Properties of charmed and bottom hadrons in nuclear matter: A plausible study

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Abstract

Changes in properties of heavy hadrons with a charm or a bottom quark are studied in nuclear matter. Effective masses (scalar potentials) for the hadrons are calculated using quark-meson coupling model. Our results also suggest that the heavy baryons containing a charm or a bottom quark will form charmed or bottom hypernuclei, which was first predicted in mid 70's. In addition a possibility of $B^-$-nuclear bound (atomic) states is briefly discussed.

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Extensive studies with hypernuclei have been carried out over the last 20 years [1, 2]. These involve embedding a Λ-particle (hyperon), with one (or two) strange quark (quarks) combined with u and (or) d quarks (quark), in finite nuclei and then studying the single particle states, spin-orbit interaction and finally the overall binding of the particle in nuclei with different A, number of ordinary baryons, nucleons, n and p. Such studies have been hindered since there has been no high intensity source of kaon beams that interact with nuclei to produce Λ-particles.

Recently theoretical studies have been extended to take account of the quark structure of the baryons [3, 4, 5]. Agreement with sparse experimental data [2] is impressive. Lately there have been attempts to look for a bound state of 6-quarks, the so-called H particle predicted by Jaffe [6], with no success [7]. There has been confirmation of a bound state of two Λ-particles to a finite nucleus (double hypernucleus) [8]. All these experimental and theoretical studies were directed to learn about the hadrons containing strange quarks in a surrounding of nuclear sea made of mainly valence u and d quarks, although probably there are no quark studies for the double hypernucleus up to now, in spite of its importance and recent experimental achievements.

The approved construction of the Japan Hadron Facility (JHF) will be essentially a kaon factory, thus it is expected to produce large fluxes of hyperons that should allow a detailed study of hypernuclei. However, the facility will be much more than a kaon factory. With a beam energy of 50 GeV, it will produce charmed hadrons profusely and bottom hadrons in lesser numbers but still with an intensity that is comparable to the present hyperon production rates. In mid 70's, a possible formation of the charmed hypernuclei were predicted theoretically [9, 10]. There was an experimental search of the charmed and bottom hypernuclei at the ARES facility [11], and it was also investigated at the possible $c\tau$-factory [12]. It is clear that situation for the experiments to search for such charmed and bottom hypernuclei is now becoming realistic and would be realized at JHF.

This brings us to initiate a careful study of nuclei with charm or bottom quarks. The production of charmonium ($\bar{c}c$), mesons with charm, and baryons with charm quarks will be sufficiently large to make it possible to study charmed hypernuclei. Study of such nuclei would initially involve single particle energies, spin-orbit interaction and overall binding energies. Studies with a charm quark and a bottom quark in a many-body system would provide the first opportunity to learn about the behavior of hadrons containing heavy quarks in a sea of valence u and d quarks. Eventually a study of the decay of such hadrons will be a valuable lesson in finding the effect of many-body systems on the intrinsic properties of charmed and bottom hyperons. The advantage of using hadrons with heavy quarks is that they can convey an information at short distance, i.e., that of the very central region of the nucleus from charmed and bottom hypernuclei. Meson nuclear atomic bound states provide useful information about the surface of the nucleus.

The present investigation is devoted to a study of baryons (and mesons) which contain a charm or a bottom quark (will be denoted by $C$) in nuclear matter. Although the baryons with a charm or a bottom quark which we wish to study have a typical mean life of the order $10^{-12}$ seconds (magnitude is shorter than hyperons), we would like to gain an understanding of the movement of such a hadron in its nucleonic environment. This would lead to an effective mass (scalar potential) for the hadron. The light quark in the hadron (and nucleons) would change its property in nuclear medium in a self-consistent manner, and will thus affect the
overall interaction with nucleons. With this understanding we will be in a better position to learn about the hadron properties with the presence of heavy quarks, or baryons with heavy quarks in finite nuclei that will be the real ground for these experimental studies.

At JHF, in addition to charmed and bottom hyperons, mesons with open charm (bottom) like $D^-(\bar{c}d)$ ($B^-(\bar{u}b)$) will be produced. Such mesons like $K^- (\bar{u}s)$ can form mesic atoms around finite nuclei. The atomic orbits will be very small and will thus probe the surface of light nuclei and will be within the charge radii for heavier nuclei. Thus at least for light nuclei they will give a precise information about the charge density.

