Exploring the symmetry energy in nuclear equation of state with heavy ions

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Transverse and elliptical flow constraints the EoS of symmetric nuclear matter.

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Relevance to dilute and dense n-rich objects

Stability of Neutron Star and its structure

Sizes of nuclei with n-halo and n-skin

0 \rho_o \quad 5\rho_o

Epicenter

Nuclei+e^-  
Nuclei+dripped n+e^-

11_{\text{Li}}

208_{\text{Pb}}

10 km

exotics
Multifragmentation Scenario
-- consistent with mixed phase

Time Sequence
-- System expands
-- light particle emitted
-- Fragments form
-- Fragments decouple

Time Dependence
-- Initial compression and energy deposition
-- Expansion
-- Cooling
-- Disassembly and freezeout

Different Approaches
Dynamical (AMD, BNV); Rate equations (EES);
Equilibrium at freeze-out density (BUU-SMM)
Varying the neutron contents

<table>
<thead>
<tr>
<th>System</th>
<th>$^{112}\text{Sn}+^{112}\text{Sn}$</th>
<th>$^{124}\text{Sn}+^{124}\text{Sn}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(N/Z)_0$</td>
<td>1.24</td>
<td>1.48</td>
</tr>
<tr>
<td>$A_0$</td>
<td>224</td>
<td>248</td>
</tr>
<tr>
<td>$Z_0$</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>$N_0$</td>
<td>124</td>
<td>148</td>
</tr>
</tbody>
</table>

$^{112}\text{Sn}+^{112}\text{Sn} \rightarrow ^{124}\text{Sn}+^{124}\text{Sn}$

Gain = 24 Neutrons

$\hat{\rho}_{n}^{112} = 1$ \hspace{2cm} $\hat{\rho}_{n}^{124} \approx 1.078$

$\hat{\rho}_{p}^{112} = 1$ \hspace{2cm} $\hat{\rho}_{p}^{124} \approx 0.903$
n-enhancements observed from isotopes ratios

\[ \rho_n \propto e^{\Delta\alpha} \]

*Enrichment of n in the gas*

\[ \rho_p \propto e^{\Delta\beta} \]

*Depletion of p in the gas*

*PRL, 85, 716 (2000)*
Isoscaling from Relative Isotope Ratios

\[ R_{21} = \frac{Y_2}{Y_1} \]

\[ \propto e^{N \Delta \mu_n + Z \Delta \mu_p} \]

\[ \propto (\rho_n)^N (\rho_p)^Z \]

Factorization of yields into p & n densities

Cancellation of effects from sequential feedings

Robust observables to study isospin effects
Compact representation of isoscaling

Central Collisions
Sn+Sn
E/A=50 MeV

\[ S = R_{21} \times \exp(0.41Z) \]

\[ \exp(0.37N - 0.41Z) \]

\[ \exp(0.37N) \]
Isoscaling observed in many reactions

\[ \frac{Y_2}{Y_1} \propto e^{(N\Delta \mu_n + Z\Delta \mu_p)/T} \]

\[ PRL, 86, 5023 (2001) \]
DIC

\[ R_{21} \propto \exp\left[\left(-\Delta S_n \cdot N - \Delta S_p \cdot Z\right)/T\right] \]

Separation Energy

\[ E_{\text{Coul}} \quad E_{\text{sym}} \]

Evaporation

\[ R_{21} \propto \exp\left[\left(-\Delta S_n + \Delta f_n^*\right) \cdot N + \left(-\Delta S_p + \Delta f_p^* + \Delta \Phi\right) \cdot Z\right]/T \]

Multifragmentation

\[ R_{21} \propto \exp\left[\left(-\Delta \mu_n \cdot N - \Delta \mu_p \cdot Z\right)/T\right] \]

Chemical Potentials

\[ E_{\text{Coul}} \quad E_{\text{sym}} \quad \rho_p \quad \rho_n \]
Origin of isoscaling

- Isoscaling disappears when the symmetry energy is set to zero.
- Provides an observable to study symmetry energy.
Role of density dependent asymmetry term

- Where do the fragments originate?

• Various models predict different dependence on density dependence of asymmetry term.
  - Equilibrium models: fragments originate in interior.
  - EES model: fragments emitted from surface.
Expanding Emitting Source model
W. Friedman
PRC42, 667 (1990)

Thermal instability at low density.
Density Dependence of Symmetry Energy

\[ E_{\text{sym}} = C \left( \frac{\rho}{\rho_o} \right)^\gamma \]

Strong influence of symmetry term on fragment isotopic ratios.

*PRL, 86, 5023 (2001)*
Symmetry Terms

\[ E(\rho, \beta) = E(\rho, 0) + E_{\text{sym}}(\rho) \beta^2 \]

\[ K(F_1) = +61 \text{ MeV} \]

\[ K(F_3) = -69 \text{ MeV} \]
Sensitivity to the isospin terms in the EOS

Isotope Ratios

Asy–stiff

Asy–soft

Isotone Ratios

Freeze-out source

Data

PRC, C64, 051901R (2001).
Summary

- **Density dependence of symmetry energy can be examined experimentally.**

- **Existence of isoscaling relations**

- **Conclusions from fragmentation work are model dependent:**
  - SMM and SMF favor $\rho^2$ dependence of $S(\rho)$.
  - EES favors $\rho^{2/3}$ dependence of $S(\rho)$. 