Binding of $D$, $\bar{D}$ and $J/\Psi$ mesons in nuclei

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Abstract. We estimate the $D$, $\bar{D}$ and $J/\Psi$ meson potentials in nuclei. $J/\Psi$-nuclear potential (self-energy) is calculated based on the color-singlet mechanism, by the $DD$ and $DD^*$ meson loops. This consistently includes the in-medium properties of $D$ and $D^*$ mesons. The potential obtained for the $J/\Psi$ meson is attractive, and it is complementary to the attraction obtained from the color-octet gluon-based mechanism. We predict that the $D^-$ and $J/\Psi$ mesons will be bound in nuclei under proper conditions.

Keywords: Meson-nuclear bound state, $D$, $\bar{D}$ and $J/\Psi$ in nuclei, Quark-meson coupling model

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Introduction

The properties of charmed mesons and charmonium in a nuclear medium (nuclei) are still very little known. However, future experimental facilities such as JLab (after 12 GeV upgrade of CEABAF), J-PARC, and FAIR will make it possible to explore the in-medium properties of these mesons. Among them, below we focus on the $D$, $\bar{D}$ and $J/\Psi$ mesons.

![Figure 1](image)

**FIGURE 1.** Scalar potentials (in-medium mass minus free mass) in symmetric nuclear matter [3].

To study the in-medium properties of $D$, $\bar{D}$ and $J/\Psi$ mesons, we rely on the quark-meson coupling (QMC) model [1, 2]. The QMC model is a quark-based, relativistic mean field model of nuclear matter and nuclei [1, 2]. Relativistically moving confined light quarks in the nucleon bags self-consistently interact directly with the scalar-isoscalar $\sigma$, vector-isoscalar $\omega$, and vector-isovector $\rho$ mean fields generated by the
light quarks in the (other) nucleons. These meson mean fields are responsible for the nuclear binding. The direct interaction between the light quarks and the scalar $\sigma$ field is the key of the model, which induces the scalar polarizability at the nucleon level, and generates the nonlinear scalar potential (effective nucleon mass), or the density $\sigma$-field) dependent $\sigma$-nucleon coupling. This gives a novel, new saturation mechanism for nuclear matter. The model has opened tremendous opportunities for the studies of finite nuclei and hadrons properties in a nuclear medium (nuclei), based on the quark degrees of freedom. Many successful applications of the model can be found in Ref. [2].

In the QMC model, since the couplings between the light quark and the $\sigma$, $\omega$, and $\rho$ fields are the same for all the light quarks in the hadrons irrespective of the hadron species, the model can treat them systematically in the nuclear medium. In particular, the scalar potentials (in-medium mass minus free mass) for hadrons have turned out to be proportional to the number of light quarks in each hadron — the light quark number counting rule [3]. This is demonstrated in Fig. 1.

**D and $\bar{D}$ mesons in symmetric nuclear matter and nuclei**

First, we recall the in-medium properties of $D$ and $\bar{D}$ mesons studied in QMC [4, 5]. In Fig. 2 (left panel) we show the total (scalar plus vector) potentials for the $D$ and $\bar{D}$ mesons in symmetric nuclear matter. To calculate the $J/\Psi$ potential (self-energy) in (symmetric) nuclear matter by the $D$ and $D^*$ meson loops, in-medium properties of the $D$ and $D^*$ must be consistently included. This will be done in next section.

**FIGURE 2.** $D$ and $\bar{D}$ meson potentials in symmetric nuclear matter (left panel) [4], and total potential of the $D^-$ in a Pb nucleus including the Coulomb potential (right panel) [5]. Note that the $\omega$ vector potential (aside from the signs) for the $D$ and $\bar{D}$ in the left panel is $V_\omega = 1.96V_\omega^d$, the same as that used for kaon [6].

In Ref. [5] we studied possibilities of forming meson-nuclear bound states for the $D$ and $\bar{D}$ mesons in a Pb nucleus. The single-particle energies obtained are listed in Table 1. Among them, the $D^-$ meson is promising to explore experimentally. Since its quark content is $D^- = \bar{c}d$, the width is expected to be narrow due to no light-quark annihilation channels. Furthermore, because of the attractive Coulomb potential, there is always a chance to form the Coulomb bound state irrespective of the details in the
strong interaction potential inside the Pb nucleus. We show in Fig. 2 (right panel) the total potential calculated for the $D^-$ meson in the Pb nucleus including the Coulomb potential, for the two cases of the vector potentials, $V_\omega^q$ and $V_\omega^q = 1.96 V_\omega^q$.

