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Thomas–Fermi approximation for β-stable nuclear matter in the Landau Fermi-liquid theory

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Received 19 August 2018; received in revised form 1 October 2018; accepted 1 October 2018

Abstract

An isentropic description of the equation of state (EOS) for β-stable nuclear matter (BSNM) is presented in a semi-classical mean-field model. Within the Thomas–Fermi (TF) approximation, the Landau Fermi-liquid theory (LFT) is used in a self-consistent approach. Accordingly, isentropic thermodynamics of BSNM is investigated for the neutrino-free and neutrino-trapped cases. We find that the EOS for neutrino-trapped matter is stiffer than the one for neutrino-free matter. Our findings can set the stage for profound studies about the structure and composition of proto-neutron stars (PNSs).

Keywords: TF approximation; EOS; BSNM; LFT

1. Introduction

The equation of state (EOS) of hot nuclear matter, has been one of the most challenging issues for studying the bulk properties of matter under extreme conditions of density and temperature. Such extreme conditions of matter can be found in heavy-ion collisions at intermediate and high energy regime, supernova explosions and proto-neutron stars (PNSs) which are formed at the last stage of the gravitational collapse of type-II supernova [1–17]. Thermal effects on the nuclear EOS have been investigated in microscopic models, which are based on realistic interactions extracted from nucleon-nucleon scattering data [18–25] and phenomenological models, where the

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https://doi.org/10.1016/j.nuclphysa.2018.10.002

parameters of interactions are fixed to fulfill the saturation properties of normal nuclear matter [26–37]. However, it is an advantage for a model to provide a simple procedure for the temperature dependence of the nuclear EOS as much as possible. Hence, such a significant advantage can be found in the Thomas–Fermi (TF) approximation, as a reliable many-body approach when used in a semi-classical mean-field (MF) model [32–39]. To this purpose, the EOS of neutron star (NS) matter has been investigated successfully in Refs. [38,39]. On the other hand, a complete study of the nuclear EOS at finite temperatures has also presented in Ref. [36] through the Fermi–Dirac occupation number expressed in terms of the nucleonic effective mass with only density dependence and also the effective MF potential with momentum, density and temperature dependence as derived from full self-consistent calculations. In Ref. [37], by extending the previous model on the basis of Landau Fermi-Liquid theory [49,41], the nucleonic occupation number in asymmetric nuclear matter has been presented in terms of the Landau effective mass instead of the effective MF potential. Since, such an elaborated presentation for the nucleonic occupation number is helpful for efficient determination of the nuclear EOS, thermodynamic properties of β-stable nuclear matter (BSNM) as an uncharged mixture of nucleons and leptons which are in β-equilibrium with or without neutrino trapping, are very important for studying the interior part of PNSs. During the lifetime of the baryonic matter in the PNSs structure, the constant entropy per baryon $S \sim 1$–2 is generally adopted [2,3]. Thus, the isentropic description is necessary to study thermodynamic properties of BSNM. Based on this idea, the paper is organized as follows. In Sec. 2, our formalism on the basis of LFT is given for the EOS of BSNM. Section 3 is devoted to the discussion about the results of our calculations for isentropic studies of BSNM and finally the summary and conclusions are given in Sec. 4.

2. Formalism

In a semi-classical model where the state of each nucleon is specified by its position and momentum in phase space, the TF approximation is only applicable when the MF potential is smooth [42,43]. Thus, using the TF approximation in a new semi-classical model, nucleons interact via the phenomenological interaction of MS in BSNM [32,33]:

$$V_{12} = -2T_b\rho_0^{-1} g(\frac{r_{12}}{a})\{\frac{1}{2}(1\mp\xi)\alpha - \frac{1}{2}(1\mp\zeta)\times[\beta(\frac{p_{12}}{p_b})^2 - \gamma(\frac{p_b}{p_{12}}) + \sigma(\frac{2\bar{\rho}}{\rho_0})^{\frac{2}{3}}]\}, \quad (1)$$

with

$$g(\frac{r_{12}}{a}) = \frac{1}{4\pi a^3}\frac{exp(-\frac{r_{12}}{a})}{\frac{r_{12}}{a}}, \qquad \bar{\rho}^{\frac{2}{3}} = \frac{1}{2}(\rho_1^{\frac{2}{3}} + \rho_2^{\frac{2}{3}}). \quad (2)$$

The above interaction is Yukawa type whose strength explicitly depends on the momentum and density. Here, $p_{12} = |\vec{p}_1 - \vec{p}_2|$ and $r_{12} = |\vec{r}_1 - \vec{r}_2|$ are the relative momentum and position of each pair of nucleons in phase space, respectively. The mean density $\bar{\rho}$ is defined in terms of ρ_1 and ρ_2, the density of each pair of nucleons at the locations $\vec{r}_1$ and $\vec{r}_2$, respectively. The two elaborated versions of MS interaction, known as the TF(96) and TF(90) interactions are introduced through the seven flexible parameters $(a, \xi, \zeta, \alpha, \beta, \gamma, \sigma)$. These parameters can be fixed to improve the macroscopic nuclear properties such as nuclear optical potential, effective mass, binding energy, fission barriers and density distributions by imposing the essential constraint of a good reproduction of nuclear matter saturation properties as well as the coefficients of the *Weizsacher–Bethe* semi-empirical mass formula [44,45]. The free parameters of the TF(96)(TF(90)) interaction can be adjusted to the following values [32,33]:

Please cite this article in press as: M. Ghazanfari Mojarrad et al., Thomas–Fermi approximation for β-stable nuclear matter in the Landau Fermi-liquid theory, Nucl. Phys. A (2018), https://doi.org/10.1016/j.nuclphysa.2018.10.002