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www.elsevier.com/locate/physletb J/ψ mass shift in nuclear matterG. Krein^{a,*}, A.W. Thomas^b, K. Tsushima^c^a Instituto de Física Teórica, Universidade Estadual Paulista, Rua Dr. Bento Teobaldo Ferraz, 271-Bloco II, São Paulo, SP, Brazil^b CSSM, School of Chemistry and Physics, University of Adelaide, Adelaide SA 5005, Australia^c EBAC in Theory Center, Jefferson Lab, 12000 Jefferson Ave. Newport News, VA 23606, USA

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ABSTRACT

The J/ψ mass shift in cold nuclear matter is computed using an effective Lagrangian approach. The mass shift is computed by evaluating D and D^* meson loop contributions to the J/ψ self-energy employing medium-modified meson masses. The modification of the D and D^* masses in nuclear matter is obtained using the quark–meson coupling model. The loop integrals are regularized with dipole form factors and the sensitivity of the results to the values of form-factor cutoff masses is investigated. The J/ψ mass shift arising from the modification of the D and D^* loops at normal nuclear matter density is found to range from -16 MeV to -24 MeV under a wide variation of values of the cutoff masses. Experimental perspectives for the formation of a bound state of J/ψ to a nucleus are investigated.

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1. Introduction

A new era of nuclear matter research is envisaged with the 12 GeV upgrade of the CEBAF accelerator at the Jefferson Lab in the USA and with the construction of the FAIR facility in Germany. These new facilities will have the exciting potential of implanting low-momentum charmonia and charmed hadrons in an atomic nucleus, like the J/ψ and ψ mesons and heavy-light charmed mesons such as D and D^* . While at JLab charmed hadrons will be produced by scattering electrons off nuclei, at FAIR they will be produced by the annihilation of antiprotons on nuclei. There are several reasons for the excitement, one of the main ones being the opportunity of studying the poorly understood low-energy excitations of gluon degrees of freedom. An example where these excitations play an important role is the propagation of charmonia in matter. Since a charmonium state does not have quarks in common with the nuclear medium, its interactions with the medium necessarily involve the intervention of gluons. Basic interaction mechanisms discussed in the literature have been the excitation of QCD van der Waals forces arising from the exchange of two or more gluons between color-singlet states [1,2], and the excitation of charmed hadronic intermediate states with light quarks created from the vacuum [3,4].

Another interesting challenge is to study the properties of charmed D and D^* mesons in medium. The chiral properties of the light quarks that compose these mesons are much more sensitive to the nuclear medium than their companion, heavier charm quarks and therefore they offer the unique opportunity of studying phenomena like the partial restoration of chiral symmetry in nuclear matter. Motivated by such considerations, some very interesting phenomena involving these mesons have been predicted. Amongst these we mention the possible formation of $D(\bar{D})$ meson–nuclear bound states [5], enhanced dissociation of J/ψ meson in nuclear matter (heavy nuclei) [6], and enhancement of the D and \bar{D} meson production in antiproton–nucleus collisions [7]. Ref. [8] presents a recent review of the properties of charmonium states and compiles a fairly complete list of references on theoretical studies concerning a great variety of physics issues related to these states. On the experimental side, one of the major challenges is to find appropriate kinematical conditions to produce these hadrons essentially at rest, or with small momentum relative to the nucleus, as effects of the nuclear medium are driven by low-energy interactions.

The original suggestion [2] was that QCD van der Waals forces arising from multiple gluon exchange would be capable of binding a charmonium state by as much as 400 MeV in an $A = 9$ nucleus. The estimate was based on a variational calculation using a phenomenological ansatz for the charmonium–nucleus potential in the form of a Yukawa potential. Along the same lines but taking into account the distribution of nucleons in the nucleus by folding the charmonium–nucleon Yukawa potential with the nuclear density

* Corresponding author.

E-mail addresses: gkrein@ift.unesp.br (G. Krein), anthony.thomas@adelaide.edu.au (A.W. Thomas), tsushima@jlab.org (K. Tsushima).

