Momentum distributions of projectile residues: a new tool to investigate fundamental properties of nuclear matter

("Spin off" of the research on spallation reaction to characterize neutron sources for ADS)

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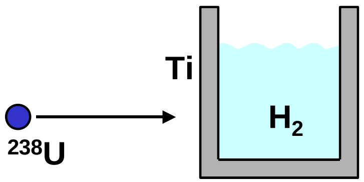
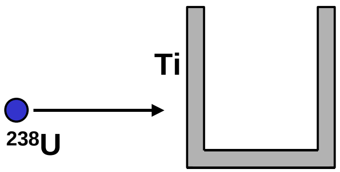
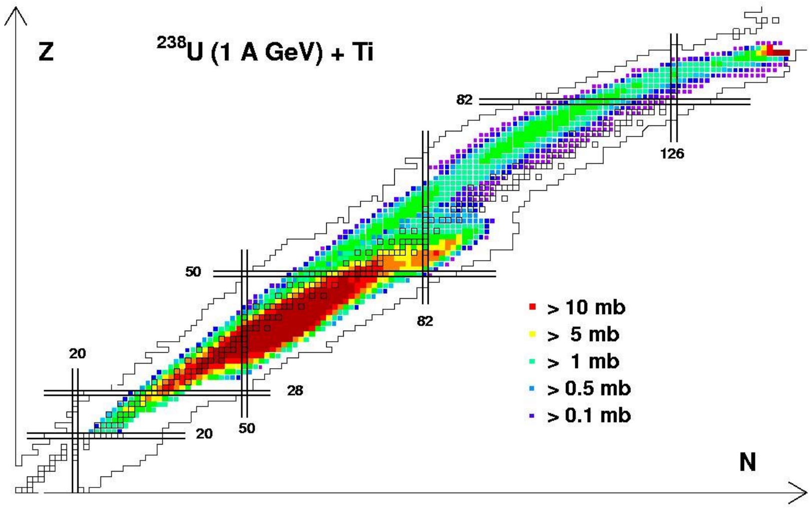
Relativistic heavy-ion collisions at the FRS

Isotopic identification of spallation residues in inverse kinematics ➡ Liquid hydrogen target with Ti windows







^{56}Fe + Ti at 1000 A MeV
^{208}Pb + Ti at 1000 A MeV
^{208}Pb + Ti at 500 A MeV
^{238}U + Ti at 1000 A MeV
^{238}U + Pb at 1000 A MeV

Production of hot and compressed nuclear matter

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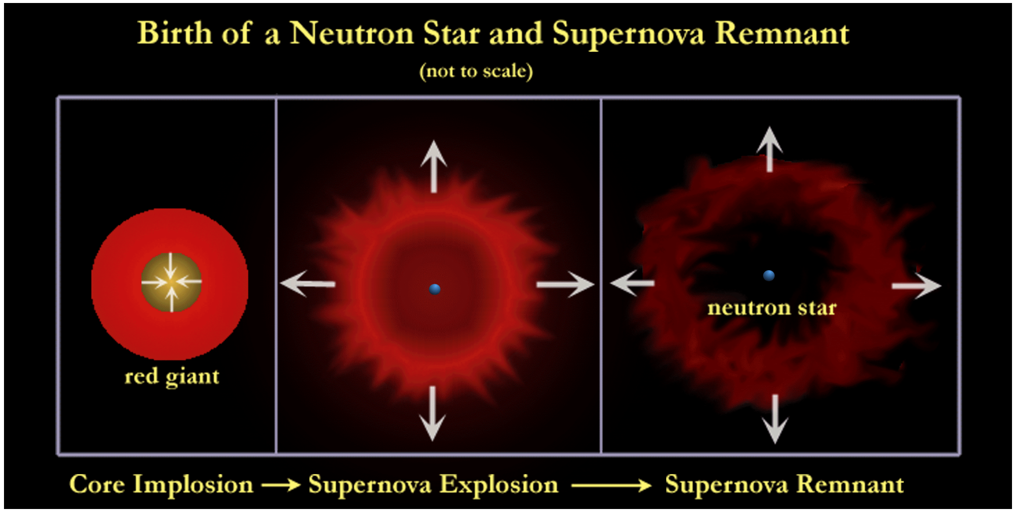
The equation of state of nuclear matter

Macroscopic properties of nuclear matter (P,V,T) are described by the corresponding equation of state

- ✓ fundamental properties of nuclear matter: incompressibility, phase transitions,...
- ✓ evolution of the early universe (Big Bang)
- ✓ stelar evolution: supernova explosions, neutron stars
- ✓ ....



