High-resolution experiments on projectile fragments

a new approach to the properties of hot and dense nuclear matter

Karl-Heinz Schmidt, GSI

- **Motivation**
  - Important properties of nuclear matter
- **Basic ideas**
  - Similarities to a real gas
- **Standard tools used at GSI**
  - FOPI, KAOS, ALADIN …
- **Fragment separator**
  - Resolution and acceptance
- **Experimental results – general view**
  - Velocity distributions
  - Nuclide distributions
- **Experimental results – specific**
  - Δ excitation in the nuclear medium
  - Dissipation in fission
  - Response of the spectator to the participant blast
  - Evolution of "isospin" in nuclear reactions
  - Fine structure in residue yields from violent collisions
- **Conclusion**
  - Valuable information from high-resolution experiments – complements data from full-acceptance experiments

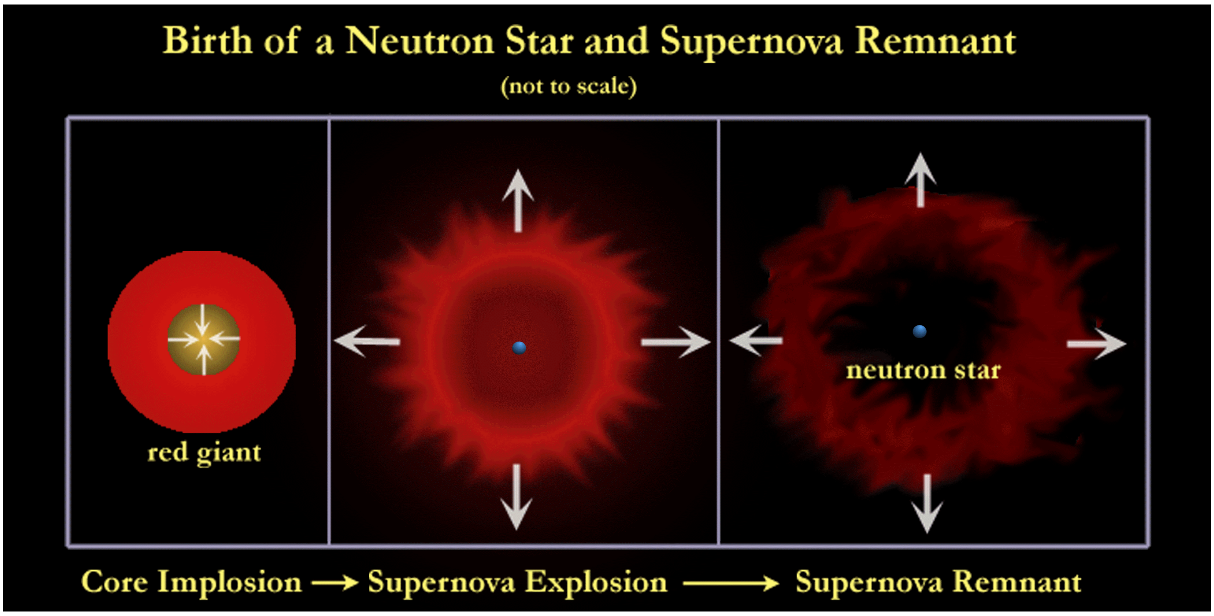
http://www-w2k.gsi.de/kschmidt/talks.htm

The motivation

Astrophysical interest

Properties of hot and dense nuclear matter are decisive for:

- Evolution of the early universe (**big bang**) at high density and temperature
- **Supernovae explosions**, a major scenario for the formation of elements beyond iron
- Formation and stability of **neutron stars** against collapsing into a black hole



Important properties of nuclear matter

The relevant **static properties** are expressed by:

- The **equation of state** of nuclear matter (the relation between temperature, pressure and volume)

Specific features addressed in this talk:

- o **Incompressibility**
- o **Phase transitions**
- o The influence of the neutron-to-proton ratio ("**isospin** degree of freedom")
- o The **excitation** of the nucleon

Important **dynamic properties**:

- The **viscosity** of nuclear matter
  - o Dissipation in collective motion
- The **momentum dependence** of the mean field
  - o Magnetic-equivalent nuclear forces

Basic ideas

Similarities of the Van-der-Waals potential between molecules and the Skyrme-like potential between nucleons (schematic):

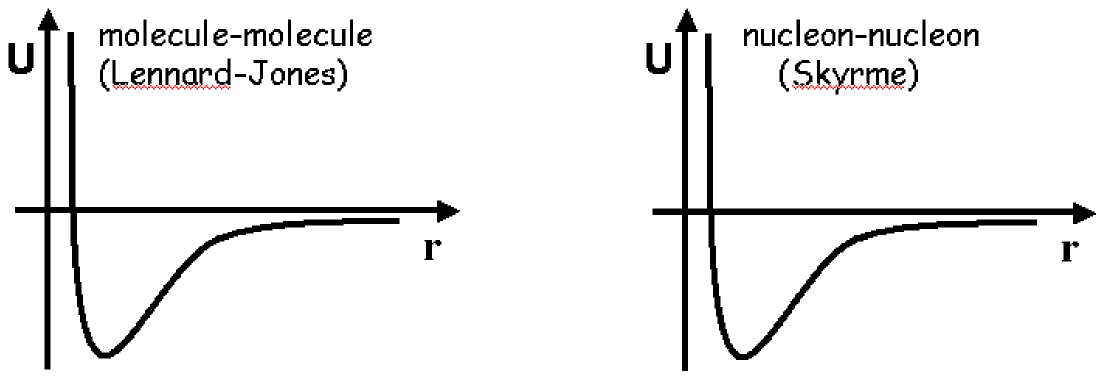


Figure: Van-der-Waals potential --- Nucleon-nucleon potential.
(units: eV and Å) (units: MeV and fm)

→ Similarities expected for the EOS

Specific features of the nucleus:

- Mesoscopic system
- Fermionic system
- Two-component system

Nuclear incompressibility

Incompressibility = stiffness of the nucleus against density variations.

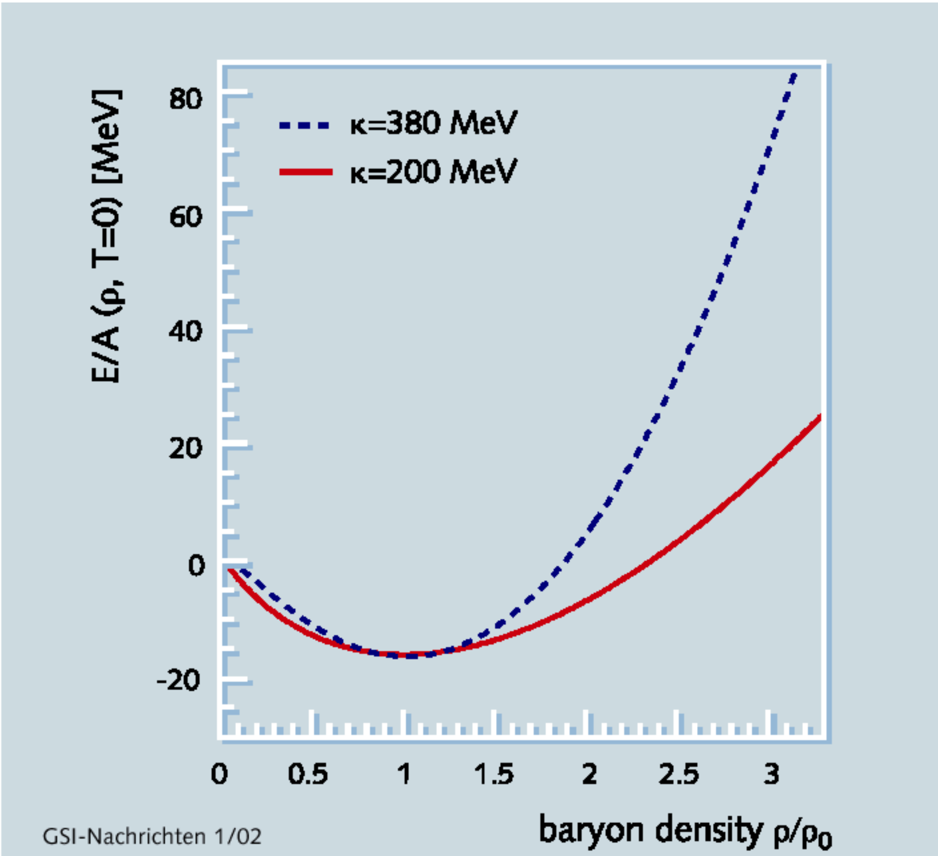


Figure: Binding energy of infinite nuclear matter as a function of density. Comparison of "soft" and "hard" equation of state.

Nuclear incompressibility is a key quantity of the nuclear equation of state.

