EoS Investigations at FRIB

EOS working group – February 2011

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Investigations at FRIB can provide data to constrain the density dependence of the nuclear symmetry energy, an important property of nuclear matter that plays a key role in neutron-rich environments including the interior of a neutron star. Here we discuss some experiments involving systems with differing isospin-asymmetries and incident energies that can place significant constraints on the density dependence of the symmetry energy at sub-saturation and supra-saturation densities. The full program will include experiments not discussed here, some focused specifically on the symmetry energy and others aimed at reducing other theoretical uncertainties in order to make the constraints on the symmetry energy more quantitative.

Overview: The density dependence of the nuclear symmetry energy

The total energy per nucleon commonly known as the nuclear Equation of State (EoS) can be written for cold nuclear matter as the sum of a symmetry energy term and the energy per nucleon of symmetric matter:

$$E(\rho, \delta) = E_0(\rho, \delta{=}0) + E_\delta, \; E_\delta = S(\rho)\delta^2, \qquad (1)$$

where the asymmetry is $\delta = (\rho_n - \rho_p)/\rho$, and ρ_n, ρ_p and ρ are the neutron, proton and nucleon number densities, and $S(\rho)$ describes the density dependence of the symmetry energy, E_δ. Measurements of isoscalar collective vibrations, collective flow and kaon production in energetic nucleus-nucleus collisions have constrained the equation of state for symmetric matter, $E_0(\rho, \delta{=}0)$, at densities of $\rho_0 \le \rho \le 5\rho_0$ [Dan02, Fuc06, You97]. The extrapolation of the EoS to neutron–rich matter depends on $S(\rho)$, which has few experimental constraints [Bro00] until recently [Tsa09, Kli07, Car10, Li10, Dan08].

Many recent efforts to constrain the density dependence of the symmetry energy have focused on its behavior near saturation density. There, one may expand the symmetry energy, $S(\rho)$, about the saturation density, ρ_o,

$$S(\rho) = S_0 + \tfrac{L}{3}\left(\frac{\rho-\rho_o}{\rho_o}\right) + \tfrac{K_{sym}}{18}\left(\frac{\rho-\rho_o}{\rho_o}\right)^2 + \ldots \qquad (2)$$

where L and K_{sym} are slope and curvature parameters at ρ_o. Knowledge of terms up to 4th order in (ρ-ρ_0) are probably needed to characterize $S(\rho)$ for $\rho_0 \le \rho \le 2\rho_0$. The slope parameter, L, is related to p_o, the pressure from the symmetry energy for pure neutron matter at saturation density as follows:

$$L = 3\rho_0 \left| dS(\rho)/d\rho \right|_{\rho_0} = [3/\rho_0]\, p_0. \qquad (3)$$

The symmetry pressure, p_o, provides the baryonic contribution to the pressure in neutron stars at saturation density [Ste05], at which the pressure from the symmetric matter vanishes. In the last few years, measurements of collective structures such as the Giant Monopole Resonance [Li09a, Li10] and the Pygmy Dipole Resonance [Kli07, Car10] in neutron-rich nuclei, the energies of isobaric analog states, and measurements of reaction observables such as isospin diffusion [Tsa04], neutron/proton emission [Fam06], and fragment isotopic ratios [Tsa01, Igl06] have provided initial constraints on the density dependence of the symmetry energy at sub-saturation densities [Li08, Tsa09].

A comparison of the isospin diffusion data to ImQMD calculations for a variety of mean field potentials with different values for S_0 and L was reported in [Tsa09]. It provides a domain of values for S_0 and L values consistent with the isospin diffusion data of ref. [Tsa04] at the 2σ level [Tsa09]. The width of this domain for S_0 =32 MeV corresponds to L = 71 ± 21 MeV, which overlaps all of the constraints from heavy ion collisions, nuclear masses and nuclear structure. It illustrates the current status of a rapidly evolving field where new measurements discussed in the following sections will have a considerable impact. Each experimental constraint has both experimental and theoretical uncertainties. The latter have a model dependent contribution that requires careful assessment. Comparing and combining multiple constraints from different observables can reduce the sensitivity to the deficiency to a particular model. Data at FRIB will reduce the region of allowed values of S_0 and L considerably.

