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Exotic dibaryons with a heavy antiquark

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The possible existence of $\bar{D}NN$ and BNN states is discussed. They are manifestly exotic dibaryons whose bound states are stable against a strong decay. As for the $\bar{D}^{(*)}N$ ($B^{(*)}N$) interactions, we consider the one pion exchange potential enhanced by the heavy quark spin symmetry. By solving the coupled-channel Schrödinger equations for the three-body systems, we find the bound states with $J^P = 0^-$ and resonances with $J^P = 1^-$ for $I = 0$ both in $\bar{D}NN$ and BNN. We also discuss the spin degeneracy of the $P_Q NN$ states in the heavy quark mass limit.

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1. Introduction

The hadron-nucleon interaction gives us rich phenomena which are not seen in normal nuclei. In the strangeness sector, the hadrons bound in nuclei cause the impurity effects such as the formation of the high density states in the $\bar{K}$ nuclei [1, 2], and the shrinking of the wave functions in the hypernuclei [3, 4].

Recently, for the heavy flavor sectors, the sufficiently strong attraction between a $\bar{D}$ (B) meson and a nucleon N has been discussed [5, 6, 7, 8]. The attraction is produced by the one pion exchange potential (OPEP), which is enhanced by the mass degeneracy between heavy pseudoscalar meson $P = \bar{D}, B$ and heavy vector meson $P^* = \bar{D}^*, B^*$. The small mass splittings of the P and P^* mesons are manifested by the heavy quark spin symmetry (HQS) [9, 10, 11]. The OPEP leads to loosely bound and resonant states of $\bar{D}N$ and BN near the thresholds. These states are manifestly exotic states having no lower hadronic channels coupled by a strong interaction.

The attraction produced by the $\bar{D}N$ (BN) forces motivates us to explore the exotic nuclear systems with heavy (anti-)quarks. In fact, there have been many works for $\bar{D}$ (B) mesons in nuclear systems with large baryon numbers (recent results are summarized in Ref. [12]), because it is expected that the bonding energy increases as baryon number increases. However, $\bar{D}$ (B) nuclei as few-body systems have not been investigated so far in the literature. The few-body systems would be more likely to be produced in the hadron colliders.

In the present work, we study the mass spectrum of $\bar{D}NN$ and BNN bound and/or resonant states. We also investigate P_QNN states, where P_Q is defined as a heavy meson having an infinite heavy quark mass.

2. Interactions

Let us discuss the basic interaction in the study. For the $P^{(*)}N$ interactions ($P^{(*)}$ stands for P or P^*), the OPEP enhanced by the HQS is the basic ingredient to provide a strong attraction. The HQS manifests the mass degeneracy of heavy pseudoscalar meson P and heavy vector meson P^*. Indeed, the mass splitting between P and P^* mesons is small, $m_{\bar{D}^*} - m_{\bar{D}} \sim 140$ MeV and $m_{B^*} - m_B \sim 45$ MeV. In contrast, in the light quark sectors, $m_\rho - m_\pi \sim 600$ MeV, and $m_{K^*} - m_K \sim 140$ MeV. Thanks to the mass degeneracy, the OPEP causing the couplings of $PN - P^*N$ and $P^*N - P^*N$ is enhanced.

The $P^{(*)}N$ force could also contain the short-range parts as discussed in Refs. [13, 14, 15, 16]. However, we expect that the OPEP as a long-range force dominates when the systems form a loosely bound state. An analogous situation occurs for the deuteron.

Let us show the OPEP between $P^{(*)}$ and N briefly. Details are given in Ref. [6, 7, 8]. The OPEPs for $PN - P^*N$ and $P^*N - P^*N$ are given by

$$V_{PN-P^*N}(r) = -\frac{g_\pi g_{\pi NN}}{\sqrt{2} m_N f_\pi} \frac{1}{3} \left[\vec{\varepsilon}^{\,\dagger} \cdot \vec{\sigma} C(r) + S_\varepsilon T(r) \right] \vec{\tau}_P \cdot \vec{\tau}_N, \tag{2.1}$$

$$V_{P^*N-P^*N}(r) = \frac{g_\pi g_{\pi NN}}{\sqrt{2} m_N f_\pi} \frac{1}{3} \left[\vec{S} \cdot \vec{\sigma} C(r) + S_S T(r) \right] \vec{\tau}_P \cdot \vec{\tau}_N, \tag{2.2}$$

as a sum of the central and tensor forces, $C(r)$ and $T(r)$, where $m_N = 940$ MeV and $f_\pi = 132$ MeV are the nucleon mass and the pion decay constant, respectively. $\vec{\varepsilon}$ ($\vec{\varepsilon}^{\,\dagger}$) is the polarization

