Constraints on the symmetry energy from heavy ion collisions

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Constraints on the Equation of State for symmetric matter (equal neutron and proton numbers) have been extracted from energetic collisions of heavy ions over a range of energies. Collisions of neutron-deficient and neutron-rich heavy ions now provide initial constraints on the Equation of State of neutron-rich matter at sub-saturation densities from isospin diffusions and neutron proton ratios. This talk reviews the experimental constraints from heavy ion reactions on the density dependence of symmetry energy at sub-saturation density. These constraints are compared to other available constraints from nuclear structures, masses and neutron skins.

1. Introduction

The Equation of State (EoS) of cold nuclear matter can be written as the sum of the energy per nucleon of symmetric matter and a symmetry energy term, E_δ,

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

where $\delta=(\rho_n-\rho_p)/\rho$ is the asymmetry; $S(\rho)$ describes the density dependence of E_δ, ρ_n, ρ_p and ρ are the neutron, proton and nucleon densities, respectively. The first term on the RHS, $E_0(\rho,\delta=0)$ is the EoS term for symmetric nuclear matter with equal fractions of neutrons and protons. Heavy ion collision measurements have constrained $E_0(\rho,\delta=0)$ for densities ranging from $\rho_0\leq\rho\leq5\rho_0$ [1,2]. Until recently, well-determined constraints on the symmetry term, E_δ, are few.

Macroscopic quantities of asymmetric nuclear matter exist over a wide range of densities in neutron stars and in type II supernovae [3]. Experimental information about the asymmetry term in the EoS can improve predictions for neutron star observables such as stellar radii and moments of inertia, crustal vibration frequencies [4,5], and neutron star cooling rates [4,6] that are currently being investigated with ground-based and satellite observatories. For many of these observables, the absence of strong constraints on the symmetry energy term of the EoS engenders major theoretical uncertainties. Consequently, determining the EoS has been a major motivation for many X-ray observations of neutron stars including the proposed International X-ray Observatory [7]. In Nuclear Physics, investigations that provide an improved understanding of E_δ will greatly improve our description of nuclear masses [8], fission barriers, energies of isovector collective vibrations [9], and the role of isovector modes in fusion and strongly damped collisions as well as the neutron skins of neutron-rich nuclei [10].

This talk focuses on investigations of the symmetry energy at sub-saturation density, where nucleus-nucleus collisions provide constraints to the symmetry energy using different experimental observables. The resulting constraints are compared to constraints obtained from nuclear structure studies. Finally, recent planned efforts to provide constraints on the symmetry energy and the EoS for neutron-rich matter over a broad range of densities will be discussed.

2. Experimental observables from heavy ion collisions

Large variations in nuclear density can be attained momentarily in nuclear collisions, and constraints on the Equation of State (EoS) can be obtained by comparing measurements to transport calculations of such collisions. Significant constraints on the symmetric matter EoS at $1 \le \rho/\rho_0 \le 4.5$ have been obtained from measurements of collective flow [1] and Kaon production [2]. The symmetry energy has been recently probed at sub-saturation densities via isospin diffusion [11,12], and by double ratios involving neutron and proton energy spectra [13]. These two observables largely reflect the transport of nucleons under the combined influence of the mean fields and the collisions induced by residual interactions; thus, they should be within the predictive capabilities of transport theory. In the following, we compare both observables to the predictions from the Improved Quantum Molecular Dynamics (ImQMD) transport model, and obtain consistent constraints on the symmetry energy at sub-saturation densities. These constraints are then compared to the results obtained from Isobaric Analog States, Sn isotope skins, Pb neutron skin thickness, results from Pygmy Dipole Resonance and the Giant Dipole Resonance experiments.

3. ImQMD: Transport calculations for heavy ion collisions

Transport models have been used to describe the dynamics of heavy ion collisions. We chose to use the Quantum Molecular Dynamic (QMD) model mainly because of its ability to describe fragments which are quite important in describing isospin observables. In the QMD model, nucleons are represented by Gaussian wave packets, and the mean fields acting on these wave packets are derived from an energy functional with the potential energy U that includes the full Skyrme potential energy with just the spin-orbit term omitted:

$$U = U\rho + U_{md} + U_{coul} \qquad (2)$$

where U_{coul} is the Coulomb energy. The nuclear contributions are represented in a local form with

$$U_{\rho,md} = \int u_{\rho,md}\, d^3 r$$

and,

$$u_\rho = \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{\eta+1}\frac{\rho^{\eta+1}}{\rho_0^{\eta}} + \frac{g_{sur}}{2\rho_0}(\nabla\rho)^2 + \frac{g_{sur,iso}}{\rho_0}[\nabla(\rho_n-\rho_p)]^2 + \frac{C_s}{2}\left(\frac{\rho}{\rho_0}\right)^{\gamma}\delta^2\rho + g_{\rho\tau}\frac{\rho^{8/3}}{\rho_0^{5/3}} \qquad (3)$$

where the asymmetry

$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p),$$

and ρ_n and ρ_p are the neutron and proton densities, respectively. A symmetry kinetic energy density of the form $\frac{C_{s,k}}{2}\left(\frac{\rho}{\rho_0}\right)^{2/3}\delta^2\rho$ and symmetry potential energy density of the form $\frac{C_{s,p}}{2}\left(\frac{\rho}{\rho_0}\right)^{\gamma}\delta^2\rho$ were used in the improved version of the QMD code (ImQMD). The energy density associated with the mean-field momentum dependence is represented by

$$u_{md} = \frac{1}{2\rho_0}\sum_{N_1,N_2=n,p}\frac{1}{16\pi^6}\int d^3p_1 d^3p_2 f_{N_1}(\vec{p}_1) f_{N_2}(\vec{p}_2)\, 1.57\left[\ln\left(1+5\times10^{-4}(\Delta p)^2\right)\right]^2 \qquad (4)$$

where f_N are nucleon Wigner functions, $\Delta p = |\vec{p}_1 - \vec{p}_2|$, the energy is in MeV and momenta are in MeV/c. The resulting interaction between wavepackets is described in Ref. [14]. Unless otherwise noted, we use α= -356 MeV, β =303 MeV and η=7/6, corresponding to a isoscalar compressibility constant of K=200 MeV, and g_{sur}=19.47 MeVfm^2, g_{suriso}=-11.35