Modified quark-meson coupling model for nuclear matter

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(Received 15 April 1996)

The quark-meson coupling model for nuclear matter, which describes nuclear matter as nonoverlapping MIT bags bound by the self-consistent exchange of scalar and vector mesons, is modified by introducing medium modification of the bag constant. We model the density dependence of the bag constant in two different ways: One invokes a direct coupling of the bag constant to the scalar meson field, and the other relates the bag constant to the in-medium nucleon mass. Both models feature a decreasing bag constant with increasing density. We find that when the bag constant is significantly reduced in nuclear medium with respect to its free-space value, large canceling isoscalar Lorentz scalar and vector potentials for the nucleon in nuclear matter emerge naturally. Such potentials are comparable to those suggested by relativistic nuclear phenomenology and finite-density QCD sum rules. This suggests that the reduction of bag constant in nuclear medium may play an important role in low- and medium-energy nuclear physics. [S0556-2813(96)02009-2]

PACS number(s): 24.85.+p, 21.65.+f, 12.39.Ba, 12.38.Lg

I. INTRODUCTION

Ultimately, the physics of nuclear matter and finite nuclei is an exercise in applied quantum chromodynamics (QCD), which governs the underlying strong interactions of quarks and gluons. In reality, however, knowledge of QCD has had very little impact, to date, on the study of low- and medium-energy nuclear phenomena. The reason is that QCD is intractable at the nuclear physics energy scales due to the nonperturbative features of QCD. A reasonable consensus is that the relevant degrees of freedom for low-energy QCD are hadrons instead of quarks and gluons.

While the description of nuclear phenomena has been efficiently formulated using the hadronic degrees of freedom, new challenges arise from the observed small but interesting corrections to the standard hadronic picture such as the EMC effect which reveals the medium modification of the internal structure of nucleon [1]. To address these new challenges, it is necessary to build theories that incorporate quark-gluon degrees of freedom, yet respect the established theories based on hadronic degrees of freedom.

A few years ago, Guichon [2] proposed a quark-meson coupling (QMC) model to investigate the direct ''quark effects'' in nuclei. This model describes nuclear matter as nonoverlapping MIT bags interacting through the self-consistent exchange of mesons in the mean-field approximation. This simple model was refined later by including nucleon Fermi motion and the center-of-mass corrections to the bag energy [3] and applied to variety of problems [4–7]. Recently, the QMC model has been applied to finite nuclei [8,9]. (There have been several works that also discuss the quark effects in nuclei, based on other effective models for the nucleon [10].)

Although it provides a simple and attractive framework to incorporate the quark structure of the nucleon in the study of nuclear phenomena, the QMC model has a serious shortcoming. It predicts much smaller scalar and vector potentials for the nucleon than obtained in relativistic nuclear phenomenology. Unless there is a large isoscalar anomalous coupling (ruled out by other considerations) this implies a much smaller nucleon spin-orbit force in finite nuclei. To lowest order in the nucleon velocity and potential depth the nucleon spin-orbit potential can be obtained in a model-independent way from the strengths of the scalar and vector potentials. The spin-orbit potential from the QMC model is too weak to successfully explain spin-orbit splittings in finite nuclei and the spin observables in nucleon-nucleus scattering.

Relativistic nuclear phenomenology is a general approach based on nucleons and mesons and has gained tremendous credibility during last 20 years. In this framework, the nucleons in a nuclear environment are treated as pointlike Dirac particles interacting with large canceling isoscalar Lorentz scalar and vector potentials. This approach has been successful in describing the spin observables of nucleon-nucleus scattering in the context of relativistic optical potentials [11,12]. Moreover, such potentials can be derived from the relativistic impulse approximation [12]. The relativistic field-theoretical models based on nucleons and mesons, quantum hydrodynamics (QHD), also feature Dirac nucleons interacting through the exchange of scalar and vector mesons [13]. QHD, at the mean-field level, has proved to be a powerful tool for describing the bulk properties of nuclear matter and spin-orbit splittings of finite nuclei [13]. It is known that the large and canceling scalar and vector potentials are central to the success of the relativistic nuclear phenomenology. Recent progress in understanding the origin of these large potentials for propagating nucleons in nuclear matter has been made via the analysis of the finite-density QCD sum rules [14].

In a recent paper [15], the present authors have pointed out that the resulting small nucleon potentials in the QMC model stem from the assumption of fixing the bag constant at its free-space value, and that this assumption is questionable. We then included a density-dependent bag constant and found that when the bag constant drops significantly in nuclear matter relative to its free-space value, the large po-

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tentials for nucleons in nuclear matter, as seen in the relativistic nuclear phenomenology and finite-density-QCD sum rules, can be recovered. This suggests that the reduction of the bag constant in nuclear matter relative to its free-space value may be essential for the successes of relativistic nuclear phenomenology and thus may play an important role in low- and medium-energy nuclear physics. In the present paper, we present further details and model the density dependence of the bag constant in two different ways: One invokes a direct coupling of the bag constant to the scalar meson field, and the other relates the bag constant to the in-medium nucleon mass.

This paper is organized as follows: In Sec. II we sketch the QMC model for nuclear matter. We then modify the QMC model by introducing a density-dependent bag constant in nuclear matter in Sec. III. The results are presented in Sec. IV. Further discussions are given in Sec. V. Section VI is a summary.

II. QUARK-MESON COUPLING MODEL FOR NUCLEAR MATTER

In this section, we give a brief introduction to the quark-meson coupling model for nuclear matter. The reader is referred to Refs. [2–5] for further details and justifications for using a simple bag model for the in-medium nucleon.

