Exploring the symmetry energy with isospin effects in heavy-ion collisions

Abdou Chbihi
GANIL
Accessing the symmetry energy outline

• Introduction
  – Exploring the symmetry energy term of EOS with HIC
  – Isotopic distribution and Isoscaling
  – Secondary decay

• Experiments $^{40,48}\text{Ca} + ^{40,48}\text{Ca} @ E/A = 35 \text{ MeV} \ (\text{INDRA-VAMOS})$

• Analysis of projectile like frag. PLF
  • Extraction of Csym
  • Comparison to AMD + GEMINI

• Reconstruction and analysis of primary fragments
  • Study of Csym vs $E^*$ and $T$
  • Surface and volume contribution to Csym
  • Extraction of Csym
  • Comparison with AMD-N(GEMINI)

• Conclusions
Exploring the symmetry energy with HIC

- HIC at intermediate energies $E/A = 20$-100 MeV; can probe, depending of impact parameter,
  - Central collisions
    - compression and expansion,
    - production of many excited fragments,
    - Allow to scan low density regions
  - Peripheral to semi-peripheral collisions: (in this work)
    - Produces moderate excited PLF or TLF
    - Allows to scan $\rho_0$

- information on the EOS can be obtained at the freeze-out, during the production of excited fragments:
  $$E(\rho,\delta)/A = E(\rho,\delta = 0)/A + S(\rho) \cdot \left( \frac{\rho_n - \rho_p}{\rho_n + \rho_p} \right)^2$$

- Observables (after secondary decay):
  - isotopic distributions,
  - Isoscaling
Accessing the symmetry energy
From isotopic distributions…

AMD simulations: $^{48}\text{Ca}+^{48}\text{Ca}, E/A=35\text{ MeV}$ and $b > 6\text{ fm}$

Primary fragment distributions

Assuming a grand-canonical ensemble
Isotopic distribution $Y(N,Z)$ :

$$\ln Y(N,Z) = \xi(Z) N + \eta(Z) + \zeta(Z) \frac{(N-Z)^2}{N+Z}$$

$$Y(N,Z) = F(N,Z,T) . \exp \frac{B(N,Z)}{T}. \exp \frac{N\mu_n + Z\mu_p}{T}$$

$$\xi(Z) \propto \frac{1}{\sigma} \propto \frac{C_{\text{sym}}(Z)}{T}$$
Accessing the symmetry energy

From isoscaling...

AMD simulations: $^{48}$Ca+$^{48}$Ca, $^{40}$Ca+$^{40}$Ca, E/A=35 MeV and b > 6 fm

Primary fragment distributions


\[
\frac{Y_2(N,Z)}{Y_1(N,Z)} = C \exp(\alpha N + \beta Z)
\]

isoscaling parameter

\[
\alpha = \frac{\Delta \mu_n}{T}, \beta = \frac{\Delta \mu_p}{T}
\]

\[
\frac{\alpha}{4\Delta} = C_{sym}(Z)/T
\]

\[
\Delta = \left(\frac{Z}{<A_1>}\right)^2 - \left(\frac{Z}{<A_2>}\right)^2
\]
Effects of secondary decays

- Secondary decays need to be taken into account for comparison to experimental data
- Statistical model
- Or/and: experimentally provide the primary distributions
VAMOS
PLF (E503) or residues (E494s)
High Isotopic Resolution

INDRA in coincidence LCP / IMF
event characterization
(b, excitation energy)
Experiments coupling INDRA-VAMOS

Symmetry energy experiments
- $^{40}\text{Ca} + ^{40}\text{Ca} @ E/A = 35 \text{ MeV}$
- $^{40}\text{Ca} + ^{48}\text{Ca} @ E/A = 35 \text{ MeV}$  isospin diffusion
- $^{48}\text{Ca} + ^{40}\text{Ca} @ E/A = 35 \text{ MeV}$  isospin diffusion
- $^{48}\text{Ca} + ^{48}\text{Ca} @ E/A = 35 \text{ MeV}$

For $B_\rho (\text{Tm}) = 2.2, 2.12, 1.957, 1.80, 1.656, 1.523, 1.401, 1.289, 1.186, 1.091, 1.004, 0.923, 0.849, 0.782, 0.719, 0.661$
INDRA-VAMOS

INDRA:
- all charged products, $7^\circ<\Theta<176^\circ$, $M_{\text{INDRA}} \geq 1$
- $Z$, $\Theta$, $\Phi$, $E_k$ and $A$ for $Z<5$
- Impact parameter and excitation energy estimation.

VAMOS Spectrometer:
- $2^\circ<\Theta<7^\circ$, $M_{\text{VAMOS}} = 1$
- PLF : $A$, $Z$, $\Theta$, $\Phi$, velocity, $Q$ etc.
- Full trajectory reconstruction.
Isotopic distributions of PLF

- Broad $A_{\text{PLF}}$ distributions (more than 13 isotopes)
- Sensitive to the n-richness of the system
- $N/Z$ up to $1.58$ (11% $N/Z$ $^{48}\text{Ca}$) very exotic
Extraction of the quantities sensitives to $C_{sym}$

- $C_{sym}/T$ comparable for both methods: 3-8
- Odd-even effect (staggering)
- Sensitive to secondary decay

ECT*, Trento 2014
Reconstruction of primary fragments
Characteristics of LCP emitted in coincidence with the PLF

