Constraints On Symmetry Energy from Sn+Sn collisions

Outlines:
1. Motivations for using Sn+Sn reactions
2. Summary of experimental constraints
3. Questions for the theorists
4. Summary and outlooks

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Acknowledgements

ImQMD Calculations

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Results from Sn+Sn at E/A=35 MeV

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Symmetry Energy in asymmetric nuclei

\[ B = a_v A - a_s A^{2/3} + \delta - a_c \frac{Z(Z-1)}{A^{1/3}} - a_{sym} \frac{(A - 2Z)^2}{A} \]

Penalty paid for unequal number of neutrons and protons
Symmetry Energy in asymmetric nuclei

\[ B = a_V A - a_S A^{2/3} + \delta - a_c \frac{Z(Z-1)}{A^{1/3}} - a_{\text{sym}} \frac{(A-2Z)^2}{A} \]

Inclusion of surface terms results in density dependence of symmetry energy.

Affects the nuclear binding energy and properties of neutron stars.

\[ (a^V - a^S A^{2/3})(A-2Z)^2 \]

\[ a_{\text{sym}} \]

\[ a_{\text{sym}} \]

\[ \frac{F_1}{F_2/(1+u)} = u \]

\[ F_3 = \sqrt{u} \]

n and p potentials have opposite sign.

Li et al., PRL 78 (1997) 1644
Strategies used to study the symmetry energy with Heavy Ion collisions

- Vary the N/Z compositions of projectile and targets:
  - $^{124}\text{Sn} + ^{124}\text{Sn}$, $^{124}\text{Sn} + ^{112}\text{Sn}$, $^{112}\text{Sn} + ^{124}\text{Sn}$, $^{112}\text{Sn} + ^{112}\text{Sn}$

- Measure N/Z compositions of emitted particles:
  - n & p yields & flow, N/Z of fragments
  - isotopes yields – isospin diffusion
  - $\pi^+$ & $\pi^-$ at high incident energy

Isospin degree of freedom

\[
B = a_v A - a_s A^{2/3} + \delta - a_c \frac{Z(Z-1)}{A^{1/3}} - a_{sym} \frac{(A-2Z)^2}{A}
\]
Experimental Limitations: Example
Isotope Distribution Experiment

**MSU, IUCF, WU collaboration**

Sn+Sn collisions involving $^{124}$Sn, $^{112}$Sn at E/A=50 MeV

LASSA
Si strip + CsI array
Good E, position, isotope resolutions

Miniball + Miniwall
4 $\pi$ multiplicity array
Z identification, A<4
$b$ information

Limited spatial coverage
Limited particle ID
Limited particle energy range

Xu et al, PRL, 85, 716 (2000)
n/p Experiment $^{124}\text{Sn}+^{124}\text{Sn};^{112}\text{Sn}+^{112}\text{Sn}; E/A=50 \text{ MeV}$

Very different detection efficiencies for protons and neutrons
How to obtain the information about EoS?

Both astrophysical and laboratory observables can constrain the EoS, $\varepsilon(\rho,T,\delta)$ or $P(\rho,T,\delta)$ indirectly.

Experiments:

*Accelerator: Projectile, target, energy*

*Detectors: Information of emitted particles – identity, spatial info, energy, yields → construct observables*

Models

*Input: Projectile, target, energy.*

*Simulate the collisions with the appropriate physics*

*Success depends on the comparisons of observables.*

Experimental observables in Sub-saturation density:

*n/p ratios, isospin diffusion, rapidity dependence of ID, incident energy dependence of ID, N/Z of fragments, t/3He ratio yields, pp correlations, …*
What are the uncertainties in theoretical predictions?

**Transport models:**
Describe dynamical evolution of the collision process
• Self consistent mean field
• $n-n$ collisions,
• Pauli exclusion

**Uncertainties**
Semi-classical
Approximations needed to make computation feasible.

Symmetry energy included in the nuclear EOS for infinite nuclear matter at various densities from the beginning of collision.

**Statistical Models**
Describe longer time scale decays from single source.
• nuclear mass,
• level densities (isospin?)
• decay rates

**Uncertainties**
Source parameters: $A_o$, $Z_o$, $E_o$, $V_o$, $J$
Information obtained is for finite nuclei, not for infinite nuclear matter

**Advantages**
fast CPU turn around
Production of very rare isotopes provide lots of physics insights

**In principle, all calculations are two steps:**
1. **Transport model**
2. Sequential decays with statistical models
Density Dependence Symmetry energy from IBUU04

1. \( \frac{y}{y_{\text{beam}}} \) dependence of ID
2. N/Z fragments
3. ID data at \( E/A = 35 \text{ MeV} \)
ImQMD model describes np ratios and two isospin diffusion measurements:

\[ S(\rho) = 12.5 (\rho/\rho_o)^{2/3} + 17.6 (\rho/\rho_o)^{\gamma_i} \]