The nuclear incompressibility depends on

- **temperature (→big bang, supernova) and**
- **"isospin" (→ neutron stars).**

Similarities to a Van-der-Waals gas

Liquid-gas phase transition

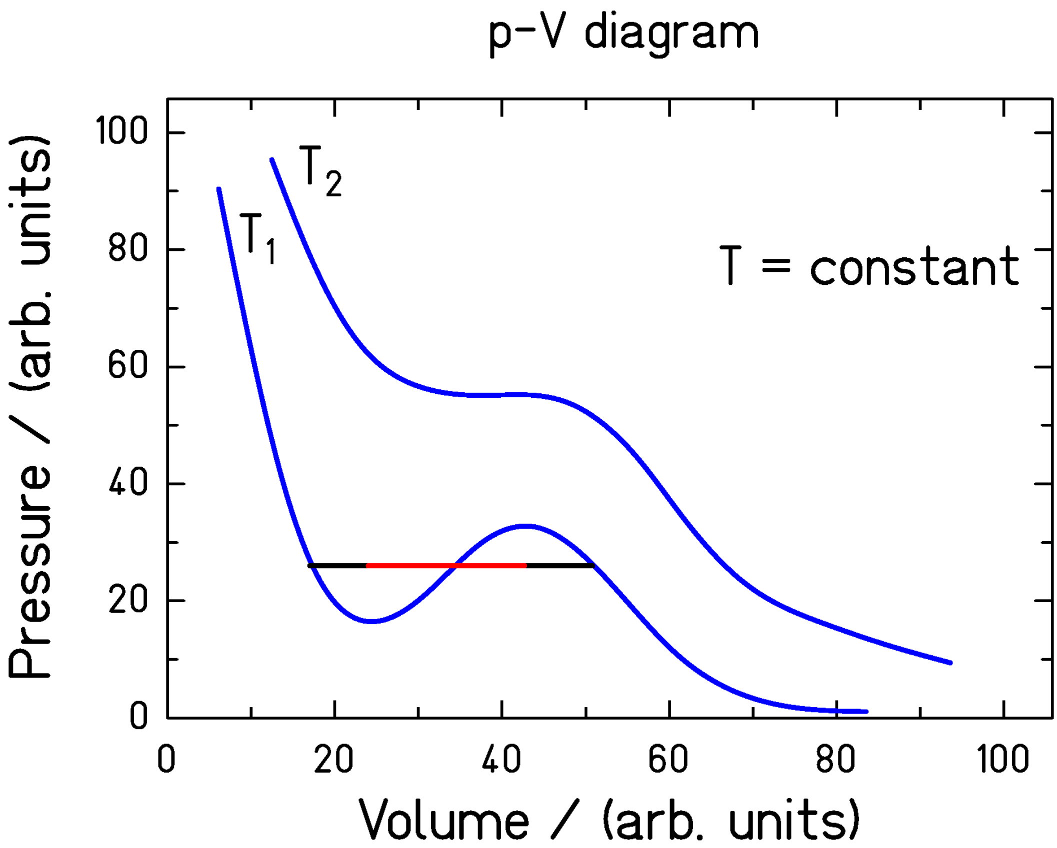


Figure: Schematic diagram - pressure versus volume - for a one-component system

Coexistence of liquid and gas phase in the spinodal region (red line) $\rightarrow$ first-order phase transition

EOS for a two-component system

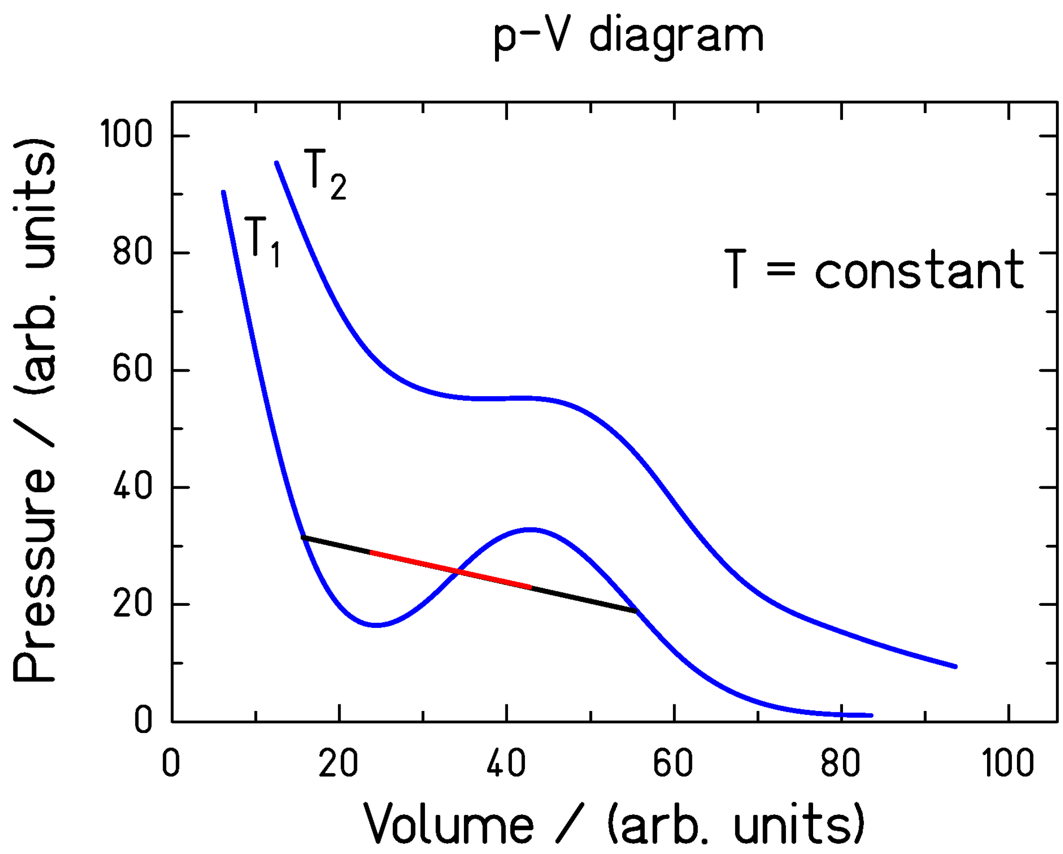


Figure: Schematic diagram - pressure versus volume - for a two-component system

Importance of the "isospin" degree of freedom:
(H. Müller, B. D. Serot, Phys. Rev. C 52 (1995) 2072)

- Two-component liquid (like alcohol-water)
  - o Symmetric matter (most stable ⇔ water)
  - o Neutron matter (less stable ⇔ alcohol)
- Second-order phase transition
  - o Composition of liquid and gas phases varies in the spinodal region
- Neutron distillation in spinodal decomposition ("boiling" → gas bobbles or "condensation" → fog) and evaporation

Standard experimental tools

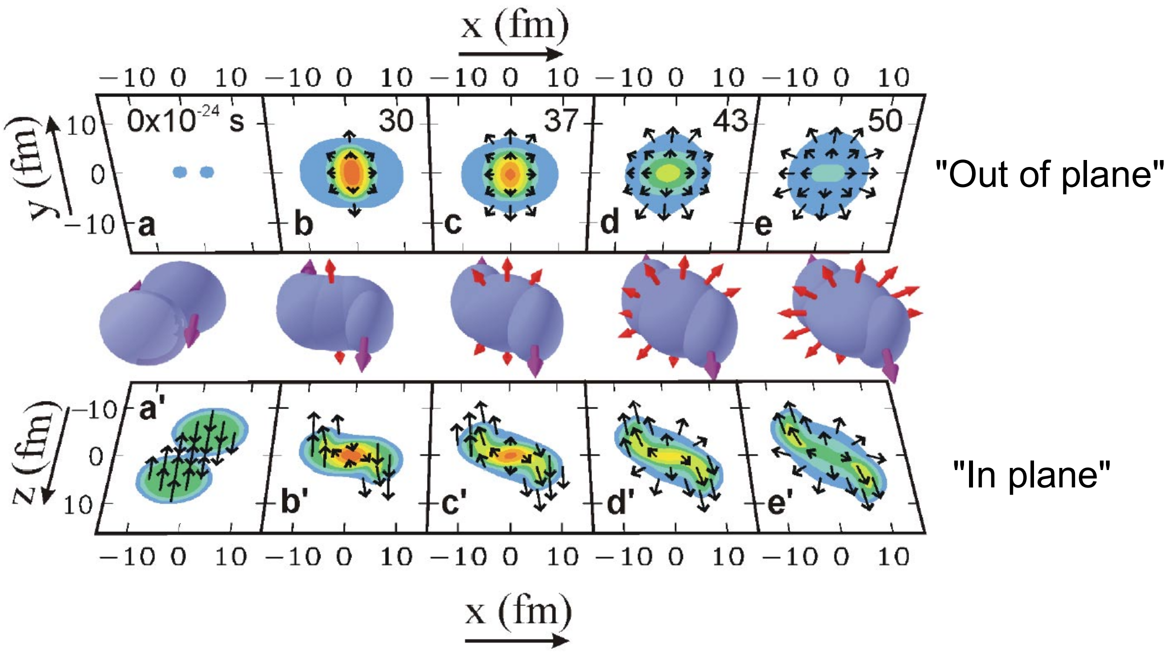
Properties of hot and dense nuclear matter are explored by the study of **nucleus-nucleus collisions.**

“Standard” experiments: Detection of **nucleons**, produced **particles** (mostly kaons), and **very light fragments** in large-acceptance (preferentially 4 π) experiments

Dynamics and non-equilibrium processes in nuclear reactions

- Necessity for dynamic (transport) calculations for interpreting experimental data

Transport calculation for the reaction: Au + Au, 2 A GeV:

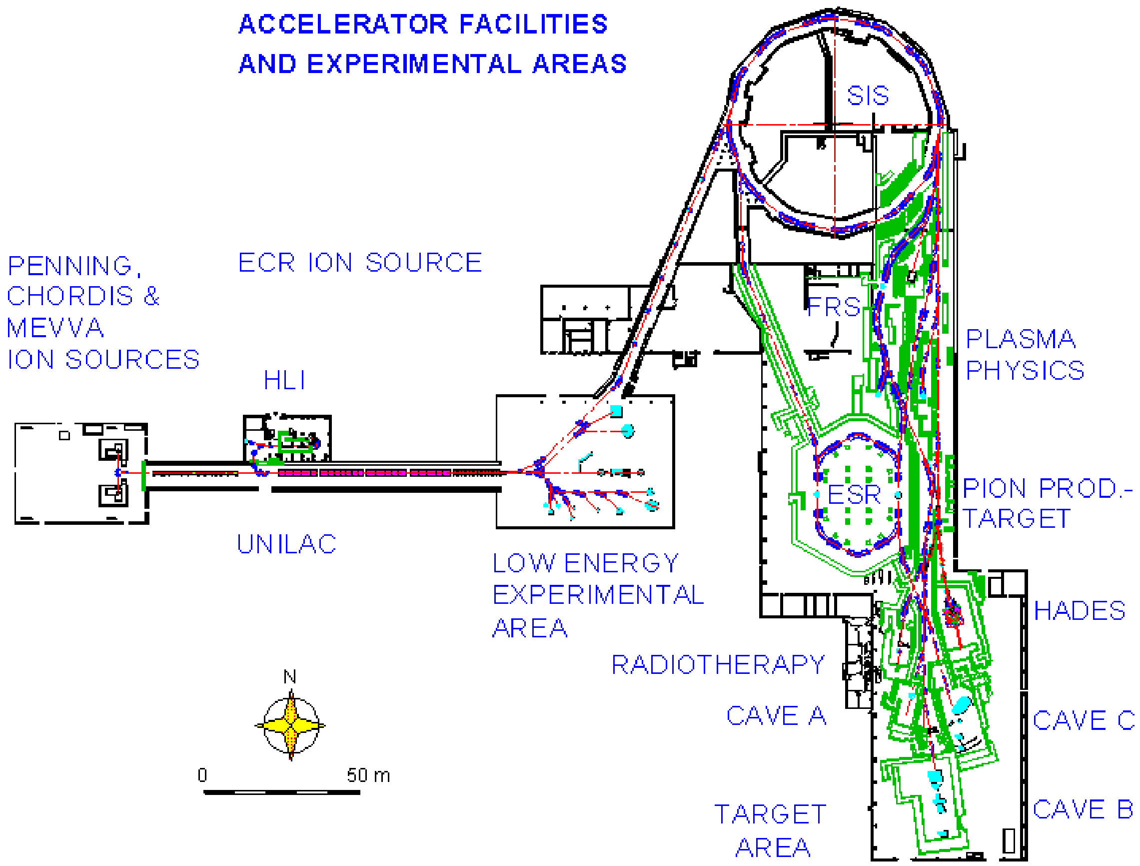


(Figure 1 of Danielewicz, Science 298 (2002) 1592)

The standard experimental devices:

FOPI (flow with full acceptance)
KAOS (K^+ production: early signature of the collision, flow)
ALADIN (Z for all fragments, Z and A for light fragments)
(others: Bevalac, MSU, EOS, INDRA, …)

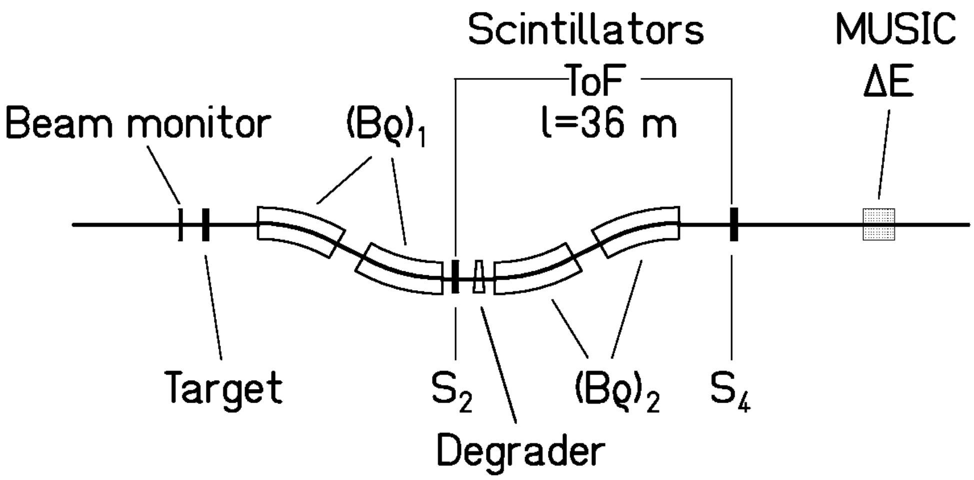
The GSI experimental facility



Installations of GSI:

UNILAC: Universal linear accelerator ($E \leq 20$ A MeV).
SIS18: Heavy-ion synchrotron ($E \leq 1 \ldots 2$ A GeV).
FRS: High-resolution magnetic spectrometer.
ESR: Experimental storage ring.
CAVE B: 4π detector FOPI.
Large-acceptance magnet ALADIN.
CAVE C: Kaon spectrometer KAOS.
HADES: Dilepton spectrometer.

The fragment separator



Powerful focusing magnetic spectrometer
(72 m long, sum of bending angles: 120^{o})

- **Angular acceptance**
  - 15 mrad around the beam axis
- **Momentum acceptance**
  - $\pm$ 1.5 % in $\Delta p/p$
- **Resolution**
  - *Bρ*: 3 mm in position → $5{\cdot}10^{-4}$
  - TOF: 100 ps on 36 m → $2.5{\cdot}10^{-3}$ in $\beta{\cdot}\gamma$

TOF sufficient for mass resolution $\Delta A/A \approx 400$. $B\rho = \dfrac{\mathrm{Am_o}\beta\gamma c}{Ze}$

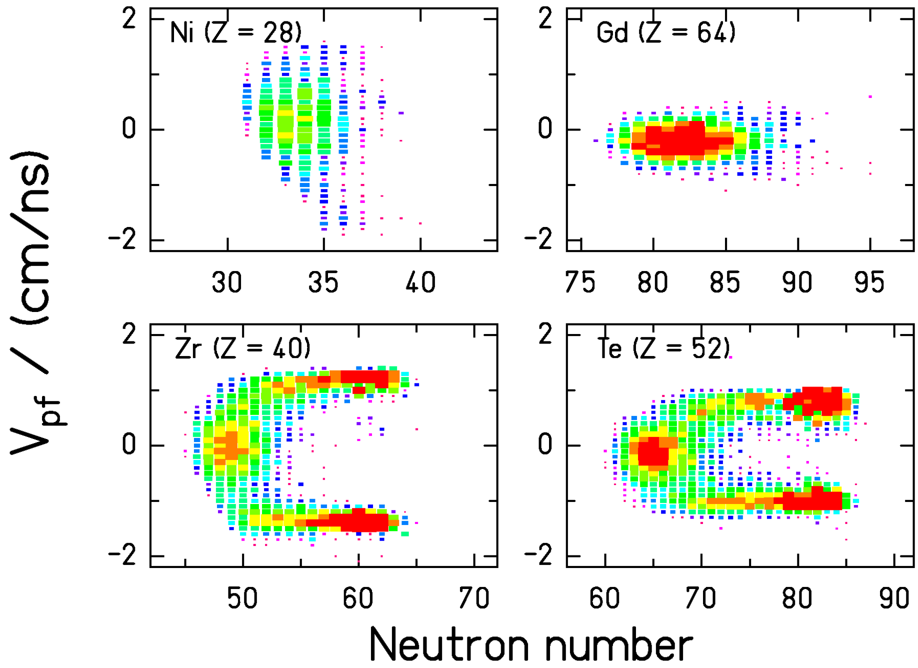
After identification of *Z* and *A*: (*Z* and *A* are integer numbers)
Bρ provides velocity with high precision
→ **resolution of $5{\cdot}10^{-4}$ in $\beta{\cdot}\gamma$!**

Precise measurement of **one** (heavy) reaction product.
No correlation to other products, no multiplicities.

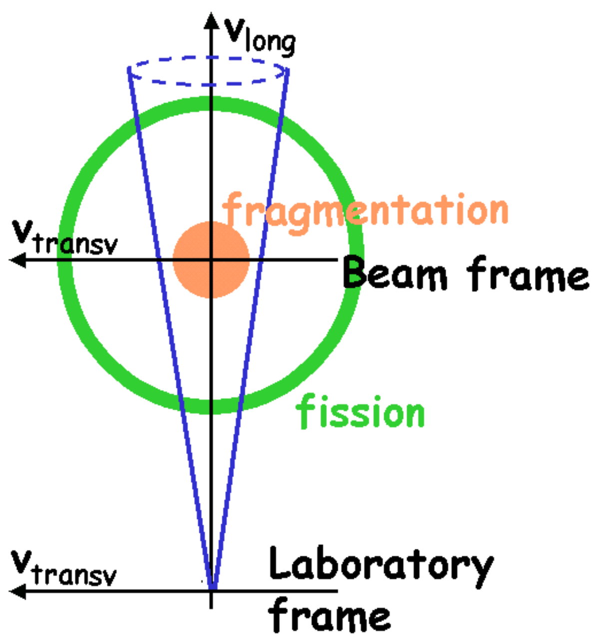
Full acceptance for most fragmentation products.
Low acceptance (≈ 10 %) for fission and very light fragmentation products.

