# Heavy-Quarkonia Interactions with Nucleons and Nuclei

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The problem of the existence of heavy-quarkonia bound states in nuclei is discussed. The method of multipole expansion and low-energy QCD theorems are used to calculate the $c\bar{c}$-nucleon scattering amplitude. It is shown that an effective interaction is too weak to produce bound states with light nuclei for $S$-wave $c\bar{c}$ systems. $S$-wave quarkonia can be bound in nuclei with $A > 10$ with binding energy of the order of some MeV.

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Physics of charmed particles and particles with hidden charm is an essential ingredient of the physical program for future experiments at CERN Super LEAR (Low Energy Antiproton Ring). There are many different aspects of charmed particle physics in antiproton interactions with nucleons and nuclei at intermediate energies: production of charmed particles in binary reactions, color transparency, the possible existence of quarkonia bound in nuclei, and supernuclei formation. Here we are going to make some remarks on the possibility of quarkonia being bound in nuclei.

Recently, Brodsky, Schmidt, and de Teramond [1,2] suggested that quarkonia states ($J/\psi$, $\eta_c$, and others) may form bound states with nuclei. They note that a heavy quark $Q\bar{Q}$ state interacts with nucleons only via gluonic exchanges and it is a QCD van der Waals type interaction. Pomeron exchange at high energies can be also considered as a manifestation of gluonic exchanges in the $t$ channel. So in order to determine the strength of this interaction and to decide whether it can lead to $Q\bar{Q}$ bound states with nuclei (or nucleon), Brodsky, Schmidt, and de Teramond considered the high energy limit of $Q\bar{Q}$-$A$ elastic scattering amplitude $MA \rightarrow MA$ and parametrized it in the form $d\sigma(MA \rightarrow MA)/dt = 4\pi\alpha^2/(\mu^2 - t)^2$, corresponding to the Yukawa potential of the vector type. On the other hand, a model with a coherent interaction of the Pomeron with nuclei was used, where $d\sigma/dt = [2\beta F_M(t)]^2[3A\beta F_A(t)]^2/4\pi$. The functions $F_M(t)$ and $F_A(t)$ are the corresponding form factors. The value of $\beta$ was assumed to be nearly universal for all hadrons and $\mu$ was chosen as 0.6 GeV; then the value of $\alpha$ for $MN$ scattering is 0.4–0.6. Note that this corresponds to the total cross section of the $MN$ interaction of 12–18 mb. With these values of parameters the authors of Ref. [1] came to the conclusion that for the $\eta_c A$ interaction there are bound states starting already from $^3$H with the binding energy of the order of some tens (and hundreds for heavy nuclei) of MeV.

We would like to note that the quarkonia-nucleon amplitude at high energies is very different from the same amplitude at low energies near the threshold. Pomeron exchange corresponds at high energy to a pure imaginary amplitude (while the vector type potential leads to a real one). The Pomeron corresponds to the scattering (absorption) due to many open inelastic channels at high energy. It also has a $C$ parity and properties with respect to crossing which are different from the vector exchange. The secondary poles $f$, $\rho$, $\omega$, and $a_2$, which can give a contribution to a real part of the amplitude, are associated with planar quark diagrams, and do not contribute to the reaction considered. So in our opinion it is impossible to obtain information on the effective potential or the amplitude at low energies near threshold studying the Pomeron.

Here we will try to estimate the real part of this amplitude near threshold using the multipole expansion for heavy-quarkonia interactions with gluon fields [3–6] and the low-energy QCD theorems [7,8] for gluon interactions with nucleons.

The starting point of this approach is the fact that for a heavy-quarkonium system of size $a \ll R$, where $R$ is the characteristic confinement radius, the interaction with gluon fields can be expanded in powers of $a/R$ (operator expansion) and for nonrelativistic heavy quarks (with mass $m_Q$) in powers of $v/c \approx 1/m_Q a$ (multipole expansion).

Then following [5,6] in the leading approximation the interaction amplitude for a heavy-quarkonium state $M$ with mass $M_{c\bar{c}}$ with hadron $h$ can be written in the form

$$T = \frac{4\pi}{3} M_{c\bar{c}} \langle M | r^i \frac{1}{\epsilon + H_a} r^j | M \rangle \langle h | \alpha_s E^i E^j | h \rangle , \qquad (1)$$

where $(\epsilon + H_a)^{-1}$ is the Green function of heavy quarkonium in a color octet state (after emission of one gluon), $r^i$ is the radius vector between quarks, and $E^i$ is the chromoelectric gluon field strength.