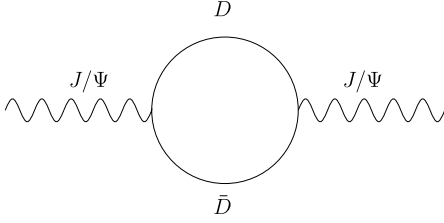


Fig. 1. DD -loop contribution to the J/ψ self-energy. We include also DD^* and D^*D^* contributions.

distribution, Ref. [9] found a maximum of 30 MeV binding energy in a large nucleus. A somewhat more QCD-oriented estimate was made in Ref. [10]. Using a lowest-order multipole expansion for the coupling of multiple gluons to a small-size charmonium bound state [1], it is possible to show on the basis of the operator product expansion that the mass shift of charmonium in nuclear matter is given, in the limit of infinitely heavy charm quark mass, by an expression similar to the usual second-order Stark effect in atomic physics, which depends on the chromo-electric polarizability of the nucleon. Using an estimate [1] for the value of this polarizability, the authors of Ref. [10] obtained a 10 MeV binding for J/ψ in nuclear matter. On the other hand, for the excited charmonium states, a much larger binding energy was obtained, e.g. 700 MeV for the excited charmonium state $\psi'(2S)$, an admittedly untrustworthy number. Following this same procedure, but keeping the charm quark mass finite and using realistic charmonium bound-state wave-functions, Ref. [4] found 8 MeV binding energy for J/ψ in nuclear matter, but still over 100 MeV binding for the charmonium excited states. While an increase in the QCD Stark effect is expected for excited states (because of their larger size), the extreme values for the binding energies for these states found in the literature are widely considered to be unrealistic. The source for such an overestimate is attributed to the breakdown of the multipole expansion for the larger-sized charmonium states.

There are some other studies on charmonium interactions with ordinary hadrons and nuclear matter, in particular involving the J/ψ meson. QCD sum rules studies estimated a J/ψ mass decrease in nuclear matter ranging from 4 to 7 MeV [11–13], while an estimate based on color polarizability [14] gave larger than 21 MeV. In addition, there are studies of the charmonium–nucleon interaction and of J/ψ dissociation cross sections based on a one-boson exchange model [15], effective Lagrangians [16,17] and the quark-model [18]. In Ref. [19] the charmonium–hadron interaction was studied in lattice QCD.

A first estimate for the mass shifts of charmonium states (we denote charmonium states generically by ψ) in nuclear medium arising from the excitation of a pair of D and D^* mesons – see Fig. 1 – was performed in Ref. [4]. Employing a gauged effective Lagrangian for the coupling of D mesons to the charmonia, the mass shifts were found to be positive for J/ψ and $\psi(3770)$, and negative for $\psi(3660)$ at normal nuclear matter density ρ_0 . These results were obtained for density-dependent D and \bar{D} masses that decrease linearly with density, such that at ρ_0 they are shifted by 50 MeV. The loop integral in the self-energy (Fig. 1) is divergent and was regularized using form factors derived from the 3P_0 decay model with quark-model wave functions for ψ and D . The positive mass shift is at first sight puzzling, since even with a 50 MeV reduction of the D masses, the intermediate state is still above threshold for the decay of J/ψ into a $D\bar{D}$ pair and so a second-order contribution should be negative. As we shall explain below, this was not realized in the calculation of Ref. [4] because of the interplay of the form factor used and the gauged nature of the interaction.

In the present Letter we reanalyze the mass shift of J/ψ in terms of the excitation of intermediate charmed mesons using effective Lagrangians. In addition to the $D\bar{D}$ loops, we also include $D\bar{D}^*$, $D^*\bar{D}$ and $D^*\bar{D}^*$ loops. The medium dependence of the D and D^* masses is included by an explicit calculation using the quark–meson coupling (QMC) model [20]. The QMC is a quark-based model for nuclear structure which has been very successful in describing nuclear matter saturation properties and has been used to predict a great variety of changes of hadron properties in nuclear medium. A review of the basic ingredients of the model and a summary of results and predictions can be found in Ref. [21].

The Letter is organized as follows. In the next section we present the effective Lagrangians used to calculate the J/ψ self-energy and give explicit expressions for the contributions of the different intermediate states. In Section 3 we briefly review the QMC description of the D and D^* mesons in nuclear matter and present numerical results for the density dependence of the D and D^* masses. A full set of numerical results for the density dependence of the J/ψ self-energy is presented in Section 4. We show results for the separate contributions of the $D\bar{D}^*$, $D^*\bar{D}$ and $D^*\bar{D}^*$ loops and also investigate the sensitivity of our results to the cut-off masses. Our conclusions and perspectives for future work are presented in Section 5.

