Experimental approaches to spallation reactions

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Outline

- Introduction

Why studying spallation reactions

Experimental challenges

- Experimental approaches

Direct kinematics

Inverse kinematics

For neutrons and light charged particles see e.g. :

Herbach et al, Nucl. Instr. Meth. A 503 (2003) 315;

Borne et al, Nucl. Instr. Meth. A 385 (1997) 339;

Trebukhovsky et al, Phys. Atom. Nucl. 68 (2005) 3

- Next generation experiments

- Conclusions

Definition

Wikipedia (http://en.wikipedia.org):

'In nuclear physics, it is the process in which a heavy nucleus emits a large number of nucleons as a result of being hit by a high-energy proton, thus greatly reducing its atomic weight'

First observations:

Shopper et al, Naturw. 25 (1937) 557 – interaction of cosmic rays in a track detector

Seaborg, PhD thesis 1937 - inelastic scattering of neutrons

The concept of nuclear spallation was first coined by Glenn T. Seaborg: 'In order to distinguish these reactions from the ordinary nuclear reactions in which only one or two particles are ejected, in 1947 I coined the term "spallation" reactions. This term has since become standard in the field'.

Interest in spallation reactions

Basic research

See talks by: K.-H. Schmidt, P. Napolitani, A. Botvina

Applications

- Astrophysics (Reedy et al., J. Geophys. Res. 77 (1972) 537)

- Transmutation of nuclear waste (Bowmann et al, Nucl. Instr. Meth. A320 (1992) 326; Rubbia et al, Report CERN/AT/95-44/(ET), 1995)

- Space technologies (Buchner et al, IEEE Trans. Nucl. Sci. 47 (2000) 705Tang et al, Mat. Res. Soc. Bull. 28 (2003))

- Biology and medicine (Wambersie et al, Radiat. Prot. Dosim 31 (1990) 421; Bartlett et al, Radiat. Res. Cong. Proc. 2 (2000) 719)

- Radioactive-beam production (EURISOL project)

- Spallation-neutron sources (SNS, ESS)

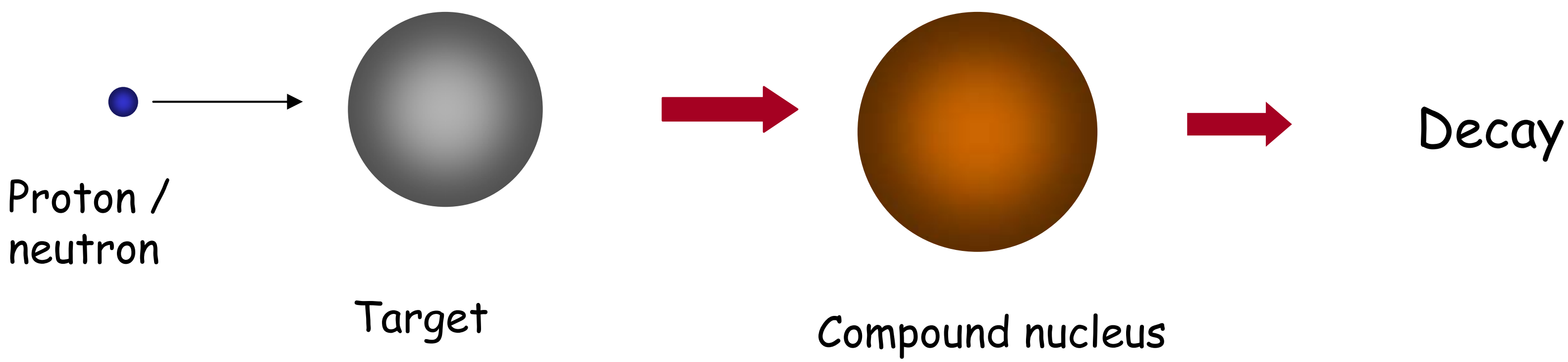
Facilities

SATURNE (F), IPNO (F), COSY (D), GSI (D), PSI (CH), ITEP (RU), JINR (RU), LANL (USA), BEVATRON (USA), KEK (J)

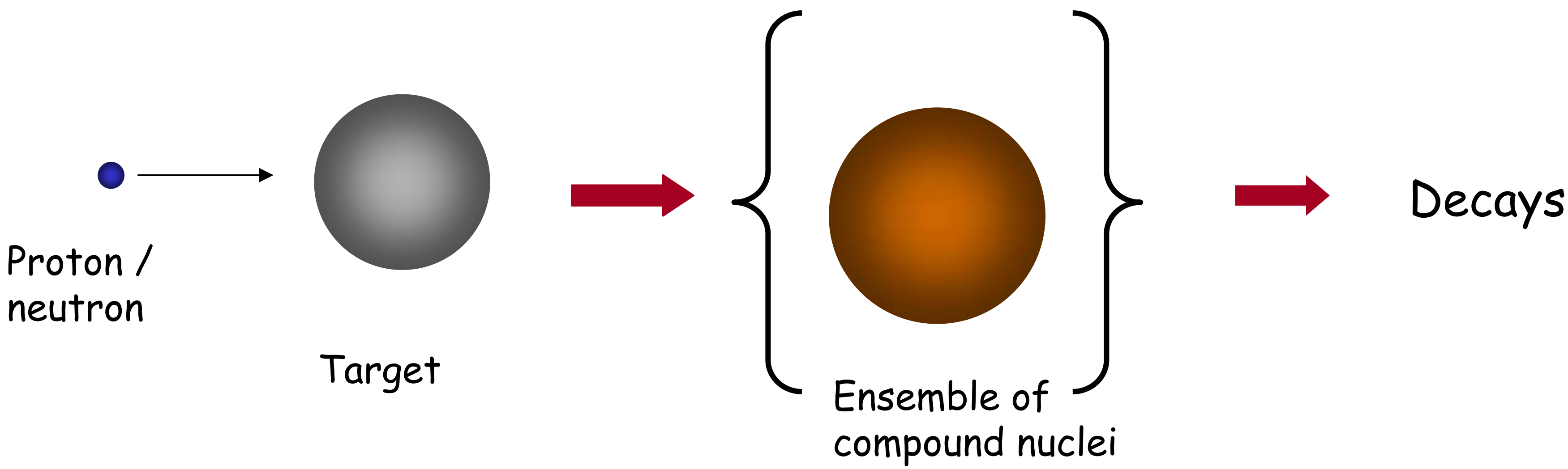
Experimental challenge

Experimental challenge

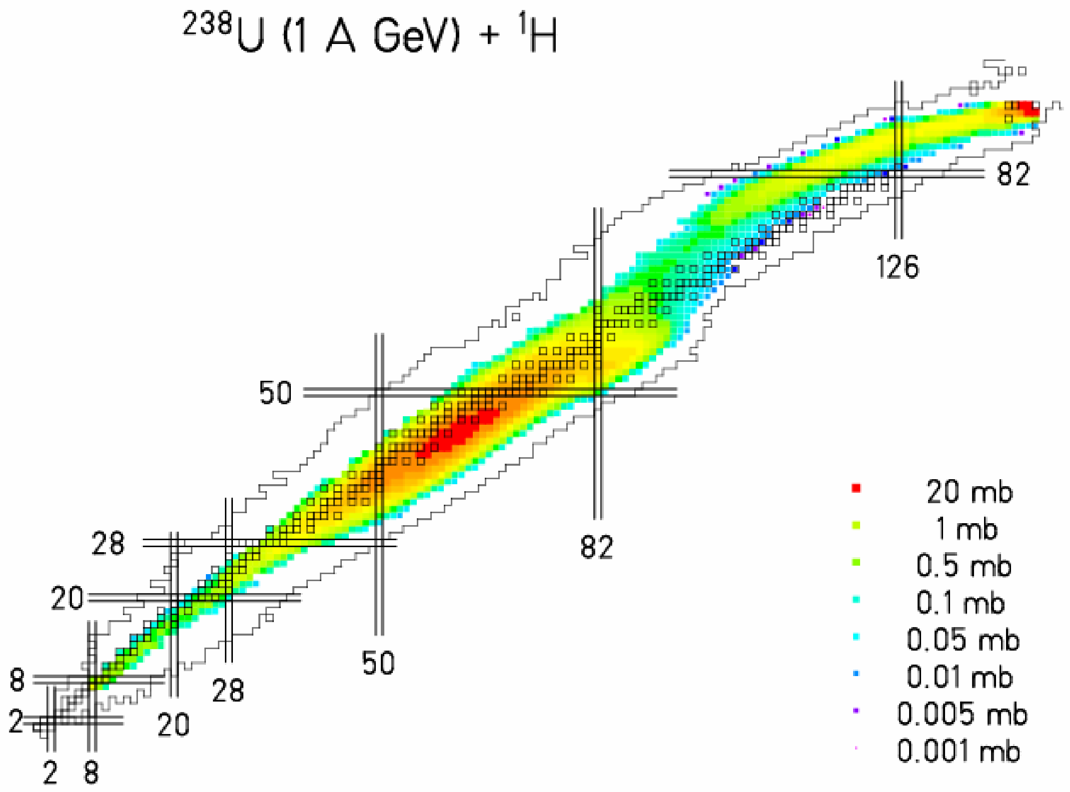
Low-energy reactions (~ MeV)