To estimate the first matrix element in Eq. (1) we will use the result of Ref. [6]. For $1S$ $c\bar{c}$ state

$$\langle M | r^i \frac{1}{\epsilon + H_a} r^j | M \rangle = \delta^{ij} \frac{28}{27} \pi a^3 , \qquad (2)$$

where $a$ for $c\bar{c}$ quarkonia is equal to $\approx 0.8$ GeV$^{-1}$ [6].

The second factor in Eq. (1) can be determined, using the relation between the gluonic fields and the energy-momentum tensor, which is due to triangle anomaly [9,10]:

$$\theta_{\mu\mu} = \frac{\beta(\alpha_s)}{4\alpha_s} G^a_{\mu\nu} G^a_{\mu\nu} , \tag{3}$$

where $\beta(\alpha_s)$ is the Gell-Mann–Low function.

This leads to the relation

$$\alpha_s E^i E^i = \frac{2\pi}{b} \theta_{\mu\mu} + O(\alpha_s) , \tag{4}$$

where $b=9$ is the first coefficient of $\beta(\alpha_s)$. It can be shown using the results of Ref. [8] that the corrections of the order of $\alpha_s$ in Eq. (4) are small.

The matrix element of the energy-momentum tensor is given by the following expression:

$$\langle h | \theta_{\mu\nu} | h \rangle |_{p_1 = p_2 = p} = 2 p_\mu p_\nu . \tag{5}$$

Now we can calculate the amplitude of elastic $\eta_c(J/\psi)$-nucleon scattering at the threshold ($p_0 = m_N$), which is real:

$$T = \frac{64\pi^3}{3^6} 7 M_{\eta_c} m_N^2 a^3 . \tag{6}$$

This amplitude corresponds to the strength of effective potential of Ref. [1] (with $\mu = 0.6$) of

$$\alpha = \frac{T\mu^2}{16\pi M_{\eta_c} m_N} = 0.06 , \tag{7}$$

which is nearly an order of magnitude smaller than the value used in Ref. [1]. The scattering length is equal to

$$a_s = \frac{T}{8\pi(M_{\eta_c} + m_N)} = 0.05 \text{ fm} . \tag{8}$$

The effective potential of charmonium-nucleon interaction satisfies in Born approximation (which is valid because of the small value and small radius of the potential) the equation

$$\int V_{\eta_c N} d^3 r = -2\pi \frac{M_{\eta_c} + m_N}{M_{\eta_c} m_N} a_s . \tag{9}$$

Now following [11] we may calculate the $\eta_c$-nucleus potential,

$$V_{\eta_c A}(r) = \int d^3 r' V_{\eta_c N}(r - r') \rho_A(r') . \tag{10}$$

As long as the radius of the charmonium-nucleon potential is small when compared with the mean distance between nucleons in the nucleus [5], we can estimate an effective charmonium-nucleus potential as

$$V_{\eta_c A}(r) = \rho_A(r) \int d^3 r' V_{\eta_c N}(r') = -\frac{T}{4 M_{\eta_c} m_N} . \tag{11}$$

With $\rho(r) = \rho_{\rm nm} \approx 0.17 \text{ fm}^{-3}$ we have for the depth of the potential well in heavy nuclei the value

$$V_0 = -\frac{T}{4 M_{\eta_c} m_N} \rho_{\rm nm} = 3 \text{ MeV} , \tag{12}$$

which is an order of magnitude less than the value obtained in Ref. [11].

The condition for existence of a bound state has the form

$$V_0 > \pi^2 / 8 M_{\eta_c} R_A^2 , \tag{13}$$

where $R_A$ is the nucleus radius which coincides in our case with the radius of the potential well. Equation (13) is valid for $A > 10$. This means that bound states may exist for heavy nuclei only and the binding energy is very small (of the order of some MeV). Even if such states do exist their production in $\bar{p}A$ collisions will be strongly suppressed because of very high momenta of relative motion in nuclei needed to produce stopped charmonia states.

The low-energy amplitude can be larger for 2$S$- or $P$-wave states, because of larger coefficients in Eq. (2) (larger value of the radius). However, for these states with $a \approx 1$ fm the operator expansion is less reliable and it is difficult to draw any definite conclusions on the possibility to produce a bound state with nuclei.

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