Current status and future direction on symmetry energy determination using HIC

Graffiti Art, Dequindre Cut, Detroit, August, 2012

Artist: Kobie Solomon

How does this subfield intersect with other subfields
**EoS of asymmetric matter**

\[
E/A (\rho, \delta) = E/A (\rho,0) + \delta^2 S(\rho) \quad \delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A \approx 1
\]

- The symmetry energy influences many properties of neutron stars:
  - Radii, moments of inertia
  - Cooling rates
  - Phase transitions in interior

- The symmetry energy dominates the uncertainty in the n-matter EOS.

**Constraints from Heavy Ion Collisions (HIC)**

\[
E_{\text{sym}} = S_0 + \frac{L}{3} \left( \frac{\rho_B - \rho_0}{\rho_0} \right) + \frac{K_{\text{sym}}}{18} \left( \frac{\rho_B - \rho_0}{\rho_0} \right)^2 + ...
\]
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)

**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 + ...**

Consistent Constraints on Symmetry Energy from different experiments \(\rightarrow\) HIC is a viable probe

major recent accomplishments

How does this subfield intersect with other subfields

Betty Tsang, Nuclear Astrophysics town meeting Slide 3
Importance of 3-body neutron-neutron force in the Equation of State of pure neutron matter

Model calculations with and without 3nn forces:

**BHF**: PRC80,045806 (2009)
Brueckner-Hartree-Fock

**DBHF**: arXiv:1111.0695
Dirac Brueckner-Hartree-Fock

**CEFT**: PRL105,161102 (2010)
Chiral Effective Field Theory

**QMC**: PRC85,032801R (2012)
Quantum Monte Carlo

Major recent accomplishments

Tsang et al. PRC (in print) arXiv:1204.0466
Effective nucleon masses

FIG. 6. Neutron and proton effective masses vs the baryon density for $\alpha = 0.5$ ($N = 3Z$). The dashed line corresponds to symmetric nuclear matter.

At $\rho < \rho_0$ density, effect of mass splitting increases with density and asymmetry

specific compelling open questions
Symmetry Energy Project: International collaboration to determine the symmetry energy over a range of densities

How can one address these open questions?
Symmetry Energy Project: International collaboration to determine the symmetry energy over a range of densities

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To probe symmetry energy at $\rho > \rho_0$ with sub-threshold pions from HIC

- **New observables**: $\pi^-/\pi^+$ ratio
- **New detectors**: SAMURARI - Time Projection Chamber
  Active Target - Time Projection Chamber

Specific compelling open questions
Properties of AT-TPC
• Length 1 m. Diameter 0.7 m
• 10000 Pad
• Self-triggering electronics

How can one address these open questions?
MSU Active Target - Time Projection Chamber

Lead PI: W. Mittig; Project leader: D. Bazin; Co-PI: W. Lynch

- Broad innovative scientific program.
- Two alternate modes of operation
  - Fixed Target Mode with solid target inside chamber:
    - $4\pi$ tracking of charged particles allows full event characterization
  - Active Target Mode:
    - Chamber gas acts as both detector and target ($H_2$, $D_2$, $^3$He, Ne, etc.)
    - Provides a thick target for low intensity beams while retaining high resolution and efficiency

- AT-TPC will allow inverse kinematics studies in astrophysical, resonant, transfer, breakup, fusion, fission reactions and to study the EOS using giant resonances and heavy ion reactions.
- AT-TPC will make use of the full range of beam energies and intensities available from ReA3 and FRIB.
- Half-size proto-type is working

high impact nuclear experiments
SAMURAI-TPC (2014)

- Time-projection chamber (TPC) will sit within SAMURAI dipole magnet
- Auxiliary detectors for heavy-ions and neutrons, and trigger

Drawing courtesy of T. Isobe
Isospin diffusion experiments with RIB  
The possibilities are unlimited

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DISCUSSION POINTS

1. What are the major recent accomplishments? constraints at subsaturation density
2. What are the specific compelling open questions? (Unexplained observations, problems in theoretical modeling, etc.)
   \[ \rho/\rho_0 > 1: S(\rho); \text{effective nucleon masses, effect of 3n forces in EOS} \]
3. How can one address these open questions? What are the high impact nuclear experiments, observations, theoretical studies that need to be done?
   $; \text{new detectors; FRIB (high intensity RIB); improved theories} \]
4. In which direction should this area evolve in light of expected new observational, theoretical, and experimental capabilities?
   exploration of \[ \rho/\rho_0 > 1 \text{ and } \rho/\rho_0 << 1; \text{understanding of basic physics properties of nuclear matter (m*)}. \]
5. How does this subfield intersect with other subfields? (For example, is there work needed in other subfields to move this subfield forward).
   Improvement in transport theories; neutron star observations;
ASY-EOS experiment @GSI, May 2011

\[ \text{Au+Au} \ @ \ 400 \text{ AMeV} \]
\[ ^{96}\text{Zr}+^{96}\text{Zr} \ @ \ 400 \text{ AMeV} \]
\[ ^{96}\text{Ru}+^{96}\text{Ru} \ @ \ 400 \text{ AMeV} \]

