Change of MIT bag constant in nuclear medium and implication for the EMC effect

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The modified quark-meson coupling model, which features a density-dependent bag constant and bag radius in nuclear matter, is checked against the EMC effect within the framework of dynamical rescaling. Our emphasis is on the change in the average bag radius in nuclei, as evaluated in a local density approximation, and its implication for the rescaling parameter. We find that when the bag constant in nuclear matter is significantly reduced from its free-space value, the resulting rescaling parameter is in good agreement with that required to explain the observed depletion of the structure functions in the medium Bjorken x region. Such a large reduction of the bag constant also implies large and canceling Lorentz scalar and vector potentials for the nucleon in nuclear matter which are comparable to those suggested by the relativistic nuclear phenomenology and finite-density QCD sum rules. [S0556-2813(97)00903-5]

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While most nuclear models treat nucleons and mesons as the relevant degrees of freedom for describing low- and medium-energy nuclear physics, nuclear effects on nucleon structure functions, the EMC effect [1], reveal the distortion of internal structure of the nucleon by the nuclear medium [2]. To study this distortion, it is desirable to build models that incorporate the fundamental building blocks of the nucleon, quark and gluon degrees of freedom, yet respect the established theories based on hadronic degrees of freedom. Since the underlying theory of strong interactions, quantum chromodynamics (QCD), is intractable at the nuclear physics energy scales, such models are necessarily quite crude.

The quark-meson coupling (QMC) model, proposed by Guichon [3], provides a simple and attractive framework to incorporate the quark structure of the nucleon in the study of nuclear phenomena [3–9]. (There have been several works that also discuss the quark effects in nuclei, based on other effective models for the nucleon [10].) Recently, the present authors have modified the QMC model by allowing the MIT bag constant to depend on the local density or σ field [11–13]. This modification can lead to the recovery of relativistic nuclear phenomenology, in particular the large canceling isoscalar Lorentz scalar and vector potentials and hence the strong spin-orbit force for the nucleon in nuclear matter. However, comparison to relativistic nuclear phenomenology [14] and finite-density QCD sum rules [15] suggests a large reduction of the bag constant in nuclear matter.

In this paper, we examine the implications for the EMC effect of a large reduction of the bag constant in nuclear matter within the framework of dynamical rescaling [16–21] (see also [22–26]). The dynamical rescaling relies on having the effective confinement size of quarks and gluons in a nucleus greater than that in a free nucleon [21]. The crucial input is the rescaling parameter $\xi_A(Q^2)$ [Eq. (5)] which is determined by the extent to which the confinement size changes from a free nucleon to a bound nucleon. Decreasing the MIT bag constant in the nuclear medium, as implemented in the modified QMC model, implies a decrease of the bag pressure in nuclear environment. This leads to an increase of the bag radius in nuclei relative to its free-space value. Thus, the prediction of a change in the effective quark confinement size emerges naturally in the modified QMC model. This change yields a prediction for the rescaling parameter, which, in turn, gives rise to predictions for the EMC effect in the framework of dynamical rescaling.

We use a local density approximation to evaluate the average bag radius in a nucleus. This radius is then used to determine the rescaling parameter. We find that when the bag constant is significantly reduced in nuclear matter, e.g., $B/B_0 \sim 35-40\,\%$ at the nuclear matter saturation density, the predictions for the rescaling parameter are in good agreement with those required to explain the depletion of the structure function observed in a range of nuclei. Such a large reduction of the bag constant, as shown in previous works [11,12], also implies large and canceling Lorentz scalar and vector potentials for the nucleon in nuclear matter which are comparable to those suggested by the relativistic nuclear phenomenology and finite-density QCD sum rules. This indicates that the reduction of bag constant and hence the increase of confinement size in nuclei may play an important role in low- and medium-energy nuclear physics and the modified QMC model provides a useful framework to accommodate both the change of confinement size and the quark structure of the nucleon in describing nuclear phenomena. (The nuclear structure functions have been studied [7] within the simple QMC model (see also Ref. [27]) by using the techniques of Ref. [28].)

