Magnetic moment of hyperons in nuclear matter by using quark-meson coupling models

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Abstract

We calculate the magnetic moments of hyperons in dense nuclear matter by using relativistic quark models. Hyperons are treated as MIT bags, and the interactions are considered to be mediated by the exchange of scalar and vector mesons which are approximated as mean fields. Model dependence is investigated by using the quark-meson coupling model and the modified quark-meson coupling model; in the former the bag constant is independent of density and in the latter it depends on density. Both models give us the magnitudes of the magnetic moments increasing with density for most octet baryons. But there is a considerable model dependence in the values of the magnetic moments in dense medium. The magnetic moments at the nuclear saturation density calculated by the quark meson coupling model are only a few percents larger than those in free space, but the magnetic moments from the modified quark meson coupling model increase more than 10% for most hyperons. The correlations between the bag radius of hyperons and the magnetic moments of hyperons in dense matter are discussed.

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I. INTRODUCTION

Deep inelastic muon-nucleus scattering in the European Muon Collaboration showed that the electromagnetic (EM) properties of the nucleon in nuclear medium could be different from those in free space \cite{1}. It was shown that the magnetic moment of the proton in $^{12}$C seemed enhanced by about 25\% compared to that in free space \cite{2}. Experiments were performed to explore various observables that could indicate medium effects on the EM properties of the nucleon, such as longitudinal response function, polarization transfer, induced polarization, and etc. A very recent experiment at JLab \cite{3} provides another positive indication of the medium modification of the EM form factors of the nucleon. On the theoretical side, several models that treat the nucleon as a composite system of quarks were proposed to calculate the in-medium EM form factors of the nucleon \cite{4, 5, 6, 7, 8, 9}. A cloudy bag model calculation \cite{4} predicted a substantial enhancement of the magnetic moment in the nuclear medium in the range 2–20\%. On the other hand, models such as light-front constituent quark model \cite{5}, quark-meson coupling model with pion cloud \cite{6}, Skyrme model \cite{7}, chiral quark soliton model \cite{8} and Nambu-Jona-Lasino model \cite{9} give less enhancement, up to 10\% at most.

Quasi-elastic electron-nucleus scattering was expected to provide possible indications for the in-medium modification of nucleon structure functions, and investigations along this line were performed. In Refs. \cite{10, 11}, the cross sections for quasi-elastic ($e, e'$) scattering were calculated with and without the in-medium EM form factors. But the results showed no clear indication of medium modification. Although much work has been done in both theory and experiment, the situation still remains controversial, especially for the magnetic moment.

In this work we calculate the magnetic moments of the octet baryons in nuclear matter with the quark-meson coupling (QMC) \cite{12} and the modified quark-meson coupling (MQMC) \cite{13} models. Based on the MIT bag model, these models provide a simple but robust tool for the description of baryon properties in free space and bulk properties of symmetric and asymmetric nuclear matter \cite{14} and neutron stars \cite{15, 16}. Saito and Thomas calculated the in-medium magnetic moment of the proton in symmetric matter with the QMC model \cite{17}. An interesting result in their work is the dependence of the magnetic moment on the bag radius. Three values of the bag radius, 0.6, 0.8 and 1.0 fm were adopted for the proton in free space. Changes in the values of the magnetic moments due to the
medium from those in free space are relatively small, but the changes depend considerably on the bag radius in free space. For instance, the magnetic moment in medium at the nuclear saturation density is only about 1% larger than that in free space if the bag radius is chosen as 0.6 fm, but if the bag radius is 1.0 fm the magnetic moment becomes about 7% larger.

We shall investigate the model dependence of the magnetic moments in medium by considering both the QMC and MQMC models. While the QMC model has the problem of yielding too small a spin-orbit interaction, the MQMC model with the density-dependent bag constant produces the magnitudes of $\sigma$ and $\omega$ meson fields similar to those obtained from the Dirac phenomenology and quantum hadrodynamics, which produce the right magnitudes of the spin-orbit interaction. The MQMC model is also able to reproduce the nuclear saturation properties better than the QMC model, which will be presented in Sec.IIA. A big difference between the bag properties obtained from QMC and MQMC is in the behavior of the bag radius in nuclear matter. In the QMC model, the bag radius decreases as density increases, but in the MQMC model the bag radius increases with density \[18\]. Since the magnetic moment depends on the bag radius, it is expected that the prediction of the magnetic moment from the MQMC model will differ from that obtained from the QMC model.