The equation of state of nuclear matter

Real gas:

$$P = \frac{nRT}{V - nb} - a\frac{n^2}{V^2} \qquad P \approx 1 + \frac{n}{V}\left(b - \frac{a}{RT}\right) + \cdots = 1 + B_{2V}(T) + B_{3V}(T) + \cdots$$

$$B_{2V}(T) = \frac{n}{V}\left(b - \frac{a}{RT}\right) = -2N\pi\int_0^\infty (e^{-U(r)/kT} - 1)\ r^2 dr$$

U(r): molecular interaction

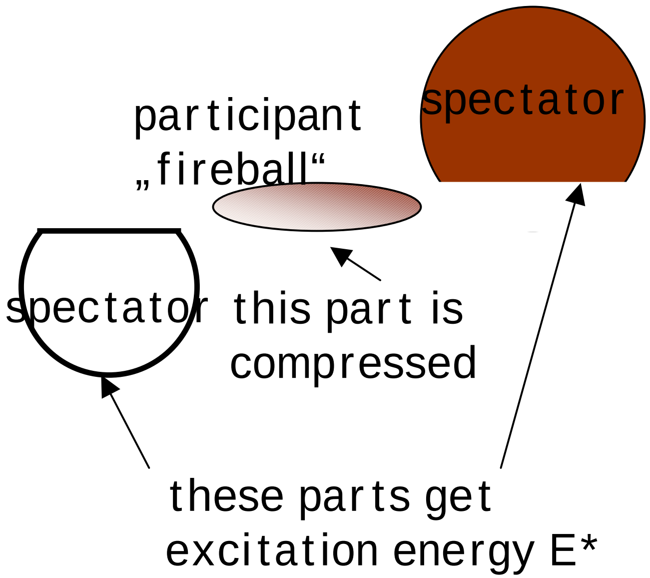
✓ Similar relations can be found between the nuclear equation of state and the nuclear mean field

✓ The nuclear mean field should be investigated under extreme conditions of pressure and temperature

→Nuclear incompressibility (hard or shoft EOS)
→ Momentum dependence of the nuclear mean field

Methods for EOS investigation

Relativistic heavy-ion collisions



Participant→ EOS incompressibility:

- ✓ collective flow
- ✓ kaon production
- ✓ charged particles correlations
- ✓ ....

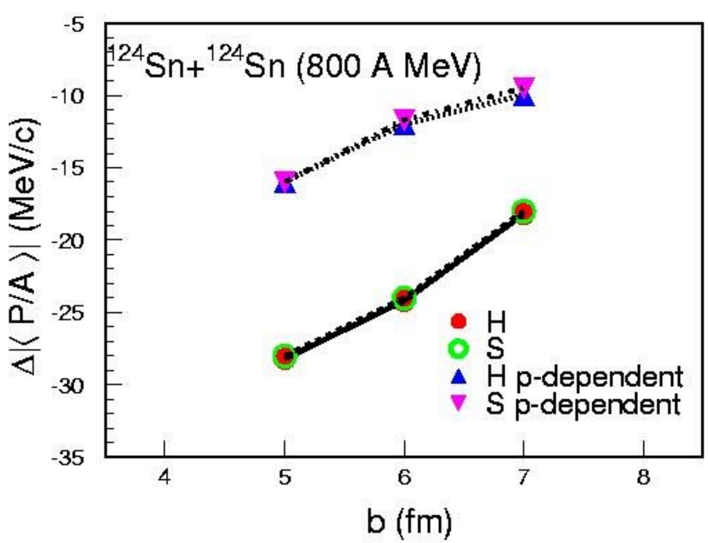
Spectator→ liquid-gas phase transition:

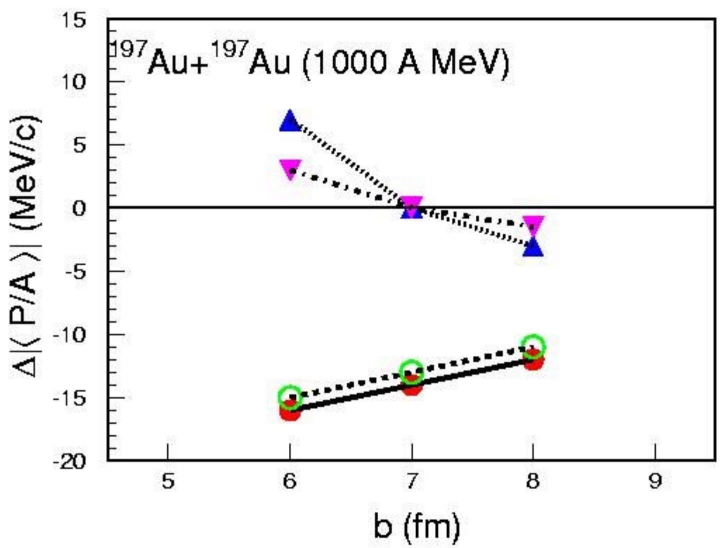
- ✓ multifragmentation
- ✓ calorimetry
- ✓ thermometers
- ✓ ....

Does the spectator feel the fireball?

Spectator response to the participant blast

L. Shi, P. Danielewicz and R. Lacey, Phys. Rev. C 64 (2001) 034601





✓ light systems: sensitivity of the spectator longitudinal momentum to the momentum dependence of the mean field

✓ heavy systems: acceleration of the spectator with a momentum-dependent mean field -> participant nucleons push the spectator

Experimental requirements

Search for a post-acceleration in projectile-spectator residues produced in relativistic heavy ion collisions

Required accuracy in c.m. velocity measurements at 1 A GeV → $\Delta v \ll 0.25$ cm/ns

✓ Time-of-fligth methods:

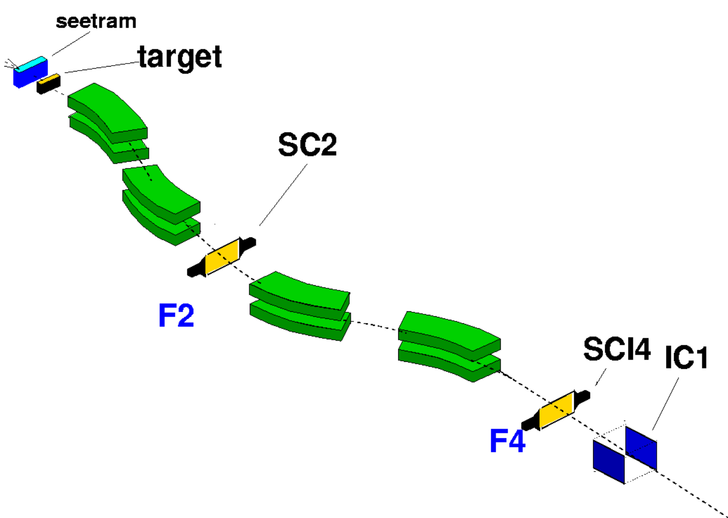
flight path 10 m, ΔToF 100 ps → $\Delta v = 0.5$ cm/ns

✓ High-resolving power magnetic spectrometers

$\Delta B\rho / B\rho = 10^{-3}$ → $\Delta v = 0.05$ cm/ns

Experimental technique

Momentum distributions of projectile-like residues produced in relativistic heavy-ion collisions investigated with the FRagment Separator (FRS) at GSI



$$\left(\frac{A}{Z}\right) = \frac{B\rho}{L} c \cdot ToF \sqrt{1 - \frac{L^2}{c^2 ToF^2}}$$