Consistent constraints from the \( \chi^2 \) analysis of three observables \( 0.4 \leq \gamma_i \leq 1 \)
N/Z ratios from bound fragments ($Z=3-8$) → complementary to n/p ratios

$$E_{\text{sym}} = 12.7 \left( \frac{p}{p_0} \right)^{2/3} + 19 \left( \frac{p}{p_0} \right)^{\gamma_i}$$

Hot fragments produced in calculations.
N/Z ratios from bound fragments (Z=3-8) \rightarrow complementary to n/p ratios

\[ E_{\text{sym}} = 12.7(\rho/\rho_o)^{2/3} + 19(\rho/\rho_o)^{\gamma_i} \]
MSU+INFN, LNS Catania

$^{124}\text{Sn}+^{124}\text{Sn}$, $^{124}\text{Sn}+^{112}\text{Sn}$, $^{112}\text{Sn}+^{124}\text{Sn}$, $^{112}\text{Sn}+^{112}\text{Sn}$ at $E/A=35$ MeV

Chimera array
Isospin diffusion data at $E/A=35$ MeV

Data are in good agreement with $\gamma_1 \approx 0.5$, consistent with $E/A=50$ MeV data.

No complete stopping & no isospin equilibrations in central collisions.
Constraints from HIC at sub-saturation density: Sn+Sn collisions at $E/A=35$ and 50 MeV

Consistent with IAS, PDR & GDR
\[ E_{\text{sym}} = 12.5 \left( \frac{\rho}{\rho_0} \right)^{2/3} + C_{s,p} \left( \frac{\rho}{\rho_0} \right)^{\gamma_i} \]

Current constraints on symmetry energy from HIC

\[ E_{\text{sym}} = S_o + \frac{L}{3} \left( \frac{\rho_B - \rho_0}{\rho_0} \right) + \frac{K_{\text{sym}}}{18} \left( \frac{\rho_B - \rho_0}{\rho_0} \right)^2 + \ldots \]

\[ L = 3 \rho_0 \frac{\partial E_{\text{sym}}}{\partial \rho_B} \bigg|_{\rho_B=\rho_0} = \frac{3}{\rho_0} P_{\text{sym}} \]
Experimental+theoretical accuracies are comparable to PREX experiment to determine Pb skin thickness.

\[ \delta R_{np} = \pm 0.04 \text{ fm} \]

\[ \delta R_{Pb} = 0.28 \text{ fm} \]

\[ S = S_o + \frac{L}{3} \left( \frac{\rho_B - \rho_0}{\rho_0} \right) + \frac{K_{sym}}{18} \left( \frac{\rho_B - \rho_0}{\rho_0} \right)^2 + \ldots \]

\[ L = 3\rho_0 \left. \frac{\partial E_{sym}}{\partial \rho_B} \right|_{\rho_B=\rho_0} = \frac{3}{\rho_0} P_{sym} \]
Cluster effects!
A=3 fragments

\[ \frac{Y(n)}{Y(p)} \sim \frac{Y(t)}{Y(\text{^3He})} \] single ratios

Lack of rigorous theoretical proofs!
n/p Double Ratios (central collisions)

Double Ratio \[ \frac{^{124}\text{Sn} + ^{124}\text{Sn}}{^{112}\text{Sn} + ^{112}\text{Sn}}; \frac{Y(n)}{Y(p)} \]

minimize systematic errors

Zhang, et al., PL B664 (08) 145,

Cluster effects cannot explain the discrepancies with IBUU04 & sequential decays

Data : Famiano et al. PRL 97 (2006) 052701
Need higher energy data with $E_{CM}/A > 40$ MeV.

Experiments with $E_{beam}/A \sim 140$ MeV are underway.

$Y(n)/Y(p) \sim Y(t)/Y(^{3}\text{He})$ single ratios ?
Lessons learned from LE measurements:

1. HI collision dynamics are complex but prove to be sensitive to density dependence of symmetry energy – for high density, it is the only game in town.

2. Need multiple observables to place various constraints on the input parameters of the transport models

3. Problems still remain, e.g.
   • How to extract results to T=0;
   • Control of input parameters in transport models.

Low and Intermediate Energy Heavy Ion Collisions Workshop ECT*
Summary

The density dependence of the symmetry energy is of fundamental importance to nuclear physics and neutron star physics.

Observables in HI collisions provide unique opportunities to probe the symmetry energy over a range of density especially for dense asymmetric matter

Need more guidance from theory regarding observables and interpretation of experimental results.

The availability of intense fast rare isotope beams at a variety of energies at RIKEN, FRIB & FAIR allows increased precisions in probing the symmetry energy at a range of densities – international co-ordination of a global program.
Extra effort to understand symmetry energy at high densities

Observables: n/p spectra & flows; np, pp correlations, $\pi^+/\pi^-$ spectra & flows, kaons, hyperon production.

Require: New Detectors, travel money, theory support