Furthermore, in considering recent experimental situation on high energy heavy ion collisions, to study general properties of heavy hadrons in nuclear medium is useful, because elementary hadronic reactions occur in high nuclear density zone of the collisions, and many hadrons produced there are under effects of a surrounding nuclear medium. Thus, we need to understand the properties of heavy hadrons in nuclear medium. Some such applications were also made for $J/\Psi$ dissociation in nuclear matter, and $D$ and $\overline{D}$ productions in antiproton-nucleus collisions [13].

At present we need to resort to a model which can describe the properties of finite nuclei as well as hadron properties in nuclear medium based on the quark degrees of freedom. Although some studies for heavy mesons with charm in nuclear matter were made by QCD sum rule for $J/\Psi$ [14, 15] and $D(\overline{D})$ [16] there seems to exist no studies for heavy baryons with a charm or a bottom quark. With its simplicity and applicability, we use quark-meson coupling (QMC) model [17], which has been extended and successfully applied to many problems in nuclear physics [18, 19, 20, 21, 22, 23, 24] including a detailed study of the properties of hypernuclei [3], and harmonic properties in nuclear medium [13, 25, 26, 27]. In particular, recent measurements of polarization transfer performed at MAMI and Jlab [28] support the medium modification of the proton electromagnetic form factors calculated by the QMC model. The final analysis [29] seems to become more in favor of QMC, although still error bars may be large to draw a definite conclusion. This gives us confidence that such a quark-meson coupling model will provide us with valuable glimpse into the properties of charmed- and bottom-hypernuclei.

We start to consider static, (approximately) spherically symmetric charmed and bottom hypernuclei (closed shell plus one heavy baryon configuration) ignoring small nonspherical effects due to the embedded heavy baryon. We adopt Hartree, mean-field, approximation. In this approximation, $\rho NN$ tensor coupling gives a spin-orbit force for a nucleon bound in a static spherical nucleus, although in Hartree-Fock it can give a central force which contributes to the bulk symmetry energy [18, 19]. Furthermore, it gives no contribution for nuclear matter since the meson fields are independent of position and time. Thus, we ignore the $\rho NN$ tensor coupling as usually adopted in the Hartree treatment of quantum hadrodynamics (QHD) [30, 31].

Using the Born-Oppenheimer approximation, mean-field equations of motion are derived for a charmed (bottom) hypernucleus in which the quasi-particles moving in single-particle orbits are three-quark clusters with the quantum numbers of a charmed (bottom) baryon or a nucleon. Then a relativistic Lagrangian density at the hadronic level [18, 19] can be constructed, similar to that obtained in QHD [30, 31], which produces the same equations of motion when expanded to the same order in velocity:

$$\mathcal{L}_{QMC}^{CHY} = \mathcal{L}_{QMC} + \mathcal{L}_{QMC}^{C},$$
\[ \mathcal{L}_{QMC} = \bar{\psi}_N(r) \left[ i\gamma \cdot \partial - M_N^*(\sigma) - (g_\omega \omega(r) + g_\rho r^N \rho(r) + \frac{e}{2}(1 + \tau_3^N)A(r)) \gamma_0 \right] \psi_N(r) \]

\[ - \frac{1}{2} \left[ (\nabla \sigma(r))^2 + m_\sigma^2 \sigma(r)^2 \right] + \frac{1}{2} \left[ (\nabla \omega(r))^2 + m_\omega^2 \omega(r)^2 \right] \]

\[ + \frac{1}{2} \left[ (\nabla b(r))^2 + m_b^2 b(r)^2 \right] + \frac{1}{2} (\nabla A(r))^2, \]

\[ \mathcal{L}_{QMC}^C = \sum_{C=\Lambda_c, \Sigma_c, \Xi_c, \Lambda_b} \bar{\psi}_C(r) \left[ i\gamma \cdot \partial - M_C^*(\sigma) - (g_C^C \omega(r) + g_C^\rho I_3^C \rho(r) + eQ_C A(r)) \gamma_0 \right] \psi_C(r), \quad (1) \]

