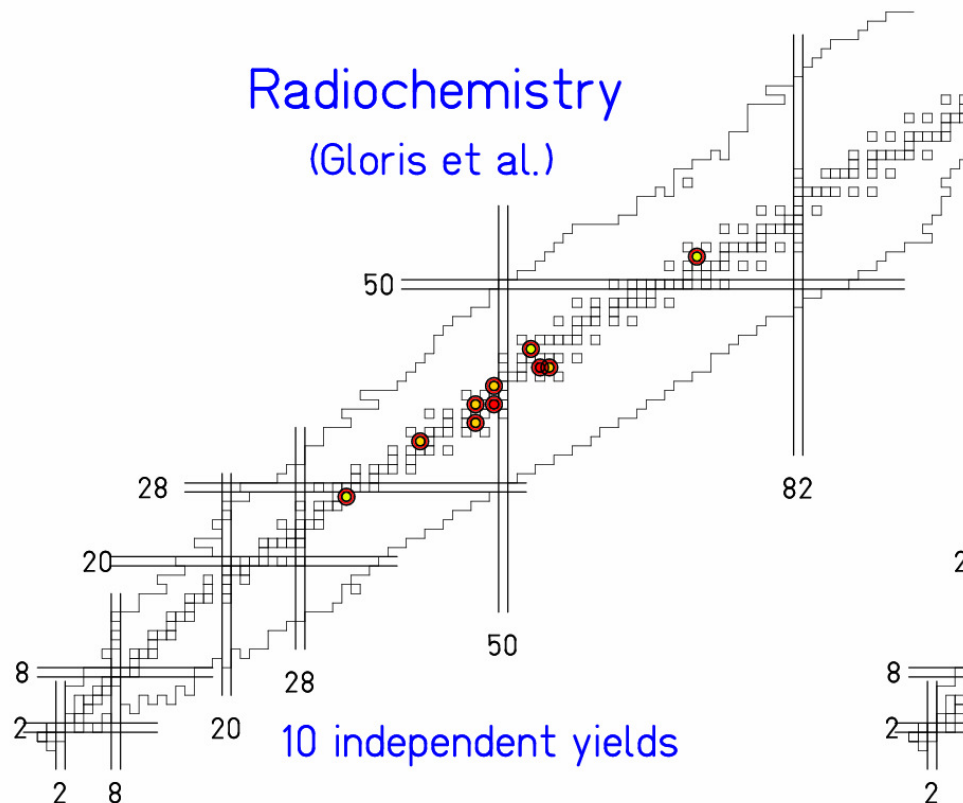
^{56}Fe (1 A GeV) + ^1H



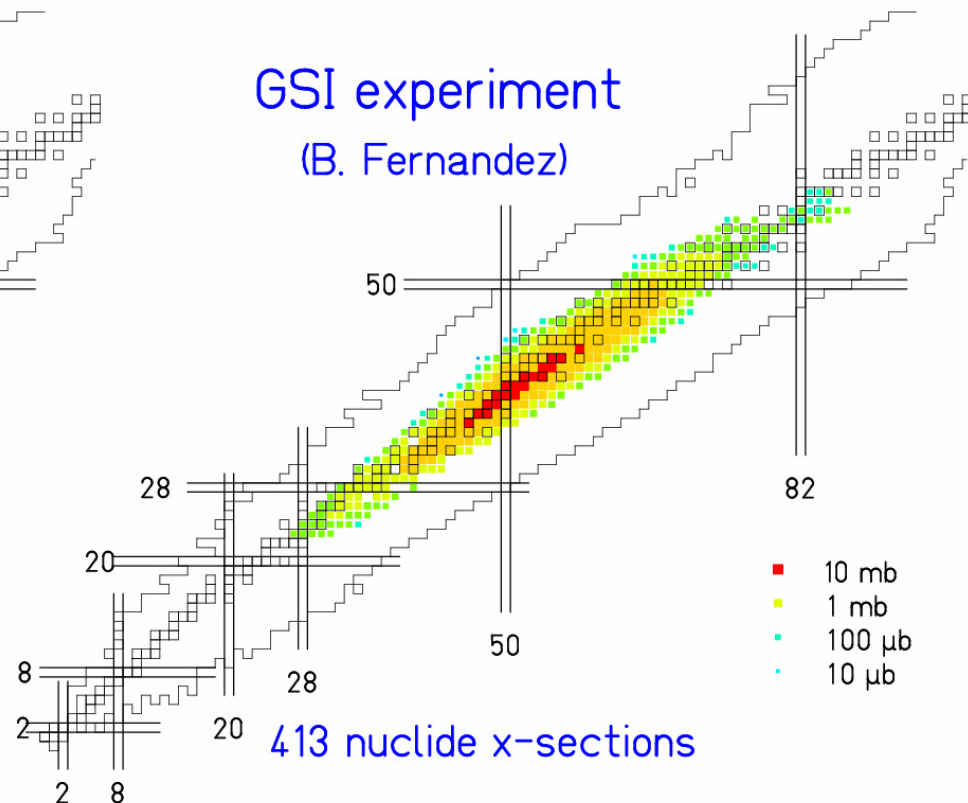
Napolitani PhD, Villagrasa PhD

Experimental progress by inverse kinematics

Example: Fission of lead induced by ≈ 500 MeV protons



Protons (553 MeV) on lead



^{208}Pb (500 A MeV) on hydrogen

