Λ_c^+ and Λ_b hypernuclei

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Λ_c^+ and Λ_b hypernuclei are studied in the quark-meson coupling (QMC) model. Comparisons are made with the results for Λ hypernuclei studied in the same model previously. Although the scalar and vector potentials felt by the Λ, Λ_c^+, and Λ_b in the corresponding hypernuclei multiplet which has the same baryon numbers are quite similar, the wave functions obtained, e.g., for the $1s_{1/2}$ state, are very different. The Λ_c^+ baryon density distribution in $^{209}_{\Lambda_c^+}$Pb is much more pushed away from the center than that for the Λ in $^{209}_{\Lambda}$Pb due to the Coulomb force. On the contrary, the Λ_b baryon density distributions in Λ_b hypernuclei are much larger near the origin than those for the Λ in the corresponding Λ hypernuclei due to its heavy mass. It is also found that level spacing for the Λ_b single-particle energies is much smaller than that for the Λ and Λ_c^+.

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Recently we have made a systematic study of the changes in properties of the heavy hadrons which contain a charm or a bottom quark in nuclear matter [1]. The results suggest that the formations of charmed and bottom hypernuclei, which were predicted first in mid-1970s [2,3], are quite likely. The experimental possibilities were also studied later [4]. In addition, we predicted the B^--nuclear (atomic) bound states, based on analogy with kaonic atom [5], and also based on a study was made for the D- and $\bar{D}$-nuclear bound states [6] using the quark-meson coupling (QMC) model [7–9].

The QMC model, which was used there and is used in this study, has been successfully applied to many problems associated with nuclear physics and hadronic properties in nuclear medium [10,11]. For example, the model was applied to the study of J/Ψ dissociation in nuclear matter [12] and D and $\bar{D}$ productions in antiproton-nucleus collisions [13]. Furthermore, although only limited studies for heavy mesons (not for heavy baryons) with charm in nuclear matter were made by the QCD sum rule [for J/Ψ [14,15] and $D(\bar{D})$ [16]], a study [1] for heavy baryons with a charm or a bottom quark based on quarks was made using the QMC model. In particular, recent measurements of polarization transfer performed at MAMI and JLab [17] support the medium modification of the proton electromagnetic form factors calculated by the QMC model. The final analysis [18] seems to have become more in favor of QMC, although still error bars may be too large to draw a definite conclusion.

Certainly, the model has shortcomings to be improved eventually. Difficulties in handling it will be increased rapidly if we adopt the Hartree-Fock approximation even for nuclear matter [19] and the inclusion of Pauli blocking at the quark level, and ΣN-ΛN channel couplings have not been implemented yet in a consistent manner with the underlying quark degrees of freedom [10]. (It should be mentioned that in the case of Σ hypernuclei no narrow states have been observed. It is unlikely that it will be possible to find such states in the present case [20].) Furthermore, an application to double hypernuclei has not been attempted, although recently the existence was confirmed [21]. Nevertheless, with its simplicity and successful applicability achieved so far, we feel some confidence that such a quark-meson coupling model will provide us with a valuable glimpse into the properties of charmed and bottom hypernuclei.

In this article, we make a quantitative study of the Λ_c^+ and Λ_b hypernuclei by solving a system of equations for finite nuclei, embedding a Λ_c^+ or a Λ_b into the closed-shell nucleus in a Hartree, mean-field, approximation. Then, the results are compared with those for the Λ hypernuclei [10], which were studied in the QMC model. It is shown that, although the scalar and vector potentials felt by the Λ, Λ_c^+, and Λ_b in the corresponding hypernuclei multiplet which has the same baryon numbers are quite similar, the wave functions obtained, e.g., for the $1s_{1/2}$ state are very different. Namely, the Λ_c^+ baryon density distribution in $^{209}_{\Lambda_c^+}$Pb is much more pushed away from the center than that for the Λ in $^{209}_{\Lambda}$Pb due to the Coulomb force. On the contrary, the Λ_b baryon density distributions in Λ_b hypernuclei are much more central than those for the Λ in the corresponding Λ hypernuclei due to heavy Λ_b mass. In addition it turns out that the level spacing for the Λ_b single-particle energies is much smaller than that for the Λ and Λ_c^+, which may imply many interesting new phenomena, which will be discovered in due course by experiments. We hope this study opens a new possibility for experiments, related to nuclear and hadronic physics, especially for Japan Hadron Facility (JHF).

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 a Hartree, mean-field, approximation. In this approximation, the ρNN tensor coupling gives a spin-orbit force for a nucleon bound in a static spherical nucleus, although in the Hartree-Fock approximation it can give a central force which

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contributes to the bulk symmetry energy [8,9]. Furthermore, it gives no contribution for nuclear matter since the meson fields are independent of position and time. Thus, we ignore the ρNN tensor coupling in this study as usually adopted in the Hartree treatment of quantum hadrodynamics (QHD) [22].

