Pentaquark Θ^+ in nuclear matter and Θ^+ hypernuclei

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(Received 17 October 2004; published 30 June 2005)

We study the properties of the Θ^+ in nuclear matter and Θ^+ hypernuclei within the quark mean-field model, which has been successfully used for the description of ordinary nuclei and Λ hypernuclei. With the assumption that the nonstrange mesons couple only to the *u* and *d* quarks inside baryons, a sizable attractive potential of the Θ^+ in nuclear matter is achieved as a consequence of the cancellation between the attractive scalar potential and the repulsive vector potential. We investigate the Θ^+ single-particle energies in light, medium, and heavy nuclei. More bound states are obtained in Θ^+ hypernuclei in comparison with those in Λ hypernuclei.

DOI: 10.1103/PhysRevC.71.065208 PACS number(s): 21.65.+f, 21.30.Fe, 21.60.−n, 21.80.+a

I. INTRODUCTION

The signature of the pentaquark was found in an experiment with giga-electron-volt photons on ^{12}C at the Laser-Electron Photon facility at SPring-8 (LEPS) [1,2]. The $\gamma n \to K^+K^-n$ reaction was analyzed, and a narrow resonance state was identified with a mass of 1.54 GeV and a width smaller than 25 MeV. Such a narrow state was predicted by Diakonov Petrov, and Polyakov [3] as a pentaquark state at nearly the same energy. There were many experimental works published after the original study that used various reactions [4]. Recently, many further experiments, particularly at very high energies, reported negative results, except for a few positive results [4]. At this moment, the spin and parity of the state are not known. Even the width is not precisely identified experimentally.

There are many theoretical works [4]. It seems that those models, which emphasize the importance of the chiral symmetry, suggest the positive parity ($J^P = 1/2^+$) of the original predication of Diakonov *et al.* [3]. On the other hand, the naive constituent quark models tend to provide the negative parity ($J^P = 1/2^-$). The QCD-originated works, such as the lattice QCD and the QCD sum-rule approaches, seem to provide the negative parity, although these methods face the difficulty of handling the nearby K^+n threshold and the small pion mass. Hence we are at this moment not sure about the presence of the pentaquark state, the spin-parity, and even the width of this state [4].

We should make further efforts to get more information for the pentaquark state. There are several interesting theoretical works that study the pentaquark in nuclear medium [5–9]. In Ref. [7], the authors study the interaction of the pentaquark with nucleons by using the meson-exchange model. They obtained a large binding potential with a small width to take the pentaquark nucleus seriously. This work then motivated a theoretical work to calculate the (K^+, π^+) reaction for the formation of the pentaquark nuclei [10]. There is a good possibility of seeing the Θ^+ hypernucleus in such a reaction. It is then very interesting to study the Θ^+ hypernucleus from a different viewpoint.

We studied nuclei and hypernuclei in terms of the quark mean-field (QMF) model [11,12]. We assume in the QMF model that up and down quarks in the baryons interact with σ, ω, and ρ mesons (mesons made of up and down quarks) in nuclear matter and in nuclei. Hence the interaction of the Θ^+ with other nucleons is obtained without the introduction of new parameters in the QMF model. The only assumption needed here is that the isospin of the Θ^+ is $I = 0$. The interactions of quarks with the meson fields change the properties of the baryons in hadronic matter, and hence the hadronic matter property is obtained from these interactions self-consistently.

In the next section, we present the formulation of the Θ^+ hypernuclei in the relativistic QMF model. In Sec. III, we provide the numerical results for various Θ^+ hypernuclei. Section IV is be devoted to the conclusion and discussions.

II. QUARK MEAN-FIELD MODEL FOR THE Θ^+ IN MEDIUM

We start with the description of the Θ^+ in nuclear medium, which is comparable with the treatment of Λ hypernuclei in our previous work [12]. The Θ^+ is known to be an exotic baryon containing five quarks ($uudd\bar{s}$) with strangeness $S = +1$, isospin $I = 0$, and charge $Q = +1$. However, its parity is still ambiguous experimentally. In this work, we use the constituent quark model to describe the Θ^+ and nucleons in medium, whereas the exchanged mesons couple directly to the quarks inside baryons. The constituent quarks satisfy the Dirac equation:

