FISSION: RECENT RESEARCH AND NEW APPLICATIONS

New applications of nuclear fission

- Accelerator-driven systems (ADS)
  - Incineration of nuclear waste,
  - Energy production,
  - Research program **HINDAS**.
- Next-generation secondary-beam facilities
  - Production of neutron-rich nuclei,
  - Design studies **EURISOL**, **R3B**, (RIA).

GSI tools for fission experiments

- FRS: full identification of one fission fragment or preparation of heavy secondary beams.
- ΔE-TOF and tracking: Z_1, Z_2 and TKE.
- ALADIN, LAND: Z_1, Z_2, neutrons, (A_1, A_2).

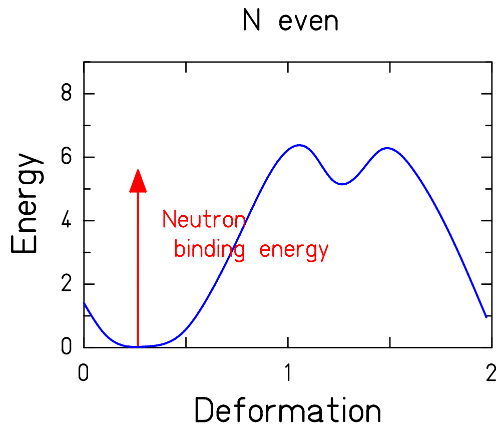
Research topics

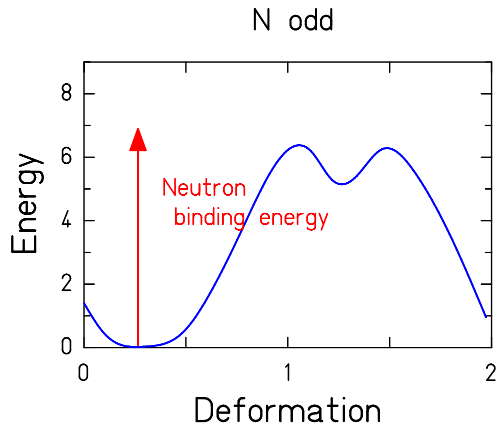
- Which are the fissioning nuclei?
  - Importance of dissipation.
- What are their fission-fragment distributions?
  - Systematics of fission channels.
- What are the best conditions to produce neutron-rich fragments?
  - Fluctuations in polarisation, neutron evaporation.
- What is the mass range populated in fission?
  - Fluctuations in mass.

Primordial Heavy Nuclei, Resources of Cosmic Energy

232Th: Z = 90, N = 142, (100%)
234U: Z = 92, N = 142, (0,0055%)
235U: Z = 92, N = 143, (0,72%)
238U: Z = 92, N = 146, (99.2745%)

Excitation by thermal neutrons





Only nuclei with odd neutron number fission after capture of thermal neutrons, energy release ≈ 200 MeV.

Nuclei with even neutron number are fertile.
(By capture of fast neutrons, a nucleus with odd neutron number is formed.)

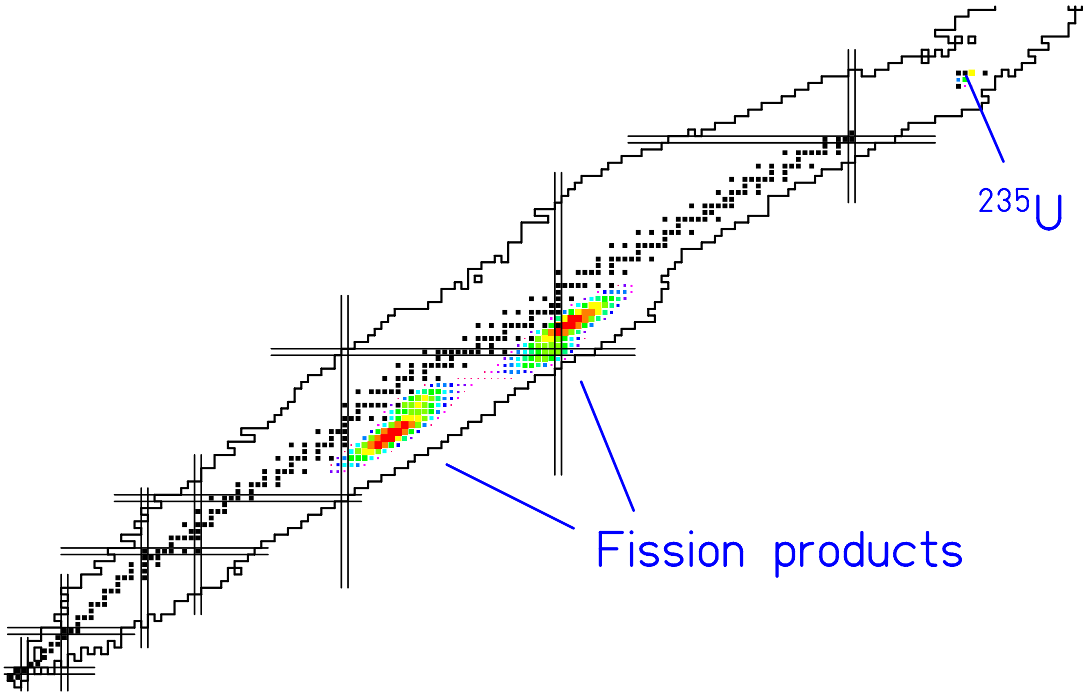
The only natural nuclear fuel for conventional (thermal) fission reactors is 235U.

Fission reactors based on 235U cannot solve the medium-range energy problem of mankind!

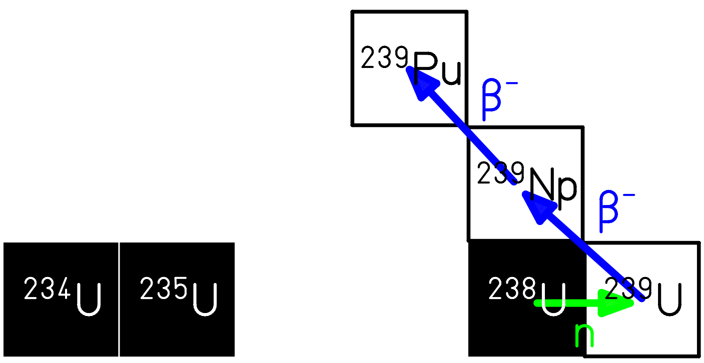
Possible solutions: breeding from 238U or 232Th.

Nuclei produced in a Fission Reactor

Fission products

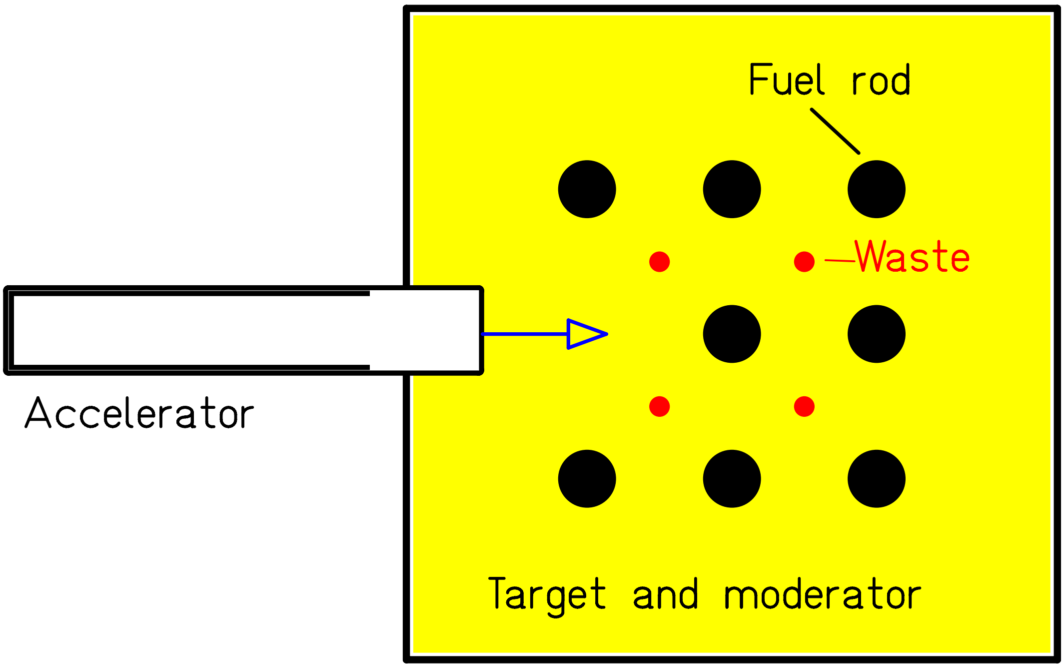


Breeding of ^{239}Pu and minor actinides



The Hybrid Reactor (ADS)

A device for energy production and for the incineration and transmutation of radioactive waste (promoted by Rubbia).



A subcritical reactor with additional neutrons produced by 1 GeV protons.

- **Can use ^{232}Th fuel (resources for 20000 years).**
- **No breeding of ^{239}Pu (proliferation!).**
- **Intrinsically safer than conventional reactors.**
- **Can help to solve the nuclear-waste problem.**

Solution of the energy problem, based on current technology -- alternative to fusion reactors!

R&D programs supported by EU.

Nuclear reactions up to 1 GeV must be known!

HINDAS (High- and intermediate-energy nuclear data for accelerator-driven systems)

Participants:

UCL Louvain-la-Neuve, Belgium
Subatech Nantes, France
LPC Caen, France
RuG Groningen, Netherlands
UU Upsala, Sweden
ZSR Hannover, Germany
PTB Braunschweig, Germany
IPP Zürich, Switzerland
PSI Zürich, Switzerland
FZJ Jülich, Germany
CEA Saclay, France
CEA Bruyères-le-Châtel, France
GSI Darmstadt, Germany
Universidad Santiago de Compostela, Spain
Ulg Liège, Belgium
NRG Petten, Netherlands

Experiments on residue production at GSI:

