Precision Studies of Relativistic Nuclear Collisions

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For the CHARMS collaboration

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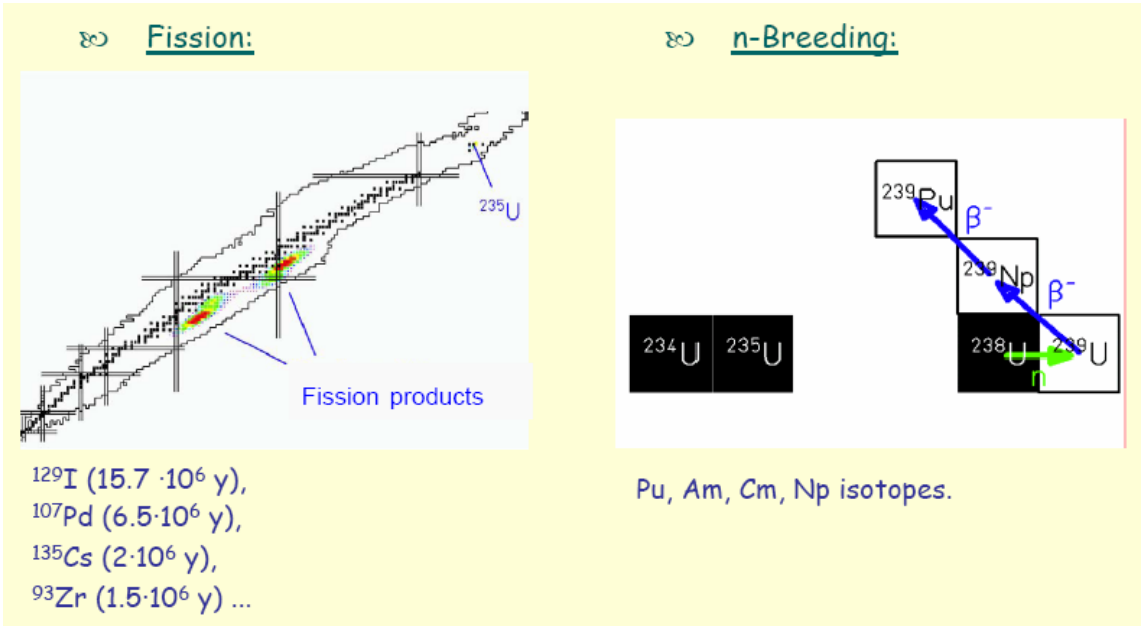
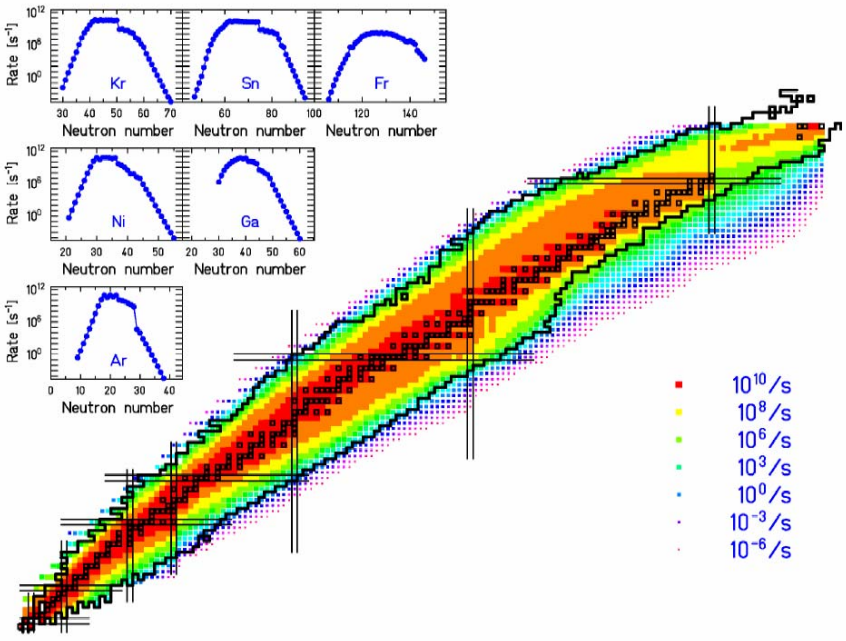
- Motivation
- Experimental approach
- Results
  - Nuclear technology
  - Nuclear structure
  - Dissipation
  - Excitation of the nucleon
  - Equation of state
- Summary

Motivation: Production of heavy residues in relativistic nuclear collisions

- **Design of ADS for transmutation of radioactive waste**

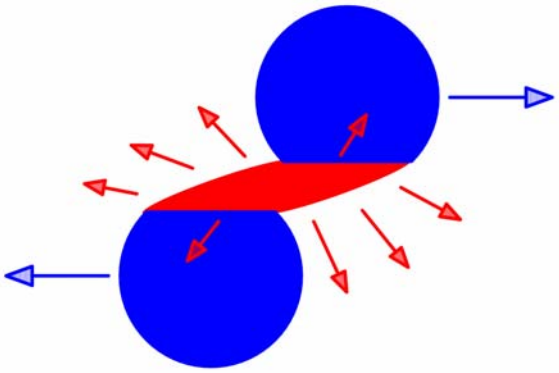


- **Production of rare isotopes (FAIR, RIA)**



- **Spallation in interstellar medium ...**

- **Physics of semi-peripheral nuclear collisions and spallation reactions**



Spectators:

"Swiss-cheese like" Fermionic system

- **Punching holes in Fermi sphere**
- **Thermalization**
- **Expansion – break-up – freeze-out**
  - **Nörenberg et al., EPJ A9 (2000) 327**
- **Evaporation and fission**