Comparatively, there is very little data in the supra-saturation density region. A recent theoretical analysis [Xia09] of the $\pi^+/\ \pi^-$ yield ratio data for Au+Au reactions from Ref. [Rei07] suggested that the symmetry energy at $\rho/\rho_0 \geq 2.5$ is much smaller than it is at saturation density and that the symmetry energy must reach a maximum between 1-2 times the saturation density. This conclusion, however, was based on a single set of data that has not been optimally chosen to constrain the symmetry energy at supra-saturation densities. Data at FRIB will improve the understanding of the high density behavior of $S(\rho)$ the considerably.

Investigations of the symmetry energy at sub-saturation densities

Nuclear structure observables: The GMR has the virtue of being an $\ell = 0$ breathing mode vibration whose energy can be related to the incompressibility, K_∞, of the nuclear matter EoS at saturation density [Har01, You99] and thereby to the first and second derivatives of the nuclear symmetry energy [Col04]. Investigations of the GMR energy along isotopic chains can therefore provide constraints on the density dependence of the symmetry energy near saturation density and on the incompressibility of neutron-rich nuclear matter [Li10]. New phenomena may emerge in very neutron rich or proton rich nuclei that reflect couplings of collective motions such as the GMR to the neutron-skin or proton-skin in such nuclei, adding exciting opportunities to the study of this collective mode in neutron rich nuclei.

To enable this program, the AT-TPC needs to be completed and installed on a beam line that can deliver fast rare isotope beams. This will enable significant independent constraints on the density dependences of the symmetry energy near saturation density and on the incompressibility for neutron rich matter. Measuring the Isoscalar Giant Dipole and Isovector Spin Dipole Resonance in rare isotopes as well can provide additional information.

Nuclear reaction observables: Additional measurements of nuclear reactions observables are planned to place more stringent constraints at sub-saturation densities. One observable probes the diffusion, during a peripheral collision, of neutrons and protons between two nuclei with different asymmetries, which continues until the two residues separate or the chemical potentials for neutrons and protons become equal in both nuclei. Calculations predict larger (smaller) diffusion rates for symmetry energies with weaker (stronger) density dependencies corresponding to larger (smaller) values of the symmetry energy at densities of $\rho \approx 0.5\rho_0$ to which the diffusion observable is primarily sensitive [Tsa04].

Measurements of isospin diffusion can be performed using the S800 spectrograph, which should provide more accurate constraints on the symmetry energy. Careful investigations of isotope diffusion using stable and unstable nickel or tin isotopes, such as $^{54-70}Ni$ + $^{58,64}Ni$ or $^{106-132}Sn$ + $^{112,124}Sn$, can provide information about the sensitivity of diffusion to the nuclear surface, while taking advantage of the reduced model dependence for residue observables.

These require the continued availability of a large target chamber for the S800 Spectrograph and the spectrograph itself. In addition, there can be significant gain for all experiments involving the spectrograph if the untriggered rate capability of the focal plane detector can be raised to 50k and the data acquisition rate of the system can be increased by a factor of 30.

The shapes of the fragment isospin distributions themselves can also provide information about the density dependence of the symmetry energy [Tsa01, Igl06]. ***Measurements of those fragments that are emitted outside of the acceptance of the S800 benefit from the availability of a large solid angle high-resolution charged particle array capable of unit mass and charge resolution.***