In the QMC model, the nucleon in nuclear medium is assumed to be a static spherical MIT bag in which quarks interact with the scalar and vector fields $\overline{\sigma}$ and $\overline{\omega}$ and these fields are treated as classical fields in the mean-field approximation. (Here we only consider up and down quarks.) The quark field $\psi_q(t,\mathbf{r})$ inside the bag then satisfies the equation of motion

$$[i\partial\!\!\!/ - (m_q^0 - g_\sigma^q \overline{\sigma}) - g_\omega^q \overline{\omega}\gamma^0]\psi_q(t,\mathbf{r}) = 0, \tag{2.1}$$

where m_q^0 is the current quark mass and g_σ^q and g_ω^q denote the quark-meson coupling constants. We will neglect isospin breaking and take $m_q^0 = (m_u^0 + m_d^0)/2$ hereafter. The normalized ground state for a quark in the bag is given by [2–4]

$$\psi_q(t,\mathbf{r}) = \mathcal{N} e^{-i\epsilon_q t/R} \begin{pmatrix} j_0(xr/R) \\ i\beta_q \sigma\cdot\hat{r} j_1(xr/R) \end{pmatrix} \frac{\chi_q}{\sqrt{4\pi}}, \tag{2.2}$$

where

$$\epsilon_q = \Omega_q + g_\omega^q \overline{\omega} R, \quad \beta_q = \sqrt{\frac{\Omega_q - Rm_q^*}{\Omega_q + Rm_q^*}}, \tag{2.3}$$

$$\mathcal{N}^{-2} = 2R^3 j_0^2(x)[\Omega_q(\Omega_q - 1) + Rm_q^*/2]/x^2, \tag{2.4}$$

with $\Omega_q \equiv \sqrt{x^2 + (Rm_q^*)^2}$, $m_q^* = m_q^0 - g_\sigma^q \overline{\sigma}$, R the bag radius, and χ_q the quark spinor. The x value is determined by the boundary condition at the bag surface:

$$j_0(x) = \beta_q j_1(x). \tag{2.5}$$

The energy of a static bag consisting of three ground state quarks can be expressed as

$$E_{\rm bag} = 3\frac{\Omega_q}{R} - \frac{Z}{R} + \frac{4}{3}\pi R^3 B, \tag{2.6}$$

where Z is a parameter which accounts for zero-point motion and B is the bag constant. In the discussions to follow, we use R_0, B_0, and Z_0 to denote the corresponding bag parameters for the free nucleon. After the corrections of spurious center-of-mass motion in the bag, the effective mass of a nucleon bag at rest is taken to be [3,4]

$$M_N^* = \sqrt{E_{\rm bag}^2 - \langle p_{\rm c.m.}^2 \rangle}, \tag{2.7}$$

where $\langle p_{\rm c.m.}^2\rangle = \Sigma_q \langle p_q^2 \rangle$ and $\langle p_q^2\rangle$ is the expectation value of the quark momentum squared $(x/R)^2$.

The equilibrium condition for the bag is obtained by minimizing the effective mass M_N^* with respect to the bag radius:

$$\frac{\partial M_N^*}{\partial R} = 0. \tag{2.8}$$

In free space, one may fix M_N at its experimental value 939 MeV and use the equilibrium condition to determine the bag parameters. For several choices of bag radius, $R_0 = 0.6$, 0.8, and 1.0 fm, the results for $B_0^{1/4}$ and Z_0 are 188.1,157.5, and 136.3 MeV and 2.030,1.628, and 1.153, respectively.

The total energy per nucleon at finite density, ρ_N, including the Fermi motion of the nucleons, can be written as [4]

$$E_{\rm tot} = \frac{\gamma}{(2\pi)^3 \rho_N} \int^{k_F} d^3k \sqrt{M_N^{*2} + \mathbf{k}^2} + \frac{g_\omega^2}{2m_\omega^2}\rho_N + \frac{m_\sigma^2}{2\rho_N}\overline{\sigma}^2, \tag{2.9}$$

where γ is the spin-isospin degeneracy and $\gamma = 4$ for symmetric nuclear matter and $\gamma = 2$ for neutron matter.[1] Note that the mean field $\overline{\omega}$ created by uniformly distributed nucleons is determined by baryon number conservation to be [2–4]

$$\overline{\omega} = \frac{3 q_\omega^q \rho_N}{m_\omega^2} = \frac{g_\omega \rho_N}{m_\omega^2}, \tag{2.10}$$

where $g_\omega \equiv 3 g_\omega^q$. The scalar mean field is determined by the thermodynamic condition

$$\left(\frac{\partial E_{\rm tot}}{\partial \overline{\sigma}}\right)_{R,\rho_N} = 0. \tag{2.11}$$

If one *assumes*

$$B = B_0 \tag{2.12}$$

and $Z = Z_0$, Eq. (2.11) yields the self-consistency condition

[1]Here we only consider symmetric nuclear matter and neutron matter. The generalization to a general asymmetric nuclear matter is straightforward (see, for example, Ref. [4]).

$$\overline{\sigma}=\frac{g_\sigma}{m_\sigma^2}C(\overline{\sigma})\frac{\gamma}{(2\pi)^3}\int^{k_F}d^3k\frac{M_N^*}{\sqrt{M_N^{*2}+\mathbf{k}^2}}, \tag{2.13}$$

with

$$g_\sigma C(\overline{\sigma})=g_\sigma\frac{E_{\text{bag}}}{M_N^*}\left[\left(1-\frac{\Omega_q}{E_{\text{bag}}R}\right)S(\overline{\sigma})+\frac{m_q^*}{E_{\text{bag}}}\right], \tag{2.14}$$

where $g_\sigma\equiv 3g_\sigma^q$ and

$$S(\overline{\sigma})=\frac{\Omega_q/2+Rm_q^*(\Omega_q-1)}{\Omega_q(\Omega_q-1)+Rm_q^*/2}. \tag{2.15}$$

The two coupling constants g_σ and g_ω can be chosen to fit the nuclear matter binding energy at the saturation density. For a given density, Eqs. (2.5), (2.8), and (2.13) form a set of equations for calculating x, R, and $\overline{\sigma}$.