$$\left[i\gamma_\mu\partial^\mu - m_q - \chi_c - g_\sigma^q\sigma - g_\omega^q\omega\gamma^0 - g_\rho^q\rho\tau_3\gamma^0\right]\phi^q(r) = 0, \tag{1}$$

where χ_c is the confining potential taken as the quadratic form, $\chi_c = \frac{1}{2}kr^2$. Because the Lorentz structure of the confining interaction is not well known yet, here we use a scalar confinement. In our previous studies for finite nuclei and Λ hypernuclei [11,12], both scalar and scalar-vector confinements have been taken into account, but it is known that antiquarks cannot be confined by a scalar-vector confinement when the

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vector part is equal or larger than the scalar part. Therefore we just adopt the scalar confinement in the present calculation of Θ^+. We assume that the nonstrange mesons, σ, ω, and ρ, couple exclusively to the up and down quarks and not to the strange quark (or antiquark) according to the Okubo-Zweig-Iizuka (OZI) rule; hence the strange antiquark inside Θ^+ satisfies the Dirac equation in which the terms coupled to the nonstrange mesons vanish ($g_\sigma^{s,\bar{s}} = g_\omega^{s,\bar{s}} = g_\rho^{s,\bar{s}} = 0$). We note that the Dirac equation for the strange antiquark $\bar{s}$ in Θ^+ is identical to the equation for the strange quark s in Λ when a scalar confining potential is adopted in Eq. (1). We follow Ref. [11] to take into account the spin correlations and remove the spurious center-of-mass motion, and then obtain the effective mass of the Θ^+ in medium as

$$M_\Theta^* = \sqrt{\left(4e_q + e_{\bar{s}} + E_{\rm spin}^\Theta\right)^2 - \left(4\langle p_q^2\rangle + \langle p_{\bar{s}}^2\rangle\right)}, \qquad (2)$$

and the effective mass of the nucleon is expressed as

$$M_N^* = \sqrt{\left(3e_q + E_{\rm spin}^N\right)^2 - 3\langle p_q^2\rangle}. \qquad (3)$$

Here, the subscript q denotes the u or d quark. We can obtain the energies (e_q and $e_{\bar{s}}$) and momenta ($\langle p_q^2\rangle$ and $\langle p_{\bar{s}}^2\rangle$) by solving the corresponding equations. We determine the spin correlations ($E_{\rm spin}^\Theta$ and $E_{\rm spin}^N$), which are taken as parameters in the QMF model, by fitting the baryon masses in free space ($M_\Theta = 1540$ MeV and $M_N = 939$ MeV). The effective masses of baryons are influenced by the σ mean field in nuclear medium, which provides a scalar potential to the u and d quarks in baryons and as a consequence reduces the constituent quark mass to $m_q^* = m_q + g_\sigma^q \sigma$ ($q = u, d$). However, the ω and ρ mean fields could not cause any change in the baryon masses, and they appear merely as the energy shift. Therefore we obtain the effective masses of baryons as functions of the σ mean field, $M_\Theta^*(\sigma)$ and $M_N^*(\sigma)$, expressed by Eqs. (2) and (3).

We now derive a self-consistent treatment for a Θ^+ hypernucleus, which contains a pentaquark Θ^+ and many nucleons. The baryons in this system interact through the exchange of σ, ω, and ρ mesons, just as in the case of a single Λ hypernucleus. The effective Lagrangian at the hadron level within the mean-field approximation can be written as

$$\begin{aligned}\mathcal{L} = {}& \bar{\psi}\Big[i\gamma_\mu\partial^\mu - M_N^*(\sigma) - g_\omega\omega\gamma^0 - g_\rho\rho\tau_3\gamma^0 \\ & - e\frac{(1+\tau_3)}{2}A\gamma^0\Big]\psi + \bar{\psi}_\Theta\left[i\gamma_\mu\partial^\mu - M_\Theta^*(\sigma)\right. \\ & \left. - g_\omega^\Theta\omega\gamma^0 - eA\gamma^0\right]\psi_\Theta - \frac{1}{2}(\nabla\sigma)^2 - \frac{1}{2}m_\sigma^2\sigma^2 \\ & - \frac{1}{4}g_3\sigma^4 + \frac{1}{2}(\nabla\omega)^2 + \frac{1}{2}m_\omega^2\omega^2 + \frac{1}{4}c_3\omega^4 \\ & + \frac{1}{2}(\nabla\rho)^2 + \frac{1}{2}m_\rho^2\rho^2 + \frac{1}{2}(\nabla A)^2, \end{aligned} \qquad (4)$$