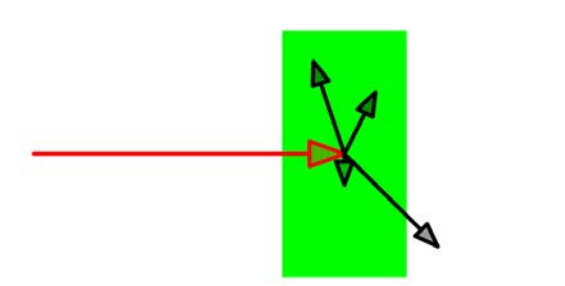
Participants:

Hot and dense nuclear matter (EoS)

- **Incompressibility (statics)**
- **Momentum-dependent mean field (dynamics)**

The Experimental Approach: Inverse Kinematics

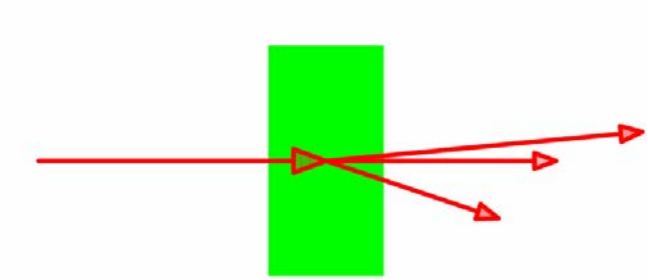
Conventional experiments detect target-like reaction products by gamma decay



Suffer from:

- Stopping of the products in the target
- Radioactive decay before detection

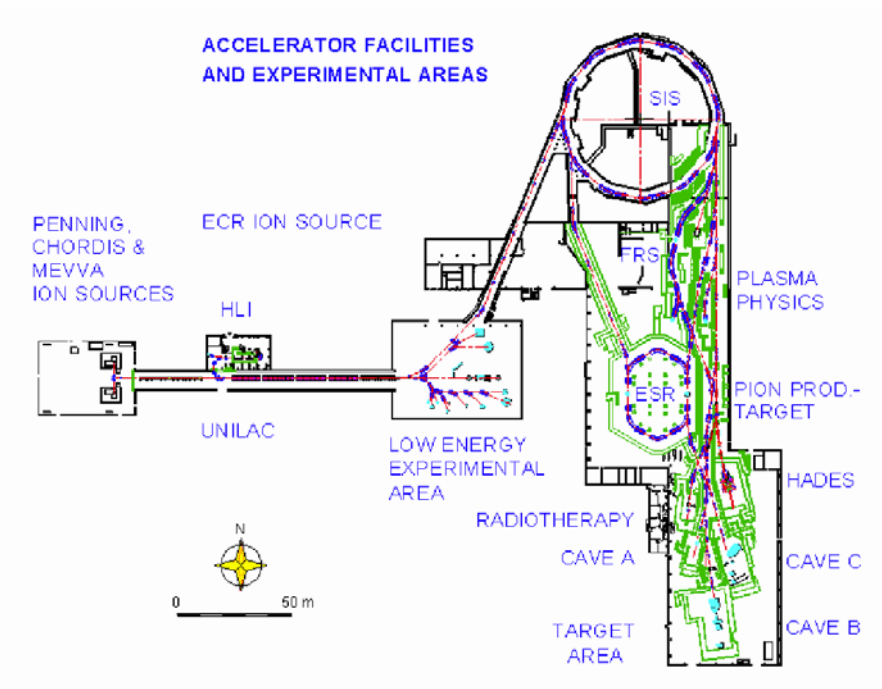
GSI-experiments investigate projectile-like reaction products in-flight



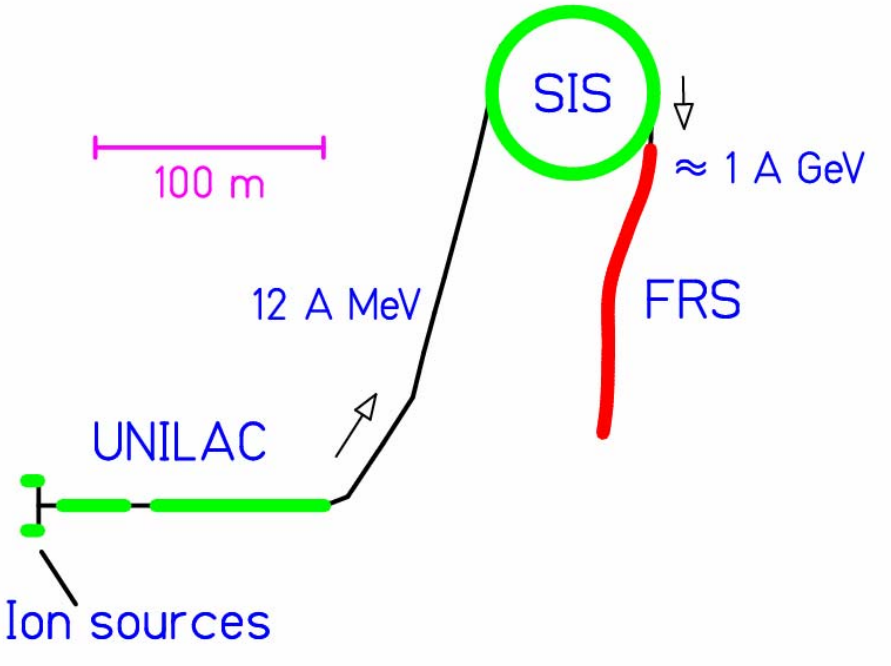
Requires:

- A powerful heavy-ion accelerator
- Adapted high-resolution in-flight detection devices