III. MODIFIED QUARK-MESON COUPLING MODEL

In this section, we modify the QMC model by introducing a density-dependent bag constant. We propose two models for the modification of the bag constant, featuring a decreasing bag constant with increasing nuclear matter density. In principle, the parameter Z may also be modified in the nuclear medium. However, it is unclear how Z changes with the density. Here we assume that the medium modification of Z is small at low and moderate densities and take[2] $Z=Z_0$.

A. Direct coupling model

The bag constant in the MIT bag model contributes $\sim 200-300$ MeV to the nucleon energy and provides the necessary pressure to confine the quarks. Thus, the bag constant is an inseparable ingredient of the bag picture of a nucleon. When a nucleon bag is put into the nuclear medium, the bag as a whole reacts to the environment. As a result, the bag constant may be modified. There is little doubt that at sufficiently high densities, the bag constant is eventually melted away and quarks and gluons become the appropriate degrees of freedom. Therefore, it is reasonable to believe that the bag constant is modified and decreases as density increases. This physics is obviously bypassed in the QMC model by the assumption of $B=B_0$.

To reflect this physics, we modify the QMC model by introducing a direct coupling between the bag constant and the scalar mean field:

$$\frac{B}{B_0}=\left[1-g_\sigma^B\frac{4}{\delta}\frac{\overline{\sigma}}{M_N}\right]^\delta, \tag{3.1}$$

where g_σ^B and δ are real positive parameters and the introduction of M_N is based on the consideration of dimension. (The case $\delta=1$ was also considered by Blunden and Miller [9].) Note that g_σ^B differs from g_σ^q (or g_σ). When $g_\sigma^B=0$, the usual QMC model is recovered.

This direct coupling can be partially motivated from considering a nontopological soliton model for the nucleon where a scalar soliton field provides the confinement of the quarks. Roughly speaking, the bag constant in the MIT bag model mimics the effect of the scalar soliton field in the soliton model. Now, when a nucleon soliton is put into nuclear environment, the scalar soliton field will interact with the scalar mean field (see, for example, Refs. [16,10]). Therefore, it is reasonable to couple the bag constant directly to the scalar mean field.

The factor $C(\overline{\sigma})$ of Eq. (2.14), appearing in the self-consistency condition (2.13), then becomes

$$g_\sigma C(\overline{\sigma})=g_\sigma\frac{E_{\text{bag}}}{M_N^*}\left[\left(1-\frac{\Omega_q}{E_{\text{bag}}R}\right)S(\overline{\sigma})+\frac{m_q^*}{E_{\text{bag}}}\right]$$
$$+g_\sigma^B\frac{E_{\text{bag}}16}{M_N^*\,3}\pi R^3\frac{B}{M_N}\left[1-\frac{4}{\delta}\frac{g_\sigma^B\overline{\sigma}}{M_N}\right]^{-1}. \tag{3.2}$$

The other equations are not affected. In the limit of $\delta\to\infty$, Eq. (3.1) reduces to an exponential form with a single parameter g_σ^B:

$$\frac{B}{B_0}=e^{-4g_\sigma^B\overline{\sigma}/M_N}. \tag{3.3}$$

In the limit of zero current quark mass (i.e., $m_q^0=0$) and $g_\sigma=0$, the nucleon mass scales like $B^{1/4}$ from dimensional arguments (see also the Appendix). Then from Eq. (3.1) we get

$$M_N^*/M_N=(B/B_0)^{1/4}=\left[1-g_\sigma^B\frac{4}{\delta}\frac{\sigma}{M_N}\right]^{\delta/4}. \tag{3.4}$$

We observe that the linear σ-nucleon coupling is just g_σ^B while δ controls the nonlinearities. For $\delta=4$, the nonlinearities vanish and, as discussed in the next section, we recover QHD-I but with a density-dependent bag radius.

B. Scaling model

In the previous paper [15], we have considered a scaling model, which relates the in-medium bag constant to the in-medium nucleon mass directly:

$$\frac{B}{B_0}=\left[\frac{M_N^*}{M_N}\right]^\kappa, \tag{3.5}$$

where κ is a real positive parameter and $\kappa=0$ corresponds to the usual QMC model. The factor $C(\overline{\sigma})$, in this case, is given by

$$g_\sigma C(\overline{\sigma})=g_\sigma\frac{E_{\text{bag}}}{M_N^*}\left[\left(1-\frac{\Omega_q}{E_{\text{bag}}R}\right)S(\overline{\sigma})+\frac{m_q^*}{E_{\text{bag}}}\right]$$
$$\times\left[1-\kappa\frac{E_{\text{bag}}}{M_N^{*2}}\frac{4}{3}\pi R^3 B\right]^{-1}. \tag{3.6}$$

[2]Recently, Blunden and Miller [9] have considered a density-dependent Z. However, it is found that for reasonable parameter ranges changing Z has little effect and tends to make the model worse.

TABLE I. Coupling constants and nuclear matter results as obtained from the direct coupling model. The free-space bag radius is fixed at $R_0=0.6$ fm. Here the nuclear matter compressibility K_V^{-1} is given in unit of MeV, r_m^* and r_m denote the quark root-mean-square radius in nuclear matter and in free space, respectively, and $U_v\equiv g_\omega\overline{\omega}$ is the vector mean field. The mass parameters are taken to be $m_q=0$, $m_\sigma=550$ MeV, and $m_\omega=783$ MeV.