The modified QMC model has been discussed extensively in Refs. [11–13], where two models for the in-medium bag constant have been proposed. The direct coupling model [12] (model I) invokes a direct coupling of the bag constant to the scalar meson field

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

where g_σ^B and δ are real positive parameters and $\overline{\sigma}$ denotes

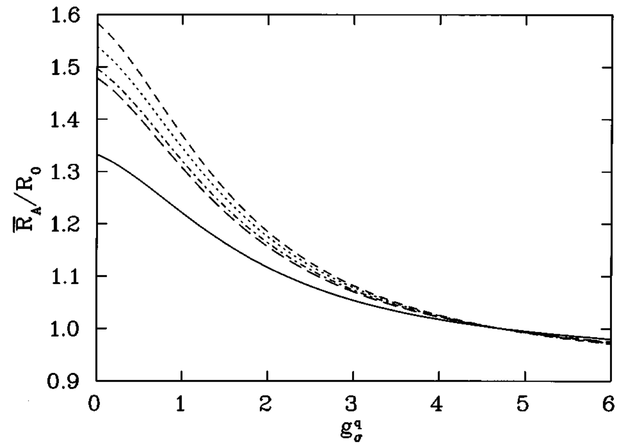

FIG. 1. Result for the ratio $\overline{R_A}/R_0$ as a function of g_σ^q, with $\delta=4$ and $R_0=0.8$ fm. Here model I Eq. (1) is adopted. The five curves correspond to $A=12$ (solid), 56 (long-dashed), 118 (dot-dashed), 197 (short-dashed), and 208 (dotted), respectively.

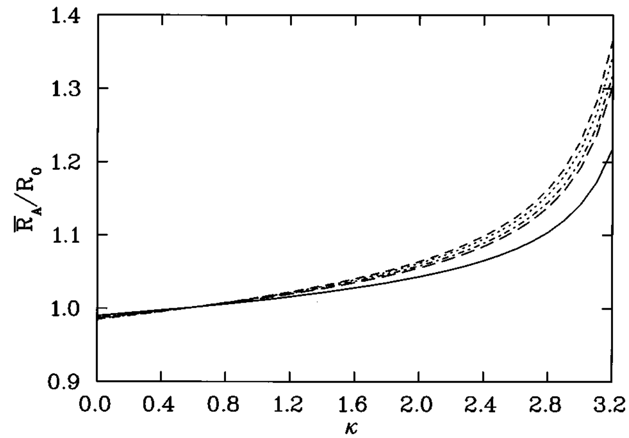

FIG. 2. Result for the ratio $\overline{R_A}/R_0$ as a function of κ, with $R_0=0.6$ fm. Here model II Eq. (2) is adopted. The five curves correspond to $A=12$ (solid), 56 (long-dashed), 118 (dot-dashed), 197 (short-dashed), and 208 (dotted), respectively.

the scalar mean field. The scaling model [11,12] (model II) relates the in-medium bag constant directly to the in-medium nucleon mass M_N^*

$$\frac{B}{B_0}=\left[\frac{M_N^*}{M_N}\right]^\kappa, \tag{2}$$

where κ is a real positive parameter. It has been found in Refs. [12,13] that if the reduction of the bag constant is significant (e.g., $B/B_0\sim 35-40$ %), the bag radius in saturated nuclear matter is $25-30$ % larger than its free-space value. This result is essentially determined by the value of B/B_0 at ρ_N^0.

With the density dependence of the bag radius obtained from the modified QMC model, we evaluate the average bag radius in a finite nucleus A in the local density approximation

$$\overline{R_A}\equiv\frac{\int d^3rR[\rho_A(r)]\rho_A(r)}{\int d^3r\rho_A(r)}, \tag{3}$$

where $\rho_A(r)$ is the density distribution of the nucleus A and $R[\rho_A(r)]$ denotes the bag radius at the density $\rho_A(r)$. Here we adopt the phenomenological fits in a form of the Woods-Saxon-type function for the density distribution $\rho_A(r)$ [29]

$$\rho_A(r)=\frac{\overline{\rho_A}}{1+\exp[(r-\mathcal{R}_A)/a]}. \tag{4}$$

Here the three parameters, $\overline{\rho_A}$, $\mathcal{R}_A$, and a, are used to fit shapes of nuclei. Their values for various nuclei can be found in Ref. [29].

Figure 1 shows the resulting ratio $\overline{R_A}/R_0$ from model I Eq. (1) as a function of g_σ^q for different nuclei, with $\delta=4$ and $R_0=0.6$ fm. Here g_σ^B and the quark-vector meson coupling g_ω^q are adjusted to fit the nuclear matter binding energy. The case $g_\sigma^q=0$ ($\delta=4$) corresponds to QHD I (but with density dependent bag radius) [12], and the case $g_\sigma^q\simeq 5.309$ gives the usual QMC model, where the bag constant is independent of density (i.e., $B/B_0=1$). When $g_\sigma^q>5.309$, the in-medium bag constant increases instead of decreases relative to B_0 (i.e., $B/B_0>1$). We also find that for a given g_σ^q, increasing δ leads to the decrease of $\overline{R_A}/R_0$, and for fixed g_σ and δ, the results are insensitive to the choice of R_0. The result from model II Eq. (2) is illustrated in Fig. 2, where the ratio $\overline{R_A}/R_0$ as a function of κ is plotted with $R_0=0.6$ fm. Here the quark-meson couplings g_σ^q and g_ω^q are chosen to reproduce the nuclear matter binding energy. The case $\kappa=0$ corresponds to the usual QMC model. The ratio $\overline{R_A}/R_0$ in this case has similar A dependence and sensitivity to R_0 as in model I.