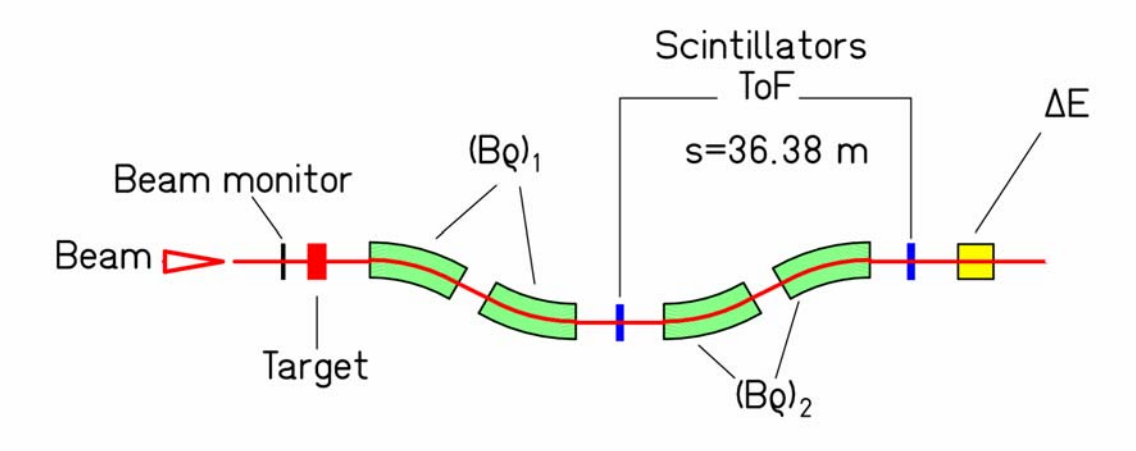
The GSI Facility



Installations used for the experiments:



The Fragment Separator (FRS)



- A/Z identified by $(B\rho)_2$ and ToF in FRS

  $B\rho = p/q \sim A \cdot \gamma \cdot v/Z$

- Z identified by ΔE in ionization chamber

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

  → Z and A are exactly known.

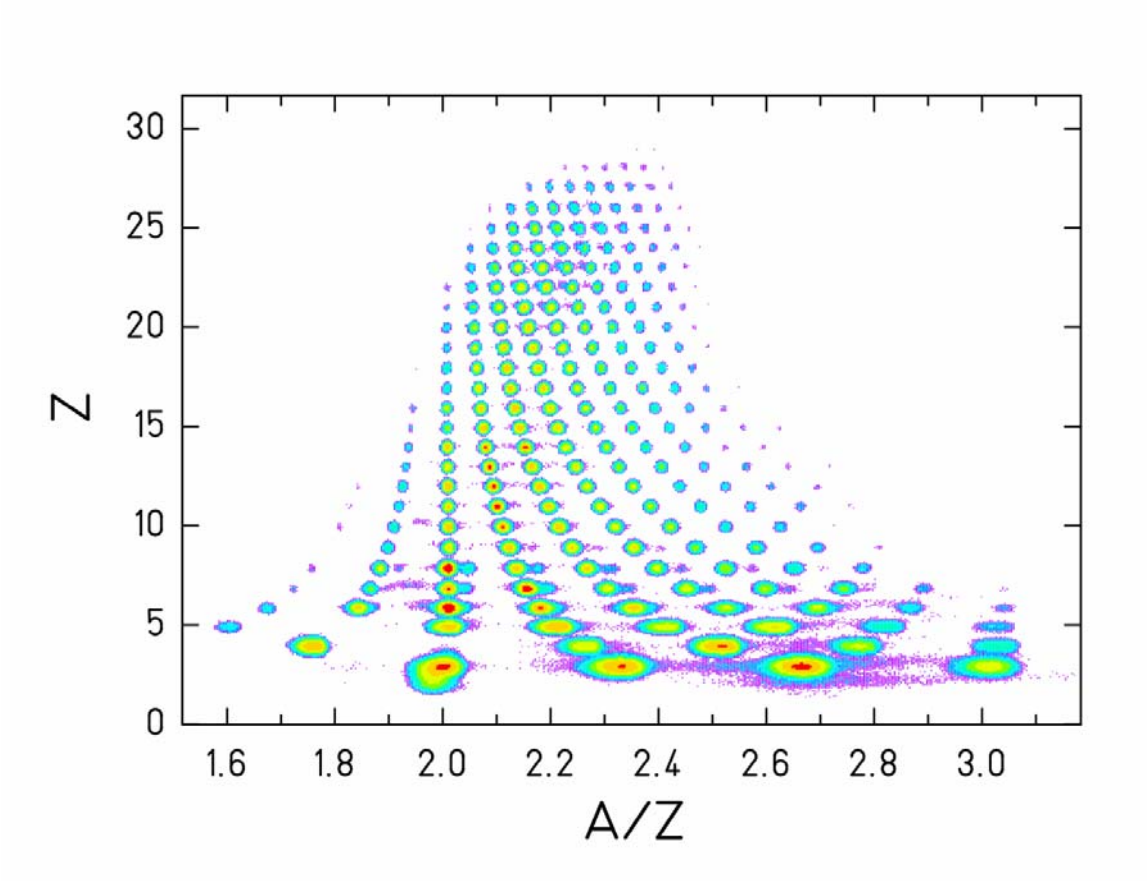
- Velocity precisely determined by $(B\rho)_1$

