Symmetry energy of nuclear matter with liquid-gas phase transition and cluster formation*

S. Typel[1]*, H.H. Wolter*[2]*, G. Röpke*[3]*, and D. Blaschke*[4,5]

[1]GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany; [2]Ludwig-Maximilians-Universität München, Germany; [3]Institut für Physik, Universität Rostock, Germany; [4]Instytut Fizyki Teoretycznej, Uniwersytet Wrocławski, Poland; [5]Bogoliubov Laboratory for Theoretical Physics, JINR Dubna, Russia

The symmetry energy $E_{\rm sym}$ characterizes the energy change of strongly interacting matter when the isospin asymmetry δ is varied and all other independent quantities such as the baryon density n_B or temperature T are kept constant. The density dependence of $E_{\rm sym}$ is widely studied in experiment and theory since its precise form has a strong impact on the evolution of core-collapse supernovae and the structure and cooling of (proto) neutron stars.

For nuclear matter, the symmetry energy is usually calculated by assuming a uniform distribution of the constituent particles. However, dilute nuclear matter is not stable against density fluctuations and inhomogeneous matter on different length scales develops. E.g., at densities below saturation, clusters or macroscopic phases appear, which affect the actual density dependence of $E_{\rm sym}$. At finite temperatures, the symmetry free energy $F_{\rm sym}$ and the symmetry internal energy $U_{\rm sym}$ have to be distinguished. In addition, the results depend on the precise definition of the symmetry energy. These effects are studied in Ref. [1] using a relativistic density functional (RDF) approach with density dependent meson-nucleon couplings. The parameters of this phenomenological description are well constrained by fitting to properties of finite nuclei [2].

In nuclear matter at densities below saturation, the liquid-gas phase transition with coexisting low and high density phases was explicitly considered in the determination of the symmetry energy. As an example, the density dependence of $U_{\rm sym}$ for various temperatures is depicted in Figure 1 employing the finite difference formula, i.e. taking the difference of the energy per nucleon in pure neutron matter and in symmetric nuclear matter. This is equivalent to the standard definition using second derivatives with respect to the asymmetry δ only if the energy per nucleon is a quadratic function of δ. However, the former, finite difference definition gives more appropriate results for studying the variation of the energy with isospin. The liquid-gas phase transition leads to a substantial increase of the binding energy in symmetric nuclear matter due to the occurrence of a strongly bound high density phase. Hence a large finite symmetry energy is observed in particular at low temperatures even at very low densities.

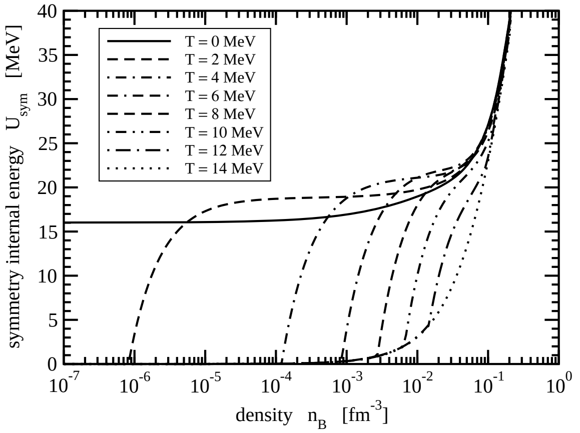

Figure 1: Density dependence of the symmetry internal energy of nuclear matter with liquid-gas phase transition for various temperatures.

In stellar matter, not only the strong interaction between the particles but also the electromagnetic interaction, which is artificially switched off in nuclear matter calculations, has to be considered. The charge neutrality condition is ensured by adding electrons and muons in proper amounts. The interplay between the surface tension and Coulomb repulsion leads to cluster formation on typical length scales with the size of nuclei. The RDF approach for nuclear matter has been extended to a generalized RDF with explicit cluster degrees of freedom [1, 2] including internal excitations of nuclei. Besides light (^{2}H, ^{3}H, ^{3}He, ^{4}He) and heavy nuclei ($A > 4$), nucleon-nucleon correlations in the continuum are included in an effective way [3]. They are necessary in order to reproduce the model-independent low-density benchmark, the virial equation of state. The formation and dissolution of cluster correlations are modeled by medium-dependent mass shifts, which are mainly driven by the action of the Pauli principle. With proper corrections for the effects of the Coulomb interaction, the symmetry energy in stellar matter exhibits similar features as in nuclear matter with liquid-gas phase transition.

References

[1] S. Typel, H.H. Wolter, G. Röpke and D. Blaschke, Eur. Phys. J. A 50 (2014) 17.

[2] S. Typel, G. Röpke, T. Klähn, D. Blaschke, and H.H. Wolter, Phys. Rev. C 81 (2010) 015803.

[3] M.D. Voskresenskaya and S. Typel, Nucl. Phys. A 887 (2012) 42.

---

[*] Work supported by the Helmholtz Association through the Nuclear Astrophysics Virtual Institute (VH-VI-417).

doi:10.15120/GR-2014-1-THEORY-06