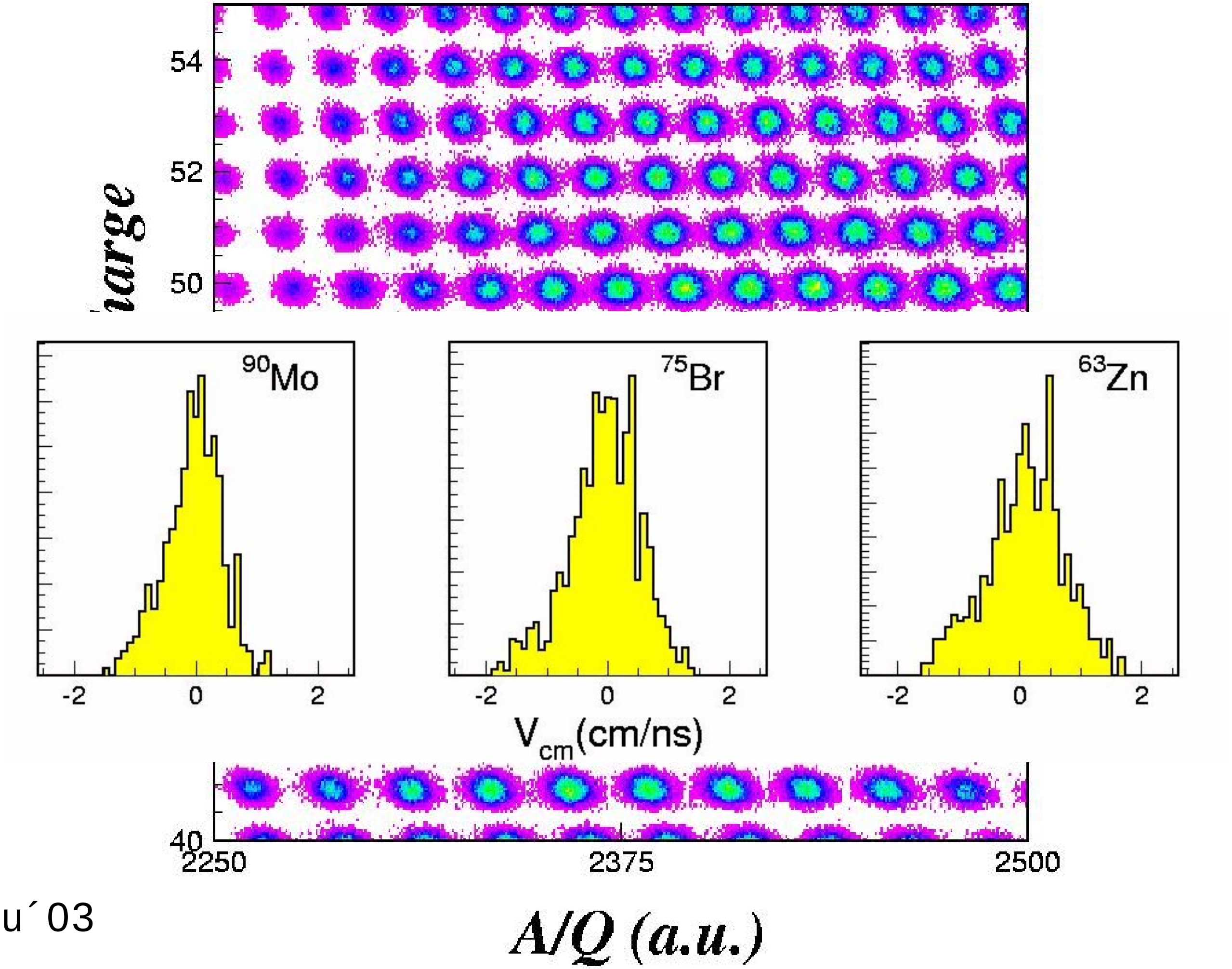
$$B\rho = \left(1 - \frac{x_2}{D}\right) \qquad Z \approx \sqrt{dE}$$

A, Z integer numbers

Isotopic identification and momentum measurement of the projectile residues

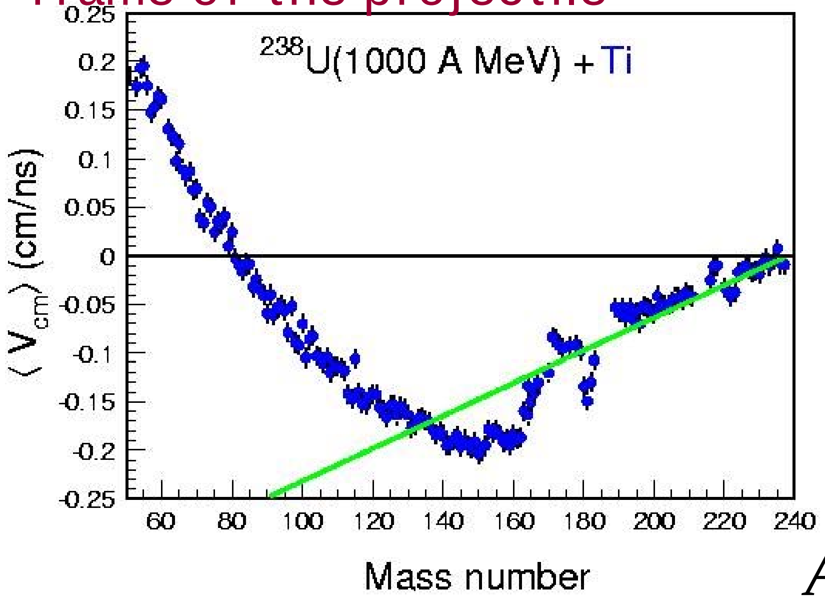
$$\beta\gamma = \frac{B\rho}{(A/Z)} \qquad \frac{\Delta B\rho}{B\rho} = \frac{\Delta\beta\gamma}{\beta\gamma} = \frac{\Delta \mathrm{v}}{\mathrm{v}}$$