where ψ and ψ_Θ are the Dirac spinors for the nucleon and Θ^+. The mean-field values are denoted by σ, ω, and ρ, respectively, and m_σ, m_ω, and m_ρ are the masses of these mesons. The electromagnetic field, denoted by A, couples to both the proton and Θ^+, which carry a positive charge. The influences of the σ mean field on baryons are contained in the effective masses $M_N^*(\sigma)$ and $M_\Theta^*(\sigma)$. The ω meson, which couples directly to the u and d quarks inside baryons, provides an interaction at the hadron level with the coupling constant $g_\omega^i = n_i g_\omega^q$, where n_i is the number of the u and d quarks in the baryon i. When $i = \Theta^+$ ($i = N$), we get $g_\omega^\Theta = 4g_\omega^q$ ($g_\omega^N = g_\omega = 3g_\omega^q$). The ρ meson does not couple to the Θ^+, which is an isoscalar particle, but it couples to the nucleon with the coupling constant $g_\rho^N = g_\rho = g_\rho^q$, as given in Ref. [11]. In the QMF model, the basic parameters are the quark-meson couplings (g_σ^q, g_ω^q, and g_ρ^q), the nonlinear self-coupling constants (g_3 and c_3), and the mass of the σ meson (m_σ), which we have determined by fitting the properties of nuclear matter and finite nuclei in Ref. [11]. Therefore, no more adjustable parameters exist when it is extended to the calculations for Θ^+ or Λ hypernuclei. From the Lagrangian given in Eq. (4), we obtain the following Euler-Lagrange equations:

$$\Big[i\gamma_\mu\partial^\mu - M_N^*(\sigma) - g_\omega\omega\gamma^0 - g_\rho\rho\tau_3\gamma^0 - e\frac{(1+\tau_3)}{2}A\gamma^0\Big]\psi = 0, \qquad (5)$$

$$\left[i\gamma_\mu\partial^\mu - M_\Theta^*(\sigma) - g_\omega^\Theta\omega\gamma^0 - eA\gamma^0\right]\psi_\Theta = 0, \qquad (6)$$

$$\left(-\Delta + m_\sigma^2\right)\sigma = -\frac{\partial M_N^*(\sigma)}{\partial\sigma}\rho_s - \frac{\partial M_\Theta^*(\sigma)}{\partial\sigma}\rho_s^\Theta - g_3\sigma^3, \qquad (7)$$

$$\left(-\Delta + m_\omega^2\right)\omega = g_\omega\rho_v + g_\omega^\Theta\rho_v^\Theta - c_3\omega^3, \qquad (8)$$

$$\left(-\Delta + m_\rho^2\right)\rho = g_\rho\rho_3, \qquad (9)$$

$$-\Delta A = e\left(\rho_p + \rho_v^\Theta\right), \qquad (10)$$

where ρ_s (ρ_s^Θ), ρ_v (ρ_v^Θ), ρ_3, and ρ_p are the scalar, vector, third component of isovector, and proton densities, respectively. The preceding coupled equations are solved self-consistently with the effective masses $M_N^*(\sigma)$ and $M_\Theta^*(\sigma)$ obtained at the quark level.

The application of the QMF model to the description of Λ hypernuclei has been reported in our previous work [12]. Without the adjustment of any parameters, the properties of Λ hypernuclei could be described reasonably well. The Λ single-particle energies obtained in the QMF model are slightly underestimated in comparison with the experimental values. In the present work, we investigate the Θ^+ hypernuclei within the QMF model and then provide the predictions for Θ^+ single-particle energies in light, medium, and heavy nuclei.