Using the Born-Oppenheimer approximation, a relativistic Lagrangian density which gives the same mean-field equations of motion for a charmed or a bottom hypernucleus, in which the quasiparticles moving in single-particle orbits are three-quark clusters with the quantum numbers of a charmed baryon, a bottom baryon or a nucleon, when expanded to the same order in velocity, is given by the QMC model [8–10]:

$$\mathcal{L}^{CHY}_{QMC}=\mathcal{L}_{QMC}+\mathcal{L}^{C}_{QMC},$$

$$\mathcal{L}_{QMC}=\overline{\psi}_N(\vec{r})\left[i\gamma\cdot\partial-M^\star_N(\sigma)-\left(g_\omega\omega(\vec{r})+g_\rho\frac{\tau^N_3}{2}b(\vec{r})+\frac{e}{2}(1+\tau^N_3)A(\vec{r})\right)\gamma_0\right]\psi_N(\vec{r})-\frac{1}{2}\{[\nabla\sigma(\vec{r})]^2+m^2_\sigma\sigma(\vec{r})^2\}+\frac{1}{2}\{[\nabla\omega(\vec{r})]^2+m^2_\omega\omega(\vec{r})^2\}+\frac{1}{2}\{[\nabla b(\vec{r})]^2+m^2_\rho b(\vec{r})^2\}+\frac{1}{2}[\nabla A(\vec{r})]^2,$$

$$\mathcal{L}^{C}_{QMC}=\sum_{C=\Lambda_c^+,\Lambda_b}\overline{\psi}_C(\vec{r})\{i\gamma\cdot\partial-M^\star_C(\sigma)-[g^C_\omega\omega(\vec{r})+g^C_\rho I^C_3 b(\vec{r})+eQ_C A(\vec{r})]\gamma_0\}\psi_C(\vec{r}), \tag{1}$$

where $\psi_N(\vec{r})$ [$\psi_C(\vec{r})$] and $b(\vec{r})$ are, respectively, the nucleon [charmed and bottom baryons] and the ρ meson [the time component in the third direction of isospin] fields, while m_σ, m_ω, and m_ρ are the masses of the σ, ω, and ρ meson fields. g_ω and g_ρ are the ω-N and ρ-N coupling constants which are related to the corresponding (u,d)-quark-ω, g^q_ω, and (u,d)-quark-ρ, g^q_ρ, coupling constants as $g_\omega=3g^q_\omega$ and $g_\rho=g^q_\rho$ [8,9]. Hereafter we will use notation for the quark flavors, $q\equiv u,d$ and $Q\equiv s,c,b$.

In an approximation where the σ, ω, and ρ fields couple only to the u and d quarks, the coupling constants in the charmed and bottom baryons are obtained as $g^C_\omega=(n_q/3)g_\omega$ and $g^C_\rho\equiv g_\rho=g^q_\rho$, with n_q being the total number of valence u and d (light) quarks in the baryon C. I^C_3 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 σ-N and σ-C coupling strengths predicted by the QMC model, $g_\sigma(\sigma)$ and $g^C_\sigma(\sigma)$, related to the Lagrangian density, Eq. (1), at the hadronic level are defined by

$$M^\star_N(\sigma)\equiv M_N-g_\sigma(\sigma)\sigma(\vec{r}), \tag{2}$$

$$M^\star_C(\sigma)\equiv M_C-g^C_\sigma(\sigma)\sigma(\vec{r}), \tag{3}$$

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 [8–10]. Hence, unlike QHD [22], even though $g^C_\sigma(\sigma)/g_\sigma(\sigma)$ 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. More explicit expressions for $g^C_\sigma(\sigma)$ and $g_\sigma(\sigma)$ will be given later. From the Lagrangian density, Eq. (1), a set of equations of motion for the charm or bottom hypernuclear system is obtained,

$$\left[i\gamma\cdot\partial-M^\star_N(\sigma)-\left(g_\omega\omega(\vec{r})+g_\rho\frac{\tau^N_3}{2}b(\vec{r})+\frac{e}{2}(1+\tau^N_3)A(\vec{r})\right)\gamma_0\right]\psi_N(\vec{r})=0, \tag{4}$$

$$\{i\gamma\cdot\partial-M^\star_C(\sigma)-[g^C_\omega\omega(\vec{r})+g_\rho I^C_3 b(\vec{r})+eQ_C A(\vec{r})]\gamma_0\}\psi_C(\vec{r})=0, \tag{5}$$

