Signatures of multifragmentation in spallation reactions

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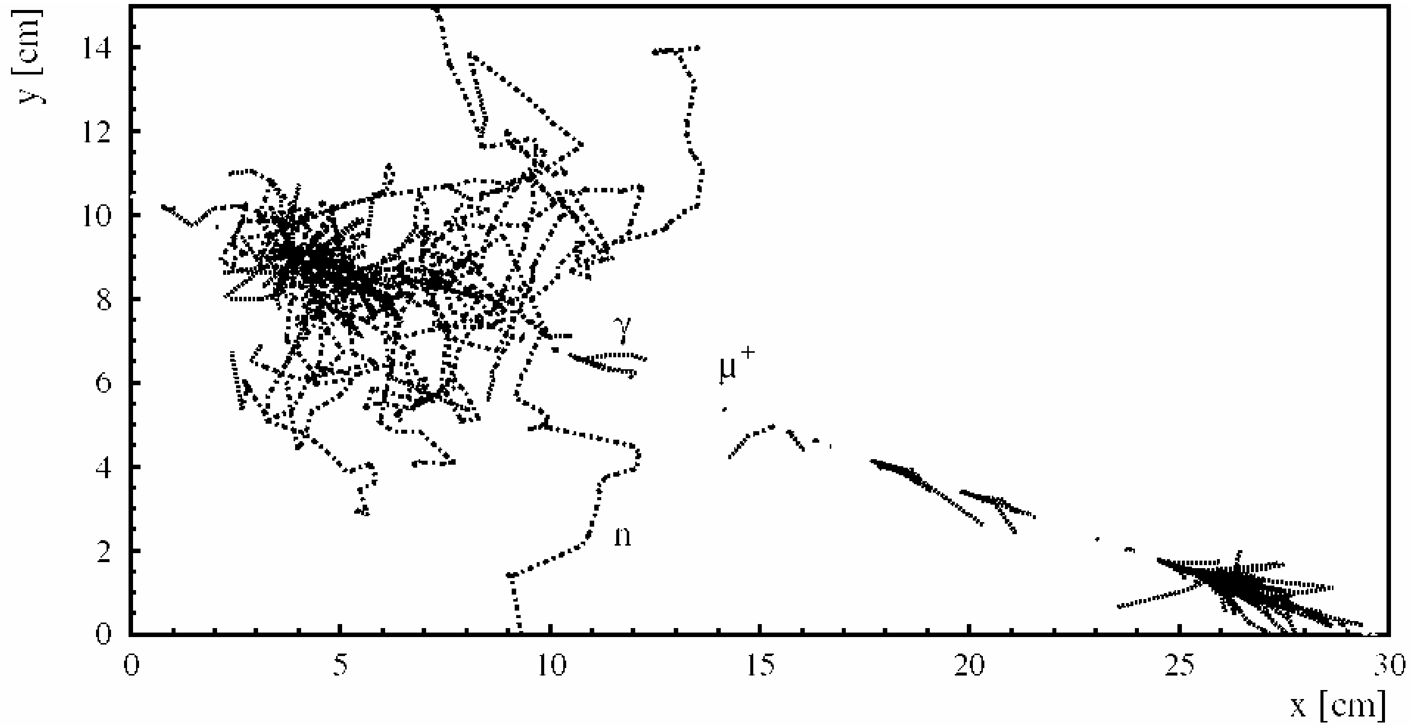
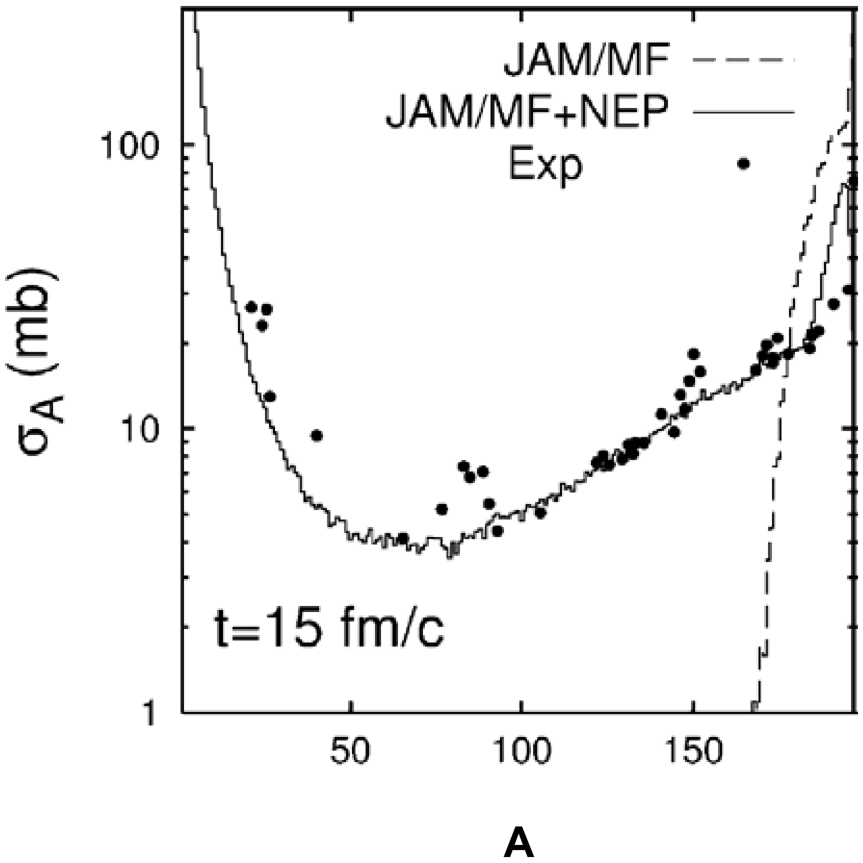
What is a spallation reaction?



Collision of a μ^+ of 41.2 GeV with an iron nucleus, recorded with the KARMEN detector.

