Probing the EoS of asymmetric matter

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- Symmetry energy, EoS and neutron stars.
- Laboratory constraints on the symmetry energy at $\rho < \rho_0$
- Extension of constraints to $\rho > \rho_0$
- Outlook

$\varepsilon(\rho, \delta)$ is the equation of state

$\varepsilon(\rho, \delta) = (E/A(\rho, \delta) = E/A(\rho, 0) + ^{TM} \cdot S(\rho)$

$^{TM} = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$

$P = \rho^2 \frac{\partial (E/A)}{\partial \rho} \bigg|_{s/a}$

$P$ is the pressure

$\rho$ is the number density

$S(\rho)$ is the symmetry energy
Influence of $S(\rho)$ on a neutron star

$S(\rho)$: = density dep. of symmetry energy

$\rho < \rho_0$

Inner crust:
Neutron gas in coexistence with "Coulomb lattice" of nuclei. $S(\rho)$ governs thickness of crust and the observed frequencies in star quakes.

Inner boundary of inner crust: Cylindrical and plate-like nuclear "pasta"

$\rho > \rho_0$

Outer core:
Composed of neutron-rich nuclear matter. $S(\rho)$ governs stellar radii, and moments of inertia.

Inner core:
Composition is unknown. Could be nuclear, quark or strange matter.
Laboratory constraints on Symmetry energy at $\rho<\rho_0$

- Such experimental observables have been analyzed to provide constraints on $S_0=S(\rho_0)$ and $L$.

- Some sensitive observables:
  - masses
  - Isobaric Analog States (IAS)
  - Electric dipole polarizability ($\alpha_0$)
  - Diffusion of neutrons and protons in peripheral collisions HIC (Sn+Sn)

- Calculations often use Skyrme functionals for these observables of the form:
  \[
  S(\rho) = a + b^{1+} + c^{2/3} + d^{5/3}
  \]
  - $c$ and $d$ provide kinetic energy and effective mass contributions to $S(\rho)$ and are independent of $S_0$ and $L$.
  - Constraints on $S_0$ and $L$ come from the fit values of $a$ and $b$, where

\[
\begin{align*}
a &= S_0 / \rho_0 \\
b &= L / 3 - S_0 + c^{2/3} + d^{5/3}
\end{align*}
\]

- The values for $S_0$ and $L$ are obtained at subsaturation densities, and are extrapolated to $\rho_0$. 

\[
S(\rho) = S_0 + \frac{L}{3} \left( \frac{B}{\rho_0} \right) + \frac{K_{sym}}{18} \left( \frac{B}{\rho_0} \right)^2 + \ldots
\]
What density does each observable actually probe? consider the fits of Alex Brown to masses.

- Alex fit the masses of doubly closed shell nuclei well, but allowed different neutron skin thicknesses of $\Delta R_{np} = 0.16$, 0.20 and 24 fm. These correspond to the 3 different regions in the $(S_0, L)$ plane.

- All Brown fits provide $S(\rho) = 24.8$ MeV at $\rho/\rho_0 = 0.63 \pm 0.03$. This is what the masses determine.

- Let’s test the linear extrapolation

- The symmetry energy functional is not linear between $0.6 < \rho/\rho_0 < 1$.

- Extrapolation to $\rho_0$ depends on the non-linearity of $S(\rho)$ at $0.63 < \rho < 1$, which is not constrained. Constraints on $S_0$ and $L$ depend on this non-linear extrapolation.
What does that tell us?

