Experimental Observables to study the nuclear symmetry energy with Heavy Ion Collision

Betty Tsang
The National Superconducting Cyclotron Laboratory
Michigan State University

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The National Superconducting Cyclotron Laboratory
Michigan State University

U.S. flagship user facility for rare isotope research and education in nuclear science, astro-nuclear physics, accelerator physics, and societal applications
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.
282 employees, including 24 faculty, 46 graduate, and 51 undergraduate students. (as of March 05)

489 employees, including 40 faculty, 64 graduate and 70 undergraduate students
(as of August 16, 2011)
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.
Nuclear Equation of State

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

\[ \delta = \frac{(\rho_n - \rho_p)}{(\rho_n + \rho_p)} = \frac{(N-Z)}{A} \]

Research with rare isotope beams

✓ **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?*
Equation of State (EoS)

Ideal gas: $PV = nRT$

EOS for Asymmetric Matter
- Soft ($\beta = 0, K = 200$ MeV)
- Asy-soft, $\beta = 1/3$ (Colonna)
- Asy-stiff, $\beta = 1/3$ (PAL)

$$E/A \ (\text{MeV})$$
$$\rho \ (\text{fm}^{-3})$$

$$\beta = (\rho_n - \rho_p) / (\rho_n + \rho_p)$$

Ideal gas: $PV = nRT$
Definition of Symmetry Energy

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

\[ E/A (\rho, \delta) = E/A (\rho, 0) + \delta^2 \cdot S(\rho); \]
\[ \delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A \]
Two observables: n/p ratios and isospin diffusion

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

\[ u = \rho / \rho_o \]

Y(n)/Y(p); t/³He, \( \pi^+ / \pi^- \)

Isospin Diffusion; low \( \rho \), \( E_{\text{beam}} \)
Symmetry energy constraints from HIC

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

\[ L = 3\rho_0 \frac{\partial E_{sym}}{\partial \rho_B} \bigg|_{\rho_B=\rho_0} = \frac{3}{\rho_0} P_{sym} \]

\[ 0.4 \leq \gamma_i \leq 1 \]
Symmetry energy constraints from HIC

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

HIC has been successful in obtaining constraints on the symmetry energy at 0.3<\rho/\rho_0<1

\[ L = 3\rho_0 \frac{\partial E_{\text{sym}}}{\partial \rho_B} \bigg|_{\rho_B=\rho_0} = \frac{3}{\rho_0} P_{\text{sym}} \]
Symmetry Energy constraints for $0.3<\rho/\rho_0<1$ are consistent even though different experimental techniques and theories are involved.

3n force is needed in the description of EoS of pure n-matter.
Challenges: Constraints on the density dependence of symmetry energy at supra normal density

Xiao et al., PRL102, 062502 (2009)
Russotto et al., PL B697 (2011) 471

arXiv:1204.0466
HIC has been successful in obtaining constraints on the symmetry energy at $0.3 < \rho/\rho_o < 1$

**Lessons learned from LE measurements:**

1. HI collision dynamics are complex but prove to be sensitive to density dependence of symmetry energy.
2. Need multiple observables to verify results and to add credibility to the constraints
3. Problems still remain, e.g.
   - How to extract results to $T=0$;
   - Control of input parameters in transport models.
4. Provide guidance to the experiments at high energy

**Talk Outline**

1. Review of LE experimental observables
2. Discussions of HE experimental observables and experiments at RIKEN, KoRIA & FRIB
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.

What are the experimental challenges?

What are the theory challenges?
Density Dependence of Symmetry Energy

Density region sampled depends on reaction mechanisms (impact parameter) & beam energy

Observables:
- $\rho < \rho_0$: Isospin diffusion, n/p ratios, flow and observables from NS.
- $\rho > \rho_0$: HIC the only game in town: n/p, $t^3\text{He}$, flow, $p^+/p^-$ ratio
Heavy Ion collision: $^{124}$Sn+$^{124}$Sn, E/A=50 MeV

Reaction mechanism of fragment productions depends on impact parameters.

