Improved density-dependent quark mass model with quark-σ meson and quark-ω meson couplings

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We present an improved quark mass density-dependent model with the nonlinear scalar sigma field and the ω-meson field. By comparing with the quark-meson coupling model, we show that our model can successfully describe saturation properties, the equation of state, the compressibility and the effective nuclear mass of nuclear matter under the mean field approximation.

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I. INTRODUCTION

Owing to the nonperturbative nature of quantum chromodynamics (QCD) in low energy regions, it is very difficult to study nuclear system by using QCD directly. Phenomenological models reflecting the characteristic of the strong interaction are widely used in the studying of the properties of hadrons and nuclear matter. The quantum hadrodynamics (QHD-I) is a pioneering framework to describe the nuclear system as a relativistic many-body system of baryons and mesons. Along this direction, many important extensions of QHD-I model had been made, for example, adding nonlinear scalar field to improve the compressibility value of nuclear matter, adding isovector ρ meson to study the isospin effects (QHD-II model), adding pions to investigate the chiral symmetry and PCAC, etc. The best review for the progress of QHD can be found in Refs. [1–3], and references therein. Recently, this model has been extended to include the hyperons for studying the strange hadronic matter [4–7].

Since the QCD of quarks and gluons is the fundamental theory of the strong interaction, it is natural to extend above discussions to quark level. The first famous model, namely, the quark-meson coupling (QMC) model was suggested by Guichon [8]. It describes the nuclear matter as a collection of nonoverlapping MIT bags, scalar σ meson and vector ω meson. The quarks inside the MIT bag couple with the scalar σ meson and vector ω meson self-consistently. By means of this model and the mean field approximation (MFA), many dynamical and thermal properties of nucleon systems have been studied [9–11].

Although the QMC model is successful for describing the physical properties of a nuclear system, two shortcomings arise when one uses this model to discuss the quark deconfinement. The first difficulty comes because that it is a permanent quark confinement model and the MIT boundary condition cannot be destroyed by temperature and density. The second difficulty arises from MIT boundary condition. If we hope to do the nuclear many-body calculations beyond MFA by quantum field theory, it is essential to find the free propagators of quark, σ meson and ω meson, respectively. But the constraint of the MIT bag boundary condition presents obstacles to get the corresponding propagators in free space. Because the interactions between quarks and mesons are limited within the bag regions, and multireflection of quarks and mesons by the boundary must be taken into account.

In order to keep the quark confined property and to give up the MIT boundary condition, we focus our attention on the quark mass density-dependent (QMDD) model suggested by Fowler, Raha, and Weiner [12] first.

According to the QMDD model, the masses of u, d quarks and strange quarks (and the corresponding antiquarks) are given by

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

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

where n_B is the baryon number density, m_{s0} is the current mass of the strange quark, and B is the bag constant. At zero temperature

$$n_B = \tfrac{1}{3}(n_u + n_d + n_s), \tag{3}$$

where n_u, n_d, n_s represent the density of the u quark, d quark, and s quark, respectively. The basic hypothesis (1) and (2) in the QMDD model can be understood from the quark confinement mechanism. A confinement potential, which is proportional to r (or r^2), must be added to a quark system in the phenomenological effective models because the perturbative QCD cannot give us the confinement solution of quarks. The confinement potential kr prevents the quark from going to infinity or to the very large regions. The large regions or the large volume means that the density is small. This mechanism of confinement can be mimicked through the requirement that the mass of isolated quark becomes infinitely large so that the vacuum is unstable to support it. Thus, for a system of quarks at zero temperature, the energy density tends to a constant value while the mass tends to infinity, as the volume increases to infinity or the density decreases to zero [13,14]. This is just the picture given by Eqs. (1) and (2). This confinement mechanism is similar to that of the MIT bag model.

The boundary condition of confinement for MIT bag model corresponds to that wherein the quark mass is zero inside the bag but infinite at the boundary or outside the bag, Due to

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this similarity, Benvento and Lugones [15] investigated the equation of state, the stability window of strange matter and the M-R curves of strange star. They claimed that in almost all cases they found that the properties of the strange matter in the QMDD model are nearly the same as those obtained in the MIT bag model [15]. Their conclusion had also been confirmed by many other authors [16–18]. Here we emphasize that the MIT bag boundary constraint has been given up in the QMDD model.