- This analysis provides an unambiguous value for $S(\rho)=24.8 \pm 0.8$ MeV at $\rho/\rho_0=0.63\pm0.03$
- This is the density where Brown’s analyses constrain $S(\rho)$ best.
- Additional information can be provided by separately analyzing the fits of masses over different mass ranges. (e.g. Danielewicz, et al, Nucl. Phys. A 922 (2014) 1.)
Constraints from ratios of neutron and proton spectra

- Symmetry potential expels neutrons and attracts protons. Sensitive to $L$, $S_0$, and nucleon effective masses.
- Measured ratios spectra for neutrons and protons at $90^0$ in the center of mass for central $^{124}$Sn+$^{124}$Sn and $^{112}$S+$^{112}$Sn collisions at $E/A=120$ MeV.

$$R_{n/p} = \frac{dM_n\left(\frac{cm}{90^0}\right)/dE_{cm}}{dM_p\left(\frac{cm}{90^0}\right)/dE_{cm}}$$

- Theory predicts that smaller $L$ will result in larger $R_{n/p}$.
- Calculate the ratios with ImQMD transport theory varying $S_0$, $L$, $m_n^*$ and $m_p^*$
Constraints from ratios of neutron/proton spectra in central $^{124}$Sn+$^{124}$Sn and $^{112}$Sn+$^{112}$Sn collisions

- Four dimensional Bayesian analyses of spectral ratios using Madai:
  - Parameters: $S_0$, $L$, $m_n^*$ and $m_p^*$
  - We obtain $\rho_s/\rho_0 = 0.39 \pm 0.6$ and $S(\rho_s) = 16.1 \pm 1.8$ MeV.
  - The effective masses are very important for neutron-star cooling, and will be measured more precisely next spring.
  - Best fit: $m_s^*/m_N = 0.77 \pm 0.11$ and $\left( m_n / m_n^* \ m_p / m_p^* \right) / (2 \cdot) = 0.5 \pm 0.6$
What density do the constraint contours imply?

- Major axis of contour is in the direction of $\vec{u}$ and has slope $M$

$$M(\rho_s) = \left( \frac{S(\rho_s)}{L} \right) \left( \frac{S(\rho_s)}{S_0} \right);$$

$M$ depends monotonically on $\rho_s$

- Best point to evaluate $M$ and determine $\rho_s$ and $S(\rho)$ is at the center of the ellipse.

- $\rho_s$ is not very model dependent, however.

- For Brown $M_{\text{exp}} = -0.100 \pm 0.008$, $\rho_s/\rho_0 = 0.63 \pm 0.3$ and $S(\rho_s) = 24.7 \pm 0.8$ MeV, same as before.
Density dependence of symmetry energy

- Figure shows the values for $S(\rho)$ obtained by these analyses.
- The best constrained values are at $0.6 < \rho/\rho_0 < 0.80$. Little or no constraints above $\rho/\rho_0 \approx 0.8$.
- Red curve is the ab-initio calculation by C. Drischler et al. PRC (2014).
- Constraints are similar to the density dependence from IAS recently published by Danielewicz et al., NPA (2017) shown by blue contour.
- Constraints from IAS and asymmetry skins by Danielewicz et al., NPA (2017) shown by red contour.
- The polarizability constraint is not directly a constraint on symmetry energy and can not be analyzed as the others. I refer you to Zhang PRC 92, (20150.
Intermediate Summary

• Constraint contours, as shown on the right, are inherently misleading.
  – To obtain the values for $L$ and $S_0$ shown by these contours, one must do an unconstrained non-linear extrapolation from the sensitive density $\rho_s$ to $\rho_0$.
  – We know little about $S(\rho)$ near $\rho_0 \Rightarrow$ this extrapolation is rather uncertain.

• It is much better to provide the symmetry energy at the sensitive density of each observable.
Many nuclear structure and reactions have constrained the symmetry energy at $\rho<\rho_0$, as I have discussed.
- At $\rho<\rho_0$, situation improving rapidly.

