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Charmed Deuteron

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Bound states of two baryons with one or two charm quarks, such as $\Lambda_c N$ and $\Lambda_c\Lambda_c$, are considered in the meson exchange potential model. Effective Lagrangian for light mesons and charmed baryons is constructed with chiral symmetry, heavy quark symmetry and hidden local symmetry. The π, ρ, ω, and the σ (a scalar meson for the correlated two-pion exchange) mesons are the main components. In particular, we point out that the tensor force due to the pion exchange, which induces the coupling of Λ_c with Σ_c and Σ_c^* baryons, plays important roles for the binding of the two baryons. We find that both the $\Lambda_c N$ system with spin 0 and 1 and also the $\Lambda_c\Lambda_c$ system with spin 0 will have a bound state. All the bound states have significant mixings of $\Sigma_c^{(*)}N$, or $\Sigma_c^{(*)}\Sigma_c^{(*)}$ components.

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1. Introduction

Recent developments of heavy hadron spectroscopy have revealed that newly observed quarkonium-like meson resonances, such as $X(3872)$, $Z(4430)$, $Z_b(10610)$ and $Z_b(10650)$, etc., seem to be "exotic" so that they are not simply $\bar{q}q$ states. It has been conjectured that those are either tetra-quarks ($q^2\bar{q}^2$) or molecular bound states of two heavy hadrons. These narrow states are novel in hadron physics because no corresponding states are found in light hadrons.

Here we explore possibility of having two baryon bound states with heavy quarks. It is very interesting to study possible two-baryon bound states in the heavy quark sector, because such bound states will give us precious information on the inter-baryon interactions and will open a new branch of exotic nuclear physics. We also note that the heavy quarks (c and b) are district because their masses m_c ($\sim$ 1.2 GeV), and m_b ($\sim$ 4.5 GeV) are much larger than the intrinsic scale of QCD, $\Lambda_{\rm QCD} \sim 250$MeV.

We have several new properties in the heavy baryon interactions.
(1) First, the heavy baryon mass suppresses the kinetic energy and favors forming bound states.
(2) Compared to the hyperon-nucleon interaction, where the kaon exchange is an important contributor, the heavy-quark mesons ($D(B)$, $D^*(B^*)$) are not significant in the meson exchange potentials, because it is suppressed by the factor $1/m_Q$, and the force range is short. Thus the meson exchange potential is dominated by the light-flavor mesons.
(3) The heavy quark spin symmetry makes the spin $1/2$ baryon Σ_Q and the spin $3/2$ baryon Σ_Q^* degenerate, and thus enhances couplings of Σ_Q and Σ_Q^* baryons. Accordingly effects of the channel coupling become important in the two baryon systems with heavy quarks.
These properties are important in studying the bound states of heavy-quark baryons.

In sect. 2, we consider the possible channel couplings for the charmed deuteron systems, and in sect. 3, we construct the chiral effective Lagrangian for the heavy baryon. In sect. 4, we show the results and the conclusion is given in sect. 5.

2. Charmed Deuteron

The interaction between the charmed baryon and the nucleon was first studied in Ref.[1], when the authors employed the meson-exchange potential approach based on the SU(4) symmetric extention of the Nijmegen NN potential model. Further studies of the same principle carried out by Bando and Nagata[2] found that both Λ_c- and Λ_b-nuclear bound states may exist for $A \geq 4$, while no two-body bound state was found.

On the other hand, our recent studies[3, 4] based on the modern effective theory with chiral symmetry and heavy-quark symmetry have shown that it is plausible to have $\Lambda_c N$ and also $\Lambda_c\Lambda_c$ bound states. It is found that a significant attraction is induced by the channel couplings. Table 1 summarizes the channels which are relevant for the bound states. The $J^\pi = 0^+$ bound state of $\Lambda_c N$ system is realized by coupling three channels, $\Lambda_c N$ ($^1S_0$), $\Sigma_c N$ ($^1S_0$), and $\Sigma_c^* N$ ($^5D_0$). The last one with ($J = 0$, $L = S = 2$) couples only by the tensor force, which comes from the one-pion exchange between the baryons. Seven channels given in Table 1 may contribute for the $J^\pi = 1^+$ $\Lambda_c N$ system. Among them, four channels are in the D wave so that only the tensor force can connect these states with the main component of the bound-state wave function.