where \( \psi_N(r) \) (\( \psi_C(r) \)) and \( b(r) \) are respectively the nucleon (charmed and bottom baryon) and the \( \rho \) meson (the time component in the third direction of isospin) fields, while \( m_\sigma, m_\omega, \) and \( m_\rho \) are the masses of the \( \sigma, \omega \) and \( \rho \) meson fields. \( g_\omega \) and \( g_\rho \) are the \( \omega-N \) and \( \rho-N \) coupling constants which are related to the corresponding \((u,d)\)-quark-\( \omega \), \( g_\omega^q \), and \((u,d)\)-quark-\( \rho \), \( g_\rho^q \), coupling constants as \( g_\omega = 3g_\omega^q \) and \( g_\rho = g_\rho^q \) [18, 19]. (See also Eqs. (4) and (5).) Note that in usual QMC (QMC-I) the meson fields appearing in Eq. (1) represent the quantum numbers and Lorentz structure as those used in QHD [31], corresponding, \( \sigma \leftrightarrow \phi_0 \), \( \omega \leftrightarrow V_0 \) and \( b \leftrightarrow b_0 \), and they are not directly connected with the physical particles, nor quark model states. Their masses in nuclear medium do not vary in the present treatment. For the other version of QMC (QMC-II), where masses of the meson fields are also subject to the medium modification in a self-consistent manner, see Ref. [20]. However, for a proper parameter set (set B) the typical results obtained in QMC-II are very similar to those of QMC-I. The difference is \( \sim 16 \% \) for the largest case, but typically \( \sim 10 \% \) or less. (For the effective masses of the hyperons, it is less than \( \sim 8 \% \).)

In an approximation where the \( \sigma, \omega \) and \( \rho \) fields couple only to the \( u \) and \( d \) quarks, the coupling constants in the charmed (bottom) baryon are obtained as \( g_\omega^C = (n_\ell / 3)g_\omega \) and \( g_\rho^C = g_\rho = g_\rho^q \), with \( n_\ell \) being the total number of valence \( u \) and \( d \) (light) quarks in the baryon \( C \). \( I_3^C \) and \( Q_C \) are the third component of the baryon isospin operator and its electric charge in units of the proton charge, \( e \), respectively. The field dependent \( \sigma-N \) and \( \sigma-C \) coupling strengths predicted by the QMC model, \( g_\sigma(\sigma) \) and \( g_\sigma^C(\sigma) \), related to the Lagrangian density, Eq. (1), at the hadronic level are defined by:

\[ M_N^*(\sigma) \equiv M_N - g_\sigma(\sigma)\sigma(r), \quad (2) \]

\[ M_C^*(\sigma) \equiv M_C - g_\sigma^C(\sigma)\sigma(r), \quad (3) \]

where \( M_N \) (\( M_C \)) is the free nucleon (charmed and bottom baryon) mass (masses). Note that the dependence of these coupling strengths on the applied scalar field must be calculated self-consistently within the quark model [3, 18, 19]. Hence, unlike QHD [30, 31], even though \( g_\omega^C(\sigma)/g_\sigma(\sigma) \) may be \( 2/3 \) or \( 1/3 \) depending on the number of light quarks in the baryon in free space \((\sigma = 0)^1\), this will not necessarily be the case in nuclear matter.

In the following, we consider the system in the limit of infinitely large, uniform (symmetric) nuclear matter, where all scalar and vector fields become constants. Furthermore, under this limit, we may also treat a hadron \( h \) embedded in the nuclear matter system, in the same way as that for the charmed (bottom) baryon. (A Lagrangian density for a meson-nuclear sys-

\[ ^1 \text{Strictly, this is true only when the bag radii of nucleon and heavy baryon } C \text{ are exactly the same in the present model. See Eq. (8), below.} \]
tem can be also written in a similar way to that of the charmed (bottom) hypernuclei system, if $\mathcal{L}_{QMC}$ is replaced by the corresponding meson Lagrangian density in Eq.(1.)

Then, the Dirac equations for the quarks and antiquarks in nuclear matter, in bags of hadrons, $h$, ($q = u$ or $d$, and $Q = s, c$ or $b$, hereafter) neglecting the Coulomb force in nuclear matter, are given by ($|\mathbf{x}| \leq$ bag radius) [25, 26, 27]:

\[
\begin{align*}
\left[ i\gamma \cdot \partial_x - (m_q - V^q_\omega) \right] \psi_u(x) &\equiv \gamma^0 \left( V^q_\omega + \frac{1}{2} V^q_\rho \right) \psi_u(x) = 0, \quad (4) \\
\left[ i\gamma \cdot \partial_x - (m_q - V^q_\omega) \right] \psi_d(x) &\equiv \gamma^0 \left( V^q_\omega - \frac{1}{2} V^q_\rho \right) \psi_d(x) = 0, \quad (5) \\
[i\gamma \cdot \partial_x - m_Q] \psi_Q(x) &\equiv \gamma^0 \left( V^Q_\omega - \frac{1}{2} V^Q_\rho \right) \psi_Q(x) = 0. \quad (6)
\end{align*}
\]

The (constant) mean-field potentials for a bag in nuclear matter are defined by $V^q_\omega \equiv g^q_\omega \sigma$, $V^q_\rho \equiv g^q_\rho \omega$ and $V^Q_\omega \equiv g^Q_\omega h$, with $g^q_\omega$, $g^q_\rho$ and $g^Q_\omega$ the corresponding quark-meson coupling constants.