$$(-\nabla^2_r+m^2_\sigma)\sigma(\vec{r})=-\left[\frac{\partial M^\star_N(\sigma)}{\partial\sigma}\right]\rho_s(\vec{r})-\left[\frac{\partial M^\star_C(\sigma)}{\partial\sigma}\right]\rho^C_s(\vec{r})\equiv g_\sigma C_N(\sigma)\rho_s(\vec{r})+g^C_\sigma C_C(\sigma)\rho^C_s(\vec{r}), \tag{6}$$

$$(-\nabla^2_r+m^2_\omega)\omega(\vec{r})=g_\omega\rho_B(\vec{r})+g^C_\omega\rho^C_B(\vec{r}), \tag{7}$$

$$(-\nabla^2_r+m^2_\rho)b(\vec{r})=\frac{g_\rho}{2}\rho_3(\vec{r})+g^C_\rho I^C_3\rho^C_B(\vec{r}), \tag{8}$$

$$(-\nabla^2_r)A(\vec{r})=e\rho_p(\vec{r})+eQ_C\rho^C_B(\vec{r}), \tag{9}$$

where $\rho_s(\vec{r})$ [$\rho^C_s(\vec{r})$], $\rho_B(\vec{r})$ [$\rho^C_B(\vec{r})$], $\rho_3(\vec{r})$, and $\rho_p(\vec{r})$ are the scalar, baryon, third component of isovector, and proton densities at the position $\vec{r}$ in the charmed or bottom hypernuclei [8–10]. On the right-hand side of Eq. (6), $-[\partial M^\star_N(\sigma)/\partial\sigma]=g_\sigma C_N(\sigma)$ and $-[\partial M^\star_C(\sigma)/\partial\sigma]=g^C_\sigma C_C(\sigma)$, where $g_\sigma\equiv g_\sigma(\sigma=0)$ and $g^C_\sigma\equiv g^C_\sigma(\sigma=0)$, are a new and characteristic feature of the QMC model beyond QHD [22–24]. The effective mass for the charmed or bottom baryon C is defined by

$$\frac{\partial M^\star_C(\sigma)}{\partial\sigma}=-n_q g^q_\sigma\int_{bag}d\vec{y}\ \overline{\psi}_q(\vec{y})\psi_q(\vec{y})\equiv-n_q g^q_\sigma S_C(\sigma)=-\frac{\partial}{\partial\sigma}[g^C_\sigma(\sigma)\sigma], \tag{10}$$

[1]Strictly, this is true only when the bag radii of the nucleon and baryon C are exactly the same in the present model. See the last line in Eq. (11).

with the MIT bag model quantities [7–10]

$$M_C^\star(\sigma)=\sum_{j=q,Q}\frac{n_j\Omega_j^*-z_C}{R_C^*}+\frac{4}{3}\pi(R_C^*)^3B,$$

$$S_C(\sigma)=\frac{\Omega_q^*/2+m_q^*R_C^*(\Omega_q^*-1)}{\Omega_q^*(\Omega_q^*-1)+m_q^*R_C^*/2},$$

$$\Omega_q^*=\sqrt{x_q^2+(R_C^*m_q^*)^2},\quad \Omega_Q^*=\sqrt{x_Q^2+(R_C^*m_Q)^2},$$

$$m_q^*=m_q-g_\sigma^q\sigma(\vec{r}),$$

$$C_C(\sigma)=S_C(\sigma)/S_C(0),$$

$$g_\sigma^C\equiv n_qg_\sigma^qS_C(0)=\frac{n_q}{3}g_\sigma S_C(0)/S_N(0)\equiv\frac{n_q}{3}g_\sigma\Gamma_{C/N}. \tag{11}$$

Quantities for the nucleon are similarly obtained by replacing the indices $C\to N$. Here, z_C, B, $x_{q,Q}$, and $m_{q,Q}$ are the parameters for the sum of the c.m. and gluon fluctuation effects, bag pressure, lowest eigenvalues for the quarks, q or Q, respectively, and the corresponding current quark masses. z_N and B (z_C) are fixed by fitting the nucleon (charmed or bottom baryon) mass in free space. Concerning the sign of m_q^* in the (hyper)nucleus, it reflects nothing but the strength of the attractive scalar potential, and thus a naive interpretation of the mass for a (physical) particle, which is positive, should not be applied.

