Kinematical properties of spectator fragments in heavy-ion collisions at relativistic energies

-Antoine Bacquias-

Collaboration for High-Accuracy experiments on nuclear Reaction Mechanisms with a magnetic Spectrometer = CHARMS

http://www-w2k.gsi.de/charms/index.htm

present members:

A. Bacquias, V. Föhr, A. Kelic, M.V. Ricciardi, K.-H. Schmidt

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    - Mean longitudinal velocity
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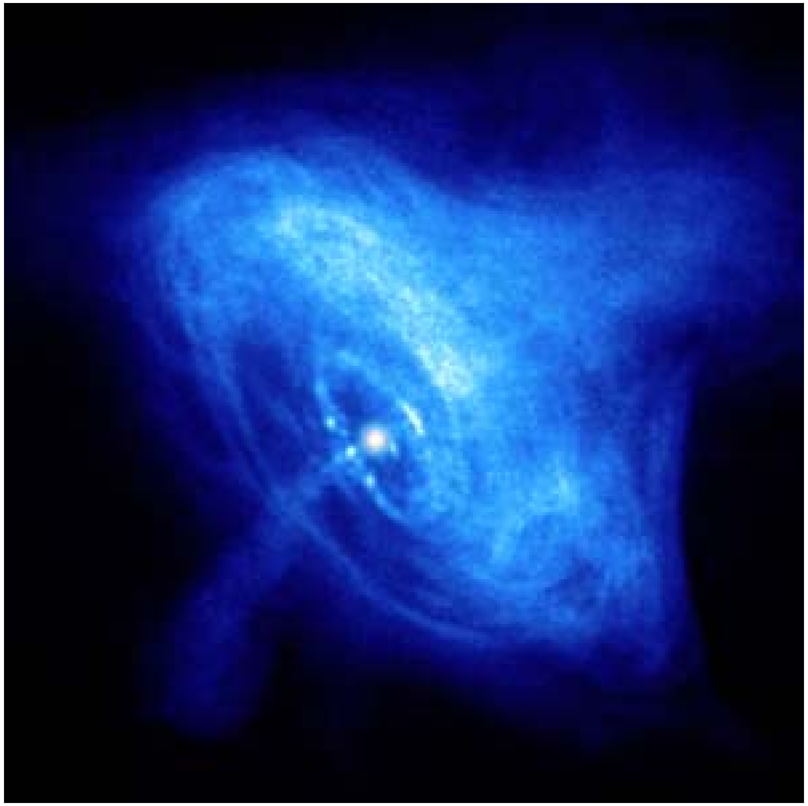
Why study the properties of nuclear matter?

Different aspects:

- static
- dynamic

→ fundamental interests (Equation of State) but also applications in other domains

Neutron stars



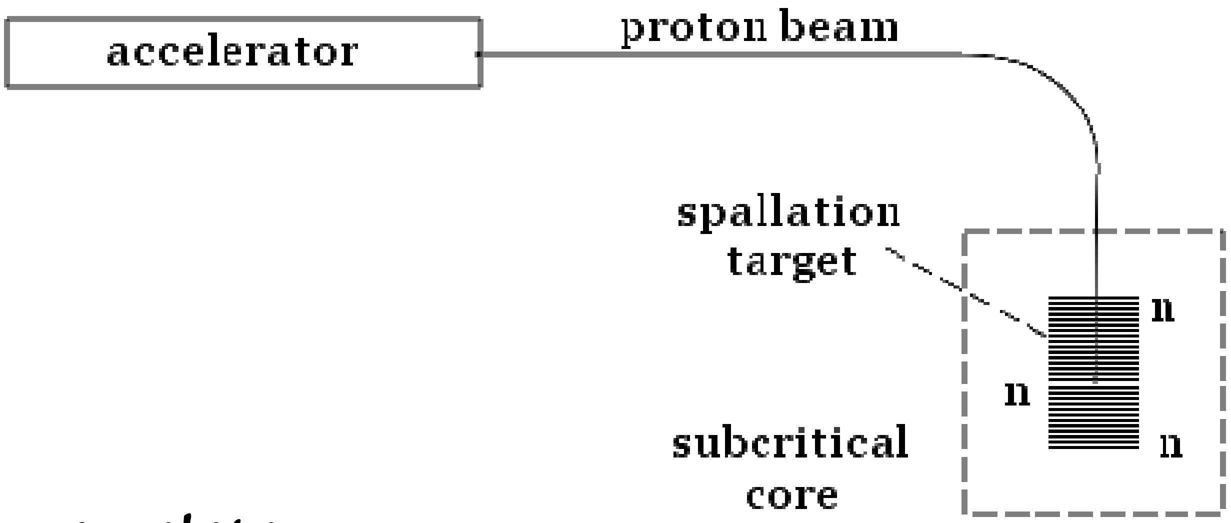
Crab Nebula X-ray emission seen by CHANDRA

radius limit depends on compressibility of nuclear matter see for example discussion in

Danielewicz et al., *Determination of EoS of dense matter*, Science (2002)

Technical applications

- Accelerator Driven Systems



- Secondary-beam facilities
emittance governed by kinematics of the fragments

Tests on nuclear matter in labs: collisions needed
case of relativistic energies

Beam energy around 1000 A MeV
Fermi energy inside the nuclei around 30 MeV

→ Fermi motion inside colliding nuclei is slow vs. beam velocity (distributions of rapidity do not overlap)