The magnetic moment of a hyperon in medium was experimentally studied only recently. The magnetic moment of a $\Lambda$ hyperon in a hypernucleus $^7\Lambda$Li has been measured at BNL \[19\]. The result is still preliminary with large errors. Further experiments are needed, for example, in J-PARC \[19\] to determine the in-medium EM properties of the hyperon. Thus it is timely to investigate the magnetic moment of hyperons in medium theoretically.

In Sec. II, basic ingredients of the models are presented. The magnetic moments of octet baryons are expressed in terms of the quark wave functions. Sec. III shows numerical results, and discussions on the model dependence and the correlation between the bag radius and the magnetic moments follow. Sec. IV summarizes the paper.
II. MODELS

A. QMC and MQMC models for nuclear matter

In the QMC model a nucleon in nuclear matter is described by a static MIT bag in which quarks couple to meson fields that are treated as mean fields. The quark field $\psi_q$ inside the bag satisfies the Dirac equation

$$[i\gamma \cdot \partial - (m_q - g^q_\sigma \sigma) - g^q_\omega \gamma^0 \omega_0] \psi_q = 0,$$

where $m_q$ ($q = u, d, s$) is the bare quark mass, $\sigma$ and $\omega_0$ are the mean fields of $\sigma$ and $\omega$ mesons, respectively, and $g^q_\sigma$ and $g^q_\omega$ are the quark-meson coupling constants. Here, we assume $m_u = m_d = 0$ and $m_s = 150$ MeV.

The ground state solution of the Dirac equation is given by

$$\psi_q(r, t) = N_q \exp(-i\epsilon_q t/R) \begin{pmatrix} j_0(x_q r/R) \\ i \beta_q \sigma \cdot \hat{r} j_1(x_q r/R) \end{pmatrix} \frac{\chi_q}{\sqrt{4\pi}},$$

with

$$N_q^{-2} = 2R^3 j_0^2(x_q)\Omega_q(\Omega_q - 1) + R m_q^*/2]/x_q^2,$$

$$\epsilon_q = \Omega_q + g^q_\sigma \omega_0 R,$$

$$\beta_q = \sqrt{\frac{\Omega_q - R m_q^*}{\Omega_q + R m_q^*}},$$

$$\Omega_q = \sqrt{x_q^2 + (R m_q^*)^2},$$

$$m_q^* = m_q - g^q_\sigma \sigma,$$

where $R$ is the bag radius, $j_0(x)$ and $j_1(x)$ the spherical Bessel functions, and $\chi_q$ the quark spinor. The value of $x_q$ is determined from the boundary condition on the bag surface;

$$j_0(x_q) = \beta_q j_1(x_q).$$

The energy of a baryon with ground state quarks is given by

$$E_B = \sum_q \frac{\Omega_q}{R_B} - \frac{Z_B}{R_B} + \frac{4\pi R_B^3}{3} B_B,$$

where $B_B$ is the bag constant, and $Z_B$ is a phenomenological constant introduced to take into account the zero-point motion of the baryon. We use the subscript ‘$B$’ to denote the
\[ m_B^* = \sqrt{E_B^2 - \sum_q \left( \frac{x_q}{R_B} \right)^2}. \] (10)

There are three bag parameters for each baryon, \( R_B, B_B \) and \( Z_B \). If one of them can be fixed, the other two can be determined to reproduce the mass \( m_B \) of a baryon \( B \) in free space at a bag radius \( R_B \), where \( \partial m_B / \partial R_B = 0 \). For nucleons in free space, we choose \( R_N \) as a free parameter assuming \( R_N = R_p = R_n \). In actual calculations, we consider a wide range of \( R_N, R_N = (0.6, 0.8, 1.0) \) fm. For hyperons, we assume the bag radius of hyperons to be the same as that of nucleons, \( R_Y = R_N \), which then allows us to fix \( B_Y \) and \( Z_Y \) in the prescribed manner. The bag constant \( B_B \) and \( Z_B \) for \( R_0 = 0.6 \) fm are taken from Ref. [20] and those for \( R_0 = 0.8 \) and 1.0 fm are listed in Table I.