g_σ^q	δ	$(g_\sigma^B)^2/4\pi$	$g_\omega^2/4\pi$	M_N^*/M_N	U_v/M_N	K_V^{-1}	B/B_0	x/x_0	R/R_0	r_m^*/r_m
0	4	8.45	12.84	0.55	0.37	540	0.09	1.0	1.83	1.83
	8	5.68	6.46	0.75	0.18	313	0.31	1.0	1.34	1.34
	12	5.40	5.68	0.77	0.16	295	0.35	1.0	1.30	1.30
	13	5.28	5.57	0.77	0.16	293	0.36	1.0	1.29	1.29
	∞	4.95	4.62	0.80	0.13	270	0.41	1.0	1.25	1.25
1.0	4	5.69	10.84	0.61	0.32	490	0.19	0.97	1.51	1.52
	8	4.20	6.78	0.74	0.19	333	0.36	0.97	1.28	1.29
	12	3.96	6.14	0.76	0.18	315	0.39	0.97	1.25	1.26
	∞	3.69	5.24	0.78	0.15	289	0.45	0.98	1.22	1.22
2.0	3.6	3.16	8.03	0.70	0.23	431	0.36	0.93	1.27	1.29
	4	2.99	7.42	0.72	0.21	398	0.39	0.94	1.25	1.27
	8	2.54	5.81	0.77	0.17	336	0.48	0.95	1.18	1.20
	12	2.43	5.48	0.76	0.16	324	0.50	0.95	1.17	1.19
	∞	2.30	4.96	0.79	0.14	305	0.54	0.95	1.15	1.17
5.309	−−	0.0	1.56	0.89	0.04	223	1.0	0.93	0.98	1.0

Note that in this model the effective nucleon mass M_N^* and the bag constant B are determined self-consistently by combining Eqs. (2.6), (2.7), and (3.5).

One notices that both Eqs. (3.1) and (3.5) give rise to a reduction of the bag constant in a nuclear medium relative to its free-space value. While the scaling model is characterized by a single free parameter κ, it leads to a complicated and implicit relation between the bag constant and the scalar mean field. On the other hand, the direct coupling model features a straightforward coupling between the bag constant and the scalar mean field, which, however, introduces two free parameters, g_σ^B and δ.

IV. RESULTS

In this section, we present numerical results. The two models for the in-medium bag constant discussed in previous section will be considered. The current quark masses are taken to be $m_u=m_d=0$ for simplicity. Inclusion of small current quark masses only leads to numerically small refinement of present results.

Let us start from the direct coupling model. For a given value of g_σ^q, we adjust the coupling constants g_σ^B and g_ω to reproduce the nuclear matter binding energy (-16 MeV) at the saturation density ($\rho_N^0=0.17$ fm^{-3}). The resulting coupling constants and nuclear matter results are given in Table I for various δ values with $R_0=0.6$ fm. For the special case $g_\sigma^q=0$ and $\delta=4$, the present model leads to exactly the same nuclear matter results as obtained in QHD-I (see first row of Table I). This is also shown analytically in the Appendix.

The most important feature is that the reduction of B relative to B_0 leads to the decrease of M_N^*/M_N and the increase of U_v/M_N relative to their values in the simple QMC model. In the usual QMC model, the required vector coupling is very small. This, in Refs. [3,4], is attributed to the repulsion provided by the center-of-mass corrections to the bag energy. In our modified QMC model, the reduction of the bag constant in nuclear medium provides a new source of attraction as it effectively reduces M_N^*. Consequently, additional vector field strength is required to obtain the correct saturation properties of nuclear matter.

The above physics is clearly reflected in Table I. It can be seen from Table I that when the bag constant is reduced significantly in nuclear matter relative to its free-space value, the resulting magnitudes for $M_N^*-M_N$ and $U_v\equiv g_\omega\overline{\omega}$ are qualitatively different from those obtained in the simple QMC model. In particular, for δ = (13.0, 8.0, 3.6), corresponding to g_σ^q = (0, 1.0, 2.0), we get $B/B_0\simeq0.36$ and

$$M_N^*\simeq 660-720\ \text{MeV}, \tag{4.1}$$

$$U_v\simeq 150-215\ \text{MeV}, \tag{4.2}$$

at $\rho_N=\rho_N^0$. Since the equivalent scalar and vector potentials appearing in the wave equation for a pointlike nucleon are $M_N^*-M_N$ and U_v, respectively [8,9], Eqs. (4.1) and (4.2) imply large and canceling scalar and vector potentials for the nucleon in nuclear matter. Such potentials are comparable to those suggested by Dirac phenomenology [11,12], Brueckner calculations [12], and finite-density QCD sum rules [14], but smaller than those obtained in QHD-I [13]. These potentials also imply a strong nucleon spin-orbit potential. Therefore, the essential features of relativistic nuclear phenomenology are recovered. The corresponding results for the nuclear matter compressibility, K_V^{-1}, are slightly larger than the corresponding value in the usual QMC model, but significantly smaller than that in QHD-I. The resulting total energy per nucleon for symmetric nuclear matter is shown in Fig. 1.

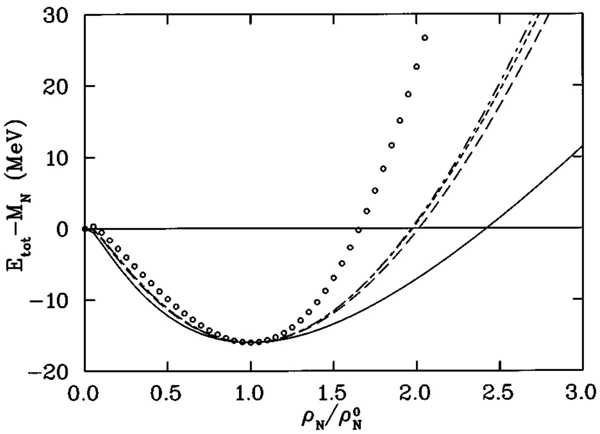

FIG. 1. Energy per nucleon for symmetric nuclear matter as a function of the medium density, with $R_0 = 0.6$ fm and $\delta = 8$. Here the direct coupling model Eq. (3.1) for the in-medium bag constant is used. The solid curve corresponds to the usual QMC model, and the result from QHD-I is given by the open circles. The other three curves correspond to $g_\sigma^q = 0$ (long-dashed curve), 1 (dot-dashed curve), and 2 (short-dashed curve), respectively.

