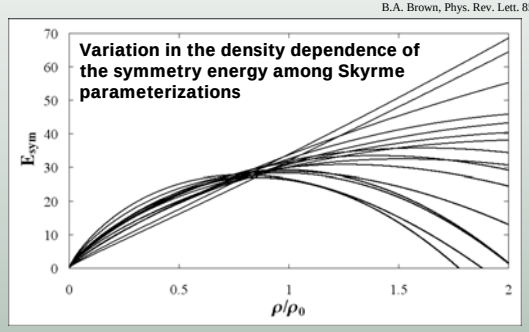
Constraining the Symmetry Energy in the Equation of State

Motivation

The Nuclear Equation of State (EOS) describes relationships between density, pressure, temperature, energy, and isospin asymmetry in nuclear matter.

- The density dependence of the EOS is well-determined for symmetric nuclear matter.
- The density dependence of asymmetric nuclear matter is unconstrained, and even the direction of the trend is unconstrained at high densities.

B.A. Brown, Phys. Rev. Lett. 85, 5296 (2001)



The energy per nucleon is expressed as a symmetric term and a term that is quadratic in the isospin asymmetry, δ. The coefficient E_{sym} is called the symmetry energy.

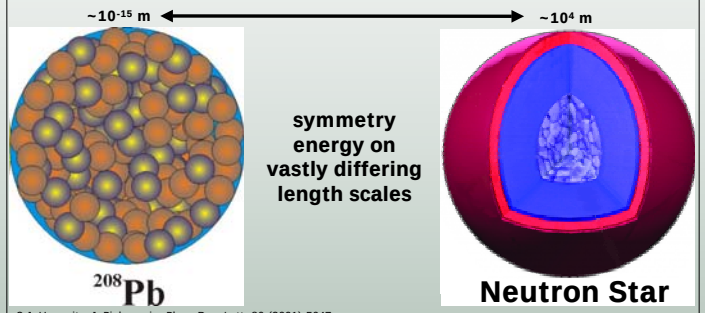
$$\frac{E}{A}(\rho,\delta) = \frac{E}{A}(\rho,0) + E_{sym}(\rho)\delta^2 \qquad \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

The density dependence of the symmetry energy affects astrophysical systems.

- properties of neutron stars (internal structure, radius, mass..)
- supernova phenomena

It also affects fundamental nuclear properties.

- radii of n-rich nuclei
- neutron skins of heavy nuclei



C.J. Horowitz, J. Piekarewicz,Phys. Rev. Lett. 86 (2001) 5647

How can we probe the symmetry energy in the lab?

- heavy ion collisions of nuclei with differing isospin content
- Study observables that are sensitive to the difference between proton and neutron potentials

Experimental Observables

Neutron-Proton Ratios:

The ratio of the free neutron spectrum to the free proton spectrum in central collisions. Measured in NSCL exp. 01032, additional measurement in upcoming NSCL experiment 05049.

Proton-Proton Correlations:

A measure of how emitted protons interacted just before they were ejected from the collision. Measured in NSCL exp. 03045.

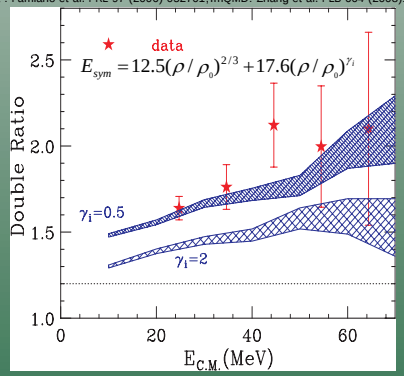
Isospin Transport Ratio:

A measure of how charge and mass diffuse between nuclei in peripheral collisions. Measured in previous experiments, and will increase precision in NSCL exp. 07038.

Pion ratios:

The ratio of differently-charged pions produced in a collision. Planning and construction of the AT-TPC detector is underway to enable measurements in the region of 1-2ρ_0 density.

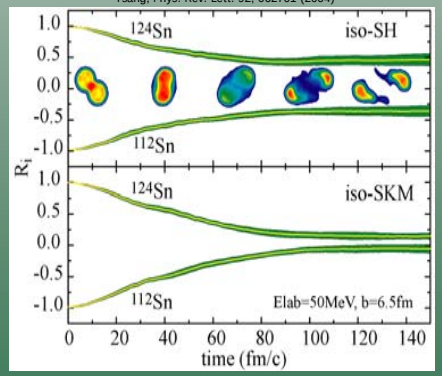
Data : Famiano et al. PRL 97 (2006) 052701;ImQMD: Zhang et al. PLB 664 (2008)145



Neutron-Proton Double Ratio

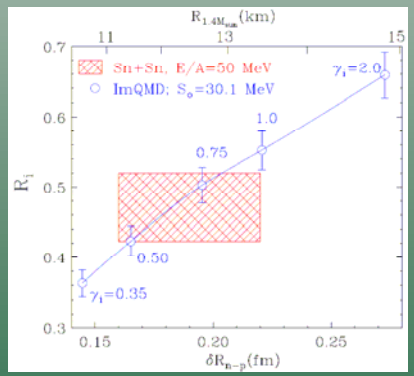
Current data compared to BUU calculations indicates a soft density dependence, γ_i = 0.5. More data is needed to achieve precise conclusions.

Tsang, Phys. Rev. Lett. 92, 062701 (2004)



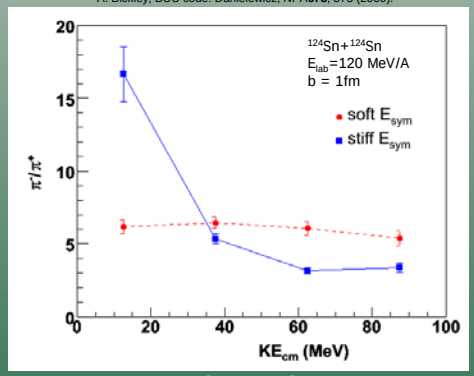
Isospin Transport Ratio

These BUU calculations illustrate the concept of the isospin transport ratio, R_i. When the reaction begins and no diffusion has occurred, the ratio is near ±1. The symmetry energy moves the system towards to equilibrium, R_i=0.



Comparison of isospin diffusion data to ImQMD calculations indicates a density dependence near γ_i = 0.45-0.95. The effect of this symmetry energy on the size of 1.4 solar mass neutron stars and on the neutron skin thickness of ^{208}Pb is plotted above.

A. Bickley; BUU code: Danielewicz, NPA**673**, 375 (2000).



Pion Ratios

The ratio of charged pions corresponds to the N/Z ratio in the dense center of a collision, and thus to the symmetry energy at densities $\rho > \rho_0$. Current data at these densities is very limited.

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