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Possible existence of charmonium-light-nucleus bound states

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The relations between two-body charmonium($c\bar{c}$)-nucleon(N) scattering length a and the binding energies of $(c\bar{c})$ bound states in few-nucleon systems are studied. We adopt a Gaussian potential as an effective $(c\bar{c})-N$ interaction. The results show that $a \leq -0.95$ fm is needed to form a $(c\bar{c})$-deuteron bound state. Also, a $(c\bar{c})-{}^4$He and a $(c\bar{c})-{}^8$Be bound states exist for $a \leq -0.24$ fm and $a \leq -0.16$ fm, respectively. Comparing our results with the recent lattice QCD data of a, we see that $(c\bar{c})-$nucleus bound states may exist for the nuclei with $A \geq 4$.

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1. Introduction

Interactions between charmonium $(c\bar{c})$ and nucleon (N) seems to have unique features as the strong interaction of hadrons. It is quite different from the other hadronic interactions. First, the charmonium and the nucleon have no valence quarks in common, so interactions mediated by flavor singlet meson exchanges are strongly suppressed by the Okubo-Zweig-Iizuka (OZI) rule. For the same reason, the Pauli exclusion principle for quarks does not cause a repulsion at short distances. Further, a single gluon exchange is prohibited since $(c\bar{c})$ and N are both color singlet. Thus the $(c\bar{c})-N$ interactions are dominated by multiple-gluon exchanges. Therefore, the role of gluons and QCD in low energy hadronic interaction can be studied in the $(c\bar{c})-N$ system. It is very difficult to carry out low energy $(c\bar{c})-N$ scattering experiment. But if $(c\bar{c})-$nucleus bound states exist, we can obtain the information of the strength and detailed structures of the $(c\bar{c})-N$ interaction indirectly from the spectroscopy of the $(c\bar{c})-$nucleus, as was done for $\Lambda-N$ interaction from the spectroscopy of hypernuclei.

One of the typical multiple-gluon exchange interactions is the QCD color van der Waals interaction, which is known to be attractive in principle. Recent lattice QCD calculation [1, 2] showed that the $(c\bar{c})$-nucleon interaction is weakly attractive and thus confirmed the previous studies. Considering the heavy mass of the $(c\bar{c})$, it is highly possible that $(c\bar{c})-$nucleus bound states exist, when the nucleon number A increases [3].

In this paper, we consider bound states of the charmonium, $J/\psi(J^\pi = 1^-)$ or $\eta_c(0^-)$, with few-nucleon systems [4]. In order to make an analysis independent from the microscopic models of the $(c\bar{c})-N$ interaction, we here employ a phenomenological potential model and obtain a relation between the binding energy B of $(c\bar{c})-$nucleus and the $(c\bar{c})-N$ scattering length a. Then we can compare the results with the microscopic studies of $(c\bar{c})-N$ interaction in QCD, e.g., the value of the scattering length a obtained from lattice QCD.

We consider $(c\bar{c})-NN$, $(c\bar{c})-{}^4$He, and $(c\bar{c})-\alpha-\alpha$ cases and apply the Gaussian Expansion Method (GEM) [5] to obtain their binding energies and the wave functions. Then we determine the value of the scattering length that is needed to form a bound state of $(c\bar{c})$ with the deuteron, ^{4}He (α) or ^{8}Be $(\alpha-\alpha)$.

2. Formalism

In present analysis, we consider η_c $(J^\pi = 0^-)$ and J/ψ (1^-) for the charmonium, both of which are charge neutral and have no electromagnetic interaction. Since the $(c\bar{c})-N$ interaction is considered to be weak and short ranged, we only calculate the ground state with orbital angular momentum $L = 0$. Then, the spin-orbit force does not contribute. Furthermore, for simplicity, we do not consider the tensor force, which is supposed to be weaker than the central force.