In the usual QMC model, the bag radius decreases slightly and the quark root-mean-square (rms) radius increases slightly in nuclear matter with respect to their free-space values. When the bag constant drops relative to its free-space value, the bag pressure decreases and hence the bag radius increases in the medium. When the reduction of the bag constant is significant, the bag radius in saturated nuclear matter is 25–30 % larger than its free-space value. The quark rms radius also increases with density, with essentially the same rate as for the bag radius. This implies a ''swollen'' nucleon in nuclear medium, which has many attendant consequences [17–23]. It is also interesting to note that the result of the 25–30 % increase in the nucleon size is comparable to those suggested in Refs. [17–19] (see, however, Ref. [20]). In the special case, $g_\sigma = 0$ and $\delta = 4$, we find that the reduction of B in the nuclear matter is too large ($B/B_0 \sim 10\%$). This leads to unreasonably large values for the bag radius and the quark rms radius in nuclear matter.

The results corresponding to the limit of $\delta \rightarrow \infty$ [i.e., Eq. (3.3)] are also listed in Table I. These results are not far from those with finite δ values. As δ increases, the results will approach saturation. The last row of Table II gives the results obtained from fixing g_σ^q at its value predicted by the simple QMC model, 5.309 (for $R_0 = 0.6$ fm). In this case, it is found that for any given δ value the self-consistent solution requires $g_\sigma^B = 0$. When the coupling g_σ^q is tuned from zero to its corresponding value in the simple QMC model, the results interpolate between the QHD-I results and the usual QMC model results. If g_σ^q exceeds its value in the simple QMC model, the in-medium bag constant will increase instead of decrease relative to its free-space value, which is in contradiction with the physics discussed in the present paper.

For a fixed g_σ^q, the coupling constants g_σ^B and g_ω get smaller as δ gets larger. Recall that the reduction of B is controlled by both g_σ^B and δ. While B/B_0 and M_N^* increase, U_v, R/R_0, and K_V^{-1} decrease as δ increases. From Table I, one can see that for a given value of B/B_0, one finds smaller M_N^* and larger U_v with a larger value of g_σ^q. We also find that when δ gets too small, a self-consistent solution no longer exists.

For curiosity, we have also explored the results for negative δ values. One can see from Eq. (3.1) that negative δ values can also lead to a decreasing bag constant. In fact the physical quantities are continuous as $1/\delta$ goes through zero.

TABLE II. Coupling constants and nuclear matter results as obtained from the scaling model. The case of $\kappa = 0$ corresponds to the simple QMC model and the last row gives the result of QHD-I. Here the nuclear matter compressibility K_V^{-1} is given in unit of MeV, r_m^* and r_m denote the quark root-mean-square radius in nuclear matter and in free space, respectively, and $U_v \equiv g_\omega \overline{\omega}$ is the vector mean field. The mass parameters are the same as in Table I.

R_0 (fm)	κ	$g_\sigma^2/4\pi$	$g_\omega^2/4\pi$	M_N^*/M_N	U_v/M_N	K_V^{-1}	B/B_0	x/x_0	R/R_0	r_m^*/r_m
0.6	0	20.18	1.56	0.89	0.04	223	1.0	0.93	0.98	1.0
	1.0	11.90	2.27	0.87	0.06	258	0.87	0.93	1.02	1.03
	2.0	5.92	3.60	0.83	0.10	319	0.69	0.94	1.08	1.10
	2.95	2.24	7.78	0.71	0.22	590	0.36	0.94	1.27	1.29
	3.0	2.11	8.32	0.69	0.24	628	0.33	0.94	1.30	1.32
0.8	0	22.01	1.14	0.91	0.03	202	1.0	0.90	0.99	1.02
	1.0	12.78	1.76	0.89	0.05	235	0.89	0.91	1.02	1.04
	2.0	6.20	2.88	0.85	0.08	289	0.73	0.93	1.08	1.10
	3.0	2.06	6.39	0.75	0.18	479	0.42	0.93	1.24	1.26
	3.1	1.78	7.32	0.72	0.21	543	0.36	0.93	1.28	1.31
1.0	0	22.48	0.96	0.91	0.03	192	1.0	0.88	1.0	1.03
	1.0	12.94	1.54	0.89	0.04	225	0.89	0.89	1.03	1.05
	2.0	6.21	2.58	0.86	0.07	276	0.75	0.91	1.07	1.10
	3.0	2.01	5.68	0.77	0.16	432	0.46	0.92	1.21	1.24
	3.17	1.54	7.18	0.72	0.20	502	0.36	0.92	1.29	1.32
QHD-I	−−	8.45	12.84	0.55	0.37	540	−−	−−	−−	−−

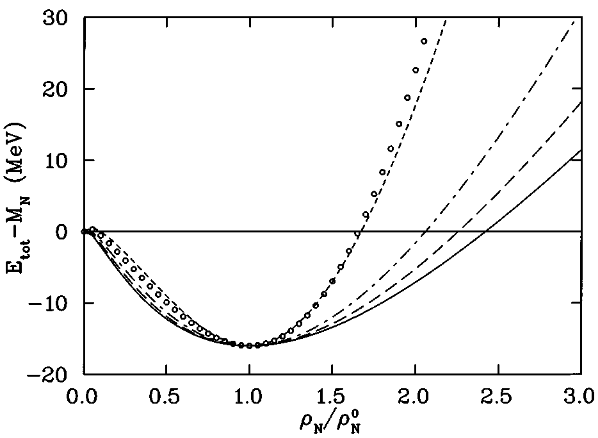

FIG. 2. Energy per nucleon for symmetric nuclear matter as a function of the medium density, with $R_0=0.6$ fm. Here the scaling model Eq. (3.5) for the in-medium bag constant is adopted. The four curves correspond to $\kappa=0$ (solid curve), 1 (long-dashed curve), 2 (dot-dashed curve), and 3 (short-dashed), respectively. The result from QHD-I is given by the open circles.

As $1/\delta$ decreases from zero (δ goes negative), the scalar and vector potentials continue the decrease seen in Table I. For $g_\sigma^q=0$ and $\delta\sim-1.0$, the resulting M_N^* and U_v are similar to those found in the usual QMC model. The compressibility is somewhat lower.

