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Possible $\Lambda_c N$ molecular bound state

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Abstract. $\Lambda_c N$ bound state problem is investigated in the one-meson-exchange potential model. The potentials are obtained from an effective Lagrangian reflecting the heavy quark symmetry, chiral symmetry, and hidden local symmetry. We also consider the contributions from the coupled channels of $\Sigma_c N$ and $\Sigma_c^* N$. It is found that the channel coupling is very important in binding the baryons. We find that the formation of the nearly degenerate $J^P = 0^+$ and $J^P = 1^+$ $\Lambda_c N$ molecular bound states is plausible, although the results are sensitive to the cutoff parameters,.

Keywords: Heavy quark, bound state, effective Lagrangian, potential model, coupled channel
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INTRODUCTION

With the development of experimental facilities and techniques, number of exotic heavy quark hadrons like $X(3872)$ have been observed. Most of them are near-threshold states, which triggered lots of discussions about the two-body molecule problem in the heavy quark sector. Types of molecules for the discussions involved hidden charm mesons or baryons, charmed meson/baryon-nucleon states, and so on. Here we concentrate on the $\Lambda_c N$ system, which is the most fundamental charmed nucleon state and was first discussed in Ref. [1].

For the cluster containing heavy quark baryons, the kinetic term of the system Hamiltonian has relatively small contributions, which is helpful for the formation of hadronic molecules. In addition, the heavy quark symmetry results in degenerate doublets and the coupled channel effects may be important. It is worthwhile to give the $\Lambda_c N$ a serious study with the modern effective theory and channel couplings to $\Sigma_c N$ and $\Sigma_c^* N$. For this purpose, we here revisit the system in the one-meson-exchange potential model. Table 1 lists the channels we are considering. Details of the formulations and results are given elsewhere [2].

TABLE 1. The S-wave $\Lambda_c N$ states and the channels which couple to them.

Channels	1	2	3	4	5	6	7
$J^P = 0^+$	$\Lambda_c N(^1S_0)$	$\Sigma_c N(^1S_0)$	$\Sigma_c^* N(^5D_0)$				
$J^P = 1^+$	$\Lambda_c N(^3S_1)$	$\Sigma_c N(^3S_1)$	$\Sigma_c^* N(^3S_1)$	$\Lambda_c N(^3D_1)$	$\Sigma_c N(^3D_1)$	$\Sigma_c^* N(^3D_1)$	$\Sigma_c^* N(^5D_1)$

LAGRANGIAN

In the meson-exchange approach, the potential model generally incorporates the contributions from the pseudoscalar, scalar, and vector mesons. To get the non-relativistic

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potentials, we construct the Lagrangian according to the heavy quark symmetry, chiral symmetry, and hidden local symmetry. The obtained heavy baryon part reads

$$
\begin{aligned}
\mathscr{L}_B &= \mathscr{L}_{B_{\bar{3}}} + \mathscr{L}_S + \mathscr{L}_{int}, &(1)\\
\mathscr{L}_{B_{\bar{3}}} &= \frac{1}{2}\mathrm{tr}[\bar{B}_{\bar{3}}(iv\cdot D)B_{\bar{3}}] + i\beta_B \mathrm{tr}[\bar{B}_{\bar{3}}v^\mu(\Gamma_\mu-\rho_\mu)B_{\bar{3}}] + \ell_B\mathrm{tr}[\bar{B}_{\bar{3}}\sigma B_{\bar{3}}] &(2)\\
\mathscr{L}_S &= -\mathrm{tr}[\bar{S}^\alpha(iv\cdot D-\Delta_B)S_\alpha] + \frac{3}{2}g_1(iv_\kappa)\varepsilon^{\mu\nu\lambda\kappa}\mathrm{tr}[\bar{S}_\mu A_\nu S_\lambda]\\
&\quad + i\beta_S\mathrm{tr}[\bar{S}_\mu v_\alpha(\Gamma^\alpha - V^\alpha)S^\mu] + \lambda_S\mathrm{tr}[\bar{S}_\mu F^{\mu\nu}S_\nu] + \ell_S\mathrm{tr}[\bar{S}_\mu\sigma S^\mu] &(3)\\
\mathscr{L}_{int} &= g_4\mathrm{tr}[\bar{S}^\mu A_\mu B_{\bar{3}}] + i\lambda_I\varepsilon^{\mu\nu\lambda\kappa}v_\mu\mathrm{tr}[\bar{S}_\nu F_{\lambda\kappa}B_{\bar{3}}] + h.c. &(4)
\end{aligned}
$$