We observe that the results for $\overline{R_A}/R_0$ are largely controlled by the change of the bag constant in nuclear medium with respect to its free-space value. To illustrate this point, we have listed the values of $\overline{R_A}/R_0$ for different nuclei in Table I, with the ratio B/B_0 fixed at $B/B_0=40\%$ (at $\rho_N=\rho_N^0$). One can see that the results are fairly model inde-

TABLE I. Predictions for the ratio $\overline{R_A}/R_0$, with B/B_0 fixed to $B/B_0=40\%$ (at $\rho_N=\rho_N^0$).

	$\overline{R_A}/R_0$ (Model I with $\delta=4$)			$\overline{R_A}/R_0$ (Model II)		
Nucleus	$R_0=0.6$	0.8	1.0 fm	$R_0=0.6$	0.8	1.0 fm
^{12}C	1.113	1.119	1.121	1.115	1.121	1.123
^{20}Ne	1.113	1.118	1.121	1.115	1.121	1.123
^{27}Al	1.137	1.143	1.146	1.139	1.146	1.148
^{56}Fe	1.152	1.159	1.162	1.154	1.161	1.164
^{63}Cu	1.145	1.152	1.155	1.147	1.154	1.157
^{107}Ag	1.157	1.165	1.168	1.160	1.168	1.170
^{118}Sn	1.159	1.166	1.169	1.162	1.169	1.172
^{197}Au	1.179	1.188	1.191	1.182	1.190	1.194
^{208}Pb	1.170	1.178	1.181	1.173	1.181	1.184

TABLE II. Predictions for the rescaling parameter $\xi_A(Q^2)$ at $Q^2=20$ GeV^2. Here the values of $\overline{R_A}/R_0$ with $R_0=0.6$ fm listed in Table I have been used. The last column gives the results of Ref. [18].

Nucleus	$\xi(Q^2)$ (Model I)	$\xi(Q^2)$ (Model II)	$\xi(Q^2)$ (Ref. [18])
^{12}C	1.69	1.70	1.60
^{20}Ne	1.69	1.70	1.60
^{27}Al	1.88	1.89	1.89
^{56}Fe	2.00	2.02	2.02
^{63}Cu	1.95	1.96	2.02
^{107}Ag	2.04	2.07	2.17
^{118}Sn	2.06	2.09	2.24
^{197}Au	2.24	2.27	2.46
^{208}Pb	2.16	2.18	2.37

pendent and the sensitivity to R_0 is very small ($\sim 1\%$). When R_0 increases, the ratio $\overline{R_A}/R_0$ increases slightly, which can be compensated by tuning down the ratio B/B_0 slightly. We have also tested the sensitivity of model-I results to the δ value and found that the results are insensitive to δ. (In the limit of $\delta\to\infty$, B/B_0 at $\rho_N=\rho_N^0$ is always larger than 40% for positive g_σ^q value.)

We now turn to the calculation of the rescaling parameter, which can be related to the ratio of the quark confinement scale in the nucleus A and that in the nucleon [19]

$$\xi_A(Q^2)=[(\overline{R_A}/R_0)^2]^{\alpha_s(\mu^2)/\alpha_s(Q^2)}, \tag{5}$$

with $\alpha_s(\mu^2)/\alpha_s(Q^2)=\ln(Q^2/\Lambda_{\rm QCD}^2)/\ln(\mu^2/\Lambda_{\rm QCD}^2)$, where $\Lambda_{\rm QCD}$ is the QCD scale parameter. Here we follow Ref. [19] and take $\Lambda_{\rm QCD}=0.25$ GeV and $\mu^2=0.66$ GeV^2. In Eq. (5) we have identified $\overline{R_A}$ and R_0 as the quark confinement sizes in the nucleus A and in the free nucleon, respectively.