Let us consider an effective $(c\bar{c})-N$ potential. For η_c, we only have a spin-independent central force, given by a single Gaussian, as $v_{\eta_c-N}(r) = v_0 e^{-\mu r^2}$. For the $J/\psi-N$ potential, in order to take into account the spin structure of the $J/\psi-N$ interaction, we define

$$v_{J/\psi-N}(r) = (v_0 + v_s(\mathbf{S}_{J/\psi}\cdot\mathbf{S}_N))e^{-\mu r^2} \equiv v_{\rm eff}(S_{J/\psi-N})e^{-\mu r^2}, \tag{2.1}$$

where $\mathbf{S}_{J/\psi}$ and $\mathbf{S}_N$ are the spin operators of the J/ψ and N, respectively. Here we assume that the ranges of the spin-independent and spin-dependent terms are equal for simplicity, and also because they both come from gluon exchanges. $v_{\rm eff}(S_{J/\psi-N}) = v_0 - v_s$ $\big(\text{for}\, S_{J/\psi-N} = 1/2\big)$, $v_0 + \frac{1}{2}v_s$ $\big(\text{for}\, S_{J/\psi-N} = 3/2\big)$. The $J/\psi - N$ scattering lengths $a_{J/\psi-N}$ can be calculated as a function of $v_{\rm eff}$ in Eq. (2.1) by solving the non-relativistic Schrödinger equation at $E = 0$ (see Ref. [4] for the results).

Using various values of the $(c\bar{c}) - N$ potential parameters, we calculate the $(c\bar{c}) - NN$ three-body system using the Gaussian Expansion Method (GEM)[5]. The total Hamiltonian and the Schrödinger equation are given by $(H-E)\Psi_{JM} = 0,\ H = T + V_{N_1-N_2} + v_{c\bar{c}-N_1} + v_{c\bar{c}-N_2}$, where T is the kinetic-energy operator and $V_{N_1-N_2}, v_{c\bar{c}-N_1}, v_{c\bar{c}-N_2}$ are the potentials between $N-N$ and $(c\bar{c}) - N$. For the $N-N$ interaction, we employ the Minnesota potential [6].

The total wave function is expanded in GEM as

$$\Psi_{JM} = \sum_{c=1}^{3}\sum_{n=1}^{n_{max}}\sum_{N=1}^{N_{max}}\sum_{I} C^c_{nNI}\phi^c_{nlm}(\mathbf{r_c})\psi^c_{NLM}(\mathbf{R_c})[[\chi_s(1)\chi_s(2)]_I\chi_s(3)]_{JM} \tag{2.2}$$

where $\phi^c_{nlm}(\mathbf{r}) = r^l e^{-\nu_n r^2} Y^m_l(\hat{\mathbf{r}})$ with $\nu_n = 1/r_n^2,\ r_n = r_1 a^{n-1}$ $(n = 1,\dots,n_{max})$ and $\psi^c_{NLM}(\mathbf{R}) = R^L e^{-\lambda_N R^2} Y^M_L(\hat{\mathbf{R}}),\ \lambda_N = 1/R_N^2,\ R_N = R_1 A^{N-1}$ $(N = 1,\dots,N_{max})$. We take sum over all the sets of the Jacobi coordinates, each denoted by $c = 1,2,3$. Here, r_c and R_c $(c = 1,2,3)$ are the Jacobi coordinates for each channel and $\chi_s(1)$, $\chi_s(2)$ and $\chi_s(3)$ are the spin wave functions of the particles 1, 2 and 3. The orbital angular momenta l,m and L,M correspond to r and R, respectively. The number of the basis functions used in the present calculation are $n^{(c)}_{max} = 10$ and $N^{(c)}_{max} = 10$ for $c = 1,2$ and $n^{(c)}_{max} = 12$ and $N^{(c)}_{max} = 14$ for $c = 3$.

The only possible state for s-wave $\eta_c - NN$ system has the total angular momentum $J = 1$, $S_{NN} = 1$ and isospin $T = 0$. We do not consider the $T = 1$ state, since the NN ($S_{NN} = 0$, $T = 1$) state has a weaker attraction.

The binding energy of $J/\psi - NN$ system is affected by the spin-dependence of the $J/\psi - N$ interaction Eq. (2.1). We consider three channels, $J^\pi = 0^-, 1^-$ and 2^- with $T = 0$ for the three-body system. For $J^\pi = 0^-$ and $J^\pi = 2^-$, $S_{J/\psi-N}$ is uniquely given as $1/2$ and $3/2$, respectively. On the other hand, for the $J^\pi = 1^-$, $T = 0$ state, both $S_{J/\psi-N} = 1/2$ and $3/2$ are mixed. In solving this system, we can simply take an effective (spin-averaged) potential given by

$$V^{(J,T=0)}_{\rm eff} e^{-\mu r^2} \equiv \left\langle (NN)_{S_{NN}=1}, J/\psi; J \,\middle|\, v_{J/\psi-N}(r) \,\middle|\, (NN)_{S_{NN}=1}, J/\psi; J \right\rangle \tag{2.3}$$