→ no exchange of nucleons between projectile & target

Tests on nuclear matter in labs: collisions needed
case of relativistic energies

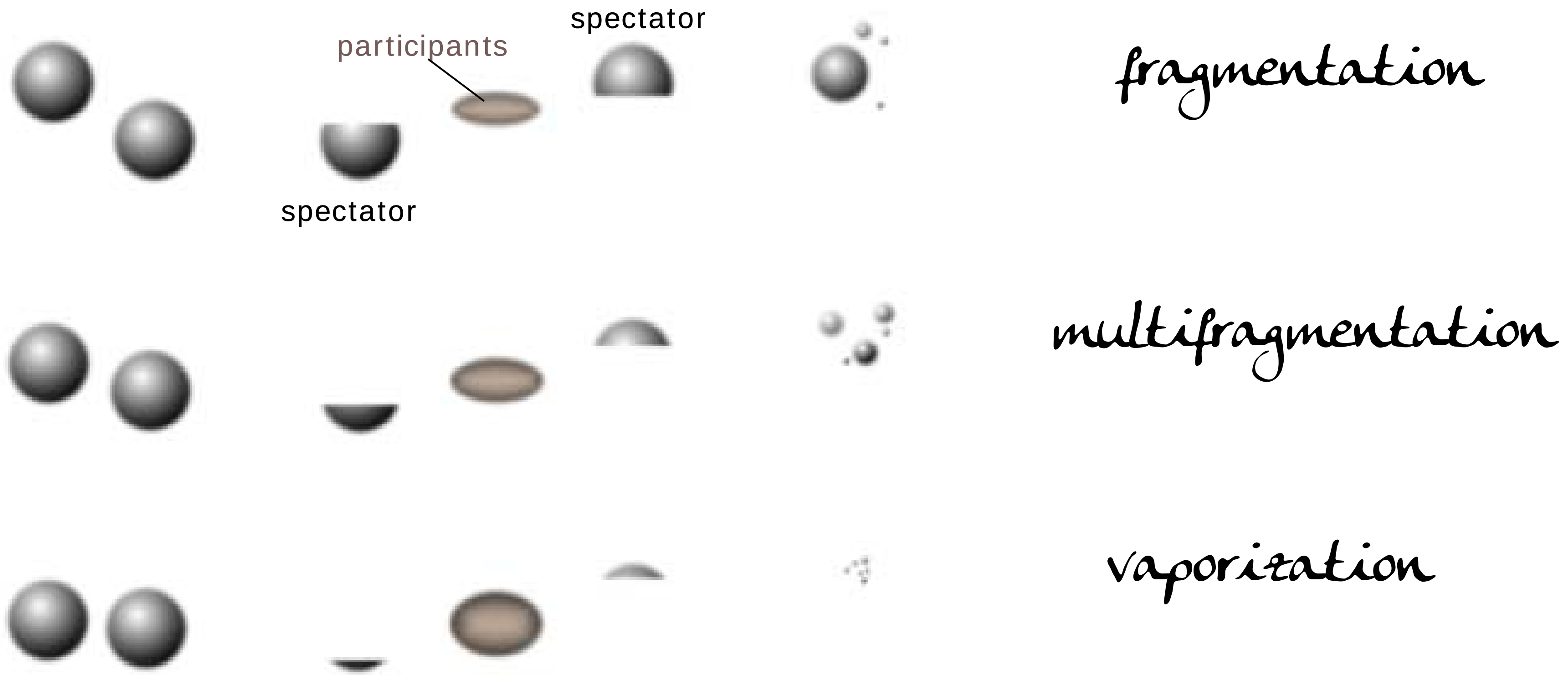
Nuclei consist of nucleons bound by nuclear force
Potential well around 40 MeV deep

→ Nuclear force negligible compared to the beam energy

Collision between bags of free nucleons at rest in their bag

This constitutes the basis of the original INC model

Various scenarii depending on the centrality



Various studies on nuclear matter

fire ball (ex: FOPI):

- hot and compressed matter
- particle production
- collective effects (flow)

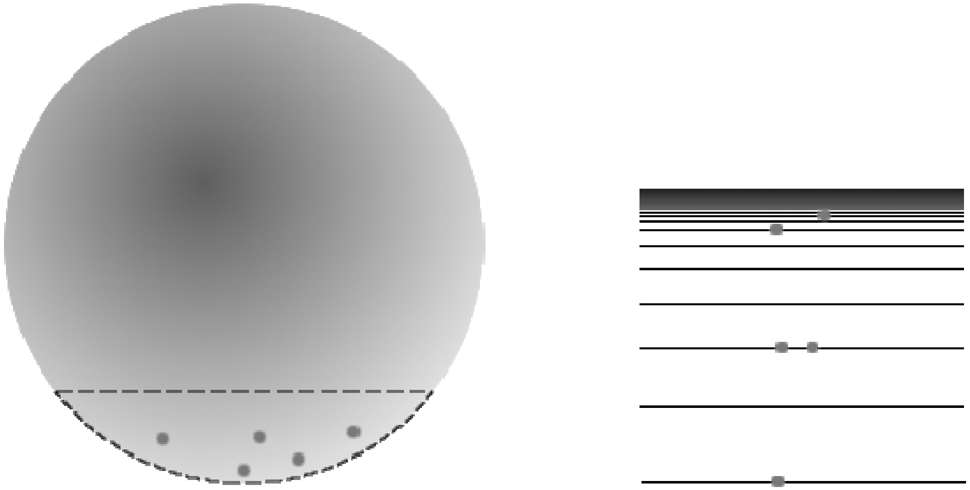
spectators:

- excited but not compressed
- phase transition of nuclear matter (ALADiN)
- reaction mechanisms & kinematics (this work)

spectators are excited products of the collision

removed nucleons:

