J/Ψ Mass Shift and J/Ψ-Nuclear Bound State

Kazuo Tsushima[*], D. H. Lu[†], Gastao Krein[**] and Anthony W. Thomas[*]

[*]*CSSM, School of Chemistry and Physics, University of Adelaide, Adelaide SA 5005, Australia*
[†]*Department of Physics, Zhejiang University, Hangzhou 310027, P.R.China*
[**]*Instituto de Física Teórica, Universidade Estadual Paulista*
Rua Dr. Bento Teobaldo Ferraz, 271 - Bloco II, São Paulo, SP, Brazil

Abstract. We calculate mass shift of the J/Ψ meson in nuclear matter arising from the modification of DD, DD^* and D^*D^* meson loop contributions to the J/Ψ self-energy. The estimate includes the in-medium D and D^* meson masses consistently. The J/Ψ mass shift (scalar potential) calculated is negative (attractive), and is complementary to the attractive potential obtained from the QCD color van der Waals forces. Some results for the J/Ψ-nuclear bound state energies are also presented.

Keywords: J/Ψ-nuclear bound state, in-medium J/Ψ self-energy, Quark-meson coupling model.
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INTRODUCTION

The properties of charmonia and charmed mesons in a nuclear medium (nuclei) are still poorly known. However, with the 12 GeV upgrade of the CEBAF accelerator at the Jefferson Lab and with the construction of the FAIR facility, we expect tremendous progress in understanding the properties of these mesons in a nuclear medium. The new facilities will be able to produce low-momenta charmonia and charmed mesons such as J/Ψ, ψ, D and D^* in an atomic nucleus. One of the major challenges is to find appropriate kinematical conditions to produce these mesons essentially at rest, or with small momentum relative to the nucleus. Amongst many new possible experimental efforts, searching for the J/Ψ-nuclear bound states may be one of the most exciting ones. Finding of such bound states would provide us with evidence for the negative mass shift of the J/Ψ meson discussed here.

Studies of J/Ψ and η_c binding in nuclei is a relatively long history. The original suggestion [1] that multiple gluon QCD van der Waals forces would be capable of binding a charmonium state, estimated a binding energy as large as 400 MeV in an $A = 9$ nucleus. However, the same approach but taking into account the nucleon density distributions in the nucleus, Ref. [2] found a maximum of 30 MeV binding energy in a large nucleus. Based on Ref. [3], which showed the mass shift of charmonium in nuclear matter is possible to be expressed similar to the usual second-order Stark effect due to the chromo-electric polarizability of the nucleon, the authors of Ref. [4] obtained a 10 MeV binding for J/Ψ in nuclear matter, in the limit of an infinitely heavy charm quark mass. Following the same procedure, but keeping the charm quark mass finite and using realistic charmonium bound-state wave-functions, Ref. [5] found 8 MeV binding energy for J/Ψ in nuclear matter.

There are some other studies on the J/Ψ mass in nuclear medium. QCD sum rules

estimated a J/Ψ mass decrease in nuclear matter ranging from 4 MeV to 7 MeV [6, 7, 8], while an estimate based on color polarizability [9] gave larger than 21 MeV. Since the J/Ψ and nucleons have no quarks in common, the quark interchange or the effective meson exchange potential should be none or negligible to first order in elastic scattering [1]. Furthermore, there is no Pauli blocking even at the quark level. Thus, if the J/Ψ-nuclear bound states are formed, the signal for these states will be sharp and show a clear narrow peak in energy dependence of the cross section.

In this contribution we report on our study [10] made for the mass shift of J/Ψ. In addition we also report some results obtained for the J/Ψ-nuclear bound states [11].

J/Ψ MASS SHIFT IN SYMMETRIC NUCLEAR MATTER

We study first the J/Ψ meson mass shift in medium arising from the modification of DD, DD^* and D^*D^* meson loop contributions to the J/Ψ self-energy [10]. As an example, the DD-loop contribution to the J/Ψ self-energy is shown in Fig. 1.
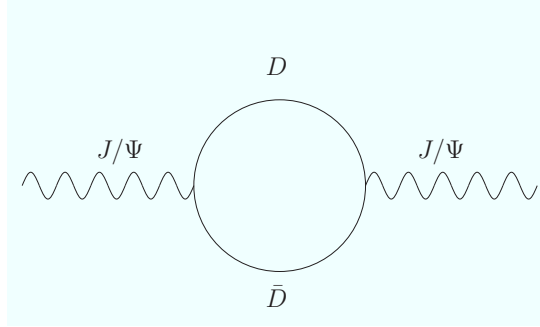

