Nuclear Matter and Neutron-Star Properties with the framework of Skyrme Hartree Fock Theory

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In order to calculate neutron-star models, it is neccessary to have an equation of state linking pressure and total energy density and the equation of state is required for determining the mass radius relationship for neutron star, and hence the range of physically allowable neutron star masses. Also the nuclear symmetry energy and, consequently, the proton/neutron ratio are crucial factors in constructing an EOS for asymmetric nuclear matter based on nucleon-nucleon interactions.

In this paper we investigate the properties of infinite nuclear matter, calculated as a functions of density, for new set of Skyrme NN-interaction parameters given by Klupfel et al [1]. By construction, only 6 out of 15 set of parameters give plausible results for finite nuclei. For each acceptable set of Skyrme parameters we then construct as EOS for neutron star matter and calculate the predicted properties of corresponding neutron-star models. The general form of the effective Skyrme interaction, as used for describing finite nuclei in mean field models, is well known. The total binding energy of a nucleus can be expressed as the integral of a density functional $\mathcal{H}$ which is given as a function of empirical parameters [2],

$$\mathcal{H} = \mathcal{K} + \mathcal{H}_0 + \mathcal{H}_3 + \mathcal{H}_{eff}, \quad (1)$$

where $\mathcal{K}$ is kinetic-energy term and the $\mathcal{H}_0$ (zero range), $\mathcal{H}_3$ (density-dependent), and $\mathcal{H}_{eff}$ (effective-mass-dependent) terms, which are relevant for calculating the properties of nuclear matter, are functions of nine parameters t_0, t_1, t_2, t_3, x_0, x_1, x_2, x_3, and α, and are given as follows:

$$\mathcal{H}_0 = \frac{1}{4}t_0[(2+x_0)\rho^2 - (2x_0+1)(\rho_p^2+\rho_n^2)], \quad (2)$$

$$\mathcal{H}_3 = \frac{1}{24}t_3\rho^{\alpha}[(2+x_3)\rho^2 - (2x_3+1)(\rho_p^2+\rho_n^2)], \quad (3)$$

$$\begin{aligned}\mathcal{H}_{eff} &= \frac{1}{8}[t_2(2x_2+1) - t_1(2x_1+1)](\tau_p\rho_p + \tau_n\rho_n) \\ &+ \frac{1}{8}[t_1(2+x_1) + t_2(2+x_2)]\tau\rho \quad (4)\end{aligned}$$

Important variable for discussions of asymmetric nuclear matter is the *symmetry energy* $\mathcal{S}$, defined as the difference in energy between symmetric and pure neutron matter

$$\mathcal{S}(\rho) = \mathcal{E}(\rho, I=0) - \mathcal{E}(\rho, I=1). \quad (5)$$

$\mathcal{S}(\rho)$ can be expanded about the value of the energy for symmetric nuclear matter with the second-order term being related to the *asymmetry coefficient* a_s in the semiempirical mass formula

$$a_s = \frac{1}{2}\frac{\partial^2\mathcal{E}}{\partial I^2}\bigg|_{I=0} \quad (6)$$

An equation of state for zero-temprature β-stable nucleon+lepton matter can be constructed from the Skyrme interaction following the procedure described in Refs. [2, 3]. The total energy density of the n+p+e+μ matter is written as the sum of the nucleon and lepton contributions [2]:

$$\begin{aligned}\varepsilon(\rho_p, \rho_n, \rho_e, \rho_\mu) &= \varepsilon_N(\rho_p, \rho_n) + \varepsilon_e(\rho_e) + \varepsilon_\mu(\rho_\mu) \\ &+ \rho_p m_p c^2 + \rho_n m_n c^2 \quad (7)\end{aligned}$$

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where $\varepsilon_N = \rho_b \mathcal{E}_N$. Given these definitions and conditions, the EOS is determined by expression:

$$P(\rho_b) = \rho_b^2 \frac{d\mathcal{E}_N}{d\rho_b}, \tag{8}$$

Using a tabulated form of the composite EOS's, we numerically integrated the Tolman-Oppenheimer-Volkov equation [3] to obtain sequence of neutron-star models, which for any specified central density give directly the corresponding values for the total gravitational mass M and radius R of the star. The gravitational mass depends upon the compactness of the neutron stars, and hence indirectly on the radius of the star.

Fifteen SV parameters [1] can be grouped into two groups depending upon the behavior of asymmetry coefficient (a_s) with density. Six parameters (SV-sym34, SV-sym32, SV-min, SV-mas08, SV-mas07, SV-kap00 –group I) predict different behavior of asymmetry coefficient than the remaining nine parameters (SV-tls, SV-sym28, SV-mas10, SV-kap06, SV-kap02, SV-bas, SV-K218, SV-K226, SV-K241 – group II). Parameter sets (SV-sym34, SV-mas07) of group I show a monotonic increase of a_s with increasing baryon number density (Fig.1, left panel). On the other hand sets (SV-sym32, SV-min, SV-mas08, SV-kap00) belonging to group I and group II show a distinctly different behavior (Fig. 1, left panel and right panel–note the change of the vertical scale): a_s reaches a maximum value at one particular density and then decreases with increasing ρ until it becomes negative at some density. The difference between the predictions for a_s from group I and II is in that those from group II typically give a_s reaching negative values at lower densities than for those of group I.

The pressure depends on the gradient of $\mathcal{E}$ (ρ) (see Eq. 8) and hence in turn also on asymmetry coefficient as (see Eq. 6). So it follows that the parametrizations of group II give lower pressures for a given density than those of group I, even giving unphysical negative pressures at higher densities. None of those from group II can produce neutron-star models with masses as high as the "canonical" 1.4 $M_\odot$ and so they can all be excluded from consideration on those grounds. In contrast, all six parametrs sets of group I give neutron-star models with mass-radius relations which do not contradict present observational data, as illustrated in Fig. 2.The maximum radii and corresponding nuclear densities for the group I models lie in the ranges 10 − 12 km and 0.88 − 1.17 fm^{-3}, respectively.

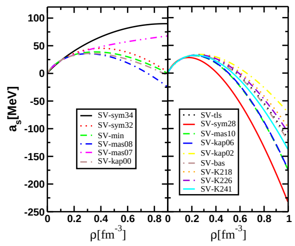

FIG. 1: The asymmetry coefficient a_s is plotted as a function baryon number density ρ with different set of parameterizations.

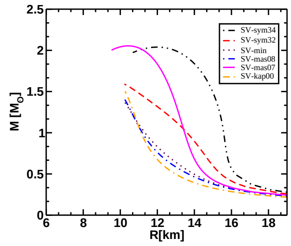

FIG. 2: The gravitational masses of nonrotating neutron-star models (measured in solar masses) plotted against radius (in kilometers) using selected Skyrme interactions.

References

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