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Possible molecular bound state of two charmed baryons

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Abstract. One-boson-exchange approach is widely used in the study of baryon-baryon interactions. Because of the higher masses, charmed baryons are likely to form molecular bound states. We here investigate this possibility in the $\Lambda_c\Lambda_c$ ($J^P = 0^+$, $I = 0$) system, which may be the lowest mass state composed of two charmed baryons. Since the long-range interactions must play an important role for the formation of possible molecular bound states, we consider the one-pion-exchange potential explicitly and embed the short-range effects into a phenomenological cutoff parameter. As single pion exchange does not occur between two Λ_c's, couplings to the nearby $\Sigma_c\Sigma_c$, $\Sigma_c\Sigma_c^*$ and $\Sigma_c^*\Sigma_c^*$ channels may be crucial in binding two Λ_c's. We find that it is possible to have a molecular bound state of two Λ_c's, where the tensor force plays a crucial role, although the predicted binding energies are sensitive to the cutoff parameter.

Keywords: Hadronic molecule, heavy quark spin symmetry
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INTRODUCTION

Hadronic molecules are loosely bound states of hadrons and their inter-hadron distances are larger than the quark confinement size. The deuteron (NN), triton (NNN), hypertriton (Λpn) and so on are regarded as molecular bound states of the light baryons. Compared with light baryons, the heavy baryons are more likely to be bound for two reasons. One is the larger reduced mass of the heavy baryon systems, which suppresses the kinetic energy and this is advantageous for the bound state. The other reason is the heavy quark spin symmetry [1]. The heavy quark interactions manifest the spin symmetry because the current masses are larger than the typical scale of QCD ($\Lambda_{\text{QCD}} \simeq 100 \sim 300$ MeV) and the color magnetic interaction vanishes for the infinitely heavy quarks. Due to this symmetry, e.g., the mass difference between Σ_c and Σ_c^* is smaller than that between Σ and Σ^*. In general, coupled channel effects become important when two channels are closer, so it is necessary to include such effects in the study of heavy quark baryon interactions. In this study we explore possible existence of $\Lambda_c\Lambda_c$ molecule with $I(J^P) = 0(0^+)$, by considering the coupled channel effects.

MODEL

We use the one-boson-exchange potential model for the study. Because the long-range interactions are important for loosely bound molecular states, we adopt only the one-pion-exchange potential which is derived from the effective Lagrangian satisfying the heavy quark symmetry and chiral symmetry. A cutoff parameter Λ is introduced at each

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vertex through the monopole type form factor. This cutoff encodes the information of the scale of the charmed baryons and the short-range interactions. Since we include the coupled channel effects, there are in principle five cutoffs in the model ($\Lambda_{\Lambda_c\Sigma_c\pi}$, $\Lambda_{\Lambda_c\Sigma_c^*\pi}$, $\Lambda_{\Sigma_c\Sigma_c\pi}$, $\Lambda_{\Sigma_c\Sigma_c^*\pi}$, and $\Lambda_{\Sigma_c^*\Sigma_c^*\pi}$). To simplify the calculation, all the cutoffs are put as the same value. Because we consider the possible molecular bound state (loosely bound), we neglect the $\Xi_{cc}N$ channel which may be important at short distance. It had been proposed that a bound state may exist in the $\Xi_{cc}N$ system [2].