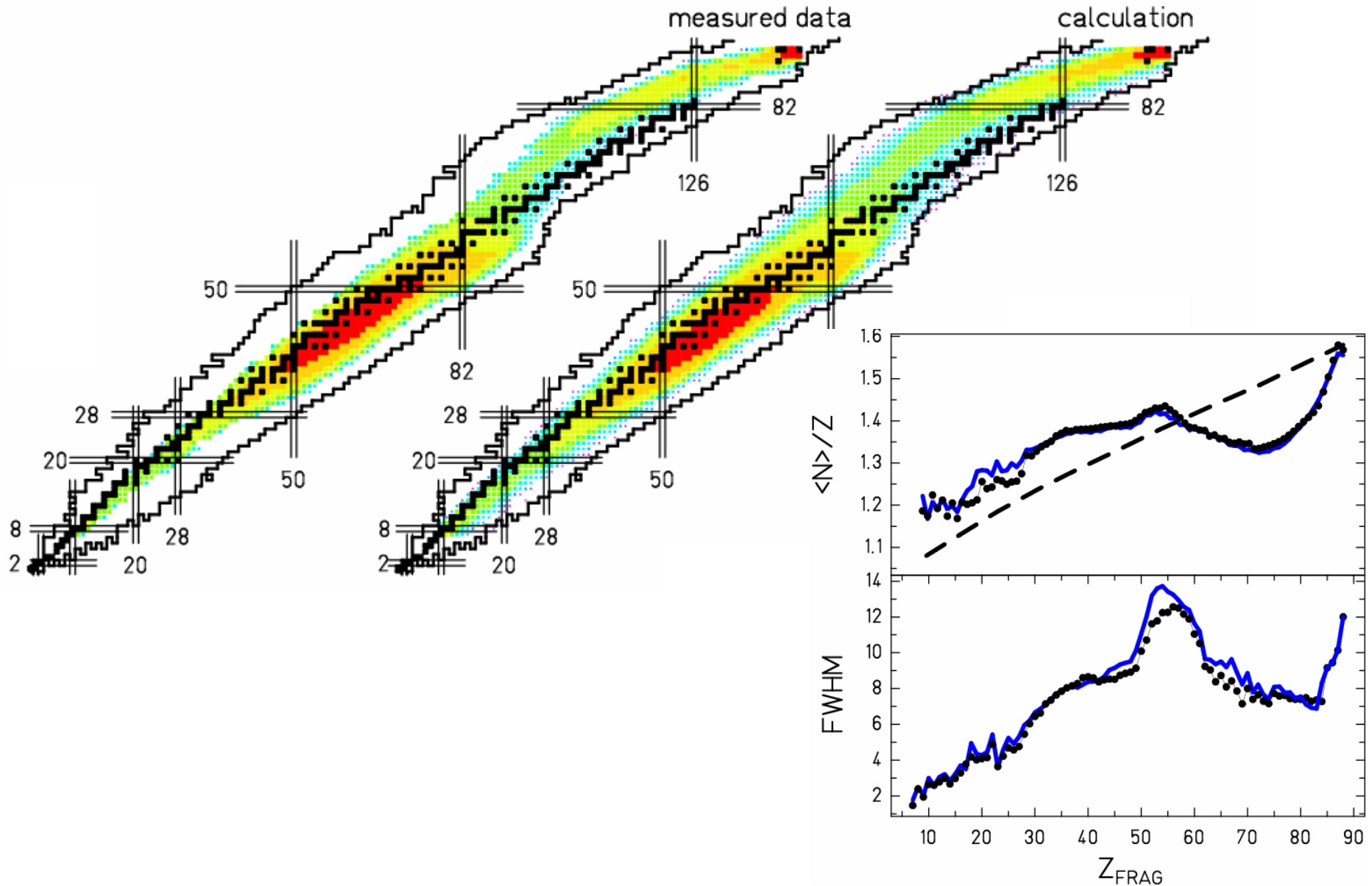
New insight in physics

The following activities arose from the study of experimental data:

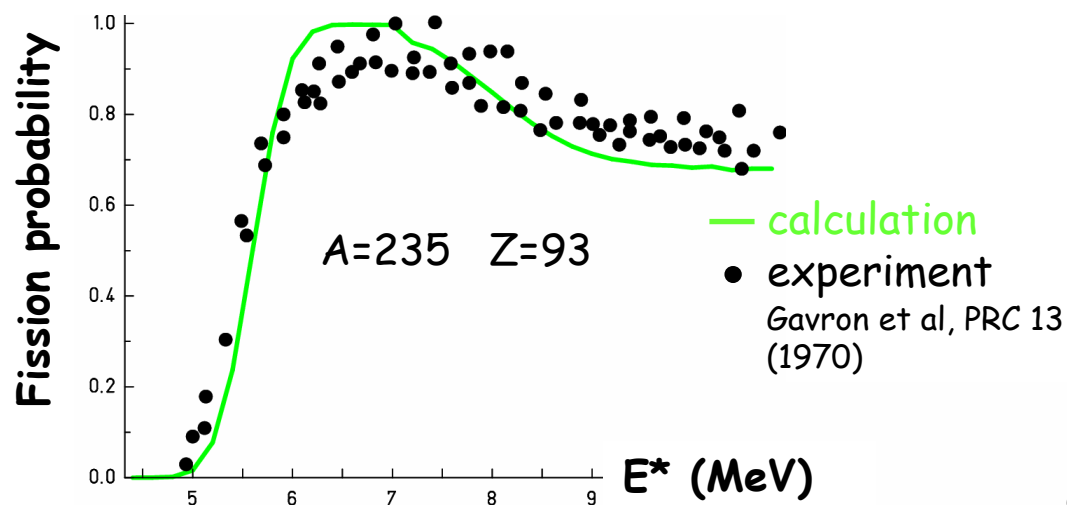
- fission: shell effects and pairing correlations, viscosity of nuclear matter, fission barriers
- statistical evaporation from a compound nucleus
- nuclear thermometry
- kinematical properties of the spectator, EOS
- multifragmentation, liquid-gas phase transition
- superfluid-liquid phase transition (nuclear structure, even-odd)
- charge-pickup reactions

More information at <http://www.gsi.de/charms/Publications/publica.htm>

Model calculations (high energy)