2. Effective Lagrangians and J/ψ self-energy

We use the following phenomenological Lagrangian densities for the vertices J/ψ - D and J/ψ - D^* (in the following we denote by ψ the field representing J/ψ):

$$\mathcal{L}_{\psi DD} = ig_{\psi DD} \psi^\mu [\bar{D}(\partial_\mu D) - (\partial_\mu \bar{D})D], \quad (1)$$

$$\mathcal{L}_{\psi DD^*} = \frac{g_{\psi DD^*}}{m_\psi} \varepsilon_{\alpha\beta\mu\nu} (\partial^\alpha \psi^\beta) [(\partial^\mu \bar{D}^{*\nu})D + \bar{D}(\partial^\mu D^{*\nu})], \quad (2)$$

$$\begin{aligned} \mathcal{L}_{\psi D^* D^*} = ig_{\psi D^* D^*} \{ & \psi^\mu [(\partial_\mu \bar{D}^{*\nu})D_v^* - \bar{D}^{*\nu}(\partial_\mu D_v^*)] \\ & + [(\partial_\mu \psi^\nu)\bar{D}_v^* - \psi^\nu(\partial_\mu \bar{D}_v^*)]D^{*\mu} \\ & + \bar{D}^{*\mu}[\psi^\nu(\partial_\mu D_v^*) - (\partial_\mu \psi^\nu)D_v^*] \}. \end{aligned} \quad (3)$$

Our convention for the D -meson-field isospin doublets is

$$\begin{pmatrix} \bar{D}^0 & D^- \\ D^+ & \end{pmatrix}, \quad D = \begin{pmatrix} D^0 \\ D^+ \end{pmatrix}. \quad (4)$$

We note that these Lagrangians are an $SU(4)$ extension of light-flavor chiral-symmetric Lagrangians of pseudoscalar and vector mesons. In the light flavor sector, they have been motivated by a local gauge symmetry principle, treating vector mesons either as massive gauge bosons or as dynamically generated gauge bosons. In the first case, there appear contact interactions involving two pseudoscalar and two vector mesons. When extended to the charm sector, in Eq. (1) for instance, there is an additional term of the form $2g_{\psi DD}^2 \psi^\mu \psi_\mu \bar{D}D$. In view of the fact that $SU(4)$ flavor symmetry is strongly broken in nature, and in order to stay as close as possible to phenomenology, we use experimental values for the charmed mesons masses and use the empirically known meson coupling constants. For these reasons we choose not to use gauged Lagrangians – a similar attitude was followed in Ref. [22] in a study of hadronic scattering of charmed mesons. However, in order to compare results with Ref. [4] and assess the impact of a contact term of the form $\psi\psi DD$, we will also present results for the J/ψ mass shift including such a term.

We are interested in the difference of the in-medium, m_ψ^* , and vacuum, m_ψ , masses of J/ψ ,

$$\Delta m = m_\psi^* - m_\psi, \quad (5)$$

with the masses obtained from

$$m_\psi^2 = (m_\psi^0)^2 + \Sigma(k^2 = m_\psi^2). \quad (6)$$

Here m_ψ^0 is the bare mass and $\Sigma(k^2)$ is the total J/Ψ self-energy obtained from the sum of the contributions from the DD , DD^* and D^*D^* loops. The in-medium mass, m_ψ^* , is obtained likewise, with the self-energy calculated with medium-modified D and D^* meson masses.

We take the averaged, equal masses for the neutral and charged D mesons, i.e. $m_{D0} = m_{D\pm}$ and $m_{D^*0} = m_{D^*\pm}$. Averaging over the three polarizations of J/Ψ , one can write each of the loop contributions to the J/Ψ self-energy Σ_l , $l = DD, DD^*, D^*D^*$, as

$$\Sigma_l(m_\psi^2) = -\frac{g_{\psi l}^2}{3\pi^2} \int_0^\infty dq \mathbf{q}^2 F_l(\mathbf{q}^2) K_l(\mathbf{q}^2), \quad (7)$$

where $F_l(\mathbf{q}^2)$ is the product of vertex form-factors (to be discussed later) and the $K_l(\mathbf{q})$ for each loop contribution are given by

$$K_{DD}(\mathbf{q}^2) = \frac{\mathbf{q}^2}{\omega_D} \left(\frac{\mathbf{q}^2}{\omega_D^2 - m_\psi^2/4} - \xi \right), \quad (8)$$

$$K_{DD^*}(\mathbf{q}^2) = \frac{\mathbf{q}^2 \bar{\omega}_D}{\omega_D \omega_{D^*}} \frac{1}{\bar{\omega}_D^2 - m_\psi^2/4}, \quad (9)$$

