Neutron star equation of state in density dependent relativistic Hartree-Fock theory*

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Abstract The equation of state of neutron stars is studied in the newly developed density dependent relativistic Hartree-Fock (DDRHF) theory with the effective interaction PKO1 and applied to describe the properties of neutron stars. The results are compared with the recent observational data of compact stars and those calculated with the relativistic mean field (RMF) effective interactions. The maximum mass of neutron stars calculated with PKO1 is about 2.45 $M_{\odot}$, which consists with high pulsar mass from PSR B1516+02B recently reported. The influence of Fock terms on the cooling of neutron stars is discussed as well.

Key words neutron stars, equation of state, relativistic Hartree-Fock theory, maximum mass

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1 Introduction

The exploration on the phase diagram of matter has been running to extreme conditions of density, pressure and temperature. Neutron stars, as bridges between nuclear physics and astrophysics, provide natural laboratories to explore the equation of state (EoS) of baryonic matter at high densities. Recently, new observational results of compact stars have been reported[1, 2], which provide stringent constraints on the EoS of strongly interacting matter at high densities. In particular, a high pulsar mass $M = 2.08 \pm 0.19$ $M_{\odot}$ for PSR B1516+02B has been presented very recently[3].

On the description of nuclear matter and finite nuclei, the relativistic mean field (RMF) theory has achieved great success during the past years[4—7]. The properties of nuclear matter and neutron stars have been studied in variety of cases[8, 9]. However, in the framework of the RMF approach, the Fock terms are dropped out, which may have remarkable effects on nuclear matter especially at high densities. During the past decades, there were several attempts to include the Fock term in the relativistic descriptions of nuclear systems[10—13]. Recently, a new relativistic Hartree-Fock method, namely, density dependent relativistic Hartree-Fock (DDRHF) theory[14, 15] has been developed. With the effective Lagrangians of Refs. [14, 15], the DDRHF theory can quantitatively describe the ground state properties of many nuclear systems comparable with the RMF calculations without dropping the Fock terms.

In this paper, the neutron star EoS will be studied in the newly developed DDRHF theory with the effective interaction PKO1. The corresponding neutron star properties will be investigated and compared with recent observational constraints of compact stars. The role of the Fock terms will be discussed as well. The paper is organized as follows: in Sec. 2, a brief description of the relativistic Hartree-Fock theory for neutron stars is presented. The results and discussions are given in the following section. Finally in the last section, a brief summary is given.

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2 DDRHF theory for neutron stars

In this section, the formalism of nuclear matter and neutron star EoS based on the newly developed DDRHF theory is outlined briefly. More extensive discussions can be found in Refs. [14, 15]. The DDRHF theory starts from an effective Lagrangian density where nucleons are described as Dirac spinors interacting via exchange of several mesons (σ,ω,π and ρ) and the photons. By using the Legendre transformation and the equations of motion for the mesons and photon field operators, the Hamiltonian can be written in a form which includes only nucleon degree of freedom,

$$H = \int \mathrm{d}^3x\,[\bar{\psi}[-\mathrm{i}\boldsymbol{\gamma}\cdot\boldsymbol{\nabla}+M]\psi] + \frac{1}{2}\int \mathrm{d}^3x\mathrm{d}^4y \times \sum_{\mathrm{i}=\sigma,\omega,\rho,\pi,A} \bar{\psi}(x)\bar{\psi}(y)\Gamma_{\mathrm{i}}(1,2)D_{\mathrm{i}}(x,y)\psi(y)\psi(x)\,, \tag{1}$$

where $\Gamma_{\mathrm{i}}(1,2)$ is the interaction vertex of the respective mesons, and $D_{\mathrm{i}}(x,y)$ is the corresponding meson propagator.

Generally, the nucleon field operator ψ can be expanded into a complete set of Dirac spinors $u(p,s,\tau)$,

$$\psi(x) = \sum_{\mathrm{p,s},\tau} u(p,s,\tau)\mathrm{e}^{-\mathrm{i}px}c_{\mathrm{p,s},\tau}\,, \tag{2}$$

where $c_{\mathrm{p,s},\tau}$ denote annihilation operators for nucleons in the state (p,s,τ), noticing that the no-sea approximation has been assumed here. The trial ground state could be constructed as $|\Phi_0\rangle = \prod_{\mathrm{i}=1}^{A} c^{\dagger}_{\mathrm{p,s},\tau}|0\rangle$, where $|0\rangle$ is the physical vacuum. From this trial state , the energy density in a given volume Ω can be built up by taking the expectation value of Hamiltonian (1),