All of the above results use the direct coupling model; we now present the results for the scaling model. The two coupling constants g_σ and g_ω are adjusted to fit the binding energy of saturated nuclear matter. There is only one free parameter κ in this case. For various values of κ and free-space bag radius R_0, the resulting coupling constants and nuclear matter results are listed in Table II.

Again, the decrease of the bag constant gives rise to the decrease of M_N^*/M_N and the increase of U_v/M_N relative to their values in the simple QMC model. We see from Table II that M_N^* decreases and U_v increases rapidly as κ increases. For $\kappa=(2.95,3.10,3.17)$, corresponding to R_0 = (0.6, 0.8, 1.0 fm), we find $B/B_0\simeq 0.36$ at the saturation density. The corresponding results for M_N^* and U_v are

$$M_N^*\simeq 660-680 \text{ MeV}, \tag{4.3}$$

$$U_v\simeq 190-225 \text{ MeV}, \tag{4.4}$$

at $\rho_N=\rho_N^0$ which are similar to the direct coupling model results given in Eqs. (4.1) and (4.2), though the magnitudes for $M_N^*-M_N$ and U_v are slightly larger. These results are also consistent with those suggested by relativistic nuclear phenomenology and finite-density QCD sum rules.

One notices from Table II that the value of K_V^{-1} increases quickly when κ value is increased. This results from the increasing g_ω with increasing κ. For the κ values leading to Eqs. (4.3) and (4.4), the corresponding values for K_V^{-1} are comparable to that obtained in QHD-I, which is too large compared with the empirical value. This feature is also shown in Fig. 2, where the total energy per nucleon for symmetric nuclear matter is plotted as a function of nuclear matter density for various κ values, with $R_0=0.6$ fm. The result from QHD-I is also plotted for comparison. The equation of state for the nuclear matter is much softer in the simple QMC model than in QHD-I. As κ gets larger, the equation of state becomes stiffer.

Both the bag radius and the quark rms radius in nuclear matter are larger than their free-space values. As discussed above, this is due to the decrease of the bag constant in the nuclear medium. For the κ values yielding Eqs. (4.3) and (4.4), the corresponding bag radius and quark rms radius at $\rho_N=\rho_N^0$ are 25–30 % larger than their free-space value. This is essentially the same as that found in the direct coupling model (see Table I).

The sensitivity of our results to the free-space bag radius R_0 is also illustrated in Table II. For a given κ value, the ratios B/B_0 and M_N^*/M_N increase and the ratios R/R_0 and U_v/M_N decrease as R_0 increases. However, for the κ values considered here, the sensitivity of our results to R_0 is small. The sensitivity of the results from the direct coupling model to the choice of R_0 is also small and similar to that in the scaling model.

V. DISCUSSION

As stressed by Saito and Thomas [4], in the simple QMC model, all the effects of the internal quark structure of the nucleon are summarized in the factor $C(\overline{\sigma})$. If $C(\overline{\sigma})=1$ is a constant, one would get exactly the same nuclear matter results as in QHD-I. In the simple QMC model, $C(\overline{\sigma})$ is much smaller than unity, which leads to much larger M_N^* and much smaller U_v than those required in QHD-I.

In the present study, we introduce the medium modification for the bag constant. As shown in Eqs. (3.2) and (3.6), the effect of this modification is completely absorbed into the factor $C(\overline{\sigma})$. We observe that for various parameters considered here, both Eqs. (3.2) and (3.6) lead to an increase in $C(\overline{\sigma})$. This indicates that the reduction of the bag constant in nuclear matter partially offsets the effect due to the internal quark structure of the nucleon. It is thus not surprising to find that our modified quark-meson coupling model gives smaller M_N^* and larger U_v than those found in the simple QMC model.

To further illustrate this point, we have plotted $C(\overline{\sigma})$ in Fig. 3 as a function of $g_\sigma^q\overline{\sigma}$ for the usual QMC model and for our modified QMC model with the scaling model for the in-medium bag constant. We see that in the simple QMC model, $C(\overline{\sigma})$ is small and decreases as $g_\sigma^q\overline{\sigma}$ increases. The introduction of a dropping bag constant gives an increase in $C(\overline{\sigma})$. When the reduction of the bag constant is large, $C(\overline{\sigma})$ is approximately constant and significantly larger than 1 for small and moderate values of $g_\sigma^q\overline{\sigma}$; as $g_\sigma^q\overline{\sigma}$ increases, $C(\overline{\sigma})$ decreases quickly. [The self-consistent solution requires $g_\sigma^q\overline{\sigma}=$ (96, 82, 69, 58 MeV) at the saturation density, corresponding to $\kappa=$ (0, 1.0, 2.0, 3.0), respectively.] A similar plot can also be done with the direct coupling model, but $C(\overline{\sigma})$ in this case is a function of g_σ^q g_σ^B and $\overline{\sigma}$, instead of $g_\sigma^q\overline{\sigma}$ alone.

We observe that the extent to which the bag constant drops in a nuclear matter determines the physical outcome. Unless one expresses the bag constant in terms of QCD operators and solves QCD in nuclear matter, the change of the bag constant in a nuclear medium is unknown. As such, one

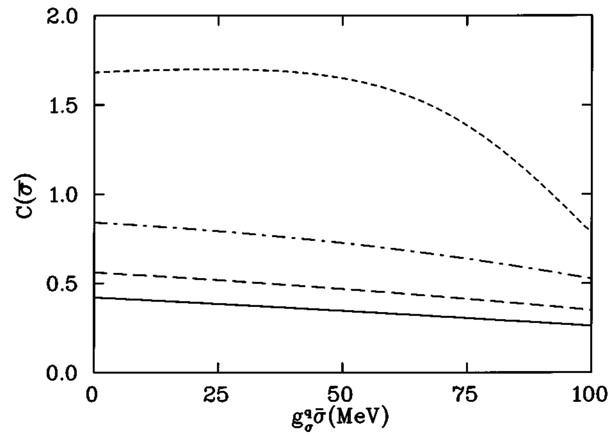

FIG. 3. The factor $C(\overline{\sigma})$ as a function of $g_\sigma^q\overline{\sigma}$, with $R_0=0.6$ fm. The solid curve is from the simple QMC model. The other three curves correspond to the scaling model, with $\kappa=1$ (long-dashed curve), 2 (dot-dashed curve), and 3 (short-dashed curve), respectively.