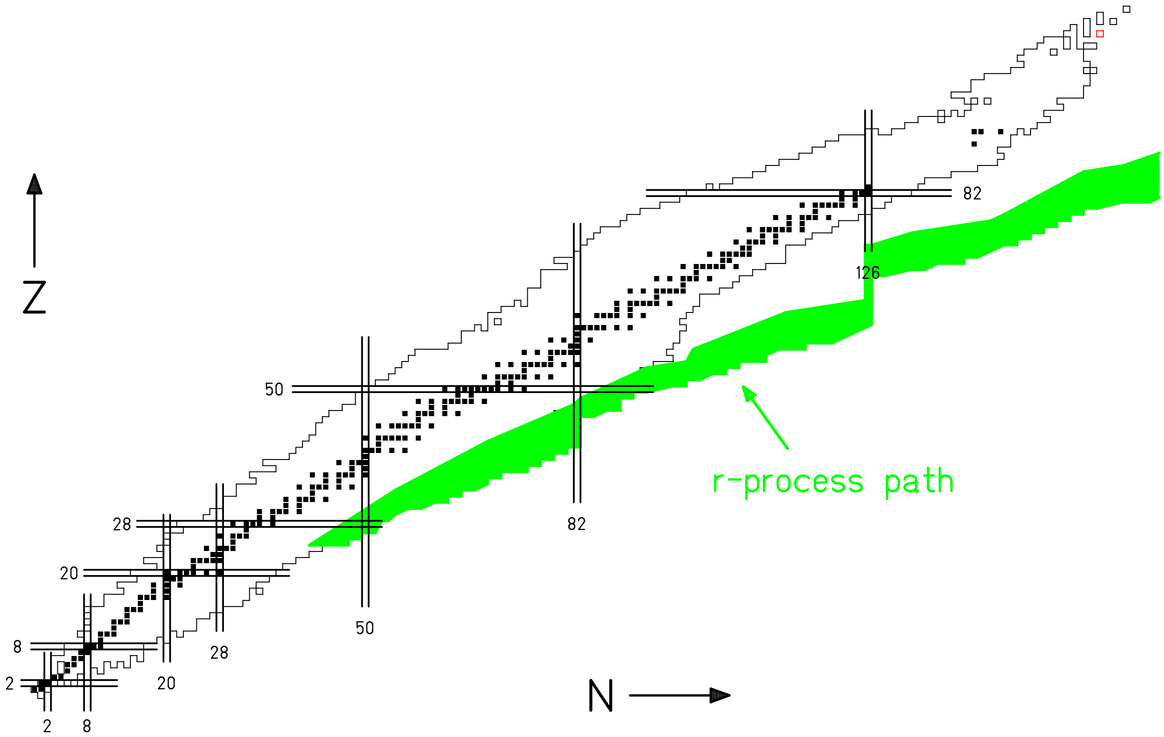
GSI Darmstadt, Germany
Universidad Santiago de Compostela, Spain
IPN Orsay, France
CEA Saclay, France
CEN Bordeaux-Gradignan, France

The Research Program at GSI to Determine Isotopic Cross Sections of Heavy Residues

- **208Pb (1 A GeV) + Cu**
- **238U (1 A GeV) + Cu**
- **238U (1 A GeV) + Pb**
- **197Au (800 A MeV) + 1H**
- **208Pb (1 A GeV) + 1H**
- **208Pb (1 A GeV) + 2H**
- **208Pb (500 A MeV) + 1H**
- **238U (1 A GeV) + 1H**
- **238U (1 A GeV) + 2H**

- **planned:**
- **56Fe (1 A GeV) + 1H**

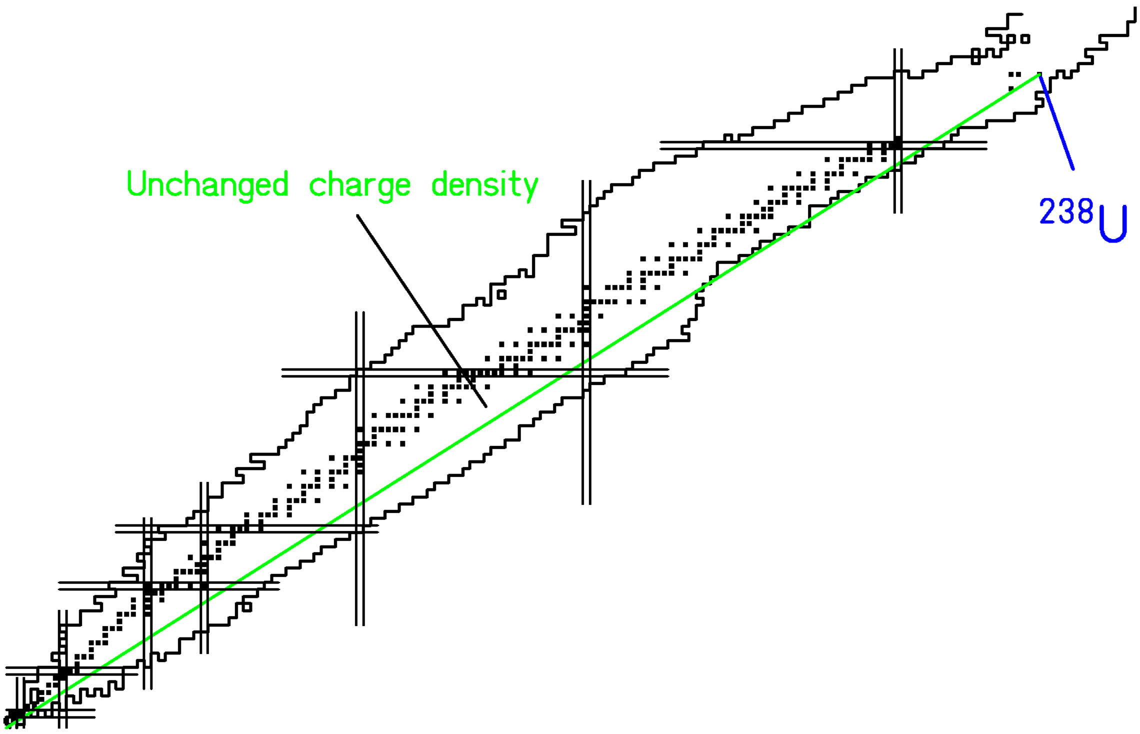
Finding Best Conditions to Produce Neutron-Rich Secondary Beams



Even nature did not reach the neutron drip line (r-process)

How to produce these neutron-rich nuclei in laboratory?

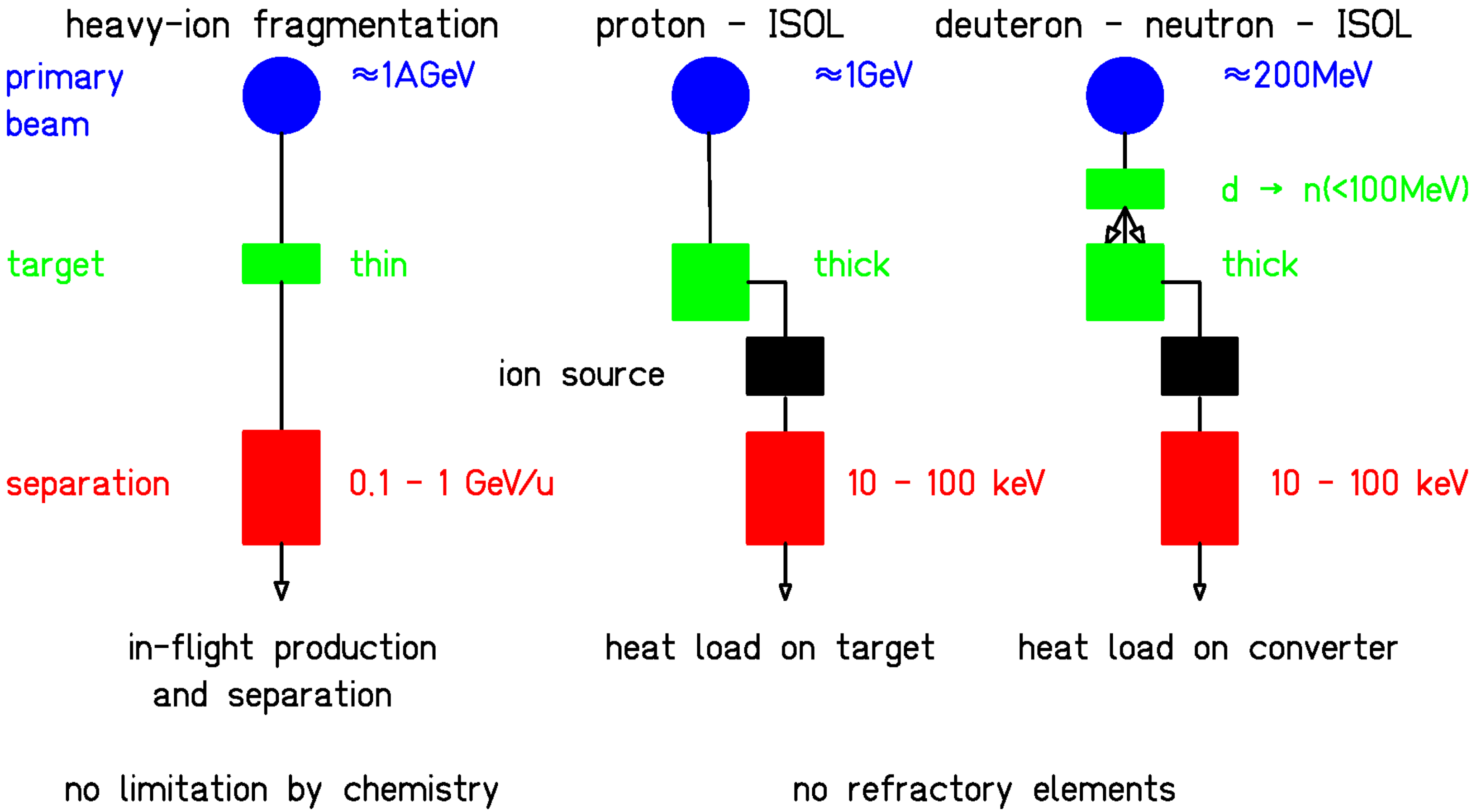
Fission



- **Basic characteristic:**
  Curvature of stability valley due to Coulomb repulsion.
  → Fission products are neutron-rich.

- **Experimental investigations:**
  Exploring optimum conditions for production of most neutron-rich isotopes.

Scenarios for the Production of Secondary Beams



Other propositions: RIA (in-flight production, stopping in gas, post-acceleration)
Fission by reactor neutrons, bremsstrahlung

EURISOL

European Isotope Separation On-Line Radioactive Nuclear Beam Facility

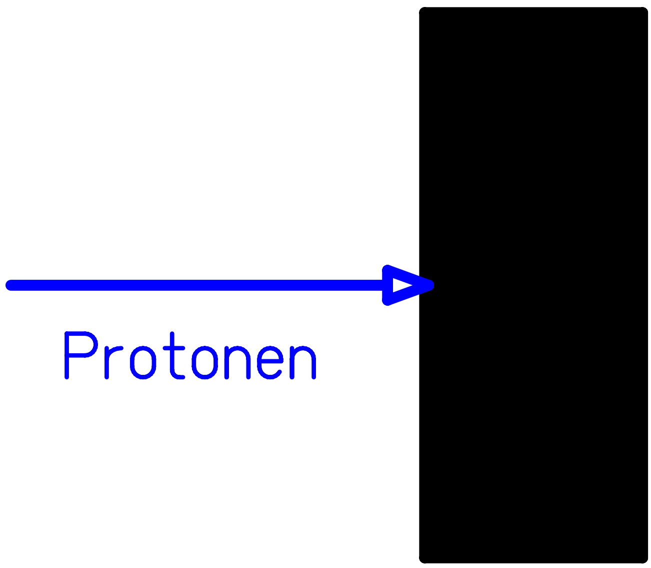
Research and Technical Development (RTD) project selected for support by the EU. The project is aimed at completing a preliminary design study of the next-generation European ISOL radioactive nuclear beam (RNB) facility.