The bag radii in-medium $R_{N,C}^*$ are obtained by the equilibrium condition $dM_{N,C}^\star(\sigma)/dR_{N,C}|_{R_{N,C}=R_{N,C}^*}=0$. The bag parameters calculated and chosen for the present study in free space are $(z_N,z_\Lambda,z_{\Lambda_c^+},z_{\Lambda_b})=(3.295,3.131,1.766,-0.643)$, $(R_N,R_\Lambda,R_{\Lambda_c^+},R_{\Lambda_b})=(0.800,0.806,0.846,0.930)$ fm, $B^{1/4}=170$ MeV, and $(m_{u,d},m_s,m_c,m_b)=(5,250,1300,4200)$ MeV. The parameters associated with the u, d, and s quarks are the same as in our previous investigations [9,10]. At the hadron level, the entire information on the quark dynamics is condensed in $C_{N,C}(\sigma)$ of Eq. (6). The parameters at the hadron level, which are already fixed by the study of infinite nuclear matter and finite nuclei [9], are as follows: $m_\omega=783$ MeV, $m_\rho=770$ MeV, $m_\sigma=418$ MeV, $e^2/4\pi=1/137.036$, $g_\sigma^2/4\pi=3.12$, $g_\omega^2/4\pi=5.31$, and $g_\rho^2/4\pi=6.93$.

We briefly discuss about the spin-orbit force in the QMC model [8]. The origin of the spin-orbit force for a composite nucleon moving through scalar and vector fields which vary with position was explained in detail in Ref. [8]—cf. Sec. 3.2. The situation for the Λ and also for other hyperons are discussed in detail in Ref. [10].

In order to include the spin-orbit potential (approximately) correctly, e.g., for the Λ_c^+, we add perturbatively the correction due to the vector potential,

$$-\frac{2}{2M_{\Lambda_c^+}^{\star 2}(\vec{r})r}\left(\frac{d}{dr}g_\omega^{\Lambda_c^+}\omega(\vec{r})\right)\vec{l}\cdot\vec{s},$$

to the single-particle energies obtained with the Dirac equation, in the same way as that added in Ref. [10]. This may correspond to a correct spin-orbit force which is calculated by the underlying quark model [8,10],

$$V_{S.O.}^{\Lambda_c^+}(\vec{r})\vec{l}\cdot\vec{s}=-\frac{1}{2M_{\Lambda_c^+}^{\star 2}(\vec{r})r}\left(\frac{d}{dr}[M_{\Lambda_c^+}^\star(\vec{r})+g_\omega^{\Lambda_c^+}\omega(\vec{r})]\right)\vec{l}\cdot\vec{s}, \tag{12}$$

since the Dirac equation at the hadronic level solved in usual QHD-type models leads to

$$V_{S.O.}^{\Lambda_c^+}(\vec{r})\vec{l}\cdot\vec{s}=-\frac{1}{2M_{\Lambda_c^+}^{\star 2}(\vec{r})r}\left(\frac{d}{dr}[M_{\Lambda_c^+}^\star(\vec{r})-g_\omega^{\Lambda_c^+}\omega(\vec{r})]\right)\vec{l}\cdot\vec{s}, \tag{13}$$

which has the opposite sign for the vector potential $g_\omega^{\Lambda_c^+}\omega(\vec{r})$. The correction to the spin-orbit force, which appears naturally in the QMC model, may also be modeled at the hadronic level of the Dirac equation by adding a tensor interaction, motivated by the quark model [25,26]. Here, we should make a comment that, as was discussed by Dover and Gal [27] in detail, the one-boson exchange model with underlying (approximate) SU(3) symmetry in a strong interaction also leads to weaker spin-orbit forces for the (strange) hyperon-nucleon (YN) coupling than that for the nucleon-nucleon (NN coupling).

However, in practice, because of its heavy mass ($M_{\Lambda_c^+}^\star$), the contribution to the single-particle energies from the spin-orbit potential, with or without including the correction term, turned out to be even smaller than that for the Λ hypernuclei and, further, smaller for the Λ_b hypernuclei. The contribution from the spin-orbit potential with the correction term is typically of order 0.01 MeV, and even for the largest case is $\cong 0.1$ MeV. This can be understood when one considers the limit $M_{\Lambda_c^+}^\star\to\infty$ in Eq. (12), where the quantity inside the square brackets varies smoothly from the order of hundred MeV to zero near the surface of the hypernucleus, and the derivative with respect to r is finite. (See also Figs. 2 and 3.)

Now we discuss the results. First, we show in Fig. 1 the total baryon density distributions in $^{41}_{j}$Ca and $^{209}_{j}$Pb ($j=\Lambda,\Lambda_c^+,\Lambda_b$), for the $1s_{1/2}$ configuration in each hypernucleus. Note that because of the self-consistency, the total baryon density distributions are dependent on the configurations of the embedded particles. The total baryon density distributions are quite similar for the Λ-, Λ_c^+-, and Λ_b-hypernuclei multiplet which has the same baryon numbers A, since the effect of Λ, Λ_c^+, and Λ_b is $\cong 1/A$ for each hypernucleus. Nevertheless, one notices that the Λ_b-hypernuclei density near the center is slightly higher than the corresponding Λ and Λ_c^+ hypernuclei. This is because the Λ_b is heavy and localized nearer the center, and contributes to the total baryon density there. The baryon (probability) density distributions for the Λ, Λ_c^+, and Λ_b in corresponding hypernuclei will be shown later.