- well defined in space
- sampled over the energy levels



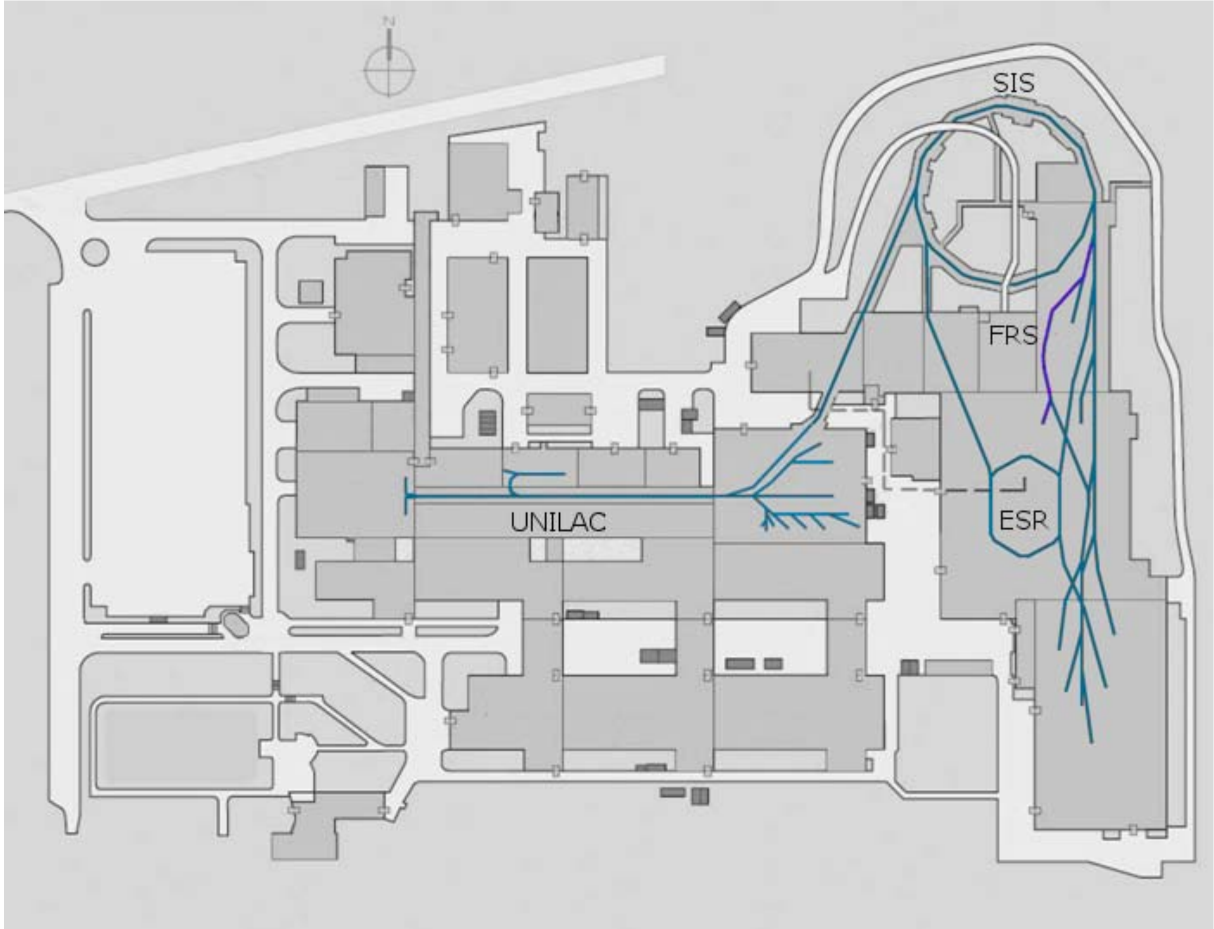
Kinematical studies on spectator matter

spectators almost keep the original beam velocity

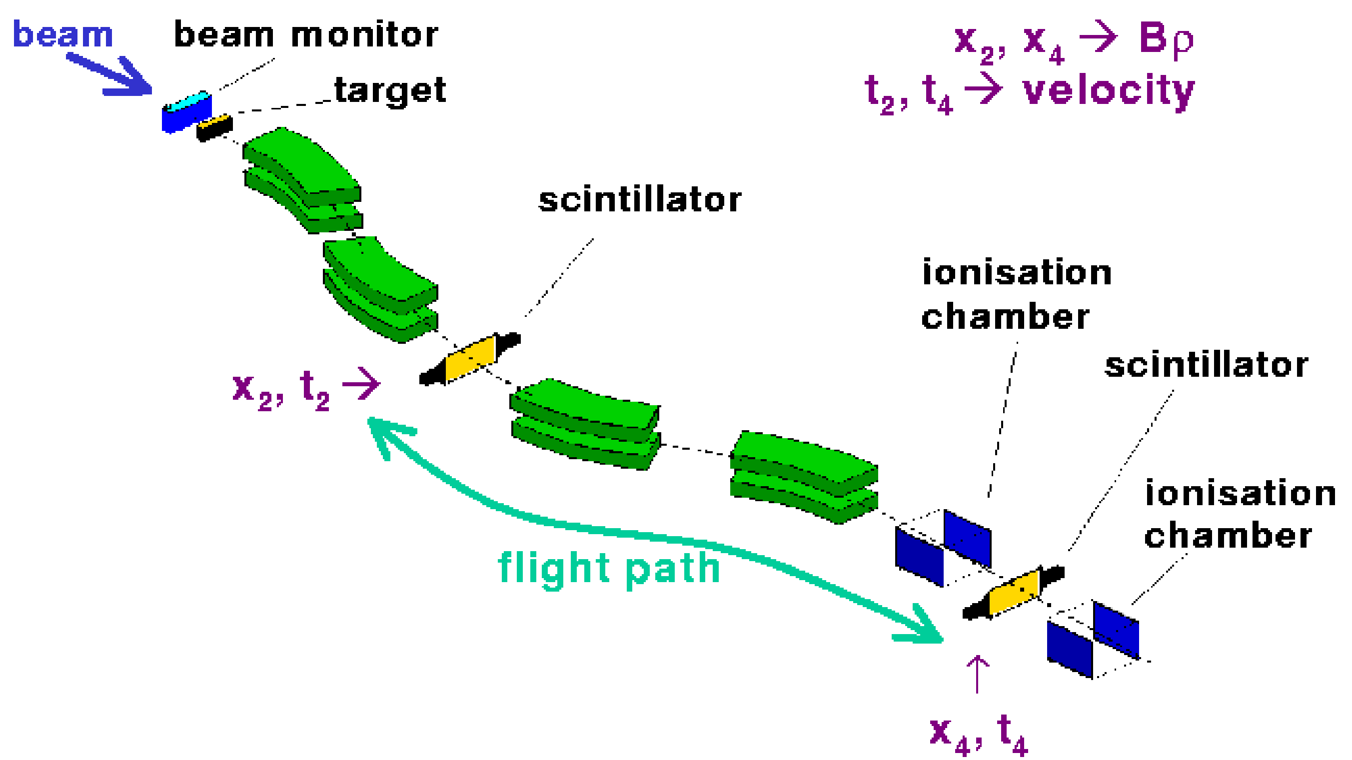
more detailed descriptions of interaction and reaction mechanisms are needed: intuitively, friction for example