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vector of the incoming (outgoing) P^*, $\vec{S}$ is the spin-one operator of P^*, and S_ε (S_S) is the tensor operator $S_{\mathscr{O}}(\hat{r}) = 3(\vec{\mathscr{O}}\cdot\hat{r})(\vec{\sigma}\cdot\hat{r}) - \vec{\mathscr{O}}\cdot\vec{\sigma}$ with $\hat{r}=\vec{r}/r$ and $r=|\vec{r}|$ for $\vec{\mathscr{O}}=\vec{\varepsilon}$ ($\vec{S}$), where $\vec{r}$ is the relative position vector between $P^{(*)}$ and N. $\vec{\sigma}$ are Pauli matrices acting on nucleon spin. $\vec{\tau}_P$ ($\vec{\tau}_N$) are isospin operators for $P^{(*)}$ (N). The coupling constant for $P^{(*)}P^*\pi$ ($NN\pi$) vertex is $g_\pi = 0.59$ ($g^2_{\pi NN}/4\pi = 13.6$). We note that the $PN-PN$ term is absent due to parity conservation. The functions $C(r)$ and $T(r)$ are

$$C(r) = \int \frac{d^3\vec{q}}{(2\pi)^3}\frac{m_\pi^2}{\vec{q}^{\,2}+m_\pi^2}e^{i\vec{q}\cdot\vec{r}}F(\vec{q}\,), \tag{2.3}$$

$$S_{\mathscr{O}}(\hat{r})T(r) = \int \frac{d^3\vec{q}}{(2\pi)^3}\frac{-\vec{q}^{\,2}}{\vec{q}^{\,2}+m_\pi^2}S_{\mathscr{O}}(\hat{q})e^{i\vec{q}\cdot\vec{r}}F(\vec{q}\,), \tag{2.4}$$

where the dipole-type form factor $F(\vec{q}\,) = (\Lambda_N^2 - m_\pi^2)(\Lambda_P^2 - m_\pi^2)/(\Lambda_N^2 + |\vec{q}\,|^2)(\Lambda_P^2 + |\vec{q}\,|^2)$ with cutoff parameters Λ_N and Λ_P is introduced for spatially extended hadrons. From a quark model estimation, we use $\Lambda_D = 1.35\Lambda_N$ for $\bar{D}^{(*)}$ meson, $\Lambda_B = 1.29\Lambda_N$ for $B^{(*)}$ meson, and $\Lambda_{P_Q} = 1.12\Lambda_N$ for a $P_Q^{(*)}$ meson, with $\Lambda_N = 830$ MeV, as discussed in Refs. [6, 7].

As for the NN interaction, we employ the Argonne v_8' potential [17], which is formed by the central forces with operators 1, $\vec{\sigma}_1\cdot\vec{\sigma}_2$, $\vec{\tau}_1\cdot\vec{\tau}_2$ and $\vec{\sigma}_1\cdot\vec{\sigma}_2\,\vec{\tau}_1\cdot\vec{\tau}_2$, the tensor forces with S_{12} and $S_{12}\,\vec{\tau}_1\cdot\vec{\tau}_2$, and the LS forces with $\vec{L}\cdot\vec{S}$ and $\vec{L}\cdot\vec{S}\,\vec{\tau}_1\cdot\vec{\tau}_2$.

The Hamiltonian is given by $H = T + V_{P^{(*)}N} + V_{NN}$, where T is the kinetic term, and $V_{P^{(*)}N}$ (V_{NN}) is the $P^{(*)}N$ (NN) potential shown above. By diagonalizing the Hamiltonian, we obtain the eigenenergies. The three-body wave functions are expressed by the Gaussian expansion method [18]. The poles of resonances are calculated by the complex scaling method [19, 20, 21, 22].

3. Numerical Results

In this section, the results for the bound and resonant states in $\bar{D}NN$, BNN and P_QNN are shown. The obtained energies are summarized in Table 1. The binding energy is given as a real negative value, and the resonance energy $E_{\rm re}$ and decay width Γ are given as $E_{\rm re} - i\Gamma/2$. The energies are measured from the lowest thresholds.