A number of European institutions are actively involved:

Project Coordinator: **Jean Vervier, Université Catholique de Louvain (UCL), Louvain-laNeuve, Belgium**
Coordinating Institute: **Grand Accélérateur National d'Ions Lourds (GANIL), Caen, France**
Chalmers University of Technology (CUT), Göteborg, Sweden
Katholieke Universiteit Leuven (KULeuven), Leuven, Belgium
Gesellschaft für Schwerionenforschung (GSI), Darmstadt, Germany
Istituto Nazionale di Fisica Nucleare (INFN), Roma, Italy
Institut de Physique Nucléaire Orsay (IPNO), Orsay, and CEA/DAPNIA, Saclay, France
ISOLDE, CERN, Genéve, Switzerland
Accelerator Laboratory, University of Jyväskylä, (JYFL) Finland
Rutherford Appleton Laboratory (RAL), Didcot, United Kingdom

Why Inverse Kinematics?

Experiments with proton beams:

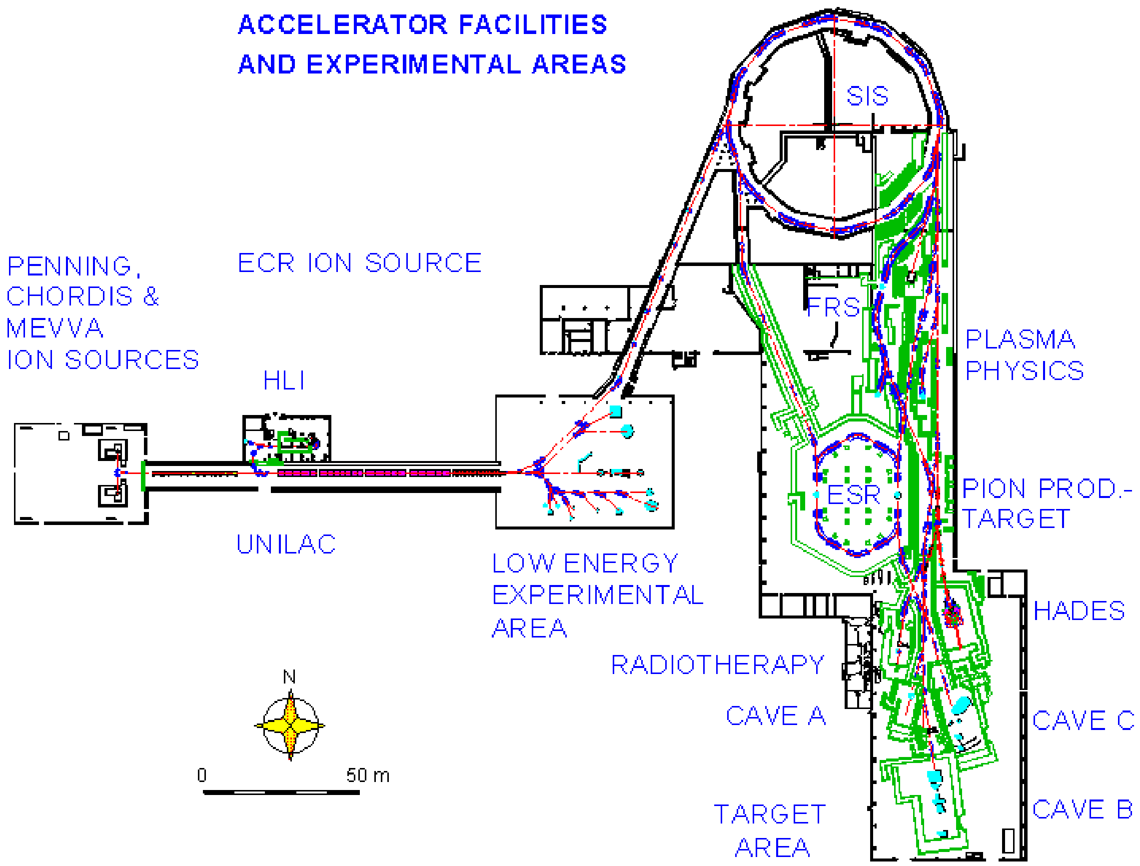


The products stick in the target.
Identification by radioactive decay
→ Insensitive to short-lived nuclides

Experiments with heavy-ion beams:

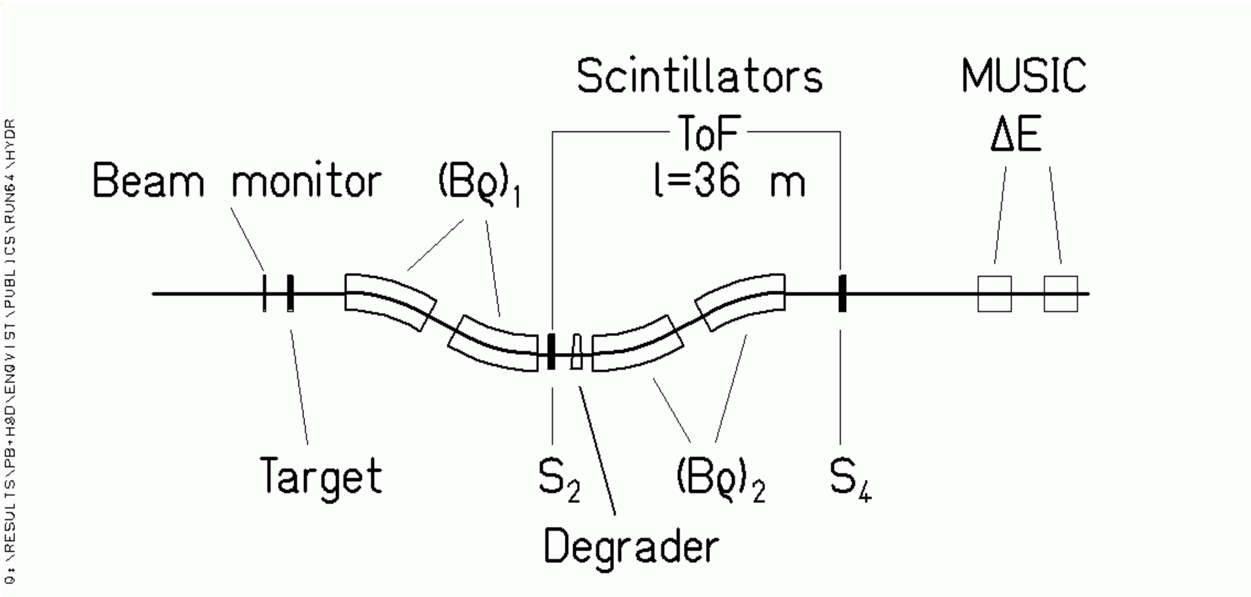
The products leave the target with high velocity
Identification in-flight
→ Sensitive to all nuclides

The facilities of GSI



Heavy nuclei (^{197}Au, ^{208}Pb, ^{238}U) are accelerated and hit the production target. The projectile-like residues are identified in-flight with the fragment separator (FRS).

The Fragment Separator



Projectile-like fragments:

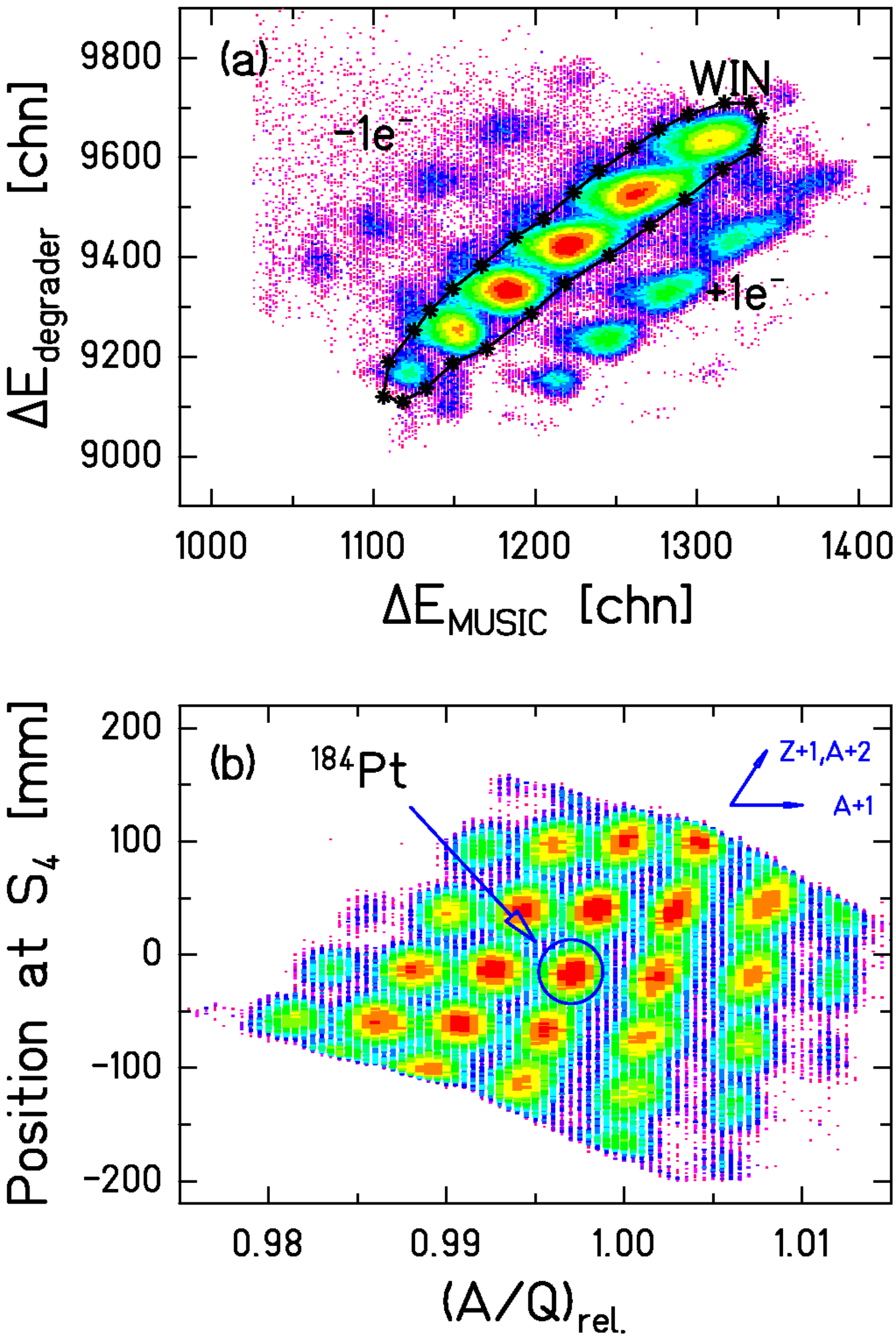
Transmitted with $\Delta B\rho/ B\rho$ = 3% and Θ_{max}=15 mr.