high resolution measurement of the kinematics
→ not a full-acceptance set-up (too costly)

Where is the FRagment Separator in GSI ?



FRS set-up



beam
beam monitor
target
x_2, x_4 → Bρ
t_2, t_4 → velocity
scintillator
ionisation chamber
scintillator
ionisation chamber
x_2, t_2 →
flight path
x_4, t_4

Procedure

1.Identification

scintillators : - position at S2 and S4 $\rightarrow B\rho_{pos}$

- time of flight $\rightarrow \beta\gamma_{TOF}$

$$\frac{A}{Z} = \frac{e}{c \cdot m_0} \cdot \frac{B\rho_{pos}}{\beta\gamma_{TOF}}$$

MUSIC : energy loss → Z

2.High-precision velocities

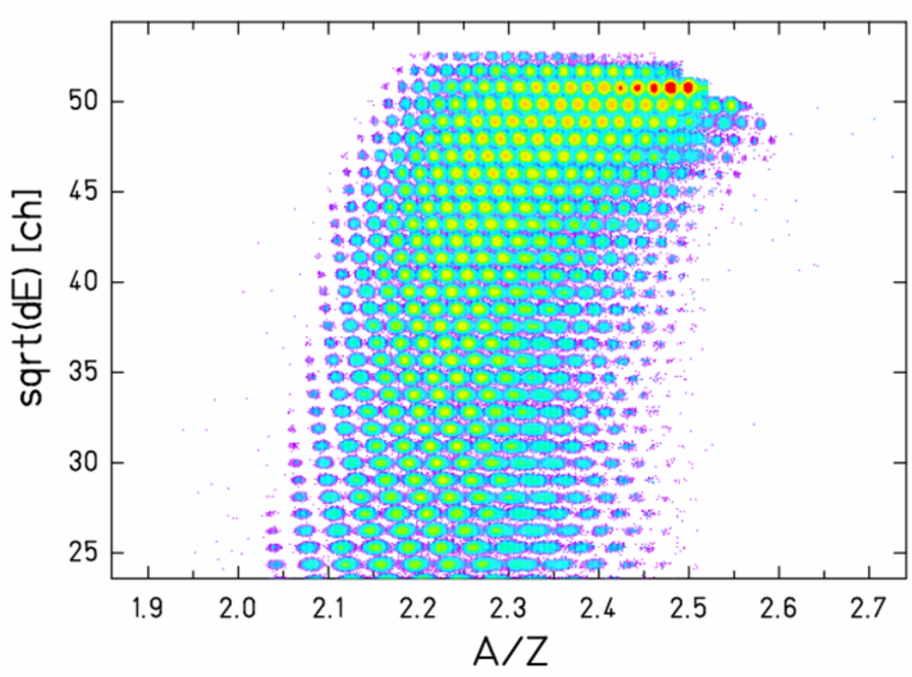
Exact values for A and Z (integers)

Precise calculation of the velocity $\Delta\beta\gamma / \beta\gamma \approx 5 \cdot 10^{-4}$

