Overview of the experimental constraints on symmetry energy

HIAS 2013 Canberra, Australia, April 8-12

Betty Tsang, NSCL/MSU
FRIB will provide intense beams of rare isotopes (that is, short-lived nuclei not normally found on Earth). FRIB will enable scientists to make discoveries about the properties of these rare isotopes in order to better understand the physics of nuclei, nuclear astrophysics, fundamental interactions, and applications for society.
Overview of the experimental symmetry energy constraints around nuclear matter density and beyond

Introduction

Experimental Observables:

- **Heavy Ion Collisions near Fermi energy** $E/A \approx 50$ MeV
  - Isospin diffusions
- **Comparison of constraints to other observables from nuclear masses and structure**
- **HIC is viable probe to study the properties nuclear matter.**

Experimental Observables:

- **Heavy Ion Collisions at high energy;** $E/A > 100$ MeV
  - $\pi^-/\pi^+$ ratios and flow;
    - charge particles $n/p$ yield ratios and flow – **new detectors**
- **Challenges**
  - $3n$ forces
  - **effective nucleon masses**
  - …

Summary and Outlook
Nuclear Equation of State

Relationship between energy, temperature pressure, density in nuclear matter

✓ 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?

\[
\begin{align*}
E/A (\rho, \delta) &= E/A (\rho, 0) + \delta^2 \cdot S(\rho) \\
\delta &= (\rho_n - \rho_p) / (\rho_n + \rho_p) = (N-Z)/A
\end{align*}
\]
EoS and symmetry energy

Ideal gas: $PV = nRT$

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

Isospin degree of freedom

Crab Pulsar

Hubble ST
Symmetry energy calculations with effective interactions constrained by Sn masses. This does not adequately constrain the symmetry energy at higher or lower densities.

\[ E/A (\rho, \delta) = E/A (\rho, 0) + \delta^2 \cdot S(\rho) \]

\[ \delta = (\rho_n - \rho_p) / (\rho_n + \rho_p) = (N-Z)/A \]

\[ P = \rho^2 \frac{\partial(E/A)}{\partial \rho} \bigg|_{s/a} \]
The Nuclear Equation of State of Symmetry matter

\[ \frac{E}{A} (\rho, \delta) = \frac{E}{A} (\rho, 0) + \delta^2 \cdot S(\rho); \quad \delta = \frac{(\rho_n - \rho_p)}{(\rho_n + \rho_p)} = \frac{(N-Z)}{A} \]

To probe density dependence, need observables sensitive to different densities

- Giant Monopole Resonance
- Kaon production
- Transverse and elliptical flow

Strategies used to study the symmetry energy with Heavy Ion collisions below $E/A=100$ MeV

- 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
  - isotopes yields: isospin diffusion
- Simulate collisions with transport theory
  - Find the symmetry energy density dependence that describes the data.
  - Constrain the relevant input transport variables.

Isospin Diffusion

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

\( R_i = \pm 1 \) no diffusion; \( R_i = 0 \) equilibration

Extent of diffuseness reflects strength of SE

mixed \( ^{124}\text{Sn} + ^{112}\text{Sn} \)

n-rich \( ^{124}\text{Sn} + ^{124}\text{Sn} \)

p-rich \( ^{112}\text{Sn} + ^{112}\text{Sn} \)
\[ E_{\text{sym}} = 12.7 \left( \frac{\rho}{\rho_o} \right)^{2/3} + 19 \left( \frac{\rho}{\rho_o} \right)^{\gamma_i} \]

\[ \gamma_i = 2.0, 1.0, 0.75, 0.5, 0.35 \]

\[ \rho_{\text{beam}} \]

\[ y/y_{\text{beam}} \]

\[ R_i \]

\[ b (\text{fm}) \]

\[ \text{Degree of isospin diffusion} \]

\[ \text{Projectile } ^{124}\text{Sn} \]

\[ \text{Target } ^{112}\text{Sn} \]
Degree of isospin diffusion

$$R_i \leq 0.4 \leq \gamma_i \leq 1$$

$$0.45 \leq \gamma_i \leq 0.95$$

$$E_{sym} = 12.7 (\rho/\rho_o)^{2/3} + 19 (\rho/\rho_o)^{\gamma_i}$$
EoS of asymmetric matter -- Constraints from Heavy Ion Collisions (HIC)