  $B\rho = p/q \sim A \cdot \gamma \cdot v/Z$

  → **Relative precision $5 \cdot 10^{-4}$**

Nuclide Identification Pattern

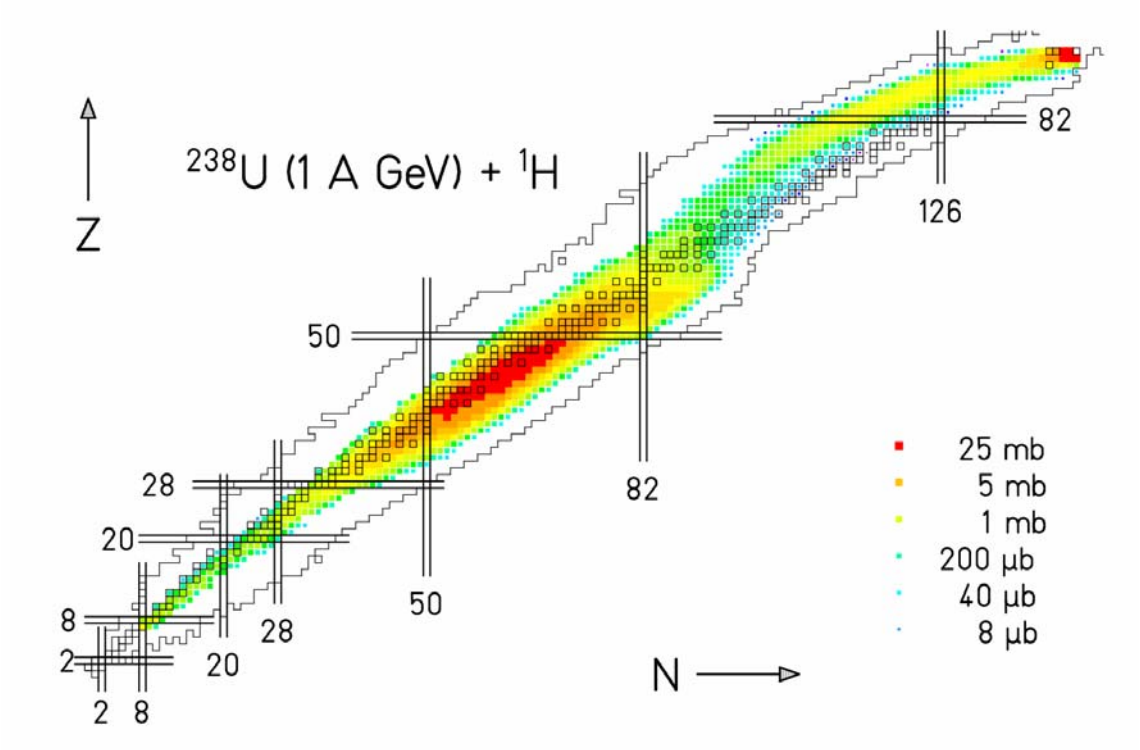
^{136}Xe + Pb, 1 A GeV



Complete separation in A and Z

D. Henzlova, PhD thesis

Nuclide distributions



Cross sections of 1368 nuclides determined.

P. Armbruster et al., Phys. Rev. Lett. 93 (2004) 212701
J. Taieb et al., Nucl. Phys. A 724 (2003) 413
M. Bernas et al., Nucl. Phys. A 725 (2003) 213
M. V. Ricciardi et al., in preparation

Systems investigated: (analyzed by)

^{238}U + ^{1,2}H,Ti,Pb (J. Taieb*, M. Bernas, M. V. Ricciardi*, E. Casarejos*, J. Pereira*, T. Enqvist)

^{208}Pb + ^{1,2}H, Ti (T. Enqvist, B. Fernandez*, A. Kelic, L.Audouin*)

^{197}Au + ^{1}H (F. Rejmund, J. Benlliure)

^{124,136}Xe + ^{1}H,^{208}Pb (P.Napolitani*, D.Henzlova*, M.Fernandez*)

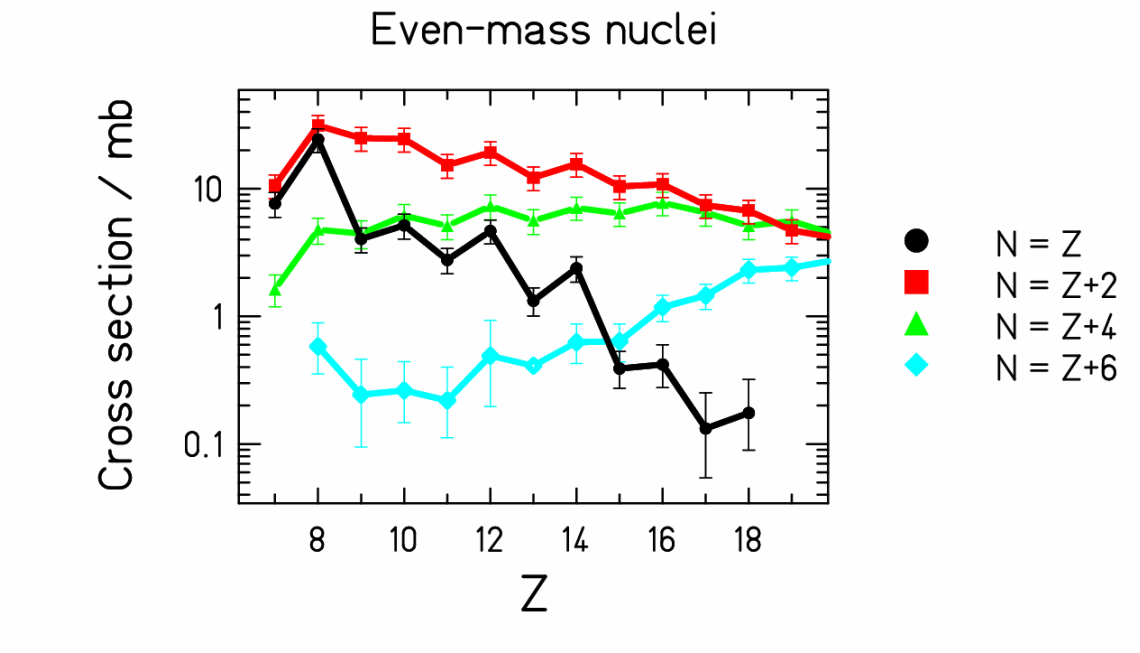
^{56}Fe + ^{1}H,Ti (C. Villagrasa*, P. Napolitani*)

^{197}Au + ^{197}Au (V. Henzl*)