Identification in Z and A by magnetic deflection in FRS, tracking, *ToF* and ΔE.

$$B\rho = m_0\, A\, c\, \beta\, \gamma / (\mathrm{e}\, Z)$$

$$\Delta E \propto Z^2 / v^2$$

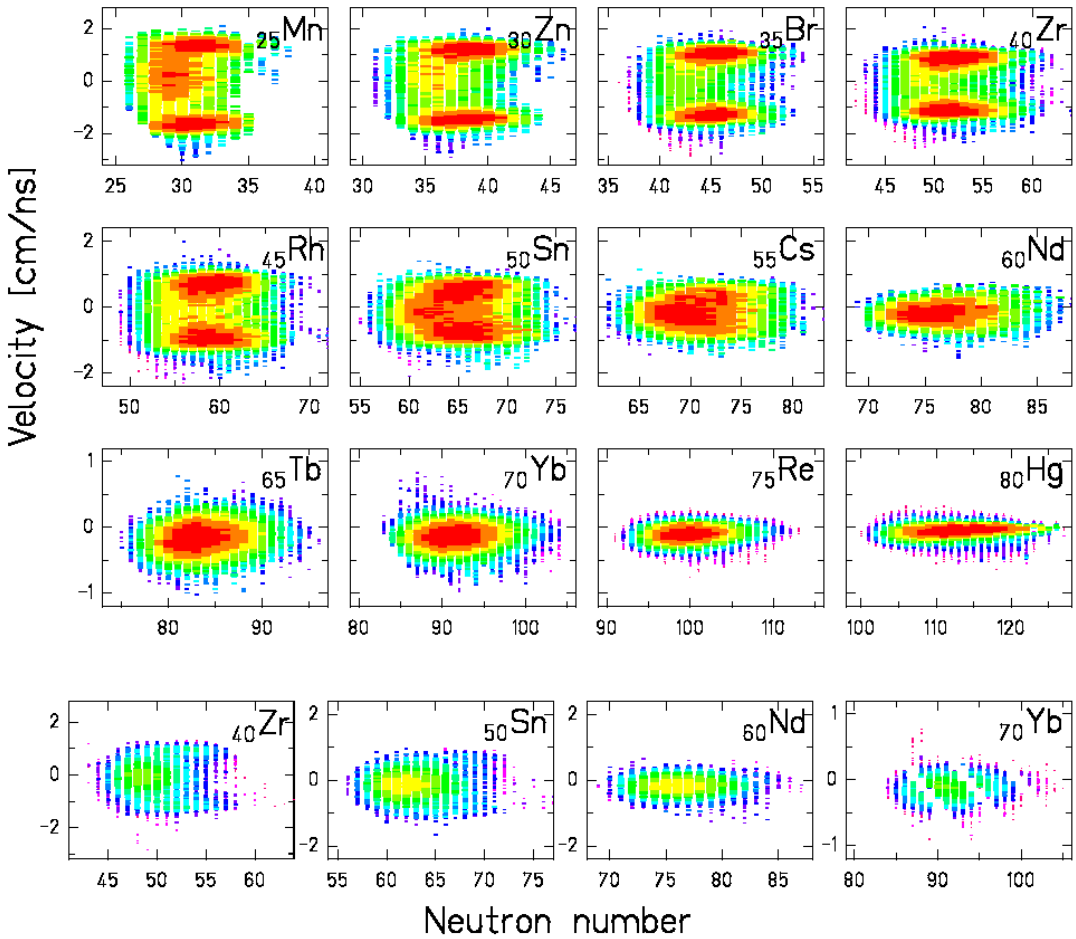
Isotopic identification



Suppression of ionic charge states (above) and isotopic identification (below).

(Data: ^{208}Pb (1 A GeV) + ^{1}H, Timo Enqvist)

Fragment velocities

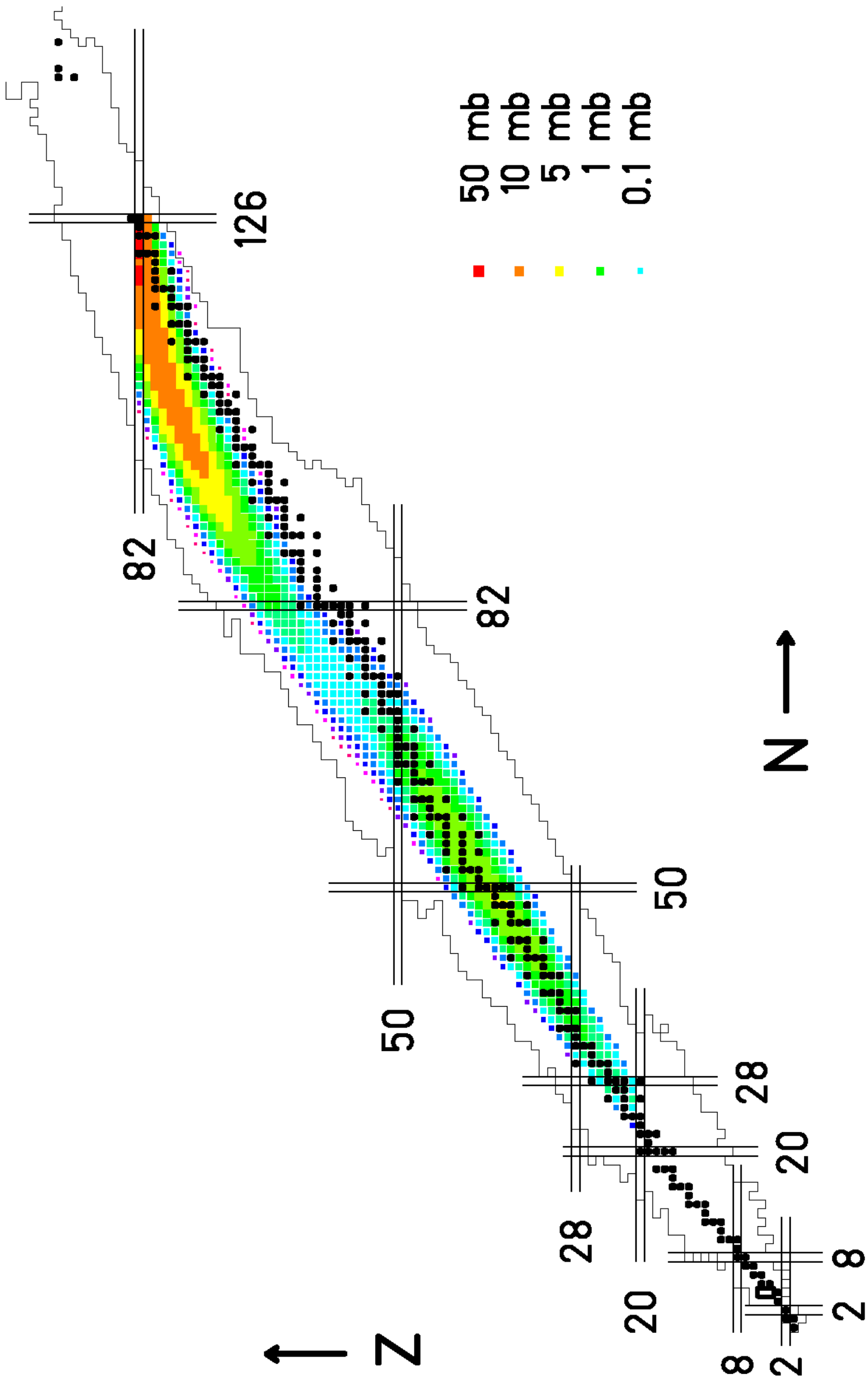


Reactions in H_2 target (above) and Ti windows (below).

Signature of the reaction mechanism:

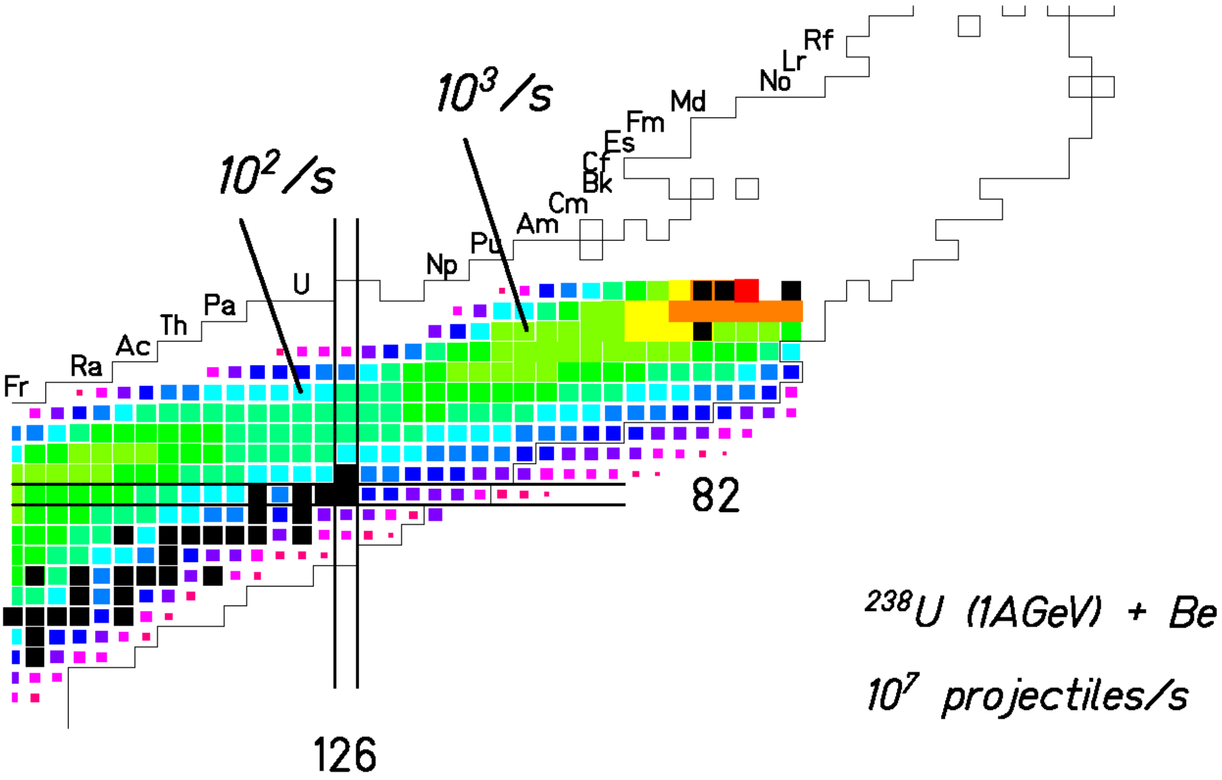
Fragmentation (single peak) and fission (two peaks).