Isotopic separation and momentum measurement

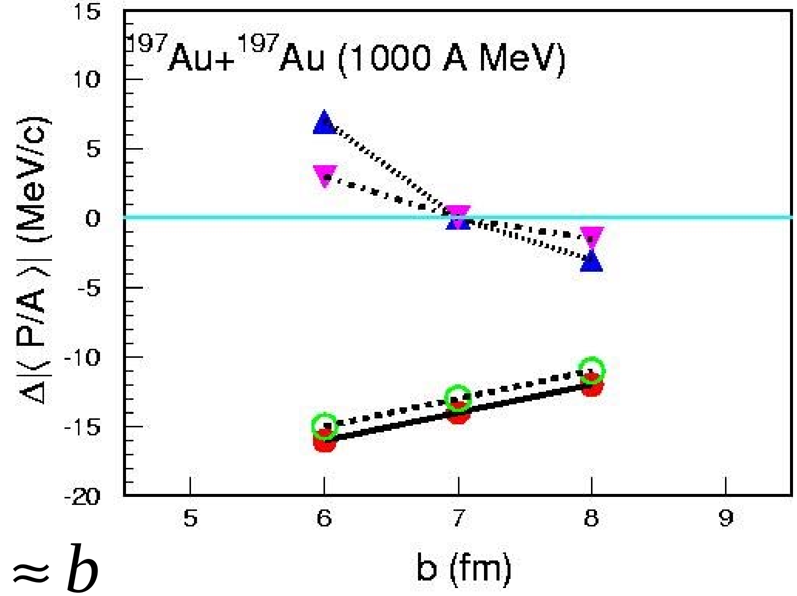


Results for ^{238}U(1 A GeV)+Ti system

Measured mean velocities of projectile-like residues in the frame of the projectile



$$A \approx b$$



150<A<240 velocity reduction due to friction (Morrisey´s systematics)

75<A<150 post-acceleration

40<A<75 residues are faster than the projectile

Experimental evidence for the response of the spectator to the participant blast -> momentum-dependent mean field

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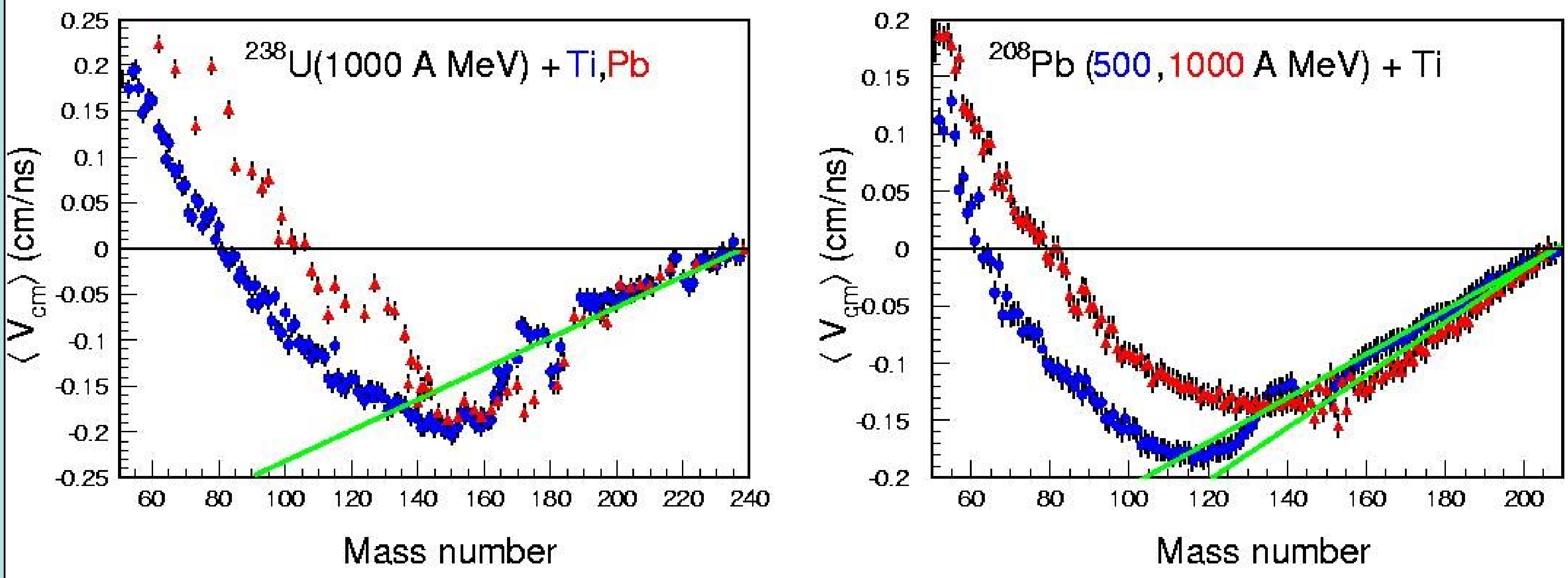
M.V. Ricciardi et al., Phys. Rev. Lett. 90 (2003) 212302

