Nuclear matter and neutron matter for improved quark mass
density-dependent model with $\rho$ mesons

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Abstract

A new improved quark mass density-dependent model including u, d quarks, $\sigma$ mesons, $\omega$ mesons and $\rho$ mesons is presented. Employing this model, the properties of nuclear matter, neutron matter and neutron star are studied. We find that it can describe above properties successfully. The results given by the new improved quark mass density-dependent model and by the quark meson coupling model are compared.

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I. INTRODUCTION

In our previous papers [1-6], a new quark meson coupling model bases on quark mass density- dependent(QMDD) model is presented. The QMDD model suggested by Fowler, Raha and Weiner [7] firstly assuming that the masses of u, d and s quarks(and the corresponding antiquarks) satisfy:

$$m_q = \frac{B}{3n_B}(i = u, d, \bar{u}, \bar{d}) \quad (1)$$

$$m_{s,\bar{s}} = m_{s0} + \frac{B}{3n_B} \quad (2)$$

where $n_B$ is the baryon number density, $m_{s0}$ is the current mass of the strange quark, and $B$ is the bag constant. As was explained in Refs.[1, 2, 5, 8], the ansatz Eqs. (1) and (2) corresponds to a quark confinement hypothesis because when $V \rightarrow \infty, n_B \rightarrow 0$ and $m_q \rightarrow \infty$, it prevents the quark goes to infinity. It is shown that the properties of strange quark matter in the QMDD model are nearly the same as those obtained in the MIT bag model [9, 10]. But the basic difference is that instead of the MIT bag boundary condition, we have the density- dependent masses of quarks in QMDD model according to Eqs. (1) and (2). It means that the ansatz Eqs. (1) and (2) can replace MIT bag boundary condition and get the nearly the same results.

Quark- meson coupling(QMC) model suggested by Guichon [11] firstly is a famous hybrid quark meson model which can describe many physical properties of nuclear matter and nuclei successfully [12]. In this model, the nuclear system was suggested as a collection of MIT bag and mesons. The interactions between quarks and mesons are limited within the MIT bag regions. As was pointed in Refs. [1, 2, 6], this model has two major shortcomings: (1) It is a permanent quark confinement model because the MIT bag boundary condition cannot be destroyed by temperature and density. Therefore, it cannot describe the quark deconfinement phase transition. (2) It is difficult to do nuclear many-body calculation beyond mean field approximation(MFA) by means of QMC model, because we cannot find the free propagators of quarks and mesons easily. The reason is that the interactions between quarks and mesons are limited within the bag regions, the multireflection of quarks and mesons by MIT bag boundary must be taken into account for getting the free propagators. These two shortcomings come from MIT bag constrain all.
To overcome these two shortcomings, we suggested an improved quark mass density-dependent (QMDD) model in Refs. [1-6]. We added the $\sigma$-meson and $\omega$-meson to improve the QMDD model. Instead of the MIT bag, after introducing the nonlinear interaction of $\sigma$-mesons and $qq\sigma$ coupling, we construct a Friedberg-Lee soliton bag in nuclear system. The quark masses are still density-dependent. The interactions between quarks and mesons are extended to the whole system. Since the MIT bag constraint is given up, our improved QMDD (IQMDD) model can describe the quark deconfinement phase transition [6] and do the nuclear many-body calculations beyond MFA in principle. We have proved that our model can successfully describe the saturation properties, the equation of state, the compressibility and the effective nucleon mass of symmetric nuclear matter and give a reasonable critical temperature of quark deconfinement [1-6].

The motivation of this paper is to extend our study to asymmetric nuclear matter, especially to the neutron matter and the neutron star. It means that we must consider the isospin dependence and distinguish the u-quark and d-quark. We will add the isospin vector $\rho$ mesons to improve the IQMDD model in this paper. We hope to compare the results of IQMDD model with those obtained by QMC model and QHD-II model for neutron matter and neutron star. In order to find their differences and similarity explicitly, we will use the same approximation as that of the QMC model [13] in our calculations. Though the study of neutron star employing QMC model in Ref. [14] is too simple, but in order to exhibit the basic differences between the IQMDD model and the QMC model, we still consider the neutron star by using the same approximation as Ref. [14].

