Light Fragment Production in Heavy Ion Collisions and the Symmetry Energy

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with
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Remi Bougault (LPC Caen), Abdou Chbihi (GANIL, Caen)
Agenda:

- Importance of the Nuclear Symmetry Energy in nuclear and astrophysics and its uncertainty
- Density and momentum dependence of the symmetry potential
- Here: early emission of nucleons and light fragments as a probe for $\rho \leq \rho_0$
- Possibility to disentangle density and momentum dependence of the symmetry energy
Investigations of the Nuclear Symmetry Energy in different density regions

\[
E(\rho, \delta)/A = E(\rho) + E_{\text{sym}}(\rho) \delta^2 + O(\delta^4) + \ldots
\]

\[
\delta = \frac{\rho_n - \rho_p}{\rho}
\]

heavy ion collisions in the Fermi energy regime

Isospin Transport properties, (Multi-)Fragmentation
Pre-equilibrium emission

Nuclear structure (neutron skin thickness, Pygmy DR, IAS)
Slope of Symm Energy

rel. heavy ion collisions
\( p, n \)
\( \pi^\pm, K^{+,0} \)

Isotopic ratios of flow, particle production
The Nuclear Symmetry Energy in different „realistic“ models

Why is symmetry energy so uncertain??
- In-medium $\rho$ mass, and short range isovector tensor correlations (e.g. B.A. Li, PRC81 (2010));
- use heavy ion collisions to investigate in the laboratory

Rel, Brueckner Variational
Rel. Mean field
Chiral perturb.
Example of the isovector dependence for a particular parametrization (used in the following results, BGBD, Bombaci-Gale-Bertsch-DasGupta)

Symmetry energy

Neutron/proton potentials as a fct of density for $p=p_F$ (left) momentum for $\rho=\rho_0$ (right)

Effective masses (for asystiff and $p=p_F$)
Symmetry energy and symmetry potentials (effective masses)

B.A. Li, X. Han, arXiv:1304.3368

establish a relation \( \{E_{\text{sym}}, L\} \leftrightarrow \{U_{\text{sym}}, m^*_{n,p}\} \) using the Hugenholtz-Van Hove theorem

\[
E_{\text{sym}}(\rho) = \frac{1}{3} \frac{\hbar^2 k_F^2}{2m^*_0} + \frac{1}{2} U_{\text{sym}}(\rho, k_F), \\
L(\rho) = \frac{2 \hbar^2 k_F^2}{3m^*_0} + \frac{3}{2} U_{\text{sym}}(\rho, k_F) + \frac{\partial U_{\text{sym}}}{\partial k} |_{k_F, k_F},
\]

\[
U_{\text{sym}}(\rho_0, k_F) = 2 \left[ \frac{E_{\text{sym}}(\rho_0)}{m^*_0} - \frac{1}{3} \frac{E_F(\rho_0)}{m^*_0} \right] + \frac{m^*_n - m^*_p}{m^*_0} \frac{E_F(\rho_0)}{k_F},
\]

Use existing determinations in the literature for \( \{E_{\text{sym}}, L\} \) to obtain values for \( \{U_{\text{sym}}, m^*_{n,p}\} \).

Without going into details, shows appearance of some consensus on the symmetry potential and the effective mass, but also the large scatter (esp. for the effective mass splitting)

\( \rightarrow \) need to constrain this better
Isospin-related Observables in Low Energy Heavy Ion Collisions

Coulomb barrier to Fermi energies

- Peripheral:
  - Isospin migration
  - Deep-inelastic
  - N/Z of PLF residue = isospin diffusion
  - N/Z of neck fragment and velocity correlations

- Central:
  - Isospin fractionation, multifragm
  - Pre-equil. light particles
  - N/Z ratio of IMF's

Discuss here
Pre-equilibrium particle emission: n/p ratio

Early emitted neutrons and protons reflect difference in potentials in expanded source, esp. ratio \( Y(n)/Y(p) \). More emission for asy-soft, since symm potential higher.