- **Collision of a high-energetic particle with a heavy nucleus.**
- **Production of a large number of light particles.**
- **First observed by Schopper et al. (Naturw. 25 (1937) 557): interaction of cosmic rays in a track detector.**

Mass distribution of spallation products



Experiment: Typical U-shaped mass distribution

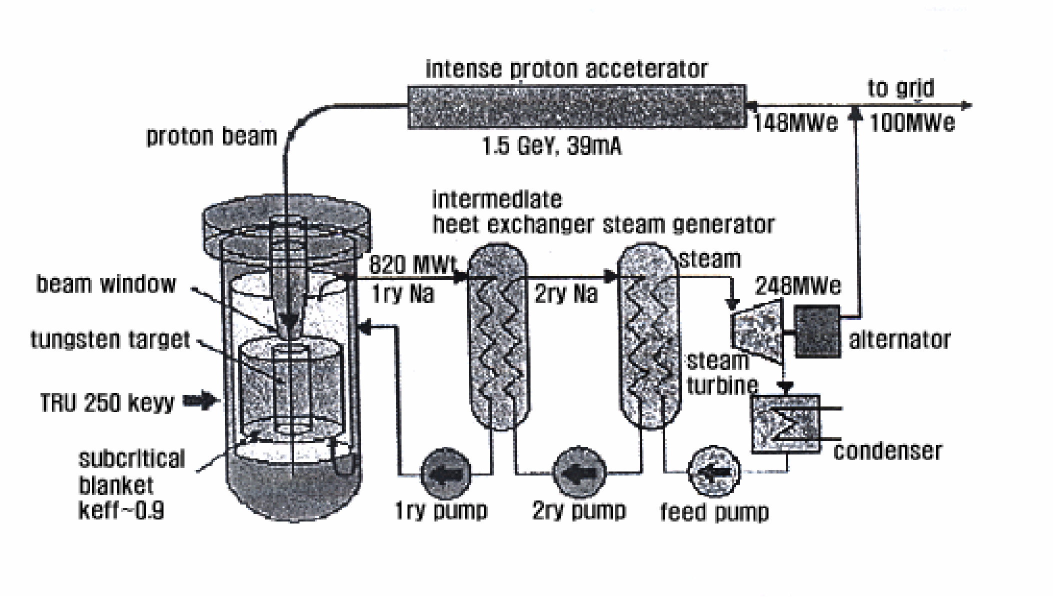
Model: Hadron-string cascade model,
QMD,
Non-equilibrium percolation model.

← ***Reaction: 12 GeV protons on gold.***

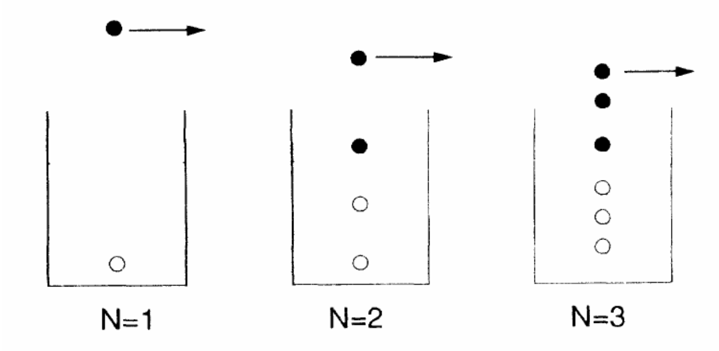
Data: Kaufmann et al., Phys. Rev. C 14 (1976) 1121
Model: Hirata et al., Nucl. Phys. A 707 (2002) 193

Importance of spallation reactions

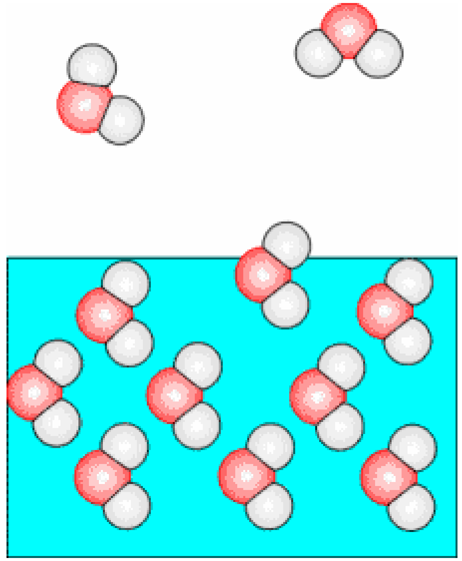
- **Nucleosynthesis in interactions of cosmic rays with interstellar matter.**
- **Spallation neutron source for neutron-physics experiments (e.g. ISIS at the Rutherford Lab., UK).**
- **Accelerator-driven system (ADS) for the incineration of nuclear waste.**



Conventional nuclear-reaction codes to model spallation



2. <u>Excition model</u>
- **Thermalization process**
- **Pre-equilibrium emission**



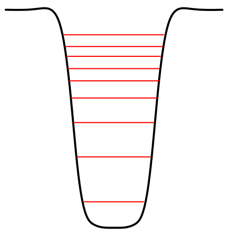
1. <u>Intra-nuclear cascade</u>
- **Elastic scattering of nucleons**
- **Classical concept**
- **Quantum-mechanical features added (Fermi motion, Pauli principle)**

3. <u>Statistical model</u>
- **Evaporation from a compound nucleus (nucleons, LCP, γs)**
- **Fission**

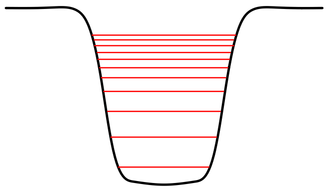
Since long time, there has been great scientific interest in other features which go beyond the conventional models.

They are connected with the density degree of freedom!