Energies: 0.2 to 1.5 A GeV

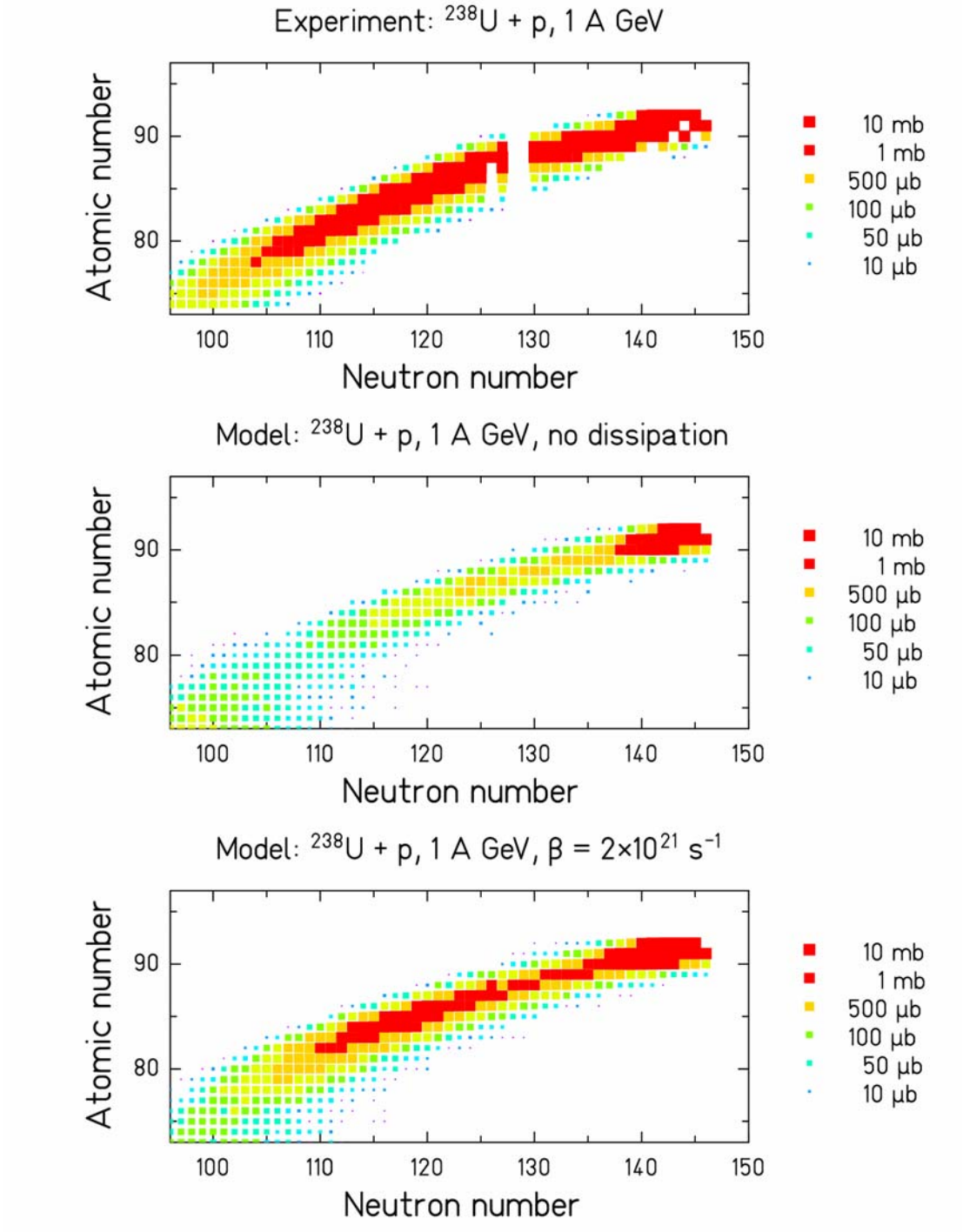
*PhD theses

Strongly enhanced production of even-even N=Z nuclei



Evidence for neutron-proton pairing / alpha clustering

Evidence for transient effects in fission

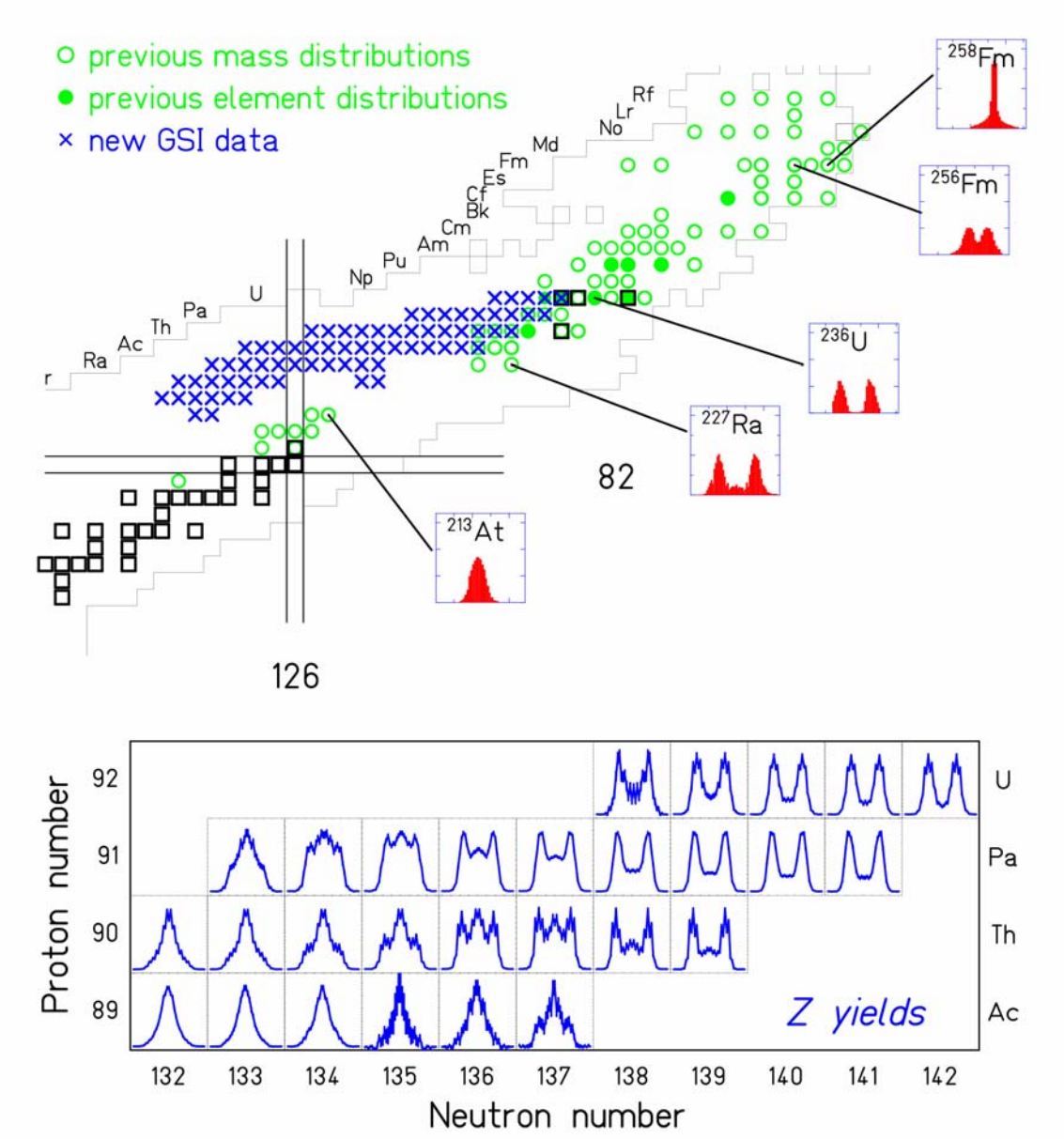


Motion from g.s. to saddle is critically damped.

J. Taieb et al., Nucl. Phys. A 724 (2003) 413

B. Jurado et al., Phys. Rev. Lett 93 (2004) 072501