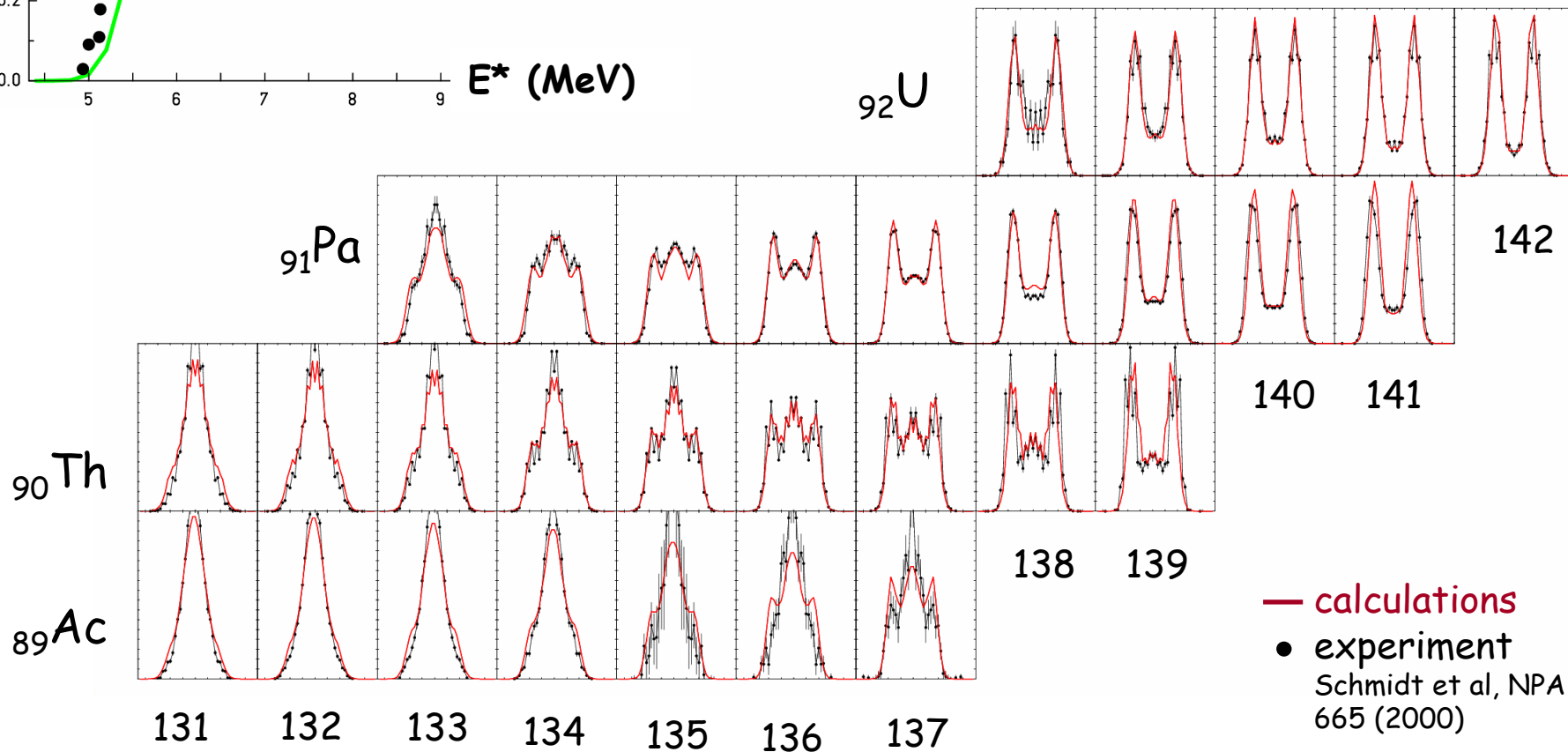


Model calculations (low energy)



Fission of secondary beams
after the EM excitation

Z distributions



Conclusions

A big step forward in the spallation studies:

- A large amount of experimental data:
 - precise cross sections for about 10000 nuclides
 - precise velocities and information on reaction mechanism
- Valuable insight on many different fields of physics
- Development of simulation codes with high predictive power