where $V^{(0,0)}_{\rm eff} = v_0 - v_s = v_{\rm eff}(1/2)$, $V^{(1,0)}_{\rm eff} = v_0 - \frac{1}{2}v_s$, and $V^{(2,0)}_{\rm eff} = v_0 + \frac{1}{2}v_s = v_{\rm eff}(3/2)$, respectively. Among the $T = 0$ states, the differences of the spin structure appear only in the coefficient of the v_s. The binding energy B of the $J/\psi-$deuteron system ($T = 0$) is determined only by the value of $V_{\rm eff}$. Therefore in the calculations we specify the value of $V_{\rm eff}$, and do not change v_0 and v_s separately, and see how the binding energy of the $J/\psi-$deuteron changes.

$J/\psi-{}^4$He system is suitable for studying spin-independent central part v_0 since the ground state of ^{4}He is spin 0 and $J/\psi-{}^4$He interaction has no contribution from v_s. As the binding energy of ^{4}He is large, its wave function may not be disturbed by the relatively weak $J/\psi - N$ interaction. Therefore we assume that the ^{4}He and the $J/\psi-{}^4$He system can be treated as a single α cluster and a $J/\psi - \alpha$ two-body system, respectively. As an effective $J/\psi - \alpha$ potential, we use the folding potential $V_{\rm fold}(r) = \int v_{J/\psi-N}(\mathbf{r}-\mathbf{r}')\rho(\mathbf{r}')d^3\mathbf{r}'$ with the center of mass correction. $\rho(r)$ is the nucleon density distribution in ^{4}He. We choose a Gaussian function $\rho(r) = \rho(0)e^{-(r/b)^2}$

with $b = 1.358$ fm, which reproduces the experimental data of charge form factor in the elastic electron$-^4$He scattering [7, 8, 9]. The same $J/\psi-\alpha$ potential is used to calculate $J/\psi-\alpha-\alpha$ three-body system. The $\alpha-\alpha$ potential is calculated by folding Hasegawa-Nagata potential with the OCM.

3. Results

3.1 Charmonium-deuteron three-body bound states

The relation between $J/\psi-$deuteron binding energy B and the potential depth $V_{\rm eff}$ of the effective potential in Eq. (2.3) is shown in Fig. 1. We fix the range parameter $\mu = (1.0 \text{ fm})^{-2}$, taken from the confinement scale of gluon and the binding energy B is measured from deuteron+J/ψ breakup threshold ($M_p + M_n + M_{J/\psi} - 2.2$ MeV). We find that there exists a $J/\psi-$deuteron bound state for $V_{\rm eff} \leq -33$ MeV. We now convert these results into a relation between the $J/\psi-N$ scattering length and the $J/\psi-$deuteron binding energy. In sect. 2, we have shown that the effective $J/\psi-N$ potential $V_{\rm eff}^{(J,T)}$ in Eq.(2.3) for a $J/\psi-NN$ system is given by a single combination of v_0 and v_s in Eq. (2.1) once the total spin J and the isospin T is determined. Then we define the effective scattering length $a_{\rm eff}$ for each channel, which corresponds to the relevant combination of v_0 and v_s, i.e., $V_{\rm eff}$ of Eq.(2.3). We obtain a relation between $a_{\rm eff}$ and the binding energy, B, which is shown in Fig. 2. The relation for η_c-NN sytem is almost identical to that of the $J/\psi-NN$. For $J=0$ ($J=2$), $a_{\rm eff}$ is the scattering length for the potential, $(v_0 - v_s)e^{-\mu r^2}$ $\left((v_0+\frac{1}{2}v_s)e^{-\mu r^2}\right)$, while for $J=1$, $a_{\rm eff}$ is for the potential, $(v_0-\frac{1}{2}v_s)e^{-\mu r^2}$, as is given by Eq.(2.3) averaging the spin of $J/\psi-N$ system. The former corresponds to the scattering length of $J/\psi-N$ with spin 1/2 (3/2), but the $J=1$ potential does not correspond to a specific spin state of $J/\psi-N$. We find in Fig. 2 that the critical value of the scattering length to have a $J/\psi-$deuteron bound state is $a_{\rm eff} = -0.95$ fm. This is a much stronger attraction than the recent lattice QCD results $a \simeq -0.35$ fm [2], which is equivalent to $v_{\rm eff} = -16.7$ MeV. So there is little possibility of making a $J/\psi-NN$ bound state according to the recent lattice QCD data. It has been checked in Ref. [4] that our results are not sensitive to the form of the $(c\bar{c})-N$ potential (Gaussian or Yukawa-type) and the value of the potential range, μ.