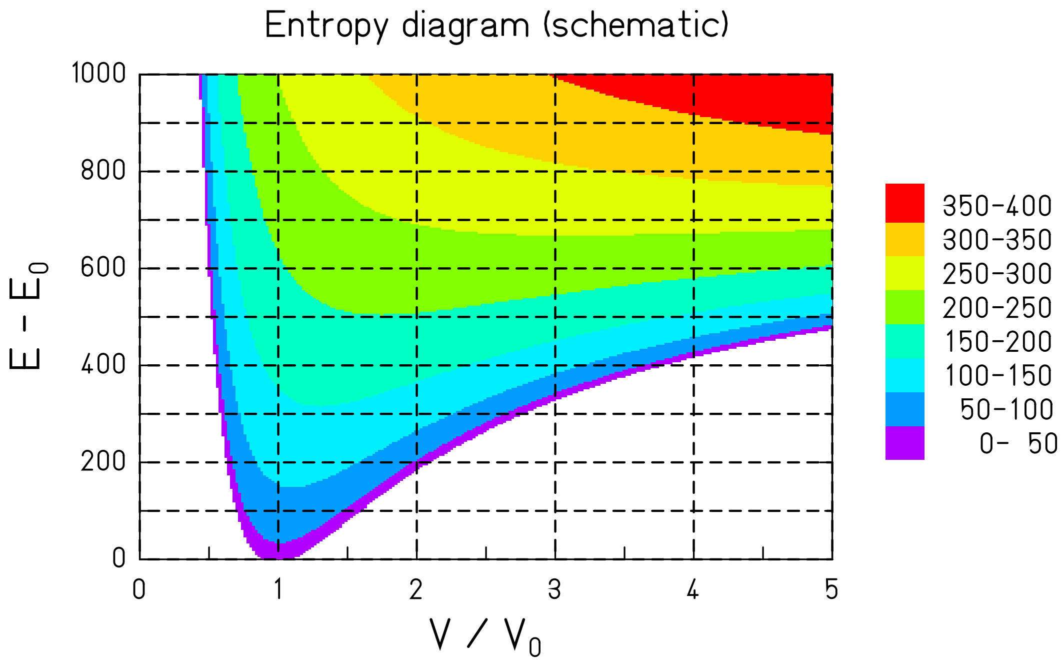
Thermal expansion



Single-particle levels
at normal nuclear density

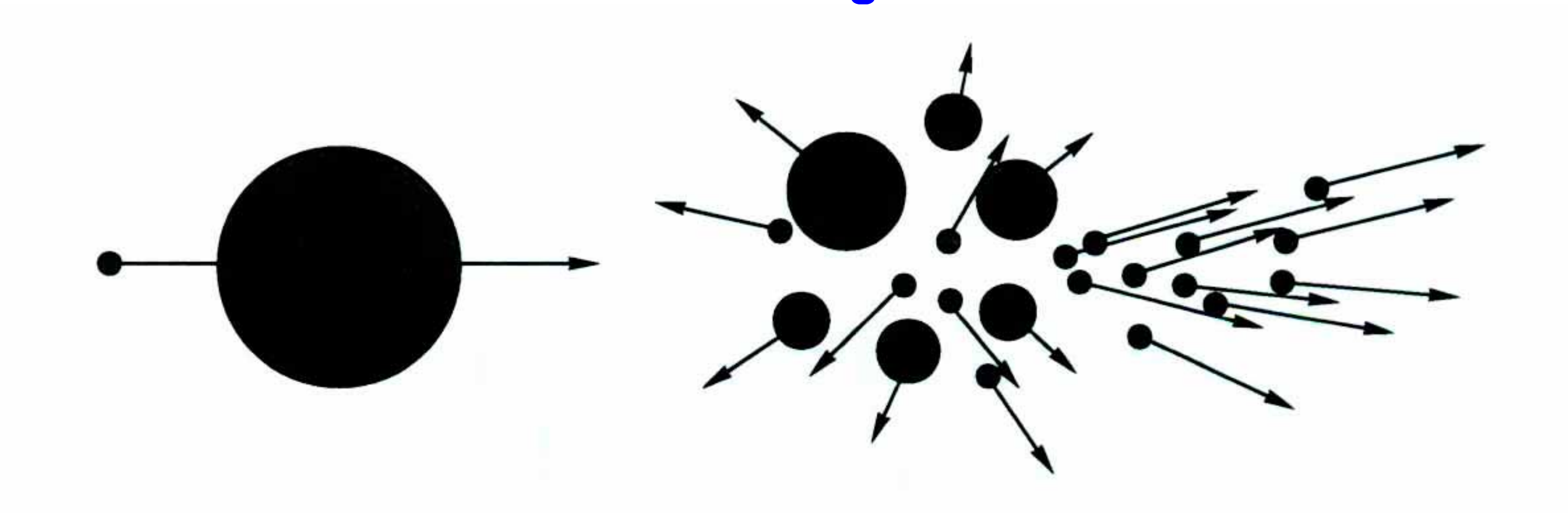


Single-particle levels
at reduced density



Compression energy and density-dependent level density lead to thermal expansion.

Thermal multifragmentation



<u>Stages of a thermal multifragmentation event:</u>

1. Intranuclear cascade
2. Pre-equilibrium emission
3. Thermal expansion
4. Spinodal instabilities (inhomogeneous mixture of gaseous and liquid phases -> fog), (like boiling of hot water when the pressure is reduced) leads to the simultaneous formation of several fragments (Details in talk of A. Botvina!)
5. Explosion of fragments due to Coulomb force
6. Evaporation from the fragments

Multifragmentation goes beyond the traditional description of spallation reactions

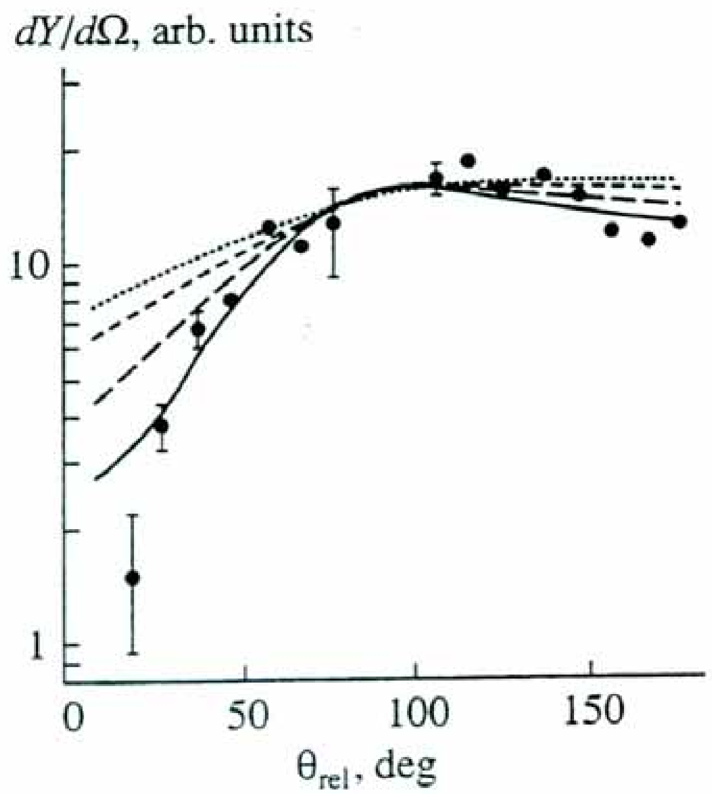
New features are expected, which are related to expansion and the nuclear liquid-gas phase transition

What are the experimental signatures?

Emission times

Multifragmentation products are emitted simultaneously.

Coulomb repulsion does not allow detection of several fragments under the same angle.