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

\[ E_{sym} = S_o + \frac{L}{3} \left( \frac{\rho_B - \rho_0}{\rho_0} \right) + \frac{K_{sym}}{18} \left( \frac{\rho_B - \rho_0}{\rho_0} \right)^2 + \ldots \]
Consistent Constraints on Symmetry Energy
from different experiments $\rightarrow$ HIC is a viable probe

Isobaric Analogue States
NPA 818, 36 (2009)

Finite Droplet Range Model
PRL 108, 052501 (2012)

Pygmy Dipole Resonances
PRC 81, 041304 (2010)

Heavy ion collisions
PRL 102, 122701 (2009)

$p$ elastic scattering
PRC 82, 044611 (2010)

Neutron-star radius
PRL 108, 01102 (2012)

Consistent Constraints on Symmetry Energy
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Tsang et al. C 86, 015803 (2012)
To Probe Symmetry Energy at $\rho > \rho_0$ with Sub-threshold Pions from HIC

- New observables: $\pi^-/\pi^+$ ratios
- New detectors
  - **MSU**: Active Target – Time Projection Chamber
  - **RIKEN**: SAMURAI – Time Projection Chamber

$^{124}\text{Sn} + ^{124}\text{Sn}$
$E_{lab} = 120 \text{ MeV/A}$
$b = 1 \text{ fm}$

Bickley et al., private comm. (2009)
Buick et al., private comm., (2009).
To Probe Symmetry Energy at $\rho > \rho_0$
with Sub-threshold Pions from HIC

- New observables: $\pi^-/\pi^+$ ratios
- New detectors
  - MSU: Active Target – Time Projection Chamber
  - RIKEN: SAMURAI – Time Projection Chamber
Challenges at high density

Large uncertainties in the symmetry energy at high density.

- GDR
- Effective nucleon masses
- 3n forces
- Chiral Effective Field Theory Calculations
- $\Delta r_{np}$ (fm)

$S(\rho)$ (MeV)
Density $\rho/\rho_o$

Pressure ($10^{27}$ bar)

Effective nucleon masses

$M^*\alpha$
Extrapolation from $^{208}\text{Pb}$ radius to pressure in n-star

Typel & Brown, PRC 64, 027302 (2001)

\[
\frac{\partial E_{\text{sym}}}{\partial \rho} \bigg|_{\rho_0} = \frac{L}{3 \rho_0}
\]
$^{208}$Pb skin: Diverse experiments but consistent results

HIC: heavy ion collisions
PRL 102, 122701 (2009)

$p$ elastic scattering, PRC 82, 044611 (2010)

Pygmy Dipole Resonances
PRC 81, 041304 (2010)

Antiprotonic Atom, PRC 81, 041304 (2010)

Tsang et al. PRC 86, 015803 (2012)
Importance of 3-body neutron-neutron force in the Equation of State of pure neutron matter

See references in PRC 86, 015803 (2012)
Challenges at high density

Hebler et al., PRL 105 161102, (2010)

Calculations beyond saturation density??
Physics at high density

Large uncertainties in the symmetry energy high density.

At $\rho<\rho_0$ density, mass splitting increase with density and asymmetry.
Nucleon Effective Masses

\[ S(\rho) = 12.7\left(\frac{\rho}{\rho_0}\right)^{2/3} + 19\left(\frac{\rho}{\rho_0}\right)^\gamma_i + \text{mean field in ImQMD05} \]

ImQMD05_sky: incorporate Skyrme interactions

<table>
<thead>
<tr>
<th>Skyrme</th>
<th>S0 (MeV)</th>
<th>L (MeV)</th>
<th>m_n*/m_n</th>
<th>m_p*/m_p</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLy4</td>
<td>32</td>
<td>46</td>
<td>0.68</td>
<td>0.71</td>
</tr>
<tr>
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<td>46</td>
<td>0.82</td>
<td>0.76</td>
</tr>
<tr>
<td>NRAPR</td>
<td>33</td>
<td>60</td>
<td>0.69</td>
<td></td>
</tr>
<tr>
<td>Gs</td>
<td>31</td>
<td>93</td>
<td>0.81</td>
<td>0.76</td>
</tr>
<tr>
<td>SkI2</td>
<td>33</td>
<td>104</td>
<td>0.66</td>
<td>0.7</td>
</tr>
</tbody>
</table>
Skyrme

\[ S(\rho) = 12.7 \left( \frac{\rho}{\rho_o} \right)^{2/3} + 19 \left( \frac{\rho}{\rho_o} \right)^{\gamma_i} + \text{mean field in ImQMD05} \]

