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The Computation of the Neutron Star Structure with Re-projected Potential

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We determine the structure of neutron star within a lowest order constrained variational (LOCV) approach based on two and three nucleon interactions. Our results for the maximum mass of the neutron star with using re-projected Argonne family potentials adding three Nucleon interaction (TNI) are above 2.01 solar masses, which are in an excellent agreement with the accepted maximum mass of non-rotating neutron star. We also obtain the NS radius for all considered potentials lower than 11 km. The significant results for radius and the maximum mass of the neutron star can be a great successful for using LOCV to calculate the equation of state of the neutron star.

I. INTRODUCTION

Neutron stars are extraordinary compact stars which consist of supranuclear density matter in their interior(several times larger than nuclear saturation density ($\rho_0 = 0.16fm^{-3}$).) with a large fraction of neutron. In densities as large as the NS matter density atomic nuclei come in the close contact and the NS treat as a gigantic nucleus. In that case, they have a unique role in nuclear physics and astrophysics.

In this study, we investigate the equation of state (EOS) of the NS matter at high density, which is the most important input for the study of the NS's properties, and then we compute the maximum mass and radius of the NS. We use the LOCV formalism to investigate the EOS of the outer core of the NS employing AV8′ and AV6′ potentials [1, 2], supplemented with a three-nucleon interaction (TNI), AV18+TNI , AV8′+TNI and AV6′+TNI.The TNI parameters were adjusted to give the correct saturation points[3]. The core of the NS contains the elementary constituents such as protons, neutrons, electrons, and possibly muons μ (the npeμ). Nucleons form a strongly interacting Fermi liquid, while electrons and mouns constitute nearly ideal Fermi gases. The energy per unit volume (energy density) is

$$\varepsilon(n_n, n_p, n_e, n_\mu) = \varepsilon_n(n_n, n_p) + \varepsilon_e(n_e) + \varepsilon_\mu(n_\mu) \tag{1}$$

where $\varepsilon_n(n_n, n_p)$, ε_e and ε_μ are respectively nucleon, electron, and mouns contributions. pressure and energy-density (EOS) of the $npe\mu$ matter can be obtained by minimizing Eq. (1) at given n_b (grand-state value of $\epsilon(n_b)$ (a full thermodynamic equilibrium is assumed)

$$P(n_b) = n_b^2 \frac{d}{dn_b}(\frac{\epsilon(n_b)}{n_b}). \tag{2}$$

In Fig. 1 one can see different EOSs of various potentials for the liquid core of the NS. The result of three potentials with adding the TNI are close to each other especially in low density. The EOS of AV8′ is somehow stronger than that from AV6′, which was predicted in [3]. This is a consequent of elimination of spin-orbit operator in AV6′. But adding TNI causes that, AV6′+TNI becomes stiffer than AV8′+TNI. The absence of the spin-orbit term is compensated with three-body force. Therefore, it would be possible to introduce two-body potential with some new terms that predict well nuclear matter properties, without the need of three-body forces.

We suppose that a non-rotating neutron star is a spherically symmetric distribution of mass in hydrostatic equilibrium without magnetic field. Therefore, the equilibrium configuration of this static NS is simply calculated by solving the Tolman-Oppenheimer-Volkoff (TOV) [5] equations for the total pressure P and the enclosed mass m,

$$\begin{aligned}\frac{dP}{dr} &= -\frac{G\epsilon m}{r^2}(1+\frac{P}{\epsilon c^2})(1+\frac{4\pi P r^3}{mc^2})(1-\frac{2Gm}{rc^2})^{-1}\\ \frac{dm}{dr} &= 4\epsilon r^2 \epsilon\end{aligned} \tag{3}$$

being r the (relativistic) radius coordinate, G the gravitational constant and ϵ energy density. Integrating these equations one gets the mass and radius as a function of the central density. We use the five EOSs from Fig. 1 for the