$$\varepsilon = \frac{1}{\Omega}\langle\Phi_0|H|\Phi_0\rangle = \varepsilon_{\mathrm{k}} + \sum_{\mathrm{i}=\sigma,\omega,\rho,\pi}\left(\varepsilon^{\mathrm{D}}_{\mathrm{i}}+\varepsilon^{\mathrm{E}}_{\mathrm{i}}\right)\,, \tag{3}$$

where the exchange terms are given by

$$\varepsilon^{\mathrm{E}}_{\mathrm{i}} = -\frac{1}{2}\sum_{\mathrm{p}_1,\mathrm{s}_1,\tau_1}\sum_{\mathrm{p}_2,\mathrm{s}_2,\tau_2}\bar{u}(p_1,s_1,\tau_1)\bar{u}(p_2,s_2,\tau_2)\times \frac{\Gamma_{\mathrm{i}}(1,2)}{m^2_{\mathrm{i}}+\boldsymbol{q}^2}u(p_1,s_1,\tau_1)u(p_2,s_2,\tau_2)\,. \tag{4}$$

For the static, uniform infinite nuclear matter, the coulomb field is neglected.

The self-energy can be determined by the variation of the energy functional self-consistently,

$$\Sigma(p)u(p,s,\tau) = \frac{\delta}{\delta\bar{u}(p,s,\tau)}\sum_{\mathrm{i}=\sigma,\omega,\rho,\pi}\left[\varepsilon^{\mathrm{D}}_{\mathrm{i}}+\varepsilon^{\mathrm{E}}_{\mathrm{i}}\right]\,. \tag{5}$$

Generally, it can also be written as

$$\Sigma(p,p_{\mathrm{F}}) = \Sigma_{\mathrm{S}}(p,p_{\mathrm{F}})+\gamma_0\Sigma_0(p,p_{\mathrm{F}})+\boldsymbol{\gamma}\cdot\hat{\boldsymbol{p}}\Sigma_{\mathrm{V}}(p,p_{\mathrm{F}})\,, \tag{6}$$

where $\hat{\boldsymbol{p}}$ is the unitary vector along $\boldsymbol{p}$, and p_{F} is the Fermi momentum. Here, the tensor term $\gamma_0\boldsymbol{\gamma}\cdot\hat{\boldsymbol{p}}\Sigma_{\mathrm{T}}(p,p_{\mathrm{F}})$ is omitted because it does not appear in the Hartree-Fock approximation for nuclear matter.

In this work, density dependent meson-nucleon couplings are used as introduced in Ref. [16]. For the coupling constants g_ρ and f_π, the exponential type of density dependence are adopted. A newly developed DDRHF effective interaction PKO1[14, 15] will be used in recent calculations.

The chemical potential can be calculated from self-energies,

$$\mu = \Sigma_0(p_{\mathrm{F}}) + \sqrt{[p_{\mathrm{F}}+\Sigma_{\mathrm{V}}(p_{\mathrm{F}})]^2+[M+\Sigma_{\mathrm{S}}(p_{\mathrm{F}})]^2}\,. \tag{7}$$

In cold neutron star matter, the chemical potentials of included components fulfill the equilibrium conditions under weak interaction, i.e., $\mu_{\mathrm{p}} = \mu_{\mathrm{n}} - \mu_{\mathrm{e}}$ and $\mu_{\mu} = \mu_{\mathrm{e}}$. Moreover, the baryon density conservation, $\rho_{\mathrm{b}} = \rho_{\mathrm{n}}+\rho_{\mathrm{p}}$, as well as the condition of charge neutrality, $\rho_{\mathrm{p}} = \rho_{\mu}+\rho_{\mathrm{e}}$, must be satisfied. Then the pressure can be obtained from the thermodynamic relation,

$$P(\rho_{\mathrm{v}}) = \rho^2_{\mathrm{v}}\frac{\mathrm{d}}{\mathrm{d}\rho_{\mathrm{v}}}\frac{\varepsilon_{\mathrm{ns}}}{\rho_{\mathrm{v}}} = \sum_{\mathrm{i=n,p,e},\mu}\rho_{\mathrm{i}}\mu_{\mathrm{i}} - \varepsilon_{\mathrm{ns}}\,. \tag{8}$$

The structure equations of a static, spherically symmetric, relativistic star are Tolman-Oppenheimer-Volkov (TOV) equations[17, 18]. Taking the neutron star EoS as the input, the star's mass and radius can be solved from the TOV equations.