The normalized, static solution for the ground state quarks or antiquarks with flavor $Q$ in nuclear medium, it reflects nothing but the strength of the attractive scalar potential as in nuclear medium, $R^*_h$, will be determined through the stability condition for the mass of the hadron against the variation of the bag radius [17, 18, 19] (see Eq. (8)).

The eigenenergies in units of $1/R^*_h$ are given by,

\[
\begin{pmatrix}
\epsilon_u \\
\epsilon_{\bar{u}}
\end{pmatrix}
\equiv \Omega^*_q \pm R^*_h \left( V^q_\omega + \frac{1}{2} V^q_\rho \right), \quad \begin{pmatrix}
\epsilon_d \\
\epsilon_{\bar{d}}
\end{pmatrix}
\equiv \Omega^*_q \pm R^*_h \left( V^q_\omega - \frac{1}{2} V^q_\rho \right), \quad \epsilon_Q = \epsilon_{\bar{Q}} = \Omega^*_Q.
\] (7)

The hadron masses in a nuclear medium $m^*_h$ (free mass will be denoted by $m_h$), are calculated by

\[
m^*_h = \sum_{j=q,s,c,b} \frac{n_j \Omega^*_j - z_h}{R^*_h} + \frac{4}{3} \pi R^*_h B, \quad \frac{\partial m^*_h}{\partial R_h} \bigg|_{R_h = R^*_h} = 0,
\] (8)

where $\Omega^*_q = \Omega^*_Q = \frac{x_q^2 + (R^*_h m_q^*)^2}{2} (q = u, d)$, with $m_q^* = m_q - g^q_\omega \sigma$, $\Omega^*_Q = \Omega^*_Q = \frac{x_Q^2 + (R^*_h m_Q^*)^2}{2} (Q = s, c, b)$, and $x_q, x_Q$ being the bag eigenfrequencies. $B$ is the bag constant, $n_q(n_Q)$ and $n_Q(n_Q)$ are the lowest mode quark (antiquark) numbers for the quark flavors $q$ and $Q$ in the hadron $h$, respectively, and the $z_h$ parametrize the sum of the center-of-mass and gluon fluctuation effects and are assumed to be independent of density. Concerning the sign of $m^*_h$ in nuclear medium, it reflects nothing but the strength of the attractive scalar potential as in Eqs. (4) and (5), and thus naive interpretation of the mass for a (physical) particle, which is positive, should not be applied. The parameters are determined to reproduce the corresponding masses in free space. We chose the values, $(m_q, m_s, m_c, m_b) = (5, 250, 1300, 4200)$ MeV for the current quark masses, and $R_N = 0.8$ fm for the bag radius of the nucleon in free space. The quark-meson coupling constants, $g^q_\omega$, $g^q_\rho$ and $g^Q_\omega$, are adjusted to fit the nuclear saturation energy and density of symmetric nuclear matter, and the bulk symmetry energy [17, 18, 19]. Exactly the same coupling constants, $g^q_\omega$, $g^q_\rho$ and $g^Q_\omega$, are used for the light quarks in the mesons and baryons as in the nucleon.

However, in studies of the kaon system, we found that it was phenomenologically necessary to increase the strength of the vector coupling to the non-strange quarks in the $K^+$ (by a
factor of $1.4^2$, i.e., $g^{q}\omega \equiv 1.4^2 g^{q}_{\omega}$, in order to reproduce the empirically extracted $K^{+}$-nucleus interaction [25]. This may be related to the fact that kaon is a pseudo-Goldstone boson, where treatment of the Goldstone bosons in a naive quark model is usually unsatisfactory. We assume this, $g^{q}_{\omega} \rightarrow 1.4^2 g^{q}_{\omega}$, also for the $D$, $\bar{D}$ [27], $B$ and $\bar{B}$ mesons to allow an upper limit situation. The scalar ($V_{s}^{h}$) and vector ($V_{v}^{h}$) potentials felt by the hadrons $h$, in nuclear matter are given by,

\begin{align}
V_{s}^{h} &= m_{h}^{*} - m_{h}, \\
V_{v}^{h} &= (n_{q} - n_{\bar{q}})V_{\omega}^{q} + I_{3}^{h}V_{\rho}^{q},
\end{align}

(9) $V^{q}_{\omega} \rightarrow 1.4^2 V^{q}_{\omega}$ for $K$, $\bar{K}$, $D$, $\bar{D}$, $B$, $\bar{B}$,

(10) where $I_{3}^{h}$ is the third component of isospin projection of the hadron $h$. Thus, the vector potential felt by a heavy baryon with a charm or bottom quark, is equal to that of the hyperon with the same light quark configuration in QMC.