Fission channels



- Z-distributions from e.m.-induced fission of 70 secondary beams (E* ~ 11 MeV).
- Transition from asymmetric to symmetric fission mapped.

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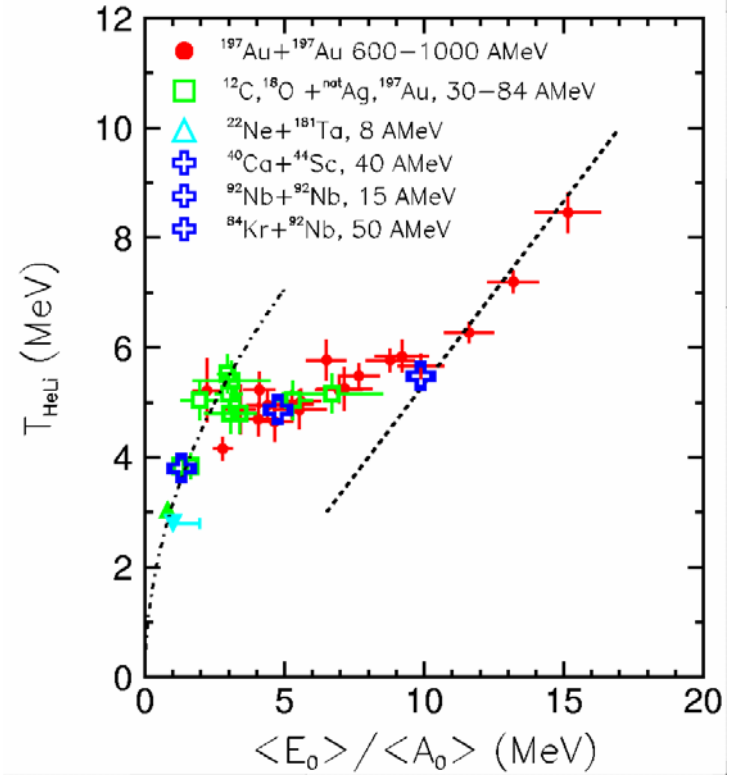
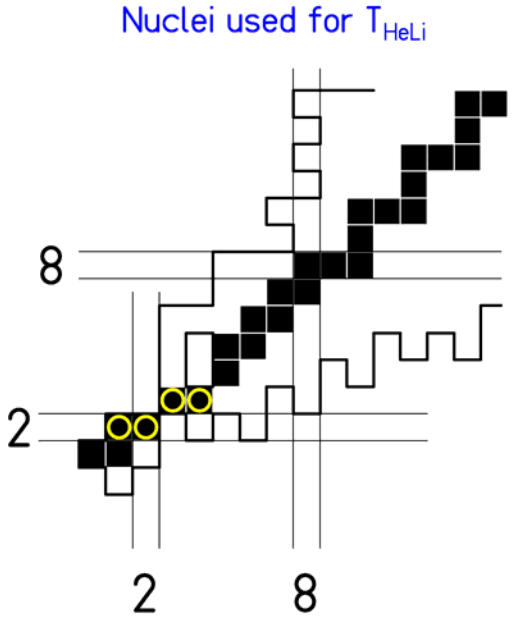
K.-H. Schmidt et al., Nucl. Phys. A 665 (2000) 221
F. Rejmund et al, Nucl. Phys. A 678 (2000) 215