| \( B \) | \( m_B \) (MeV) | \( B_B^{1/4} \) (MeV) | \( Z_B \) | \( B_B^{1/4} \) (MeV) | \( Z_B \) | \( B_B^{1/4} \) (MeV) | \( Z_B \) |
|-------|----------------|----------------|--------|----------------|--------|----------------|--------|
| \( N \) | 939.0          | 188.1          | 2.030  | 157.5          | 1.628  | 136.3          | 1.153  |
| \( \Lambda \) | 1115.6         | 197.6          | 1.926  | 164.9          | 1.454  | 142.0          | 0.896  |
| \( \Sigma^+ \) | 1189.4         | 202.7          | 1.829  | 168.8          | 1.300  | 145.1          | 0.682  |
| \( \Sigma^0 \) | 1192.0         | 202.9          | 1.826  | 168.9          | 1.295  | 145.2          | 0.674  |
| \( \Sigma^- \) | 1197.3         | 203.3          | 1.819  | 169.2          | 1.283  | 145.4          | 0.659  |
| \( \Xi^0 \) | 1314.7         | 207.6          | 1.775  | 172.6          | 1.215  | 147.9          | 0.558  |
| \( \Xi^- \) | 1321.3         | 207.9          | 1.765  | 172.9          | 1.200  | 148.1          | 0.538  |

**Table I:** Bag constants \( B_B \) and phenomenological constants \( Z_B \) for octet baryons to reproduce the free mass of each baryon for \( R_0 = 0.6, 0.8 \) and 1.0 fm.

species of a baryon. The effective mass of a baryon \( B \) in medium is given by

The coupling constants for up and down quarks with \( \sigma \) and \( \omega \) mesons can be determined from nuclear saturation properties by assuming \( g_u^\sigma = g_d^\sigma, g_u^\omega = g_d^\omega, \) and \( g_s = g_s^\sigma = 0 \). That is, \( g_u^\sigma \) and \( g_u^\omega \) can be determined to reproduce the binding energy per nucleon \( E/A = 16 \) MeV at the nuclear saturation density \( \rho_0 = 0.17 \text{ fm}^{-3} \).

In the QMC model, where the bag constant \( B_B \) is density-independent, the nucleon mass at the saturation density is predicted to be larger than the widely accepted range \( m_N^* = (0.7 - 0.8) m_N \) and the compression modulus \( K \) is obtained to be smaller than the
empirical values $K = (200 - 300) \text{ MeV}$. On the other hand, the MQMC model, having density-dependence in the bag constant with an additional parameter $g'_{\sigma} B$, can produce both the effective mass and the compression modulus in the reasonable ranges. The density dependent bag constant can be expressed as

$$B_B(\sigma) = B_B \exp \left( -4 \sum_{q=u,d} n_q g'_{\sigma} \sigma / m_B \right),$$

(11)

where $n_q$ is the number of $u$ and $d$ quarks in a baryon $B$ and $m_B$ is its free mass. The coupling constants for both the QMC and MQMC models and the resulting nuclear matter properties can be found in Table I of Ref. [21].

In the subsequent sections, we shall see that the in-medium bag radius $R_B(\rho)$ plays an important role. It is defined as the bag radius where

$$\frac{\partial m^*_B}{\partial R_B} \bigg|_{R_B=R_B(\rho)} = 0.$$  

(12)

It is known that there is a sharp contrast between the QMC and the MQMC models in the density-dependence of $R_N(\rho)$ [18]. $R_N(\rho)$ from QMC decreases just a little while that from MQMC increases by about $(10 \sim 20)\%$ at the saturation density [13]. We shall show in Sec.III there are correlations between the bag radius in medium $R_B(\rho)$ and the magnetic moments in medium $\mu_B(\rho)$.