At $\rho>\rho_0$, work just beginning.
- Important to constrain all theoretical unknowns and reconcile discrepancies.
**SPπRIT-Time Projection Chamber exp. at RIBF**

- 134 x 86 x 53 cm³ effective volume
- dE/dX – B\rangle particle identification.
- Target at the entrance of chamber.
- Readout with ~12000 pads.
- Neutrons 15°<θ<30° meas. by NeuLAND
- Experiment completed 6/1/2016

<table>
<thead>
<tr>
<th>E/A MeV</th>
<th>Reaction</th>
<th>$\frac{N - Z}{A}$</th>
<th>focus</th>
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<tbody>
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<td>270</td>
<td>$^{132}$Sn+$^{124}$Sn</td>
<td>.22</td>
<td>S(ρ), $m^<em>_n - m^</em>_p$</td>
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<td>.15</td>
<td>$\sigma_{nn}$, $\sigma_{np}$, $\sigma_{pp}$</td>
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<td>270</td>
<td>$^{112}$Sn+$^{124}$Sn</td>
<td>.15</td>
<td>$\sigma_{nn}$, $\sigma_{np}$, $\sigma_{pp}$</td>
</tr>
</tbody>
</table>
Studies with SπRIT TPC at $\rho \gg \rho_0$

- Measure the energy dependence of pion production.
- Have measured at $E/A=270$ MeV.
- Spectra are sensitive to the symmetry energy.
- Most theories predict an enhanced sensitivity to the symmetry energy at lower incident energies.
- We plan to also measure at $E/A=200$ MeV.
  - Useful test of the transport theory description of pion production near threshold
- Similar information can be obtained by comparing neutron and proton emission.
Some data: use of vertex reconstruction to separate reactions on target from reactions on counter gas.

- Reaction at target
- Some data: use of vertex reconstruction to separate reactions on target from reactions on counter gas.
- Background can be eliminated
- • Active Veto Array
- Target Ladder
- Entrance window
- • Active target
- VertexZ
  - 407879
  - 25.76
  - 208.5
  - 8382
  - 443
  - 3.991e+05
- Before target
- • A. C.
- • Entrance window
- • Target Ladder
Everything worked, data looks excellent

- We are able to identify cleanly pions through ions beyond $^7$Li.
- Right now we are finalizing our calibrations for heavier ions.
- We also determining the experimental efficiencies in regions of high track density.
- First results for next year.
Steiner et al., ApJ 722, 33 extract $R=11.5\pm1.5$ km from X-ray bursters and quiescent binary systems. Other radius measurements have differed by the order of 2 km.

Comparable constraints on pressure of $30 \text{ MeV/fm}^3 < P < 86 \text{ MeV/fm}^3$ at $n_B = 0.43 \text{ /fm}^3$ from neutron star $R$ vs. $M$ correlation and Heavy ion collisions. (Factor of 3). Heavy ion “constraints” appear much tighter at $0.3<n_B<0.4 \text{ /fm}^3$ and would be considerably improved by constraining $S(\rho)$ at $\rho>\rho_0$. 
Summary and outlook

• Significant constraints on the symmetry energy at well defined densities are emerging for $\rho<\rho_0$.
• It is important to determine the sensitive density probed by each observable and then extract the symmetry energy at that density.
  – Have constraints on $S(\rho)$ at $0.25<\rho/\rho_0<0.75$.
• Key issues are to constrain the symmetry energy at $0.80<\rho/\rho_0<2.0$.
  – $S\pi$RiT TPC experimental program should be able to explore pion and nucleon observables and provide new constraints on $S(\rho)$ in the region of at $0.80<\rho/\rho_0<2.0$. This density region is highly relevant to the mass-radius relationship of neutron stars.
• This also probes the density region where there are contradictory constraints from previous measurements of $\pi^-/\pi^+$ spectral ratios and from the comparison of n vs. p elliptical flows.
SπRIT
SAMURAI Pion Reconstruction and Ion Tracker
50+ scientists from China, Japan, Korea, Poland, France, Germany and U.S.

SπRIT TPC is designed to probe the symmetry energy at $\rho > \rho_0$ at the RIBF facility in Wakoshi, Japan.