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

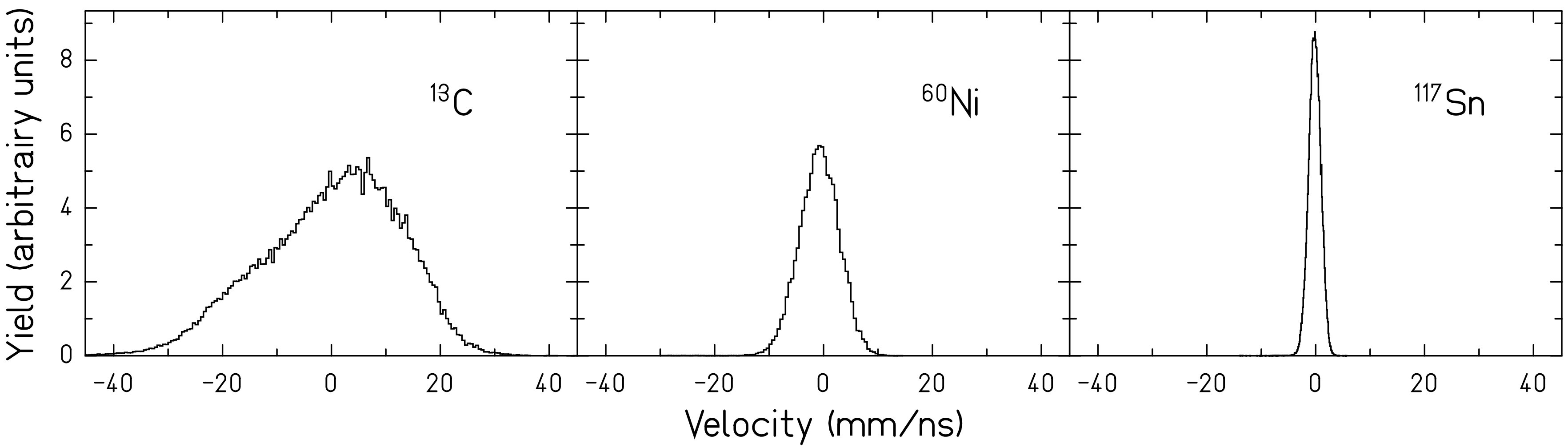
Identification pattern

^{136}Xe + Pb at 1 A GeV



Shapes of longitudinal velocity spectra

^{136}Xe + Pb at 1 A GeV



Gaussian distributions for heavy & medium masses

More complex structures for the lightest residues

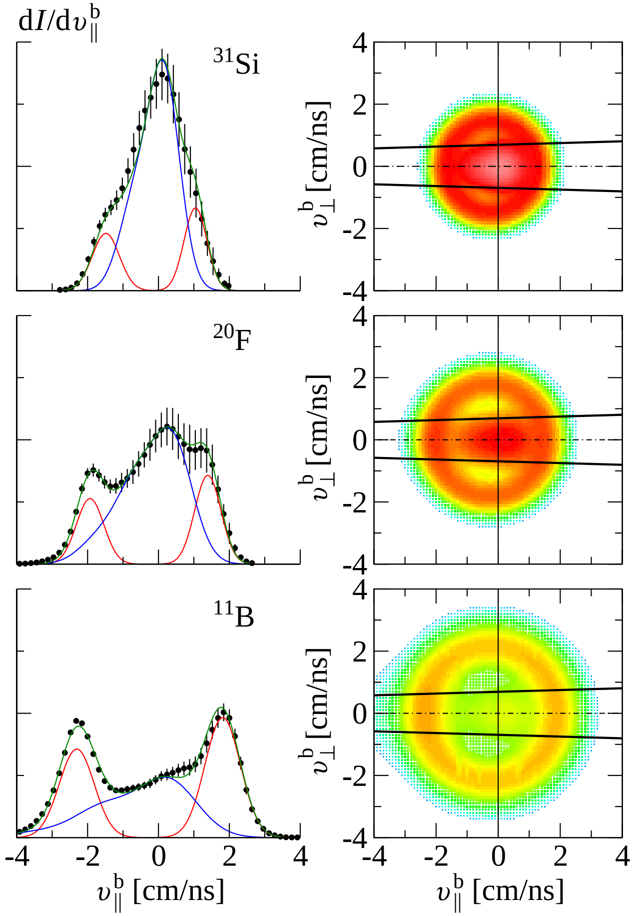
Shapes of longitudinal velocity spectra

complex structures:
with spallation experiments, more obvious
coming from two effects:
- central component (fragmentation)
- Coulomb shell (binary decay)