The Hamiltonian of this system is given as follows,

$$H = \begin{pmatrix} H_{\Lambda_c\Lambda_c(^1S_0)} & V_{\Lambda_c\Lambda_c(^1S_0)\text{-}\Sigma_c\Sigma_c(^1S_0)} & V_{\Lambda_c\Lambda_c(^1S_0)\text{-}\Sigma_c^*\Sigma_c^*(^1S_0)} & V_{\Lambda_c\Lambda_c(^1S_0)\text{-}\Sigma_c^*\Sigma_c^*(^5D_0)} & V_{\Lambda_c\Lambda_c(^1S_0)\text{-}\Sigma_c\Sigma_c^*(^5D_0)} \\ V_{\Sigma_c\Sigma_c(^1S_0)\text{-}\Lambda_c\Lambda_c(^1S_0)} & H_{\Sigma_c\Sigma_c(^1S_0)} & V_{\Sigma_c\Sigma_c(^1S_0)\text{-}\Sigma_c^*\Sigma_c^*(^1S_0)} & V_{\Sigma_c\Sigma_c(^1S_0)\text{-}\Sigma_c^*\Sigma_c^*(^5D_0)} & V_{\Sigma_c\Sigma_c(^1S_0)\text{-}\Sigma_c\Sigma_c^*(^5D_0)} \\ V_{\Sigma_c^*\Sigma_c^*(^1S_0)\text{-}\Lambda_c\Lambda_c(^1S_0)} & V_{\Sigma_c^*\Sigma_c^*(^1S_0)\text{-}\Sigma_c\Sigma_c(^1S_0)} & H_{\Sigma_c^*\Sigma_c^*(^1S_0)} & V_{\Sigma_c^*\Sigma_c^*(^1S_0)\text{-}\Sigma_c^*\Sigma_c^*(^5D_0)} & V_{\Sigma_c^*\Sigma_c^*(^1S_0)\text{-}\Sigma_c\Sigma_c^*(^5D_0)} \\ V_{\Sigma_c^*\Sigma_c^*(^5D_0)\text{-}\Lambda_c\Lambda_c(^1S_0)} & V_{\Sigma_c^*\Sigma_c^*(^5D_0)\text{-}\Sigma_c\Sigma_c(^1S_0)} & V_{\Sigma_c^*\Sigma_c^*(^5D_0)\text{-}\Sigma_c^*\Sigma_c^*(^1S_0)} & H_{\Sigma_c^*\Sigma_c^*(^5D_0)} & V_{\Sigma_c^*\Sigma_c^*(^5D_0)\text{-}\Sigma_c\Sigma_c^*(^5D_0)} \\ V_{\Sigma_c\Sigma_c^*(^5D_0)\text{-}\Lambda_c\Lambda_c(^1S_0)} & V_{\Sigma_c\Sigma_c^*(^5D_0)\text{-}\Sigma_c\Sigma_c(^1S_0)} & V_{\Sigma_c\Sigma_c^*(^5D_0)\text{-}\Sigma_c^*\Sigma_c^*(^1S_0)} & V_{\Sigma_c\Sigma_c^*(^5D_0)\text{-}\Sigma_c^*\Sigma_c^*(^5D_0)} & H_{\Sigma_c\Sigma_c^*(^5D_0)} \end{pmatrix}$$

where H_i represents the Hamiltonian of the channel i and $V_{i\text{-}j}$ represents the transition potential between the channel i and the channel j. To solve the coupled channel Schrödinger equation, we use the variational method "Gaussian Expansion Method" [3].

RESULTS

Tables 1-4 show the binding energy and inter-hadron distance (root-mean-square radius) of various cases. From the first table, there is no bound state solutions if one does not consider D-wave contributions. Table 2 and 3 give the results of coupled channel cases by adding only one D-wave channel ($\Sigma_c^*\Sigma_c^*(^5D_0)$ for Table 2 and $\Sigma_c\Sigma_c^*(^5D_0)$ for Table 3). Table 4 lists the results of the full coupled channel calculation [$\Lambda_c\Lambda_c(^1S_0)$, $\Sigma_c\Sigma_c(^1S_0)$, $\Sigma_c^*\Sigma_c^*(^1S_0)$, $\Sigma_c^*\Sigma_c^*(^5D_0)$, $\Sigma_c\Sigma_c^*(^5D_0)$]. There is no available experimental data to determine the cutoff Λ. So we treat it as a free parameter. We assume that its value is around 1.0 GeV from the analogy with the YN potentials [4]. Fig. 1 illustrates the dependence of the binding energy on the cutoff.