Dependence with the target size and projectile energy



Heavier systems induce a stronger post-acceleration effect

The post-acceleration effect increases with the energy of the projectile

M.V. Ricciardi et al., Phys. Rev. Lett. 90 (2003) 212302

B. Fernández and L. Audouin preliminary data

Conclusions

Secondary measurements performed in the framework of the spallation experiments at GSI allow to investigate the dynamics of relativistic heavy-ion collisions

Experimental evidences of the post-acceleration of projectile-like residues produced in relativistic heavy-ion collisions. The comprehensive investigation of different systems leads to the following conclusions:

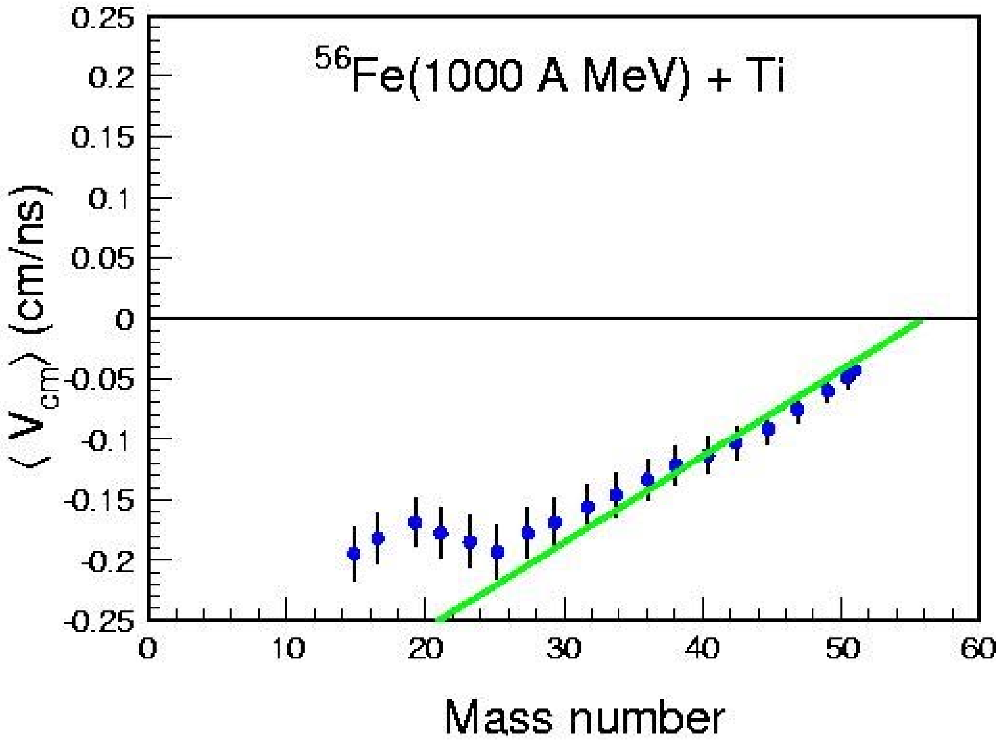
- The observed post-acceleration increases with the size of the system and the incident energy of the projectile

The required velocity resolution ($\Delta v \ll 0.25$ cm/ns) can only be obtained with high-resolution magnetic spectrometers

The qualitative comparison with the calculations of Shi and collaborators would indicate a momentum-dependent nuclear mean field

Dedicated calculations are required to obtain quantitative conclusions about the momentum dependence of the nuclear mean field and the EOS

Investigation of light systems



Light systems follows the systematics of Morrisey and no post-acceleration effect is observed

P. Napolitani, preliminary data