Shapes of longitudinal velocity spectra

similar than with lead target

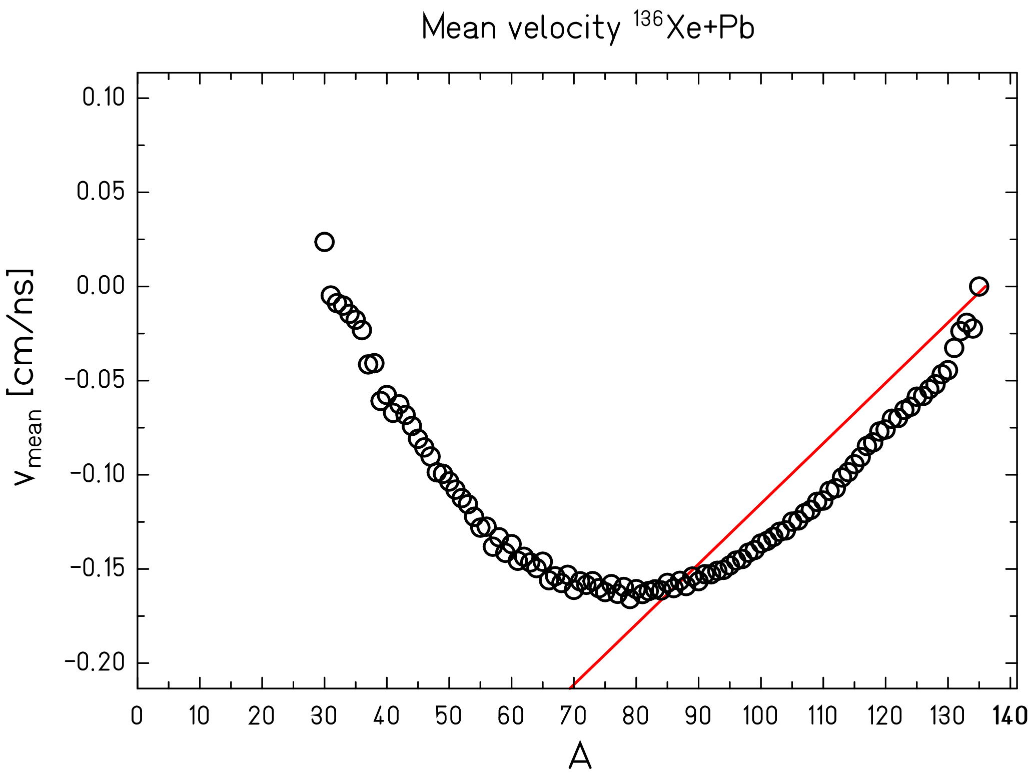
acceptance cut



Napolitani et al., arXiv_nucl-ex/0706.0646

^{136}Xe+p at 1 A GeV

Mean longitudinal velocity



slowing down
friction (Hüfner)
Morrissey systematics

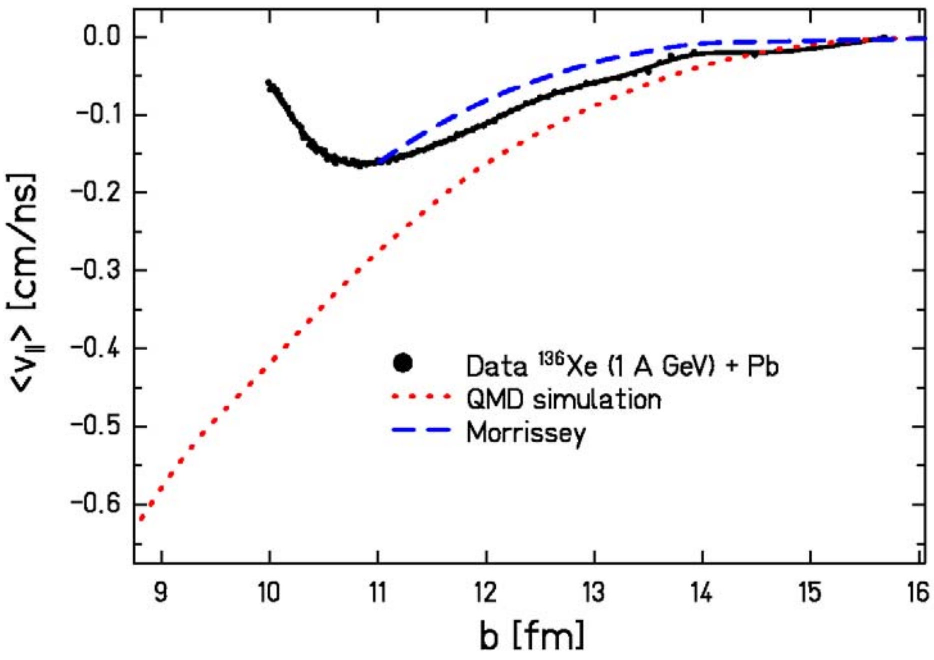
Phys. Rev. C39 (1989)

reacceleration:

- maybe connected to the EoS (momentum-dependence MF)
- possible response to the participant's blast

Ricciardi et al., PRL 90 (2003)
Henzl, PhD thesis

Mean velocity

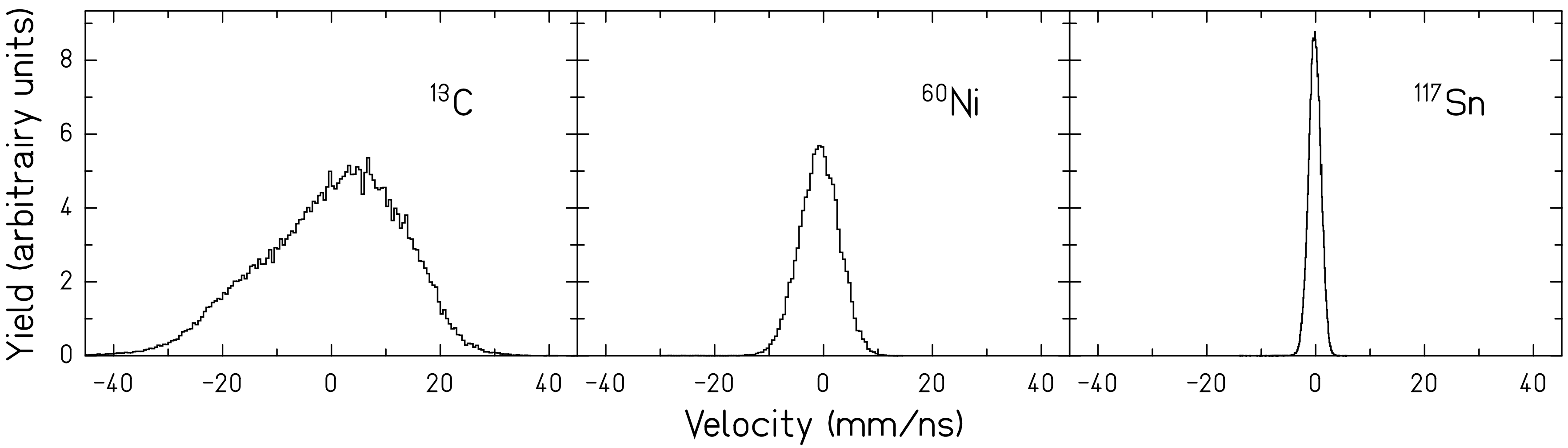


Understand the slowing down
→ compare with models
friction phenomenon related to in-medium N-N cross-sections?

Get rid of the modelization of evaporation velocities as a function of the impact parameter

connection established between observed cross-sections and predictions of Glauber theory for heavy residues