Experimental results

Systematics on nuclide distributions and velocities

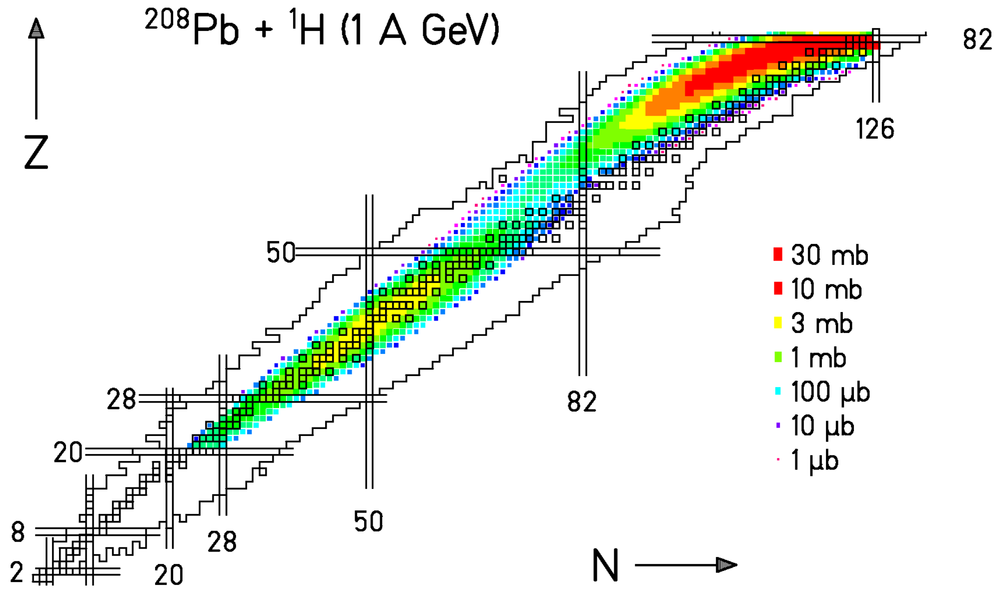


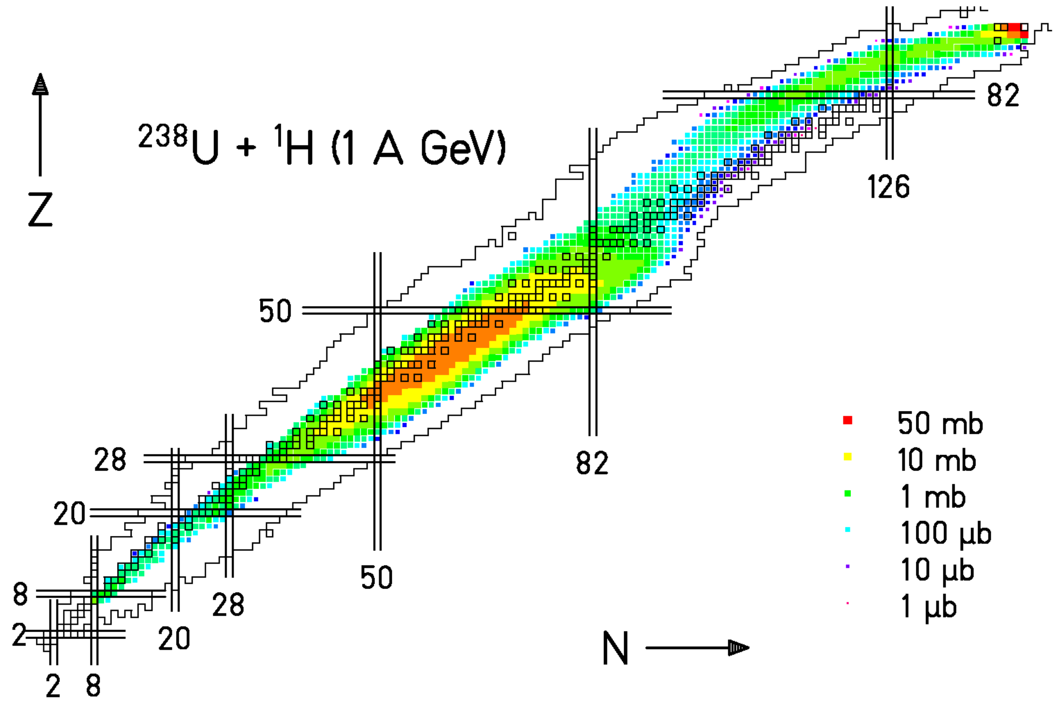
^{238}U (1 A GeV) + Pb (many settings of the FRS combined)
(T. Enqvist et al., Nucl. Phys. A 658 (1999) 47)



Fragmentation: Fully accepted
Fission: Only accepted forward and backward

Systematic nuclide distributions of evaporation and fission residues of projectile fragments (2 examples)





Our results obtained in the incineration program are the only full-coverage data on nuclide production (yields and velocities) available. (More than 1000 individual nuclides investigated for each system.)

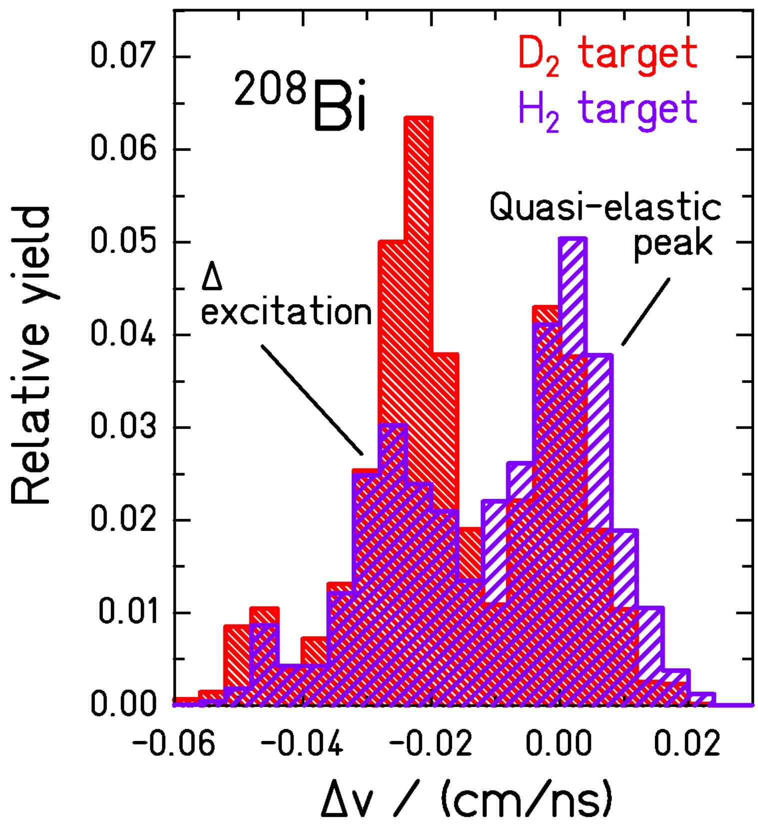
(Data analysed by M. Bernas, E. Casarejos, T. Enqvist, J. Pereira, M. V. Ricciardi, J. Taieb, W. Wlazlo; 4 publications in Nucl. Phys. A)

Charge-exchange reactions

Excitation of the nucleon in the nuclear medium

Measured: $^{208}_{82}\mathrm{Pb}\,(^{1,2}\mathrm{H}, x)\,^{193\text{-}208}_{83}\mathrm{Bi}$, $^{208}_{82}\mathrm{Pb}\,(\mathrm{Ti}, x)\,^{193\text{-}208}_{83}\mathrm{Bi}$.

Velocity of $^{208}_{83}\mathrm{Bi}$ in the frame of the projectile ($^{208}_{82}\mathrm{Pb}$)
$^{208}_{82}\mathrm{Pb}\,(^{1}\mathrm{H}, x)\,^{208}_{83}\mathrm{Bi}$ at 1 A GeV



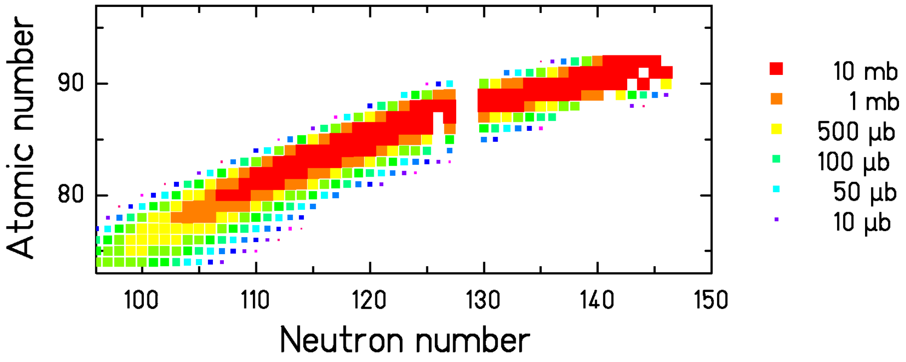
A. Kelić et al., in preparation

Two components can be distinguished:
- Quasi-elastic scattering (p replaces n in $^{208}\mathrm{Pb}$)
- Δ excitation (e.g. $n \rightarrow \Delta^0 \rightarrow p + \pi^-$)

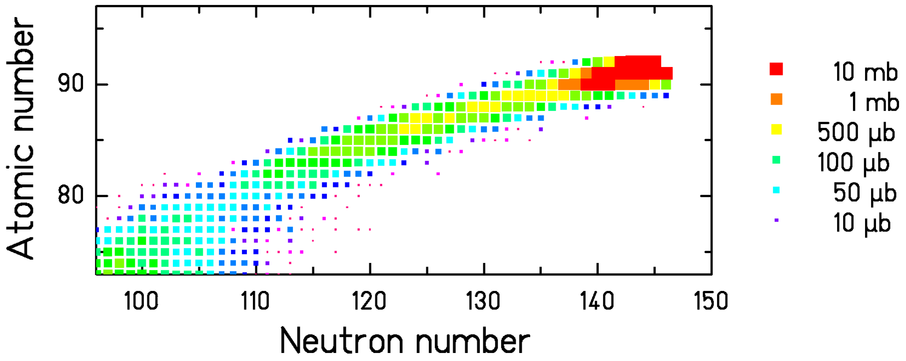
Probability for Δ excitation and energy in the nuclear medium can be deduced.