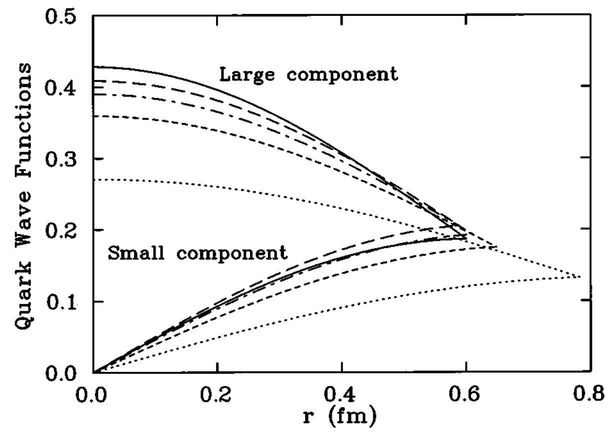

FIG. 4. Quark wave functions as functions of radial coordinate. Here the scaling model, Eq. (3.5), for the in-medium bag constant is adopted. The solid curves are the free-space quark wave functions. The other four set of curves correspond to, $\kappa=0$ (long-dashed curve), 1 (dot-dashed curve), 2 (short-dashed curve), and 3 (dotted curve), respectively.

has to invoke model descriptions in order to obtain a quantitative estimate for the reduction of the bag constant in nuclear matter.

In Ref. [24], Adami and Brown have argued that the MIT bag constant is related to the energy associated with chiral symmetry restoration (the vacuum energy difference between the chiral-symmetry-restored vacuum inside and the broken phase outside). According to the scaling ansatz advocated by Brown and Rho [25], the in-medium bag constant should scale like [24] $B/B_0\simeq\Phi^4$, where Φ denotes the universal scaling, $\Phi\simeq m_\rho^*/m_\rho\simeq f_\pi^*/f_\pi\cdots$, which is density dependent. Here, the ''starred'' quantities refer to the corresponding in-medium quantities. This scaling behavior is argued to hold approximately at the mean-field level [24–27]. Thus, one may get a rough estimate of the medium modification of the bag constant from the medium modifications of vector-meson masses which have been studied extensively [28–32]. Taking the result for m_ρ^*/m_ρ from the most recent finite-density QCD sum-rule analysis [29], we find $\Phi\simeq m_\rho^*/m_\rho\sim0.78$ at the saturation density, which gives rise to $B/B_0\simeq\Phi^4\sim0.36$. This shows a substantial reduction of the bag constant in nuclear matter relative to its free-space value. With this estimate, we obtain large and canceling scalar and vector potentials for the nucleon in nuclear matter, which are consistent with those suggested by relativistic nuclear phenomenology and finite-density QCD sum rules, though smaller than those found in QHD-I. This feature is seen in both models for the in-medium bag constant discussed here, implying a weak model dependence of our results.

However, some caveats concerning the above estimate must be added. The Brown-Rho scaling is an ansatz based on the idea of partial chiral symmetry restoration in a nuclear medium and the assumption that the scale anomaly of QCD could be modeled by a light dilaton field [25,24]. It is unclear whether this ansatz can be justified in QCD. Although it has been argued that many nuclear phenomena are connected to the partial chiral restoration in a nuclear medium [21–27,33,34], the only compelling evidence for partial chiral symmetry restoration in nuclear medium is that the magnitude of the chiral quark condensate, $\langle\overline{q}q\rangle$, is substantially reduced relative to its vacuum value [35–38]. Recently, Birse [39] has argued that the in-medium nucleon mass cannot be simply related to the change in the chiral quark condensate and there are other important contributions unrelated to partial chiral symmetry restoration. Moreover, it is known that both the MIT bag model and the QHD model are not compatible with chiral symmetry.

Clearly, how the bag constant changes in nuclear matter is an important topic for further study. The investigation of finite nuclei and nuclear structure functions in the present model may offer some independent information and/or constraints on the modification of the bag constant. Work along this direction is in progress [40]. Another direction may be in motivating an explicit functional form for the in-medium bag constant, $B(\overline{\sigma})$, from a solitonlike model for the nucleon. Recently, an explicit form for $B(\overline{\sigma})$ has been suggested in Ref. [16], based on the global color model of QCD.

The quark-meson coupling model for nuclear matter is valid only if the nucleon bags do not overlap significantly. In his original paper [2], Guichon has suggested $R_0=0.6$–0.7 fm in order to keep the overlapping effect small. In our modified QMC model, both the bag radius and the quark rms radius increase in medium relative to their values in free space due to the dropping bag constant in medium. In Fig. 4, the spatial quark wave functions are plotted as functions of radial coordinate with the scaling model for the in-medium bag constant. We see that when the bag constant drops the quark wave functions are pushed outward. This depicts a ''swollen'' nucleon picture, which has important implications in many nuclear physics issues [17–23].

On the other hand, the increasing bag radius also implies a larger overlapping effect than in the usual QMC model. When the bag constant in nuclear matter is significantly smaller than its free-space value ($B/B_0\sim0.4$), we find $R/R_0\sim1.25$–1.30 at the saturation density, which gives $4\pi R^3\rho_N^0/3\sim0.3$–$0.34$ when $R_0=0.6$ fm. This indicates that the overlap between the bags is still reasonably small at the saturation density, though a factor of 2 larger than in the usual QMC model. For larger R_0 and/or higher densities, the overlap becomes more significant and the nonoverlapping bag picture of nuclear matter may become inadequate. However, it is unclear at this stage whether the overlap between the bags is already included effectively in the reduction of the bag constant and/or in the scalar and vector mean fields. Further study is needed to clarify such an issue. We also note that in the scaling model with large κ values, the resulting nuclear matter compressibility is too large compared to the empirical value. This may be fixed by introducing self-interactions of the scalar field, which, however, will introduce more free parameters. The direct coupling model, on the other hand, produces a more reasonable value for nuclear matter compressibility.