The organization of this paper is as follows. In the next section, we give the main formulas of the IQMDD model under the mean field approximation. The main formulas of neutron stars in also included. In the third section, some numerical results are presented. The last section contains a summary and discussions.
II. FORMULAS OF THE IQMDD MODEL WITH ρ MESON

A. IQMDD model for nuclear matter

The Lagrangian density of IQMDD model with σ, ω, and ρ mesons is:

\[
\mathcal{L} = \bar{\psi} \left[ i \gamma^{\mu} \partial_{\mu} - m_q + g_{\sigma}^q \sigma - g_{\omega}^q \gamma^{\mu} \omega_{\mu} - g_{\rho}^q \gamma^{\mu} \vec{\tau} \cdot \vec{\rho}^{\mu} \right] \psi + \frac{1}{2} \partial_{\mu} \sigma \partial^{\mu} \sigma \\
- U(\sigma) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_{\mu} \omega^{\mu} + \frac{1}{2} m_\rho^2 \vec{\rho}_{\mu} \cdot \vec{\rho}^{\mu} - \frac{1}{4} \tilde{G}_{\mu\nu} \tilde{G}^{\mu\nu}
\]

where

\[
U(\sigma) = \frac{1}{2} m_\sigma^2 \sigma^2 + \frac{1}{3} b \sigma^3 + \frac{1}{4} c \sigma^4 + B,
\]

\[
- B = m_\sigma^2 \sigma_v^2 + \frac{b}{3} \sigma_v^3 + \frac{c}{4} \sigma_v^4,
\]

\[
\sigma_v = \frac{-b}{2c} \left[ 1 + \sqrt{1 - 4 m_\sigma^2 c/b^2} \right],
\]

and the quark mass \( m_q (q = u, d) \) is given by Eq. (1). \( m_\sigma \) and \( m_\omega \) are the masses of \( \sigma \) and \( \omega \) mesons, \( F_{\mu\nu} = \partial_\mu \omega_\nu - \partial_\nu \omega_\mu \), \( \tilde{G}_{\mu\nu} = \partial_\mu \vec{\rho}_\nu - \partial_\nu \vec{\rho}_\mu \), \( g_{\sigma}^q, g_{\omega}^q, g_{\rho}^q \) are the coupling constants between quark and \( \sigma \) meson, quark and \( \omega \) meson and quark and \( \rho \) meson respectively.

The equation of motion for quark field under MFA in the whole space is

\[
[ i \gamma \cdot \partial - (m_q - g_{\sigma}^q \bar{\sigma}) - \gamma^0 (g_{\omega}^q \bar{\omega} + \frac{1}{2} g_{\rho}^q \tau^z \bar{\rho}) ] \psi = 0
\]

where \( \bar{\sigma}, \bar{\omega} \) are the mean field values of the \( \sigma \) field and the corresponding time component of \( \omega \) field respectively, \( \bar{\rho} \) is the mean field value of the time component in the third direction of isospin for \( \rho \) field, \( \tau^z \) is the third component of the Pauli matrix. The effective quark mass \( m_q^* \) is given by:

\[
m_q^* = m_q - g_{\sigma}^q \bar{\sigma}
\]

In nuclear matter, three quarks constitute a Freidberg-Lee soliton bag [15], and the effective nucleon mass is obtained from the bag energy and reads:

\[
M_N^* = \Sigma_q M_q^* = \Sigma_q \frac{4}{3} \pi R^3 \frac{\gamma_q}{(2\pi)^3} \int_0^{K_F} \sqrt{m_q^*^2 + k^2} \frac{dN_q}{dk} dk
\]
where $\gamma_q$ is the quark degeneracy, $K_F^q$ is Fermi energy of quarks. $dN_q/dk$ is the density of states for various quarks in a spherical cavity. The expression of $dN_q/dk$ adopted in this paper can be found in Ref. [16].