Future plans: New generation of experiments at R3B at FAIR

To know more: www.gsi.de/charms

Collaboration

GSI

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

IPN-Paris

L. Audouin, M. Bernas, B. Mustapha, P. Napolitani, F. Rejmund, C. Stéphan, J. Taïeb, L. Tassan-Got

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

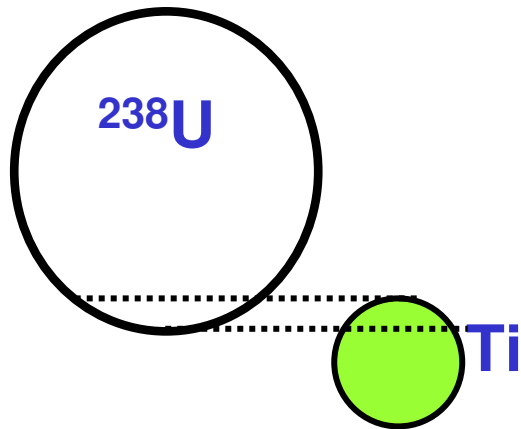
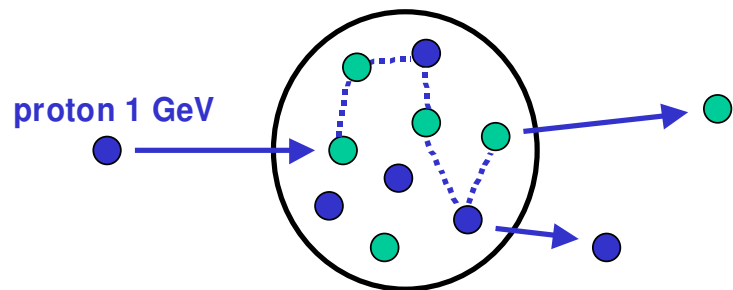
CENBG-Bordeaux

