Constraining the Density Dependence of the Symmetry energy in the Nuclear Equation of State

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The key element for constructing the nuclear Equation Of State (EOS) is the basic nucleon-nucleon interaction. Until now our understanding of the nucleon-nucleon interaction has always come from studying nuclear matter that is symmetric in isospin and close to normal nuclear matter density (ρ = 0.16 fm^{-3}). It is not known how far this understanding remains valid as one moves away from normal nuclear density and symmetric nuclear matter. Various interactions used in "ab initio" microscopic calculations predict different forms of the nuclear equation of state above and below the normal nuclear matter density, and away from the symmetric nuclear matter. As a result of which, the symmetry energy, which is the difference in energy between the pure neutron matter and the symmetric nuclear matter, show a very different behavior below and above normal nuclear density. Constraining the form of the density dependence of the symmetry energy is important for a better understanding of the nucleon-nucleon interaction, and hence the structure of atomic nuclei. It is also important for understanding the structure of compact stellar objects such as the neutron stars. The figure below shows the form of the density dependence of the symmetry energy obtained from the present isotopic yield distribution measurements in multifragmentation reactions of ^{40}Ar, ^{40}Ca, ^{58}Fe, ^{58}Ni + ^{58}Fe, ^{58}Ni at beam energies from 25 – 53 AMeV. A comparison with several other recent independent studies is also shown. The green curve corresponds

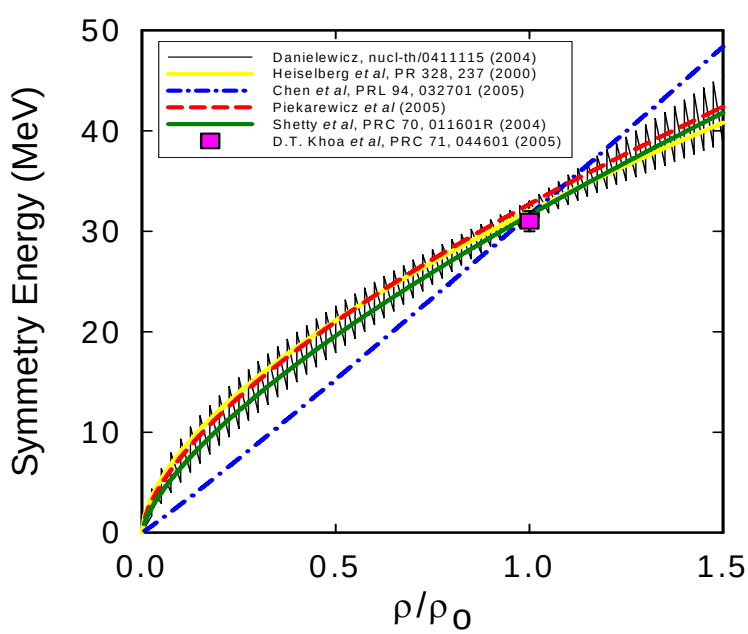

Figure 1. Comparison of the density dependence of the symmetry energy obtained from various different studies.

to the one obtained from Gogny-AS interaction that explains the present results from the fragment isotopic distribution, assuming a small sequential decay effect [1,2]. The red dashed curve correspond to

those obtained recently from an accurately calibrated relativistic mean field interaction, used for describing the Giant Monopole Resonance (GMR) in ^{90}Zr and ^{208}Pb, and the IVGDR in ^{208}Pb by Piekarewicz *et al.* [3]. The blue dot-dashed curve correspond to the one used for explaining the isospin diffusion data of NSCL-MSU by Chen *et al.* [4]. This dependence has now been modified to include the isospin dependence of the in-medium nucleon-nucleon cross-section, and is in good agreement with the present study. The shaded region in the figure corresponds to those obtained by constraining the binding energy, neutron skin thickness and isospin analogue state in finite nuclei using the mass formula of Danielewicz [5]. The yellow curve correspond to the parameterization adopted by Heiselberg *et al.* [6] in their studies on neutron stars, and obtained by fitting the predictions of the variational calculations of Akmal *et al.* [7]. Finally, the solid square point in the figure correspond to the value of symmetry energy obtained by fitting the experimental differential cross-section data in a charge exchange reaction using the isospin dependent optical potential by Khoa *et al.* [8]. The parameterized forms of the density dependence of the symmetry energy obtained from all these studies are as shown in table below. The close agreement between various studies leads to a constraint on the density dependence of the symmetry energy, which can be given as, $E_{sym}(\rho) = C(\rho/\rho_o)^{\gamma}$, where C = 31 – 33 MeV and γ = 0.6 – 1.0 . The present constrain leads to nuclear matter compressibility K ~ 230 MeV, neutron skin thickness, $R_n - R_p \sim 0.21$ fm for ^{208}Pb nuclei, radius of 11 – 13 km for the canonical neutron star and a direct URCA cooling for neutron stars above 1.4 times the solar mass.

Table I. Parameterized form of the density dependence of the symmetry energy obtained from various independent studies.

Reference	Parameterization	Studies
Heiselberg *et al.* [6]	$\mathbf{32.0(\rho/\rho_o)^{0.60}}$	**Variational calculation**
Danielewicz *et al.* [5]	$\mathbf{31(33)(\rho/\rho_o)^{0.55(0.79)}}$	**BE, Skin,Isospin analogue states**
Chen *et al.* [4]	$\mathbf{31.6(\rho/\rho_o)^{1.05}}$	**Isospin diffusion**
Piekarewicz *et al.* [3]	$\mathbf{32.7(\rho/\rho_o)^{0.64}}$	**GMR, IVGDR**
Shetty *et al.* [1,2]	$\mathbf{31.6(\rho/\rho_o)^{0.69}}$	**Isotopic distribution**

[1] D.V. Shetty *et al*., Phys. Rev. C **70**, 011601 (2004).
[2] D.V. Shetty *et al*., *nucl-ex/*0512011 (2005).
[3] J. Piekarewicz (Private Communication) (2005).
[4] L.W. Chen *et al*., Phys. Rev. Lett. **94**, 032701 (2005).
[5] P. Danielewicz, *nucl-th/*0411115 (2004).
[6] H. Heiselberg and M. Hjorth-Jensen, Phys. Rep. **328**, 237 (2000).
[7] A. Akmal *et al.*, Phys. Rev. C **58**, 1804 (1998).
[8] D.T. Khoa *et al*., Phys. Rev. C **71**, 044601 (2005).