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LOCV CALCULATIONS FOR NEUTRON STAR PROPERTIES*

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The Neutron star properties are calculated with the various interactions such as charge dependent Reid potential (Reid93) as well as Reid68 and AV_{18} interactions within the lowest order constrained variational method (LOCV). It is shown that at low densities, neutron star masses exhibit a minimum ($\simeq 0.1 M_{\odot}$) and a maximum mass between $1.4 M_{\odot}$ and $1.9 M_{\odot}$ which is strongly dependent on the equation of state.

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1. Introduction

The nuclear matter equation of state (EOS) is a necessary tool in the understanding of astrophysical studies as well as in the description of heavy ion collisions [1]. The mass of neutron stars depends mainly on the EOS of neutron matter up to densities $\rho = 5\rho_0$, where $\rho_0 = 0.16$ fm^{-3} the saturation density of symmetric nuclear matter. Direct measurement of the neutron star mass can be done by observation of the X-ray and X-ray busters, but their accuracy is rather poor and the masses of the neutron stars have been determined with high accuracy using the binary radio pulsars. The EOS plays an importance role in theoretical calculation of the maximum mass of neutron stars, therefore having a good equation of state derived from an accurate many-body calculation using various nucleon–nucleon interactions is of particular importance in mass determination for the neutron star. The method of lowest order constraint variational (LOCV) method for calculating the EOS of nuclear and neutron matter has been reviewed in several papers [2]. There are several reasons for choosing the LOCV method. This method is a fully microscopic self-consistent technique with state dependent correlation functions and dose not has any free parameters

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except those included in the interactions. The LOCV considers constraint in the form of normalization condition to keep the higher order terms as small as possible. Finally, the functional minimization procedure by solving the Euler–Lagrange equation makes method as a pure variational method and save quite enough computational time. In this article the properties of a pure neutron star are calculated by using the EOS which comes from LOCV method by employing various interactions such as Reid68, a new Reid93 potential, which is charge dependent and has been fitted very accurately to the partial wave phase shift up to $J = 9$ and AV_{18} potentials. The results are comparable with other many-body models.

2. Brief description of LOCV method

We consider a trial many-body wave function of the form [2]:

$$\psi = \mathcal{F}\varphi \,, \tag{1}$$

where φ is a Slater determinant of plane waves of N independent nucleons (ideal Fermi gas wave function) and $\mathcal{F}$ is a N-body correlation operator that can be given by the product of the two-body correlation operators (Jastrow form),

$$\mathcal{F} = \mathcal{S} \prod_{i<j} f(ij) \,. \tag{2}$$

$\mathcal{S}$ is asymmetric operator and $f(ij)$ is Jastrow two-body correlation functions and written as:

$$f(ij) = \sum_{\alpha,p} f_\alpha^{(p)}(ij) O_\alpha^{(p)}(ij) \,, \tag{3}$$

where $\alpha = \{J, L, S, T, M_T\}$, and operators $O_\alpha^{(p)}$are operators corresponding to potential operators. Typically the non-relativistic many-body Hamiltonian is expressed as:

$$H = \sum_{i=1}^{N} \frac{\hat{p}_i^2}{2m} + \sum_{i<j} v(ij) \,, \tag{4}$$

where $v(ij)$ is the two-nucleon interaction which can be written as:

$$v(ij) = \sum_{p} v_\alpha^{(p)}(12) O_\alpha^{(p)}(12) \,, \tag{5}$$

$v_\alpha^{(p)}(12)$ is the potential in each channel. Now, using the above trial wave function, we construct a cluster expansion for the expectation value of our Hamiltonian. Our lowest order constrained variational (LOCV) prescription has been the terminating of the cluster expansion to a constraint designed to ensure the rapid convergence of the cluster expansion. Therefore, we keep only the first two terms in the cluster expansion of the energy functional:

$$E = \frac{1}{A}\frac{\langle\psi|H|\psi\rangle}{\langle\psi|\psi\rangle} = E_1 + E_2 + \cdots \,, \tag{6}$$

E_1 is one-body kinetic energy and E_2 is two-body clusters energy. Now we can minimize the two-body energy, with respect to the variations in the correlation functions but subject to the normalization constraint:

$$\frac{1}{N}\sum \langle ij|h^2(12) - f^2(12)|ij\rangle_a = 0\,, \tag{7}$$

where the function $h(x)$ is the modified Pauli function:

$$h(x) = \left[1 - \frac{9}{\nu}\left(\frac{J_1(x)}{x}\right)\right]^{-1/2}\,, \tag{8}$$

where ν is degeneracy (4 for symmetric nuclear matter and 2 for pure neutron matter). Minimizing the two-body cluster energy under normalization constraint, we obtain a set of Euler–Lagrange equations. The above constraint introduces a Lagrange multiplier through which all of correlation functions are coupled. By solving these equations, we can calculate correlation functions and consequently the two-body energy E_2.