As was shown in Ref. [14], the QMDD model cannot describe the quark deconfinement phase transition and give us a correct phase diagram as that given by lattice QCD. The reason is that the temperature T tends to infinite when density $n_B \rightarrow 0$. This result can easily be understood if we notice the basic hypothesis Eqs. (1) and (2) of the QMDD model, the quark masses are divergent when $n_B \rightarrow 0$. To excite an infinite weight particle, one must prepare to pay the price for infinite energy, i.e., infinite temperature. It means that the confinement in the QMDD model is still permanent. To overcome this difficulty, we have introduced a new ansatz that the vaccum density B is a function of temperature T [14,16]:

$$B = B_0[1-(T/T_C)^2], \quad 0 \leqslant T \leqslant T_C, \tag{4}$$

$$B = 0, T > T_C. \tag{5}$$

The masses of quarks not only depend on the density n_B, but also on the temperature T,

$$m_q = \frac{B}{3n_B}[1-(T/T_C)^2], \quad (q = u, d, \bar{u}, \bar{d}), \tag{6}$$

$$m_{s,\bar{s}} = m_{s0} + \frac{B}{3n_B}[1-(T/T_C)^2], \tag{7}$$

and when $T \geqslant T_C, m_q = 0, m_{s,\bar{s}} = m_{s0}$, This quark mass density- and temperature-dependent model (QMDTD) has been employed to discuss the properties of strange quark matter [14,16], the dibaryon system [19], and the strange quark star [20,21]. Instead of the correspondence of MIT bag to the QMDD model, we have proved that QMDTD model mimicks the Freidberg-Lee (FL) soliton bag model [22,23]. In FL model, the confinement mechanism comes from the interaction between quarks and a nonlinear nontopological scalar soliton field. The vacuum density B equals to the different value between the local false vacuum minimum and absolute real vacuum minimum. It is a function of temperature. The scalar field breaks the chiral symmetry spontaneously. The nontopological soliton will disappear at a finite temperature and the quark will deconfine at the critical temperature T_C, where $B(T_C) = 0$. To avoid the ad hoc ansatz Eqs. (4)–(7), following the treatment of Friedberg and Lee, we introduced a nonlinear scalar field to improve the QMDD model in Refs. [24,25]. We found the wave functions of the ground state and the lowest one-particle excited states. By using these wave functions, we calculated many physical quantities such as root-mean-square radius, the magnetic moment of nucleon to compare with experiments and come to a conclusion that this improved QMDD (IQMDD) model is successful to explain the properties of nucleon [24]. In Ref. [25], we extended this model to finite temperature and studied its soliton solution by means of the finite temperature quantum field theory. The critical temperature of quark deconfinement T_C and the function of temperature-dependent bag constant $B(T)$ are found as an output.

This paper evolves from an attempt to employ the IQMDD to investigate the physical properties of nuclear matter. As was shown by the QHD model [1] and the QMC model [8] early, a neutral vector field coupled to the conserved baryon current is very important for describing bulk properties of nuclear matter. The large neutral scalar and vector contributions have been observed empirically from NN scattering amplitude. The main qualitative features of the nucleon-nucleon interaction: a short range repulsion between baryons coming from ω-meson exchange, and a long-range attraction between baryons coming from σ-meson exchange must be included in a successful model. Obviously, if we hope to employ the IQMDD model to mimic this repulsive and attractive interactions, except the quark and σ-meson interaction, the ω meson and the $qq\omega$ coupling must be added. This motivate us to introduce ω mesons and the $qq\omega$ coupling in this paper. In this new IQMDD model, the nonlinear scalar field coupling with quarks forms a soliton bag, and the $qq\omega$ vector coupling gives the repulsion between quarks. We will prove that this model can give us a successful description of nuclear matter.

Our second motivation is to compare the IQMDD model with ω and σ mesons and the QMC model. Instead of the MIT bag in QMC model, the confinement property of QMDD model comes from the density-dependent quark mass and the interaction between quark and nonlinear σ field. We will prove that the results given by IQMDD model are similar to that of the QMC model.

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 at zero temperature. In the third section, some numerical results are presented. The last section contains a summary and discussions.