### TABLE 1.

| state | $D^-(V_\omega^q)$ | $D^-(V_\omega^q)$ | $D^-(V_\omega^q, \text{no Coulomb})$ | $D^0(V_\omega^q)$ | $D^0(V_\omega^q)$ | $D^0(V_\omega^q)$ |
|-------|-------------------|-------------------|--------------------------------------|-------------------|-------------------|-------------------|
| 1s    | -10.6             | -35.2             | -11.2                                | unbound           | -25.4             | -96.2             |
| 1p    | -10.2             | -32.1             | -10.0                                | unbound           | -23.1             | -93.0             |
| 2s    | -7.7              | -30.0             | -6.6                                 | unbound           | -19.7             | -88.5             |

### $J/\Psi$ meson potential in symmetric nuclear matter

The $J/\Psi$ potential in nuclear matter (nuclei) has been estimated mainly based on the gluon induced mechanisms — based on an effective filed theory [7], QCD Stark effect [8], and chromo-polarizability [9]. In the following, we study the $J/\Psi$ potential (self-energy) in symmetric nuclear matter by the color-singlet mechanism, the $DD$ and $DD^*$ meson loops, where the relevant vertexes are $J/\Psi-\bar{D}-D$ and $J/\Psi-\bar{D}-D^*$, respectively. An analysis combined with the $D^*D^*$ meson loop contribution will be reported elsewhere [10].

To calculate the in-medium $J/\Psi$ self-energy by the $DD$ and $DD^*$ meson loops, we need to include the in-medium properties of $D$ and $D^*$ mesons consistently as mentioned in the previous section. In addition, we introduce the dipole form factors [11] for the $J/\Psi-\bar{D}-D$ and $J/\Psi-\bar{D}-D^*$ vertexes with the common cut-offs. The coupling constants used are, $g_{J/\Psi DD} = g_{J/\Psi DD^*} = 7.7$. The $J/\Psi$ potential calculated in symmetric nuclear matter (in-medium mass minus free mass), $m_\Psi^* - m_\Psi$, is shown in Fig. 3.

We regard the results with the cut-off values 1500 and 2000 MeV as our predictions. At normal nuclear matter density, these correspond to about 7 and 9 MeV attractions, respectively. Combined with the contribution from the color-octet gluon-based attraction [7, 8, 9], and an additional attraction expected from the $D^*D^*$ loop, we conclude that the $J/\Psi$ meson will be bound in nuclei under proper conditions. In this case, the width is expected to be narrow. The experimental search for the $J/\Psi$-nuclear bound states will be possible at JLab after 12 GeV upgrade of CEABAF.

### Summary and Conclusion

We have studied binding of $D$, $\bar{D}$ and $J/\Psi$ mesons in nuclei based on the quark-meson coupling model. Due to the attractive Coulomb potential, the $D^-$ meson will be inevitably bound in a Pb nucleus with a narrow width. This does not depend on the details of the strong interaction potential for the $D^-$ in a Pb nucleus. For the $J/\Psi$-nuclear potential, we have estimated based on the color-singlet mechanism, by the $DD$ and $DD^*$ meson loops, consistently including the in-medium properties of the $D$ and
\( \rho_B / \rho_0 \) (\( \rho_0 = 0.15 \text{ fm}^{-3} \))

FIGURE 3.  \( J/\Psi \) potential in symmetric nuclear matter. The solid, dotted, dashed, and dash-dotted curves correspond to the common cut-off values in the dipole form factors attached to the \( J/\Psi-D-D \) and \( J/\Psi-D-D^* \) vertexes, 1000, 1500, 2000, and 3000 MeV, respectively.

\( D^* \) mesons. Combined with the color-octet gluon-based attraction, and an additional attraction expected from the \( D^* D^* \) loop, we expect that the \( J/\Psi \) meson will be bound in nuclei with narrow widths under proper conditions.

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