In Figs. 1 and 2 we show ratios of effective masses (free masses + scalar potentials) versus those of the free particles, for mesons and baryons, respectively. With increasing density the ratios decrease as usually expected, but decrease in magnitude is from larger to smaller: hadrons with only light quarks, with one strange quark, with one charm quark, and with one bottom quark. This is because their masses in free space are in the order from light to heavy. Thus, the net ratios for the decrease in masses (developing of scalar masses) compared to that of the free masses becomes smaller. This may be regarded as a measure of the role of light quarks in each hadron system in nuclear matter, in a sense that by how much ratio do they lead to a partial restoration of the chiral symmetry in the hadron. In Fig. 1, one can notice somewhat anomalous behavior of the ratio for the kaon ($K$). This is related to what we meant by the pseudo-Goldstone boson nature, i.e., its mass in free space is relatively light, $m_{K} \simeq 495$ MeV, and the ratio for the reduction in mass in nuclear medium is large.

Perhaps it is much more quantitative and direct to compare scalar potentials of each hadron in the nuclear matter. Calculated results are shown in Fig. 3. From the results it is confirmed that the scalar potential felt by the hadron $h$, $V_{s}^{h}$, follows a simple light quark number scaling rule:

\begin{align}
V_{s}^{h} &\simeq \frac{n_{q} + n_{\bar{q}}}{3} V_{s}^{N},
\end{align}

(11) where $n_{q}$ ($n_{\bar{q}}$) is the number of light quarks (antiquarks) in the hadron $h$, and $V^{N}_{s}$ is the scalar potential felt by the nucleon. (See Eq.(9).) It is interesting to notice that, the baryons with a charm and a bottom quark ($\Xi_{c}$ is a quark configuration, $q_{sc}$), shows very similar features to those of hyperons with one or two strange quarks. Then, we can expect that these heavy baryons with a charm or a bottom quark, will also form charmed (bottom) hypernuclei, as the hyperons with strangeness do. (Recall that the repulsive, vector potentials are the same for the corresponding hyperons with the same light quark configurations.) Thus, an experimental investigation of such hypernuclei would be a fruitful venture at JHF.

In addition, $B^{-}$ meson will also certainly form meson-nuclear bound states, because $B^{-}$ meson is $\bar{u}b$ and feels a strong attractive vector potential in addition to the attractive Coulomb force. This makes it much easier to be bound in a nucleus compared to the $D^{0}$ [27], which is $c\bar{u}$ and is blind to the Coulomb force. This reminds us of a situation of the kaonic ($K^{-}(\bar{u}s)$) atom [32, 33]. A study of $B^{-}(\bar{u}b)$ atoms would be a fruitful experimental program. Such atoms will have the meson much closer to the nucleus and will thus probe even smaller changes in
the nuclear density. This will be a complementary information to the $D^-(\bar{c}d)$-nuclear bound states, which would provide us an information on the vector potential in a nucleus [27].

To summarize, we have studied for the first time the properties of heavy baryons (hadrons) which contain a charm or a bottom quark in nuclear matter. Our results suggest that those heavy baryons will form charmed or bottom hypernuclei as was predicted in mid 70’s. We plan to report results for the charmed and bottom hypernuclei studied quantitatively, by solving a system equations for finite nuclei embedding a baryon with a charm or a bottom quark [34]. In addition we can expect also $B^-$-nuclear bound (atomic) states based on the existing studies for the $D^0$ and kaonic atom. Furthermore, formation of $B^-$-atoms would provide precise information on the nuclear density, which would be a complementary to that of the $D^-$-nuclear bound states.

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Figure 1: Effective mass ratios for mesons in nuclear matter, where, $\rho_0 = 0.15 \text{ fm}^{-3}$. $\omega$ and $\rho$ stand for physical mesons which are treated in the quark model, and should not be confused with the fields appearing in the QMC model.
Figure 2: Effective mass ratios for baryons in nuclear matter, where, $\rho_0 = 0.15$ fm$^{-3}$.
Figure 3: Scalar potentials for various hadrons in nuclear matter, where, $\rho_0 = 0.15$ fm$^{-3}$. (See also caption of Fig. 1.)