III. NUMERICAL RESULTS

In this section, we present the results calculated in the QMF model for the Θ^+ in nuclear medium. We need first to specify the parameters used in the present calculation. For the parameters at the quark level, we take the constituent quark masses $m_u = m_d = 313$ MeV and $m_s = m_{\bar{s}} = 490$ MeV, and the strength of the confining potential $k = 700$ MeV/fm^2, the same as those used in the case of Λ hypernuclei [12]. The meson masses are taken as $m_\sigma = 470$ MeV, $m_\omega = 783$ MeV, and $m_\rho = 770$ MeV. We determined the quark-meson couplings, $g_\sigma^q = 3.14$, $g_\omega^q = 4.20$ and $g_\rho^q = 4.3$, and the nonlinear self-coupling constants, $g_3 = 50.7$ and $c_3 = 53.6$, by fitting the following equilibrium properties of nuclear matter:

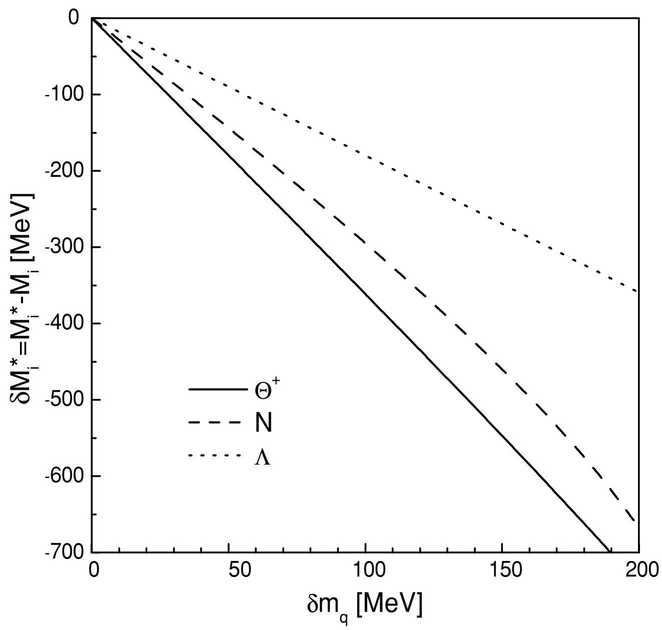

FIG. 1. Variations of the baryon effective masses, $\delta M_i^* = M_i^* - M_i$ ($i = N, \Lambda, \Theta^+$), as functions of the quark mass correction, $\delta m_q = m_q - m_q^* = -g_\sigma^q \sigma$.

equilibrium density $\rho_0 = 0.145$ fm^{-3}; binding energy $E/A = -16.3$ MeV; incompressibility $k = 280$ MeV; effective mass $M_N^* = 0.63\ M_N$; and symmetry energy $a_{\rm sym} = 35$ MeV. With the preceding parameters, the QMF model has provided quite satisfactory results for finite nuclei and Λ hypernuclei [11,12]. Now we take the same parameters as those we used above to perform the calculations for the Θ^+ in nuclear medium.

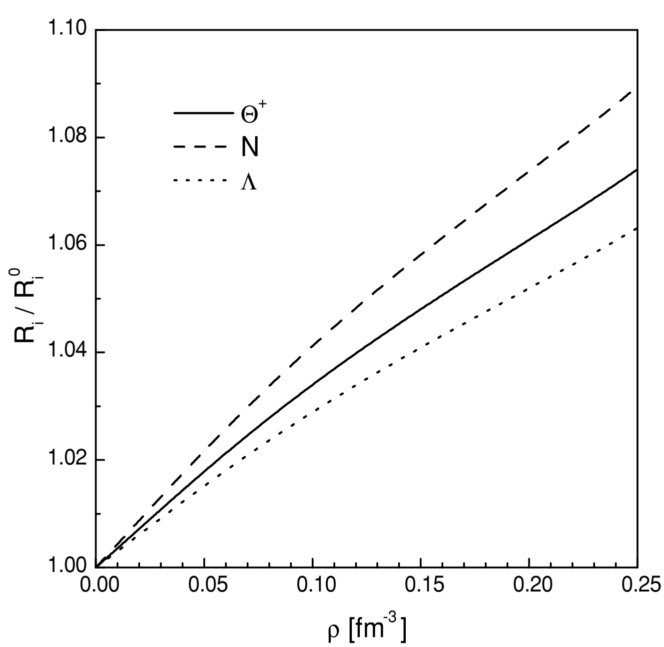

FIG. 2. Ratios of the baryon radii in nuclear matter R_i to that in free space R_i^0 as functions of the nuclear matter density ρ.