3. Results

The EOS of neutron matter has been calculated for the density range up to 0.5 fm^{-3}. The results with the Reid93 (up to $J < 9$ channels) and Reid68 and AV_{18} potentials show that the Reid93 interaction has a stiffer equation of state. In this calculation we assume that only the pure neutron matter contribute in the neutron star structure. Using the EOS of neutron star matter that comes from LOCV calculation, we can calculate the neutron star mass and radius as a function of central mass density, ρ_c, by numerical integrating the general relativistic equation of hydrostatic equilibrium, Tolman–Oppenheimer–Volkoff (TOV) equation [1]:

$$\frac{dP}{dr} = -\frac{G}{r^2}\left[\rho_g(r) + \frac{P(r)}{c^2}\right]\frac{m(r) + 4\pi r^3\frac{P(r)}{c^2}}{1 - \frac{2Gm(r)}{rc^2}}\,, \tag{9}$$

where $\rho_g = \rho[E(\rho) + mc^2]$ and $m(r) = \int_0^r 4\pi r'^2 \rho_g(r')dr'$. By selecting a central mass density under the boundary conditions $P(0) = P_c, m(0) = 0$, we integrate the TOV equation outwards to a radius $r = R$ at which P vanishes.

This yields the neutron star radius R and mass $M = m(R)$. The calculated neutron star gravitational mass (in solar mass $M_{\odot}$ units) as a function of central mass density with Reid68, Reid93 ($j < 9$) and AV_{18} potentials is presented at left panel of Fig. 1. In right panel of this figure we have plotted gravitational mass *versus* radius. The result of APR [3] calculation is presented for comparison. Our results show that at low densities neutron star masses exhibit a minimum ($\simeq 0.1M_{\odot}$) which is nearly independent of EOS and a maximum mass between $1.4M_{\odot}$ and $1.9M_{\odot}$ which is strongly dependent on the equation of state. It is seen that the given maximum mass for Reid equation of state shows a good consistency with the accurate observations of radio pulsars [3].

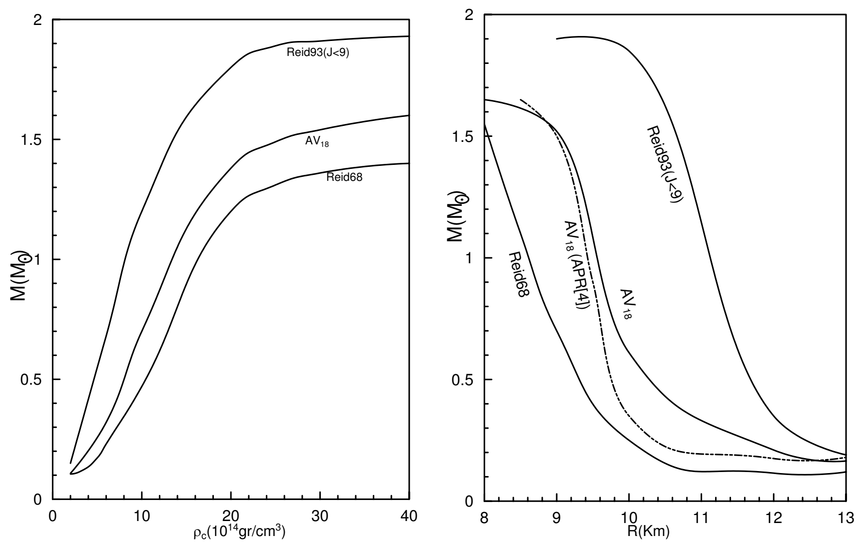

Fig. 1. Left: neutron star mass (in solar mass) *versus* central mass density. Right: neutron star mass–radius relation.

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