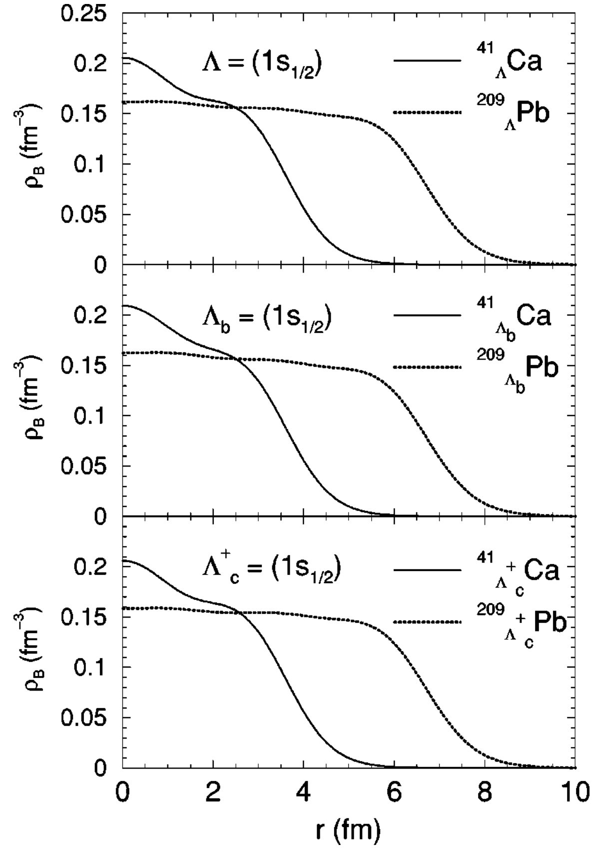

FIG. 1. Total baryon density distributions in $^{41}_{j}$Ca and $^{209}_{j}$Pb ($j = \Lambda, \Lambda_c^+, \Lambda_b$), for the $1s_{1/2}$ configuration for the Λ, Λ_c^+, and Λ_b.

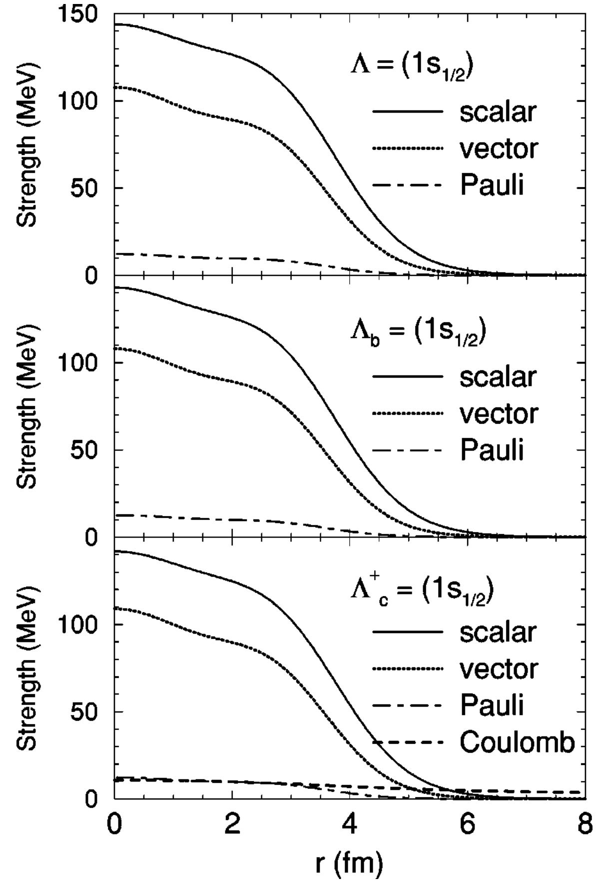

FIG. 2. Potential strengths for the $1s_{1/2}$ state felt by the Λ, Λ_c^+, and Λ_b in $^{41}_{j}$Ca ($j = \Lambda, \Lambda_c^+, \Lambda_b$). "Pauli" stands for the effective, repulsive, potential representing the Pauli blocking at the quark level plus the $\Sigma_{c,b}N$-$\Lambda_{c,b}N$ channel coupling, introduced at the baryon level phenomenologically [10].