The QMC model is probably the simplest extension of QHD to incorporate explicit quark degrees of freedom, where the exchanging mesons are treated as classical fields in the mean-field approximation. To be more consistent, the explicit quark structures of the mesons should also be included and the physics beyond the mean-field approximation should be considered. It has been emphasized above that both the MIT bag model and the QHD model are not chirally symmetric. As such, the quark-meson coupling models discussed here are not chiral models. At the hadron level, significant progress has been made in incorporating both chiral symmetry and broken scale invariance in relativistic hadronic models [41,42]. So the quark-meson coupling models may be extended by combining these hadronic chiral models and a chiral version of the bag model. Recently, it has also been argued that connections can be made between effective chiral Lagrangians and the QHD model at the mean-field level [43].

VI. SUMMARY

In this paper, we have modified the quark-meson coupling model by introducing medium modification of the bag constant. We proposed two models for the in-medium bag constant, the direct coupling model and scaling model. The former couples the bag constant directly to the scalar mean field, and the latter uses a scaling ansatz which relates the in-medium bag constant to in-medium nucleon mass. Both models feature a decreasing bag constant with increasing density.

The reduction of the bag constant in nuclear matter partially offsets the effect of the internal quark structure of the nucleon and effectively introduces a new source of attraction. This attraction needs to be compensated with additional vector field strength. The decrease of the bag constant also implies the increase of the bag radius in nuclear matter. This is consistent with the ‘‘swollen’’ nucleon picture discussed in the literature.

When the bag constant is reduced significantly in nuclear matter with respect to its free-space value, we find that our modified quark-meson coupling model predicts large and canceling scalar and vector potentials for the nucleon in nuclear matter, which is qualitatively different from the prediction of the simple QMC model. These potentials are consistent with those suggested by relativistic nuclear phenomenology and finite-density QCD sum rules. The internal quark structure of the nucleon seems to play only a relatively minor role. On the other hand, the reduction of the bag constant in a nuclear medium relative to its free-space value may play an important role in low- and medium-energy nuclear physics.

ACKNOWLEDGMENTS

This work was supported by the Natural Sciences and Engineering Research Council of Canada.

APPENDIX

In this appendix, we demonstrate that adopting Eq. (3.1) with $\delta = 4$ for the in-medium bag constant and taking $g_\sigma^q = 0$ (and $m_q^0 = 0$), one can reproduce the QHD-I results for nuclear matter. To this end, we show that the resulting expressions for the total energy per nucleon and the self-consistency condition for the scalar mean field are identical to those in QHD-I.

In free space, the nucleon mass and the equilibrium condition for the bag are given by

$$M_N = \sqrt{E_{\rm bag}^2 - 3x_0^2/R_0^2}, \tag{A1}$$

$$E_{\rm bag}\left[-3\frac{x_0}{R_0^2} + \frac{Z_0}{R_0^2} + 4\pi R_0^2 B_0\right] + 3\frac{x_0^2}{R_0^3} = 0, \tag{A2}$$

where

$$E_{\rm bag} = 3\frac{x_0}{R_0} - \frac{Z_0}{R_0} + \frac{4}{3}\pi R_0^3 B_0 . \tag{A3}$$

Solving these two equations, one finds that the combinations $B_0 R_0^4$ and $M_N R_0$ can be expressed in terms of x_0 and Z_0. This can also be seen easily from dimensional considerations. Since these two combinations are dimensionless, they must depend only on the dimensionless parameters x_0 and Z_0.

In the nuclear medium, the corresponding two equations become

$$M_N^* = \sqrt{E_{\rm bag}^2 - 3x^2/R^2}, \tag{A4}$$

$$E_{\rm bag}\left[-3\frac{x}{R^2} + \frac{Z}{R^2} + 4\pi R^2 B\right] + 3\frac{x^2}{R^3} = 0. \tag{A5}$$

Similarly, BR^4 and $M_N^* R$ are only dependent on x and Z. Since we take $g_\sigma^q = 0$ and $Z = Z_0$, x $(= x_0)$ and Z are independent of the nuclear matter density. One therefore concludes that

$$\frac{B}{B_0} = \left(\frac{M_N^*}{M_N}\right)^4 = \left(\frac{R_0}{R}\right)^4 . \tag{A6}$$

Using Eq. (3.1) with $\delta = 4$, one gets

$$\frac{M_N^*}{M_N} = 1 - \frac{g_\sigma^B \overline{\sigma}}{M_N}. \tag{A7}$$

One can then rewrite the total energy per nucleon at finite nuclear matter density as

$$E_{\rm tot}=\frac{\gamma}{(2\pi)^3\rho_N}\int^{k_F}d^3k\sqrt{M_N^{*2}+\mathbf{k}^2}+\frac{g_\omega^2}{2m_\omega^2}\rho_N+\frac{m_\sigma^2}{2\,(g_\sigma^B)^2\rho_N}(M_N-M_N^*)^2. \tag{A8}$$

The self-consistency condition for the scalar field, Eq. (2.13), can be expressed as

$$M_N^*=M_N-\frac{(g_\sigma^B)^2}{m_\sigma^2}\frac{\gamma}{(2\pi)^3}\int^{k_F}d^3k\frac{M_N^*}{\sqrt{M_N^{*2}+\mathbf{k}^2}}. \tag{A9}$$

These two equations are identical to those required in QHD-I. Thus, fitting the nuclear matter binding energy at the saturation density, one should find the same scalar and vector couplings and hence the same strengths for scalar and vector mean fields as obtained in QHD-I.

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