Neutrons difficult to measure, thus “Double Ratios”

Data: Famiano et al. PRL 06
Calc.: Danielewicz, et al. 07

\[ ^{124}\text{Sn} + ^{124}\text{Sn} \]
\[ ^{112}\text{Sn} + ^{112}\text{Sn} \]

\( \delta = 0.2 \)

\( \nu \) neutrons
\( \rho \) protons

\( \text{asysoft} \) (red)
\( \text{asystiff} \) (blue)
\( \text{asysuperstiff} \)

Effect of mass splitting of same magnitude

Similar qualitatively but smaller effect

\( m_n^* > m_p^* \) asysoft (red)
\( m_n^* < m_p^* \) (blue)

\( m_n^* > m_p^* \) (red)
\( m_n^* < m_p^* \) (blue)

\( \Rightarrow \) A sensitive observable, but perhaps double ratio not optimal. Light charged particles?
Previous studies of t/3He ratios:

Yield ratios, mainly studied at high energy

$^{197}$Au+$^{197}$Au
600 AMeV b=5 fm, $y(0) \leq 0.3$

\begin{itemize}
  \item m$_n^* < m_p^*$
  \item m$_n^* > m_p^*$
\end{itemize}

effect of effective mass more prominent than of asystiffness

(V. Giordano, et al., PRC 81(2010))

Z.Q. Feng, NPA878, 3 (2012)

Flow ratios
At low energy

$R_{^3\text{He}^3\text{H}} = \frac{F_{^3\text{He}}}{F_{^3\text{H}}}$

Effect of symm energy seen, but far away from data

Z. Kohley, et al., PRC83, 044601 (2011)

Also studies at higher energy, e.g. G.C. Yong, et al., PRC80, 044608 (2009)

Situation not so clear,
More data desirable
Systematic study useful

Symmetric collisions, 35 AMeV
Study of Light Fragment Emission: $^{136,124}$Xe$+^{124,112}$Sn, $E = 32,.,150$ AMeV, Prelim. data from R. Bougault, et al., GANIL

Cluster recognition by two methods: Coalescence (CO) in phase space, Density cut (DC, "gas" (p,n) and "liquid")

Global charge distributions agree reasonably

Calculations with variation of symmetry energy and effective mass splitting

asy-soft

asy-stiff

\[
\begin{align*}
  \text{SO} & \quad \{ \text{n} \} \\
  \text{ST} & \quad \{ \text{m}_n^* \rightarrow \text{m}_p^* \} \\
  \text{STP} & \quad \{ \text{m}_p^* \rightarrow \text{m}_n^* \}
\end{align*}
\]
Study of Light Fragment Emission: $^{136,124}$Xe+$^{124,112}$Sn, $E = 32,.,150$ AMeV,
Yields and spectra in comp. to experiment

136Xe+124Sn (n-rich)

Total yields

<table>
<thead>
<tr>
<th>Yield per collision</th>
<th>Neutron</th>
<th>Proton</th>
<th>Triton</th>
<th>$^3$He</th>
<th>Deuteron</th>
<th>$^7$Li</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{inc}/A$ [MeV]</td>
<td><img src="image" alt="Graph" /></td>
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</tbody>
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- phase space coalescence,
- open symbols: density cut method

Transverse energy spectra

- calc. using diff. asy-stiffness and $m^*$.
- Data

Absolute light fragment yields and spectra not well reproduced by calculations – important to improve!

→ Look at ratios: p/n, t/$^3$He single ratios and double ratios
Study of Light Fragment Emission: $^{136,124}$Xe+$^{124,112}$Sn, $E = 32, 65, 150$ AMeV

Single ratios

**n/p**

- Neutron rich: $^{136}$Xe+$^{124}$Sn
- Neutron poor: $^{124}$Xe+$^{112}$Sn

**t/3He**

- Neutron rich: $^{136}$Xe+$^{124}$Sn
- Neutron poor: $^{124}$Xe+$^{112}$Sn

AsyEOS – eff mass dominates

Possibility to separate density and momentum dependence of symmetry energy

Effects smaller for light clusters $t/3$He improve statistics!