Next, in Figs. 2 and 3, we show the scalar and vector potentials felt by the Λ, Λ_c^+, and Λ_b for $1s_{1/2}$ state in $^{41}_{j}$Ca and $^{209}_{j}$Pb ($j = \Lambda, \Lambda_c^+, \Lambda_b$) and the corresponding probability density distributions in Fig. 4. In Figs. 2 and 3 "Pauli" stands for the effective, repulsive, potential representing the Pauli blocking at the quark level plus the $\Sigma_{c,b}N$-$\Lambda_{c,b}N$ channel coupling, introduced at the baryon level phenomenologically [10]. For the Λ_c^+, the Coulomb potentials are also shown. As for the case of nuclear matter [1], the scalar and vector potentials felt by these particles in the hypernuclei multiplet which has the same baryon numbers are also quite similar. Thus, as far as the total baryon density distributions and the scalar and vector potentials are concerned, Λ, Λ_c^+, and Λ_b hypernuclei show quite similar features within the multiplet. However, as shown in Fig. 4, the wave functions obtained for the $1s_{1/2}$ state are very different. The Λ_c^+ baryon density distribution in $^{209}_{\Lambda_c^+}$Pb is much more pushed away from the center than that for the Λ in $^{209}_{\Lambda}$Pb due to the Coulomb force. On the contrary, the Λ_b baryon density distributions in Λ_b hypernuclei are much larger near the origin than those for the Λ in the corresponding Λ hypernuclei due to its heavy mass.

Having obtained reasonable ideas about the potentials felt by Λ, Λ_c^+, and Λ_b, we show the calculated single-particle energies in Tables I and II. Results for the Λ hypernuclei are from Ref. [10]. In these calculations, effective Pauli blocking, the effect of the $\Sigma_{c,b}N$-$\Lambda_{c,b}N$ channel coupling, and correction to the spin-orbit force based on the underlying quark structure are included in the same way as adopted in Ref. [10]. (However, recall the negligibly small contribution from the correction terms for the spin-orbit force and also contributions from the spin-orbit force itself.) Note that since the mass difference of the Λ_c^+ and Σ_c is larger than that of the Λ and Σ, and it is probably also true for the Λ_b and Σ_b, we expect the effect of the channel coupling for the charmed and bottom hypernuclei is smaller than those for the strange hypernuclei, although the same parameters were used in the present calculation. In addition, we searched for the single-particle states up to the same highest state as that of the core neutrons in each hypernucleus, since the deeper levels are usually easier to observe in experiment.

In Tables I and II, it is clear that the Λ_c^+ single-particle energy levels are higher than the corresponding levels for the Λ and Λ_b. This is a consequence of the Coulomb force. This feature becomes stronger as the proton number in the core nucleus increases.

Second, the level spacing for the Λ_b single-particle energies is much smaller than that for the Λ and Λ_c^+. This may be ascribed to its heavy mass (or $M_b^\star$). In the Dirac equation for the Λ_b, the mass term dominates more than that of the

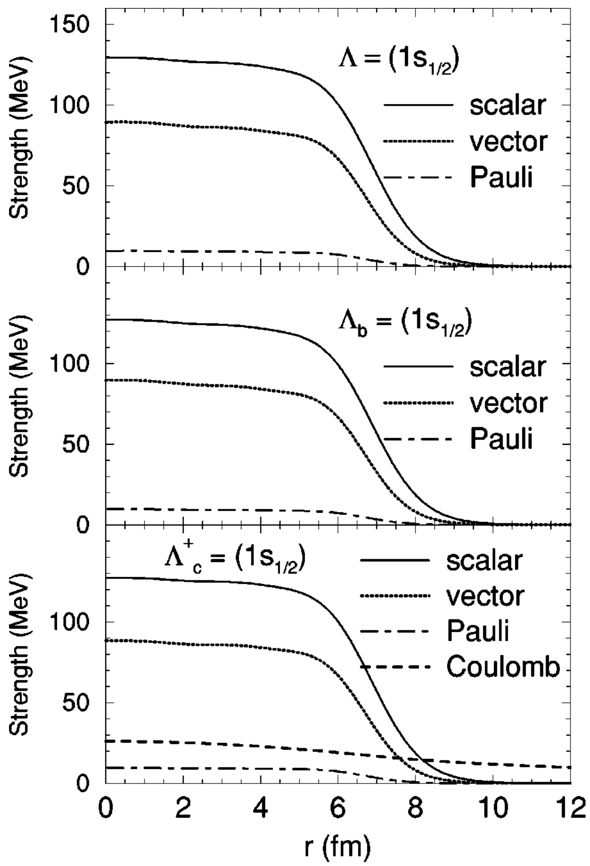

FIG. 3. Potential strengths for the $1s_{1/2}$ state felt by the Λ, Λ_c^+, and Λ_b in $^{209}_{j}$Pb ($j=\Lambda,\Lambda_c^+,\Lambda_b$). See also the caption of Fig. 2.