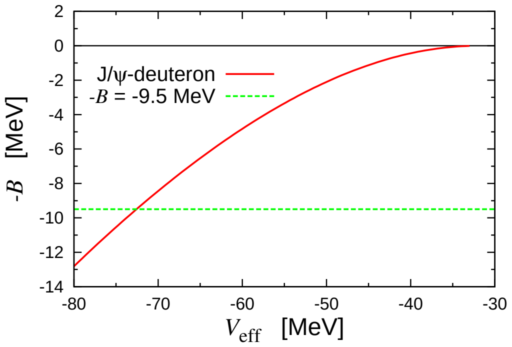

Figure 1: The relation between the binding energy B (MeV) of $J/\psi-$deuteron and $V_{\rm eff}$ (MeV) of $J/\psi-N$ potential.

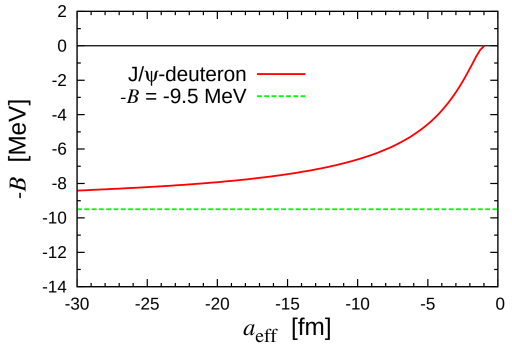

Figure 2: The relation between the binding energy B (MeV) of $J/\psi-$deuteron and the scattering length $a_{\rm eff}$ (fm) of $J/\psi-N$.

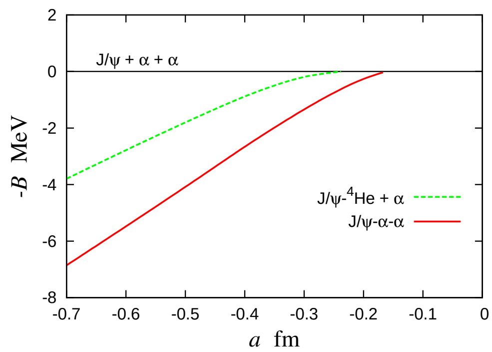

Figure 3: The relation between the scattering length $a_{\rm eff}$ of $J/\psi - N$ and the binding energy B of $J/\psi{-}^4$He and $J/\psi - \alpha - \alpha$.

3.2 $J/\psi{-}^4$He and $J/\psi - \alpha - \alpha$ systems

The relations between the $J/\psi - N$ scattering length $a_{\rm eff}$ and the binding energy B of $J/\psi{-}^4$He and $J/\psi - \alpha - \alpha$ are shown in Fig. 3. There exists a $J/\psi{-}^4$He bound state when $a_{\rm eff} \leq -0.24$ fm. The binding energies are, for example, when $a_{\rm eff} = -0.35$ fm, $B = 0.5$ MeV. Comparing with the lattice QCD data[2], $a_{J/\psi-N} \simeq -0.35$ fm, this result supports the existence of a shallow $J/\psi{-}^4$He bound state. Similarly, for $J/\psi - \alpha - \alpha$ case, a bound state is formed when $a_{\rm eff} \leq -0.16$ fm, and its binding energy is $B = 2$ MeV from $J/\psi + \alpha + \alpha$ break up threshold and 1.5 MeV from $J/\psi{-}^4$He bound state for $a_{\rm eff} = -0.35$ fm. Note that the net spin-spin interactions between the nucleon and J/ψ in both $J/\psi{-}^4$He and $J/\psi - \alpha - \alpha$ systems cancel out so that the contribution only from the spin-independent part, v_0 of Eq. (2.1), comes into account. Therefore the effective scattering length $a_{\rm eff}$ corresponds only to the spin-independent part, v_0.

Since $c\bar{c} - N$ interaction is attractive, we conclude from simple effective potential analyses that the charmonium ($c\bar{c}$) may form bound states in the nuclei of $A \geq 4$, supposing that the current lattice QCD evaluation of the charmonium-nucleon scattering lengths are reliable.

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