II. FORMULAS OF THE IMPROVED QMDD MODEL

The Lagrangian density of the IQMDD model is

$$L = \bar{\psi}[i\gamma^\mu\partial_\mu - m_q + g_\sigma^q\sigma - g_\omega^q\gamma^\mu\omega_\mu]\psi + \tfrac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - U(\sigma) - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \tfrac{1}{2}m_\omega^2\omega_\mu\omega^\mu, \tag{8}$$

where

$$F_{\mu\nu} = \partial_\mu\omega_\nu - \partial_\nu\omega_\mu \tag{9}$$

and the quark mass m_q is given by Eqs. (1) and (2), m_σ and m_ω are the masses of σ and ω mesons, g_σ^q and g_ω^q are the couplings constants between quark-σ meson and quark-ω meson, respectively. And

$$U(\sigma) = \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{3}b\sigma^3 + \frac{1}{4}c\sigma^4 + B \tag{10}$$

$$-B = \frac{m_\sigma^2}{2}\sigma_v^2 + \frac{b}{3}\sigma_v^3 + \frac{c}{4}\sigma_v^4, \tag{11}$$

where σ_v is the absolute minimum of $U(\sigma)$, $U(\sigma_v) = 0$ and $U(0) = B$. We omit the contribution of the s quark and the couplings of hyperons here and consider the nuclear matter only.

It can easily show the equation of motion for $u(d)$ quark field in the whole space is

$$[\gamma^\mu(i\partial_\mu + g^q_\omega \omega_\mu) - (m_q - g^q_\sigma \sigma)]\psi = 0. \quad (12)$$

Under mean field approximation, the effective quark mass m_q^* is given by

$$m_q^* = m_q - g^q_\sigma \bar{\sigma}. \quad (13)$$

In nuclear matter, three quarks constitute a soliton bag [26,27], and the effective nucleon mass is obtained from the bag energy and reads

$$M_N^* = \Sigma_q E_q = \Sigma_q \frac{4}{3}\pi R^3 \frac{\gamma_q}{(2\pi)^3}\int_0^{K_F^q}\sqrt{m_q^{*2}+k^2}\left(\frac{dN_q}{dk}\right)dk, \quad (14)$$

where quark degeneracy γ_q=6, K_F^q is the Fermi energy of quarks. dN_q/dk is the density of states for various quarks in a spherical cavity. It is given by [28]

$$N(k) = A(kR)^3 + B(KR)^2 + C(KR), \quad (15)$$

where

$$A = \frac{2\gamma_q}{9\pi}, \quad (16)$$

$$B\left(\frac{m_q}{k}\right) = \frac{\gamma_q}{2\pi}\left\{\left[1+\left(\frac{m_q}{k}\right)^2\right]\arctan\left(\frac{k}{m_q}\right) - \frac{m_q}{k} - \frac{\pi}{2}\right\}, \quad (17)$$

$$C\left(\frac{m_q}{k}\right) = \tilde{C}\left(\frac{m_q}{k}\right) + \left(\frac{m_q}{k}\right)^{1.45}\frac{\gamma_q}{3.42\left(\frac{m_q}{k}-6.5\right)^2+100}, \quad (18)$$

$$\tilde{C}\left(\frac{m_q}{k}\right) = \frac{\gamma_q}{2\pi}\left\{\frac{1}{3}+\left(\frac{m_q}{k}+\frac{k}{m_q}\right)\arctan\left(\frac{k}{m_q}\right) - \frac{\pi k}{2m_q}\right\}. \quad (19)$$

Equations (16) and (17) are in good agreement with those given by multireflection theory [29–31] and Eqs. (18) and (19) are given by a best fit of numerical calculation for the MIT bag model. The curvature term $\tilde{C}$ given by Madsen [29] cannot be evaluated by the multireflection theory except for two limiting cases $m_q \to 0$ and $m_q \to \infty$.

At zero temperature, the Fermi energy K_F^q of quarks reads

$$3 = \tfrac{4}{3}\pi R^3 n_B, \quad (20)$$

where n_B satisfies

$$n_B = \Sigma_q \frac{\gamma_q}{(2\pi)^3}\int_0^{K_F^q}\left(\frac{dN_q}{dk}\right)dk. \quad (21)$$