$$K_{D^*D^*}(\mathbf{q}^2) = \frac{1}{4m_\psi \omega_D} \left[\frac{\mathcal{A}(q^0 = \omega_{D^*})}{\omega_{D^*} - m_\psi/2} - \frac{\mathcal{A}(q^0 = \omega_{D^*} + m_\psi)}{\omega_{D^*} + m_\psi/2} \right], \quad (10)$$

where $\omega_D = (\mathbf{q}^2 + m_D^2)^{1/2}$, $\omega_{D^*} = (\mathbf{q}^2 + m_{D^*}^2)^{1/2}$, $\bar{\omega}_D = (\omega_D + \omega_{D^*})/2$, $\xi = 0$ for the non-gauged Lagrangian of Eq. (1) and $\xi = 1$ for the gauged Lagrangian of Ref. [4], and

$$\mathcal{A}(q) = \sum_{i=1}^4 \mathcal{A}_i(q), \quad (11)$$

with

$$\mathcal{A}_1(q) = -4q^2 \left\{ 4 - \frac{q^2 + (q-k)^2}{m_{D^*}^2} + \frac{[q \cdot (q-k)]^2}{m_{D^*}^4} \right\}, \quad (12)$$

$$\mathcal{A}_2(q) = 8 \left[q^2 - \frac{q \cdot (q-k)}{m_{D^*}^2} \right] \left[2 + \frac{(q^0)^2}{m_{D^*}^2} \right], \quad (13)$$

$$\mathcal{A}_3(q) = 8(2q^0 - m_\psi) \left\{ q^0 - (2q^0 - m_\psi) \frac{q^2 + q \cdot (q-k)}{m_{D^*}^2} + q^0 \frac{[q \cdot (q-k)]^2}{m_{D^*}^4} \right\}, \quad (14)$$

$$\mathcal{A}_4(q) = -8 \left[q^0 - (q^0 - m_\psi) \frac{q \cdot (q-k)}{m_{D^*}^2} \right] \times \left[(q^0 - m_\psi) - q^0 \frac{q \cdot (q-k)}{m_{D^*}^2} \right]. \quad (15)$$

In these last expressions, q and k are four-vectors given by $q = (q^0, \mathbf{q})$ and $k = (m_\psi, 0)$.

3. Quark-meson coupling model and D and D^* mesons in matter

In this section we briefly review the QMC description of the D and D^* mesons in nuclear matter. Notations and explicit expressions are given in Refs. [5,26].

The QMC model was created to provide insight into the structure of nuclear matter, starting at the quark level [20,23,21]. Nuclear internal structure was modeled by the MIT bag, while the binding was described by the self-consistent couplings of the confined light quarks (u, d) (not s nor heavier quarks) to the scalar- σ and vector- ω meson fields generated by the confined light quarks in the other nucleons. The self-consistent response of the bound light quarks to the mean σ field leads to a novel saturation mechanism for nuclear matter, with the enhancement of the lower components of the valence Dirac light quark wave functions. The direct interaction between the light quarks and the scalar σ field is a key ingredient of the model, it induces a nucleon *scalar polarizability* [24,25] and generates a nonlinear scalar potential (effective nucleon mass), or equivalently a density-dependent (σ -field dependent) σ -nucleon coupling. The model has opened tremendous opportunities for studies of the structure of finite nuclei and of hadron properties in a nuclear medium (nuclei) with a model based on the underlying quark degrees of freedom [21].

In QMC the Dirac equations for the quarks and antiquarks in nuclear matter, inside the bags of D and D^* mesons ($q = u$ or d , and c) neglecting the Coulomb force in nuclear matter, are given by:

$$\left[i\gamma \cdot \partial_x - (m_q - V_\sigma^q) \mp \gamma^0 \left(V_\omega^q + \frac{1}{2} V_\rho^q \right) \right] \begin{pmatrix} \psi_u(x) \\ \psi_{\bar{u}}(x) \end{pmatrix} = 0, \quad (16)$$

$$\left[i\gamma \cdot \partial_x - (m_q - V_\sigma^q) \mp \gamma^0 \left(V_\omega^q - \frac{1}{2} V_\rho^q \right) \right] \begin{pmatrix} \psi_d(x) \\ \psi_{\bar{d}}(x) \end{pmatrix} = 0, \quad (17)$$

$$[i\gamma \cdot \partial_x - m_c] \psi_c(x) \text{ (or } \psi_{\bar{c}}(x)) = 0. \quad (18)$$

The (constant) mean-field potentials for a light quarks in nuclear matter are defined by $V_\sigma^q \equiv g_\sigma^q \sigma$, $V_\omega^q \equiv g_\omega^q \omega$ and $V_\rho^q \equiv g_\rho^q b$, with g_σ^q , g_ω^q and g_ρ^q the corresponding quark-meson coupling constants.