The Fermi energy $K_F^q$ of quarks is given by

$$3 = \frac{4}{3} \pi R^3 n_B$$

(10)

where $n_B$ satisfies

$$n_B = \Sigma_q \frac{\gamma_q}{(2\pi)^3} \int_0^{K_F^q} (dN_q/dk) dk$$

(11)

The bag radius $R$ is determined by the equilibrium condition for the nucleon bag:

$$\frac{\delta M_N^*}{\delta R} = 0$$

(12)

In nuclear matter, the total energy density and pressure density read

$$\varepsilon_{\text{matter}} = \frac{\gamma_N}{(2\pi)^3} \left( \int_0^{K_p^N} + \int_0^{K_n^N} \right) \sqrt{M_N^* + p^2} dp^3 + \frac{g_\omega^2}{2m_\omega} \rho_3^2$$

$$+ \frac{1}{2} m_\sigma^2 \sigma^2 + \frac{1}{3} b \sigma^3 + \frac{1}{4} c \sigma^4 + \frac{g_\rho^2}{8m_\rho^2} \rho_3^2$$

(13)

and

$$p_{\text{matter}} = \frac{1}{3} \frac{\gamma_N}{(2\pi)^3} \left( \int_0^{K_p^N} + \int_0^{K_n^N} \right) \frac{p^2}{\sqrt{M_N^* + p^2}} dp^3 + \frac{g_\omega^2}{2m_\omega} \rho_3^2$$

$$- \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{1}{3} b \sigma^3 - \frac{1}{4} c \sigma^4 + \frac{g_\rho^2}{8m_\rho^2} \rho_3^2$$

(14)

where $\gamma_N = 2$ is degeneracy of proton or neutron, $K_F^p$ and $K_F^n$ is Fermi momenta of proton and neutron, and $\rho_3$ is the difference between the proton and neutron densities, respectively. Therefore

$$\rho_p = \frac{1}{3\pi^2} K_F^3, \quad \rho_n = \frac{1}{3\pi^2} K_F^3,$$

(15)

Where $\rho_p$ and $\rho_n$ is the density of proton and neutron respectively, and the density of nuclear matter $\rho_B$ reads

$$\rho_B = \rho_p + \rho_n$$

(16)
In Eqs. (13, 14), $g_\omega$ and $g_\rho$ are the coupling constants between nucleon and $\omega$ meson, nucleon and $\rho$ meson respectively. They satisfies $g_\omega = 3g_\omega^a$ and $g_\rho = g_\rho^a$ [13]. In MFA, the $\bar{\omega}$ is determined by baryon number conservation

$$\bar{\omega} = \frac{g_\omega \rho B}{m_\omega^2} \tag{17}$$

As that of the QMC model [13], $\bar{\sigma}$ and $\bar{\rho}$ are given by the thermodynamics conditions:

$$\left(\frac{\partial \varepsilon_{\text{matter}}}{\partial \bar{\sigma}}\right)_{R,\rho B} = 0, \quad \text{and} \quad \left(\frac{\partial \varepsilon_{\text{matter}}}{\partial \bar{\rho}}\right)_{R,\rho B} = 0 \tag{18}$$

respectively. Therefore, $\bar{\rho}$ is expressed by

$$\bar{\rho} = \frac{g_\rho}{2m_\rho^2}\rho_3 \tag{19}$$

and $\bar{\sigma}$ is given by

$$m_\sigma^2 \bar{\sigma} + b\bar{\sigma}^2 + c\bar{\sigma}^3 = -\frac{\gamma_N}{(2\pi)^3} \left(\int_0^{K_F} + \int_0^{K_F^p}\right) \frac{M_N^*}{\sqrt{M_N^2 + p^2}} d^3p \left(\frac{\partial M_N^*}{\partial \bar{\sigma}}\right)_R \tag{20}$$

Eqs. (13-20) form a complete set of equations and we can solve numerically. Our numerical results will be shown in the next section.

Noting that the left hand side of Eq. (20) is a cubic order function of $\bar{\sigma}$, except one solution $\bar{\sigma} = 0$, there are still two solutions. This is a general character for adding a nonlinear scalar $\sigma$ field and using MFA to a physical model [17]. But as was pointed in Ref. [1], we can prove that one of these solutions corresponds to unstable and unphysical branch, and the other corresponds a stable soliton solution. Hereafter we give up the unphysical solution and consider the physical solution only.