S. Czajkowski, M. Pravikoff



14 PhD

Our nuclear-reaction code based on the statistical model



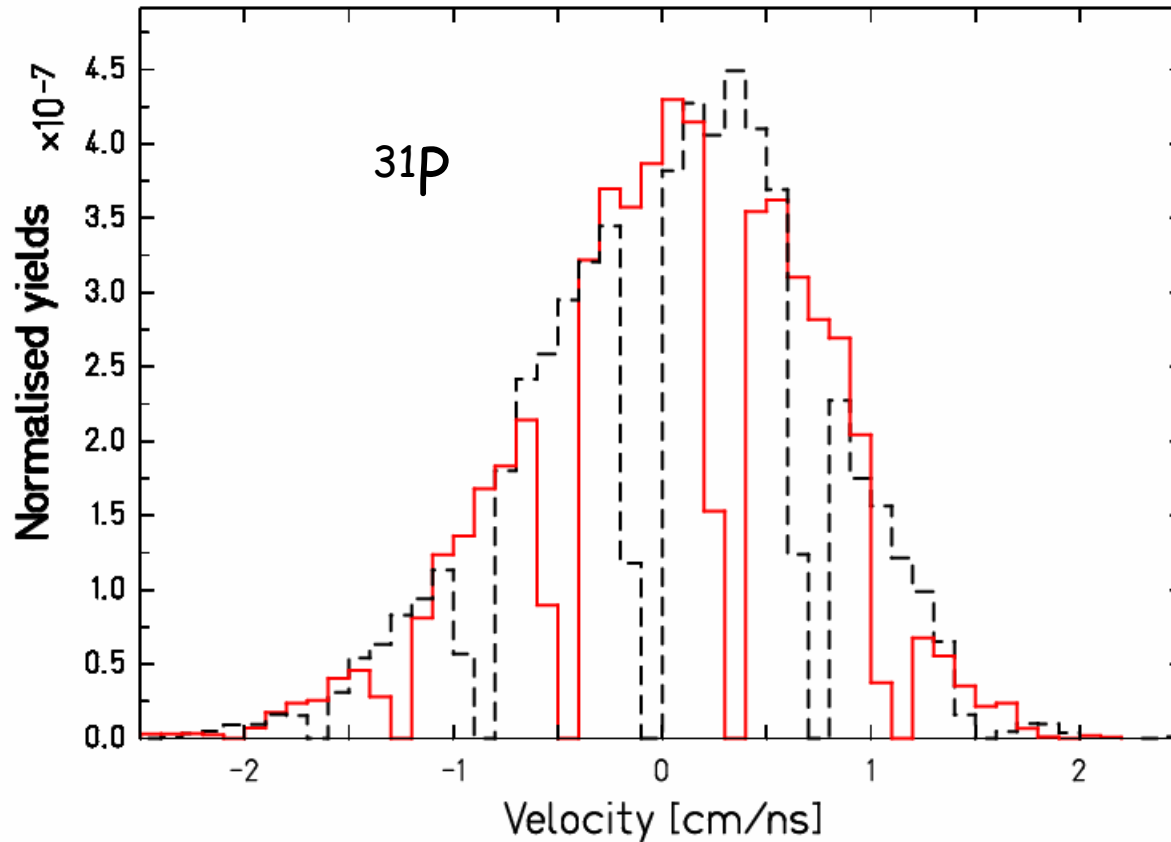
ABLA

excited
compound
nucleus
or
ensemble of
compound
nuclei

sequential
evaporation

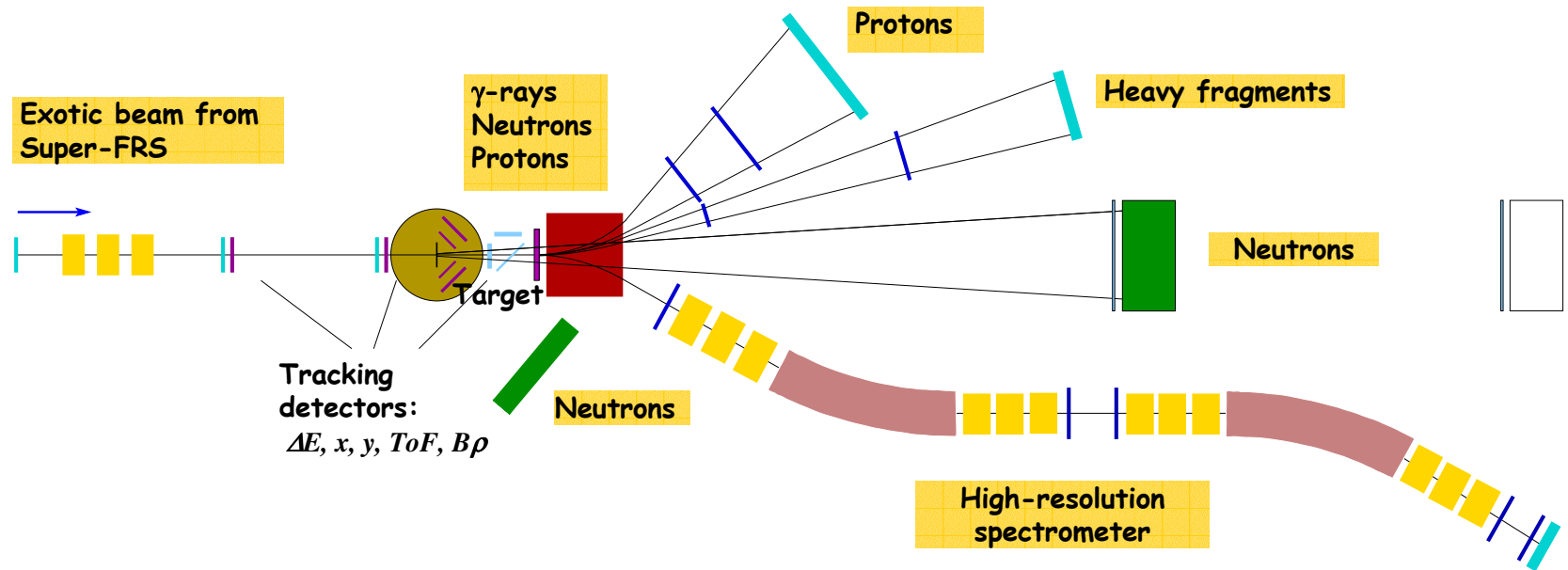
fission

Limited momentum acceptance



Overlap of measurements with different magnetic-field settings.