FIGURE 1. *DD-loop contribution to the J/Ψ self-energy.*

To calculate the J/Ψ self-energy due to the DD, DD^* and D^*D^* meson loops, we use the effective Lagrangian densities (in the following we denote by ψ the field representing J/Ψ),

$$\mathscr{L}_{\psi DD} = ig_{\psi DD}\, \psi^\mu \left[\overline{D}\left(\partial_\mu D\right) - \left(\partial_\mu \overline{D}\right) D\right], \tag{1}$$

$$\mathscr{L}_{\psi DD^*} = \frac{g_{\psi DD^*}}{m_\psi} \varepsilon_{\alpha\beta\mu\nu}\left(\partial^\alpha \psi^\beta\right)\left[\left(\partial^\mu \overline{D^*}^\nu\right) D + \overline{D}(\partial^\mu D^{*\nu})\right], \tag{2}$$

$$\mathscr{L}_{\psi D^*D^*} = ig_{\psi D^*D^*} \left\{ \psi^\mu \left[\left(\partial_\mu \overline{D^*}^\nu\right) D_\nu^* - \overline{D^*}^\nu \left(\partial_\mu D_\nu^*\right)\right]\right.$$
$$\left. + \left[\left(\partial_\mu \psi^\nu\right) \overline{D^*}_\nu - \psi^\nu \left(\partial_\mu \overline{D^*}_\nu\right)\right] D^{*\mu} + \overline{D^*}^\mu \left[\psi^\nu \left(\partial_\mu D_\nu^*\right) - \left(\partial_\mu \psi^\nu\right) D_\nu^*\right]\right\}, \tag{3}$$

with the coupling constant value, $g_{\Psi DD} = g_{\Psi DD^*} = g_{\Psi D^*D^*} = 7.64$. Only the scalar part contributes to the J/Ψ self-energy, and the scalar potential for the J/Ψ meson is the difference of the in-medium, m_ψ^*, and vacuum, m_ψ, masses of J/Ψ,

$$\Delta m = m_\psi^* - m_\psi, \tag{4}$$

with the masses obtained from

$$m_\psi^2 = (m_\psi^0)^2 + \Sigma(k^2 = m_\psi^2). \tag{5}$$

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.

In the calculation we use phenomenological form factors to regularize the self-energy loop integrals following a similar calculation for the ρ self-energy [12]:

$$u_{D,D^*}(\mathbf{q}^2) = \left(\frac{\Lambda_{D,D^*}^2 + m_\psi^2}{\Lambda_{D,D^*}^2 + 4\omega_{D,D^*}^2(\mathbf{q}^2)} \right)^2 . \tag{6}$$

For the vertices $J/\Psi DD, J/\Psi DD^*$ and $J/\Psi D^*D^*$, we use the form factors $F_{DD}(\mathbf{q}^2) = u_D^2(\mathbf{q}^2)$, $F_{DD^*}(\mathbf{q}^2) = u_D(\mathbf{q}^2)u_{D^*}(\mathbf{q}^2)$, and $F_{D^*D^*}(\mathbf{q}^2) = u_{D^*}^2(\mathbf{q}^2)$, respectively, with Λ_D and Λ_{D^*} being the cutoff masses, and the common value, $\Lambda_D = \Lambda_{D^*}$ is used.
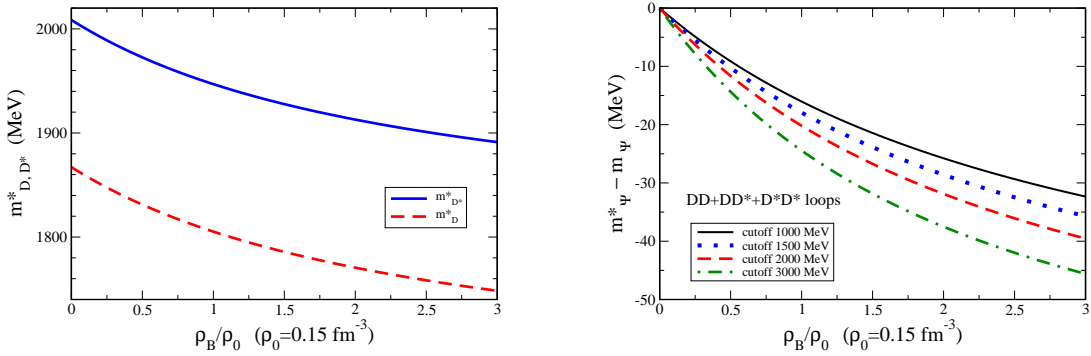

FIGURE 2. In-medium masses of the D^* (the solid line) and D (the dashed line) mesons calculated in the QMC model (left panel), and the J/Ψ potential in symmetric nuclear matter (right panel). In the right panel the solid, dotted, dashed, and dash-dotted curves correspond to the common cut-off values in the dipole form factors in Eq. (6), 1000, 1500, 2000, and 3000 MeV, respectively.