We note that the expression for the total energy density, Eq. (13), is very similar to that of QHD-II model and QMC model. The differences comes from the effective nucleon mass Eqs. (9) and (1), and the self-consistency condition for $\sigma$ field, Eq. (20). Let us consider the self-consistency condition and $\left(\frac{\partial M_N^*}{\partial \bar{\sigma}}\right)_R$ further. Using the same argument as that of Ref. [13], we find that the $\left(\frac{\partial M_N^*}{\partial \bar{\sigma}}\right)_R$ can be expressed as

$$\left(\frac{\partial M_N^*}{\partial \bar{\sigma}}\right)_R = -g_\sigma \times \begin{pmatrix} 1 \\ C_1(\bar{\sigma}) \\ C_2(\bar{\sigma}) \end{pmatrix} \text{ for } \begin{pmatrix} \text{QHD-II} \\ \text{QMC} \\ \text{IQMDD} \end{pmatrix} \text{ model} \tag{21}$$

where the expression of scalar density factor $C_1(\bar{\sigma})$ for QMC model can be found in Ref. [13]. For IQMDD model, $C_2(\bar{\sigma})$ can be obtained numerically. The curves of $C_1(\bar{\sigma})$ and $C_2(\bar{\sigma})$ will be shown in Sec. 3.
B. IQMDD model for neutron star

We now turn to investigate the neutron matter and neutron star for the IQMDD model. Since the aim of this paper is to compare the IQMDD model and the QMC model, we use the same approximation to study the neutron star as that of the QMC model [14]. More detailed treatment of neutron star such as the phase transition for the quark matter and the neutron matter, the contribution of hyperon and etc, has been neglected. Two basic assumptions: the neutron star matter is charge neutrality and reaches to the $\beta$-equilibrium, are adopted [14]. Since we assume that the nucleons and light leptons exist in the neutron star only, charge neutrality is expressed as

$$\rho_p = \sum_{l=e,\mu} \rho_l, \quad (22)$$

where $\rho_l$ is the number density of particle $i (= p, e, \mu)$. Under $\beta$-equilibrium, the processes

$$n \rightarrow p + e^- + \bar{\nu}_e, p + e^- \rightarrow n + \nu_e \quad (23)$$

occur at the same rate. This condition can be satisfied when the chemical potentials before and after the decay are same. The chemical potential of each particle reads

$$\mu_n = \sqrt{K_n^2 + m_N^2 + g_\omega \bar{\omega} - \frac{1}{2} g_{\rho\bar{\rho}}} \quad (24)$$

$$\mu_p = \sqrt{K_p^2 + m_N^2 + g_\omega \bar{\omega} + \frac{1}{2} g_{\rho\bar{\rho}}} \quad (25)$$

$$\mu_l = \sqrt{K_l^2 + m_l^2} \quad (26)$$

where $K_l$ is the Fermi momentum of the lepton $l (e, \mu)$. The chemical equilibrium condition is expressed as

$$\mu_n = \mu_p + \mu_e, \quad (27)$$

$$\mu_e = \mu_\mu \quad (28)$$

Once the solution has been found, the equation of state (EoS) can be calculated from

$$\varepsilon = \frac{\gamma_N}{(2\pi)^3} \left( \int_0^{K_p^p} + \int_0^{K_p^p} \right) \sqrt{M_N^2 + p^2 dp^3 + \frac{g_\omega^2}{2m_\omega^2} \rho_\omega^2 + \frac{1}{2} m_\omega^2 \sigma^2}
+ \frac{1}{3} b \sigma^3 + \frac{1}{4} c \sigma^4 + \frac{g_\rho^2}{8 m_\rho^2} \rho_3^2 + \frac{1}{\pi^2} \sum_l \int_0^{k_l^l} \sqrt{k^2 + m_l^2 k^2} dk, \quad (29)$$
\[ p = \frac{1}{3} \frac{\gamma_N N}{(2\pi)^3} \left( \int_0^{K_F^p} + \int_0^{K_F^n} \right) \frac{p^2}{\sqrt{M_N^*} + p^2} dp^3 + \frac{g_\omega^2}{2m_\omega^2} \beta_B^2 - \frac{1}{2} m_\sigma^2 \sigma^2 \]

\[ - \frac{1}{3} b \sigma^3 - \frac{1}{4} c \sigma^4 + \frac{g_\rho^2}{8m_\rho^2} \rho_3^2 + \frac{1}{3\pi^2} \sum_i \int_0^{k_i} \frac{k^4}{\sqrt{k^2 + m_i^2}} dk, \quad (30) \]