J^π		channels for the single charm deuteron			
0^+	$L=0$	$\Lambda_c N(^1S_0)$	$\Sigma_c N(^1S_0)$		
	$L=2$	$\Sigma_c^* N(^5D_0)$			
1^+	$L=0$	$\Lambda_c N(^3S_1)$	$\Sigma_c N(^3S_1)$	$\Sigma_c^* N(^3S_1)$	
	$L=2$	$\Lambda_c N(^3D_1)$	$\Sigma_c N(^3D_1)$	$\Sigma_c^* N(^3D_1)$	$\Sigma_c^* N(^5D_1)$
J^π		channels for the double charm deuteron			
0^+	$L=0$	$\Lambda_c\Lambda_c(^1S_0)$	$\Sigma_c\Sigma_c(^1S_0)$	$\Sigma_c^*\Sigma_c^*(^1S_0)$	
	$L=2$	$\Sigma_c^*\Sigma_c^*(^5D_0)$	$\Sigma_c\Sigma_c^*(^5D_0)$		

Table 1: The channels relevant for the bound $\Lambda_c N$ ($J^\pi = 0^+$ and 1^+) and $\Lambda_c\Lambda_c$ ($J^\pi = 0^+$) states.

Similarly, five channels are considered for $\Lambda_c\Lambda_c$ with $I(J^\pi) = 0(0^+)$ (Table 1)[1]. Again, two of them, $\Sigma_c^*\Sigma_c^*(^5D_0)$ and $\Sigma_c\Sigma_c^*(^5D_0)$, are coupled by the tensor force. Note that $\Lambda_c\Lambda_c$ may mix also with $\Xi_{cc}N$ by exchanging charmed mesons. Since we consider a loosely bound molecular state, such a mixing occurring at short distance may be unimportant and thus the $\Xi_{cc}N$ channel is not included in the present work.[2]

3. Effective Interactions

The present approach takes the meson-exchange potential model for the long-range baryonic interaction. We employ an effective lagrangian for constructing the meson exchange potential. Only the light mesons are exchanged between the baryons so that the heavy quark flavor is not exchanged. We consider the pseudoscalar, scalar, and vector mesons, and construct an effective Lagrangian using chiral symmetry, heavy quark symmetry and hidden local symmetry[3].

The effective field theory is based on the $(1/m_Q)$ expansion, which leads to the super-selection rule of the heavy quark velocity. For small momentum transfer, the velocity (v^μ) of the heavy quark is preserved. Then, we can remove the large momentum component by defining a new effective heavy quark field, $Q_v(x) = e^{im_Q v\cdot x}Q(x)$ with $p_\mu = m_Q v_\mu + k_\mu$, where $k_\mu = O(\Lambda_{\rm QCD}) \ll m_Q v_\mu$.

In order to treat the heavy baryons, we introduce the flavor $\bar{3}$, $B_{\bar{3}}(J^\pi = 1/2^+)$, the flavor 6, $B_6(J^\pi = 1/2^+)$ and $B^*_{6\mu}(J^\pi = 3/2^+)$ baryon fields:[3]

$$B_{\bar{3}} = \begin{pmatrix} 0 & \Lambda_c^+ & \Xi_c^+ \\ -\Lambda_c^+ & 0 & \Xi_c^0 \\ -\Xi_c^+ & -\Xi_c^0 & 0 \end{pmatrix}, \quad B_6 = \begin{pmatrix} \Sigma_c^{++} & \frac{1}{\sqrt{2}}\Sigma_c^+ & \frac{1}{\sqrt{2}}\Xi_c^{\prime +} \\ \frac{1}{\sqrt{2}}\Sigma_c^+ & \Sigma_c^0 & \frac{1}{\sqrt{2}}\Xi_c^{\prime 0} \\ \frac{1}{\sqrt{2}}\Xi_c^{\prime +} & \frac{1}{\sqrt{2}}\Xi_c^{\prime 0} & \Omega_c^0 \end{pmatrix} \tag{3.1}$$

and a similar notation for $B^*_{6\mu}$. The heavy quark spin symmetry allows us to combine B_6 and $B^*_{6\mu}$ fields into

$$S_\mu = B^*_{6\mu} - \frac{1}{\sqrt{3}}(\gamma_\mu + v_\mu)\gamma^5 B_6, \tag{3.2}$$

[1] $J^\pi = 1^+$ is not allowed by the Pauli principle for the two identical baryons.

[2] If $\Xi_c cN$ threshold is below that of the $\Lambda_c\Lambda_c$, the bound state of $\Lambda_c\Lambda_c$ will decay into $\Xi_{cc}N$, but the width must be suppressed.

[3] We use the Rarita-Schwinger field $B^*_{6\mu}$ for the spin 3/2 baryons. It satisfies $\gamma^\mu B^*_{6\mu} = 0$

where v_μ is the velocity of the heavy baryon.