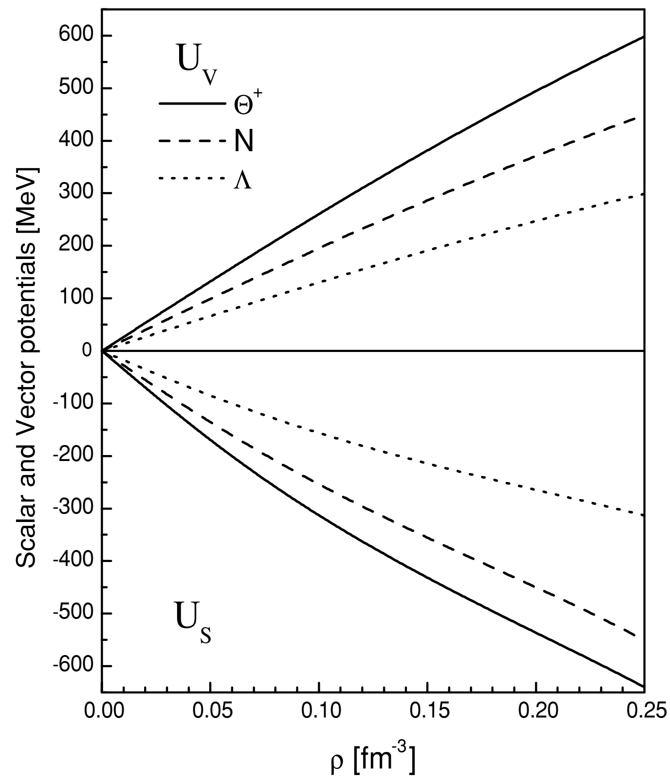

FIG. 3. Scalar and vector potentials U_S and U_V as functions of the nuclear matter density ρ.

It is interesting to see how the Θ^+ properties change in nuclear matter. In Fig. 1, we present the variation of the effective mass of the Θ^+, in compared with those for the nucleon and Λ, as a function of the quark mass correction that is due to the presence of the σ mean field, $\delta m_q = m_q - m_q^* = -g_\sigma^q \sigma$ ($q = u, d$). It is obvious that the reduction of M_Θ^* is larger than those of M_N^* and M_Λ^*, as there are four u and d quarks in the Θ^+ that are influenced by the σ mean field, but only three or two quarks influenced in the nucleon or Λ. We note that the dependence of the effective masses on the σ mean field must be calculated self-consistently within the quark model; therefore the effective masses of baryons obtained in the QMF model are not simply linear functions of σ, as given in the relativistic mean field (RMF) models [13,14]. We show in Fig. 2 the ratios of the baryon radii in medium to those in free space as functions of the nuclear matter density. It is found that all of the baryons, Θ^+, Λ, and N (nucleon), show a significant increase in radius in nuclear medium, which is consistent with the famous European Muon Collaboration (EMC) effect. The nucleon gains a larger increase in radius than Θ^+ and Λ, because all three quarks in N are involved in the interactions with mesons whereas only four-fifths in Θ^+ and two-thirds in Λ are involved. The baryon radii increase by about 4%–6% at normal matter density in the present model. In Fig. 3, we plot the scalar and vector potentials of the Θ^+ in medium as functions of the nuclear matter density, and the results of the nucleon (N) and Λ are also shown for comparison. At $\rho = \rho_0 = 0.145$ fm^{-3}, we get $U_S^\Theta = -420$ MeV and $U_V^\Theta = 370$ MeV; therefore an residual

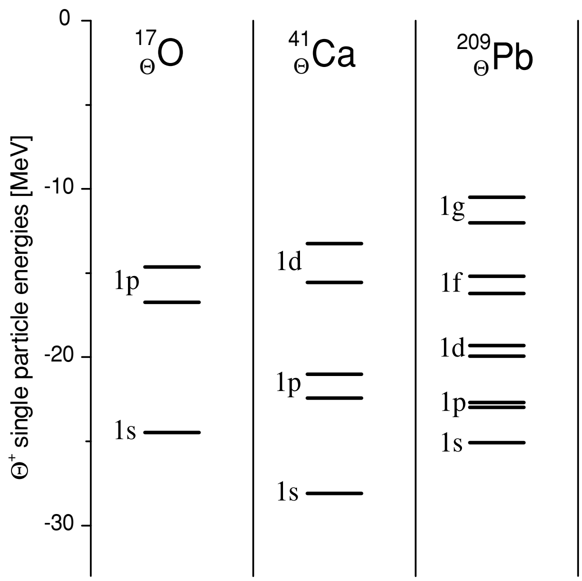

FIG. 4. Θ^+ single-particle energies in $^{17}_{\Theta}$O, $^{41}_{\Theta}$Ca, and $^{209}_{\Theta}$Pb.

