Exploring the symmetry Energy of Asymmetric Matter with Heavy Ion Reactions

Betty Tsang for HiRA/Chimera Collaboration

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Outline:
1. Introduction
2. Isospin diffusion at E/A=35 and 50 MeV
3. Symmetry energy determined from isospin diffusion
4. Summary & Outlook

Catania, Italy
Nov 4-7, 2009
Nuclear Equation of State

\[ E/A (\rho, \delta) = E/A (\rho, 0) + \delta^2 \cdot S(\rho) \]
\[ \delta = (\rho_n - \rho_p) / (\rho_n + \rho_p) = (N-Z)/A \]

Physics with rare isotope beams facilities, RIBF, FRIB, FAIR.

✓ Nuclear Structure – What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?
✓ Nuclear Astrophysics – What is the nature of neutron stars and dense nuclear matter? What is the origin of elements heavier than iron in the cosmos? What are the nuclear reactions that drive stars and stellar explosions?
✓ Tests of Fundamental Symmetries – Why is there now more matter than antimatter in the universe?
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

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

\[ (a^V_{\text{sym}} A - a^S_{\text{sym}} A^{2/3}) \frac{(A - 2Z)^2}{A^2} \]

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

Affects the nuclear binding energy and properties of neutron stars.
Probing the asymmetry term

Sensitive observables:

At sub-saturation densities

- Isospin diffusion
- Asymmetry of bound residues.
- Pre-equilibrium n vs. p emission
- Transverse flow (n vs. p).
- Difference between neutron and proton matter radii.

At supra-saturation densities

- Isospin dependencies of pion production.
- Transverse flow (n vs. p).
- Pion ratios

Additional measurements are needed to constrain the n,p effective masses and the isospin dependences of the cross sections.

- Sign of mean field opposite for protons and neutrons.
- Shape is influenced by incompressibility.

![Graph showing sensitive observables](Li et al., PRL 78 (1997) 1644)

\[ V_{asy} = \frac{2u^2}{1+u}, \quad F_2 = u, \quad F_3 = \sqrt{u} \]

\[ u = \frac{\rho}{\rho_o} \]
Isospin diffusion occurs only in asymmetric systems $A+B$

No isospin diffusion between symmetric systems

Non-isospin diffusion effects
→ same for $A$ in $A+B$ & $A+A$ ; same for $B$ in $B+A$ & $B+B$

Cancel non-isospin diffusion effects using isospin transport ratios

$$R_i = 2 \frac{x_{AB} - (x_{AA} + x_{BB})/2}{x_{AA} - x_{BB}}$$

To minimize Coulomb effects, study collisions of different isotopes

$A=^{124}\text{Sn}; B=^{112}\text{Sn}$
Isospin diffusion occurs \( \sim 120 \) fm/c.

Isospin “diffuse” through low-density neck region.

Isospin diffusion is measured with fragments emitted from the neck region.

Probe the symmetry energy at subsaturation densities in semi-peripheral collisions, e.g. \(^{124}\text{Sn} + ^{112}\text{Sn}\) at \(b=6\) fm.

\[
R_i = 2 \frac{x_{AB} - (x_{AA} + x_{BB})}{2} \frac{x_{AA} - x_{BB}}{
\]

\(x(\text{data})=\alpha, \ln(Y(^7\text{Li})/Y(\text{Be}))\)

\(x(\text{theory})=\delta\)
Chimera array

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

- $4\pi$ array: 1192 Si + CsI telescopes
- [http://www.lns.infn.it/research/chimera/](http://www.lns.infn.it/research/chimera/)

$Y(\text{Li}) \& Y(\text{Be}) \rightarrow R_7$

$N_c, E_t \rightarrow b$
Nc vs. Et

b-selection

\[
\frac{b}{b_{\text{max}}} = \sqrt{\frac{\int_0^{E_t} N(E) \, dE}{\int_0^{\infty} N(E) \, dE}}
\]

\[
\frac{b}{b_{\text{max}}} = \sqrt{\frac{\sum_{i=1}^{n} N_i}{\sum_{i=1}^{\infty} N_i}}
\]
Isospin transport observable

$Y(\text{Li})$ enhanced from $^{124}\text{Sn}$

$Y(\text{Be})$ enhanced from $^{122}\text{Sn}$
Isospin transport observable

\[ R_i = \frac{2x_{AB} - x_{AA} - x_{BB}}{x_{AA} - x_{BB}} \]

Y(\(^7\)Li) enhanced from \(^{124}\)Sn

Y(\(^7\)Be) enhanced from \(^{112}\)Sn

Mainly dominated by Coulomb
Isospin Transport Ratio

\[ R_i = \frac{2x_{AB} - x_{AA} - x_{BB}}{x_{AA} - x_{BB}} \]