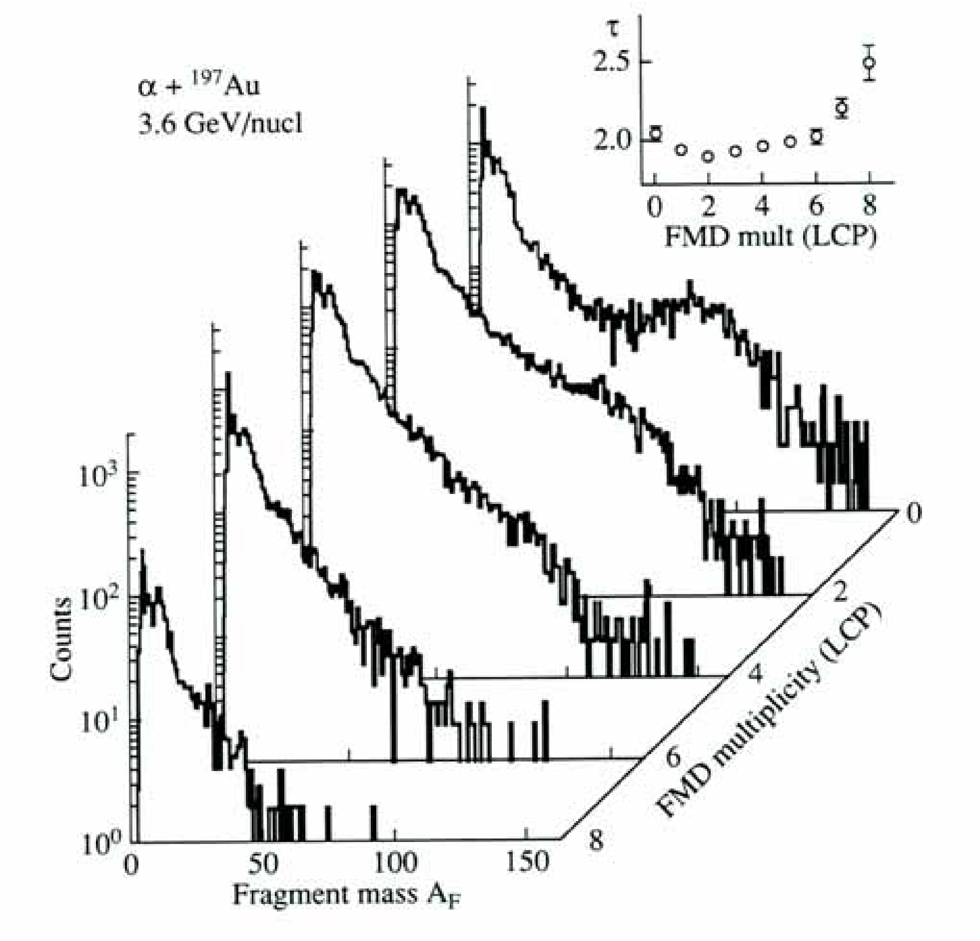
Relative angles between IMFs (6 ≤ A ≤ 30) in ^{197}Au + ^{4}He at 3.65 A GeV. Curves from mean lifetime 0 fm/c (full line) to 800 fm/c (dotted line). (Shmakov et al., Phys. At. Nuclei 58 (1995) 1635)

Angular correlation gives the direct proof of simultaneous emission.

Only observable in correlation experiments.

No direct importance for nuclide yields and kinematics.

Mass yields – power law



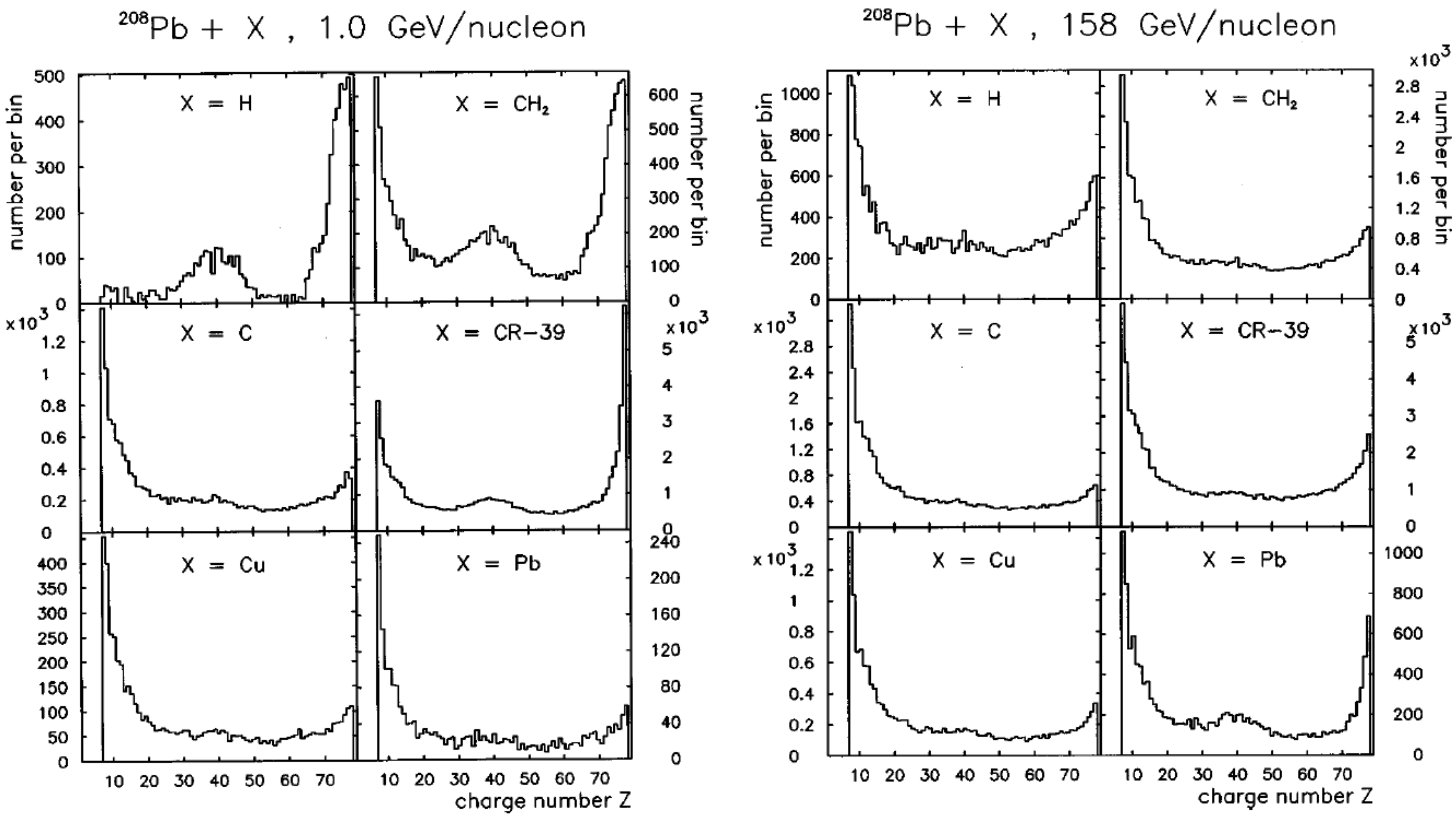
Mass spectra for ^{4}He + ^{197}Au at 3.6 A GeV as a function of LCP multiplicity (V. A Karnaukov, Phys. Part. Nucl. 37 (2006) 165.)