Smaller neutron excess: effects smaller

Single ratios

- $n/p$ neutron rich $^{136}$Xe+$^{124}$Sn
- $n/p$ neutron poor $^{124}$Xe+$^{112}$Sn

- $t/3$He neutron rich $^{136}$Xe+$^{124}$Sn
- $t/3$He neutron poor $^{124}$Xe+$^{112}$Sn

son: asysoft, $m_n^* > m_p^*$

stn: asystiff, $m_n^* > m_p^*$

sop: asysoft, $m_n^* < m_p^*$

stp: asystiff, $m_n^* < m_p^*$

$E = 32$ MeV/A

$E = 65$ MeV/A

$E = 150$ MeV/A
Study of Light Fragment Emission: $^{136,124}\text{Xe}+^{124,112}\text{Sn}$, $E = 32, 65, 150$ AMeV.

Double ratios

Single ratio \( \frac{n}{p} \)

- neutron rich $^{136}\text{Xe}+^{124}\text{Sn}$
- neutron poor $^{124}\text{Xe}+^{112}\text{Sn}$

Single ratio \( \frac{n}{p} \)

Double ratio \( \frac{n}{p} \)

- neutron rich
- neutron poor

<table>
<thead>
<tr>
<th>E (AMeV)</th>
<th>Son: asysoft, ( m_n^* &gt; m_p^* )</th>
<th>Stn: asystiff, ( m_n^* &gt; m_p^* )</th>
<th>Sop: asysoft, ( m_n^* &lt; m_p^* )</th>
<th>Stp: asystiff, ( m_n^* &lt; m_p^* )</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
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<td>65</td>
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<tr>
<td>150</td>
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</table>

Double ratio also shows effect but less sensitive to symmetry energy.
Moments of single ratios: characterize behavior on asy-EoS and \( m^\ast \)

- **son**: asysoft, \( m_n^\ast > m_p^\ast \)
- **stn**: asystiff, \( m_n^\ast > m_p^\ast \)
- **sop**: asysoft, \( m_n^\ast < m_p^\ast \)
- **stp**: asystiff, \( m_n^\ast < m_p^\ast \)

Calculate moments of the single ratios, e.g. for \( n/p \) ratio

\[
R^{(k)}_\alpha (E_{\text{inc}}) = \frac{1}{E_f} \int_0^{E_f} dE_{\text{tr}} f^{(k)} (E_{\text{tr}}) \left( R_\alpha (E_{\text{inc}}, E_{\text{tr}}) - \frac{N}{Z} \right)
\]

- **emphasize high** \( E_{\text{tr}} \)
  - single ratio moments, linear weight, (full positive slope)
  - \( m_n^\ast < m_p^\ast \) go together

- **emphasize low** \( E_{\text{tr}} \)
  - single ratio moments, linear weight, (dashed negative slope)
  - asysoft go together
  - asystiff go together

Characteristic patterns depending on asy-EoS and \( m^\ast \): perhaps an observable?
Comparison to data $^{136,124}{\text{Xe}} + ^{124,112}{\text{Sn}}$, $E = 32,\ldots,150$ AMeV

data R. Bougault, A. Chbihi (Ganil, prelim, IWM11)

son: asysoft, $m_n^* > m_p^*

stn: asystiff, $m_n^* > m_p^*$

sop: asysoft, $m_n^* < m_p^*$

stp: asystiff, $m_n^* < m_p^*$

Single ratio $n/p$
neutron rich $^{136}{\text{Xe}} + ^{124}{\text{Sn}}$

Single ratio $t/3\text{He}$
neutron rich $^{136}{\text{Xe}} + ^{124}{\text{Sn}}$

The single $t/3\text{He}$ ratio seems to be a promising observable
• Illustrate with Danielewicz BUU with cluster production.
• Approx. QM description of cluster production up to A=3 (but not beyond)
  • \( m^* = 0.7m_0, \ m^*_p = m^*_n \)
• Calculations underpredict the double-ratio
  Figure courtesy of Z. Chajecki.

• Alpha production not included in the model => alphas end up being t or \(^3\)He
• **Check**: combine experimental alpha spectra with tritons and helium-3 and compare to the model predictions.
• Need to extend cluster production past \( A=4 \).
Conclusions:

- The nuclear symmetry potential is density and momentum dependent; both behaviors are not well known from nuclear matter theories

- Both are important for isospin sensitive observables in HIC; one should study many observables simultaneously to constrain the symmetry energy

- The ratios of p/n and light fragment spectra are promising to disentangle the density and momentum behaviour. New observable: moments of ratios?