The eigenenergies for the quarks in the D and D^* mesons in units of $1/R_{D,D^*}^*$ are given by,

$$\begin{pmatrix} \epsilon_u \\ \epsilon_{\bar{u}} \end{pmatrix} = \Omega_q^* \pm R_{D,D^*}^* \left(V_\omega^q + \frac{1}{2} V_\rho^q \right), \quad (19)$$

$$\begin{pmatrix} \epsilon_d \\ \epsilon_{\bar{d}} \end{pmatrix} = \Omega_q^* \pm R_{D,D^*}^* \left(V_\omega^q - \frac{1}{2} V_\rho^q \right), \quad (20)$$

$$\epsilon_c = \epsilon_{\bar{c}} = \Omega_c. \quad (21)$$

Then, the D and D^* meson masses in a nuclear medium m_{D,D^*}^* are calculated by

$$m_{D,D^*}^* = \sum_{j=q,\bar{q},c,\bar{c}} \frac{n_j \Omega_j^* - z_{D,D^*}}{R_{D,D^*}^*} + \frac{4}{3} \pi R_{D,D^*}^3 B, \quad (22)$$

$$\left. \frac{\partial m_{D,D^*}^*}{\partial R_{D,D^*}^*} \right|_{R_{D,D^*}^* = R_{D,D^*}^*} = 0, \quad (23)$$

where $\Omega_q^* = \Omega_{\bar{q}}^* = [x_q^2 + (R_{D,D^*}^* m_q^*)^2]^{1/2}$ ($q = u, d$), with $m_q^* = m_q - g_\sigma^q \sigma$, $\Omega_c^* = \Omega_{\bar{c}}^* = [x_c^2 + (R_{D,D^*}^* m_c)^2]^{1/2}$, and $x_{q,c}$ being the bag eigenfrequencies. B ($= (170.0 \text{ MeV})^4$) is the bag constant, n_q ($n_{\bar{q}}$) and n_c ($n_{\bar{c}}$) are the lowest mode quark (antiquark) numbers for the quark flavors q and c in the D and D^* mesons, respectively, and the z_{D,D^*} parameterize the sum of the center-of-mass and gluon fluctuation effects and are assumed to be independent of density. We choose the values $(m_q, m_c) = (5, 1300) \text{ MeV}$ for the current quark masses, and $R_N = 0.8 \text{ fm}$ for the bag radius of the nucleon in free space. The quark-meson coupling constants, g_σ^q , g_ω^q and g_ρ^q , are adjusted to fit the nuclear saturation energy and density of symmetric nuclear matter, and the bulk symmetry energies [21]. Exactly the same coupling constants, g_σ^q , g_ω^q and g_ρ^q , are

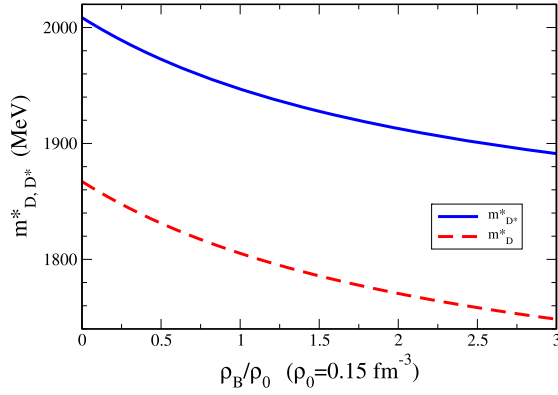


Fig. 2. D and D^* meson (scalar) effective masses as a function of baryon density.

used for the light quarks in the D and D^* mesons and baryons as in the nucleon.

