High-Precision Momentum Measurements of Projectile Fragments in Sn+Sn Collisions at 1 AGeV

Ville Föhr¹,²

¹GSI
Darmstadt

²Department of Physics
University of Jyväskylä

ESF Exploratory Workshop - PESC: How To Constrain The High Density Symmetry Energy , 15-18 October, 2009
Outline

1 Introduction
   - Motivation
   - Experimental observables

2 Experimental techniques
   - Set-up
   - Mass and nuclear charge identification
   - Velocity distributions

3 Results
   - Cross sections
   - Width of the distribution
   - Mean value of the distribution

4 Theoretical investigation
   - BUU
   - Comparison with data

5 Summary

6 Acknowledgements
Motivation

Fundamental interests

- Properties of nuclear matter
  - static: compressibility, symmetry energy, phase transitions...
  - dynamic: viscosity, momentum dependence of the mean field...
- Astrophysical and cosmological phenomena
  - Formation and stability of neutron stars
  - Supernova explosions
  - Evolution of the early universe
### Observables

<table>
<thead>
<tr>
<th></th>
<th>Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flow</td>
</tr>
<tr>
<td></td>
<td>Spectators</td>
</tr>
<tr>
<td></td>
<td>Kinematical properties</td>
</tr>
</tbody>
</table>

- **Motivation**
- **Experimental observables**
- **Experimental techniques**
  - Set-up
  - Mass and nuclear charge identification
  - Velocity distributions
- **Results**
  - Cross sections
  - Width of the distribution
  - Mean value of the distribution
- **Theoretical investigation**
  - BUU
  - Comparison with data
- **Summary**
- **Acknowledgements**
History of spectator kinematics

Morrissey systematics
- Explained low mass losses

High resolution measurements

- $^{238}\text{U} + \text{Pb}$: T. Enqvist et al. NPA 658(1999)47
- $^{208}\text{Pb} + \text{Ti}$: T. Enqvist et al. NPA 703(2002)435465
- $^{238}\text{U} + \text{Ti}$: V. Ricciardi et al. PRL 90(2003)212302
- $^{197}\text{Au} + \text{Au}$: V. Henzl, PhD thesis (2005)
- $^{56}\text{Fe} + \text{Ti}$: C. Villagrassa-Canton et al. PRC 75(2007)044603
- $^{136}\text{Xe} + \text{Pb}$: A. Bacquias, PhD thesis (2009)
Theoretical investigations

Spectator Response to the Participant Blast

L. Shi, P. Danielewicz, R. Lacey, PRC 64 (2001) 034601

BUU calculations

- Sensitivity to
  - Momentum dependence of the mean field
  - NN cross section
- Almost no sensitivity to stiffness of the EOS
Why $^{112,124}\text{Sn} + ^{112,124}\text{Sn}$ at 1 A GeV?

- Isospin influence on the re-acceleration
- Symmetric systems assures constant N/Z of the participant zone for all possible impact parameters
- Low fission cross section compared to heavier systems
- High enough energy
**Experiment setup**

**The Fragment Separator**

\[ Z \text{ from IC: } \Delta E \propto Z^2 \]

\[
\frac{A}{Z} \text{ from time and position: } A = \frac{e}{m_0}\frac{B\rho}{c\beta\gamma}
\]

After mass and charge have been identified the velocity is calculated from \( B\rho \) (\( A, Z \) are integers):

\[
\beta\gamma = \frac{e}{cm_0}\frac{Z}{A} B\rho
\]

Very high precision: \( \Delta P/P = 10^{-4} \)
Mass and nuclear charge identification

$^{124}\text{Sn} + ^{124}\text{Sn} @ 1 \text{ A GeV}$

Heavy residues

Light residues

$A/\Delta A \approx 400$

$\Delta Z \approx 0.4$
Obtaining the velocity distributions

Corrections

Limited momentum acceptance

Limited angular acceptance

- Combining data from several magnetic settings

- Advantage in separating different production mechanisms
Longitudinal velocity distributions