Using the Oppenheimer and Volkoff equation

\[ \frac{dp(r)}{dr} = -\frac{G m(r) \varepsilon}{r^2} \left( 1 + \frac{p}{\varepsilon C^2} \right) \left( 1 + \frac{4\pi r^3 p}{m(r) C^2} \right) \left( 1 - \frac{2G m(r)}{r C^2} \right)^{-1} \quad (31) \]

\[ dM(r) = 4\pi r^2 \varepsilon(r) dr \quad (32) \]

where \( G \) is gravitational constant and \( C \) is the velocity of light, and the equation of state for neutron matter given by Eqs. (29), (30) and (9), we can study the physical behavior of neutron star for IQMDD model.

### III. NUMERICAL RESULT

Before numerical calculation, let us discuss the parameters in IQMDD model. First, we choose \( m_\omega = 783 \text{ MeV} \), \( m_\rho = 770 \text{ MeV} \) and \( m_\sigma = 509 \text{ MeV} \) as that of Ref. [18]. Fixing the nucleon mass \( M_N = 939 \text{ MeV} \), we get \( B = 174 \text{ MeV fm}^{-3} \). Obviously, the behaviors at the saturation point must be explained for a successful model. It reveals that nuclear matter saturates at a density \( \rho_0 = 0.15 \text{ fm}^{-3} \) with a binding energy per particle \( E/A = -15 \text{ MeV} \) at zero temperature, and the compression constant to be about \( K(\rho_0) = 210 \text{ MeV} \). Therefore we fixed \( g_\omega^a = 2.44, g_\rho^a = 4.67, \beta = -1460 \text{ MeV} \) to explain above data. In addition, the symmetry energy coefficient \( a_{\text{sym}} \) satisfies

\[ a_{\text{sym}} = \frac{1}{2} \left( \frac{\partial^2 (\varepsilon/\rho)}{\partial \alpha^2} \right)_{\alpha=0} = \left( \frac{g_\rho}{m_\rho} \right)^2 \frac{k_0^3}{12\pi^2} + \frac{k_0^2}{6\sqrt{k_0^2 + M_N^*}} \quad (33) \]

where

\[ \alpha = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}, \quad k_0 = 1.42 \text{ fm}^{-1} \quad (34) \]

Using the data \( a_{\text{sys}} = 33.2 \text{ MeV} \) we fix \( g_\rho = 9.07 \). The parameters used to calculate and the results of \( K \) and \( M_N^* \) for IQMDD model are shown in Table 1. For comparison, we also show the corresponding parameters for QMC model in Table 1. The data and results for
QMC model are taken from Ref. [13]. We see in Table 1 all parameters and results are very similar for these two models. Their differences are not remarkable.

|          | $g^q_\sigma$ | $g^q_\omega$ | $g^q_\rho$ | R(fm) | K(MeV) | $M_N^*(\rho_0)(MeV)$ |
|----------|--------------|--------------|------------|-------|--------|-----------------------|
| QMC      | 5.53         | 1.26         | 8.44       | 0.80  | 200    | 851                   |
| IQMDD    | 4.67         | 2.44         | 9.07       | 0.85  | 210    | 775                   |

Our results for symmetric nuclear matter and neutron matter are shown in Fig. 1-3. The scalar density factor $C(\bar{\sigma})$ as a function of $\bar{\sigma}$ is shown in Fig. 1 where the dashed curve refers to $C_1(\bar{\sigma})$ and solid curve to $C_2(\bar{\sigma})$ respectively. This factor plays an essential role to demonstrate the main character of quark structure for different models. We see from Fig. 1 that the scalar density factors $C_1(\bar{\sigma})$ and $C_2(\bar{\sigma})$ are both smaller than unity (QHD-II model) and decrease when $\bar{\sigma}$ increases. In particular, $C_2(\bar{\sigma})$ is located between the line of unity and the curve of $C_1(\bar{\sigma})$. It means that the values of main physical quantities given by IQMDD model will almost located between the values given by QHD-II model and by QMC model. Our results confirm this conclusion.