B. Magnetic moment of baryons

The nucleon bags in both QMC and MQMC models become a simple MIT bag in free space. We thus briefly describe first the calculation of the magnetic moments of baryons by using the MIT bag model, whose detailed explanation can be found, for example, in Ref. [22].

The magnetic moment operator can be written as

$$\sum_i \hat{\mu}_i = \sum_i \frac{\hat{Q}_i}{2} \mathbf{r}_i \times \alpha,$$

(13)

where $\hat{Q}_i$ and $\mathbf{r}_i$ are the charge and the position operators of the $i$-th quark ($i = 1, 2, 3$) in the bag, and $\alpha = \gamma_0 \gamma$. The normalized SU(6) wave function of a spin-up proton is given as

$$|\Psi_p\rangle = \frac{1}{3\sqrt{2}} \{2u^\dagger(1)u^\dagger(2)d^\dagger(3) - uu^\dagger(1)u^\dagger(2)d^\dagger(3) - uu^\dagger(1)u^\dagger(2)d^\dagger(3)$$

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\[-u^\dagger(1)d^\dagger(2)u^\dagger(3) + 2u^\dagger(1)d^\dagger(2)u^\dagger(3) - u^\dagger(1)d^\dagger(2)u^\dagger(3)\]
\[-d^\dagger(1)u^\dagger(2)d^\dagger(3) - d^\dagger(1)u^\dagger(2)d^\dagger(3) + 2d^\dagger(1)u^\dagger(2)d^\dagger(3)\}, \tag{14} \]

where \(q^x(i)\) denotes a quark wave function given by Eq. (2) with its spin state \(x (=\uparrow \text{ or } \downarrow)\).

The magnetic moment of a proton then reads

\[
\mu_p = \langle \Psi_p | \sum_i \mu_i | \Psi_p \rangle = \frac{e}{2} \int d^3r \ u^\dagger(\mathbf{r} \times \mathbf{\alpha}) u^\dagger \\
\equiv \frac{e}{2} D_u e_z, \tag{15} \]

where \(e_z\) is the unit vector along the \(z\)-axis and the integral \(D_q\) is given by

\[
D_q = \frac{4}{3} N_q^2 \beta_q \left( \frac{R_B}{x_q} \right)^4 \int_0^{x_q} y^2 j_0(y) j_1(y) dy. \tag{16} \]

Wave functions for other baryons can be obtained by acting the SU(3) shift operators \(\hat{T}_\pm, \hat{U}_\pm\) successively to the proton wave function \(|p \uparrow\rangle\) as follows:

\[
|n \uparrow\rangle = \hat{T}_- |p \uparrow\rangle, \quad |\Sigma^+ \uparrow\rangle = \hat{U}_- |p \uparrow\rangle, \\
|\Sigma^0 \uparrow\rangle = \hat{T}_- |\Sigma^+ \uparrow\rangle, \quad |\Sigma^- \uparrow\rangle = \hat{T}_- |\Sigma^0 \uparrow\rangle, \\
|\Xi^- \uparrow\rangle = \hat{U}_- |\Sigma^- \uparrow\rangle, \quad |\Xi^0 \uparrow\rangle = \hat{T}_+ |\Xi^- \uparrow\rangle, \tag{17} \]

and \(|\Lambda \uparrow\rangle\) can be obtained by the orthonormality condition. Once the wave functions are obtained, the calculation of the matrix elements is straightforward. Applying the magnetic moment operator to the wave functions of octet baryons, we obtain

\[
\mu_p = \frac{e}{2} D_u, \\
\mu_n = -\frac{e}{3} D_u, \\
\mu_\Lambda = -\frac{e}{6} D_s, \\
\mu_{\Sigma^+} = \frac{e}{6} \left[ \frac{8}{3} D_u + \frac{1}{3} D_s \right], \\
\mu_{\Sigma^0} = \frac{e}{6} \left[ \frac{2}{3} D_u + \frac{1}{3} D_s \right], \\
\mu_{\Sigma^-} = \frac{e}{6} \left[ -\frac{4}{3} D_u + \frac{1}{3} D_s \right], \\
\mu_{\Xi^0} = -\frac{e}{3} \left[ \frac{1}{3} D_u + \frac{2}{3} D_s \right], \\
\mu_{\Xi^-} = \frac{e}{6} \left[ \frac{1}{3} D_u - \frac{4}{3} D_s \right]. \tag{18} \]
### TABLE II: The ratios $\mu_B/\mu_p$ for octet baryons in free space for three choices of $R_0$ values. The experimental values of the magnetic moments are taken from Ref. [24].