The chiral SU(3) effective Lagrangian for the HQ baryons is given by

$$\mathscr{L}_B = \mathscr{L}_{B_{\bar{3}}} + \mathscr{L}_S + \mathscr{L}_{int}, \tag{3.3}$$

$$\mathscr{L}_{B_{\bar{3}}} = \frac{1}{2}\mathrm{tr}[\bar{B}_{\bar{3}}(iv\cdot D)B_{\bar{3}}] + i\beta_B \mathrm{tr}[\bar{B}_{\bar{3}}v^\mu(V_\mu - \rho_\mu)B_{\bar{3}}] + \ell_B \mathrm{tr}[\bar{B}_{\bar{3}}\sigma B_{\bar{3}}], \tag{3.4}$$

$$\begin{aligned}\mathscr{L}_S = & -\mathrm{tr}[\bar{S}^\alpha(iv\cdot D - \Delta_B)S_\alpha] + i\frac{3}{2}g_1\varepsilon^{\mu\nu\lambda\kappa}v_\kappa \mathrm{tr}[\bar{S}_\mu A_\nu S_\lambda] \\ & + i\beta_S \mathrm{tr}[\bar{S}_\mu v_\alpha(V^\alpha - \rho^\alpha)S^\mu] + \lambda_S \mathrm{tr}[\bar{S}_\mu F^{\mu\nu}S_\nu] + \ell_S \mathrm{tr}[\bar{S}_\mu \sigma S^\mu],\end{aligned} \tag{3.5}$$

$$\mathscr{L}_{int} = g_4 \mathrm{tr}[\bar{S}^\mu A_\mu B_{\bar{3}}] + i\lambda_I \varepsilon^{\mu\nu\lambda\kappa}v_\mu \mathrm{tr}[\bar{S}_\nu F_{\lambda\kappa}B_{\bar{3}}] + h.c., \tag{3.6}$$

where V_μ and A_μ are the vector and axial-vector currents of the pseudo-scalar mesons, ρ_μ and $F_{\mu\nu} = \partial_\mu\rho_\nu - \partial_\nu\rho_\mu + [\rho_\mu, \rho_\nu]$ represent the vector meson nonet field. (See [3] for the other notations.) We further introduce a coupling to the flavor-singlet scalar field σ.[4] Δ_B is the mass difference between the $\bar{3}$ and 6 baryons in the heavy quark limit.

The coupling constants are determined by the observed strong decay rates of the heavy baryons, the quark model, the chiral multiplet assumption, the vector meson dominance and the QCD sum rule results. Their values and the effective Lagrangian for the nucleon part are given in [3].

In deriving the one-boson exchange potential, we have neglected $\mathscr{O}(1/M_{Y_c})$ corrections and the δ-functional terms. To represent the short-range part of the interactions, we introduce a phenomenological cutoff Λ at each interacting vertex through the monopole-type form factor

$$F(q) = \frac{\Lambda^2 - m^2}{\Lambda^2 - q^2}, \tag{3.7}$$

where m is the mass of the exchanged meson and q is its 4-momentum. The cutoffs are taken as parameters and their values are varied around $1.0 - 1.5$ GeV.

4. $\Lambda_c N$ bound states

The results for the single-charm deuteron ($\Lambda_c N$) states are summarized as follows.

1. The one-pion exchange (OPE) potential gives a bound $\Lambda_c N$ bound states in both the $J^\pi = 0^+$ and 1^+ channels for the cutoff $\Lambda_\pi \geq 1.2$ GeV. As the OPE does not contribute to the diagonal $\Lambda_c N$ potential, the binding force comes purely from the channel coupling effects. Indeed, we find significant mixings of the $\Sigma_c N$ and $\Sigma_c^* N$ states, for example, 10% for the binding energy of 18.5 MeV ($\Lambda_\pi = 1.4$ GeV). Fig. 1 shows the variations of the binding energies *v.s.* the cutoff Λ_π. Fig.2 shows the wave functions of the channels ordered given in Table 1.

2. Exchanges of the vector and scalar mesons make the binding energies larger for both the channels. The binding energies are found to be similar for the $J^\pi = 0^+$ and 1^+ channels. For the cutoff $\Lambda = 0.9$ GeV, $\Lambda_c N$ is bound by around 14 MeV for both the channels.

[4] We here suppose that the σ is a flavor SU(3) singlet meson, $\propto (\bar{u}u + \bar{d}d + \bar{s}s)$, but for the non-strange HQ systems, the isospin, $I = 0$, only matters.