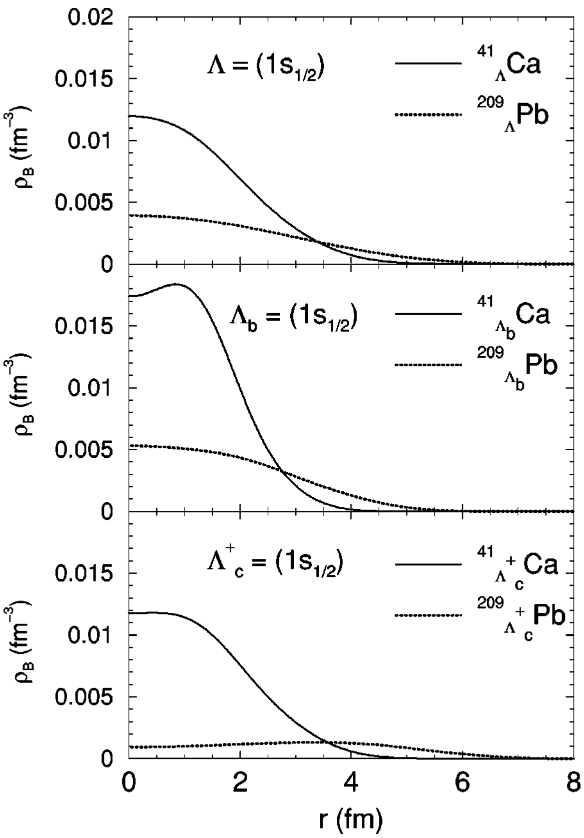

FIG. 4. Λ, Λ_c^+, and Λ_b baryon (probability) density distributions for the $1s_{1/2}$ state in $^{41}_{j}$Ca and $^{209}_{j}$Pb ($j=\Lambda,\Lambda_c^+,\Lambda_b$).

term proportional to Dirac's κ, which classifies the states or single-particle wave functions. (See Refs. [9,10] for details.) This small level spacing would make it very difficult to distinguish the states in experiment or to achieve such high resolution. On the other hand, this may imply also many new phenomena. It will have a large probability to trap a Λ_b among one of those many states, especially in a heavy nucleus such as lead (Pb). What are the consequences? May it be that the Λ_b weak decay happens inside a heavy nucleus with a very low probability? Does it emit many photons when the Λ_b gradually makes a transition from a deeper state to a shallower state? All these questions raise a flood of speculations.

To summarize, we have made a quantitative study of Λ_c^+ and Λ_b hypernuclei in a quark-meson coupling model. We have solved a system of equations in a self-consistent approach for several finite nuclei with a closed shell plus a hyperon (Λ_c^+ or Λ_b) embedding a Λ_c^+ or Λ_b in the nucleus. Results are compared with those for the Λ hypernuclei. It is shown that, although the scalar and vector potentials felt by the Λ, Λ_c^+, and Λ_b are quite similar in corresponding hy-

TABLE I. Single-particle energies (in MeV) for $^{17}_{j}$O, $^{41}_{j}$Ca, and $^{49}_{j}$Ca ($j=\Lambda,\Lambda_c^+,\Lambda_b$). Single-particle energy levels are calculated up to the same highest states as that of the core neutrons. Results for the hypernuclei are taken from Ref. [10]. Experimental data for Λ hypernuclei are taken from Ref. [28], where spin-orbit splittings for Λ hypernuclei are not well determined by the experiments.

	$^{16}_{\Lambda}$O (Expt.)	$^{17}_{\Lambda}$O	$^{17}_{\Lambda_c^+}$O	$^{17}_{\Lambda_b}$O	$^{40}_{\Lambda}$Ca (Expt.)	$^{41}_{\Lambda}$Ca	$^{41}_{\Lambda_c^+}$Ca	$^{41}_{\Lambda_b}$Ca	$^{49}_{\Lambda}$Ca	$^{49}_{\Lambda_c^+}$Ca	$^{49}_{\Lambda_b}$Ca
$1s_{1/2}$	−12.5	−14.1	−12.8	−19.6	−20.0	−19.5	−12.8	−23.0	−21.0	−14.3	−24.4
$1p_{3/2}$	−2.5	−5.1	−7.3	−16.5	−12.0	−12.3	−9.2	−20.9	−13.9	−10.6	−22.2
$1p_{1/2}$	($1p_{3/2}$)	−5.0	−7.3	−16.5	($1p_{3/2}$)	−12.3	−9.1	−20.9	−13.8	−10.6	−22.2
$1d_{5/2}$						−4.7	−4.8	−18.4	−6.5	−6.5	−19.5
$2s_{1/2}$						−3.5	−3.4	−17.4	−5.4	−5.3	−18.8
$1d_{3/2}$						−4.6	−4.8	−18.4	−6.4	−6.4	−19.5
$1f_{7/2}$									—	−2.0	−16.8

TABLE II. Single-particle energies (in MeV) for ${}^{91}_{j}$Zr and ${}^{208}_{j}$Pb ($j=\Lambda,\Lambda_c^+,\Lambda_b$). Experimental data are taken from Ref. [29]. See caption of Table I for other explanations.