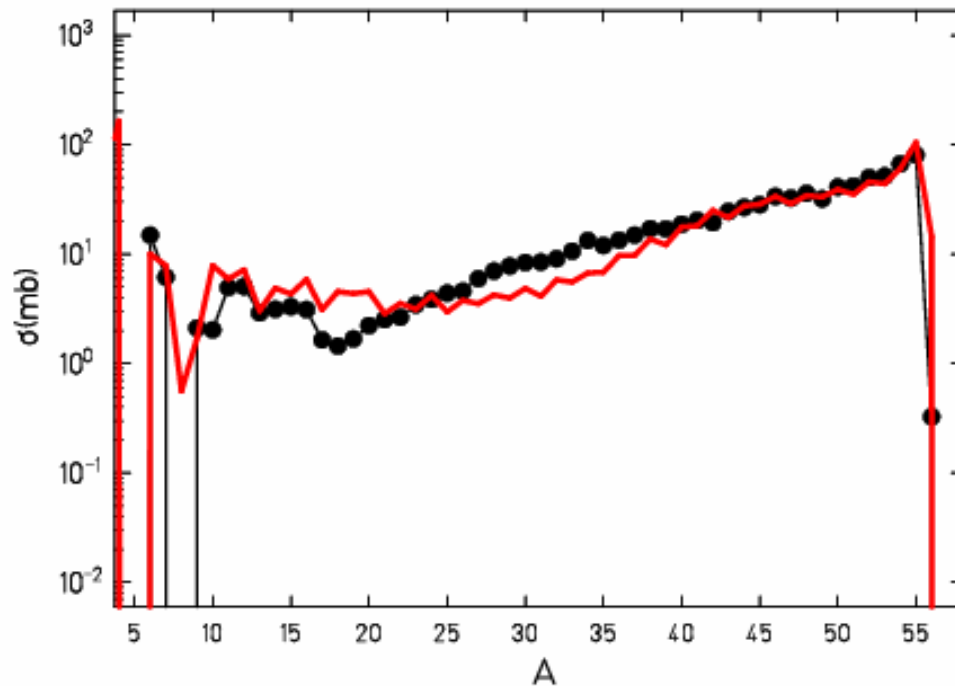
Future: R3B @ FAIR



Exclusive experiments and high resolution!

IMF emission

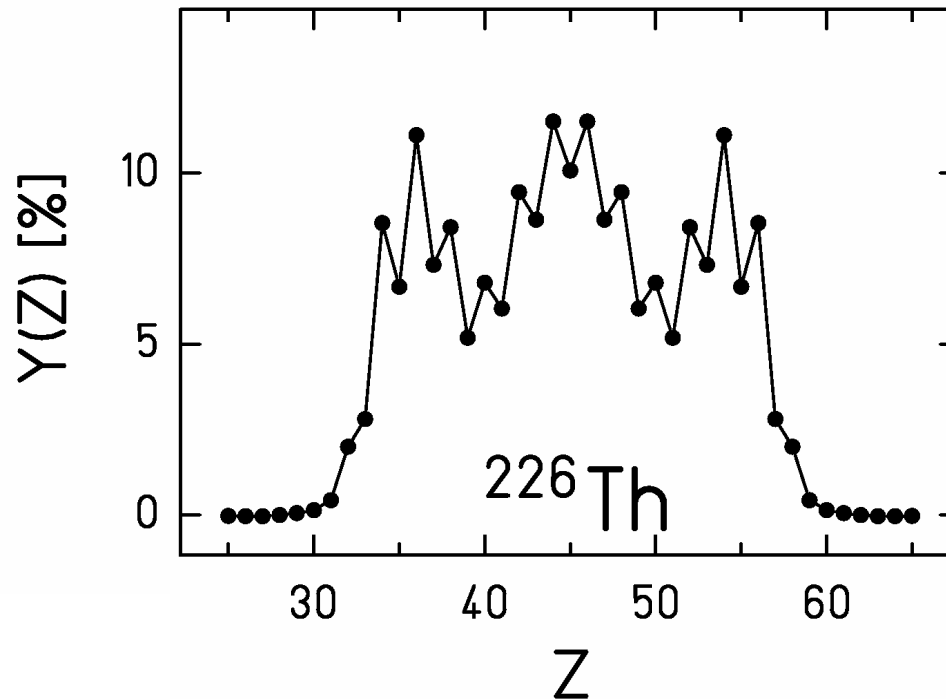
Mass distribution in $^{56}\text{Fe}+p$ at 1 A GeV



● exp - C. Villagrasa et al., P. Napolitani et al.

— INCL4 + ABLA117

EVEN-ODD STRUCTURE IN LOW-ENERGY FISSION



Results from e.m.-induced fission of 70 different secondary projectiles
(Steinhäuser et al., Nuc. Phys.A 634 (1998) 89)

Structural properties survive at low energy (SUPERFLUIDITY)

RESULT FOR 1 GeV p on ^{238}U