Because of baryon number conservation, no vector potential should contribute to the loop integrals. Then, the vector potentials for the D and D^* mesons should be the same in considering the case of the DD^* mixed loop to cancel out. However, for the K^+ meson case, g_{ω}^q associated with the vector potential had to be scaled 1.96 times to reproduce an empirically extracted repulsive potential of about 25 MeV at normal nuclear matter density [27]. The reason is that K -mesons may be regarded as pseudo-Goldstone bosons, and they are therefore difficult to describe by naive quark models as is also true for pions. For this reason, in earlier work we explored the possibility of also scaling the g_{ω}^q strength by a factor 1.96 for the D -mesons [5,7]. In the present case, this possibility is excluded by baryon number conservation. As a result, the vector potential does not contribute to the final results. Thus, we may focus on the (scalar) effective masses of D and D^* mesons. The QMC predictions for the in-medium effective masses of these mesons are shown in Fig. 2 as a function of nuclear matter density. The net reductions in the masses of the D and D^* are nearly the same as a function of density, as dictated by the light quark number counting rule [26].

4. Numerical results

Amongst the main ingredients of the present calculation are the phenomenological form factors needed to regularize the self-energy loop integrals in Eq. (7). Following previous experience with a similar calculation for the ρ self-energy [28], we use a dipole form for the vertex form factors

$$u_{D,D^*}(\mathbf{q}^2) = \left(\frac{\Lambda_{D,D^*}^2 + m_{\psi}^2}{\Lambda_{D,D^*}^2 + 4\omega_{D,D^*}^2(\mathbf{q})} \right)^2, \quad (24)$$

so that the $F_I(\mathbf{q}^2)$ in Eq. (7) are given by

$$F_{DD}(\mathbf{q}^2) = u_D^2(\mathbf{q}^2), \quad (25)$$

$$F_{DD^*}(\mathbf{q}^2) = u_D(\mathbf{q}^2)u_{D^*}(\mathbf{q}^2), \quad (26)$$

$$F_{D^*D^*}(\mathbf{q}^2) = u_{D^*}^2(\mathbf{q}^2), \quad (27)$$

where Λ_D and Λ_{D^*} are cutoff masses. Obviously the main uncertainty here is the value of these cutoff masses. In a simple-minded picture of the vertices the cutoff masses are related to the extension of the overlap region of J/ψ and D mesons at the vertices and therefore should depend upon the sizes of the wave functions of these mesons. One can have a rough estimate of Λ_D and Λ_{D^*} by using a quark model calculation of the form factors. Using a 3P_0

Table 1

In-medium J/ψ mass $m_{J/\psi}^*$ and the individual loop contributions to the mass difference Δm at nuclear matter density, for different values of the cutoff Λ_D , and using the non-gauged Lagrangian – $\xi = 0$ in Eq. (8). All quantities are in MeV.

Λ_D	$m_{J/\psi}^*$	DD	DD^*	D^*D^*	Δm
1000	3081	–3	–2	–11	–16
1500	3079	–3.5	–2.5	–12	–18
2000	3077	–4	–3	–13	–20
3000	3072	–6.5	–5	–12.5	–24

model for quark-pair creation [29] and Gaussian wave functions for the mesons, the vertex form factor can be written as [4]

$$u_{QM}(\mathbf{q}^2) = e^{-\mathbf{q}^2/4(\beta_D^2 + 2\beta_{\psi}^2)}, \quad (28)$$

where β_D and β_{ψ} are the Gaussian size parameters of the D and J/ψ wave functions. Demanding that the $u(\mathbf{q}^2)$ of Eq. (24) and $u_{QM}(\mathbf{q}^2)$ have the r.m.s. radii $\langle r^2 \rangle^{1/2}$, with

$$\langle r^2 \rangle = -6 \frac{d \ln u(q^2)}{dq^2} \Big|_{q^2=0}, \quad (29)$$

one obtains

$$\Lambda^2 = 32(\beta_D^2 + 2\beta_{\psi}^2) - 4m_D^2. \quad (30)$$

Using $m_D = 1867.2$ MeV and for the β 's the values used in Ref. [4], $\beta_D = 310$ MeV and $\beta_{\psi} = 520$ MeV, one obtains $\Lambda_D = 2537$ MeV. Admittedly this is a somewhat rough estimate and it is made solely to obtain an order of magnitude estimate, since we do not expect that Gaussian form factors should be very accurate at high \mathbf{q}^2 . In view of this and to gauge uncertainties of our results, we allow the value of Λ_D vary in the range $1000 \text{ MeV} \leq \Lambda_D \leq 3000 \text{ MeV}$. Moreover, for simplicity we use $\Lambda_D = \Lambda_{D^*}$.