| $R_0$ (fm) | $p$ | $n$ | $\Lambda$ | $\Sigma^+$ | $\Sigma^0$ | $\Sigma^-$ | $\Xi^0$ | $\Xi^-$ |
|------------|-----|-----|-----------|-----------|-----------|-----------|--------|--------|
| 0.6        | 1   | -0.667 | -0.303 | 0.977 | 0.320 | -0.337 | -0.615 | -0.291 |
| 0.8        | 1   | -0.667 | -0.295 | 0.977 | 0.318 | -0.341 | -0.607 | -0.282 |
| 1.0        | 1   | -0.667 | -0.288 | 0.975 | 0.316 | -0.344 | -0.598 | -0.272 |
| Exp.       | 1   | -0.685 | -0.219 | 0.880 | -0.415 | -0.448 | -0.233 |

In nuclear matter ($\rho \neq 0$), the $\sigma$- and $\omega$-mesons acquire non-vanishing values of their mean fields, which causes changes in the effective masses of quarks ($m_q^* = m_q - g_\sigma^q \sigma$) as well as in other quantities such as $N_q$, $\beta_q$, $x_q$ and $R_B(\rho)$. Thus, $D_q$ and the resulting values of the magnetic moments of baryons depend on the nuclear density.

### III. RESULTS

Before we present the results for $\mu_B(\rho)$ in medium, let us first show the values of $\mu_B(\rho = 0)$ in free space calculated by using Eq. (18). The ratios of $\mu_B/\mu_p$ in free space are listed in Table II, where $R_0$ denotes the bag radius in free space; $R_0 = R_B(0)$. Due to the difference in the values of parameters, the magnetic moments of this work are slightly different from those given in Ref. [22].

Let us introduce a quantity $r_B(\rho)$ defined as the ratio of the magnetic moment of a baryon $B$ in medium of density $\rho$ relative to its free space value,

$$r_B(\rho) \equiv \frac{\mu_B(\rho)}{\mu_B}. \tag{19}$$

We list the values of $r_B(\rho_0)$’s at the saturation density $\rho_0$ obtained from the QMC and the MQMC models in Table III and Table IV, respectively. To check the consistence of the results against different choices of the bag radius, we show the ratios $r_B(\rho_0)$ for different values of $R_0$. The $R_0$-dependence of $r_B(\rho_0)$ in the QMC model is found to be rather small (less than 5 %), while that in the MQMC model is even smaller (less than 2 %). Thus in the forthcoming discussion we use $R_0 = 0.8$ fm.

As seen in Table III the magnetic moments of baryons at the saturation density in the
TABLE III: The ratios $r_B(\rho_0) = \mu_B(\rho_0)/\mu_B$, where $\mu_B(\rho_0)$ and $\mu_B$ are the magnetic moments at normal nuclear matter density $\rho_0$ and in free space, respectively, are tabulated for three $R_0$ values. $\mu_B(\rho_0)$ is calculated by the QMC model.

| $R_0$ (fm) | $r_N$ | $r_\Lambda$ | $r_{\Sigma^+}$ | $r_{\Sigma^0}$ | $r_{\Sigma^-}$ | $r_{\Xi^0}$ | $r_{\Xi^-}$ |
|------------|-------|-------------|----------------|----------------|----------------|--------------|-------------|
| 0.6        | 1.029 | 0.993       | 1.037          | 1.027          | 1.057          | 1.015        | 0.980       |
| 0.8        | 1.053 | 0.997       | 1.053          | 1.040          | 1.077          | 1.021        | 0.976       |
| 1.0        | 1.071 | 0.999       | 1.067          | 1.051          | 1.095          | 1.027        | 0.970       |