In this Lagrangian,

$$
B_{\bar{3}} = \begin{pmatrix} 0 & \Lambda_c^+ & \Xi_c^+ \\ -\Lambda_c^+ & 0 & \Xi_c^0 \\ -\Xi_c^+ & -\Xi_c^0 & 0 \end{pmatrix}, \quad B_6 = \begin{pmatrix} \Sigma_c^{++} & \frac{1}{\sqrt{2}}\Sigma_c^+ & \frac{1}{\sqrt{2}}\Xi_c^{\prime +} \\ \frac{1}{\sqrt{2}}\Sigma_c^+ & \Sigma_c^0 & \frac{1}{\sqrt{2}}\Xi_c^{\prime 0} \\ \frac{1}{\sqrt{2}}\Xi_c^{\prime +} & \frac{1}{\sqrt{2}}\Xi_c^{\prime 0} & \Omega_c^0 \end{pmatrix}, \tag{5}
$$

$$
\Pi = \sqrt{2}\begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}, \tag{6}
$$

$$
V^\mu = i\frac{g_V}{2}\begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}^\mu, \tag{7}
$$

$$
\xi = \exp[\tfrac{i\Pi}{2f}], \quad A_\mu = \tfrac{i}{2}[\xi^\dagger(\partial_\mu\xi) + (\partial_\mu\xi)\xi^\dagger], \quad \Gamma_\mu = \tfrac{1}{2}[\xi^\dagger(\partial_\mu\xi) - (\partial_\mu\xi)\xi^\dagger], \tag{8}
$$

$$
F_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu + [V_\mu, V_\nu], \quad S_\mu = B^*_{6\mu} - \tfrac{1}{\sqrt{3}}(\gamma_\mu + v_\mu)\gamma^5 B_6 \tag{9}
$$

$$
D_\mu B_{\bar{3}} = \partial_\mu B_{\bar{3}} + \Gamma_\mu B_{\bar{3}} + B_{\bar{3}}\Gamma_\mu^T, \quad D_\mu S_\nu = \partial_\mu S_\nu + \Gamma_\mu S_\nu + S_\nu \Gamma_\mu^T, \tag{10}
$$

where B_6^* has a similar form with B_6, v_μ is the velocity of the heavy baryon, Δ_B is the mass difference between the sextet and the anti-triplet, $f = 92.3$ MeV is the pion decay constant, and the constant $g_V = m_\rho/(\sqrt{2}f_\pi) = 5.8$ is derived with the vector meson dominance (VMD). There are eight coupling constants in the Lagrangian. To constrain their values, we have used several methods: strong decay of the heavy baryons, the quark model, the chiral multiplet assumption, VMD, and the QCD sum rule results. For the numerical evaluation, we take $g_4 = 0.999$, $g_1 = 0.94$, $\ell_B = -3.1$, $\ell_B = -6.2$, $(\beta_B g_V) = -5.04$, $(\beta_S g_V) = -10.08$, $(\lambda_S g_V) = 19.2$ GeV^{-1}, and $(\lambda_I g_V) = -6.8$ GeV^{-1}.

One derives the non-relativistic potentials from the t-channel meson-exchange diagrams with the above Lagrangian. We have neglected $\mathscr{O}(1/M_{\Lambda_c})$ corrections and thus the final potentials are independent of the heavy baryon masses. We also neglect the δ-functional terms since we are considering loosely bound molecules and the very short range interactions should in principle have small contributions. To include the size effects of the hadrons, we have introduced a phenomenological cutoff parameter at each interacting vertex. The cutoffs for various mesons may be different.

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NUMERICAL RESULTS

We use the variational method [3] to solve the Schrödinger equation. For the formation of a loosely bound molecule, the long-range pion interaction plays a crucial role. For comparison, we use both the one-pion-exchange potential (OPEP) model and the one-meson-exchange potential (OMEP) model in our study. In the former model, the information of the intermediate- and short-range interactions is encoded in the cutoff Λ_π. In the latter one, to reduce the number of parameters, we consider two cases for the parametrization of the cutoffs: (1) common cutoff $\Lambda_\pi = \Lambda_\sigma = \Lambda_\rho = \Lambda_\omega = \Lambda_{\rm com}$ and (2) scaled cutoff $\alpha_\pi = \alpha_\sigma = \alpha_\rho = \alpha_\omega = \alpha$ with $\Lambda_{meson} = m_{meson} + \alpha\Lambda_{QCD}$. For the calculation, we have considered both the case without channel coupling (w/o) and the one with channel coupling (w/). Therefore, we have totally six cases. All the binding solutions are sensitive to the cutoff parameters.

As an example, Table 2 shows the binding energy (B.E.) and the corresponding root-mean-square (RMS) radius with different cutoffs for the $J^P = 0^+$ case with channel coupling in the OPEP model. In a diagrammatic form, we illustrate the sensitivity to the cutoff parameter in Fig. 1, where we also present the $J^P = 1^+$ case for comparison. Because there is no $\Lambda_c\Lambda_c\pi$ coupling, the results indicate that the channel coupling is very important for the formation of the $\Lambda_c N$ molecule. Especially, the molecular bound state with $J^P = 0^+$ results completely from the coupled channel effects.