In Fig. 2, we draw the curves of energy per baryon vs. baryon number density for both symmetric nuclear matter and for neutron matter respectively. We see that ignoring $\rho$ meson coupling yields a smaller bound state around $\rho_B \sim 0.10 fm^{-3} \sim 0.66 \rho_0$ in the dotted curve, but it becomes unbound solid line when the $\rho$ meson contribution is introduced. The saturation curve for symmetric nuclear matter is shown by dash-dotted curve in Fig. 2. In fact, the behavior of curves in Fig. 2 is very similar to that of QMC model, but the corresponding value of $\rho_B$ is $0.60 \rho_0$ for QMC model and $0.66 \rho_0$ for IQMDD model. (See Fig. 2 of Ref. [13])

The equation of state for neutron matter is shown in Fig. 3 where the dashed curve presents the result when the $\rho$ meson contribution is ignored and the solid curve corresponds to the full calculation. We see the contribution of $\rho$ meson is important for the EoS. After comparing with the results of QHD-II model and QMC model, we come to a conclusion that the shape of equation of state for neutron matter in IQMDD model is qualitatively similar to that of QHD-II model and QMC model, it is softer than that of QHD-II model but harder than that of the QMC model, as is indicated in Fig. 1 by the behavior of scalar density.
Having shown the IQMDD model can provide an successful description for nuclear and neutron matter, we would like to study the structure and composition of neutron stars for IQMDD model. We will show that it can successfully describe the neutron star.

The EoS is given by Eqs. (9), (29) and (30) for IQMDD model when the neutron star matter reaches to $\beta$ equilibrium. The curve of EoS is shown in Fig. 4. In Fig. 5, we show the particle population including $n, p, e, \mu$ for different density by solid($n$), dashed($p$), dotted($e$), dash-dotted($\mu$) curves respectively. The mass of neutron star in units of sun mass $M/M_\odot$ as a function of central density $\varepsilon_c$ is plotted in Fig. 6. In Fig. 7 we show the mass radius relation of the neutron star. The maximum mass of neutron star $M_{\text{max}}$ found in Fig. 7 is 1.73 $M_\odot$. It is smaller than the value of 2.2$M_\odot$ given by QMC model [14]. We would like to emphasize that the above treatment for neutron star is too rough. Therefore, the value of $M_{\text{max}}$ is not important. Our aim is to demonstrate that all curves shown in Fig. 4-7 are in agreement with those given by QMC model qualitatively [14]. We come to a conclusion that perhaps the IQMDD model is a good candidate to replace the QMC model.

IV. SUMMARY AND DISCUSSION

In summary, we have added the $\rho$ meson to the IQMDD model to study the asymmetric nuclear matter, especially, the neutron matter and neutron star. The $u, d$, quarks, nonlinear scalar $\sigma$ meson field, $\omega$ meson field, $\rho$ meson field and the corresponding quark mesons couplings are including in the new IQMDD model. The isospin effect has been considered by introducing isovector $\rho$ mesons in this model. After fixing the parameters by the experimental values such as the massed of nucleon, $\sigma$ meson, $\omega$ meson, $\rho$ meson; saturation point, compression constant and the symmetry energy, under MFA, we have investigate the physical properties of nuclear matter and neutron matter. We found that the results given by IQMDD model are similar to that of QMC model. The values of the main physical quantities for neutron matter and nuclear matter given by IQMDD model locate in the regions between the values given by the QHD-II model and by the QMC model. Employing the IQMDD model, we have studied the neutron star and also found its properties almost agree with these given by QMC model. We conclude that the new IQMDD model with $\rho$ meson is successful for describing the nuclear matter and neutron matter. Perhaps it can play the
role to replace the QMC model.

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FIG. 1: Scalar density factors $C_2(\bar{\sigma})$ and $C_1(\bar{\sigma})$ as a function of $\bar{\sigma}$ for IQMDD model and QMC model respectively.
FIG. 2: Energy per nucleon for symmetric nuclear matter and for neutron matter. The dash-dotted curve is the saturation curve for nuclear matter. The solid curve (with $\rho$ meson) and the dotted curve (omit $\rho$ meson) show the results for neutron matter.
FIG. 3: The equation of state for neutron matter. The dashed line show the result for omitting $\rho$ meson, while the solid line corresponds to full consideration.
FIG. 4: Equation of state for $\beta$- equilibrium neutron star matter.
FIG. 5: Populations in neutron star matter as a function of density.
FIG. 6: Neutron star mass as a function of the central density.
FIG. 7: Masses of neutron stars vs. their radii.