QMC model change only by a few percents from those in free space for all the baryons. This behavior agrees with the results of Ref. [17]. In particular, the magnetic moment of $\Lambda$ in matter remains almost unchanged from that in free space with only about $(0.1 \sim 0.7)\%$ decrease at the saturation density. Even if we increase the matter density up to 4 times the saturation density, the change is found to be less than $2\%$ for $\Lambda$ as seen in the upper panel of Fig. 1. The reason is not difficult to understand. As the $s$-quark does not couple to the $\sigma$ and $\omega$ mesons, the effective mass of the $s$-quark remains unchanged, $m_s^* = m_s$. Thus, as can be seen from Eq. (16), the only medium effect on $\mu_\Lambda$ is through the change in the bag radius. The bag radius $R_B$ in the QMC model, however, decreases only slightly as density increases. In our calculation, the bag radius of a $\Lambda$ hyperon at the saturation density is about 99.6\% of that in free space. As a result, $D_s$ remains almost constant with respect to $\rho$, and consequently the density-dependence of $\mu_B$ coming from that of $D_s$ is very small as seen in Table III. In the upper panel of Fig. 1 we show the density dependence of the magnetic moments of octet baryons (with $R_0 = 0.8$ fm) up to $\rho = 4\rho_0$. We find that the density dependence is rather small even at $\rho = 4\rho_0$ with a change of about 10\%.

One can notice from Fig. 1 that only $r_B(\rho)$’s for $B = \Lambda$ and $\Xi^-$ are smaller than unity. This can be understood as follows. Since $D_u$ ($D_s$) is simply proportional to $\mu_p$ ($\mu_\Lambda$), one can envision $D_u$ and $D_s$ from the curves for $r_N(\rho)$ and $r_\Lambda(\rho)$, respectively, shown in Fig. 1. $D_u(\rho)$ increases with density as $r_N(\rho)$ does, but $D_s(\rho)$ remains almost constant with respect to density as $r_\Lambda(\rho)$ does in the case of the QMC model. Equation (15) shows that $\mu_n$, $\mu_\Lambda$, $\mu_{\Sigma^-}$, $\mu_{\Xi^0}$, and $\mu_{\Xi^-}$ are negative-valued. Among these, only $\mu_\Lambda$ and $\mu_{\Xi^-}$ decrease in magnitude with density (in QMC model), which causes the ratio $r_B(\rho)$ becoming smaller than unity for $\Lambda$ and $\Xi^-$. 

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FIG. 1: The ratios $r_B(\rho) = \mu_B(\rho)/\mu_B$ of the magnetic moments $\mu_B(\rho)$ of octet baryons in dense matter calculated by the QMC and MQMC models are plotted as a function of density in the upper and lower panels, respectively.

As plotted in the lower panel of Fig. 1, the magnetic moments calculated by the MQMC model are quite different from those in the QMC model. The magnetic moments of all the baryons increase uniformly, but the slope of $r_N(\rho)$ is steeper than that of other $r_B(\rho)$’s. The magnetic moments at $\rho = \rho_0$ are listed in Table IV. At the saturation density, the magnetic
moment of a nucleon in the MQMC model increases by about 25 % from its free space value, which is much larger than the increase observed with the QMC model (3 ∼ 7 %). Also, the MQMC models predicts the value of $\mu_\Lambda$ at the saturation density to increase by about 10 %, which is in sharp contrast with the QMC prediction, in which case $\mu_\Lambda$ in medium remains almost the same as the free space value.

Comparing Table III and Table IV shows the values of $r_\Sigma$’s and $r_\Xi$’s are considerably different depending on the model used. The differences in the $r_B(\rho)$ values calculated by the QMC and the MQMC models can be attributed to the fact that the bag radii change considerably in the MQMC model. Since the bag constant decreases very rapidly with density in the MQMC model, the bag radius increases with density to satisfy the minimization condition, $\partial m^*_B/\partial R = 0$.