ImQMD05.sky: modify mean field and \( S(\rho) \) to incorporate Skyrme interactions

\[
S(\rho) = \frac{\hbar^2}{32m} \rho^2 \left( \frac{3\pi^2 \rho}{2 \rho_o} \right)^2 + A_{\text{sym}} \left( \frac{\rho}{\rho_o} \right) + B_{\text{sym}} \left( \frac{\rho}{\rho_o} \right)^{\eta} + C_{\text{sym}} \left( \frac{\rho}{\rho_o} \right)^{8/3}
\]

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DR(n/p) increases with kinetic energy but decreases with incident energy.

\[ \text{DR(n/p)} = \frac{R_{124+124}(n/p)}{R_{112+112}(n/p)} \]
Experimental Layout
PhD thesis: Daniel Coupland & Michael Youngs

Neutron walls – neutrons
Forward Array – time start
Proton Veto scintillators

LASSA – charged particles
Miniball – impact parameter

Courtesy Mike Famiano
Double Ratio \[ \frac{^{124}\text{Sn} + ^{124}\text{Sn}; Y(n_c)/Y(p_c)}{^{112}\text{Sn} + ^{112}\text{Sn}; Y(n_c)/Y(p_c)} \] decreases with incident energy and increases with kinetic energy.

Thesis data:
Daniel Coupland
Michael Youngs

ImQMD05_sky
Summary

- Consistent constraints on the symmetry energy at sub-saturation densities with different experiments suggest that heavy ion collisions provide a good probe at high density.
- Experiments to measure constraints on the symmetry energy above saturation densities have started with n/p ratios and will continue with pion and flow measurements with the TPCs at RIKEN and FRIB.
- At high densities, theoretical challenges → 3n forces, nucleon effective masses
SUMMARY

Constraints established

? 3n forces

? n_n* & n_p*

RIBF’13, 14, FRIB’20, RISP?

GSI’11

S(ρ) (MeV)

Density ρ/ρ_o


FAIR →
S-TPC will be installed inside the SAMURAI dipole magnet in RIKEN.
Rigid Top Plate
Primary structural member, reinforced with ribs. Holds pad plane and wire planes.

Front End Electronics
Liquid Cooled

Field Cage
Defines uniform electric field. Contains detector gas.

Pad Plane (108x112)
Used to measure particle ionization tracks

Voltage Step-Down
Prevent sparking from cathode (20kV) to ground

Thin-Walled Enclosure
Protects internal components, seals insulation gas volume, supports pad pan while allowing particles to continue on to ancillary detectors.

Target Mechanism

Calibration Laser Optics

Rails
Inserting TPC into SAMURAI vacuum chamber

beam
Beam
Thin-Walled Enclosure
Protects internal components, seals insulation gas volume, and supports pad plane while allowing particles to continue on to ancillary detectors.

Rigid Top Plate
Primary structural member, reinforced with ribs. Holds pad plane and wire planes.

Pad Plane
Mounted to bottom of top plate. Used to measure particle ionization tracks.

Field Cage
Defines uniform electric field. Contains detector gas.

Voltage Step-Down
Prevent sparking from cathode (20kV) to ground.

Wire Planes
Mounted below pad plane. Provide signal multiplication and gate for unwanted events.

Rails
For inserting TPC into SAMURAI vacuum chamber.

SAMURAI TPC: Exploded View
Front End Electronics
STAR FEE for testing, ultimately use GET.

Target Mechanism
Calibration Laser Optics

本新学術領域：実験・観測・理論連携

X線天文衛星ASTRO-H
⇒中性子星全体の内部構造の解明

“クォークの物質科学”創始
⇒中性子過剩核物理

大強度陽子加速器J-PARC
⇒中性子物質の物性

中性子星の半径
⇒中性子物質の物性

冷却原子ガス
⇒ハイペロン粒子の間の力

“核物質EOS”を決定

日本が誇る世界最高の2大加速器と天文衛星

不安定原子核工場RIBF
A star is born through immense pressure
And we have had our fair share.
That beacon of light you see in the dark
Is our fair city rising from the night sky.

Artist: Kobie Solomon