- More experimental data desirable (FRIB!)

- But also improved treatment of cluster production in transport calc.

Thank you
backup
Effective masses:

**Non-relativistic mass**

\[
m_{NR}^* = \left[ m + \frac{1}{k} \frac{dU_{sp}}{dk} \right]^{-1} = k \left[ \frac{dE}{dk} \right]^{-1}
\]

Parametrizes non-locality in space (k-mass) and time (E-mass)

**Dirac mass**

\[
m_D^* = m + \Sigma_s
\]

Includes part of the interaction; relativistically

\[
U_{sp} \approx \frac{m_D^*}{E} \Sigma_s + \Sigma_0
\]

**k-dependence**

- Nonrelativistic mass
- Dirac mass

**ρ-dependence**

- Nonrelativistic mass
- Dirac mass

**Effective mass splitting**

\[
m_{NR,n}^* \leftrightarrow m_{NR,p}^* \quad m_{D,n}^* \leftrightarrow m_{D,p}^*
\]

**BHF:**

- >

**RMF (ρ+δ):**

- <

**DBHF (fit S):**

- >

**DBHF (project):**

- >

No agreement on ordering of n/p effective masses!


Baran, PhysRep 410
Sammarucca, PRC67
v. Dalen, Fuchs, PRL95
Example of the isovector dependence for a particular parametrization (used in the following results, BGBD, Bombaci-Gale-Bertsch-DasGupta)

**Energy density: kinetic + potential terms**

$$\varepsilon_{\text{kin}}(\rho) = \frac{3}{10} \rho E_F \left[(1 + \beta)^{5/3} + (1 - \beta)^{5/3}\right] = \frac{3}{5} E_F + \frac{1}{3} \rho E_F \beta^2 \quad \beta = \frac{N - Z}{A}$$

**Bombaci-Gale-Bertsch-Das Gupta (BGBD) interaction**

- **isoscalar**
  $$\varepsilon_A = \frac{A}{2} \frac{\rho^2}{\rho_0} - \frac{A}{3} \left(\frac{1}{2} + x_0\right) \frac{\rho^2}{\rho_0} \beta^2$$

- **isovector**
  $$\varepsilon_B = \frac{B}{\sigma + 1} \frac{\rho^\sigma + 1}{\rho_0^\sigma} - \frac{2}{3} \frac{B}{\sigma + 1} \left(\frac{1}{2} + x_3\right) \frac{\rho^\sigma + 1}{\rho_0^\sigma} \beta^2$$

**Momentum Dependence (MD): isoscalar + isovector**

$$\varepsilon_{c,z} = \frac{8}{5\rho_0} (C + 2z) I_{np} + \frac{2}{5\rho_0} (3C - 4z)(I_{nn} + I_{pp})$$

$$I_{np} = \left[\frac{2}{(2\pi)^3}\right]^2 \int d^3k \delta(k - \vec{k}) f_n(\vec{k}) f_p(\vec{k}) g(\vec{k}, \vec{k}')$$

**Symmetry energy**

Neutron/proton potentials as fct as fct of density for $p=p_F$ (left) and of momentum for $p=p_0$ (right)
Study of Light Fragment Emission: $^{136,124}\text{Xe}^{+}\text{Sn}$, $E = 32,150$ AMeV, Spectra and multiplicities

Steeper with increasing incident energy effect of AsyEoS and $m_{\text{eff}}$ seen

BE effects seen in particle yields Coalescence (CO) has too many free nucleons
Study of Light Fragment Emission: $^{136,124}\text{Xe} + ^{124,112}\text{Sn}$, $E = 32,..,150$ AMeV, Proton flows

Flows: protons, $^{136}\text{Xe} + ^{124}\text{Sn}$, $b = 2$ fm, CO

- Directed flow
- Elliptic flow

Directed flow

Elliptic flow

- Heavier particles have larger flow (known)
- AsyEoS differences small
→ Look at differences or differential flow
Differential flow

G.C. Yong, et al., PRC80, 044608 (2009)

$^{132}\text{Sn}+^{124}\text{Sn}$, 400 AMeV