attractive Θ^+ potential, $U^{\Theta} = U_S^{\Theta} + U_V^{\Theta} = -50$ MeV, is predicted in the present model. For Λ at $\rho = \rho_0$, we have the potential $U^{\Lambda} = U_S^{\Lambda} + U_V^{\Lambda} = -24$ MeV, which is approximately half of the Θ^+ potential. In Ref. [7], a large attractive Θ^+ potential ranging from -60 to -120 MeV at normal matter density was predicted by calculation of the Θ^+ self-energy tied to the *KN* decay of the Θ^+ and the two meson baryon decay channels of the Θ^+ partners in an antidecuplet of baryons. A QCD sum-rule calculation [8] predicted an attractive Θ^+ potential of about -40 to -90 MeV. Therefore the prediction of the Θ^+ potential in the QMF model is compatible with the results obtained by other groups [7,8].

We now present the results of self-consistent calculations for the Θ^+ hypernuclei containing a Θ^+ bound in nuclei. In Fig. 4, we show the predicted Θ^+ single-particle energies in $^{17}_{\Theta}$O,$^{41}_{\Theta}$ Ca, and $^{209}_{\Theta}$Pb. It is found that there are many bound states of the Θ^+ in light, medium, and heavy nuclei. We can see that the separation between the deep Θ^+ energy levels is comparable with the Θ^+ width. The theoretical prediction of the free Θ^+ width in the chiral soliton model is less than 15 MeV [3], and the Θ^+ width in medium might be reduced to approximately one-third or less of the free width because of Pauli blocking and binding, as pointed out in Ref. [7]. It is clear that large separation of the deep Θ^+ levels helps us to observe distinct peaks in the experiment to produce Θ^+ bound states [10]. It is very interesting to compare the results of Θ^+ hypernuclei with those of Λ hypernuclei. We can see that the single-particle energy of $1s_{1/2}$ Θ^+ in $^{209}_{\Theta}$Pb is smaller than the one in $^{41}_{\Theta}$Ca, which is contrary to the results of Λ hypernuclei. This is mainly because Θ^+ carrying a positive charge behaves like a proton in nuclei, whereas Λ is a charge-neutral particle, more like a neutron. The Coulomb energies of Θ^+ in heavy nuclei are much larger than those in light nuclei; Θ^+ single-particle energies in heavy nuclei can be reduced by the large positive Coulomb energy. We plot in Fig. 5 the scalar, vector, and Coulomb potentials in $^{41}_{\Theta}$Ca with a Θ^+ bound at

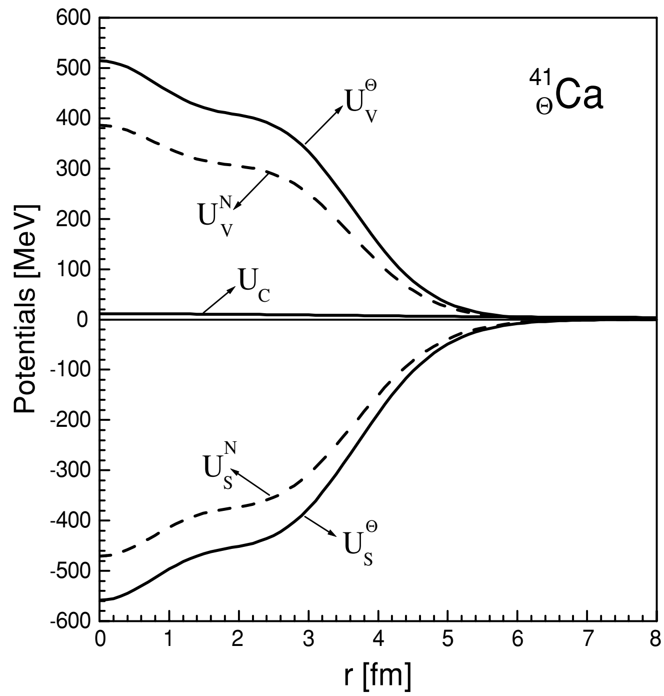

FIG. 5. Scalar potential U_S^i, vector potential U_V^i, and Coulomb potential U_C for the nucleon ($i = N$) and the Θ^+ ($i = \Theta$) in $^{41}_{\Theta}$Ca with a Θ^+ bound at $1s_{1/2}$ state.