High-energy reactions (~ GeV)



Experimental challenge



Data measured at GSI*

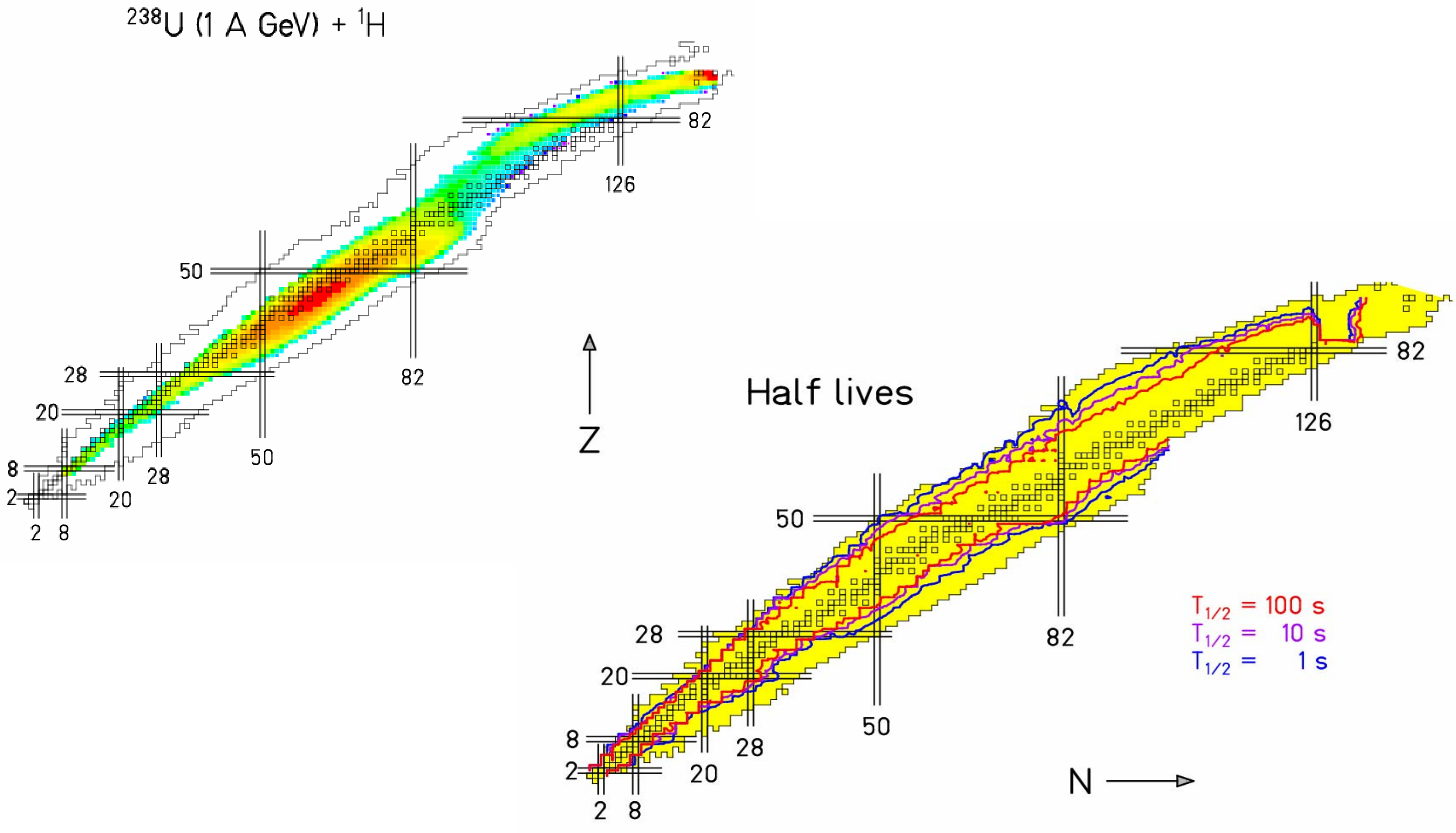
* Ricciardi et al, Phys. Rev. C 73 (2006) 014607; Bernas et al., Nucl. Phys. A 765 (2006) 197; Armbruster et al., Phys. Rev. Lett. 93 (2004) 212701; Taïeb et al., Nucl. Phys. A 724 (2003) 413; Bernas et al., Nucl. Phys. A 725 (2003) 213

www.gsi.de/charms/data.htm

More than 1000 different nuclides produced in the spallation reaction.

Need for identifying all nuclides – from the lightest to the heaviest products.

Experimental challenge

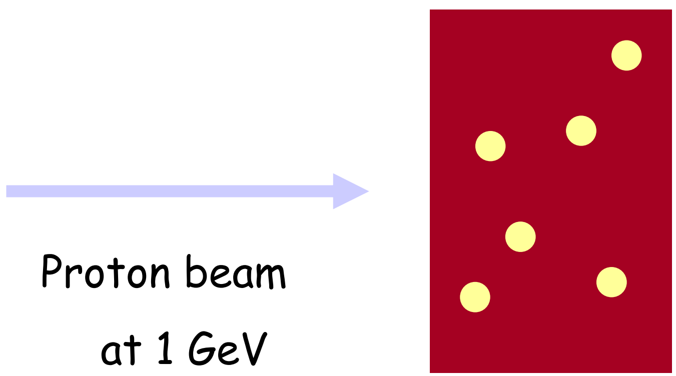


Short-lived as well as stable nuclei have to be detected.

Experimental approaches

Experimental approaches

Direct kinematics



Proton beam
at 1 GeV

Heavy-ion target

- Chemistry
- γ-spectroscopy
- Accelerator-mass spectrometry

Advantages:

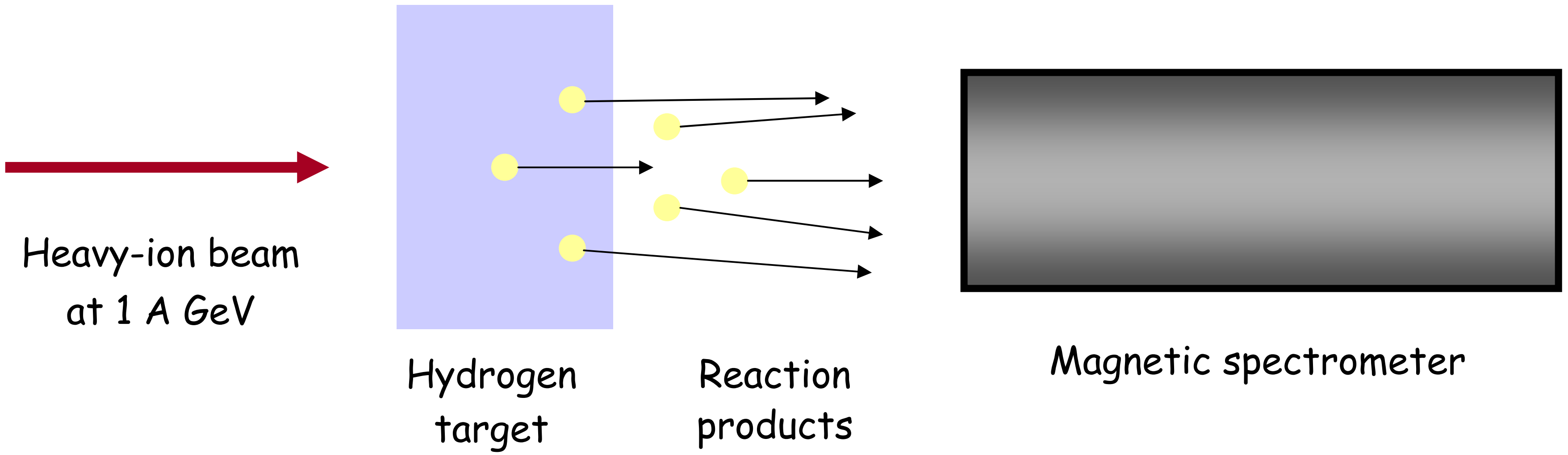
- Excitation functions readily measured
- Separation between isomer and ground-state production