To see how much the magnetic moments are correlated with the values of the bag radius $R_B(\rho)$, we plot in Fig. 2 $r_B(\rho)$ = $\mu_B(\rho)/\mu_B$ for $B = N$ and $\Lambda$ together with the ratio $R_B(\rho)/R_0$. (We consider here only two cases of $B = N$ and $\Lambda$ because $\mu_N(\rho)$ and $\mu_\Lambda(\rho)$ are simply proportional to $D_u$ and $D_s$, respectively.)"}

| $R_0$ (fm) | $r_N$ | $r_\Lambda$ | $r_{\Sigma^+}$ | $r_{\Sigma^0}$ | $r_{\Sigma^-}$ | $r_{\Xi^0}$ | $r_{\Xi^-}$ |
|------------|-------|-------------|---------------|---------------|---------------|-------------|-------------|
| 0.6        | 1.237 | 1.106       | 1.125         | 1.118         | 1.135         | 1.051       | 1.037       |
| 0.8        | 1.246 | 1.103       | 1.129         | 1.121         | 1.143         | 1.052       | 1.032       |
| 1.0        | 1.254 | 1.099       | 1.134         | 1.124         | 1.151         | 1.053       | 1.027       |

TABLE IV: The ratios $r_B(\rho_0) = \mu_B(\rho_0)/\mu_B$ calculated with the MQMC model are tabulated for three different values of $R_0$, where $\mu_B(\rho_0)$ and $\mu_B$ are the magnetic moments at the normal nuclear matter density and in free space, respectively.
FIG. 2: Comparison of $R_B(\rho)/R_0$ and $r_B(\rho)$ ($B = N$ and $\Lambda$) as a function of density. $R_0$ is chosen as 0.8 fm. In the upper panel the dashed curve overlaps with the dash-dotted curve.

The behaviour of $r_N$ ($r_\Lambda$) is rather similar to that of $R_N/R_0$ ($R_\Lambda/R_0$). It is known that for massless quarks $D_q$ is proportional to the bag radius $R$, $D_q \propto R$ [22]. For general cases where $m_q^* \neq 0$, the analysis becomes complicated. Figure 2, however, indicates that such a relation still remains valid to some extent for the cases considered in this work.
IV. SUMMARY

We have considered in this work the changes of the magnetic moments of octet baryons in dense matter for the first time in the framework of the quark-meson coupling model. Both octet baryons and nuclear matter are treated in a consistent manner by using the quark-meson coupling models. Model dependence is investigated by employing the QMC and the MQMC models, which differ in the density dependence of the bag constant. The QMC model predicts that the magnetic moments of octet baryons at the saturation density change only by a few percents from those in free space. In particular, the magnetic moment of Λ practically does not change from the free-space value in the QMC model. On the other hand, we obtain quite different results from the MQMC model. In the MQMC model, the magnetic moment of a nucleon at the saturation density increases by about 25% from the free-space value, and the magnetic moment of Λ also increases by about 10%. A similar amount of increase in the magnetic moment is also observed for other hyperons. The reason for this model dependence can be ascribed mainly to the behavior of the bag radius in nuclear matter, which comes from the change in the bag constant with respect to the density. The self-consistency equations in the QMC and MQMC models are highly nonlinear. Thus it is not straightforward to see how magnetic moments are related to the bag radius. However, by comparing the density dependence of the magnetic moment with that of the bag radius for each baryon, we find that the two quantities behave rather similarly as functions of density. In the QMC model, the bag radii of the baryons decrease only slightly at the saturation density from the free-space values, by about 1%. The magnetic moments calculated with the QMC model change more or less in the same ratios. In the MQMC model, the bag radii and the magnetic moments behave very similarly and increase by about 10 – 20 % at the nuclear saturation density. Our present results for magnetic moments in nuclear matter may not be directly comparable to the magnetic moments of baryons in finite nuclei. However, our results show that there can be significant changes of the magnetic moments in nuclei, and further investigations are needed to understand the medium modification of the EM properties of baryons. In particular, it is desirable to measure the magnetic moments of these octet baryons in nuclei, which can also give us information on various medium effects on hyperons [25, 26].
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