\( \sim 5 \times 10^7 \) Events for each system
Use n/p spectral ratios and double ratios to probe $m_n^*$ and $m_p^*$ and $E_{sym}$

- $^{124}$Sn+$^{124}$Sn; $^{112}$Sn+$^{112}$Sn, $E/A=120$ MeV (Coupland, Youngs)
- $^{48}$Ca+$^{124}$Sn; $^{40}$Ca$^{112}$Sn, $E/A=140$ MeV (Hodges, Rachel)
The Equation of State of Asymmetric Matter

\[ E_{\text{sym}} = \frac{L}{S_0} + \frac{L}{3} \left( \frac{\rho_B - \rho_0}{\rho_0} \right) + \frac{K_{\text{sym}}}{18} \left( \frac{\rho_B - \rho_0}{\rho_0} \right)^2 + \ldots \]

At \( \rho < \rho_0 \) density, consistent constraints have been obtained from different experiments:

- Heavy Ion Collisions (HIC), Giant Dipole Resonances, Isobaric Analog States (IAS),
- Finite Range Droplet model (FRDM), Pygmy Dipole Resonances (PDR), Proton elastic scattering on \( \text{Pb} \), and neutron star (n-star) radius.

Future Directions

EoS of asymmetric matter at high density using heavy ion collisions with rare isotope beams at high incident energy.
NSCL Experiment 07038: Precision Measurement of Isospin Diffusion

- Investigates the density-dependence of the nuclear symmetry energy using isospin diffusion from residues – new observable
- $^{112,118,124}_{\text{Sn}} + ^{112,118,124}_{\text{Sn}}$ Collisions
- Combines the MSU Miniball, the LASSA Array, & S800 Spectrograph

Incoming Beam, 70 MeV/u

Beam-like fragments $10<Z<50$
EoS of asymmetric matter

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

\[ \delta = (\rho_n - \rho_p) / (\rho_n + \rho_p) = (N - Z) / A \approx 1 \]

Isospin degree of freedom

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

\[ -a_{sym} \frac{(A - 2Z)^2}{A} \]

Constraints from Heavy Ion Collisions (HIC)

To improve experimental constraints:
- constraints mainly obtained from ID
- Increase the \((A-2Z)^2/A\); RI beams
- Identify new observables
- remeasure n/p ratios
Large uncertainties in the symmetry energy high density.

At \( \rho < \rho_0 \) density, mass splitting increase with density and asymmetry.
Experimental challenges in detecting n and p

Small Si-CsI arrays close to target (ΔE-E)

Many more particles detected by the neutron detectors in $^{124}$Sn+$^{124}$Sn reactions than n’s

Different coverage in geometry and energy for particles

Large scintillation arrays at great distance (TOF)

$50\text{ MeV}$

$120\text{ MeV}$

Yield

$\theta_{cm}$ (deg)

$E_{cm}$ (MeV)

protons

neutrons

TOF

Rejected He

Betty Tsang, Nuclear Astrophysics town meeting
## Heavy Ion Collisions at high density with RIB

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Study of Fission barriers of exotic nuclei with AT-TPC & PAT-TPC

- Provide constraints for fission cycling, beta-delayed and neutrino-induced fission contributions to r-process yields
- Extrapolations of ground state and fission saddle point binding energies away from the valley of stability
- Measurements of the excitation functions of fission cross-sections of exotic nuclei
  - \( p^{+195} \text{Tl} \rightarrow \text{fission} \) at \( E/A = 75, 65, 55, 50, 40, 35 \text{ MeV} \) (NSCL#12014)
  - etc.

![Diagram of the detector setup](image-url)
Summary

- HiRA provides capabilities to use transfer reactions to investigate single particle levels in exotic nuclei from fast beams.
- Charged particle decay spectroscopy reveals structure and decay modes at the proton drip-line.
- 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 AT-TPC.
- The AT-TPC and its prototype have a broad science program to study fission barriers of exotic nuclei, transfer reactions, isobaric analog and cluster states and giant resonances.
- The AT-TPC will be ready for experiments with ReA3.
Nuclear Structure studies with Transfer Reactions
single particle structure of unstable nuclei – pf shell

\[ H(^{46}\text{Ar},d)^{45}\text{Ar} \]

\[ H(^{56}\text{Ni},d)^{55}\text{Ni} \]