$1s_{1/2}$ state. At the center of the Θ^+ hypernucleus, the attractive scalar potential ($U_S^{\Theta} \sim -559$ MeV) is partly canceled by the repulsive vector potential ($U_V^{\Theta} \sim 515$ MeV) and Coulomb potential ($U_C \sim 11$ MeV), and as a consequence, an attractive Θ^+ potential ($U^{\Theta} \sim -33$ MeV) remains in this case.

It is interesting and important to compare the results of the QMF model with those obtained by other groups [7,9] and to discuss the origin of the differences in the Θ^+ single-particle energies. More bound states of the Θ^+ in nuclei were predicted in some recent works [7,9]. In Ref. [7], the authors obtained more deeply bound states by solving the Schrödinger equation with two potentials: $V(r) = -60\rho(r)/\rho_0$ MeV and $V(r) = -120\rho(r)/\rho_0$ MeV. It is obvious that larger Θ^+ single-particle energies should be achieved because of the deeper Θ^+ potentials used in their calculations. In Ref. [9], the Θ^+ hypernuclei were studied by use of the RMF model with the Θ^+ couplings, $g_{\sigma}^{\Theta} = \frac{4}{3}g_{\sigma}$ and $g_{\omega}^{\Theta} = \frac{4}{3}g_{\omega}$, which are the quark model predictions close to those given in the QMC model. It may be helpful to look at the case of Λ hypernuclei, because of the similarity of the Θ^+ hypernuclei and Λ hypernuclei. It is well known that the properties of Λ hypernuclei are very sensitive to the effective coupling constants at the hadron level, especially the two relative couplings $R_{\sigma}^{\Lambda} = g_{\sigma}^{\Lambda}/g_{\sigma}$ and $R_{\omega}^{\Lambda} = g_{\omega}^{\Lambda}/g_{\omega}$ [15]. The quark model prediction, $R_{\sigma}^{\Lambda} = R_{\omega}^{\Lambda} = 2/3$, usually gives a large overbinding of Λ single-particle energies in comparison with the experimental values. For example, by taking the TM1 parameter set in the RMF model with $R_{\sigma}^{\Lambda} = R_{\omega}^{\Lambda} = 2/3$, we calculate the $1s_{1/2}$ Λ single-particle energy in $^{41}_{\Lambda}$Ca as to be -35.2 MeV, whereas in the case of the NL-SH parameter set used, it is -36.8 MeV. We note that the experimental value of the $1s_{1/2}$ Λ binding energy in $^{40}_{\Lambda}$Ca is approximately −18.7 MeV. Usually some small deviations from $R_\sigma^\Lambda = R_\omega^\Lambda = 2/3$ should be taken into account in the studies of Λ hypernuclei in order to reproduce the experimental values [15]. It has been pointed out that an ∼10% increase from $R_\omega^\Lambda = 2/3$ seemed to be needed to improve the overestimated Λ single-particle energies in the QMC model, as the R_σ^Λ calculated at the quark level in the QMC model was very close to 2/3 [16,17]. On the other hand, the QMF model yielded slightly underestimated Λ single-particle energies because of a smaller value than 2/3 of the R_σ^Λ obtained in the QMF model, which required an ∼3% reduction from $R_\omega^\Lambda = 2/3$ in order to reproduce the experimental values. It should be due to the same reason that the QMF model predicts relatively small Θ^+ single-particle energies in comparison with those obtained in the RMF model with the quark model value of the Θ^+ coupling, $g_\sigma^\Theta/g_\sigma = g_\omega^\Theta/g_\omega = 4/3$. In the QMF model, $g_\omega^\Theta = 4g_\omega^q = \frac{4}{3}g_\omega$ is adopted according to the assumption that nonstrange mesons couple to only the *u* and *d* quarks inside baryons, but $g_\sigma^\Theta = (\partial M_\Theta^*/\partial\sigma)$ has to be worked out self-consistently at the quark level. We note that the effective σ-baryon couplings in the QMF model are not simply constants as in the RMF model. Therefore the relative coupling obtained in the QMF model, $R_\sigma^\Theta = [\partial M_\Theta^*/\partial\sigma]/[\partial M_N^*/\partial\sigma]$, depends on the σ meanfield in medium, and we get smaller values than 4/3 for the R_σ^Θ in the QMF model. This is considered the dominant origin of the differences between the predictions given by the QMF model and those obtained in the RMF model [9].