Rami et al., PRL, 84, 1120 (2000)

Coulomb & other (preequilibrium & sequential) effects are “cancelled”
Impact parameter dependence of Isospin tracer at E/A=35 MeV

Lower energy; Longer interaction times
More N/Z equilibrations; $R_i \sim 0$

$$R_i = 2 \frac{x_{AB} - (x_{AA} + x_{BB})/2}{x_{AA} - x_{BB}}$$

$$x = \ln(Y(^7\text{Li}/^7\text{Be}))$$

No complete stopping & no isospin equilibrations in central collisions
No single source
Impact parameter dependence of Isospin diffusion data at E/A=35 MeV

Lower energy; Longer interaction times; More N/Z equilibrations

\[
R_i = 2 \frac{x_{AB} - (x_{AA} + x_{BB})/2}{x_{AA} - x_{BB}}
\]

\[
x = \ln(Y(7Li/7Be))
\]

\[
\frac{b}{b_{\text{max}}} = \sqrt{\int_0^{E_i} N(E)dE / \int_0^\infty N(E)dE}
\]

\[
\frac{b}{b_{\text{max}}} = \sqrt{\sum_{i=1}^n N_i / \sum_{i=1}^\infty N_i}
\]
Comparison of the impact parameter dependence of Isospin diffusion data at E/A=35 & 50 MeV
Comparison of the impact parameter dependence of Isospin diffusion data at E/A=35 & ImQMD predictions

- Calculations predict flat dependence on $b<8$ fm and sharp rise for $b>9$ fm.
- The magnitude of $R_{N,\text{frag}}$ depends on $\gamma_i$.
- Stable values at small $b$ can be compared to data.
Comparison of ImQMD calculations to data

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

No complete stopping & no isospin equilibrations in central collisions
Consistent constraints from the $\chi^2$ analysis of three observables at $E/\gamma = 50$ MeV

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

$0.4 \leq \gamma_i \leq 1.05$

Chimera data at $E/A = 35$ MeV are in good agreement with $\gamma_i \sim 0.5$, consistent with results from $E/A = 50$ MeV data.
constraints from the $\chi^2$ analysis of three observables at E/A=50 MeV

Overlap with constraints from structure and masses

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

$0.4 \leq \gamma_i \leq 1$

$E_{sym} = S_o + \frac{L}{3} \left( \frac{\rho_B - \rho_0}{\rho_0} \right) + \frac{K_{sym}}{18} \left( \frac{\rho_B - \rho_0}{\rho_0} \right)^2 + ...$

$L = 3\rho_0 \frac{\partial E_{sym}}{\partial \rho_B} \bigg|_{\rho_B=\rho_0} = \frac{3}{\rho_0} P_{sym}$
Constraints on the density dependence of symmetry energy

PRL 102, 122701 (2009)

\[ S(\rho) \] (MeV)

\[ \rho/\rho_0 \]

\[ L \] (MeV)

\[ S_0 \] (MeV/fm^3)

HIC

IAS

PDR

GDR

Sn+Sn

\( S_0 \) (MeV)
Constraints on the density dependence of symmetry energy

PRL 102, 122701 (2009)
Constraints on the density dependence of symmetry energy

\[ \frac{V_{2,\text{neut}}}{V_{2,\text{hydro}}} \]

\[ p^*_+ (\text{GeV}/c) \]

\[ L (\text{MeV}) \]

\[ \pi^+ / \pi^- \]

\[ E/A = 0.4 \text{ GeV} \]

\[ \pi^+ / \pi^- \text{ Squeeze-out} \]

\[ \text{Sn+Sn} \]

\[ E/A = 0.25-6 \text{ GeV} \]

\[ \text{Au+Au} \]

\[ \text{Data} \]

\[ x = 1 \]

\[ x = 0 \]

\[ x = -1 \]

\[ E_{\text{beam}} (\text{GeV/u}) \]

\[ S_0 (\text{MeV}) \]

PRL 102, 122701 (2009)
Symmetry Energy Project ➔ International collaboration to determine the symmetry energy over a range of density

Require: New Detectors (TPC), travel money, theory support
Symmetry Energy Project (SEP) collaboration

**Determination of the Equation of State of Asymmetric Nuclear Matter**

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5th RIKEN PAC recommends completion of TPC in 2013.

DOE FOA proposal (12/18/08):

NSF PIRE proposal (9/18/2009):

International Symposium on Symmetry Energy,
Tetsuya Murakami, Akira Ono, Hiro Sakurai, Betty Tsang
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E/A=35 MeV data from INFN-LNS, Catania
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E/A=50 MeV results from NSCL, MSU

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