Problems:

- Short-lived nuclei
- Very few independent yields
- Limitations on target materials
- No information on kinematical properties

Experimental approaches

Inverse kinematics



Advantages:

- "All" half-lives
- All nuclides
- Kinematical properties

Problems:

- Excitation functions cannot be measured in one experiment
- No separation between isomer and ground-state production

Experimental approaches

- Direct kinematics -

Experimental setup

598 *M. Gloris et al. / Nuclear Instruments and Methods in Physics Research A 463 (2001) 593–633*

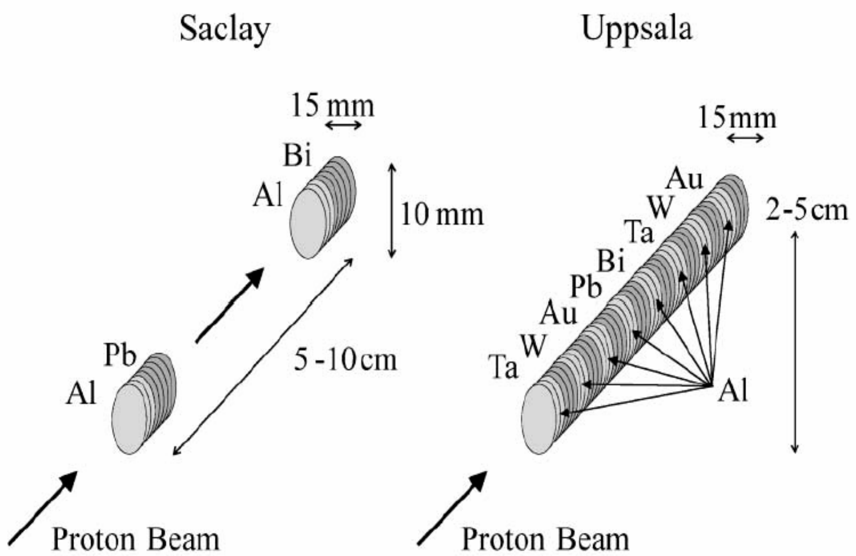
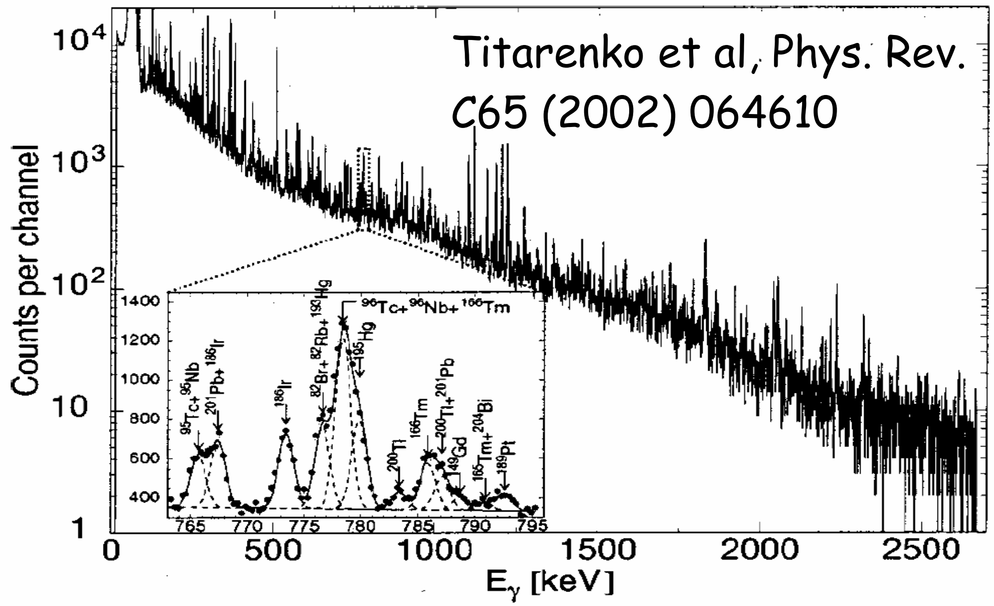


Fig. 2. Schematic view of the target arrangements used (a) at LNS for energies above 200 MeV and (b) at TSL for energies below 180 MeV.

Irradiated samples studied by γ-decay spectroscopy or in case of stable and long-lived nuclei by AMS.

Nuclide identification

γ-ray spectra measured in p (1 GeV) + ^{208}Pb by Titarenko et al.



To obtain cross sections one also needs:

- gamma transitions
- half lives
- branching ratios

Excitation functions

Independent and cumulative yields

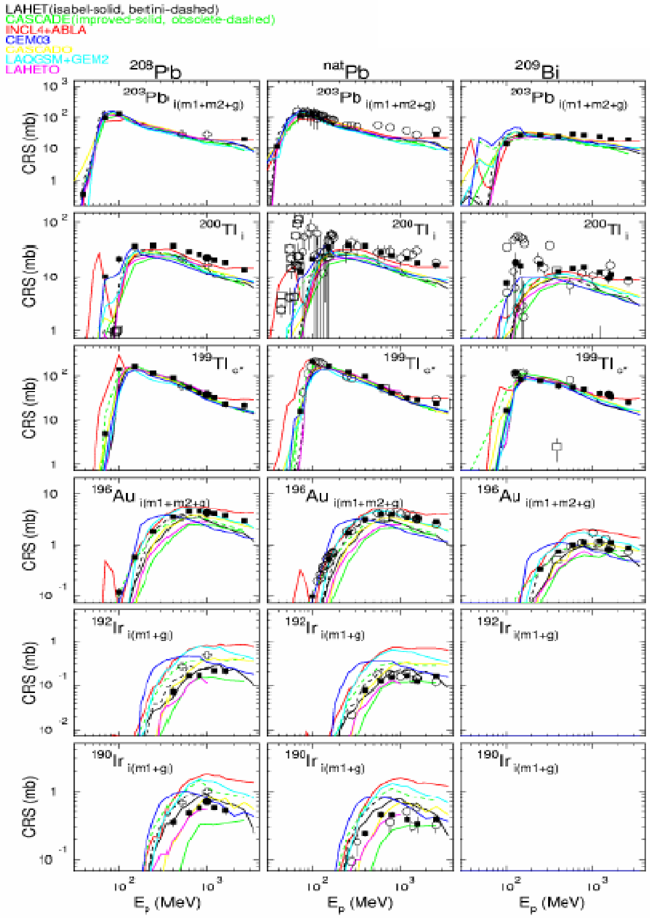


Fig. 2. Experimental and simulated excitation functions of ^{203}Pb, ^{200}Tl, ^{199}Tl, ^{196}Au, ^{192}Ir, and ^{190}Ir produced in ^{208}Pb (left), ^{nat}Pb (center), and ^{209}Bi(right). (■ – this work, ● – [2],

Titarenko et al, 2005

- About 100 (mostly cumulative) yields/system

- Uncertainty 7 – 30 %

Additional information:

- Miah et al, Nucl. Sc. Tech. Suppl. 2 (2002) 369

- Schiekel et al, Nucl. Instr. Meth. B114 (1996) 91

- Adilbish et al, Radiochem. Radioanal. Lett. 45 (1980) 227

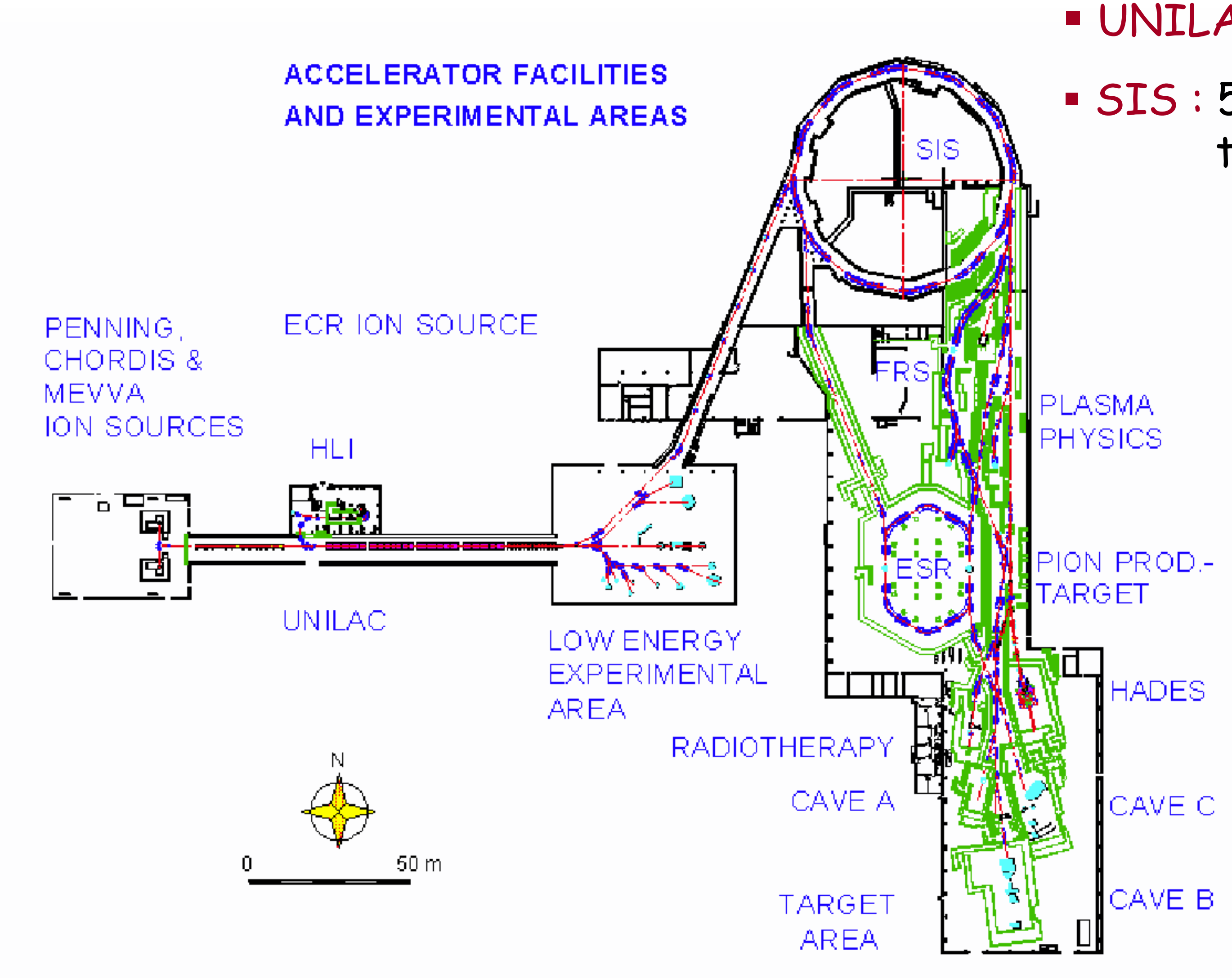
- Chu et al, Phys. Rev. C 15 (1977) 352

Experimental approaches

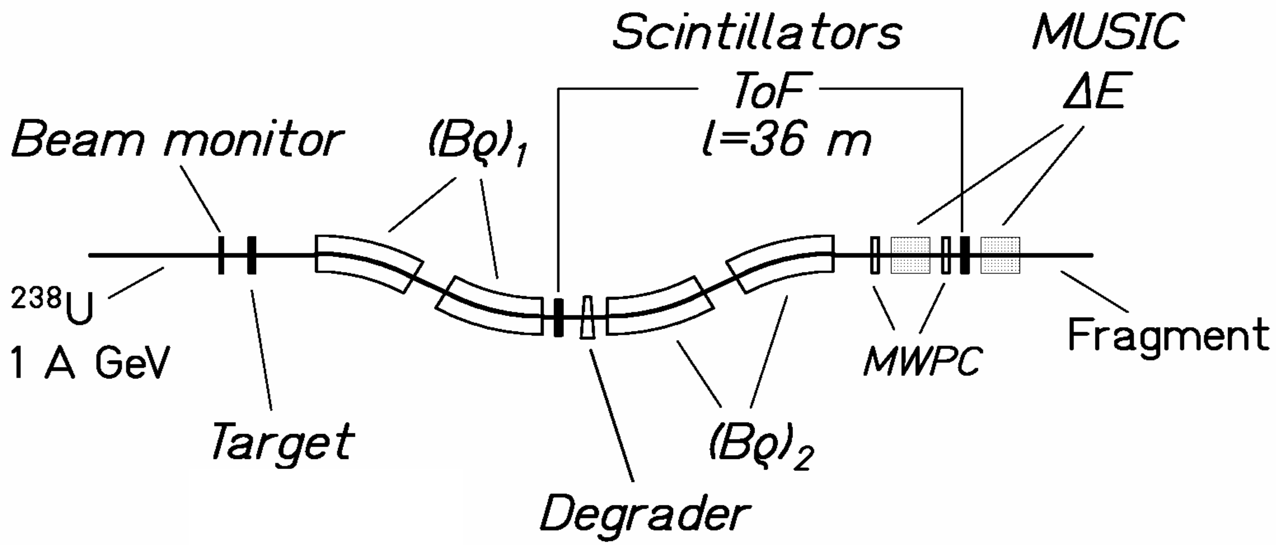
- Inverse kinematics -

GSI facility

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



Experimental setup



Θ^{max}	= 15 mrad
$\Delta p/p$	= ± 1.5 %

ToF ⇨ $\beta\gamma$

x_1, x_2 ⇨ $B\rho$

ΔE ⇨ Z