To examine the sensitivity of Θ^+ single-particle energies to the Θ^+ couplings, we perform the same calculation with a reduced coupling $0.97 \times g_\omega^\Theta$. In this case, the $1s_{1/2}$ Θ^+ single-particle energy in $^{41}_{\Lambda}$Ca changes to −38.5 MeV from the value −27.9 MeV, as shown in Fig. 4. Hence a 3% reduction of g_ω^Θ can lead to an ∼10.6-MeV decrease of the $1s_{1/2}$ Θ^+ single-particle energy in $^{41}_{\Lambda}$Ca, and it provides ∼10-MeV more attraction for the Θ^+ potential in nuclear matter at normal matter density. In the present work, we have performed self-consistent calculations for both Θ^+ and nucleons in Θ^+ hypernuclei. By comparing the results of a normal nucleus containing *A* nucleons with those of the Θ^+ hypernucleus containing *A* nucleons and one Θ^+, the effects of the Θ^+ on nucleons can be found. The existence of the Θ^+ does enlarge the scalar and vector potentials of nucleons, but the enlargements mostly cancel with each other.

IV. CONCLUSIONS

We have studied the properties of the Θ^+ in nuclear matter and performed self-consistent calculations for Θ^+ hypernuclei in the framework of the QMF model, which has been successfully applied to the descriptions of stable nuclei and Λ hypernuclei. In the present work, we used the constituent quark model to describe the Θ^+ and nucleons, which naturally allows the direct coupling of exchanged mesons with quarks inside baryons. With the parameters determined by the equilibrium properties of nuclear matter and the assumption that nonstrange mesons couple to only the *u* and *d* quarks, an attractive Θ^+ potential has been achieved as a consequence of the cancellation between the attractive scalar potential and the repulsive vector potential in nuclear matter. The QMF model provides an attractive Θ^+ potential of ∼–50 MeV and yields a reduction of effective Θ^+ mass of ∼420 MeV as well as an ∼5% increase of the Θ^+ radius at normal matter density.

We investigated the Θ^+ single-particle energies in light, medium, and heavy nuclei. It was found that there are many bound states in Θ^+ hypernuclei, and the Θ^+ seems to be more deeply bound than the Λ in hypernuclei. We discussed the sensitivity of Θ^+ single-particle energies to the Θ^+ couplings. A comparison between the results calculated in the QMF model and those obtained by other groups was made, and the origin of the differences was also discussed with reference to the case of Λ hypernuclei. The results obtained in the QMF model provide encouragement for the experimental work to produce Θ^+ hypernuclei.

We comment here on a possible method for producing Θ^+ hypernuclei. The γ-induced reaction on a nucleus for the formation of the Θ^+ leads to the Θ^+ in a scattering state because of the large momentum transfer. On the other hand, the K^+-induced reaction with a nucleus could produce the Θ^+ with a reasonable momentum of the order of 500 MeV, when an outgoing pion is observed at the forward angle. This momentum transfer would lead to high angular momentum transfer of the order of $L \simeq 10$ when the Θ^+ is produced at the nuclear surface with a medium-heavy nuclei. Hence it is highly plausible that a sharp peak with high angular momentum could be observed; a high spin Θ^+–high-spin nucleon hole state, popping up in the beginning of the continuum region as the case of the (p,π^-) reaction [18].

ACKNOWLEDGMENTS

This work was supported in part by the National Natural Science Foundation of China (No. 10135030) and the Specialized Research Fund for the Doctoral Program of Higher Education (No. 20040055010).

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