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 )


Gesellschaft fur Schwerionenforschung, Darmstadt, Germany
Universidad de Santiago de Compostela, Spain
Institut de Physique Nucleaire, Orsay, France

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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

$^{238}\text{U}$ + Ti at 1000 A MeV
$^{208}\text{Pb}$ + Ti at 1000 A MeV
$^{208}\text{Pb}$ + Ti at 500 A MeV
$^{238}\text{U}$ + Ti at 1000 A MeV
$^{238}\text{U}$ + Pb at 1000 A MeV

Production of hot and compressed nuclear matter

$^{56}\text{Fe}$ + Ti at 1000 A MeV

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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)
✓ stellar evolution: supernova explosions, neutron stars
✓ ........
The equation of state of nuclear matter

Real gas:

\[ P = \frac{nRT}{V - nb} - a \frac{n^2}{V^2} \]

\[ P \approx 1 + \frac{n}{V} \left( b - \frac{a}{RT} \right) + \cdots = 1 + B_{2V}(T) + B_{3V}(T) + \cdots \]

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

\[ U(r): \text{molecular interaction} \]

✓ 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 soft EOS)
→ Momentum dependence of the nuclear mean field

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Methods for EOS investigation

Relativistic heavy-ion collisions

Does the spectator feel the fireball?

Participant $\rightarrow$ EOS incompressibility:
- collective flow
- kaon production
- charged particles correlations
- .......

Spectator $\rightarrow$ liquid-gas phase transition:
- multifragmentation
- calorimetry
- thermometers
- .......

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Spectator response to the participant blast


✓ 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

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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 \( \Delta v \ll 0.25 \text{ cm/ns} \)

- Time-of-flight methods:
  - flight path 10 m, \( \Delta \text{ToF} \) 100 ps \( \rightarrow \Delta v = 0.5 \text{ cm/ns} \)

- High-resolving power magnetic spectrometers
  \( \Delta B / B \rho = 10^{-3} \rightarrow \Delta v = 0.05 \text{ cm/ns} \)

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

\[ \frac{A}{Z} = \frac{B \rho}{L} c \cdot \text{ToF} \sqrt{1 - \frac{L^2}{c^2 \text{ToF}^2}} \]

\[ B \rho = \left( 1 - \frac{x_2}{D} \right) \quad Z \approx \sqrt{dE} \]

A, Z integer numbers

\[ \beta \gamma = \frac{B \rho}{(A/Z)} \quad \frac{\Delta B \rho}{B \rho} = \frac{\Delta \beta \gamma}{\beta \gamma} = \frac{\Delta \nu}{\nu} \]
Isotopic separation and momentum measurement

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\( A/Q \) (a.u.)
Results for $^{238}$U(1 A GeV)+Ti system

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

- $^{238}$U(1000 A MeV) + Ti

$$\langle V_{cm} \rangle \text{ (cm/ns)}$$

- $^{197}$Au+${}^{197}$Au (1000 A MeV)

$$\Delta \langle \frac{P}{A} \rangle \text{ (MeV/c)}$$

- $150 < A < 240$: 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 $\rightarrow$ momentum-dependent mean field

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Heavier systems induce a stronger post-acceleration effect

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

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. 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 ($\Delta v \ll 0.25 \text{ cm/ns}$) 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.

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Investigation of light systems

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

P. Napolitani, preliminary data