	${}^{89}_{\Lambda}$Yb (Expt.)	${}^{91}_{\Lambda}$Zr	${}^{91}_{\Lambda_c^+}$Zr	${}^{91}_{\Lambda_b}$Zr	${}^{208}_{\Lambda}$Pb (Expt.)	${}^{209}_{\Lambda}$Pb	${}^{209}_{\Lambda_c^+}$Pb	${}^{209}_{\Lambda_b}$Pb
$1s_{1/2}$	−22.5	−23.9	−10.8	−25.7	−27.0	−27.0	−5.2	−27.4
$1p_{3/2}$	−16.0	−18.4	−8.7	−24.2	−22.0	−23.4	−4.1	−26.6
$1p_{1/2}$	($1p_{3/2}$)	−18.4	−8.7	−24.2	($1p_{3/2}$)	−23.4	−4.0	−26.6
$1d_{5/2}$	−9.0	−12.3	−5.8	−22.4	−17.0	−19.1	−2.4	−25.4
$2s_{1/2}$	—	−10.8	−3.9	−21.6	—	−17.6	—	−24.7
$1d_{3/2}$	($1d_{5/2}$)	−12.3	−5.8	−22.4	($1d_{5/2}$)	−19.1	−2.4	−25.4
$1f_{7/2}$	−2.0	−5.9	−2.4	−20.4	−12.0	−14.4	—	−24.1
$2p_{3/2}$	—	−4.2	—	−19.5	—	−12.4	—	−23.2
$1f_{5/2}$	($1f_{7/2}$)	−5.8	−2.4	−20.4	($1f_{7/2}$)	−14.3	—	−24.1
$2p_{1/2}$		−4.1	—	−19.5	—	−12.4	—	−23.2
$1g_{9/2}$		—	—	−18.1	−7.0	−9.3	—	−22.6
$1g_{7/2}$					($1g_{9/2}$)	−9.2	—	−22.6
$1h_{11/2}$						−3.9	—	−21.0
$2d_{5/2}$						−7.0	—	−21.7
$2d_{3/2}$						−7.0	—	−21.7
$1h_{9/2}$						−3.8	—	−21.0
$3s_{1/2}$						−6.1	—	−21.3
$2f_{7/2}$						−1.7	—	−20.1
$3p_{3/2}$						−1.0	—	−19.6
$2f_{5/2}$						−1.7	—	−20.1
$3p_{1/2}$						−1.0	—	−19.6
$1i_{13/2}$						—	—	−19.3

pernuclei multiplets which have the same baryon numbers, the single-particle wave functions and single-particle energy level spacings are quite different. For the Λ_c^+ hypernuclei, the Coulomb force plays a crucial role and so does the heavy Λ_b mass for the Λ_b hypernuclei. It should be emphasized that we have used the values for the coupling constants of σ (or σ-field-dependent strength), ω, and ρ to the Λ, Λ_c^+, and Λ_b determined automatically based on the underlying quark model, as for the nucleon and other baryons. [Recall that the values for the vector ω fields to any baryons can be obtained by the number of light quarks in a baryon, but those for the σ are different as shown in Eqs. (10) and (11).] Phenomenology would determine ultimately if the coupling constants (strengths) determined by the underlying quark model actually work for Λ_c^+ and Λ_b or not. Although the implications of the present results can be speculated on a great deal, we would like to emphasize that what we showed is that the Λ_c^+ and Λ_b hypernuclei would exist in realistic experimental conditions. Experiments at facilities like JHF would provide further input to gain a better understanding of the interaction of Λ_c^+ and Λ_b with nuclear matter. Additional studies are needed to investigate the semileptonic weak decay of Λ_c^+ and Λ_b hyperons. To determine the role of Pauli blocking and density in influencing the decay rates as compared to the free hyperons would be highly useful. Such a study can have an impact on the hadronization of the quark-gluon plasma and the transport of hadrons in nuclear matter of high density. Will the high density lead to a slower decay and a higher probability to survive its passage through the material? At present the study of the presence of Λ_c^+ and Λ_b in finite nuclei is its infancy. Careful investigations, both theoretical and experimental, would lead to a much better understanding of the role of heavy quarks in finite nuclei.

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