Three observables

1. Area
2. Width
3. Mean value
Production cross sections

Integrals of velocity distributions

\[ \text{Integrals of velocity distributions} \]

\[ \sigma \text{ (mb)} \]

\[ \text{Integrals of velocity distributions} \]

\[ \sigma \text{ (mb)} \]

\[ \text{Integrals of velocity distributions} \]

\[ \sigma \text{ (mb)} \]
"Well understood" physics:

- **Based on Goldhaber model**

- **Corrected for Coulomb repulsion, multifragmentation and evaporation**
  A. Bacquias, PhD thesis (2009)

- **Reveals different production steps during de-exitation**
Peripheral collisions:
- No clear difference seen

More central collisions:
- Sensitivity to collision violence
- Signs of N/Z dependence?
Comparison with other systems

\[ \langle v_{||} \rangle \text{ for different systems (1 AGeV)} \]

- \( \text{EXP } ^{124}\text{Sn} + ^{124}\text{Sn} \)
- \( \text{EXP } ^{112}\text{Sn} + ^{112}\text{Sn} \)
- \( ^{238}\text{U} + ^{208}\text{Pb} \)
- \( ^{238}\text{U} + ^{238}\text{Ti} \)
- \( ^{208}\text{Pb} + ^{238}\text{Ti} \)
- \( ^{197}\text{Au} + ^{197}\text{Au} \)
- \( ^{136}\text{Xe} + ^{208}\text{Pb} \)
- \( ^{56}\text{Fe} + ^{238}\text{Ti} \)

- Morrissey systematics
- Primary beam (1 AGeV)
Theoretical calculations

- BUU calculation cannot be compared directly with data
- Need to establish connection between impact parameter and final residue mass

1. **ABRABLA**
   - Proven to have good prediction power
   - Geometrical model of collision
   - Can’t study microscopical effects

2. **BUU**
   - Microscopical model
   - Difficult to define $E^*, A, Z$
   - Time consuming
   - No evaporation stage
BUU results

With momentum independent (MI) meanfield:

124Sn + 124Sn 1AGeV

\[ \begin{align*}
\langle p_x \rangle [\text{MeV/c}] \\
\text{B [fm]} \\
\end{align*} \]

\[ \begin{align*}
\langle p_y \rangle [\text{MeV/c}] \\
\text{B [fm]} \\
\end{align*} \]

With momentum dependent (MD) meanfield:

124Sn + 124Sn 1AGeV

\[ \begin{align*}
\langle p_x \rangle [\text{MeV/c}] \\
\text{B [fm]} \\
\end{align*} \]

\[ \begin{align*}
\langle p_y \rangle [\text{MeV/c}] \\
\text{B [fm]} \\
\end{align*} \]

This used as input for the statistical code ABRABLA
Comparison with data

Best correlation seen with MD + NN cross section
Comparison with data

Same model parameters for 3 different systems

197Au + Au data by V. Henzl, PhD thesis (2005)

Qualitative agreement very good!
Summary

- Re-acceleration phenomena is seen in all systems, its strength depends on the "violence" of the collision.
- Results support momentum dependent mean field and free NN cross section.

Outlook
- Disentanglement of N/Z from other degrees of freedom.
- Better correlation between impact parameter and final fragment mass.
Acknowledgements

CHARMS
(Collaboration for High-Accuracy Experiments on Nuclear Reaction Mechanisms with Magnetic Spectrometers)

A. Kelic¹, M.V. Ricciardi¹, K.-H. Schmidt¹,⁴

Previous members:
A. Bacquias², V. Henzl³, D. Henzlova³, S. Lukic⁵, P. Napolitani⁴

Special thanks to Pawel Danielewicz³

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

¹ GSI, Darmstadt, Germany
² CEA, Saclay, France
³ MSU, East Lansing, Michigan, USA
⁴ GANIL, Caen, France
⁵ Forschungszentrum, Karlsruhe, Germany