Charged fragments (Z=3-20) are formed at subnormal density.

Impact parameter selection is a must!

$$S(\rho) = 12.5(\rho/\rho_o)^{2/3} + 19(\rho/\rho_o)$$

Neck fragments $b=0$ fm

Multifragmentation

Charged fragments $b=7$ fm

$$\rho/\rho_o$$

$$E_{sym} (MeV)$$

$$\gamma_i=0.5$$

$$\gamma_i=2.0$$

Subnormal density
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
  ➢ n & p yields
  ➢ isotopes yields – isospin diffusion
Strategies used to study the symmetry energy with Heavy Ion collisions below E/A=100 MeV

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

- Measure N/Z compositions of emitted particles
  - n & p yields
  - isotopes yields – isospin diffusion

At E/A>100 MeV, \(\rho>\rho_o\)

Strategies should be similar but observables maybe different
\[
E/A (\rho, \delta) = E/A (\rho, 0) + \delta^2 \cdot S(\rho)
\]
\[
\delta = (\rho_n - \rho_p) / (\rho_n + \rho_p) = (N-Z)/A
\]

Two observables: n/p ratios and isospin diffusion

Data: Famiano et al. PRL 97 (2006) 052701

Double Ratio

\[
\text{Double Ratio} \rightarrow \frac{^{124}\text{Sn}+^{124}\text{Sn}; Y(n)/Y(p)}{^{112}\text{Sn}+^{112}\text{Sn}; Y(n)/Y(p)} \rightarrow \text{minimize systematic errors}
\]
n/p double yield ratios and flow ratios

Data: Famiano et al. PRL 97 (2006) 052701

50 A.MeV Sn+Sn

400 A.MeV Au + Au

Theorists’ frustration: large experimental uncertainties!
Results from better designed experiments are coming!
n/p Experiment $^{124}$Sn+$^{124}$Sn; $^{112}$Sn+$^{112}$Sn; E/A=50 MeV

Famiano et al
Complicated Experimental Layout

- Wall A
- Wall B
- LASSA – charged particles
- Miniball – impact parameter
- Neutron walls – neutrons
- Forward Array – time start
- Proton Veto scintillators

Dan Coupland, PhD thesis (2013)
Detection of $t/\beta^3\text{He}$ are better controlled but still have cut off problems at high energy due to statistics and detector limitations.

More suitable for experiments at higher beam energy
Experimental Observable: Isospin Diffusion

- Isospin “diffuse” through low-density neck region
- Symmetry energy drives system towards equilibrium.
  - stiff EOS $\rightarrow$ small diffusion; $|R_i| > 0$
  - soft EOS $\rightarrow$ fast equilibrium; $R_i \rightarrow 0$

- Advantages
  - Sequential decays and non-diffusion effects normalized by the symmetric systems

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

Tsang et al., PRL92, 062701 (2004)
Isotope distributions and isospin diffusions

This can be described by the isoscaling parameters $\alpha$ and $\beta$:

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

$\alpha$ and $\beta$ are related to the nucleon chemical potentials

Isospin diffusion $\rightarrow$ $R_i(\alpha)$

The main effect of changing the asymmetry of the projectile spectator remnant is to shift the isotopic distributions of the products of its decay.

T.X. Liu et al., PRC76, 034603 (2007)

Tsang et al., PRL92, 062701 (2004)
Isospin Diffusion

No diffusion

Complete mixing

\[ \frac{\gamma_i}{Y(7\text{Li})/Y(7\text{Be})} \]

\[ \frac{\gamma_i}{\text{E/A}} \]

\[ b=6 \text{ fm} \]

\[ \text{Target } ^{112}\text{Sn} \]

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

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

Tsang et al., PRL102, 122701 (2009)
HIC constraints at sub-saturation densities

\[ S(\rho) = 12.5 \left( \frac{\rho}{\rho_0} \right)^{2/3} + 17.6 \left( \frac{\rho}{\rho_0} \right)^{\gamma_i} \]

where \( 0.4 \leq \gamma_i \leq 1 \)