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

$$\frac{\delta M_N^*}{\delta R} = 0. \quad (22)$$

In nuclear matter, the total energy density is given by

$$\varepsilon_{\text{matter}} = \frac{\gamma_N}{(2\pi)^3}\int_0^{K_F^N}\sqrt{M_N^{*2}+p^2}\,d^3p + \frac{g_\omega^2}{2m_\omega^2}\rho_B^2 + \frac{1}{2}m_\sigma^2\bar{\sigma}^2 + \frac{1}{3}b\bar{\sigma}^3 + \frac{1}{4}c\bar{\sigma}^4, \quad (23)$$

where $\gamma_N = 4$ is degeneracy of nucleon, K_F^N is Fermi energy of nucleon, and ρ_B is the density of nuclear matter

$$\rho_B = \frac{\gamma_N}{(2\pi)^3}\int_0^{K_F^N} d^3k. \quad (24)$$

In Eq. (23), g_ω is the coupling constant between the nucleon and the ω meson and it satisfies $g_\omega = 3g_\omega^q$. As that of the QMC model [8–12], the $\bar{\sigma}$ is yielded by the equation

$$m_\sigma^2\bar{\sigma} + b\bar{\sigma}^2 + c\bar{\sigma}^3 = -\frac{\gamma_N}{(2\pi)^3}\int_0^{K_F^N}\frac{M_N^*}{\sqrt{M_N^{*2}+p^2}}d^3p\left(\frac{\partial M_N^*}{\partial\bar{\sigma}}\right)_R. \quad (25)$$

Equations (13)–(25) form a complete set of equations and we can solve them numerically. Our numerical results will be shown in the next section.

III. NUMERICAL RESULTS

Before numerical calculation, let us consider the parameters of this model first. As that of Refs. [1,36], the masses of ω-meson and σ-meson are fixed as $m_\omega = 783$ MeV, $m_\sigma = 509$ MeV, respectively. We choose the bag constant $B = 174$ MeV fm^{-3} to fit the mass of nucleon $M_N = 939$ MeV. When B is determined, the parameters b and c are not independent because of Eq. (11). we choose b as the free parameter. There are still three parameters, namely, g_ω^q, g_σ^q, b are needed to be fixed in this model.

To study the physical properties of nuclear matter, we investigate the nuclear saturation, the equation of state and the compressibility. The pressure of nuclear matter P is given by

$$P = \rho_B^2 \frac{\partial}{\partial\rho_B}\frac{\varepsilon_{\text{matter}}}{\rho_B}, \quad (26)$$

where ρ_B is the baryon density in the nuclear matter. The compressibility for nuclear matter reads

$$K = 9\frac{\partial}{\partial\rho_B}P \quad (27)$$

at saturation point, the binding energy per particle $E/A = -15$ MeV, and the saturation density $\rho_0 = 0.15$ fm^{-3}.

Our numerical results are shown in Figs. 1–4. In Fig. 1, we choose ω-meson and σ-meson satisfy $\bar{\sigma} = 0$, $\bar{\omega} = 0$ and depict the bag energy as a function of bag radius at zero temperature. We find the stable radius of a "free" nucleon $R = 0.85$ fm.

In Figs. 2–4 we show the effective mass $M^\star$ of nucleon, the saturation curve and the equations of state of nuclear matter at zero temperature for the IQMDD model, respectively, where we fix the parameter $b = -1460$ (MeV), $g_\sigma = 4.67$, and $g_\omega = 2.44$, respectively. We find $E/A = -15$ MeV and

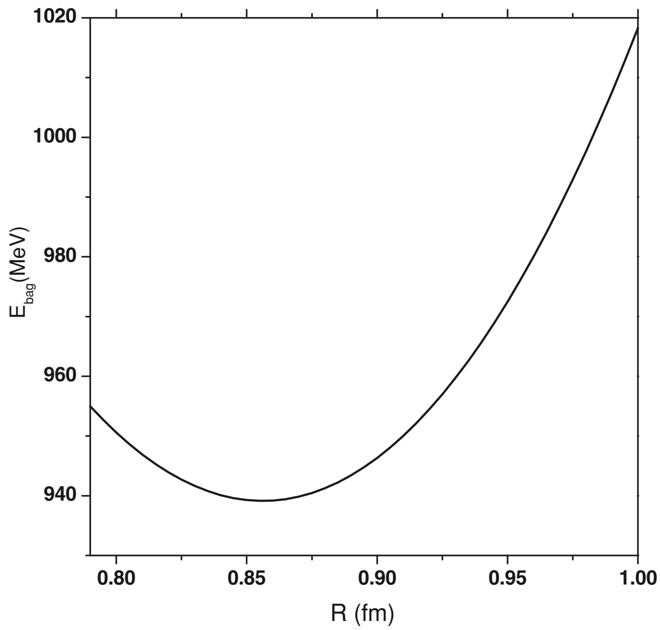

FIG. 1. The bag energy as a function of bag radius at zero temperature for $\bar{\omega} = 0, \bar{\sigma} = 0$.