The mass spectra have the shape of a power law:

$$\frac{d\sigma}{dA} \propto A^{-\tau}$$

with $\tau \approx 2$**.**

Mass yields – dependence on available energy



Hüntrup et al., Phys. Rev. C 61 (2000) 034903 (Track detectors)

Kinematics

Comparison of fusion-evaporation reactions with multifragmentation reactions

Fusion-evaporation

1. Fusion: Formation of a CN with

$$p_{CN} = p_{projectile}$$

2. Evaporation

$$\frac{d\sigma}{d\varepsilon} \propto \varepsilon \cdot e^{-\varepsilon/T}$$

(Maxwell-Boltzmann distribution)

3. Acceleration in Coulomb field

Spallation - multifragmentation

1. Nucleon-nucleon collisions (INC stage)

Fluctuations in *p* of pre-fragment due to

Fermi motion of nucleons

Partial momentum transfer

2. Expansion and formation of fragments

3. Freeze-out (no nuclear interactions)

a) Fermi momentum

$$\frac{dI}{d\varepsilon} \propto \sqrt{\varepsilon} \cdot e^{-e/\tau}$$

(τ is not a temperature !)

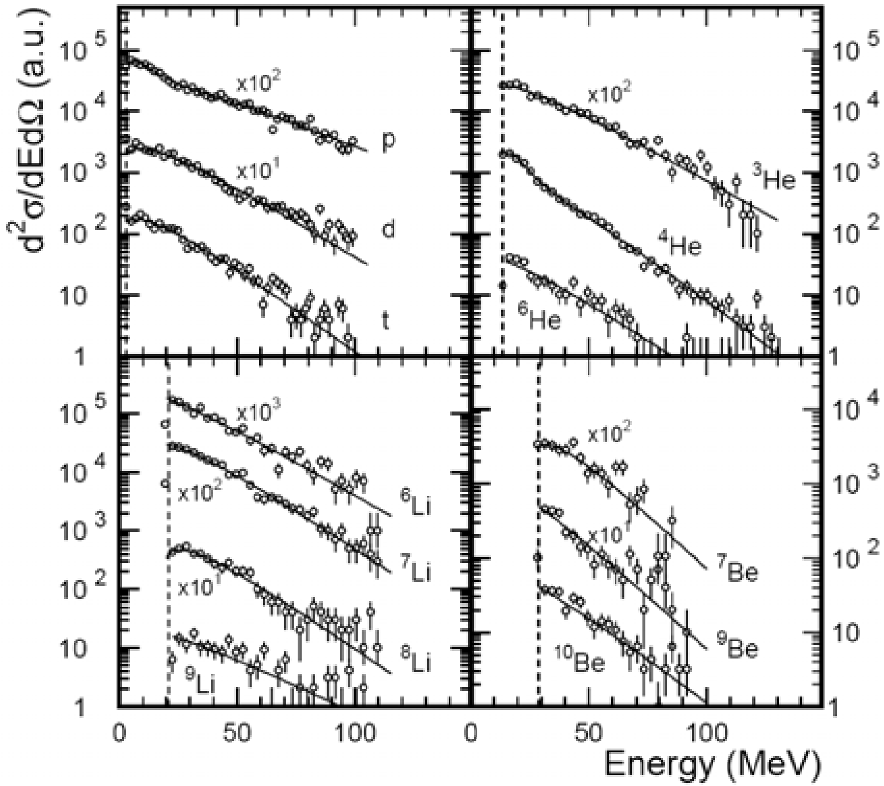
b) Thermal motion

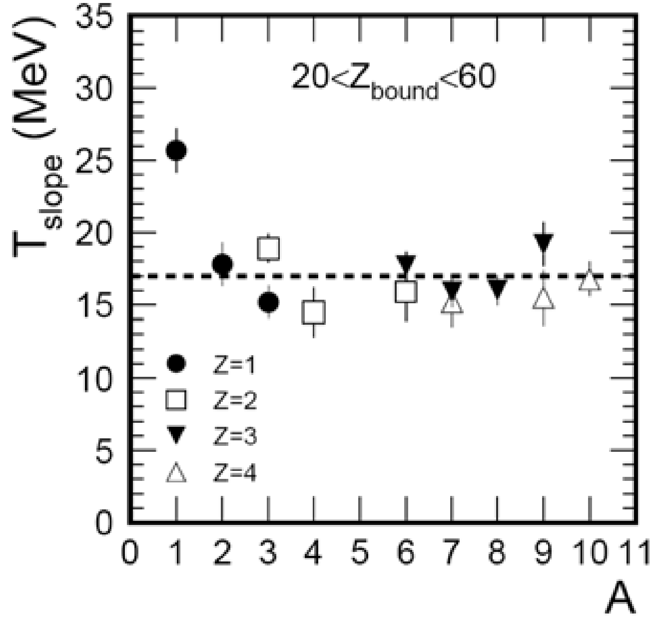
c) Radial flow

4. Acceleration in Coulomb field

→ Many sources of fluctuations in kinematics of multifragmentation products (Napolitani!).

Energy spectra





Energy spectra of light charged particles and fragments with Z ≤ 4 at 150°, integrated over 20 ≤ Z_{bound} ≤ 60 (Au + Au at 1 A GeV).

