Study of nuclear matter at sub-saturation densities by QMD simulations: Role of Symmetry energy

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Introduction

One of the main reasons to study heavy-ion physics and astrophysics is to understand the properties of nuclear matter under extreme conditions. At sub-nuclear densities nuclei in nuclear matter form crystalline structures. At higher densities, when nuclei are about to dissolve into uniform matter, various interesting spatial structures such as cylindrical and slab shaped nuclei and cylindrical and spherical bubbles etc., collectively called nuclear "pasta", may appear [1]. The study of the pasta phase is important for various reasons: neutrino-pasta scattering is important for neutrino transport in core-collapse supernova, e^--pasta scattering is important to determine the transport properties of the neutron star crust, etc. The properties of the pasta phase have been studied mostly using static methods such as the liquid-drop model, the Thomas-Fermi method and the Hartree-Fock method. All these models assume few specific shapes and obtain the favourable shape by minimizing the free energy. But for a better understanding of the pasta phase physics it is important to adopt a dynamical approach, which allows for arbitrary nuclear structures. Properties of this pasta phase depend on nuclear symmetry energy and its density dependence. Experiments constrain the symmetry energy (E_{sy}) at saturation density to be around ~ 32 MeV but the slope of the symmetry energy L is still very uncertain and lies in the range $\sim 20-120$ MeV. Static calculations suggest that higher L disfavours the pasta phase [2]. This motivates us to study the effect of nuclear symmetry energy and its slope on the pasta phase within the framework of quantum molecular dynamics (QMD).

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QMD

For the simulation we use a QMD Hamilonian developed by Maruyama *et al* [3]. It is written as

$$\mathcal{H} = T + V_{\text{Pauli}} + V_{\text{Skyrme}} + V_{\text{sym}} + V_{\text{MD}} + V_{\text{Coul}} \quad (1)$$

where T is the kinetic energy, V_{Pauli} is the phenomenological Pauli potential, V_{Skyrme} is the Skyrme-like interaction, V_{sym} is the symmetry energy, V_{MD} is the momentum dependent potential and V_{Coul} is the Coulomb potential. These potentials contain several parameters that are determined to reproduce the saturation properties of nuclear matter and ground states of finite nuclei [3]. To study the effect of the symmetry energy slope L we have prepared three different values for it, namely 79, 94 and 118 MeV, keeping the symmetry energy fixed at ~ 34.6 MeV.

To simulate the dynamic relaxation we adopt QMD equations of motion with friction terms:

$$\begin{aligned} \dot{\mathbf{R}}_\mathbf{i} &= \frac{\partial H}{\partial \mathbf{P}_\mathbf{i}} - \mu_R \frac{\partial H}{\partial \mathbf{R}_\mathbf{i}}, \\ \dot{\mathbf{P}}_\mathbf{i} &= -\frac{\partial H}{\partial \mathbf{R}_\mathbf{i}} - \mu_P \frac{\partial H}{\partial \mathbf{P}_\mathbf{i}}, \end{aligned} \quad (2)$$

where $\mathbf{R}_\mathbf{i}$ and $\mathbf{P}_\mathbf{i}$ are the position and momentum of the i-th particle, respectively and μ_R and μ_P are positive definite damping coefficients.

Results

We have performed QMD simulations at $T = 0$ for various densities (from $\rho = 0.1\rho_0$ to ρ_0) and fixed proton fractions $Y_p = 0.5$ and 0.3, taking 2048 nucleons in a cubic box. To simulate infinite nuclear matter we impose periodic boundary conditions. Electrons make

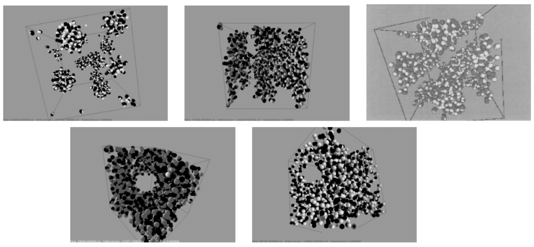

FIG. 1: The nucleon distributions of pasta phases at $Y_p = 0.5$. Protons (neutrons) are represented by black (white) spheres.

the system charge neutral. They are relativistic and degenerate and are treated as a uniform background. To calculate the Coulomb interaction we employ the Ewald method.

As an initial configuration we take randomly distributed nucleons in phase space. Then we cool the system down according to Eq. 2 until we reach the energy minimum configuration. For speeding up the simulation we ported the QMD code to a GPU version, which makes the code faster by about 2 orders of magnitude. Figure 1 shows final nucleon distributions for various densities and $Y_p = 0.5$. From the figure we can see that all the simple structures as predicted from static calculations are reproduced here. To quantify various nuclear shapes obtained from the simulation we use Minkowski functionals [4]. In our case various pasta shapes can be characterised by two Minkowski functionals, integral mean curvature H and Euler characteristic χ as: (a) $H > 0,\ \chi > 0 \rightarrow$ sphere, (b) $H > 0,\ \chi = 0 \rightarrow$ cylinder, (c) $H = 0,\ \chi = 0 \rightarrow$ slab, (d) $H < 0,\ \chi = 0 \rightarrow$ cylindrical hole and (e) $H < 0,\ \chi > 0 \rightarrow$ spherical hole. In Fig. 2 we plot the normalised Euler characteristic χ/V for three different L at $Y_p = 0.3$. It is seen that apart from the regular shapes mentioned earlier there are intermediate shapes characterised by $\chi < 0$, for a wide range of density. This can have important effects on various properties of neutron stars as well as for core-collapse supernovae. We also see that at higher densities corresponding to bubble phases, there are differences in results for different L. Especially, at lower L bubble phases tend to survive longer. This should be verified by further studies and work is in progress in this direction.

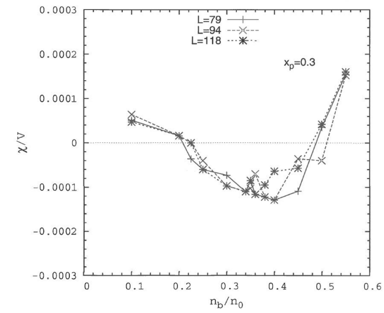

FIG. 2: χ/V vs n_b/n_0 for different L

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