(Data: ^{208}Pb (1 A GeV) + ^{1}H, Timo Enqvist)


50 mb
10 mb
5 mb
1 mb
0.1 mb
N
Z
2
8
20
28
50
82
126

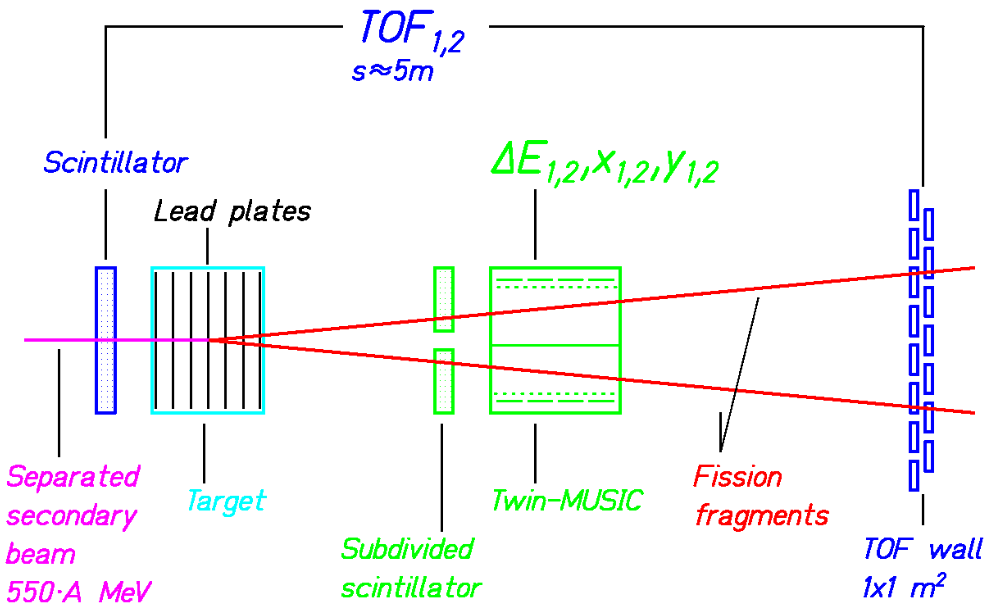
Production rates of secondary beams

(Model calculation adapted to experimental data)



Coverage of the transitional region from symmetric to asymmetric fission

Setup for the fission experiment



Method:

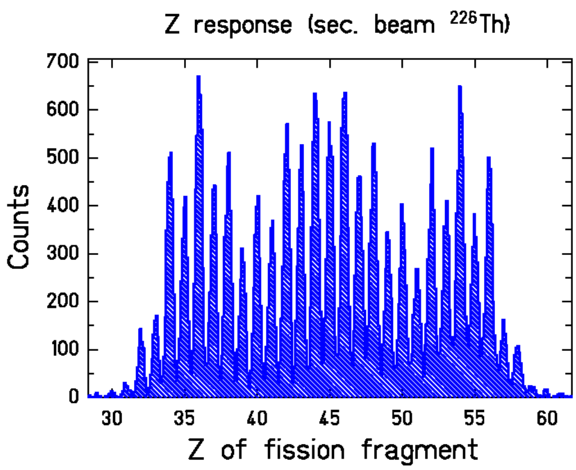
electromagnetic excitation → fission
(E^* ≈ 5 MeV above fission barrier)

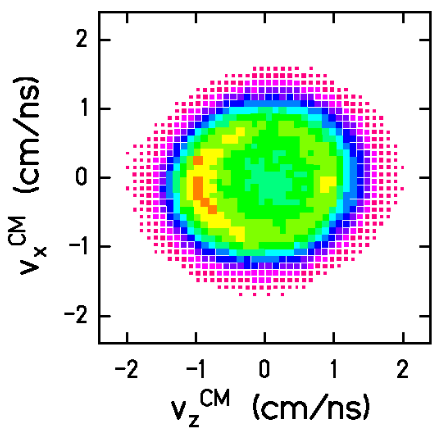
Features:

full detection of both fission fragments
excellent Z resolution
kinematic analysis

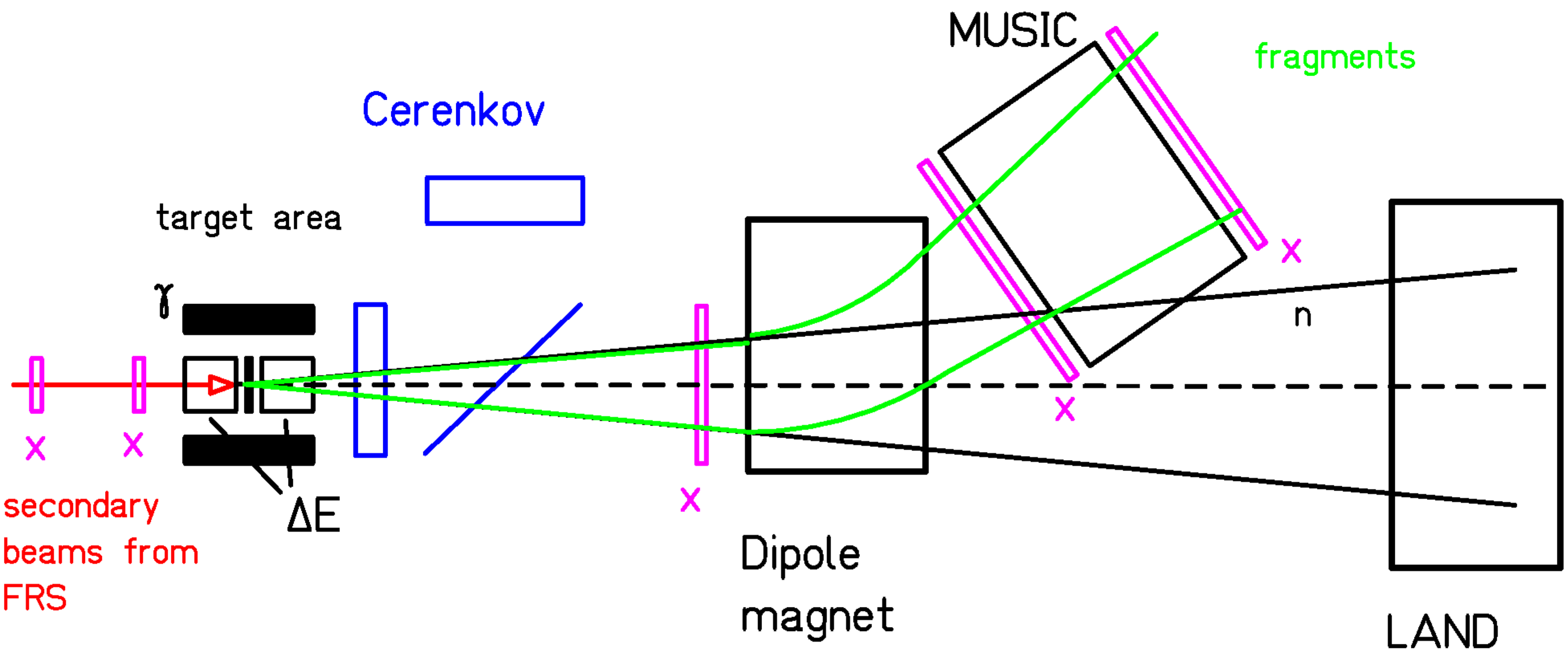
Results:

Z yields
total kinetic energies

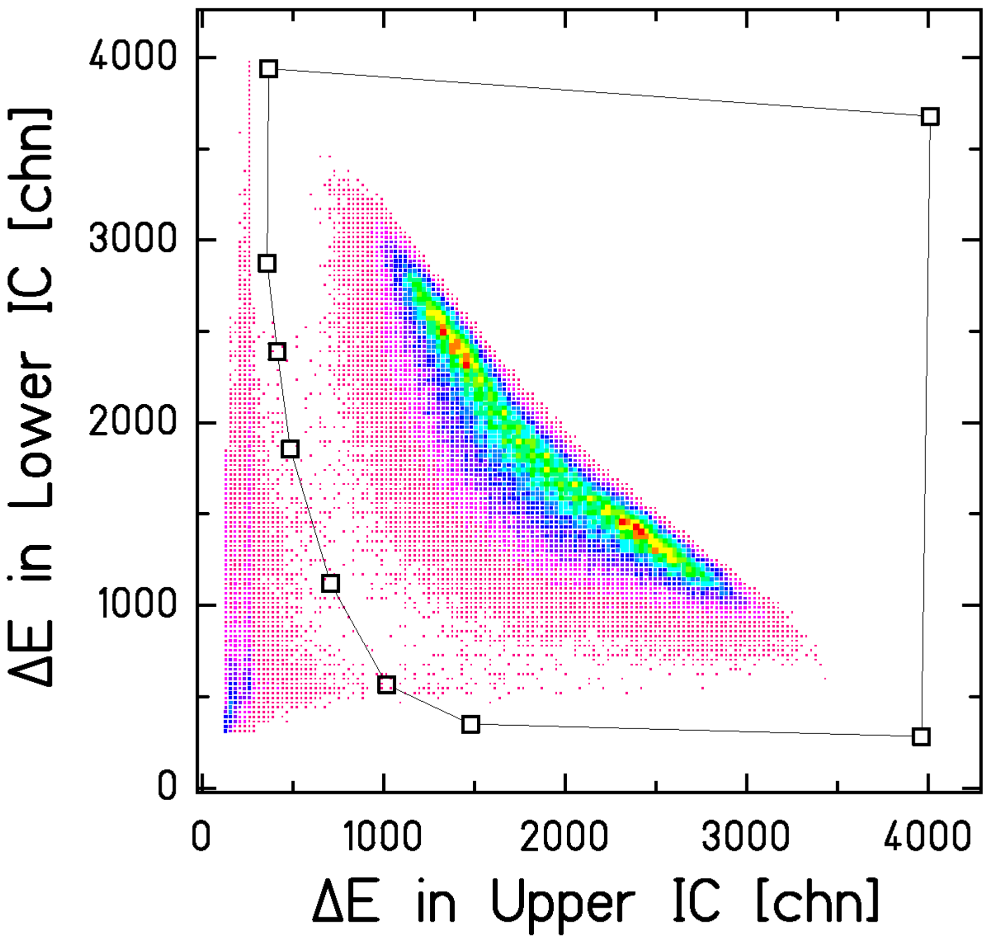




Dipole, RICH and LAND:
Atomic number, mass and neutrons measured



Atomic number of fissioning system



^{238}U (1 A GeV) + ^{208}Pb

From ΔE_1 and ΔE_2 $\rightarrow$
Z_1 and Z_2 are determined.