Dispersion

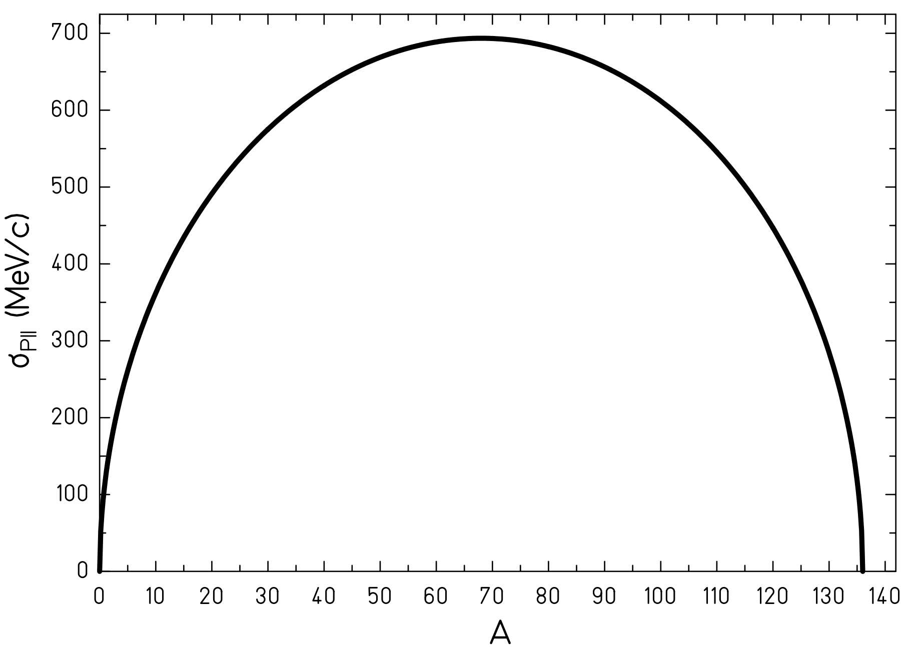


Yield (arbitrairy units)
0
2
4
6
8
^{13}C
^{60}Ni
^{117}Sn
-40
-20
0
20
40
Velocity (mm/ns)

Momentum dispersion

considerations true for longitudinal and transversal components of projectile-like and target-like spectators

Goldhaber formula for A_p = 136



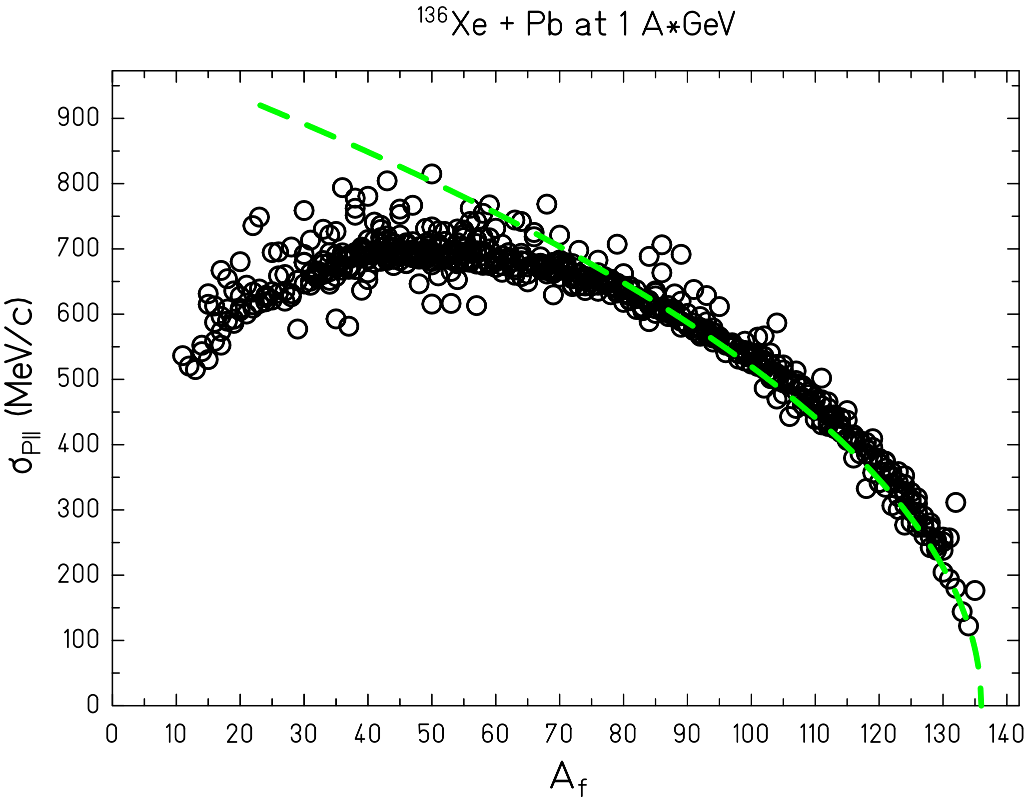
Goldhaber model
partition of fermions

$$\sigma_{P_\parallel}^2 = \frac{p_F^2}{5}\frac{A(A_p - A)}{(A_p - 1)}$$

Phys. Lett. 53B (1974)

only one step (abrasion)

Momentum dispersion



Morrissey fit function

not going back to zero!

$$\sigma_{P_\parallel}^2 = \frac{150^2}{3} \cdot (A_p - A_f)$$

Phys. Rev. C39 (1989)