Using $m_{D^*} = 2008.6$ MeV for the average of the vacuum masses of the D^* 's, there remain to be fixed the bare J/ψ mass m_{ψ}^0 and the coupling constants. The bare mass is fixed by fitting the physical mass $m_{J/\psi} = 3096.9$ MeV using Eq. (6). For the coupling constants we use $g_{\psi DD} = g_{\psi DD^*} = g_{\psi D^*D^*} = 7.64$, which are obtained by invoking vector-meson-dominance and use of isospin symmetry [30].

We are now in a position to present the results for the in-medium mass shift Δm of J/ψ , defined in Eq. (5). We calculate the in-medium self-energy using the in-medium D meson mass as given by the QMC model presented in Section 3. We present results for $\xi = 0$ (no gauge coupling) and for $\xi = 1$ (with gauge coupling).

Initially we present results for $\xi = 0$. In Table 1 we present the in-medium J/ψ mass $m_{J/\psi}^*$ and the individual loop contributions to the mass difference Δm at nuclear matter density ρ_0 , for different values of the cutoff mass Λ_D . First of all, one sees that the net effect of the in-medium mass change of the D mesons gives a negative shift for the J/ψ mass. The total shift ranges 16 to 24 MeV at normal nuclear matter density. The results show in addition that the D^*D^* loop gives the largest contribution of the three. Also, this contribution is rather insensitive to the cutoff mass values used in the form factors. A negative self-energy means that the nuclear mean field provides attraction to J/ψ . The important question is of course whether such an attraction is enough to bind J/ψ to a large nucleus. A partial answer can be obtained as follows. One knows [31] that for an attractive spherical well of radius R and depth V_0 , the condition for the existence of a nonrelativistic s -wave bound state of a particle of mass m is

$$V_0 > \frac{\pi^2 \hbar^2}{8mR^2}. \quad (31)$$

Table 2
Same quantities as in Table 1, but using the gauged Lagrangian – $\xi = 1$ in Eq. (8).

A_D	$m_{J/\psi}^*$	DD	DD^*	D^*D^*	Δm
1000	3084	+1	-2	-12	-13
1500	3082	+1	-2.5	-12.5	-14
2000	3080	+1	-3	-14	-16
3000	3078	+0.5	-5.5	-13.5	-18.5

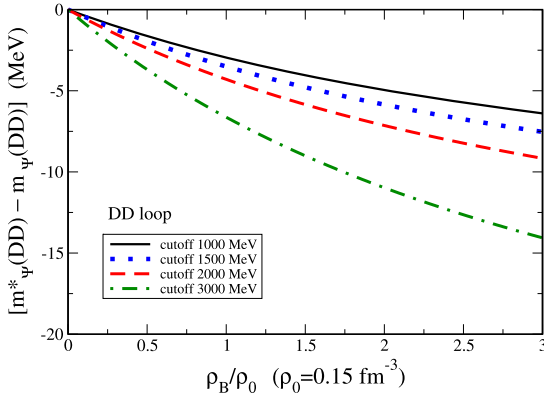


Fig. 3. Contribution from the DD loop to the difference of the in-medium and vacuum J/ψ masses Δm as a function of nuclear matter density for different values of the cutoff mass A_D .

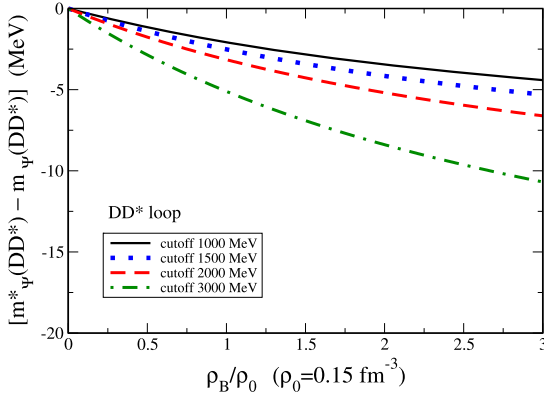


Fig. 4. Contribution from the DD^* loop. See also caption of Fig. 3.

Using for $m = m_{J/\psi}^*$ and $R = 5$ fm (radius of a medium-size nucleus), one obtains $V_0 > 1$ MeV. Therefore, the prospects of capturing a J/ψ if produced almost at rest in a nucleus are quite favorable.

Next, we assess the impact of using a gauged Lagrangian for the DD loop on $m_{J/\psi}^*$ and Δm . The results are shown in Table 2. The contribution of the DD loop to Δm is still much smaller than the DD^* and D^*D^* contributions, but of opposite sign. The net J/ψ mass shift is still sizable, varying from 13 MeV to 18.5 MeV as the cutoff is varied from 1000 MeV to 3000 MeV. The small, positive value of the DD loop contribution is in agreement with the result of Ref. [4].