Typel & Brown, PRC 64, 027302 (2001)
Symmetry energy constraints from HIC

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

HIC has been successful in obtaining constraints on the symmetry energy at \(0.3 < \rho/\rho_0 < 1\)
Constraints on the density dependence of symmetry energy

Heavy Ion Collisions

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

\[ n/p \text{ squeeze-out} \]

\[ S(\rho) \text{ (MeV)} \]

\[ \rho / \rho_0 \]

\[ \pi^+ / \pi^- \text{ ratios} \]
Symmetry Energy Project ➔ International collaboration to determine the symmetry energy over a range of density

Require: New Detectors (TPC), & theory support

<table>
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<th>facility</th>
<th>Probe</th>
<th>Beam Energy</th>
<th>Travel (k) $</th>
<th>year</th>
<th>density</th>
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<td>2-3ρ₀</td>
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<td>2018-</td>
<td>2-2.5ρ₀</td>
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<td>FAIR</td>
<td>K⁺/K⁻</td>
<td>800-1000</td>
<td>?</td>
<td>2018</td>
<td>3ρ₀</td>
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</table>
The Time projection chamber is being built in the US to measure $\pi^+/\pi^-$ & light charge particles in RIKEN
E/A=50-100 MeV
Neutron/proton and t/³He and light isotopes energy spectra & flow

E/A>150 MeV
• $\pi^+/$$\pi^-$ spectra
• $\pi^+/\pi^-$ flow

Preliminary data shows:
n/p remains robust at E/A=120 MeV. May be able to extend measurements to E/A~200 MeV

Isospin Observables in HIC at supra-normal densities

RIBF, FRIB, KoRIA
A new isospin observable

- $\pi^-$ generated from n+n collisions
- $\pi^+$ generated from p+p collisions
- Collisions of neutron rich nuclei: $N(\pi^-) > N(\pi^+)$
- $\pi^-$ multiplicity dependent on density dependence of EOS

\[
\frac{\pi^-}{\pi^+} \propto e^{\left(\frac{\mu_n - \mu_p}{T}\right)}
\]

Slide credit: A. Bickley

Different transport codes make different predictions!
New Detector(s)

At beam energy > 100 A.MeV, fragment production decreases. Observables are:
n/p ratios, flow, t/3He ratios, flow, π+/ π- ratios

Properties of the Time projection chamber (TPC)
Particle identification (dE/dX–track rigidity)
   Charged pions, Proton, Light ions (t, 3He)

Centrality Determination (b):
   momentum measurement

Reaction plane determination
   Ability to measure large number of multiple particles
Superconducting Magnet 3T with 2m dia. pole 
(designed resolution 1/700) 
80cm gap (vertical) 
TPC 
Large Vacuum Chamber 
Rotational Stage
SAMURAI-TPC

The SAMURAI Time Projection Chamber (TPC) tracks the light charged particles and pions after the heavy ion collisions.

SAMURAI Dipole Magnet

TPC in the Vacuum Chamber

Slide credit: A. Bickley

Jon Barney
The SAMURAI TPC

Since the field cage is where the magic happens, we want to maximize the height of the field cage.

The height is limited by the magnet chamber to 80 cm, but by minimizing the height of other parts we can maximize the field cage height.
Summary

• Success at low energy HIC program suggests paths forward to higher energy program to determine the density dependence of symmetry energy at high density – important program in any nuclear science LR plans.
• HIC is the only way on earth to create nuclear matter with $\rho > \rho_0$.
• Challenges remains:
  • New detectors to measure new observables. TPC to detect $p$’s.
  • Extension of current observables to high energy ($n/p$, $t/3He$...)
  • HIC experiments are complicated, need advance planning and “floor place/footprint” in new facilities.

Much work remains – exciting time to join the international effort!

Russotto et al., PL B697 (2011) 471

Xiao et al., PRL 102, 062502 (2009)