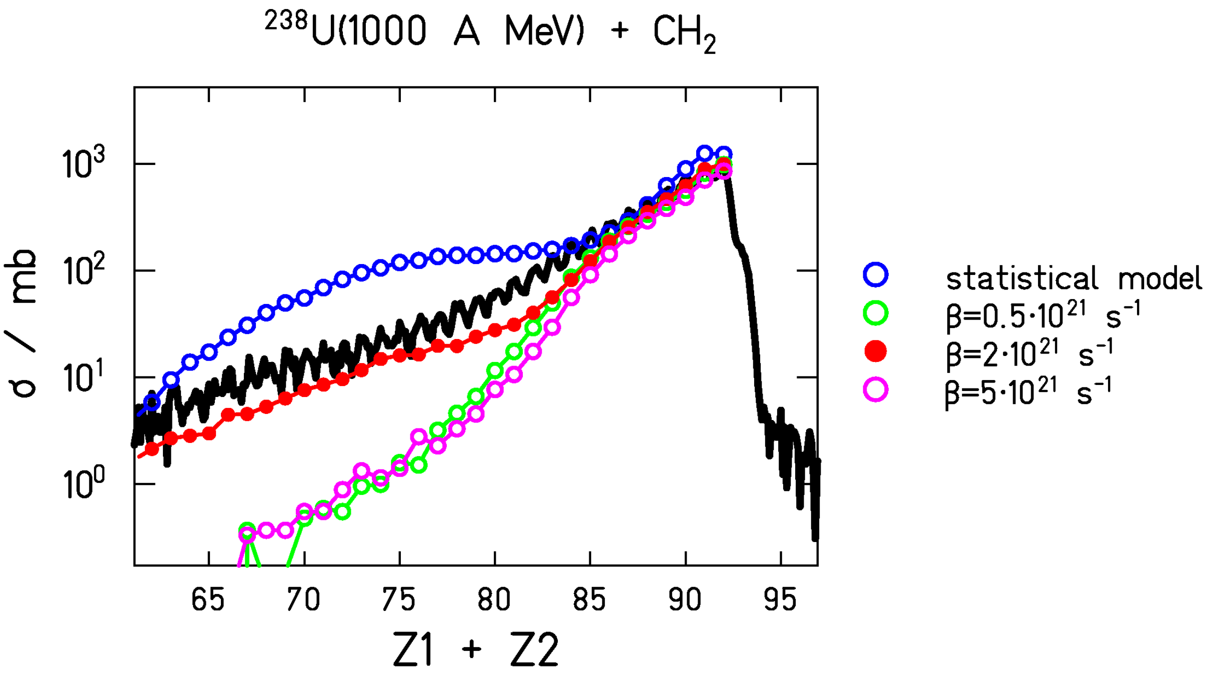
Evaporation of protons suppressed $\rightarrow$
Z_1+Z_2 gives atomic number of fissioning system

B. Jurado, PhD thesis, in preparation

Fission of 1 A GeV ^{238}U induced in $(CH_2)_n$

Which are the nuclei that fission?

$Z_1 + Z_2$ gives Z of the fissioning nucleus.

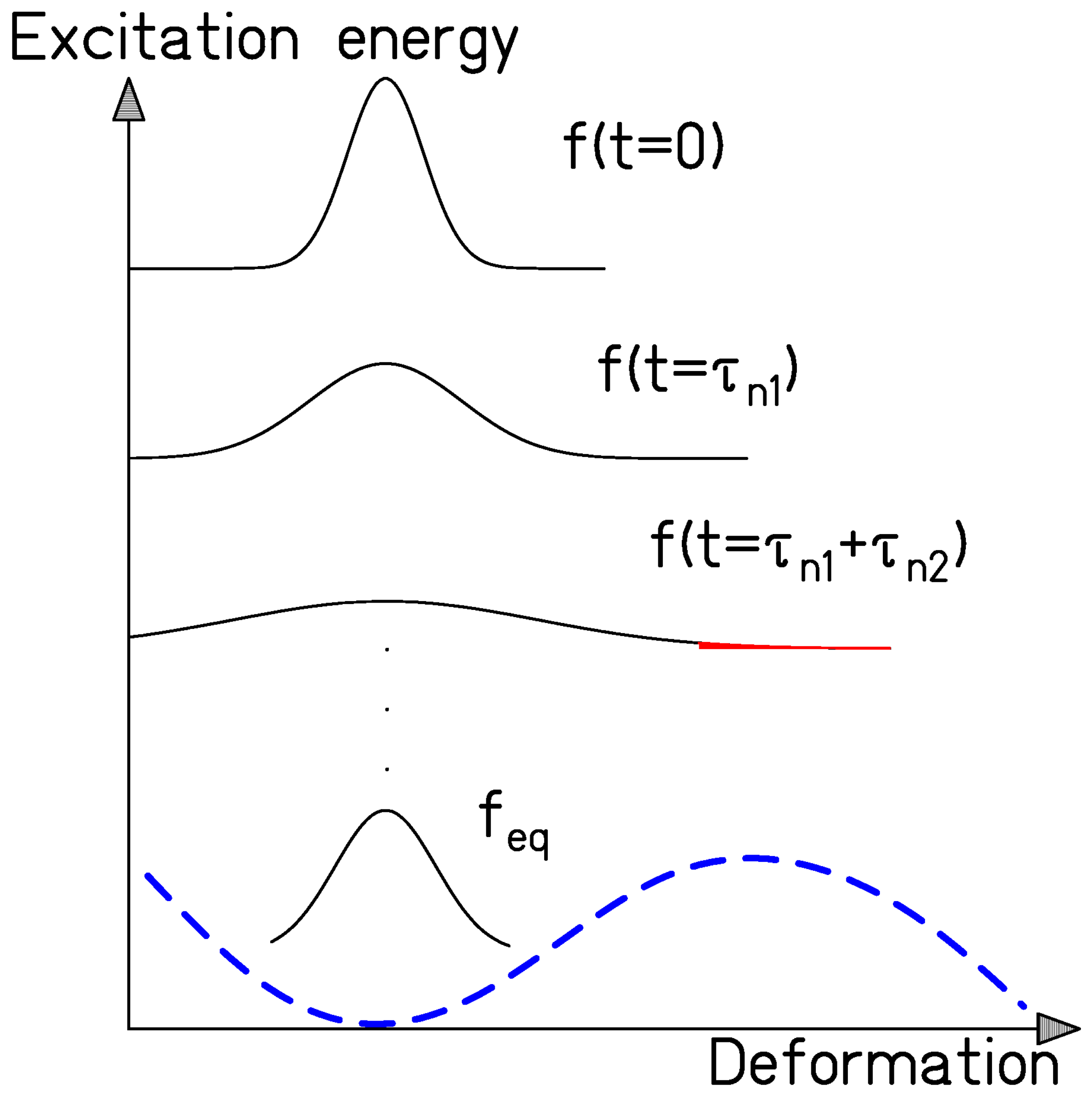


Many elements contribute to the fission-fragment distribution. There fission properties can only be studied by secondary beams.

Nuclear dissipation is a key parameter.

B. Jurado, PhD thesis, in preparation

Hindrance of fission due to dissipation

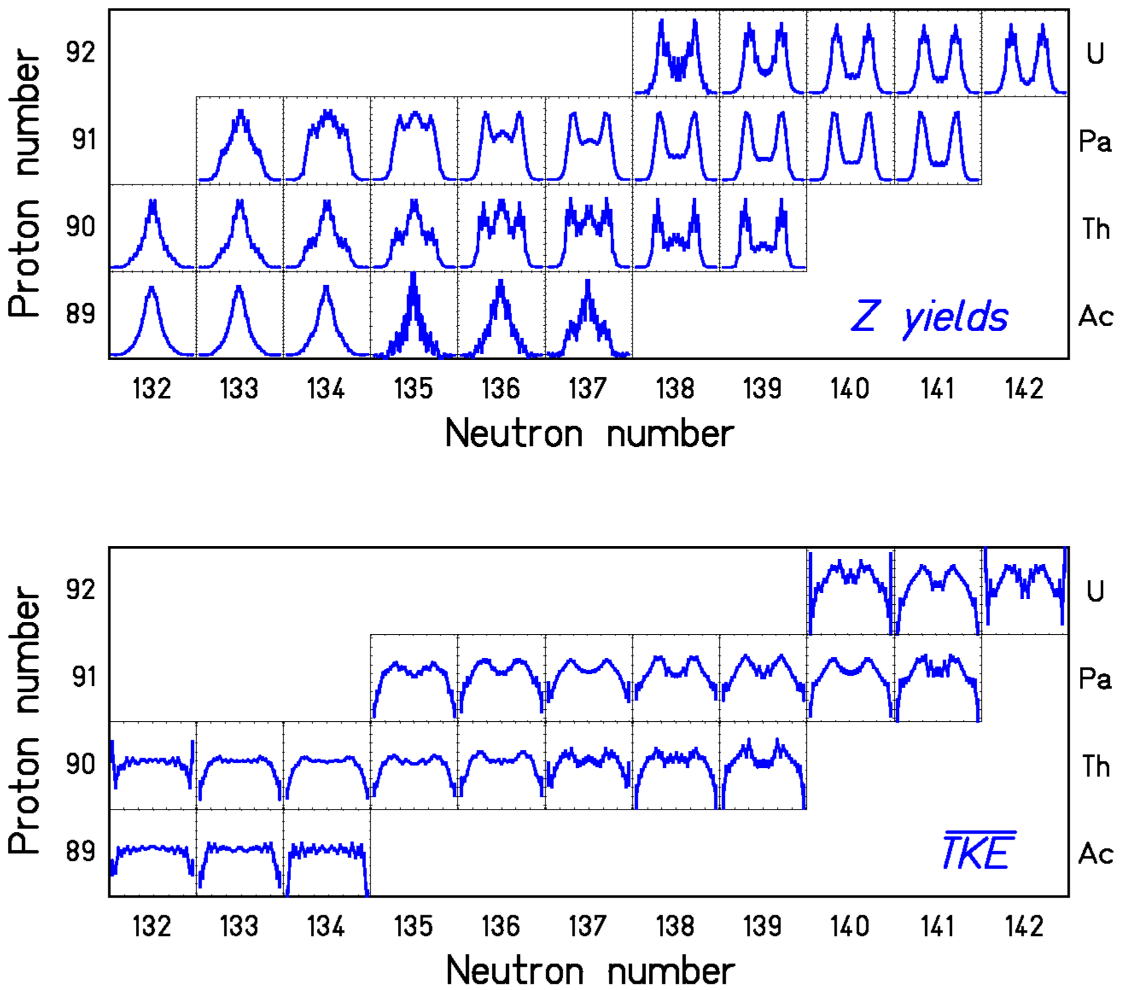


Time evolution of the deformation distribution during the deexcitation cascade.

- Fission sets in with a time delay, while evaporation starts immediately.
- Fragmentation provides unique conditions: high excitation energies with low angular momenta and small shape distortions

Mapping the fission properties of neutron-deficient actinides with secondary beams.