not based on a model

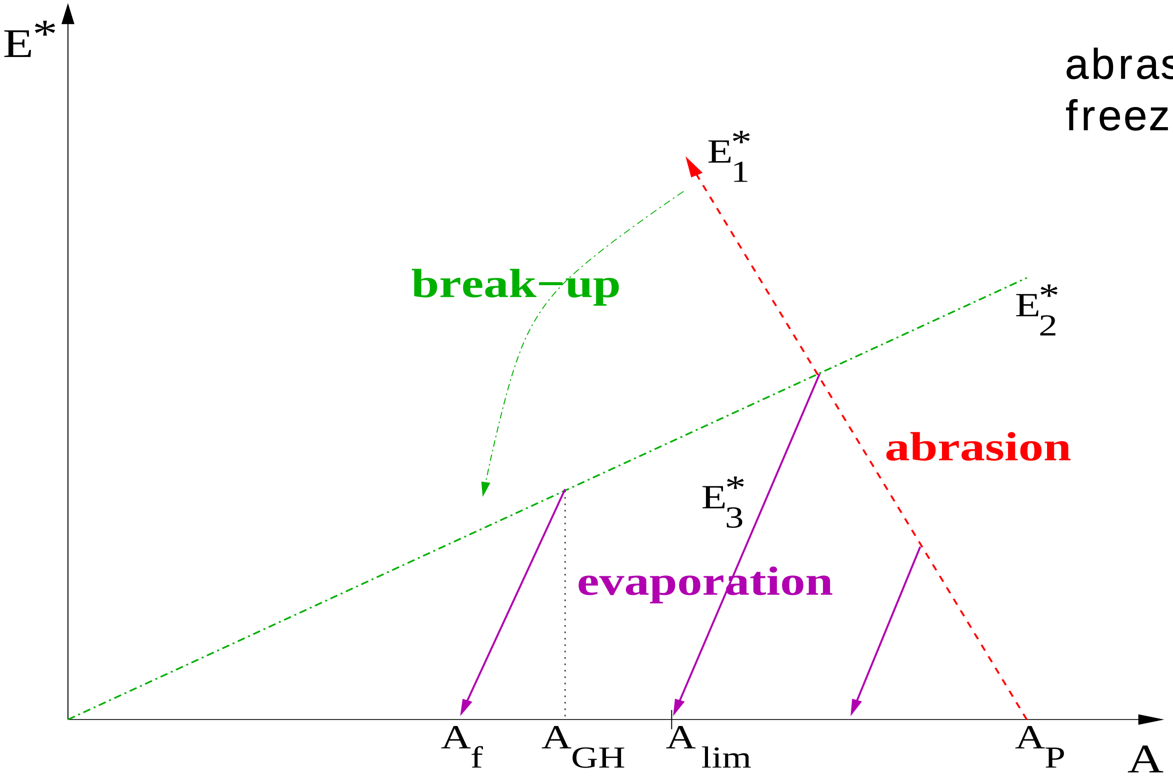
Momentum dispersion

Need for a new model with more physics

taking excitation into account
- fragmentation (abrasion)
- evaporation (sequential emission)
- multifragmentation (if reached)

also Coulomb repulsion

Evolution of excitation energy



abrasion of one nucleon: +27 MeV
freeze-out temperature : 5 MeV

Schmidt et al., NPA 710 (2002)

To build an analytical formula, need of other assumptions

Mean evaporation: ~15 MeV per evaporated nucleon

Observed fragment mass:

- above A_{lim}, it undergone abrasion and evaporation
- below A_{lim}, it is a product of multifragmentation

No Intermediate Mass Fragment emission

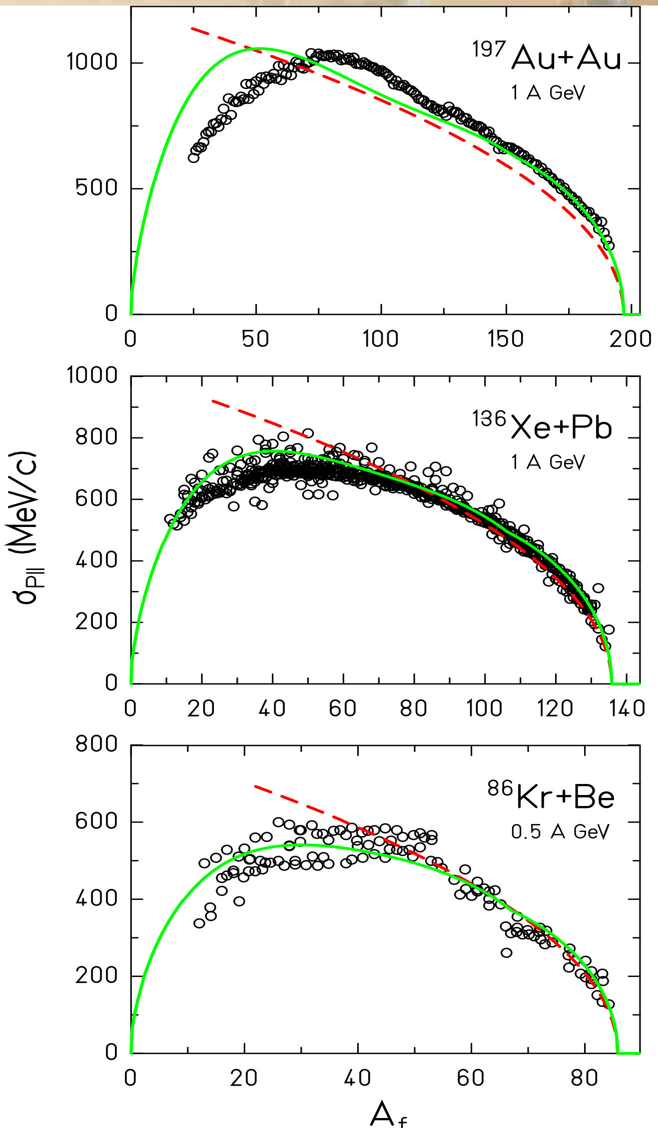
Momentum dispersion

Ingredients of the new model

- Fermi motion inside the projectile (Goldhaber style)
→ for both abrasion and break-up stages

- recoil momentum from evaporated particles
→ fit parameter or from Coulomb barriers

- Coulomb repulsion at break-up
→ upper estimation (biggest mother nucleus...)



good agreement for several systems
most of the mass range covered

small discrepancies due to

- overestimation of charge repulsion
- no expansion of the system at break-up (system diluted, lower Fermi momentum)

gold data: V. Henzl, PhD thesis
krypton data: M. Weber, PhD thesis

to summarize

Longitudinal velocity distributions of spectator fragments:

- 1st moment variations linked with EoS and N-N x-sections
- 2nd moment reflects the different production steps

"spectators" are not so innocent:

their kinematics show features of the reaction mechanisms

kinematical studies help improving simulations (ABRABLA)