$\rho_0 = 0.15$ fm^{-3} and $K(\rho_0) = 210$ MeV. Our model can explain the properties of nuclear matter successfully.

To illustrate our results more transparently, we show the dependence of the properties of nuclear matter on the parameters $b, g_\sigma^q, g_\omega^q$ in Table I for fixing binding energy $E/A = -15$ MeV and $\rho_0 = 0.15$ fm^{-3}. We find that the compressibility $K(\rho_0)$ and effective nucleon mass $M_N^*(\rho_0)$ at saturation point all decrease when g_σ^q, g_ω^q increase and b decreases. At was shown in Table I, the variational regions for

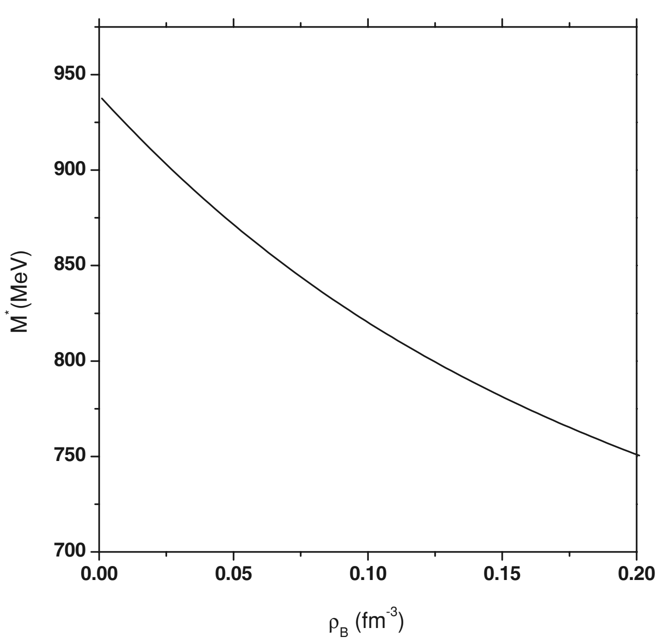

FIG. 2. Effective nucleon mass vs. baryon density at zero temperature where the parameters $g_\sigma^q = 4.67, g_\omega^q = 2.44, b = -1460$ (MeV).

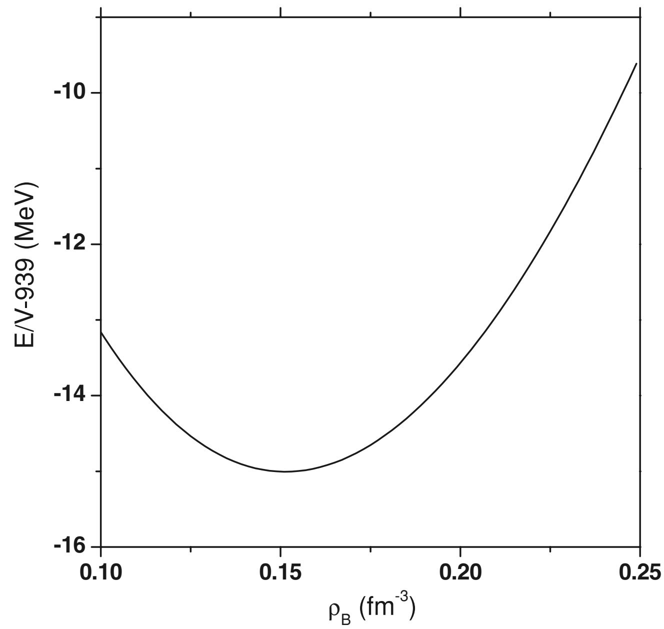

FIG. 3. Saturation curve of nuclear matter at zero temperature. The parameters are same as those of Fig. 2.