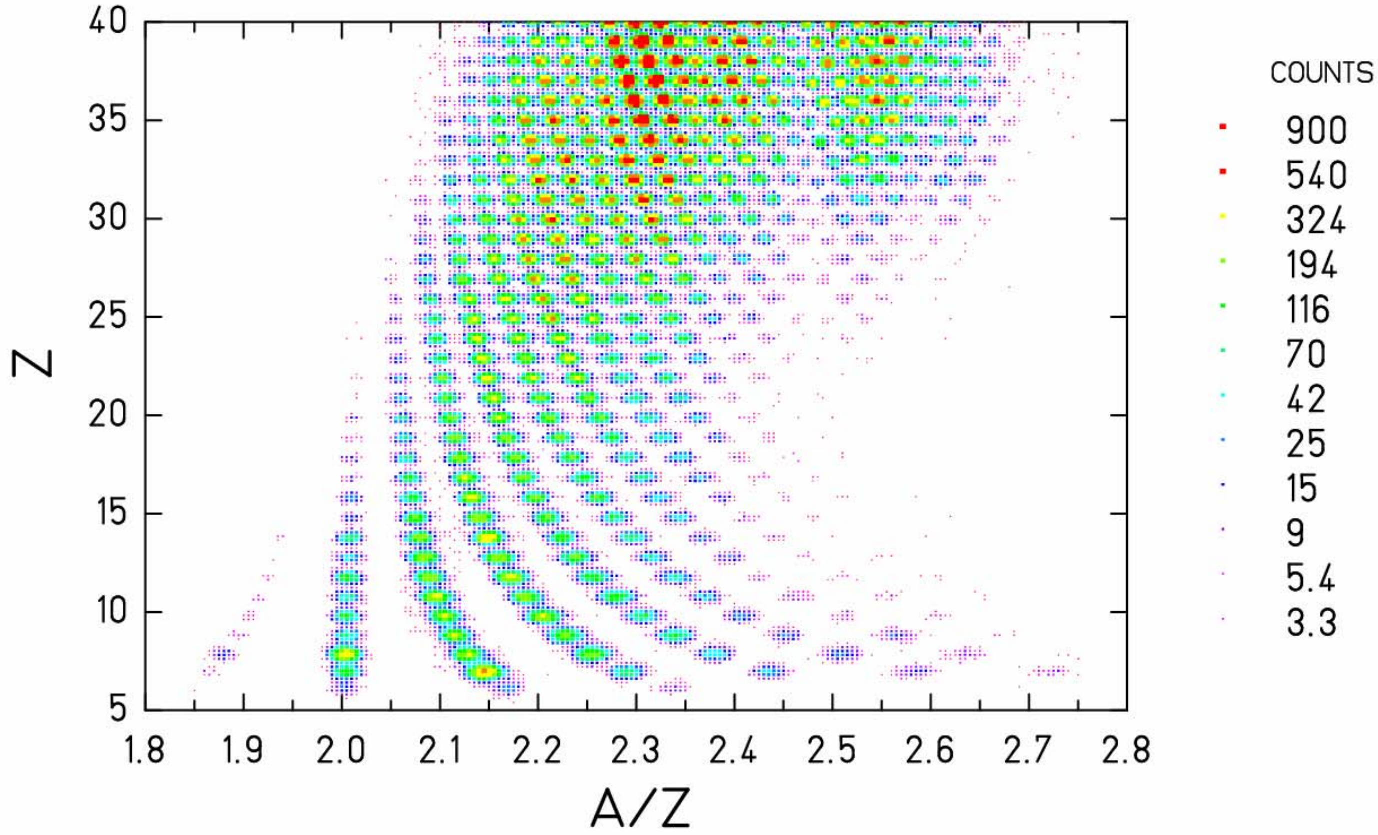
$$\boxed{\frac{A}{Z} = \frac{e}{m_0 c} \cdot \frac{B\rho}{\beta \cdot \gamma}}$$

Resolution:

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

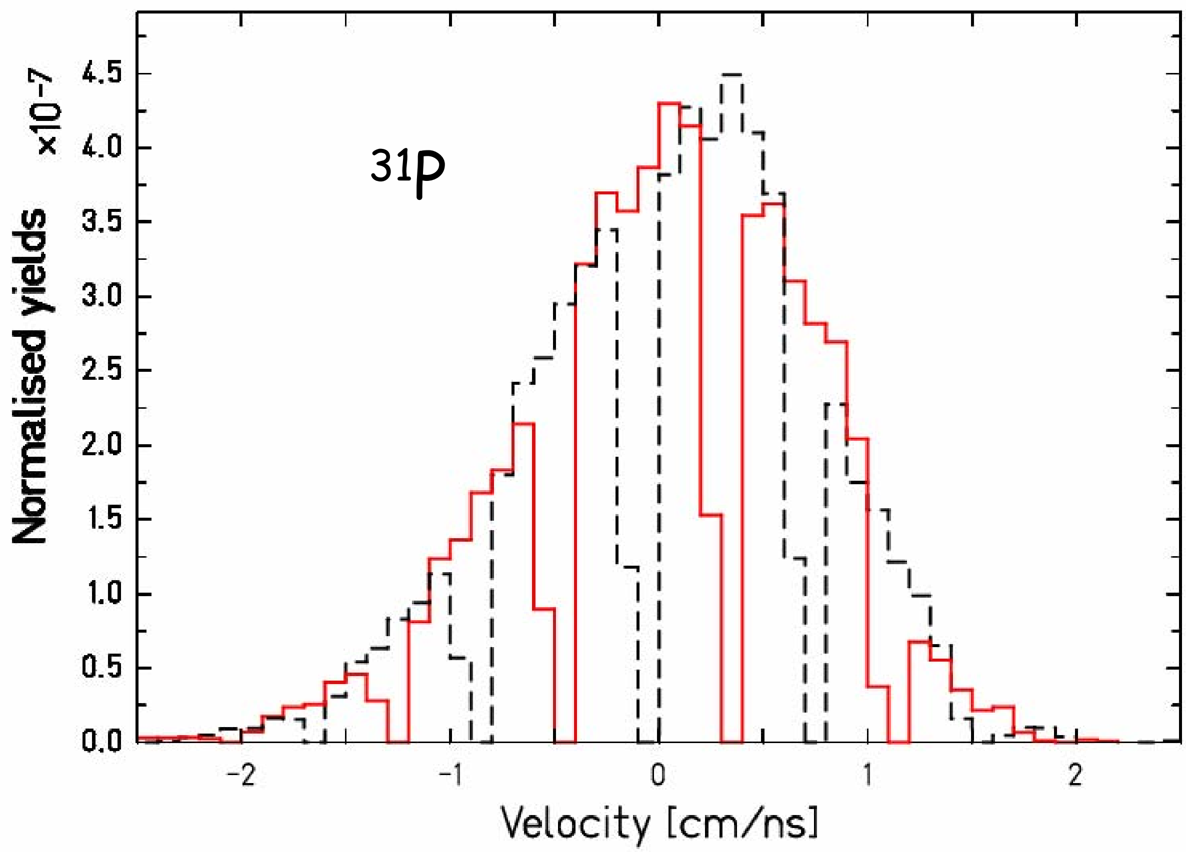
Nuclide identification

$^{238}U + {}^{1}H$ at 1 *A* GeV



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

Limited momentum acceptance

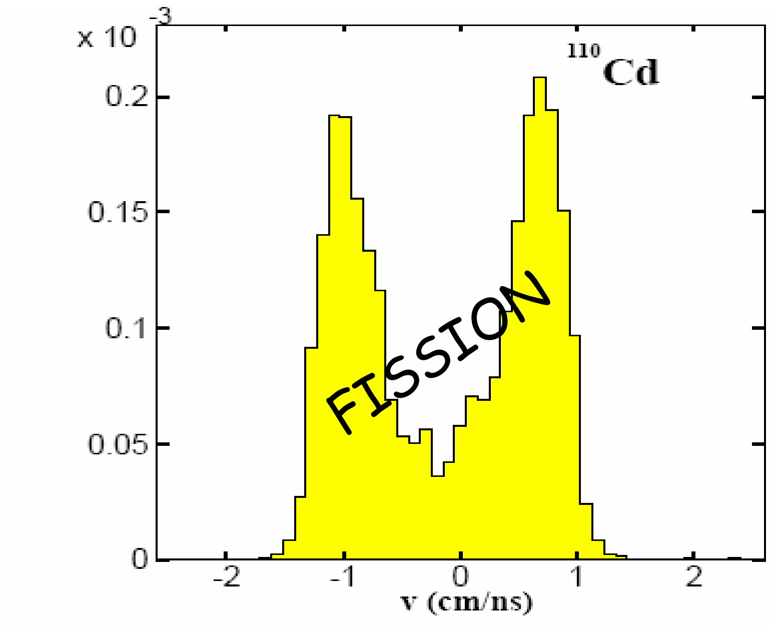


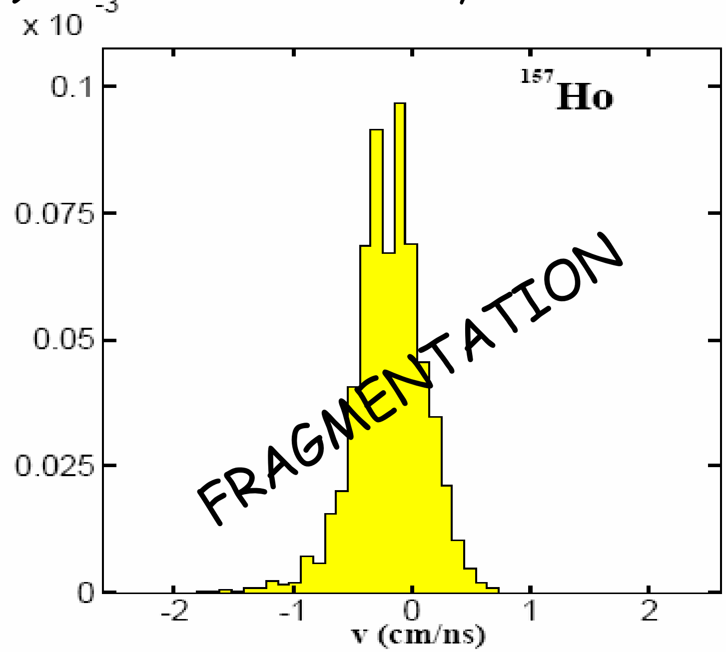
Overlap of measurements with different magnetic-filed settings.