TABLE 1. 3 channels $[\Lambda_c\Lambda_c(^1S_0), \Sigma_c\Sigma_c(^1S_0), \Sigma_c^*\Sigma_c^*(^1S_0)]$

Λ(cutoff) [GeV]	1.0	1.1	1.2	1.3	1.4	1.5
Binding Energy [MeV]	×	×	×	×	×	×
Inter-hadron distance [fm]	×	×	×	×	×	×

TABLE 2. 4 channels $[\Lambda_c\Lambda_c(^1S_0), \Sigma_c\Sigma_c(^1S_0), \Sigma_c^*\Sigma_c^*(^1S_0), \Sigma_c^*\Sigma_c^*(^5D_0)]$

Λ(cutoff) [GeV]	1.0	1.1	1.2	1.3	1.4	1.5
Binding Energy [MeV]	×	×	×	0.408	5.45	18.2
Inter-hadron distance [fm]	×	×	×	4.98	1.61	1.01

TABLE 3. 4 channels $[\Lambda_c\Lambda_c(^1S_0), \Sigma_c\Sigma_c(^1S_0), \Sigma_c^*\Sigma_c^*(^1S_0), \Sigma_c\Sigma_c^*(^5D_0)]$

Λ(cutoff) [GeV]	1.0	1.1	1.2	1.3	1.4	1.5
Binding Energy [MeV]	0.0680	3.83	15.0	35.8	68.2	114
Inter-hadron distance [fm]	11.8	1.93	1.15	0.857	0.695	0.591

TABLE 4. 5 channels $[\Lambda_c\Lambda_c(^1S_0), \Sigma_c\Sigma_c(^1S_0), \Sigma_c^*\Sigma_c^*(^1S_0), \Sigma_c^*\Sigma_c^*(^5D_0), \Sigma_c\Sigma_c^*(^5D_0)]$

Λ(cutoff) [GeV]	1.0	1.1	1.2	1.3	1.4	1.5
Binding Energy [MeV]	3.37	14.4	35.4	68.3	115	177
Inter-hadron distance [fm]	2.05	1.19	0.882	0.714	0.606	0.529

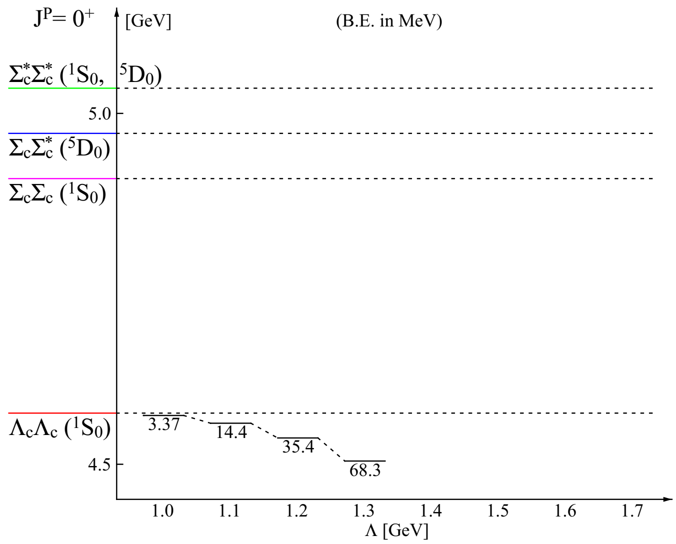

FIGURE 1. Cutoff dependence of binding energies

CONCLUSION

Possible bound state of $\Lambda_c\Lambda_c$ $(J^P = 0^+,\ I = 0)$ has been studied using the one-pion-exchange potential model. Details of the results will be given elsewhere [5]. There is no bound state solution when one considers only the S-wave channels. It is shown that the tensor force is important to include the D-wave channels for the bound states. We do not have enough information to determine the cutoff parameter now. The bound state solutions with $\Lambda = 1.0 \sim 1.2$ GeV are molecule-like because binding energies are not so deep and the inter-hadron distances are larger than 1 fm. But the solutions with $\Lambda = 1.3 \sim 1.5$ GeV are much tightly bound and may be beyond our model. Although the resulting binding energy is sensitive to the cutoff Λ, it is possible to have a molecular bound state of two Λ_c's. We hope that this bound state will be discovered experimentally in near future.

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