First, let us present the results of $\bar{D}NN$ and BNN for $J^P = 0^-$. We obtain bound states with $(I,J^P) = (1/2, 0^-)$. The binging energies are -5.2 MeV for $\bar{D}NN$ and -26.2 MeV for BNN. We find that the BNN state is more deeply bound than the $\bar{D}NN$ state, because the $PNN - P^*NN$ mixing effects are enhanced, when P and P^* mesons become more degenerate.

We analyze the expectation values of the potentials, V_{PN-P^*N}, $V_{P^*N-P^*N}$ and V_{NN}, summarized in Table 2. We find that the tensor forces of V_{PN-P^*N} provide the dominant contribution both in $\bar{D}NN$ and BNN. For V_{NN}, the tensor force in V_{NN} which is a driving force in the deuteron d is almost irrelevant, while the central force is rather dominant. This is reasonable because d (with angular momentum and parity 1^+) cannot exist in the main component of $\bar{D}NN$ with $J^P = 0^-$.

In scattering states, we find resonances both for $\bar{D}NN$ and BNN with $(I,J^P) = (1/2, 1^-)$. We obtain $E_{\rm re} - \Gamma/2 = 111.2 - i9.3$ MeV for $\bar{D}NN$, and $6.8 - i0.2$ MeV for BNN, respectively. When we consider only the P^*NN channel, bound states of P^*NN are present. The results indicate that these resonances are Feshbach resonances.

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Table 1: Energies of $\bar{D}NN$, BNN and $P_Q NN$ from Ref. [8]. All values are given in units of MeV.

(I,J^P)	$\bar{D}NN$	BNN	$P_Q NN$
$(1/2,0^-)$	-5.2	-26.2	-38.5
$(1/2,1^-)$	$111.2-i9.3$	$6.8-i0.2$	-38.5

Table 2: Expectation values of central, tensor and LS forces of the $\bar{D}^{(*)}N$ ($B^{(*)}N$) and NN potentials in the bound state of $\bar{D}NN$ (BNN). All values are in units of MeV.

PNN	$\langle V_{\bar{D}N-\bar{D}^*N}\rangle$	$\langle V_{\bar{D}^*N-\bar{D}^*N}\rangle$	$\langle V_{NN}\rangle$	$\langle V_{BN-B^*N}\rangle$	$\langle V_{B^*N-B^*N}\rangle$	$\langle V_{NN}\rangle$
Central	-2.3	-0.1	-9.5	-6.5	0.3	-11.6
Tensor	-47.1	0.7	-0.2	-92.0	-2.7	-1.0
LS	—	—	-0.03	—	—	-0.1

Finally, we consider $P_Q NN$ systems in the heavy quark limit, where P_Q and P_Q^* are exactly degenerate in mass. Interestingly, we find the degenerate bound states for $J^P=0^-$ and 1^- with the same binging energy -38.5 MeV. This indicates that the spin degeneracy due to the HQS, discussed in Refs. [11, 23], is realized in the $P_Q NN$ states. The degenerate states contain common light component with $J^P=1/2^+$ and $I=0$. As shown in Table 1, the energy splitting between the states with $J^P=0^-$ and 1^- decreases as the heavy quark mass increases, and finally those states become degenerate in the heavy quark limit.

4. Summary

We have explored the possible existence of $\bar{D}NN$, BNN and $P_Q NN$. The OPEP and Argonne v_8' potentail were employed as the $P^{(*)}N$ and NN interactions, respectively. By solving the coupled-channel equations for PNN and P^*NN, we have obtained bound states with $J^P=0^-$ and Feshbach resonances with $J^P=1^-$ for $I=1/2$ both in $\bar{D}NN$ and BNN. The tensor force of the OPEP mixing PN and P^*N plays an important role to produce a strong attraction. For the $P_Q NN$ systems we have obtained degenerate bound states of $J^P=0^-$ and 1^- for $I=0$. Hence, the bound states with $J^P=0^-$ and the resonances with $J^P=1^-$ in the charm and bottom sectors have common origin which is the degenerate states in the heavy quark limit.

The $\bar{D}NN$ and BNN states can be searched in relativistic heavy ion collisions in RHIC and LHC [24, 25]. Furthermore, the search for the $\bar{D}NN$ would be also carried out in J-PARC and GSI-FAIR.

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