Velocity distributions

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

Pereira, PhD thesis

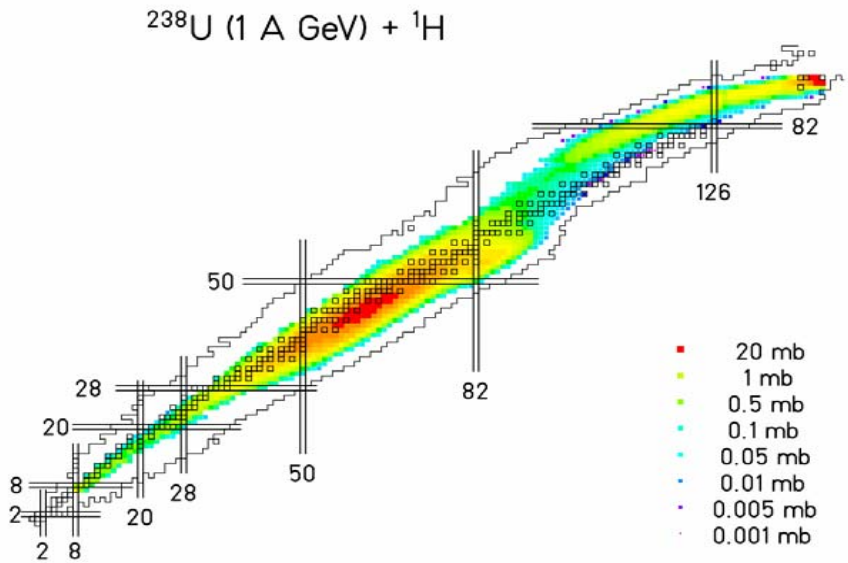




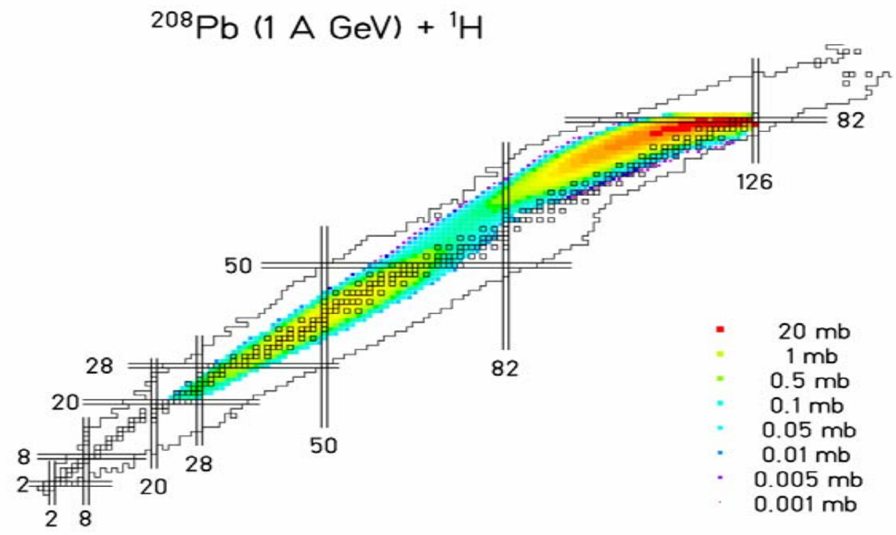
Limited angular acceptance of FRS together with different kinematical properties of fission and fragmentation residues $\Rightarrow$ reaction mechanism

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

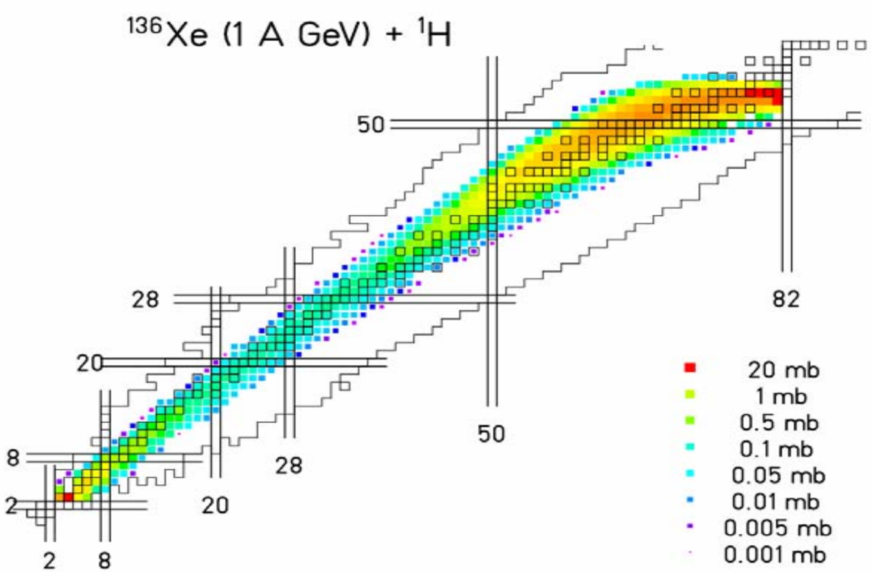
An overview of measured data



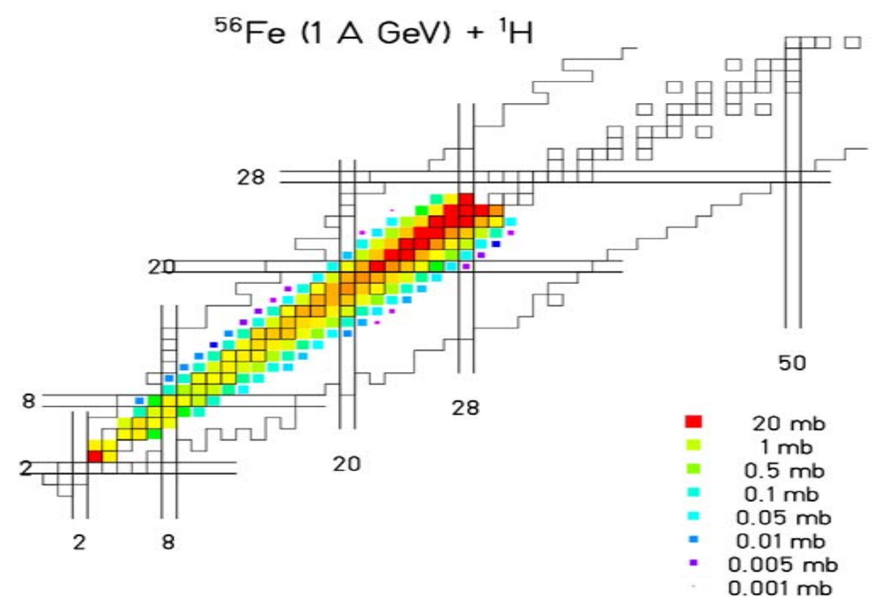
Taieb et al, Bernas et al, Ricciardi et al