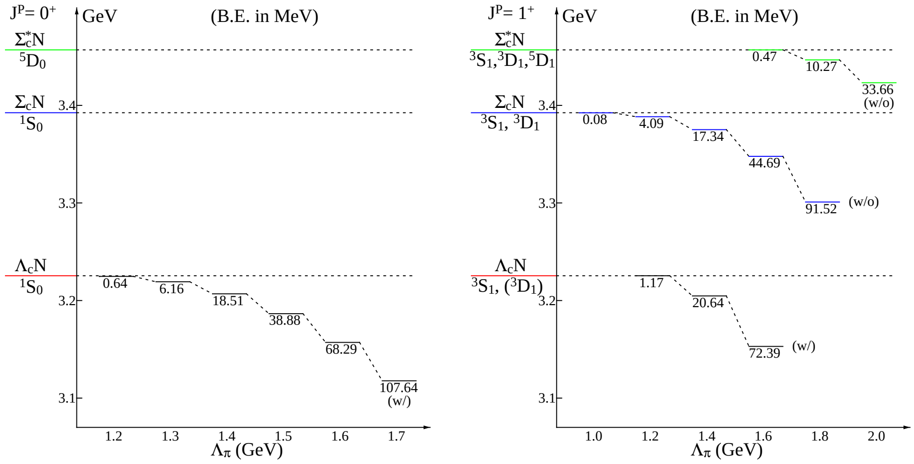
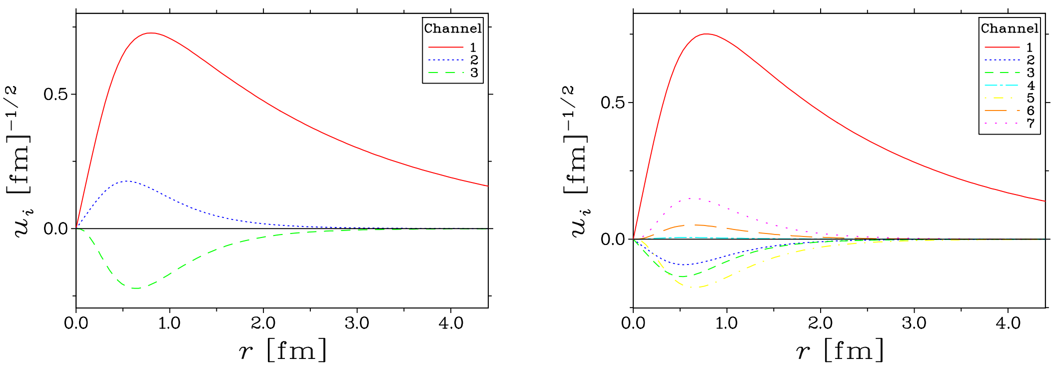


Figure 1: The binding energy (B.E.) *v.s.* the cutoff Λ_π in the OPEP model in $J^\pi = 0^+$ (left) and $J^\pi = 1^+$ (right) for the cases without (w/o) and with (w/) channel coupling.



(a) (b)

Figure 2: The wave functions u_i (i=1,2, ..., 7) of different channels with $\Lambda_\pi = 1.3$ GeV in the OPEP model: (a) $J^\pi = 0^+$ case, (b) $J^\pi = 1^+$ case. The channels 3 of $J^\pi = 0^+$ and 5, 6, 7 of $J^\pi = 1^+$ are the D wave components.

5. $\Lambda_c\Lambda_c$ bound states

The double charm bound states (siblings of the H dibaryon) are also obtained using the OPE potential model[4]. The binding energies and the D wave probabilities are given in Table 2, which shows again strong effects of the tensor force and significant mixings of the Σ_c and Σ_c^* baryons in the wave functions.

Λ_π (GeV)	1.0	1.1	1.2	1.3	1.4
B.E. (MeV)	3.4	14.5	35.5	68.4	115
D-wave prob.	2.2%	4.7%	7.2%	9.6%	11.8%

Table 2: Binding energy (B.E.), and the D wave probabilities of the $\Lambda_c\Lambda_c(0^+)$ bound states.

In the present approach, the short-range part of the potential is parameterized by the cut-off parameters. The results are rather sensitive to the choice of the cutoff. It is an important and interesting future problem to evaluate the short range part of the baryonic interaction from first principles of QCD.

6. Further possibilities and Conclusion

From the meson-exchange model analyses of the two-baryon systems with heavy baryon(s), we have shown that the significant mixings of the $\Sigma_c^{(*)}$ baryons and the D wave components, favor bound states in the $\Lambda_c N$ ($J^\pi = 0^+$ and 1^+) and $\Lambda_c\Lambda_c$ (0^+) channels. It is very interesting to observe such charmed deuteron states as well as further heavier charmed nuclei.

In general, dynamics of heavy quark hadrons opens many interesting possibilities. Recent work done by Bayar et al.[5] has shown that a strong DN attraction may form a D-nucleus bound states, which are analogous to the recently studied $\bar{K}$-nucleus bound states[6]. The possibility may also be extended to the bottom hadrons, which will further show roles and properties of the heavy-quark symmetry.

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