Odeh et al., Phys. Rev. Lett. 84 (2000) 4557

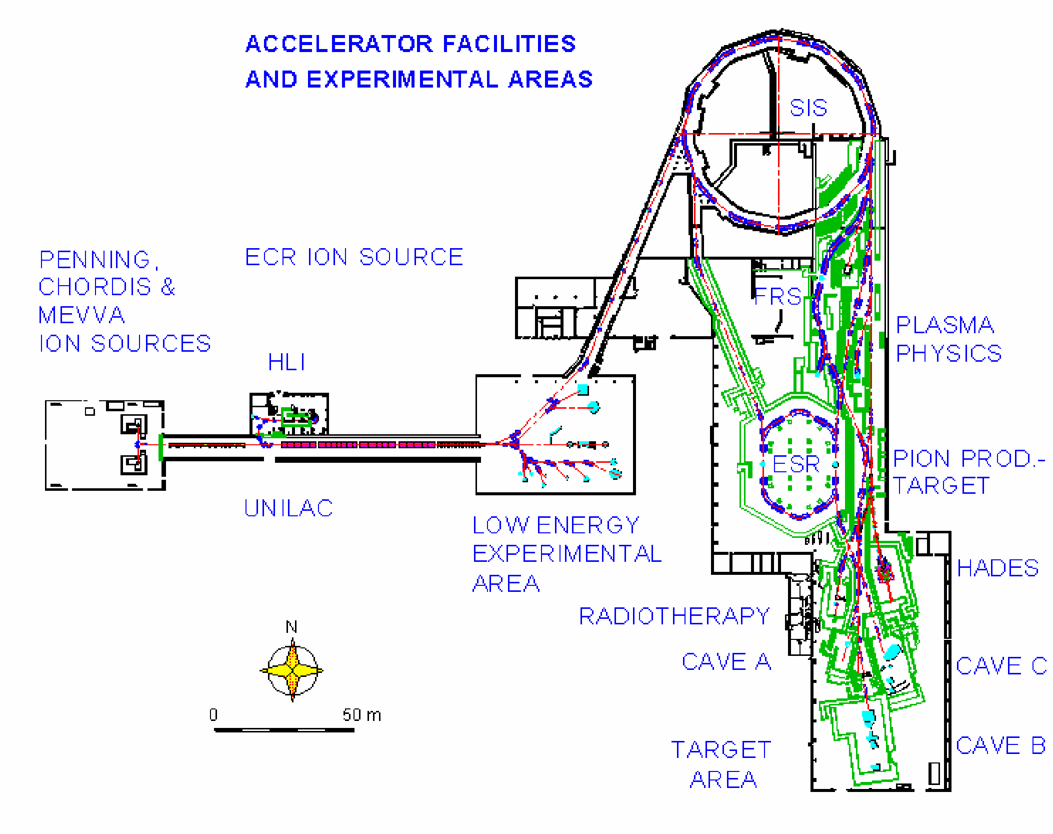
Deduced slope parameters

(From independent measurement:

T ≈ 5 to 6 MeV!)

Slope parameter reflects Fermi motion and/or expansion.

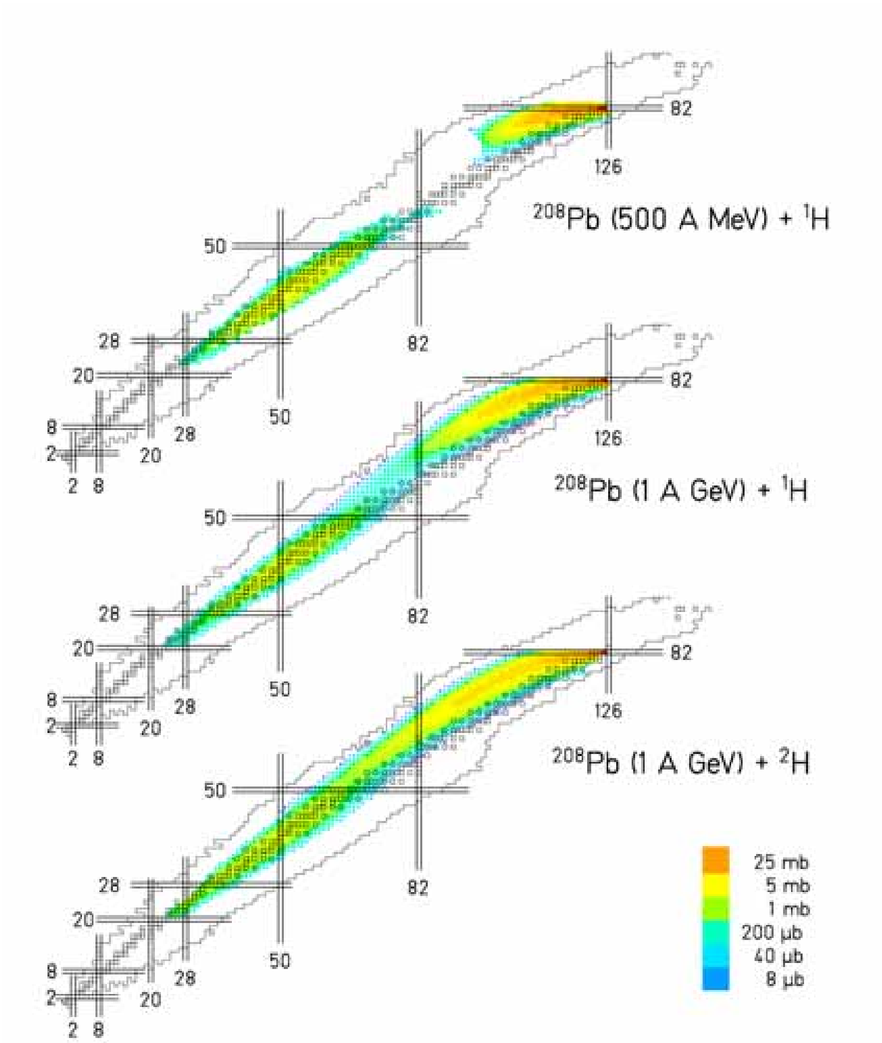
New generation of experiments on nuclide yields and kinematics at GSI



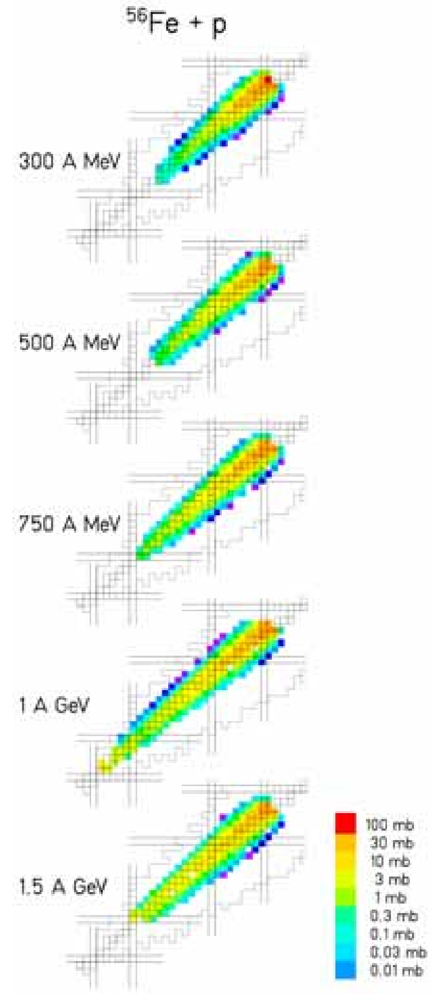
Relativistic heavy-ion beams + liquid H_2 target + powerful magnetic spectrometer
→ Experiments in inverse kinematics (Details in talk of A. Kelic!)