Enqvist et al, Bernas et al, Kelić et al



Napolitani PhD

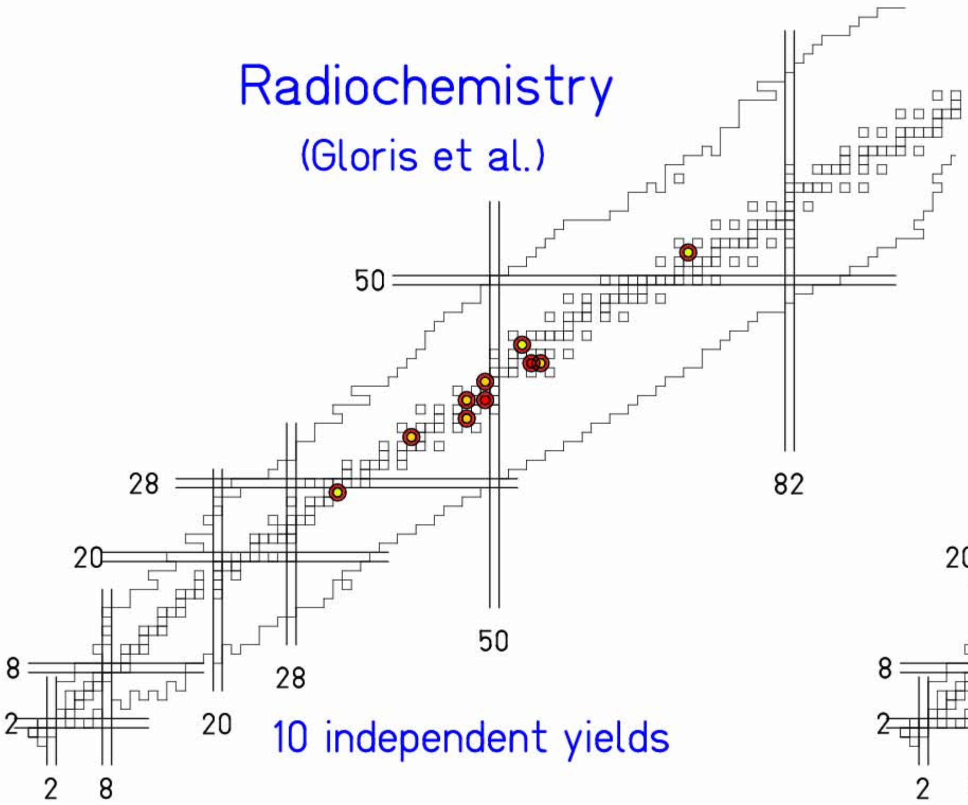


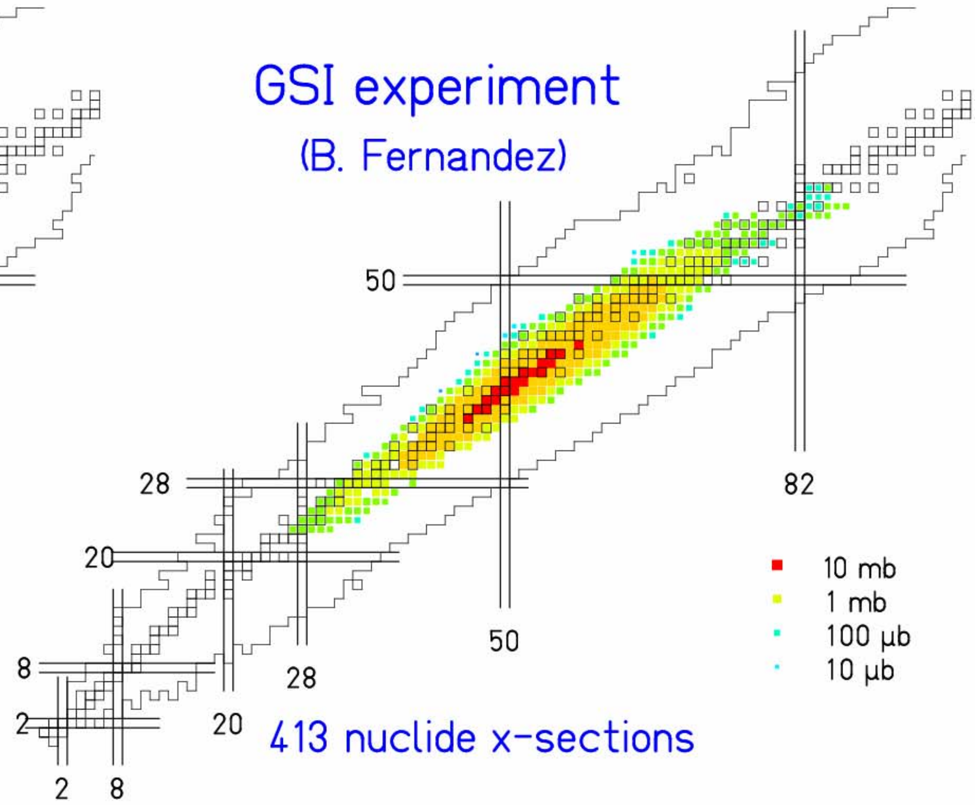
Napolitani PhD, Villagrasa PhD

www.gsi.de/charms/data.htm

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

Experimental progress by inverse kinematics

Projectile	Target	Energy [A GeV]
^{56}Fe	^{1}H, ^{2}H	0.2 - 1.5
$^{136,124}Xe$	$^{1,2}H$, Be, 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

More than 1000 nuclei/system measured

Data accuracy:

Statistic: below 3%

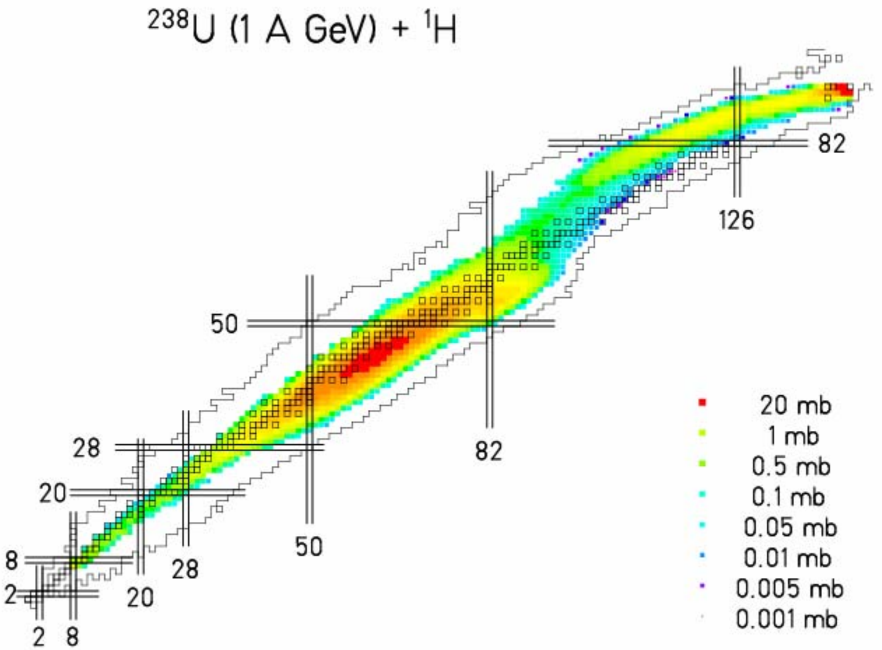
Systematic: 9 - 15 %

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

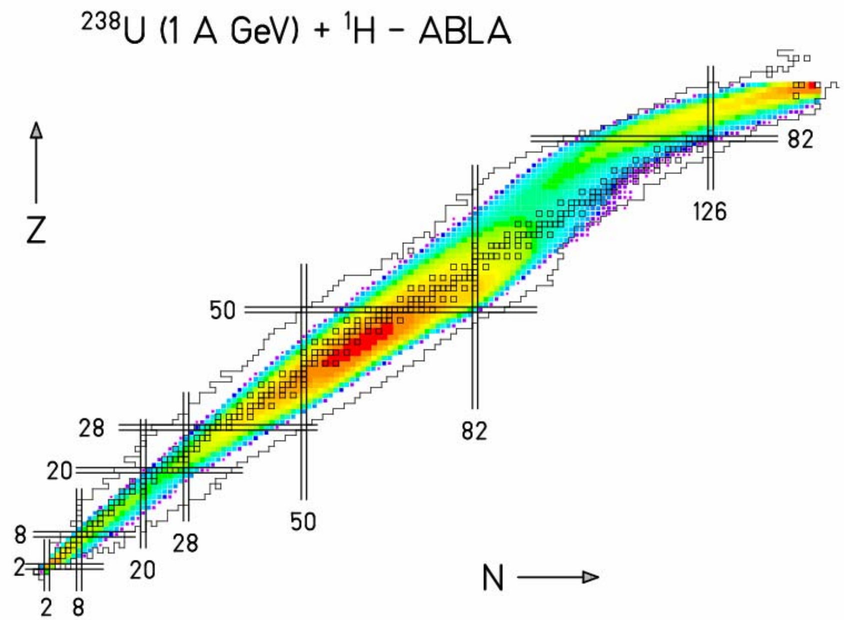
Model calculations

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

Experimental data:



Model calculations (model developed at GSI):

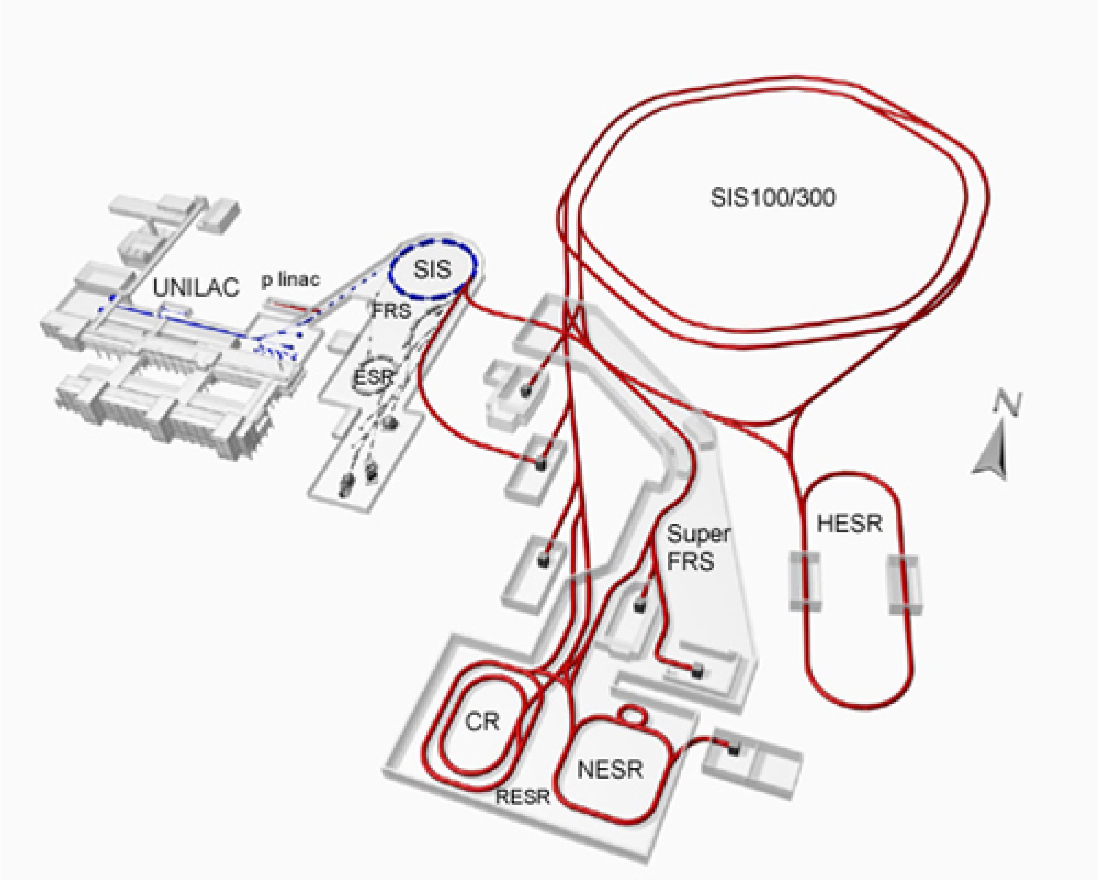


Next generation experiments

Future

- Full identification of heavy residues with simultaneous measurement of neutrons, light charged particles and gammas

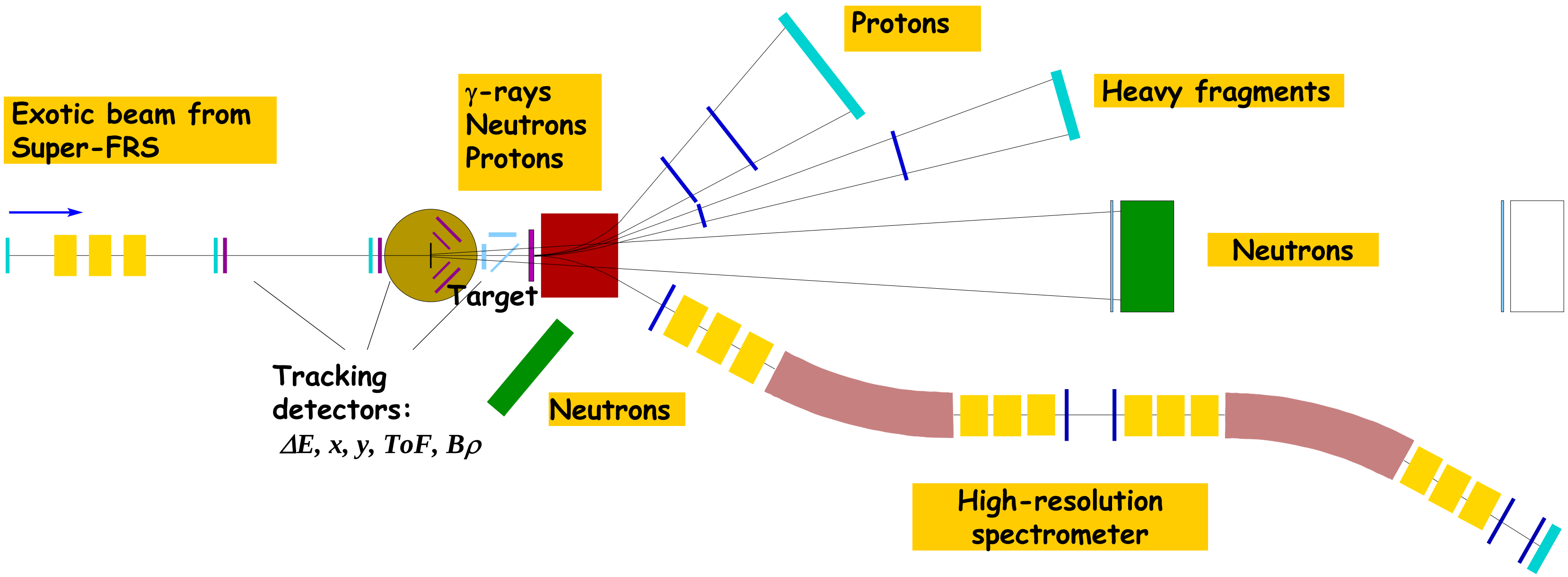
$\Rightarrow$ Aiming for a kinematically complete experiment.



-Increased beam energies and intensities

-Spectrometers with larger acceptance and/or better resolution

R3B @ FAIR



Exclusive experiments and high resolution!

Conclusions

- Large field of applications

- Two approaches
  - Direct kinematics – excitation functions, direct measurement on long-term activation
  - Inverse kinematics – more than 1000 nuclides / system, information on velocities and production mechanisms.

The combined information of these two techniques form the basis for an improved understanding of the nuclear-reaction aspects and for essential improvements of the nuclear models.

- New generation of experiments in preparations. Goal -> kinematically complete experiment

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