Dissipation in fission

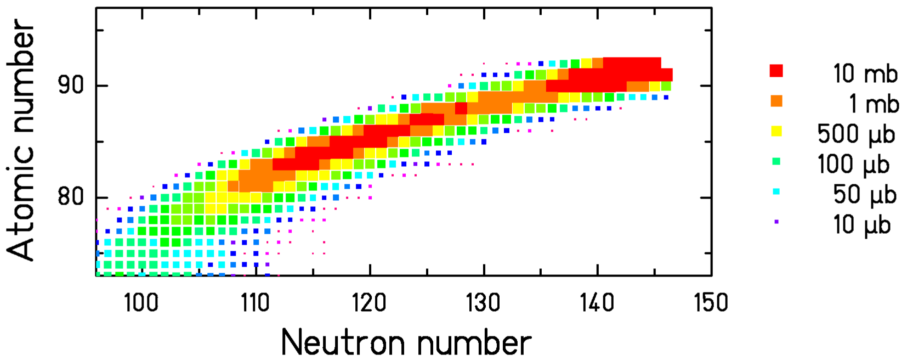
Experiment: ^{238}U + p, 1 A GeV



Model: ^{238}U + p, 1 A GeV, no dissipation



Model: ^{238}U + p, 1 A GeV, $\beta = 2\times10^{21}\ s^{-1}$



Nuclide yields are very sensitive to nuclear dissipation.

Evidence for suppression of fission at high E*.

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

(Further studies by B. Jurado and C. Schmitt)

Nuclear incompressibility

Incompressibility = stiffness of the nucleus against density variations.

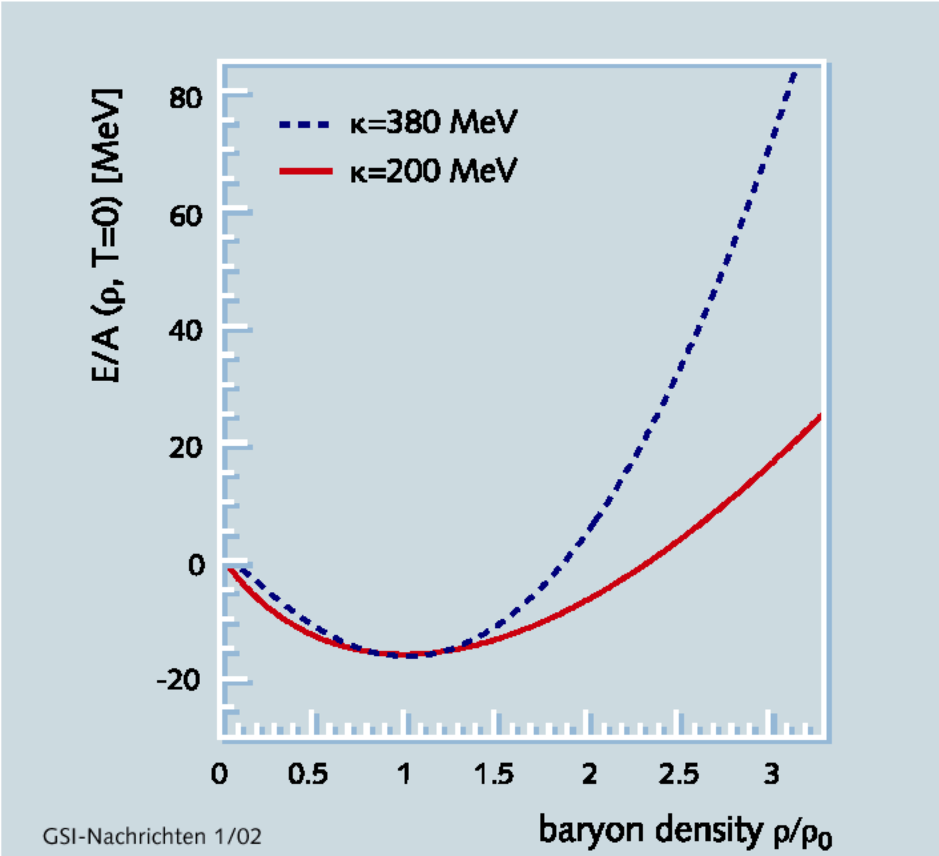


Figure: Binding energy of infinite nuclear matter as a function of density. Comparison of "soft" and "hard" equation of state.

Nuclear incompressibility is a key quantity of the nuclear equation of state.

The nuclear incompressibility depends on

- **temperature ($\rightarrow$ big bang, supernova) and**
- **"isospin" ($\rightarrow$ neutron stars).**

The stiffness of the EOS

Danielewicz has analyzed the constraints from available experiments:

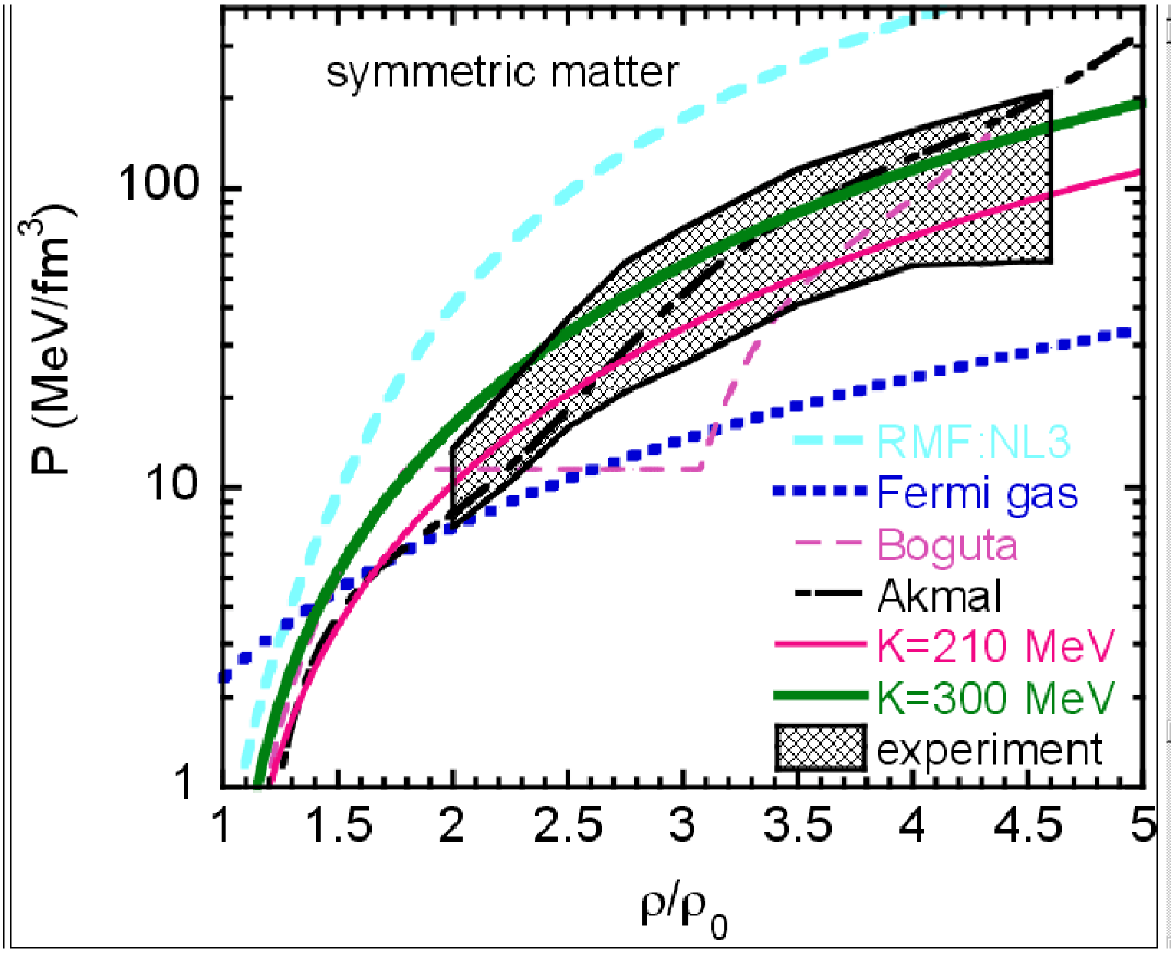


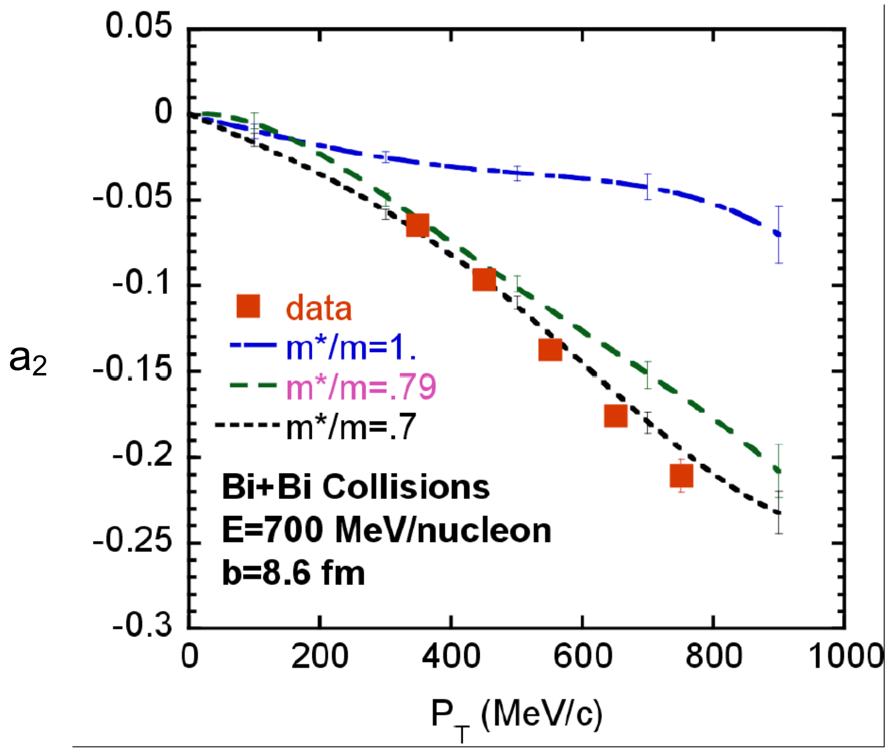
Figure 3 from Danielewicz , Science 298 (2002) 1592

The interpretation of most experiments on the EOS also depends on the momentum dependence of the mean field!

→ Ambiguities in the determination of the stiffness of the EOS.

The momentum dependence of the nuclear mean field

Elliptic flow of protons measured by of the KAOS collaboration
(D. Brill et al., Z. Phys. A 355 (1996) 61)



$N(\varphi) \propto 1 + a_1 \cdot \cos(\varphi) + a_2 \cdot \cos(2\varphi)$

Calculations by
Danielewicz, Nucl. Phys. A 673 (2000) 375:
Enhanced emission of protons **out-of-plane** ($a_2 < 0$) is preferentially sensitive to the momentum dependence of the mean field.

(Momentum dependent mean field is characterized by a reduced nucleon mass in the nuclear medium.)

Interpretation is based on complex transport calculations (e.g. assumptions on the density-dependent nucleon-nucleon cross sections).
→ Danielewicz et al. propose additional signatures:

Response of the spectator to the participant blast

A measure of the momentum dependence of the nuclear mean field

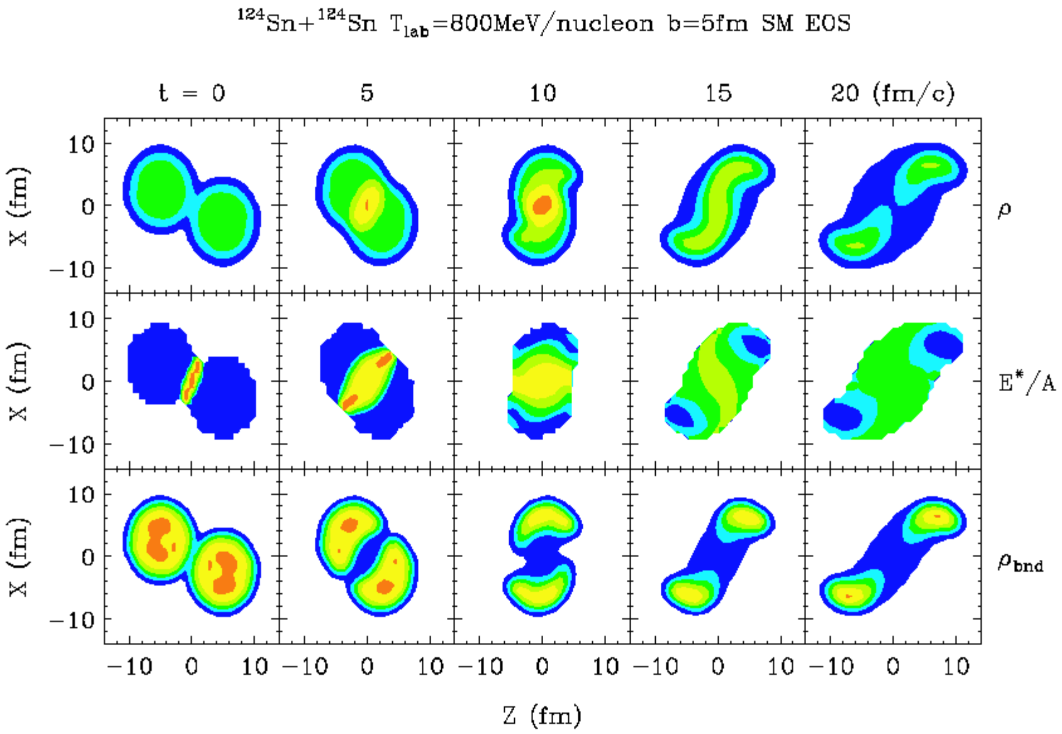


Figure 1 of Shi et al., Phys. Rev. C 64 (2001) 034601

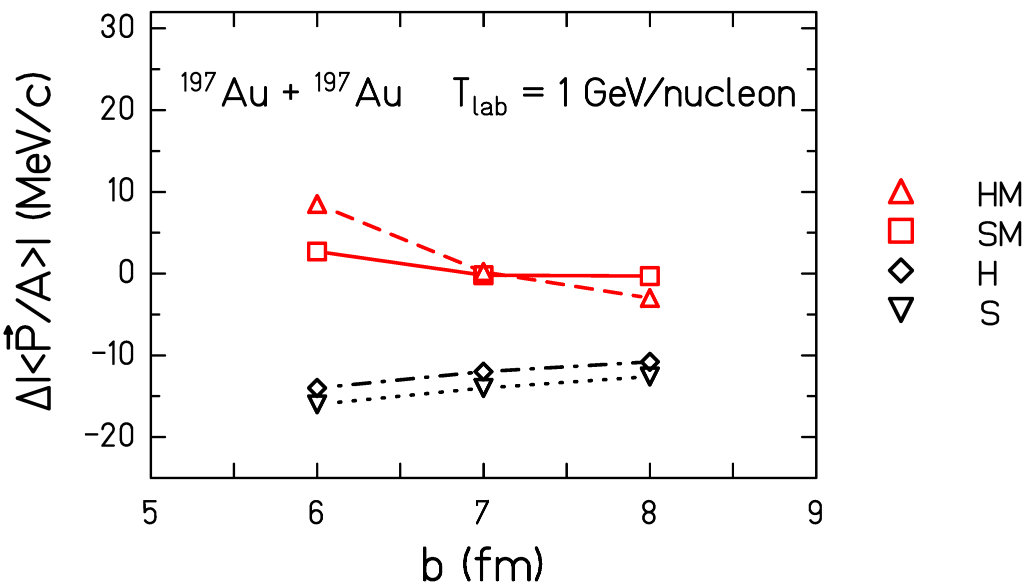
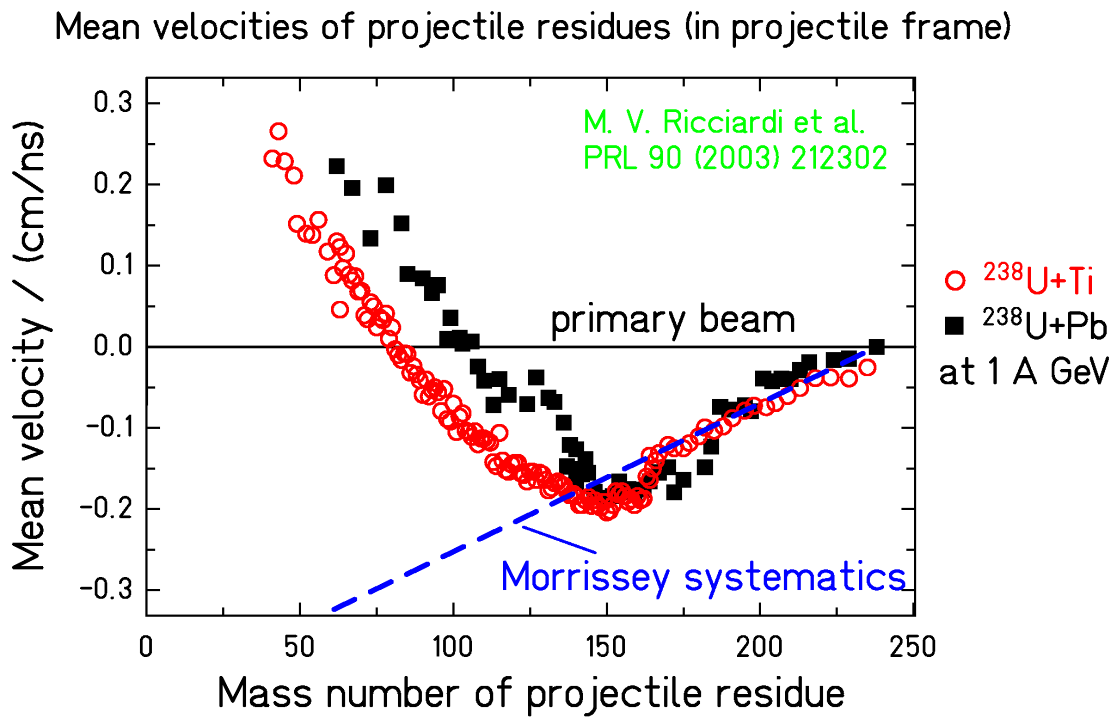