- Two components drawing coulomb rings:
- One centered on the PLF velocity (origin)
- Second centered on the TLF.
- Velocity selection to associate LCP and PLF emitted from the same frag.
- $V_{CM} > 0$

$Z_{PLF} = 20$

Corrected for the reaction plan

ECT*, Trento 2014

A. Chbihi
Mean multiplicities of evaporated LCP

- Small multiplicities proton and alpha up to 1.5

- →Moderate Ex*

- Trend in agreement with n-richness of the system
  - Mp, M3He decreases Mt and M6He increases with n-rich
  - Similar trend for d, alpha
  - same number of n, p
reconstruction of primary fragments

evt/evt

\[ Z_{pr} = Z_{PLF} + \sum_{i=1}^{M_{LCP}} Z_i \]

\[ A_{pr} - M_n = A_{PLF} + \sum_{i=1}^{M_{LCP}} A_i \]

\(<Z_{pr}>\) centered at 20
Max around \(Z_{pr} = 25\)

ECT*, Trento 2014
A. Chbih
Can be used as an observable

\[ A_{pr} - M_{n} = A_{PLF} + \sum_{i=1}^{M_{LCP}} A_{i} \]

- Up to 20 isotopes
- Average value and \( \sigma \) increases with \( Z_{pr} \)
- Small differences for light \( Z_{pr} \)
- Strong dependence on the n-richness of the system for heavy fragments
- Small dependence on the n-richness of the target

ECT*, Trento 2014
A. Chbihi
Neutron influence on the width of isotopic distributions

\[ A_{pr} - M_n = A_{PLF} + \sum_{i=1}^{M_{LCP}} A_i \]

Comparison of the width of iso-dist AMD (hot) and AMD-N (GEMINI)

Differences in the width between AMD and AMD-N as uncertainties when applied to data

ECT*, Trento 2014
A. Chbihi
Symmetry energy from primary fragments

- Similar Csym/T for both methods
- Less increase than for PLF
- Less staggering than for PLF
- Trend ??

ECT*, Trento 2014
Staggering effect for PLF and primary frag

ECT*, Trento 2014
A. Chbihi
Characteristic of the primary source
Excitation energy and temperature

$E^*$ estimation, calorimetry

$N = Z_{pr} (1 + n / z) - A_{PLF}$

$n / z = 1.0, (4040)$

$n / z = 1.4, (4848)$

$n / z = 1.3, (4840)$

$n / z = 1.1, (4048)$
Symmetry energy term vs the excitation energy comparison with AMD-N(Gemini), b>6 fm

\[ \sigma = \sqrt{\frac{1}{N} \sum (\text{exp} - \text{calc})^2} \]

From width of isotopic dist

<table>
<thead>
<tr>
<th>( E^*/A ) (MeV/A)</th>
<th>Gogny</th>
<th>Gogny-AS</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.00 - 3.50</td>
<td>3.54</td>
<td>4.36</td>
</tr>
<tr>
<td>3.50 - 4.00</td>
<td>2.25</td>
<td>3.16</td>
</tr>
<tr>
<td>4.00 - 4.50</td>
<td>2.17</td>
<td>2.68</td>
</tr>
<tr>
<td>4.50 - 5.00</td>
<td>1.16</td>
<td>2.07</td>
</tr>
</tbody>
</table>
Symmetry energy term vs the excitation energy comparison with AMD-N(Gemini), b > 6 fm

From isoscaling

\[ \sigma = \sqrt{\frac{1}{N} \sum (\text{exp.-calc})^2} \]

<table>
<thead>
<tr>
<th>E*/A (MeV/A)</th>
<th>Gogny</th>
<th>Gogny-AS</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.00 - 3.50</td>
<td>2.21</td>
<td>1.34</td>
</tr>
<tr>
<td>3.50 - 4.00</td>
<td>1.79</td>
<td>1.02</td>
</tr>
<tr>
<td>4.00 - 4.50</td>
<td>1.64</td>
<td>1.16</td>
</tr>
<tr>
<td>4.50 - 5.00</td>
<td>1.44</td>
<td>1.19</td>
</tr>
</tbody>
</table>
Surface to volume contribution

Fit with

\[ c(A) = c_v + c_s A^{-1/3} \]

\[ C_{\text{sym}} / T \approx 1 - \frac{C_s}{C_v} (2Z)^{-1/3} \]

Surface effect is important
No big difference between the two interactions
Values of $C_{\text{sym}} = 30$ MeV for two bins in $E^*$
Consistent with the values of saturation density
The method is validated and should be applied to more dissipative collisions
Summary and Conclusions

- Exploration of $E_{\text{sym}}(\rho)$ with HI-Collisions
- Observable: isotopic distribution of frag & isoscaling
- Accessing the symmetry energy
  - Take into account the secondary effects
  - Primary experimental isotopic distributions
    - $Z_{\text{primary}}$ distributions were reconstructed experimentally
    - $A_{\text{primary}}$ - neutrons distributions reconstructed exp. but need to take into account the effect of neutron emission on the $A_{\text{primary}}$ - neutrons distributions
    - Staggering effects are washed with this reconstruction
- Both methods (isoscaling and isotopic distributions) can be used to extract the symmetry energy term if applied for primary quantities
- $E_{\text{sym}}$ was extracted for peripheral collisions, the values obtained are consistent with the value at normal density:
- work is in progress for central collisions
Paola Marihi, Mark Boisjoli