Feeding the ratio $\overline{R_A}/R_0$ obtained above into Eq. (5), one obtains the predictions of the modified QMC model for $\xi_A(Q^2)$. The resulting values at $Q^2=20$ GeV^2 are listed in Table II, where the values of $\overline{R_A}/R_0$ given in Table I (with $R_0=0.6$ fm) are used. The results of Ref. [18] are also given for comparison. One can see that the predictions for $\xi_A(Q^2)$ agree well with the results of Ref. [18]. (For larger R_0, very similar results can be obtained with slightly smaller values of B/B_0.) In particular, for iron the predicted $\xi_A\simeq 2$ and $\overline{R_A}/R_0\simeq 1.15$ are essentially identical to those required to explain the experimental data [18]. The A dependence of $\xi_A(Q^2)$ is somewhat weaker than that found in Ref. [18]. This, however, has only small impact on the predictions for the EMC effect as the Q^2 dependence of the structure function is only logarithmic in the context of perturbative QCD. Thus, when the bag constant drops significantly in nuclear matter, $B/B_0\simeq 35-40\,\%$, the predictions of the modified QMC model for the change of average bag radius in nuclei relative the bag radius of an isolated nucleon can lead to satisfying explanation of the EMC effect in the medium x region.

As pointed out in Refs. [11–13], a significant reduction of the bag constant also implies large potentials for the nucleon in nuclear matter. In particular, when $B/B_0\simeq 35-40\,\%$ at $\rho_N=\rho_N^0$, we find [30] $M_N^*/M_N\sim 0.72$ and $U_{\rm v}/M_N\sim 0.21$, where $U_{\rm v}\equiv 3g_\omega^q\overline{\omega}$ with $\overline{\omega}$ the vector mean field. Since the equivalent scalar and vector potentials appearing in the wave equation for a pointlike nucleon are essentially $M_N^*-M_N$ and $U_{\rm v}$ [8,9], these results show large and canceling scalar and vector potentials for the nucleon in nuclear matter, which are comparable to those suggested by the relativistic nuclear phenomenology [14] and finite-density QCD sum rules [15].

Such a large reduction of the bag constant is not entirely unexpected. If one adopts the scaling ansatz advocated by Brown and Rho [31], the in-medium bag constant scales like [32], $B/B_0\simeq\Phi^4$, where Φ denotes the universal scaling, $\Phi\simeq m_\rho^*/m_\rho\simeq\cdots$, which is density dependent. Here, the ''starred'' quantities refer to the corresponding in-medium quantities. Taking the result for m_ρ^*/m_ρ from the most recent finite-density QCD sum-rule analysis [33], one finds $\Phi\simeq m_\rho^*/m_\rho\sim 0.78$ at the saturation density, which gives rise to $B/B_0\simeq\Phi^4\sim 0.36$. (There are, however, some caveats concerning this estimate [12]). Moreover, a swelling nucleon in nuclear environment also has important implications for other nuclear physics issues [34–39]. In the modified QMC model, the nucleon swelling is also reflected in the outstretched quark wave functions (see Ref. [12]). This is supported by the studies of finite-density QCD sum rules [40] and other studies of the modification of internal structure of the composite nucleon [41].

While it is attributed to the overlapping effect between two nucleons in Refs. [16–20], the change of quark confinement scale in nuclei results from the dropping bag constant in nuclear medium in the modified QMC model. The fact that the two approaches give very similar predictions may imply that they describe similar physics. Our view is that the decrease of the bag constant in nuclear medium (through the coupling to the scalar mean field) and the resulting change of confinement size in nuclei effectively parameterize the physics of the nucleon overlapping effect and/or other more complicated nuclear dynamics.

Other effects such as nuclear binding and Fermi motion may also contribute to the EMC effect in the medium x regime. These effects should be applied in addition to the predictions of the dynamical rescaling if one is to fit the observed data [42]. However, dynamical rescaling may mimic binding effects in the conventional model [43] and the nuclear convolution models [44] and dynamical rescaling may provide alternative not different explanations of the EMC effect [20]. Finally, the QMC model is only a simple extension of QHD, where the exchanging mesons are treated as classical fields in the mean-field approximation. The explicit quark structures of the mesons should also be included and the physics beyond the mean-field approximation should be considered in a more consistent treatment. It is also known that both the MIT bag model and the QHD are not compatible with the chiral symmetry. To improve this situation, one may use a chiral version of the bag model and a relativistic hadronic model consistent with the chiral symmetry.

To conclude, the modified QMC model provides a useful framework for describing nuclear phenomena, in which the decrease of the bag constant in nuclear environment plays an important role. We have seen that the model gives consistent predictions for large nucleon potentials in nuclear matter and the EMC effect. We look forward to further vindication of this model in addressing other nuclear physics problems.

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