Investigations of the symmetry energy at supra-saturation densities

For incident energies available at FRIB, transport calculations predict that pions are mainly produced in central nucleus-nucleus collisions via Δ resonance production while the system is near its highest density. Calculated values of ρ_n/ρ_p initially exceed unity in a neutron-rich system at such high densities, but may decrease with time due to the pressure of the symmetry energy, which is greater for a "stiffer" symmetry energy term with stronger density dependence [Li97, Bar01, Li08, Li04]. Isospin selection rules correlate π^- and π^+ production rates with the n-n and p-p collision rates at these densities, respectively. This leads predictions of higher ratios for the multiplicities of negative pions over positive pions for an EoS with the "softer" density dependence of the symmetry energy [Li08, Li04]. Detailed calculations indicate that: while the pion production rate increases [Rei07], the sensitivity of that production rate to the symmetry energy decreases with incident energy [Qin05, Bar05, Mos08, Li08, Xia09], possibly due to the increased role of pion absorption and rescattering at higher energies. Thus, the sensitivities of $Y(\pi^-)/Y(\pi^+)$ to the symmetry energy are significant at energies $E/A \leq 0.5$ GeV, below the free nucleon-nucleon production threshold [Qin05, Bar05, Mos08], even though the multiplicities of pions at these energies are expected to be small.

Central densities of up to $1.8\rho_0$ can be achieved in a nucleus-nucleus collision at FRIB. However, pion production remains a rare process at FRIB beam energies; pion multiplicities of the order of 1 pion per 10 central collisions are expected. While higher pion multiplicities can be achieved at facilities with higher energy beams, calculation predict that the discriminating power of the pion charge ratio may be enhanced by a factor of 2 at FRIB energies, relative to the situation at 400 A-MeV due to the reduced frequency of second-chance interactions of the pions as they exit the collision region**.** Thus, pion measurements, at FRIB will provide an excellent opportunity to constrain the density dependence of the symmetry energy despite the low pion production rates.

The Active Target Time Projection Chamber (AT-TPC) can perform accurate measurements of low pion multiplicities at FRIB. We envision comparing measurements of pion production in ^{132}Sn +^{124}Sn, ^{108}Sn+^{112}Sn, ^{40}Ca+^{40}Ca and ^{54}Ca+^{48}Ca collisions with the AT-TPC to constrain the symmetry energy at supra-saturation densities. In addition to pions, the AT-TPC will also detect and isotopically identify hydrogen and helium isotopes. Measurements of isotopically identified fragments with Z=3-30 are planned in a high resolution charged particle array capable of unit mass and charge resolution mounted behind the AT-TPC cathode foil. Nearly complete events can thereby be measured permitting precise constraints on the transport theories used to describe such data.

To enable this program, the AT-TPC needs to be instrumented with a thin cathode and installed on a beam line that can deliver fast rare isotope beams. It also benefits from the development of a large solid angle high-resolution charged particle array capable of unit mass and charge resolution. This could be provided, for example, by an expansion of the present HiRA array.

Neutron to proton (n/p) ratios and differential flows [Fam06, Li97, Li05a] also strongly reflect the symmetry energy. For example, measurements of (n/p) spectral double ratios in Sn+Sn collisions at E/A= 50 MeV have also contributed to the constraints on the symmetry energy at sub-saturation densities [Fam06, Tsa09]. We envision measurements of neutron to proton (n/p) ratios and differential flows for ^{132}Sn +^{124}Sn, ^{108}Sn+^{112}Sn, ^{40}Ca+^{40}Ca and ^{54}Ca+^{54}Ca at FRIB to probe densities up to 1.7 $\rho_{0.}$

To enable this program, an extremely efficient neutron detection time of flight array is needed. In addition, one needs a large thin-walled chamber, which would allow installation of a charged particle array for impact parameter determination.

Fission:

We do not expect fission to provide constraints on the density dependences of the symmetry energy. The asymmetry dependence of fission barriers, however, does reflect the density dependence of the symmetry energy. Fission barriers of fast rare isotope beams will be measured in inverse kinematics on hydrogen and helium targets using the AT-TPC. This will facilitate the extrapolation of fission barriers towards the r-process pathway.

To enable this program, the AT-TPC needs to be instrumented with a thin cathode and installed on a beam line that can deliver fast rare isotope beams. It also benefits from the development of a large solid angle high-resolution charged particle array capable of unit mass and charge resolution. This could be provided, for example, by an expansion of the present HiRA array.

A list of cited references can be found http://www.nscl.msu.edu/~lynch/ref.xls

The AT-TPC is an important component of this FRIB effort.

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