(Sanetullaev, PhD, 2011)
Nuclear Reactions
To study nuclear structure and the equation state of nuclear matter

Faculty: Lynch, Mittig, Tsang, Westfall
Detectors: HiRA, neutron wall, AT-TPC & its prototype

• Transfer reactions:
  – *What are the properties of single particle orbits?*

• Decay spectroscopy of Nuclei at the drip-lines:
  – *What is their structure and how do they decay?*

• Fission Barriers of exotic nuclei:
  – *How to extrapolate the Fission Barriers for nuclei relevant to the r-process?*

• What is the EoS of Asymmetric Matter?
  – *Sub-saturation densities*
  – *Supra-saturation densities*
Looking forward to the AT-TPC at ReA3

• Prototype (½ scale) AT-TPC
  • NIMA660,64(2011)
  • NIMA, (2012)

Scientific programs for AT-TPC and its prototype:

• Transfer Reactions to measure SF’s, ANC’s
  – Neutron particle states in neutron rich exotic nuclei using \( (d,p) \).
  – Proton particle states in proton-rich nuclei using \( (\text{^3He},d) \).
• Isobaric Analog Resonances: \( ^A_Z(p,p) \)
  – Probe structure of states in \( ^{A+1}_Z \): determine \( E^*, J, L, SF’s \)
• Cluster states in the continuum.
• Fission Barriers of exotic nuclei
• etc.
Experiments with AT-TPC Prototype

Prototype (½ scale) AT-TPC
NIMA660,64(2011)
NIMA (in print)

Experiments at Notre Dame:
- $^6$He+$^4$He ($^{10}$Be decay spectroscopy)
- $^{10}$Be+$^4$He ($^{14}$C decay spectroscopy)
- $^6$He+$^{40}$Ar (complete and incomplete fusion)

$\alpha+^6$He $\rightarrow \alpha + ^6$He

$\alpha+^6$He $\rightarrow \alpha + ^6$He$^*$

$\alpha+2n$
Decay spectroscopy for dripline nuclei

Decay of proton unbound nuclei – explosive hydrogen burning in X-ray bursts

- $^{69}\text{Br} \rightarrow p + ^{68}\text{Se}$ waiting point. (Rogers, PhD 2009; PRL106, 252503 (2011))
- $^{73}\text{Rb} \rightarrow p + ^{72}\text{Kr}$, (NSCL#10015)

Other programs:

- $^{8}\text{C}_{\text{g.s.}} \rightarrow 2p + 2p + \alpha$
- $^{8}\text{B}_{\text{IAS}} \rightarrow 2p + ^{6}\text{Li}_{\text{IAS}} + \gamma$
  (NSCL#10001)
- $^{16}\text{Ne}$ and $^{16}\text{F}_{\text{IAS}}$
  (NSCL#11001)
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
  - $^{124}$Sn+$^{124}$Sn, $^{124}$Sn+$^{112}$Sn, $^{112}$Sn+$^{124}$Sn, $^{112}$Sn+$^{112}$Sn
- Measure N/Z compositions of emitted particles
  - n & p yields
  - 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.
Strategies used to study the symmetry energy with Heavy Ion collisions below E/A=100 MeV

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- Simulate collisions with transport theory
  - Find the symmetry energy density dependence that describes the data.
  - Constrain the relevant input transport variables.
2. Proposed Experimental Set up

Microball from WU

Chamber from RIKEN

Scintillator & degrader foil ladder
Heavy Ion Collisions at high density with RIB

At $\rho<\rho_0$ density, consistent constraints Effect of mass splitting increase with density and asymmetry

Large uncertainties in the symmetry energy high density.

FIG. 6. Neutron and proton effective masses vs the baryon density for $\alpha=0.5$ ($N=3Z$). The dashed line corresponds to symmetric nuclear matter.

$E/A (\rho, \delta) = E/A (\rho,0) + \delta^2 S(\rho)$

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

B. Liu et al. PRC 65(2002)045201

B.A. Brown, PRL85(2000)5296

Tsang et al, PRL102,122701(2009)
Isospin Diffusion Experimental Setup at RIKEN

BigRIPS

Zero Degree Spectrometer

WU microball
The Equation of State of Asymmetric Matter

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

At \( \rho < \rho_0 \) density, consistent constraints have been obtained from different experiments:

- Heavy Ion Collisions (HIC)
- Giant Dipole Resonances (GDR)
- Isobaric Analog States (IAS)
- Finite Range Droplet model (FRDM)
- Pygmy Dipole Resonances (PDR)
- Proton elastic scattering on Pb
- and neutron star (n-star) radius

Future Directions

EoS of asymmetric matter at high density using heavy ion collisions with rare isotope beams at high incident energy.