3 Results and discussion

In the present work, the neutron star EoS and corresponding neutron star properties are studied in the DDRHF theory with the effective interaction PKO1, and the results with four RMF effective interactions are discussed as well for comparison: NL3[19] and PK1[20] with nonlinear meson self-couplings, TW99[16] and PKDD[20] with density dependent meson-nucleon couplings.

In Fig. 1 are shown the EoSs of neutron star matter for different effective interactions. It is found that the pressure of the neutron star matter with the DDRHF interaction PKO1 is strongly dependent on the baryon density. PKO1 gives stiffer EoS than those with RMF effective interactions except NL3. For the RMF calculations, NL3 has the stiffest EoS due to the contributions from the nonlinear meson self-coupling terms, while PKDD and PK1 give a little softer ones and TW99 shows the softest one.

The strong density dependence of the EoS leads to a large neutron star maximum mass. As a result, DDRHF effective interaction PKO1 give a large maximum mass of neutron stars $M_{\max} \approx 2.45\ \mathrm{M}_{\odot}$, which is compatible with the observational constraint from PSR B1516+02B[3], while nonlinear RMF effective interaction NL3 gives the largest maximum mass 2.78 $\mathrm{M}_{\odot}$ and density dependent one TW99 shows the smallest result 2.08 $\mathrm{M}_{\odot}$, as shown in Table 1.

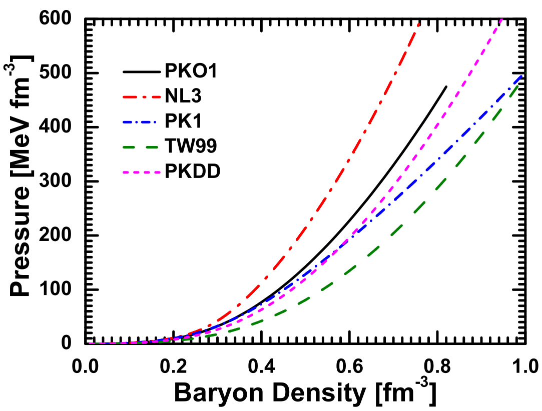

Fig. 1. The pressure of the neutron star matter as a function of the baryon density for different DDRHF and RMF effective interactions.

The cooling behavior of neutron stars could reveal information of nuclear EoSs as well. According to recent analysis[21, 22], an acceptable EoS shall not allow direct Urca processes to occur in neutron stars with masses below 1.5 $\mathrm{M}_{\odot}$, otherwise it will be in disagreement with modern observational soft X-ray data in the temperature-age diagram. As a weaker constraint, $M_{\mathrm{DU}} > 1.35\ \mathrm{M}_{\odot}$ could be used. This limits the density dependence of the nuclear symmetry energy which should not be too strong. As shown in Table 1, only density dependent RMF effective interaction TW99 could satisfy this constraint. For the DDRHF effective interaction PKO1, D-Urca will occur at fairly low mass 1.20 $\mathrm{M}_{\odot}$, which could be comprehended from the contribution of Fork terms. In fact, the effects of the Fock channel of σ and ω mesons on the symmetry energies are remarkable, which lead to strong density dependence of the nuclear symmetry energy at high densities. It's expected that new DDRHF effective interactions in the future could improve these results.

Table 1. Neutron star maximum masses, corresponding central densities, and critical neutron star masses for the occurrence of the D-Urca cooling process with the corresponding central densities for different DDRHF and RMF effective interactions.

	$M_{\max}$ /$\mathrm{M}_{\odot}$	$\rho_{\max}(0)$ /fm^{-3}	M_{DU} /$\mathrm{M}_{\odot}$	$\rho_{\mathrm{DU}}(0)$ /fm^{-3}
PKO1	2.45	0.80	1.20	0.28
NL3	2.78	0.67	1.01	0.23
PK1	2.32	0.80	0.94	0.23
TW99	2.08	1.10	-	-
PKDD	2.33	0.89	1.26	0.33

4 Summary

In conclusion, the EoS of neutron stars has been discussed in the DDRHF theory with the effective interaction PKO1 and the corresponding neutron star properties have been investigated and compared with recent observational constraints. The EoS obtained from the DDRHF interaction PKO1 is strongly baryon density dependent and the maximum mass of neutron stars calculated is compatible with high pulsar mass from PSR B1516+02B recently reported. The effects of exchange terms are remarkable for properties of asymmetric nuclear matter at high densities and affect the cooling process of neutron stars.

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