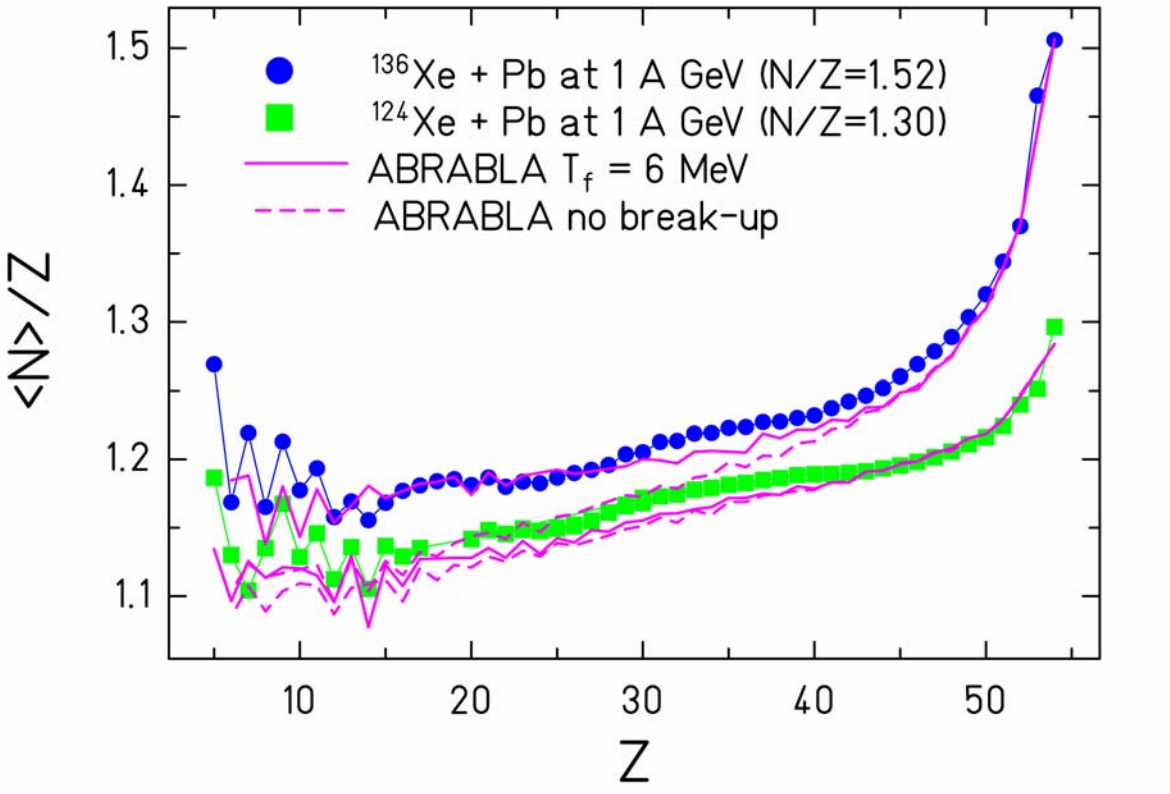
Caloric curve from ALADIN
(An indication for the liquid-gas phase transition)



The 4 nuclides, entering into the analysis:



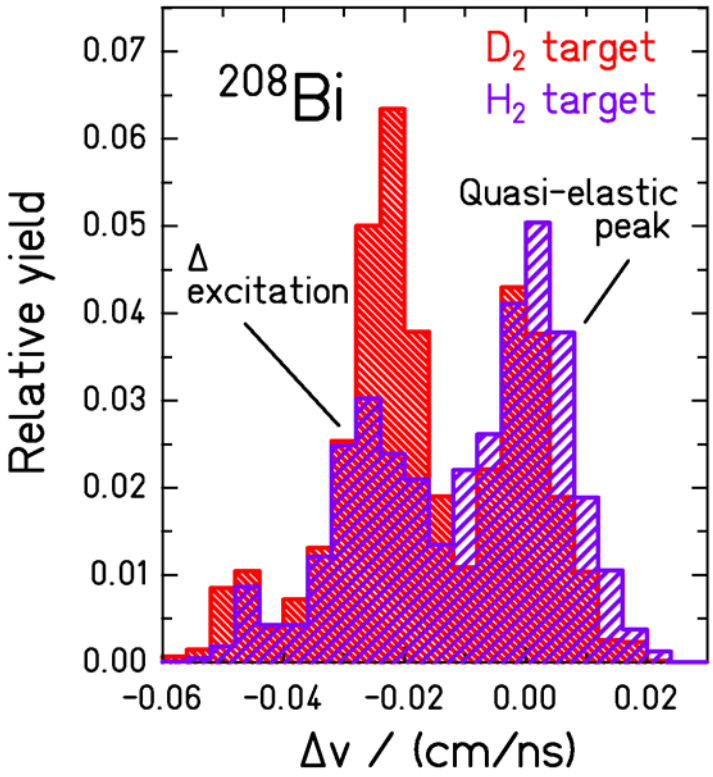
FRS Data: The Isospin Thermometer



- Memory on N/Z of projectile is preserved for all fragments.
- The data are reproduced with a three-stage model: Abrasion – Break-up – Evaporation.
- Indication for constant freeze-out temperature of ≈ 6 MeV.