TABLE 2. Binding solutions for the $J^P = 0^+$ case with channel coupling in the OPEP model. The binding energies (B.E.) are given with relative to the $\Lambda_c N$ threshold. The probabilities correspond to $\Lambda_c N(^1S_0)$, $\Sigma_c N(^1S_0)$, and $\Sigma_c^* N(^5D_0)$, respectively.

Λ_π (GeV)	1.2	1.3	1.4	1.5	1.6	1.7
$B.E.(J=0)$ (MeV)	0.64	6.16	18.51	38.88	68.29	107.64
$\sqrt{\langle r^2\rangle}$ (fm)	5.2	1.9	1.2	0.9	0.8	0.7
S-wave Prob. (%) D-wave Prob. (%)	(98.2/0.6/ 1.2)	(94.0/2.3/ 3.7)	(89.3/4.6/ 6.1)	(84.5/7.2/ 8.3)	(80.1/9.8/ 10.1)	(76.1/12.2/ 11.7)

By comparing the two diagrams in Fig. 1, one finds that the binding energies for the two cases are similar with the same cutoff. In fact, the results for the spin-singlet and triplet are also not significantly different in the OMEP model. To make a comparison among different cases, we tune the cutoff parameters to get similar binding energies. Table 3 shows the comparison.

TABLE 3. Comparison among different cases. The meaning of the numbers are [cutoff Λ in GeV or dimensionless α: binding energy in MeV, RMS radius in fm].

J^P		$\Lambda_c N$ (S-wave)	$\Lambda_c N - \Sigma_c N - \Sigma_c^* N$
0^+	OPEP (Λ)	$\times$	[1.367: 13.60, 1.38]
	OMEP (Λ)	[0.900: -1.24, 3.86]	[0.900: 13.60, 1.46]
	OMEP (α)	[1.533: -0.25, 8.13]	[1.533: 13.57, 1.37]
1^+	OPEP (Λ)	$\times$	[1.353: 13.54, 1.40]
	OMEP (Λ)	[0.900: -1.24, 3.86]	[0.900: 13.49, 1.47]
	OMEP (α)	[1.618: -0.80, 4.72]	[1.618: 13.47, 1.39]

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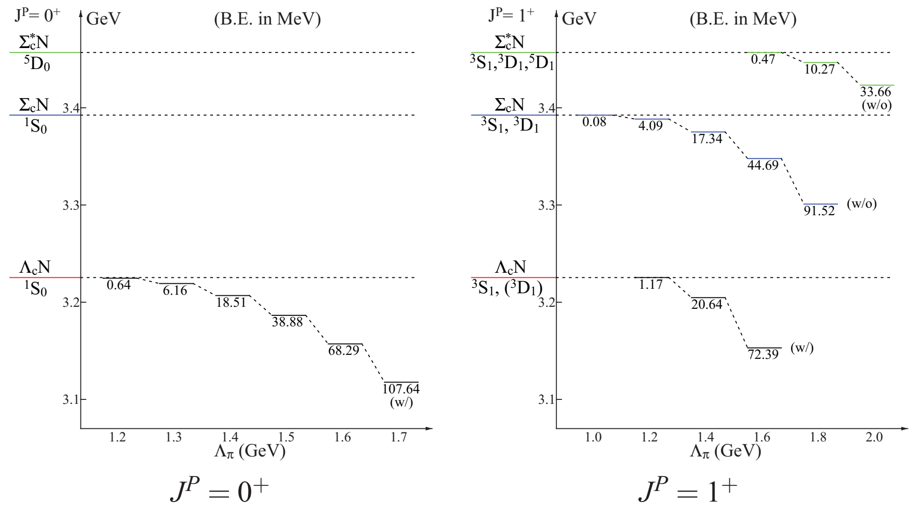

FIGURE 1. The sensitivity of the binding energy (B.E.) to the cutoff Λ_π in the OPEP model for the $J^P = 0^+$ and $J^P = 1^+$ cases. The cases without (w/o) and with (w/) channel coupling are both shown. ($^3D_1$) means there is no $S-D$ mixing when one considers only the $\Lambda_c N$ channel.

CONCLUSION

We have studied the possible $\Lambda_c N$ molecule and its coupling to $\Sigma_c N$ and $\Sigma_c^* N$ at the hadron level. The one-meson-exchange potentials are derived from an effective Lagrangian reflecting the heavy quark symmetry, chiral symmetry and hidden local symmetry. It is found that the channel coupling has important effects on the formation of the possible molecular bound states. Although the resulting binding energies are sensitive to the cutoff parameters, we get implications for the existence of the $\Lambda_c N$ hadronic molecules.

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