In Figs. 3–6 we show the separate contributions of the DD , DD^* and D^*D^* loops and their sum to the J/ψ mass shift. As the cutoff mass values increase in the form factors, obviously each loop contribution becomes larger since the integral is divergent, but the increase is less pronounced for the D^*D^* loop. Since the D^*D^* loop gives the largest contribution, it is encouraging that this loop contribution is rather insensitive to the cutoff mass values used.

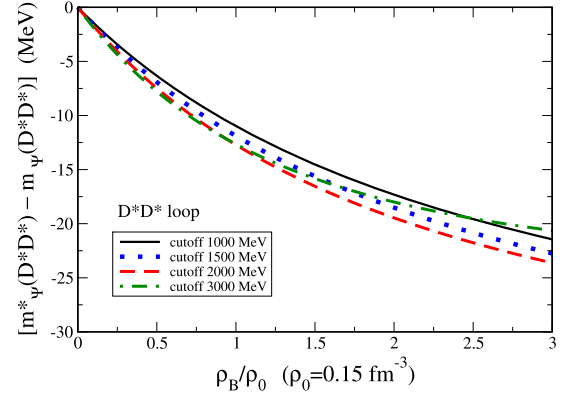


Fig. 5. Contribution from the D^*D^* loop. See also caption of Fig. 3.

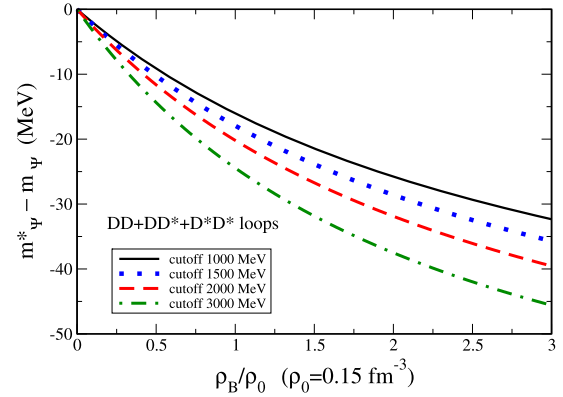


Fig. 6. The total contributions of the DD , DD^* and D^*D^* loops to the difference of in-medium and vacuum J/ψ masses Δm as a function of nuclear matter density for different values of the cutoff mass A .

5. Conclusions and perspectives

We have used an effective Lagrangian approach to evaluate the D and D^* loop contributions to the mass shift of J/ψ in cold nuclear matter. Effects of the medium on the D and D^* are calculated using the QMC model, in which effective scalar and vector meson mean fields are coupled to the light u and d quarks in the charmed mesons. There are no free parameters in this QMC calculation since all quark–meson coupling constants and bag parameters are fixed by fitting saturation properties of nuclear matter. The J/ψ – D coupling constants are taken as determined from vector meson dominance and the cutoff masses are varied over a large range of values. The QMC predicts a 62 MeV mass drop for the D and D^* mesons at nuclear matter density. This mass drop leads to a corresponding in-medium J/ψ mass shift varying between -16 MeV and -24 MeV for cutoff masses within the range of 1000 MeV and 3000 MeV. Such a mass shift is large enough to bind a J/ψ to a nucleus for a J/ψ produced at low momentum in the rest frame of the nucleus.

Although the conclusions of the present calculation are very promising towards the possibility of binding J/ψ in a nucleus, some issues clearly require further investigation. Amongst the most important ones are the calculation of effective J/ψ potentials for finite nuclei [32] and their momentum dependence, and the inclusion of D and D^* widths. Recent calculations [33] of in-medium D and D^* widths based on meson-exchange models have obtained somewhat contradictory results and further study is required. As emphasized in Ref. [34] the lack of experimental information on the free-space interaction of D mesons with nucleons is a major impediment for constraining models and the use of symmetry

principles and exploration of the interplay between quark–gluon and baryon–meson degrees of freedom is essential in this respect. Still another issue is the dissociation of J/ψ in matter by collisions with nucleons and light mesons. This subject has been studied vigorously in the last years using different approaches, like meson exchange [35] and quark models [36], QCD sum rules [37], and the NJL model [38]. Finally, we stress the need for a deeper understanding of the role played by color van der Waals forces in the J/ψ mass shift, particularly in respect with nucleons interacting in a nucleus.

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