M. V. Ricciardi, D. Henzlova, PhD theses
K.-H. Schmidt et al., Nucl. Phys. A 710 (2002) 157

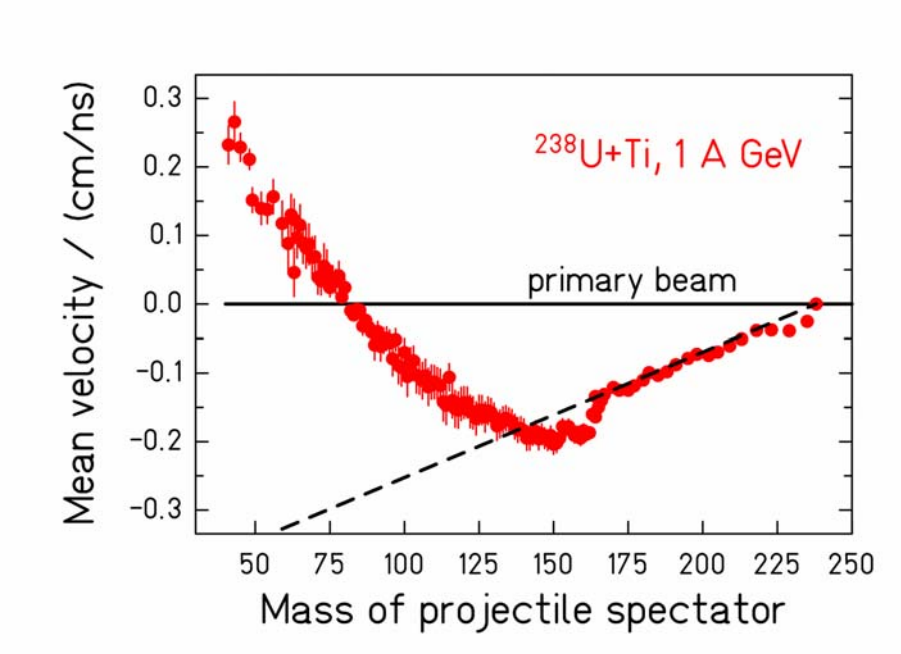
Nuclear Charge-Exchange Reaction

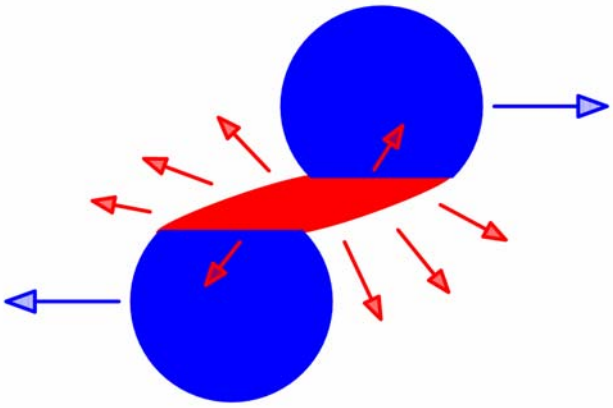


- Charge-exchange reactions: ^{1}H(^{208}Pb,^{208}Bi)x, ^{2}H(^{208}Pb, ^{208}Bi)x at 1 A GeV
- Quasielastic scattering and excitation of the Δ(1232) resonance
- Excitation of the nucleon in the nuclear medium

A.Kelic, Phys. Rev. C 70 (2004) 064608

Participant's blast on the spectators

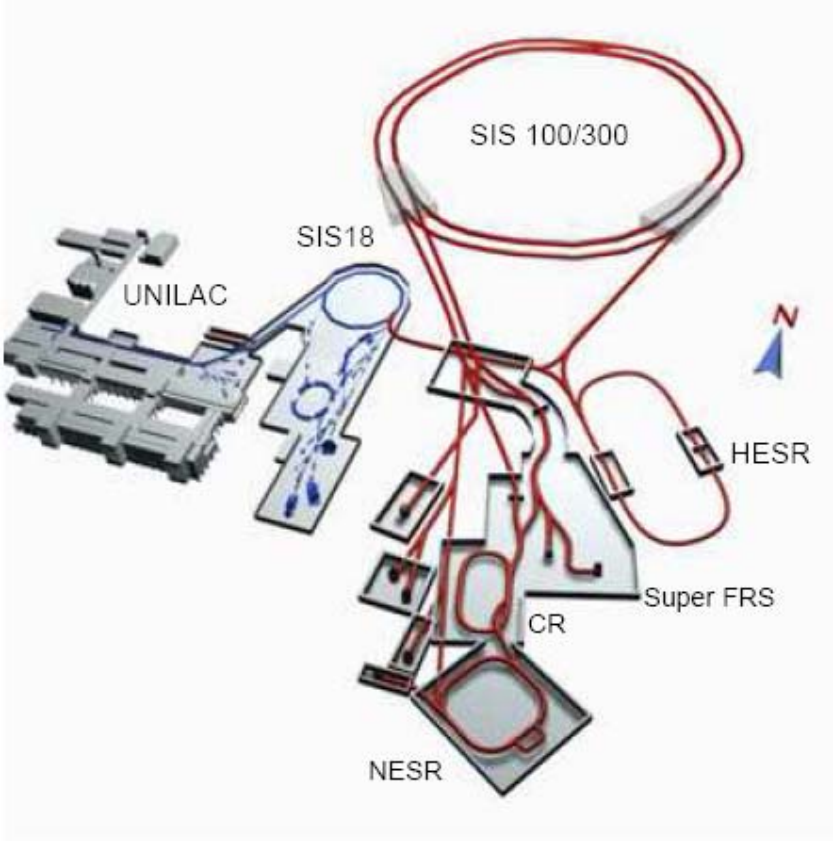




- Unexpected acceleration in violent collisions.
- Valuable information on the EOS of nuclear matter.
- Information on momentum-dependent mean field.

M.V. Ricciardi, V. Henzl, PhD theses
M. V. Ricciardi et al., PRL 90 (2003) 212302
L. Shi, P. Danielewicz, R. Lacey, PRC 64 (2001) 034601

The FAIR Project



Improved experimental possibilities for nuclear-reaction experiments by

- Higher beam intensities
- Higher beam energies
- New spectrometers and rings

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Summary

- **In-flight investigations** of projectile-like reaction products at the GSI heavy-ion facility.
- Mapping of nuclide **production cross sections**.
- Relevance for nuclear technology and astrophysics
- Yields reveal **neutron-proton pairing.**
- Fission dynamics **critically damped**.
- Mapping of the **fission channels**.
- Indications for a **break-up phase** from *N*/*Z* ratios.
- **Excitation of the nucleon** in the nuclear medium.
- **Acceleration** of projectile fragments (**EoS**).
- ... and many more observations
  (see also http://www-w2k.gsi.de/charms)

CHARMS Collaboration

(Collaboration for high-accuracy measurements of nuclear reactions with the FRS)

P. Armbruster, L. Audouin, C.-O. Bacri, J. Benlliure,
M. Bernas, B. Berthier, A. Botvina, A. Boudard,
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B. Jurado, A. Kelić, A. Krasa, A. Kugler, T. Kurtukian,
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California Institute of Technology, Pasadena, USA