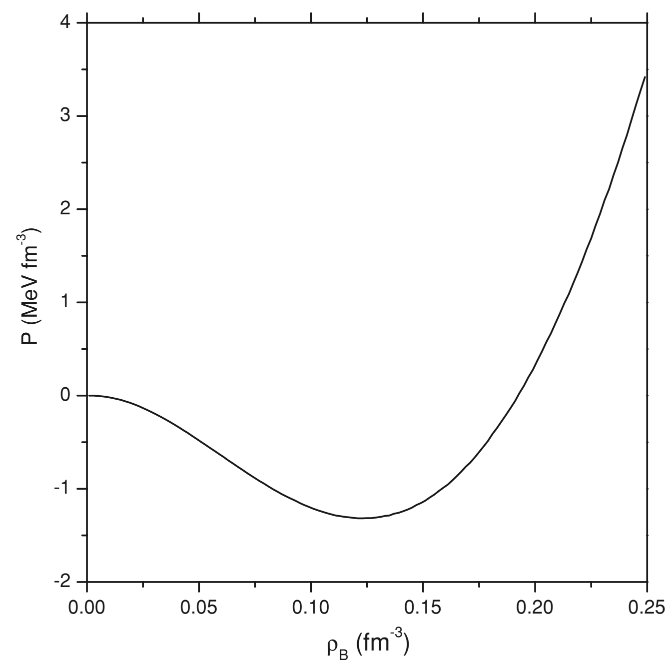

FIG. 4. Pressure of nuclear matter as a function of ρ_B. The parameters are same as those of Fig. 2.

TABLE I. Variation of the nuclear matter properties to b.

b(MeV)	g_σ^q	g_ω^q	$K(\rho_0)$(MeV)	$M_N^*(\rho_0)$(MeV)
−800	4.59	2.35	218.8	782.9
−1000	4.61	2.38	215.5	781.2
−1200	4.64	2.40	213.6	778.5
−1400	4.66	2.43	211.2	776.8
−1600	4.69	2.46	208.1	774.3
−1800	4.71	2.48	205.7	772.6

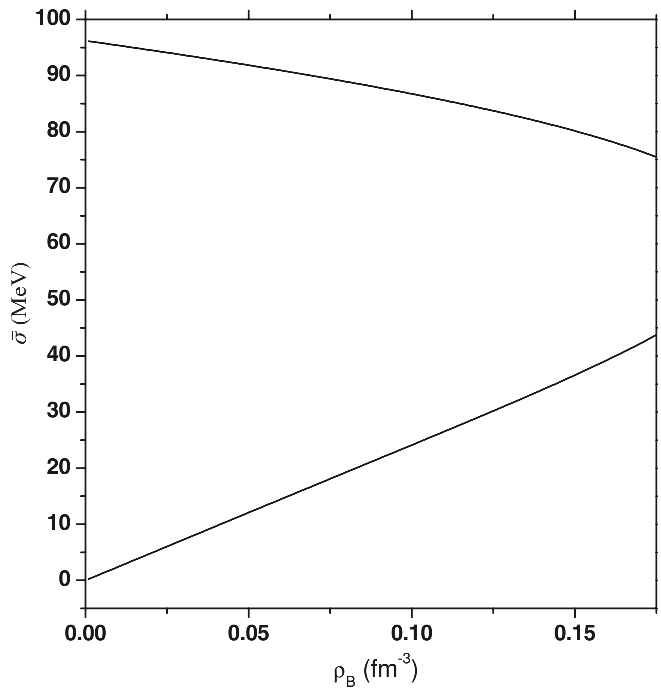

FIG. 5. The $\bar{\sigma}$ field vs. baryon density for $b = -3655$ (MeV), $g_\sigma^q = 5.23$, $g_\omega^q = 3.12$.

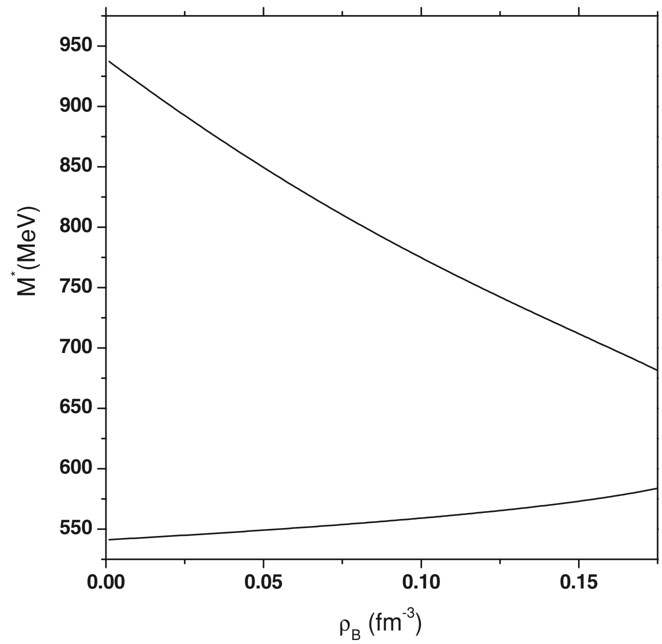

FIG. 6. Effective nucleon mass $M^\star$ vs. baryon density. The parameters are same as those of Fig. 5.

