Constraining the effective mass dependence of the Nuclear Symmetry Energy

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Outline

Motivation

Previous Experimental Work

New Experimental Setup

HiRA Upgrade

Microball

Neutron Wall

Charged-particle Veto Wall

Outlook
Motivation

Nuclear Equation of State

\[ \frac{E}{A}(\rho, \delta) = \frac{E}{A}(\rho, \delta = 0) + E_{\text{sym}}(\rho)\delta^2 \]

\[ S = \frac{\rho_n - \rho_p}{\rho_n + \rho_p} \]

Symmetry Energy: cost for N\(\neq\)Z

(largest EoS uncertainty)

Symmetry Energy affects

• Neutron Skin Thickness
• Fragment Flow
• Yield Ratios
• Isospin Diffusion

Astrophysics

• Neutron star cooling
• Mass-radius relation in neutron stars
• Production of r-process nuclei

The isovector effective mass describes how the potential energy depends on the momentum:

\[ m^* = \frac{m}{1 + \frac{m \partial V}{\rho \partial \rho}} \]

At saturation density this reduction is \(~70\%\) from the free nucleon mass. In asymmetric matter the potentials that neutrons and protons feel are expected to be different → effective-mass splitting:

\[ \Delta m^*_{np} = \frac{m_n^* - m_p^*}{m_N} \]
Effective-Mass Splitting

- Neutron rich systems show effective-mass splitting
- Greater isospin asymmetry leads to more mass splitting

Landau-Fermi Liquid Theory

Sjoberg, Nuc Phys A265, 511-516 (1976)


Theoretical models disagree whether $m_p^* > m_n^*$ or $m_n^* > m_p^*$
Previous work:
Divide n/p ratios for two reactions
Minimize systematic uncertainties in detection efficiencies of neutrons and charged particles
Reduces effects from the Coulomb force
Uncertainties large between theory and experiment

Future Improvements:
- Single ratio has better sensitivity BUT need better understanding of experimental system → NPTool simulations
- Need to probe at higher energies
- Requires upgrade to our experimental setup

Plan to measure the n/p ratio for the near symmetric systems $^{40,48}\text{Ca} + ^{64}\text{Ni}$ and the very asymmetric systems $^{40,48}\text{Ca} + ^{112,124}\text{Sn}$ at 50, 140 MeV/A.

The light, symmetric systems:
Can make extensive comparisons with nearly all transport models $\rightarrow E_{\text{sym}}$ and $m^*$ constraints.

The asymmetric systems:
More sensitive to momentum dependence and less sensitive to density dependence of mean field potential.

These data will add to the heavy, mass symmetric ($^{112,124}\text{Sn} + ^{112,124}\text{Sn}$, Coupland et al) already measured at 50, 120 MeV/A.
Upgrading the Experimental Setup
HiRA Upgrade

We are exchanging the 4-cm-long CsI(Tl) crystals for 10 cm crystals -> increased dynamic range

<table>
<thead>
<tr>
<th>Isotope</th>
<th>4 cm CsI (MeV)</th>
<th>10 cm CsI (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>116</td>
<td>200</td>
</tr>
<tr>
<td>d</td>
<td>157</td>
<td>265</td>
</tr>
<tr>
<td>t</td>
<td>186</td>
<td>314</td>
</tr>
</tbody>
</table>

This increase comes at the cost of loss in efficiency due to out-scattering and nuclear reactions

This efficiency is also a function of energy, so the most dramatic losses will occur for the highest energy particles
HiRA Upgrade

Old HiRA          HiRA Upgrade

Light Guides

CsI(Tl) Crystal

Double Sided Strip E (1.5mm)
Testing for Uniformity

\[ \text{Shift} = 100 \times \frac{(\mu_i - \mu_{av})}{\mu_{av}} \]
We are recommissioning LANA to use to detect the neutron energy spectra.

LANA is comprised of:
- Two Walls of 25 scintillator bars
  - 2 meters long, 7.7 cm square cross-section
  - NE-213 liquid scintillator

In previous work, the veto of charged particles was not perfect:
- The veto detector was small, close to the target, and did not have position information in 2D.
- Not all of the charged particles could be rejected.
Construction of a new Veto Wall

Slide from Kuan Zhu
Construction of a new Veto Wall

- Plastic Scintillator
- Supporting Wedge
- Light Guide
- Phototube socket and black mu-shell

Slide from Kuan Zhu
Construction of a new Veto Wall

Objet Connex350 Multi Material 3D Printing System

3D Printing

Slide from Kuan Zhu
Construction of a new Veto Wall
3-D Printed!

Other Detector Systems

Microball

Forward Array
Putting it all together

- Space for all of these detector systems is quite tight
  - Forward Array
  - Microball
  - HiRA10
  - Neutron Wall
Putting it all together

Microball Table (WMU) – Microball by WU not shown

Forward Array w/ Mounts
Late December → HiRA10 calibration, Veto/Neutron Wall commissioning and shakedown (3 days)

February → $^{40}$Ca + $^{112,124}$Sn, $^{58,64}$Ni (18 days) @ 50,140 MeV/A

March → HiRA10 calibration (3 days)

March → $^{48}$Ca + $^{112,124}$Sn, $^{58,64}$Ni (18 days) @ 50,140 MeV/A
The effective mass of nucleons is an important piece in the Symmetry Energy puzzle.

Neutron-to-proton energy spectra from heavy-ion collisions are a sensitive observable for constraining the effective mass of nucleons in heavy nuclei. Upgrades to the High Resolution Array (HiRA) will allow us to nearly double the energy range of detected protons. Construction of the new Charged-Particle Veto Wall will enable us to more cleanly measure the energy distribution of the neutrons. Stay tuned for results from our upcoming beam time.
Collaboration