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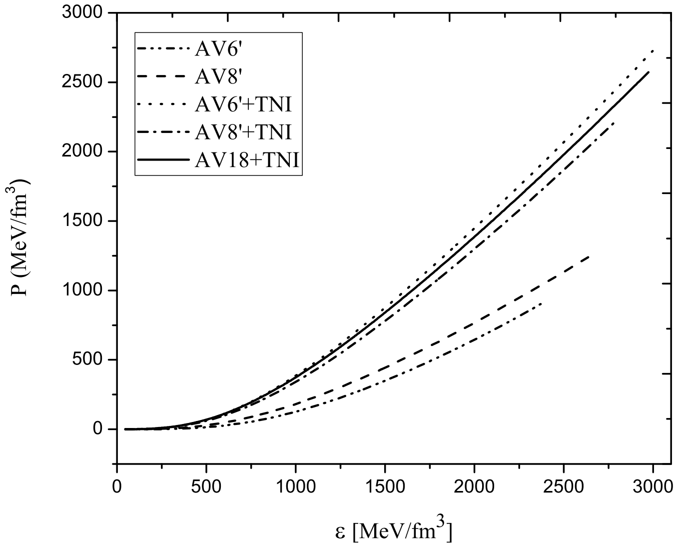

FIG. 1: Equation of State for $npe\mu$ matter for the five considered potentials [9]

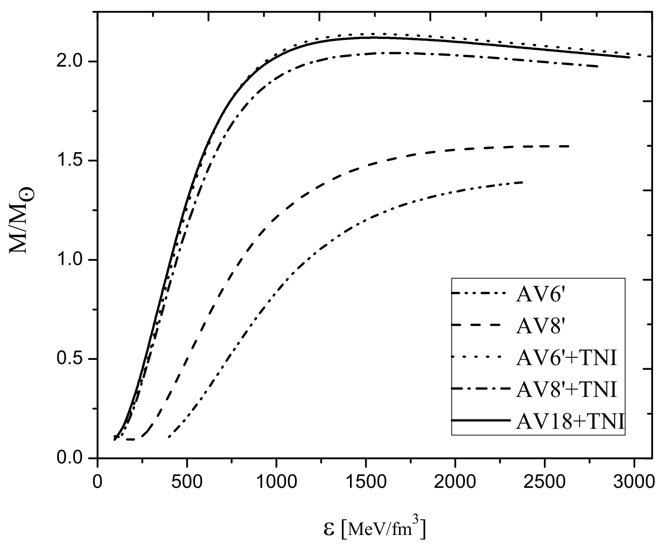

FIG. 2: Neutron Star gravitational mass as a function of the radius.

liquid core of the NS and for the outer parts of it we use the result of F. Douchin and P. Haensel [4]. In Fig. 2 the mass of the NS as a function of energy density is presented, while the result for the maximum mass, radius and the central density for our five EOSs are reported in table I. The multimessenger observation proved that, the maximum mass of the non-rotating neutron stars should be in the range $2.01M_\odot < M_{max} < 2.16M_\odot$ (where $M_\odot = 1.99 \times 10^{33}$ g is the solar mass) [6, 7]. As expected, the result for M_{max} of stiffer EOSs within AV6$'$,8$'$,and 18+TNI are in the NS maximum mass rang. It is known from the observations of galactic NS radius measurements and theoretical calculations that the NS radius is lower than 11 km [8]. We obtain the NS radius for all considered EOSs lower than 11 km, which is not usually achieved in microscopic approaches. We found higher $M_{max} = 2.12M_\odot$ with $R = 10.48km$ using AV6$'$+TNI which is significantly in agreement with observations data. As we showed two body re-projected potentials cannot gives a much lower maximum mass, only adding three body interaction the results were improved.

TABLE I: Properties of the maximum mass configuration obtained for different EOS.

EOS	n_b [fm^{-3}]	R [km]	M_{max} [$M_\odot$]
AV6$'$	1.989	7.36	1.39
AV8$'$	2	7.97	1.57
AV6$'$+TNI	1.17	10.48	2.12
AV8$'$+TNI	1.27	10.13	2.03
AV18+TNI	1.17	10.40	2.11

In [9] we have shown that the results for the other properties of the NS become much better with adding TNI.

We investigate the NS structure by calculating the EOS of the NS matter employing re-projected two-body potentials, AV8$'$ and AV6$'$ with and without TNI. We show that spin-orbit interaction has a significant effect on the nuclear potential. The elimination of this term cannot compensate with refitted the other operators. We also show that two body interactions fail to reproduce the correct maximum mass for the NS and require the introduction of three-body forces. Unfortunately, the three boy force contribution is essential to move the maximum mass of the NS to observational boundaries. We hope that adding a new component of operators and interactions can reduce the effect of three body forces in our calculation.

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