### Summary of EOS working group

#### Additional contributions from: Garg, Brown, Pagano

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**Diagram:**
- HICs
- Neutron Stars
- Neutron skin

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ICNT—International Collaborations in Nuclear Theory
http://frib.msu.edu/content/ICNT

• MSU, GSI, & RIKEN directors contribute $50k/year to host 10-20 theorists get together for 2-4 weeks.
• ICNT2013 held at NSCL/FRB -- Symmetry-energy in the context of new radioactive beam facilities and astrophysics
  • Week I (July 15 - 19): Symmetry energy at low nuclear densities
  • Week II (July 22 - 26):
  • NuSYM13 Week III (July 29 – Aug 2): Symmetry energy at high densities including astrophysical environment.
  • Week IV (Aug 5 - 9): Future Directions
• Deliverable: Write-up of a document after the ICNT

International nature of the EOS collaboration.
New results and initiatives reported from ICNT/NuSYM13
**Equation of State of Nuclear Matter**

**Summary**

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

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

Strategies used to study the Symmetry Energy with HICs:

- Vary the N/Z compositions of projectile and targets
  - e.g., \(^{108,132}\text{Sn} + ^{112,124}\text{Sn}, ^{52}\text{Ca} + ^{48}\text{Ca}\)
- Measure N/Z compositions of emitted particles including pions
- At low energy: isotopes yields → isospin diffusion
- Simulate collisions with transport theory
- Find the SE density dependence that describes the data.
- Constrain the relevant input transport variables.
Updated constraints on Symmetry Energy

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

Updates from ICNT/NuSYM13

Consistent constraints establish HIC as viable probe to study symmetry energy at supra-saturation density.
Observation:
\[ M_{NS} \sim 2M_{\text{sun}} \]
\[ R_{NS} \sim 9 \text{ km} \]

Equation of State
- Stiff EoS at high \( \rho \)
- Softening EoS at \( \rho \sim 2\rho_0 \)
Neutron star Equation of State

softening EoS at $\rho \sim 2\rho_0$
stiff EoS at high $\rho$

Central Sn+Sn collisions
$E/A = 300$ MeV
$\gamma = 0.5$
$\gamma = 1.0$
$\gamma = 2.0$

M(\pi^-)/M(\pi^+)$
K$_{cm}$ (MeV)

Pions at $\rho \sim 2\rho_0$ (pBUU simulations)

Equation of State
softening EoS at $\rho \sim 2\rho_0$
stiff EoS at high $\rho$
How to improved constraints: Pions at $\rho \sim 2\rho_0$

Spirit TPC @ MSU (for RIKEN)
- Evt45: 2-D Display
- Cosmic tracks observed

AT-TPC @ MSU
- Prototype AT-TPC functioning
- Design finalized
- Fabrication in progress
- To be placed inside SAMURAI magnet
- Fixed target
- Commissioning and first experiment 2015

EOS working group - Summary
Improved constraints: GMR, GDR

Giant Monopole Resonances in neutron-rich nuclei  
U. Garg

- $K_t$, $K_{core}$ and $K_{skin}$
  “soft GMR” akin to pigmy GDR’s.

- Need inverse reactions
  $^2H$, $^4He$, or $^6Li$ targets
  beams of 35-100 MeV/A

- TPC’s offer the best options for now.
  AT-TPC (NSCL); CAT (CNS, Tokyo), MAYA (GANIL)

Experiments being planned/proposed at RIKEN and NSCL.

FRIB: Need to move AT-TPC to fast beam area

AT-TPC @ MSU

- Design finalized
- Fabrication in progress
- To be placed inside the solenoid magnet
- thick target
- $4\pi$ acceptance of reaction products

EOS working group - Summary
Experiments to improve constraints

1. Isospin multiplet ratios in $^{112}\text{Sn} + ^{112}\text{Sn}$ and $^{124}\text{Sn} + ^{124}\text{Sn}$ at 50 and 120 MeV/A

Improvements for Neutron Walls
- Veto charged particles directly in front of NW
  - Construct new PV scintillator array
  - Increase segmentation
  - Reduce scattering of charged particles through PV’s
- Already have PMTs
- Estimated material cost: $50,000 total (~$1,000/scintillator)
Experiments to improve constraints

1. Measuring time scale of N/Z equilibration
2. Pagano et al, INFN, Catania
3. De Souza et al., Indiana University

1. Isospin diffusions with RIB
2. New observables: projectile-like residues
3. NSCL--$^{112,118,124}\text{Sn}^+$ $^{112,118,124}\text{Sn}$
4. RIKEN--$^{109}\text{In}^+$ $^{112}\text{Sn}$
5. Set up: 4pi (microball/miniball+LASSA+spectrometer)
Physics Motivations:
Neutron Star Crust Fusion Dynamics ⇒ EOS
Fusion of n-rich light nuclei may be important for heating the crust and to determine its chemical composition

Need RIBs!

Advantages:
Relatively small floor space requirement (9ft x 3ft on beamline)
Few days of beam time per isotope to measure the excitation function
Use RIBs from NSCL; enhances sensitivity to $E_{\text{sym}}$

- Dedicated experiment approved (concept tested on previous data)
- Couple with light fragment detection (HiRA?)
Summary

- Consistent constraints at low density ➔
  HIC is a good probe to study symmetry energy.
- Improvement of uncertainties require RIB
- Next frontier is the high density region ➔
  observation of small NS radius and high mass suggests a
  softening of SE at $\rho \sim 2\rho_0$
- Next experimental frontier: HIC at $E_{\text{beam}}/A \sim 100$-$400$ MeV with RIB beams
- Need theoretical support – transport model workshop scheduled in Jan, 2014 in China.
Consistent Constraints on Symmetry Energy from different experiments → HIC is a viable probe

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

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

- Isobaric Analogue States
  - NPA 818, 36 (2009)
- Finite Droplet Range Model
- Heavy ion collisions
  - PRL 102, 122701 (2009)
- p elastic scattering
  - PRC 82, 044611 (2010)
- Neutron-star radius

Pygmy Dipole Resonances
- PRC 81, 041304 (2010)

Consistency criteria:

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

Tsang et al.
- PRC 86, 015803 (2012)
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