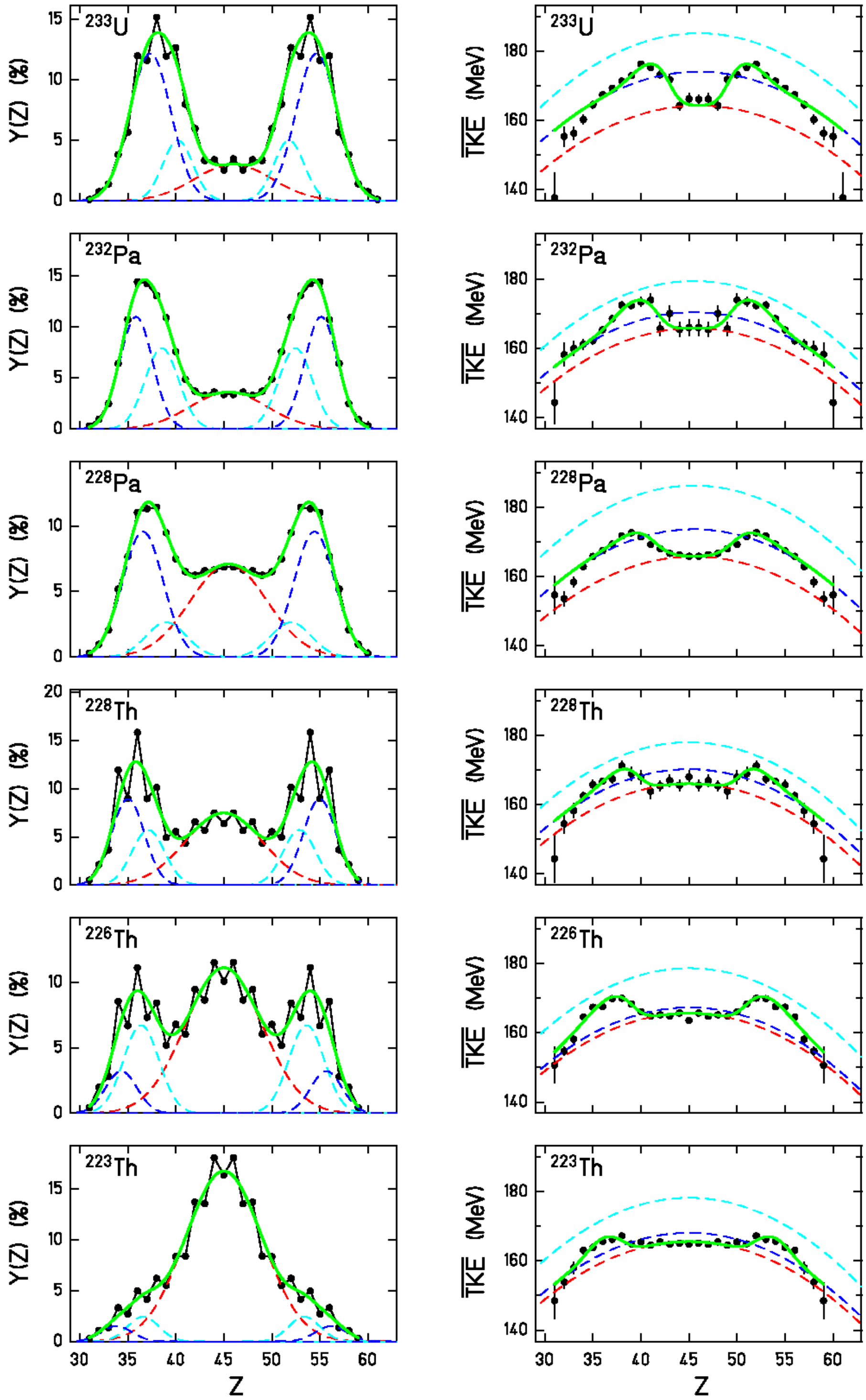
Map of Z yields and $\overline{TKE}$



70 systems measured, 28 (21) shown
Systematic coverage of the transitional region

Adapted fission channels

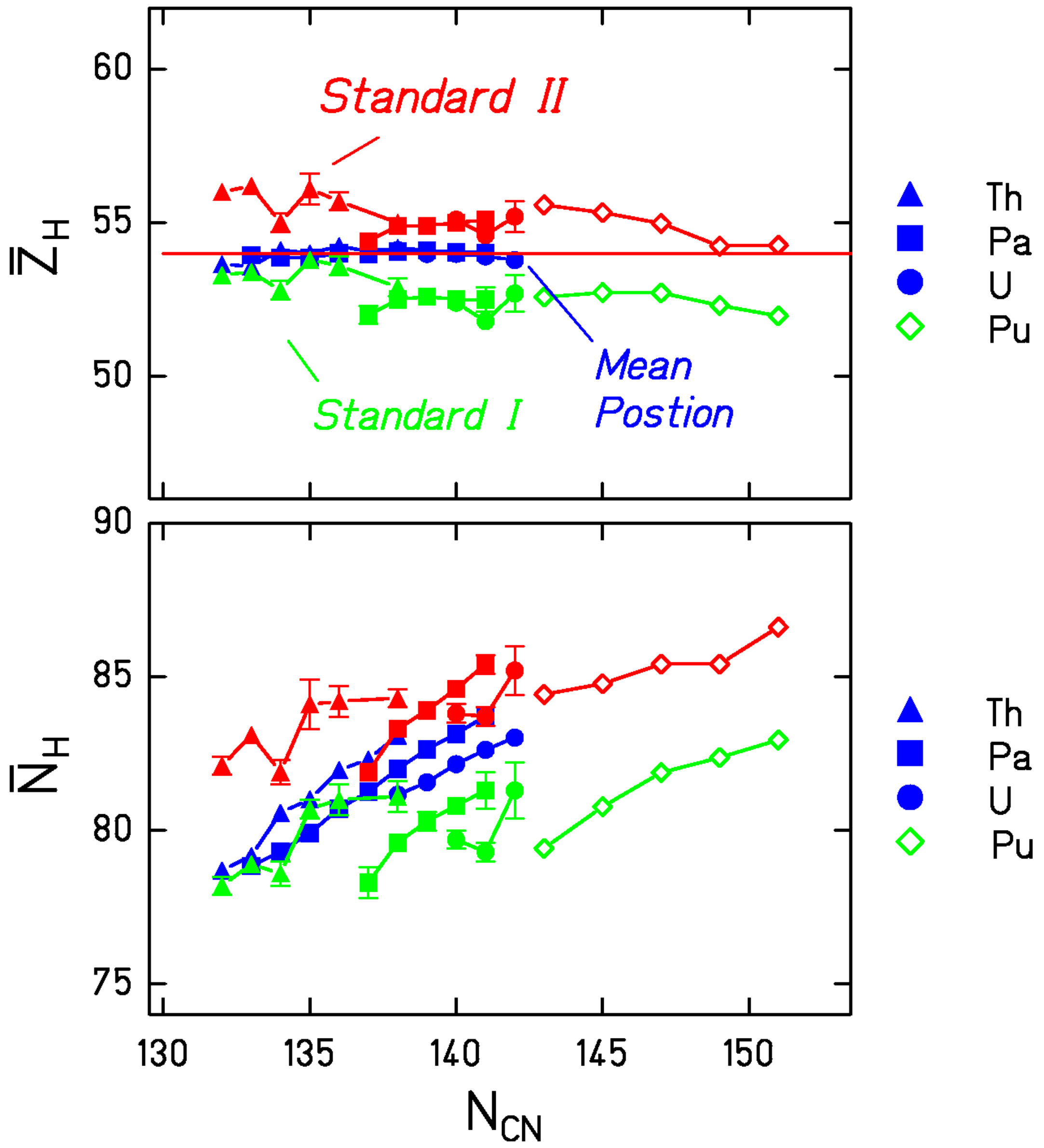
Yields $\overline{TKE}$



Simultaneous fit to Z yields and TKE

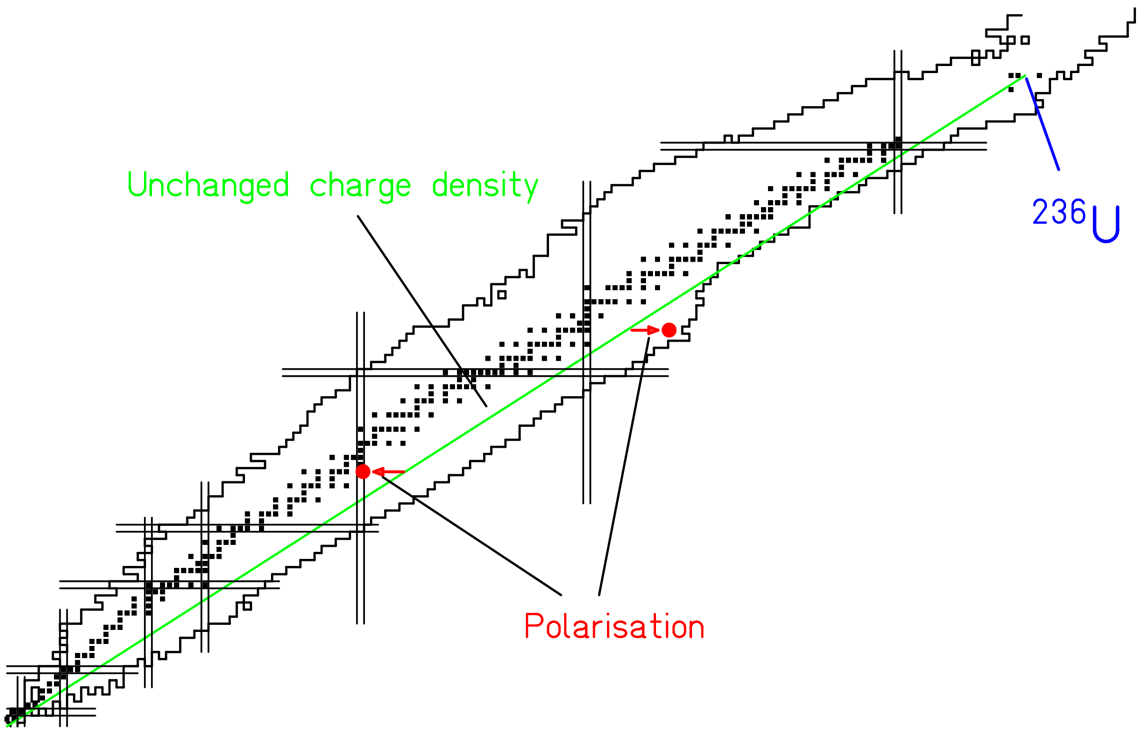
Godd reproduction of data with 3 channels

Positions of the fission channels



Expectation: Shell effects in neutron number are decisive.
Finding: Positions are stable in Z and move in N.