- **Full identification of all spallation products in Z and A.**
- **High-precision measurements of velocities.**

Systematics of nuclide yields

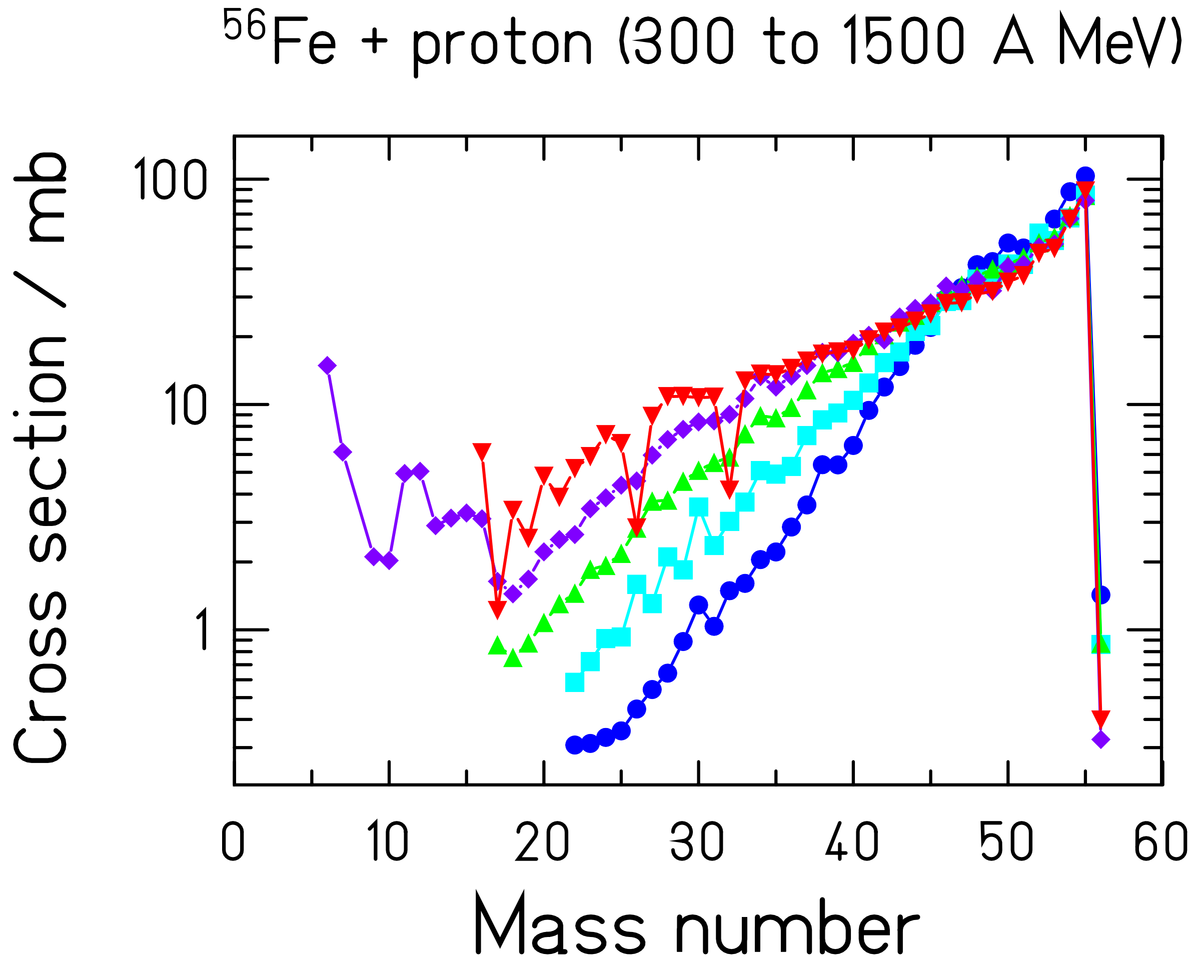


T. Enqvist, B. Fernandez, L. Audouin



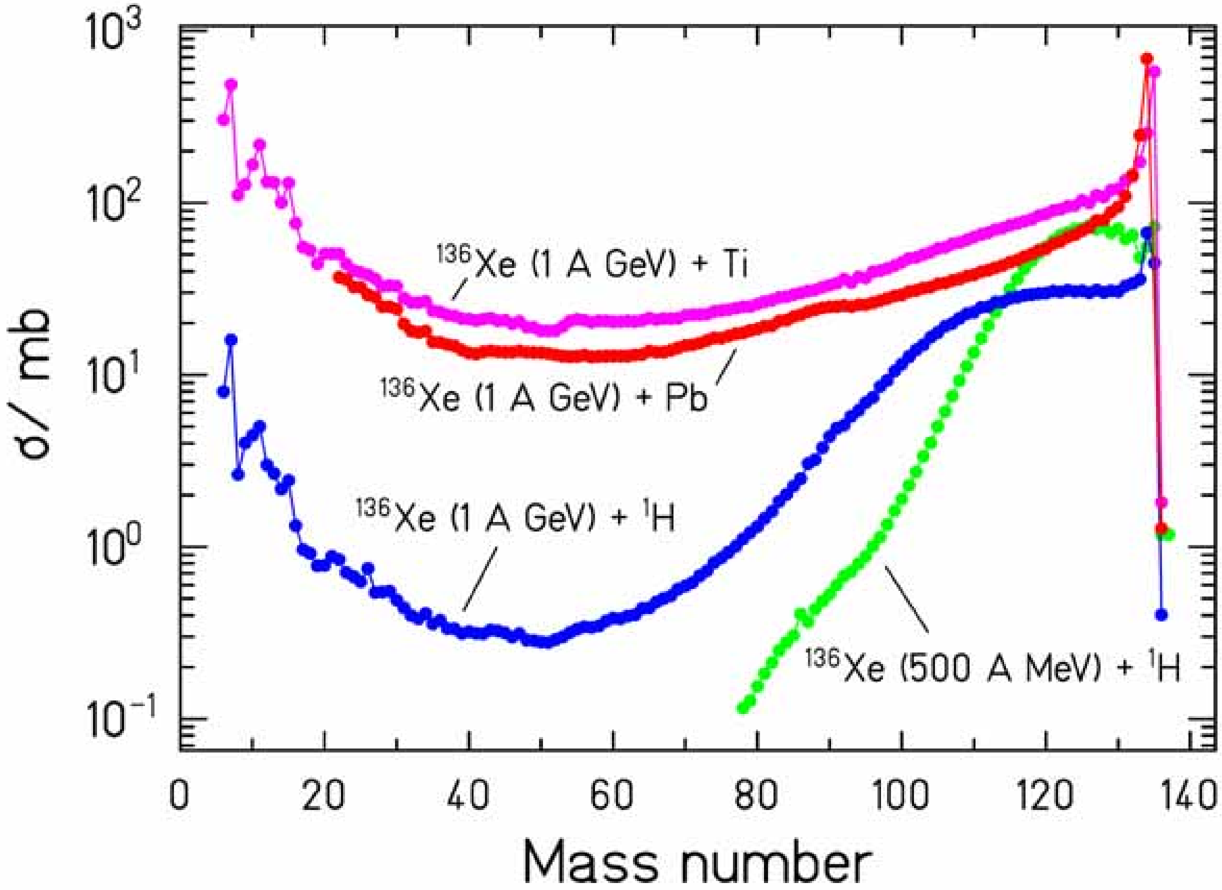
C. Villagrasa, P. Napolitani

Systematics of mass yields I



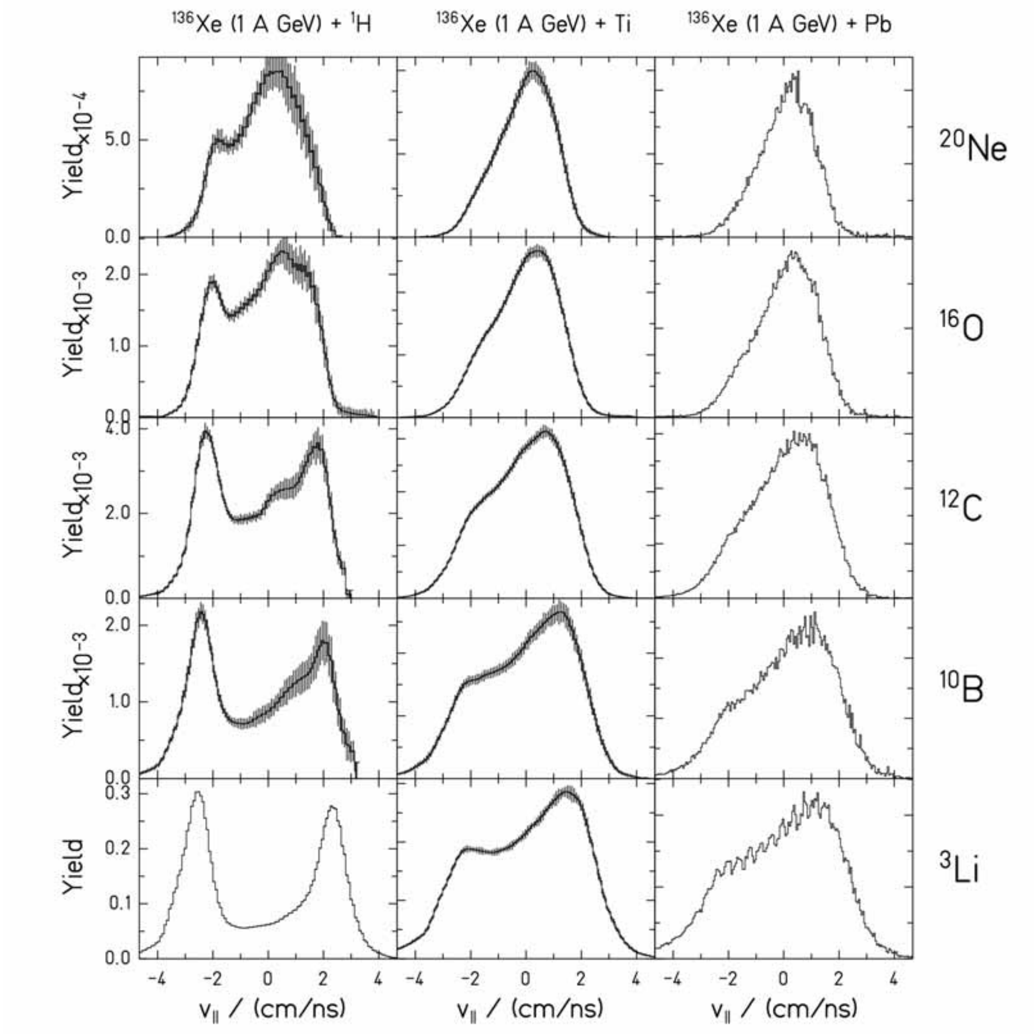
C. Villagrasa, P. Napolitani

Systematics of mass yields II



L. Giot, P. Napolitani, D. Henzlova

Systematics of kinematical properties



^{136}Xe (1 A GeV) + p:

Strong influence of Coulomb repulsion from heavy partner.

^{136}Xe (1 A GeV) + Ti, Pb

Complex shapes (binary decay + multifragm.)

(Details in talk of P. Napolitani!)

←

Longitudinal velocity distributions of fragments emitted in beam direction (invariant cross section).

P. Napolitani, D. Henzlova

Conclusion

Spallation reactions (high-energy particle – nucleus collisions) produce a large number of light fragments.

After sufficient heating, simultaneous emission of IMFs (multifragmentation) occurs. (Heavier than evaporation products and lighter than fission products.)

Conventional nuclear-reaction codes for spallation reactions
INC + pre-equilibrium + evaporation/fission
do not explain multifragmentation.

Thermal expansion and liquid-gas instabilities are thought to be responsible for multifragmentation.

Kinematics of multifragmentation products is complex.

Invariant cross sections (v distributions) seem to be a key information for the nature of multifragmentation.

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