Figure 9 of Shi et al., Phys. Rev. C 64 (2001) 034601

(Idea already introduced previously e.g. by J. J. Molitoris, A. Bonasera, B. L. Winer, H. Stöcker, Phys. Rev. C 37 (1988) 1020)

New FRS results:

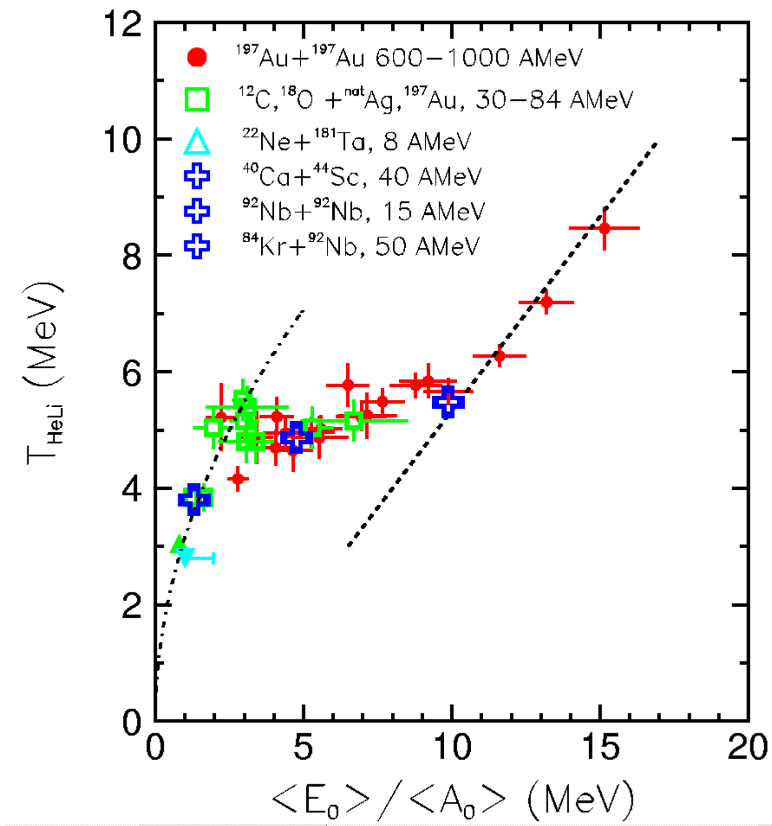
Response of the spectator to the participant blast



The data give an <u>early signature</u> (the acceleration of the spectator is acquired during contact with the fireball).

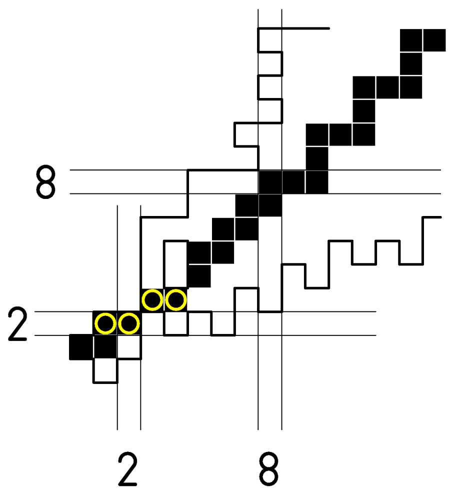
Valuable basis for general verification of transport calculations!

Evolution of the “isospin” degree of freedom in nuclear reactions



Caloric curve from ALADIN …

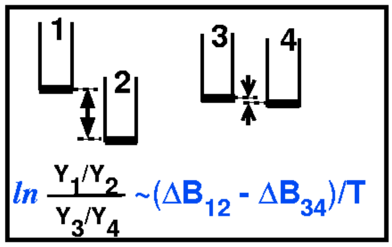
Nuclei used for T_{HeLi}



isotopic composition

(^{3}He/^{4}He)/(^{6}Li/^{7}Li)

(π^-/K^-)/(Σ^-/Ξ^-)

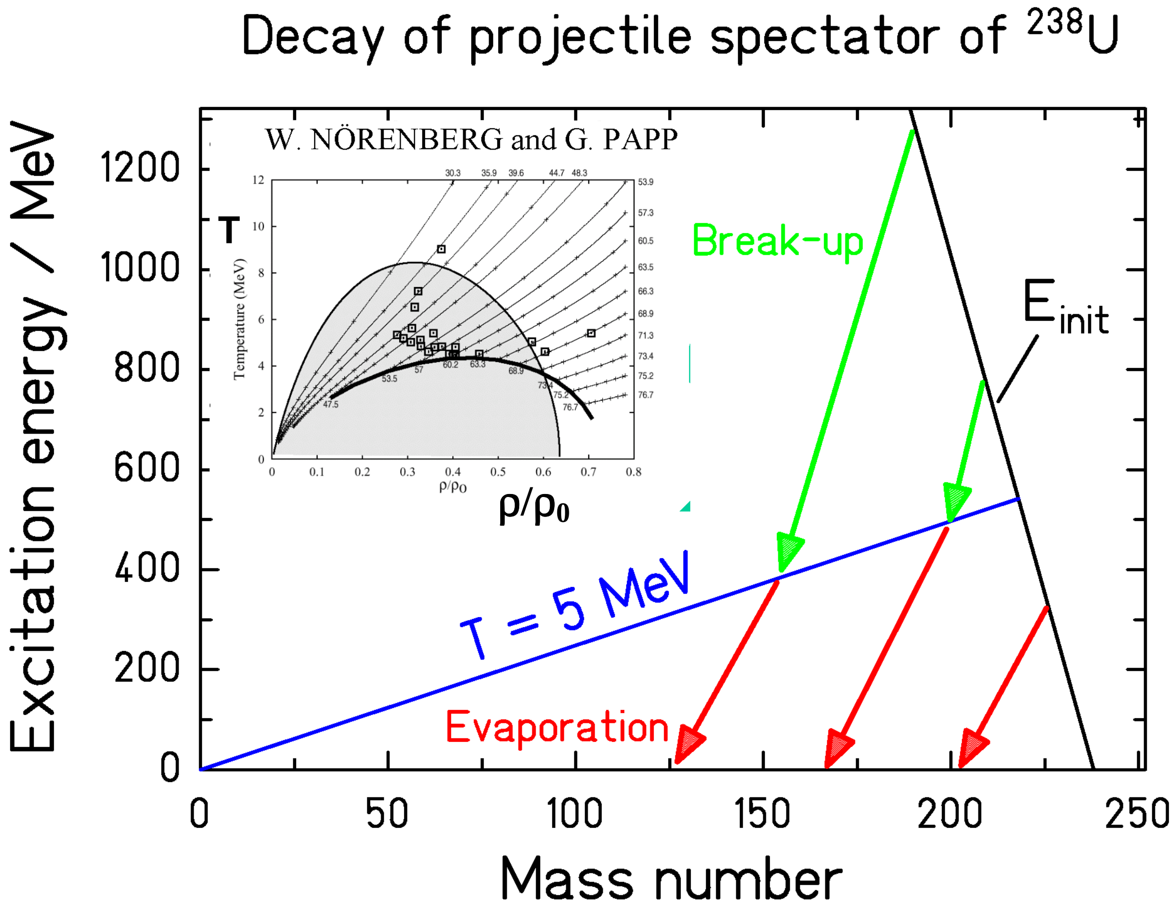


Double-isotopic ratio, experimental binding energies $\rightarrow$ $\mathbf{T_{HeLi}}$

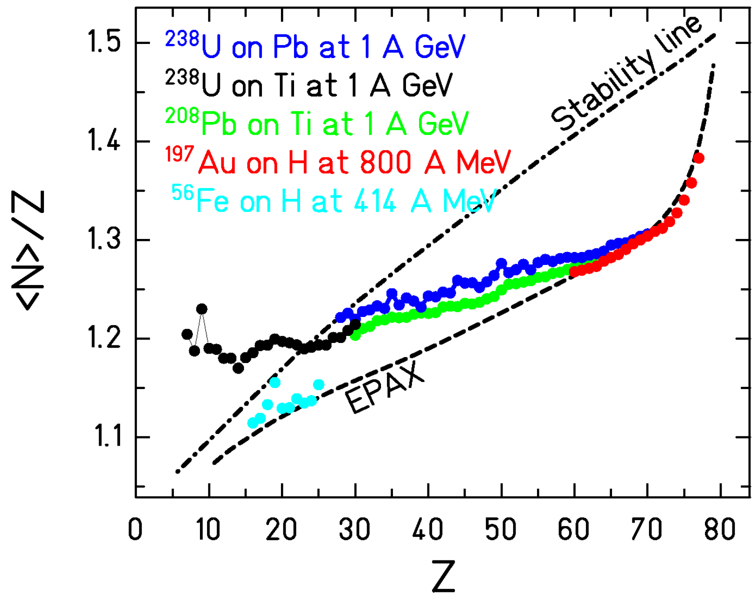
The 4 nuclides, entering into the analysis