$K(\rho_0)$ and $M_N^*(\rho_0)$ are small, and $K(\rho_0)$ and $M_N^*(\rho_0)$ decrease slowly.

It was pointed out in Ref. [32] early, adding a nonlinear scalar field in the model will cause unphysical behavior under mean field approximation in nuclear matter. This can easily be seen from Eq. (25) because the left hand side of Eq. (25) is a cubic order function of $\bar{\sigma}$, and $\bar{\sigma} = 0$ is one of its solutions. There are two solutions in low-density regions. In Figs. 5 and 6, these two solutions are shown explicitly for $\bar{\sigma}$ vs. ρ_B curve and for $M_N^\star$ vs. ρ_B curve, respectively, where the parameters are fixed as $b = -3655$ (MeV). Noting that the term of the nonlinear scalar field is essential to form a soliton bag, we conclude that the unphysical branch cannot be avoided for the soliton solutions under mean field approximation. Fortunately, the lower branch cannot be ended at the point ($M_N = 939$ MeV, $\rho_B = 0$). It is instable because for this branch its second derivative of the potential is negative at $\rho_B = 0$. It cannot give us experimental value of nucleon mass and is unstable. We will give up this unphysical branch in our calculation.

Finally, it is of interest to compare the properties of nuclear matter for IQMDD model and for the QMC model. Our results are shown in Table II, the data of nuclear matter properties for the QMC model are adopted from Ref. [32]. We find their results are very similar.

TABLE II. Comparison of properties for the IQMDD and QMC models.

	R (fm)	g_σ^q	g_ω^q	$K(\rho_0)$ (MeV)	$M_N^*(\rho_0)$ (MeV)
QMC	0.80	5.53	1.26	200	851
IQMDD ($b = 0$)	0.85	4.54	2.21	227	798
IQMDD ($b = -1460$)	0.85	4.67	2.44	210	775

From Table II, we find that although the effective mass of the nucleon at the saturation density given by the IQMDD model is smaller than that of the QMC model, it is still too large. A too large effective mass M^*/M will almost certainly correspond to a too small spin-orbit splitting in finite nuclei and in the hypernuclear system [33] because the mean fields are small. To overcome this difficulty, a tensor term which couples the antisymmetric spin current density $\bar{\psi}\sigma^{\mu\nu}\psi$ to the field strength of the vector meson field $F^{\mu\nu}$ must be added to the Lagrangian (8) [34,35]. We leave this study for the future.

IV. SUMMARY AND DISCUSSION

In summary, we present an IQMDD model which has the nonlinear σ meson field and ω meson field. The quark and σ-meson coupling and the quark and ω-meson coupling are introduced to mimic the attractive and the repulsive interactions between quarks in this model. Compared with our previous model [24,25], a new ω-meson field and a new $g_\omega\bar{\psi}\gamma^\mu\omega_\mu\psi$ coupling are presented. It is shown that the present model is successful for describing the saturation properties, the equation of state and compressibility of nuclear matter.

Our IQMDD model is similar to that of QMC model. The basic important advantage is that we drop out the MIT boundary constraint and extend the interaction between quark and meson to the whole space. Instead of the MIT bag in QMC model, a FL soliton bag is introduced in IQMDD model. In principle, we can discuss the quark deconfinement phase transition by using this model.

Although we can write down the free propagators of the quark, σ-meson, and ω-meson in the whole space directly and calculate the contributions of corresponding Feynman diagrams, we have still employed MFA in this paper. The reason is that it is enough for studying the saturation properties and the equation of state of nuclear matter. If we want to do a many-body calculation beyond MFA, for example, RPA, polarization, quark scattering, etc., the advantage of the IQMDD model is obvious. Perhaps the IQMDD model is a good candidate to replace the QMC model.

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