Polarisation in Fission

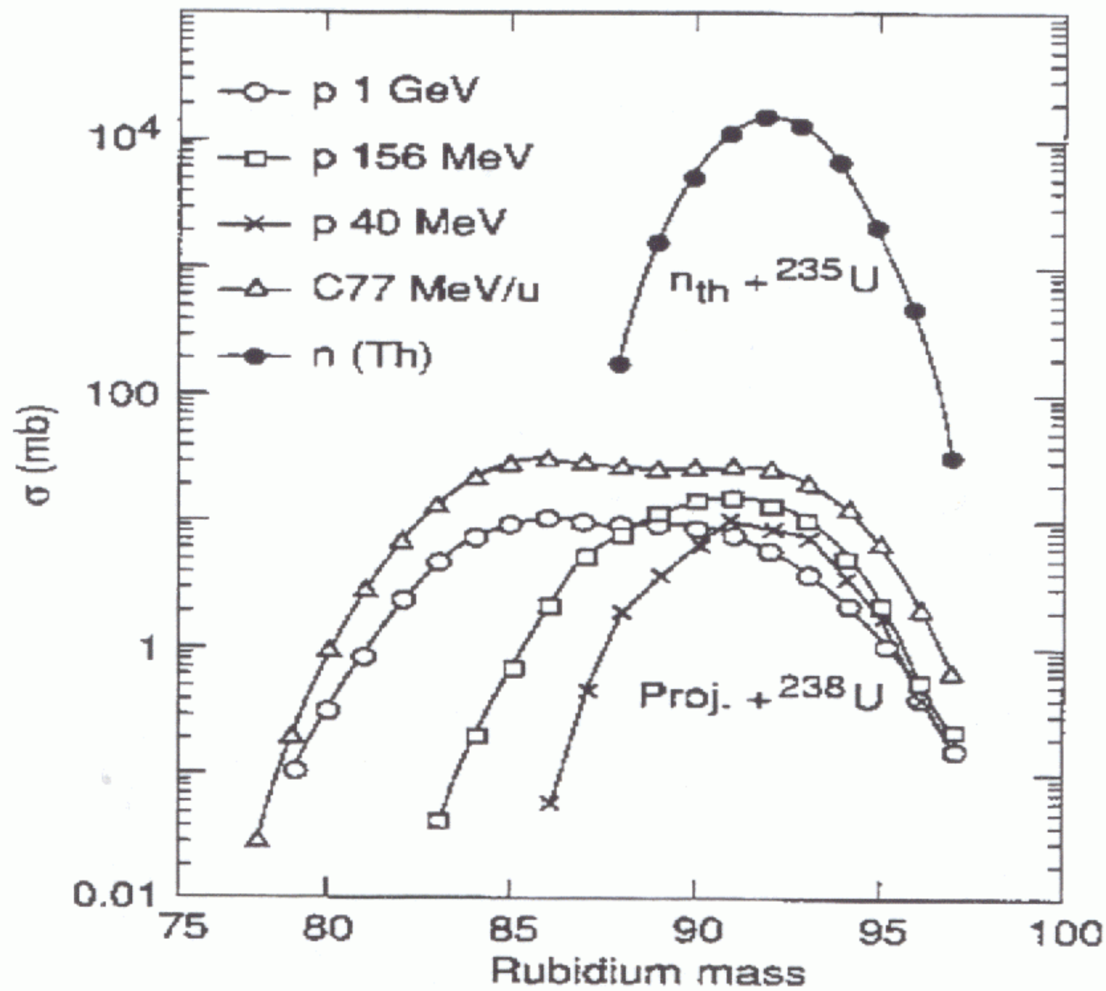


Charge polarisation (variation of the N/Z ratio of the fragments) is the only way to exceed the N/Z of the fissioning system.

Possible mechanisms for charge polarisation:

- Shell effects (e.g. ^{132}Sn)
  (Only at low excitation energies)
- Temperature fluctuations
  (but shift to neutron-deficient by evaporation)

Systematics of isotopic production of Rb



Production cross sections of neutron-rich fragments are almost independent of the projectile.

From H. L. Ravn et al. Nucl. Instr. Meth. B88 (1994) 441

Fission of relativistic 238U for production of neutron-rich isotopes

Successfully applied:

"DISCOVERY AND CROSS-SECTION MEASUREMENT OF 58 NEW FISSION PRODUCTS IN PROJECTILE-FISSION OF 750 A MeV 238U"
B. Bernas, C. Engelmann, P. Armbruster, S. Czajkowski, F. Ameil, C. Boeckstiegel, Ph. Dessagne, C. Donzaud, H. Geissel, A. Heinz, Z Janas, C. Kozhuharov, Ch. Miehe, G. Muenzenberg, M. Pfuetzner, W. Schwab, C. Stephan, K. Suemmerer, L. Tassan-Got, B. Voss
Phys. Lett. B 415 (1997) 111-116

"PRODUCTION AND IDENTIFICATION OF HEAVY Ni ISOTOPES: EVIDENCE FOR THE DOUBLY MAGIC NUCLEUS 78Ni"
Ch. Engelmann, F. Ameil, P. Armbruster, M. Bernas, S. Czajkowski, Ph. Dessagne, C. Donzaud, H. Geissel, A. Heinz, Z. Janas, C. Koshuharov, Ch. Miehe, G. Muenzenberg, M. Pfuetzner, C. Roehl, W. Schwab, C. Stephan, K. Suemmerer, L. Tassan-Got, B. Voss
Z. Phys. A 352 (1995) 351-352

Low-energy fission → Yield concentrated on a few rather neutron-rich fission fragments.

High-energy fission → Broader distributions in mass and N/Z; better conditions for extremely neutron-rich?

Modelling the Width in A and N/Z of Fission-Product Isotopic Distributions

Approximated parabolic potential

$$U(\eta) = C_\eta \cdot (\eta - \eta_o)^2$$

Statistical population:

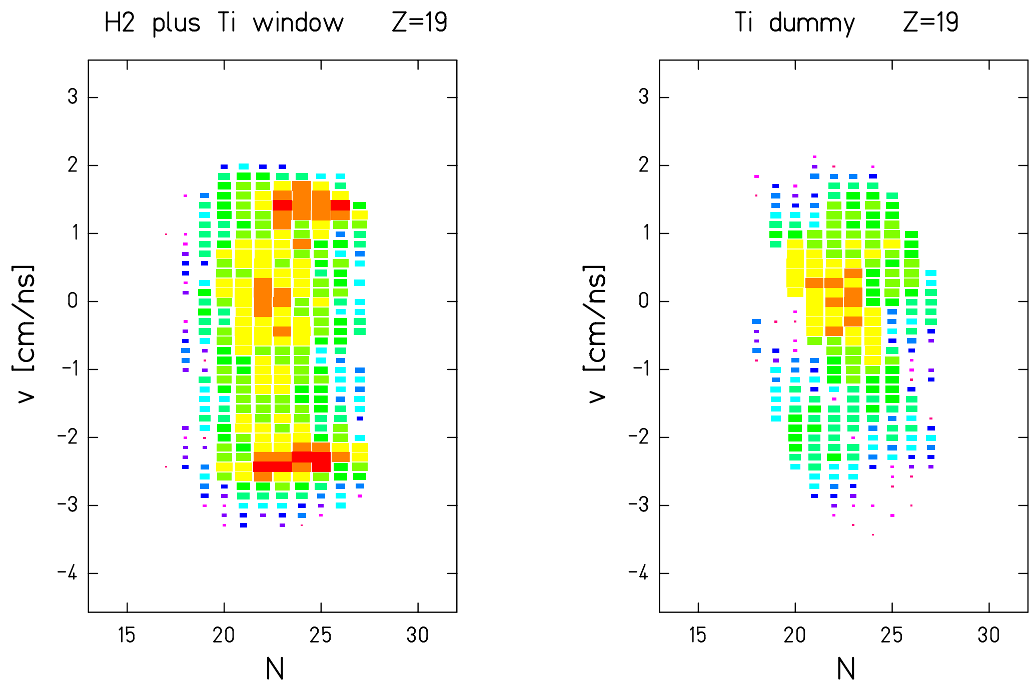
$$Y(\eta) \propto \exp\left\{2\sqrt{a(U_0 - U(\eta))}\right\} \qquad \rightarrow$$

$$Y(\eta) \propto \exp\left\{-\frac{(\eta - \eta_0)^2}{2\sigma_\eta^2}\right\} \qquad \textbf{with}$$

$$2\sigma_\eta^2 = \frac{T}{C_\eta}$$

U **= potential energy,**
η **= either A (mass split) or N/Z (polarisation),**
C_η **= stiffness of the potential,**
T **= nuclear temperature.**

Kinematic Properties of Potassium Produced from ^{238}U in Different Targets



Projectile: ^{238}U, 1 A GeV
Target left: hydrogen (+ titanium window)
right: titanium

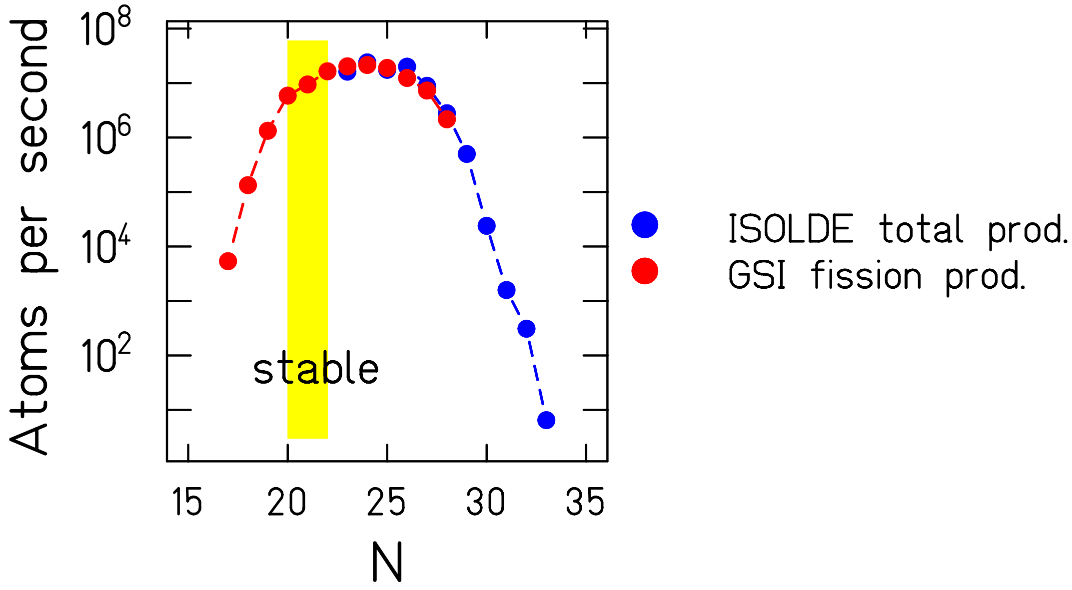
Velocity distributions of potassium isotopes

→ Production in hydrogen target from very asymmetric fission.

→ Production in titanium target from projectile fragmentation.

Data from M. V. Ricciardi, GSI, thesis in preparation.

Production of Potassium in p + ^{238}U



Isotopic yields from 600 MeV protons on ^{238}U (ISOLDE) and
fission-product yields from 1 A GeV ^{238}U + hydrogen (GSI)

No absolute cross sections from ISOLDE yields.

The distributions fit together:
ISOLDE yields of light elements from fission!

Data from
H.-J. Kluge, ISOLDE user's guide, CERN 86-05 (1986)
and
M. V. Ricciardi, GSI, thesis in preparation

Conclusion

Design of **ADS**
and next-generation **RIB facilities**
requires detailed understanding of fission
of a large variety of nuclei
over a large range of excitation energies.

Unique conditions for systematic investigations of fission by use of inverse kinematics and powerful spectrometer.

Relativistic ^{238}U beam allows
production of secondary beams and/or
full identification of fission products.

Data
on low-energy fission from e-m excitation and
on high-energy fission from nuclear excitations
are available.

Progress in understanding
dissipation, shell and temperature effects in fission.

Future plans to use even more elaborate experimental equipment.