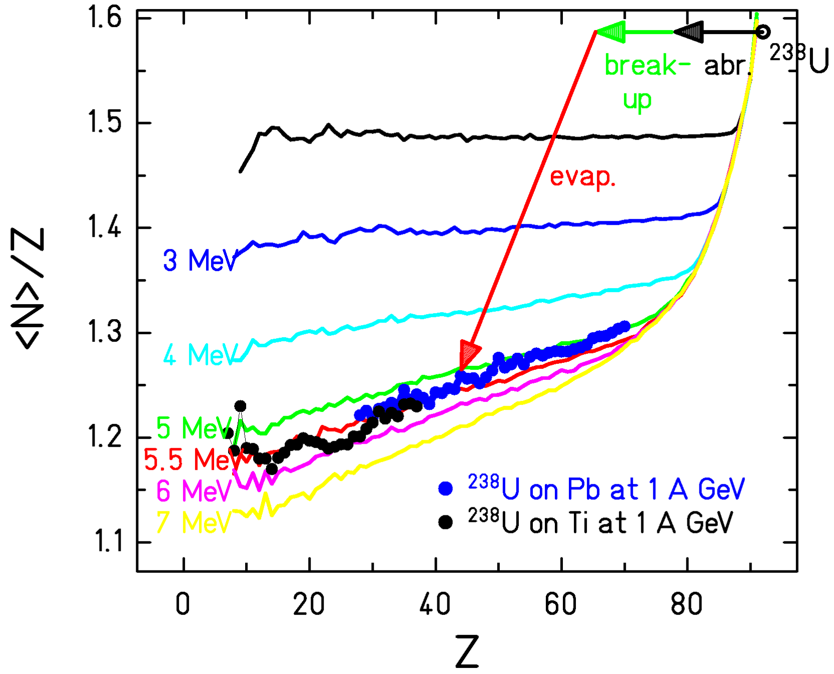
The major 3 stages of the reaction (schematic)

- **Abrasion (Geometry)**
  - o Mass loss, $E_{init} \approx \Delta A \cdot 27$ MeV induced in spectator
- **Break-up (Complex dynamic process)**
  - o Thermal expansion
  - o Spinodal instability (?)
  - o Multifragmentation (?)
  - o Freeze-out
- **Evaporation (Statistical model)**
  - o Standard evaporation code



FRS data





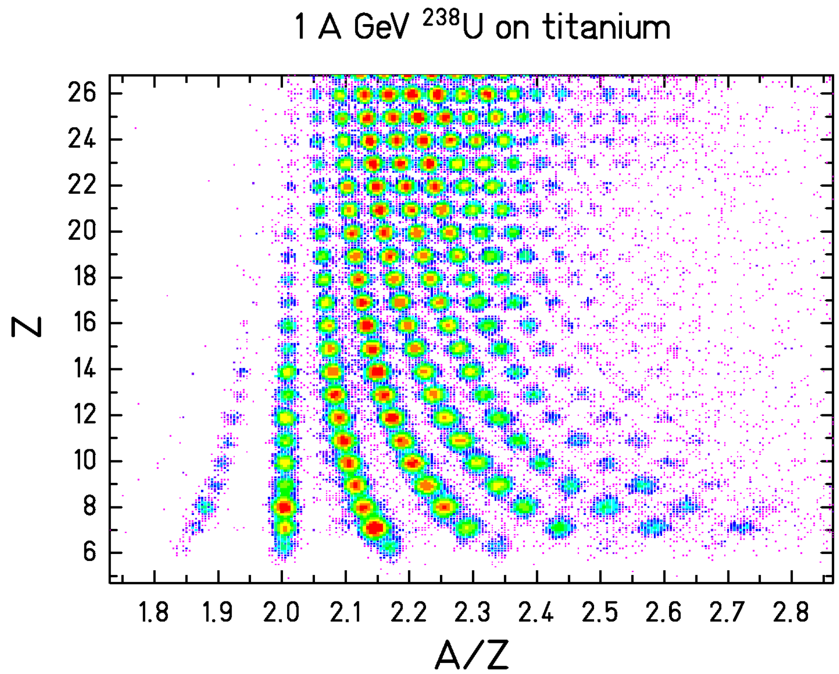
<N>/Z of ^{238}U fragmentation residues compared to EPAX and 3-stage code ABRABLA (with different freeze-out temperatures)
K.-H. Schmidt, M. V. Ricciardi, A. Botvina, T. Enqvist, Nucl. Phys. A 710 (2002) 157

Regarding "isospin" variation in evaporation only:

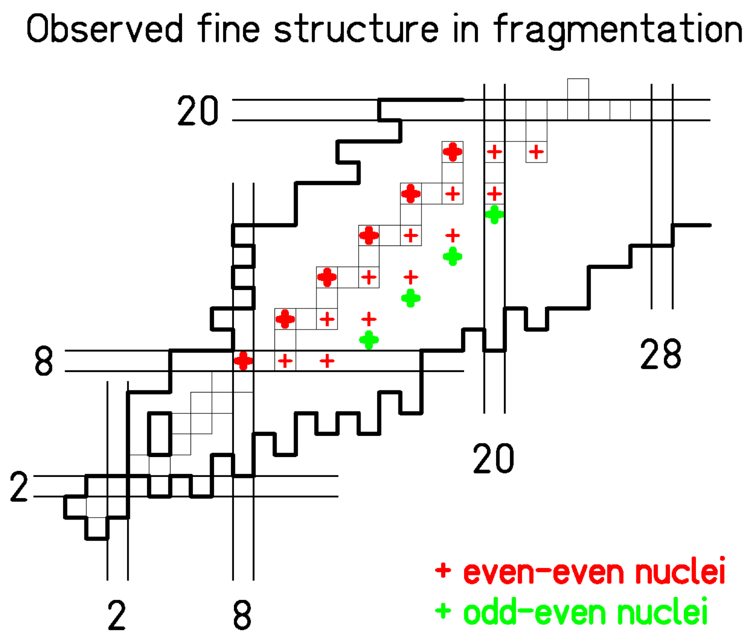
$T_{freeze\text{-}out} \approx 5$ MeV

This result is compatible with the caloric curve of ALADIN.

Fine structure in residue yields after violent nuclear collisions



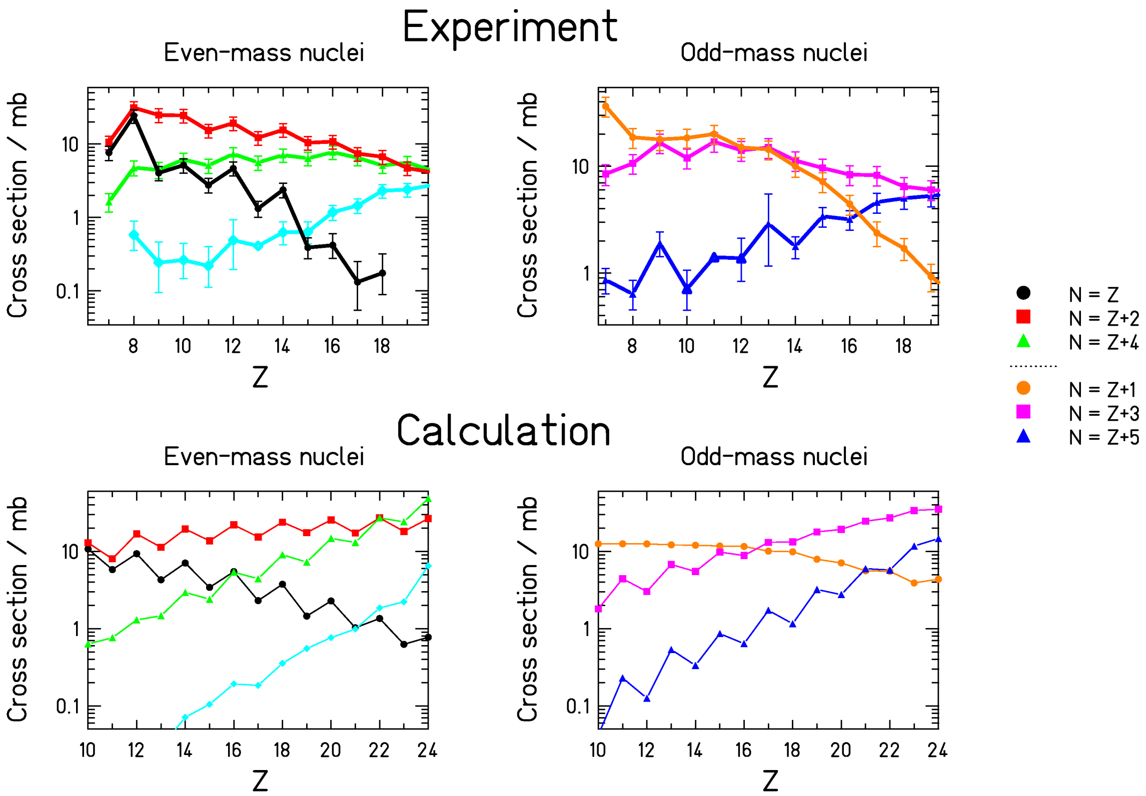
Nuclear structure even after violent nuclear collisions!



Caution when interpreting nuclide yields with thermodynamic approaches without nuclear structure!

M. V. Ricciardi et al. Nucl. Phys. A in press

Model calculations



Quantitative interpretation with an evaporation code.

Careful formulation of pairing in masses and level densities

Most features of the fine structure are reproduced,
expect the strongly enhanced structure in N=Z nuclei.
→ Alpha clustering in excited nuclei???

Conclusion

Valuable complementary information on the properties of hot and dense nuclear matter with high-resolution magnetic spectrometers

Features investigated up to now:

- **Δ excitation in the nuclear medium**
- **Nuclear viscosity**
- **Momentum dependence of the nuclear mean field**
- **Evolution of the "isospin" in nuclear reactions**
- **Fine structure in residue yields**

Results of high-resolution measurements broaden the basis for the understanding of the properties of nuclear matter far from the conditions in our terrestrial environment.

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***Ph.D. theses**
† deceased

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