To calculate the in-medium J/Ψ self-energy arising from the DD, DD^* and D^*D^* meson loops, we need to include the in-medium masses of D and D^* mesons consistently [10, 13]. For this purpose, we rely on the quark-meson coupling (QMC) model [14, 15]. The QMC model is a quark-based, relativistic mean field model of nuclear matter and nuclei [14, 15]. Relativistically moving confined light quarks in the nucleon bags self-consistently interact directly with the scalar-isoscalar σ, vector-isoscalar ω, and vector-isovector ρ 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 σ 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 (σ-field) dependent σ-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 hadron properties in a nuclear medium (nuclei), based on the quark degrees of freedom. Many successful applications of the model can be found in Ref. [15].

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 $\Lambda_D (= \Lambda_{D^*})$. 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

In Fig. 2 we show the in-medium masses of the D^* and D mesons (left panel) calculated in the QMC model [10, 13], and the J/Ψ potential in symmetric nuclear matter (right panel). To see the ambiguity due to the cut-off values in the form factors, we calculate the potential with the cut-off values, $\Lambda_D = \Lambda_{D^*} = 1000, 1500, 2000$, and 3000 MeV.

In addition we list each meson loop contribution at nuclear matter density $\rho_0 (= 0.15$ fm^{-3}) in Table 1. 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 18 and 20 MeV attractions, respectively.

J/Ψ-NUCLEAR BOUND STATE

First, we show the J/ψ-nuclear potentials calculated [11] based on the method described in the previous section. As examples, we show in Fig. 3 the potentials felt by the J/Ψ meson in ^{4}He (left panel) and ^{208}Pb (right panel) nuclei.
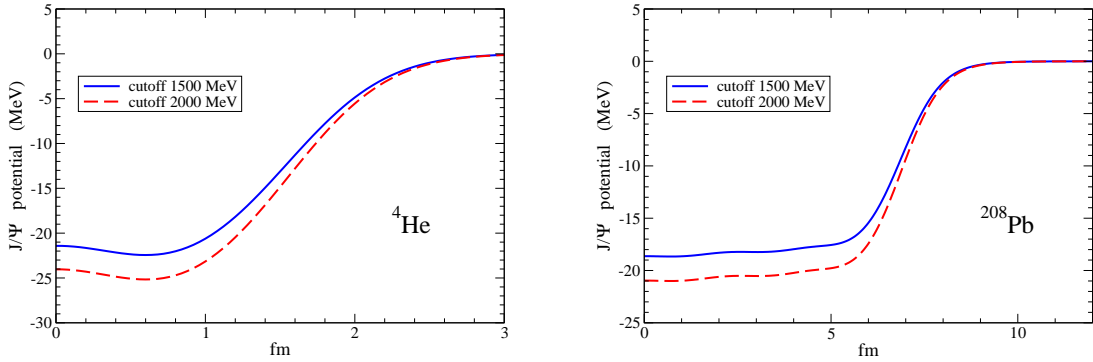

FIGURE 3. J/Ψ potentials in ^{4}He (left panel) and ^{208}Pb (right panel) nuclei for two values of the cutoff in the form factors, 1500 (the solid line) and 2000 (the dashed line) MeV.

The nucleon density distributions for nuclei (^{208}Pb nucleus in this report) are also calculated within the QMC model [16]. For a ^{4}He nucleus, we use the parametrization for the density distribution obtained in Ref. [17]. Using a local density approximation we have calculated the J/Ψ potentials in nuclei. With the potentials obtained in this manner,

we then calculate the J/Ψ-nuclear bound state energies. The detail and complete results will be reported elsewhere [11].

We follow the procedure applied in the earlier work [18] for the η- and ω-nuclear bound states. In this study we consider the situation that the J/Ψ meson is produced nearly at rest (recoilless kinematics in experiments). Then, it should be a very good approximation to neglect the possible energy difference between the longitudinal and transverse components [19] of the J/Ψ wave function. In addition we consider the J/Ψ meson is produced in medium and heavy mass nuclei, ^{40}Ca, ^{90}Zr and ^{208}Pb, where possible center-of-mass corrections should be small. Thus, after imposing the Lorentz condition, to solve the Proca equation, aside from a possible width, is equivalent to solve the Klein-Gordon equation,

$$\left[\nabla^2 + E_\Psi^2 - m_\Psi^{*2}(r)\right]\phi_\Psi(\mathbf{r}) = 0, \tag{7}$$

where E_Ψ is the total energy of the J/Ψ meson, and $m_\Psi^*(r)$ is the in-medium mass of the J/Ψ in a nucleus. Since in free space the width of J/Ψ meson is ~ 93 keV [20], we can ignore this tiny natural width. Thus, we may simply solve the Klein-Gordon equation Eq. (7) without worrying about the width, under the situation we consider now. We list in table 2 the bound state energies obtained. The results show that the J/Ψ meson is expected to form nuclear bound states.

TABLE 2. Bound state energies obtained for the J/Ψ meson. With the situation that the J/Ψ meson is produced in recoilless kinematics, the width due to the strong interactions is all set to zero, as well as its natural width of ~ 93 keV.

		$\Lambda_{D,D^*} = 1500$ MeV	$\Lambda_{D,D^*} = 2000$ MeV
		E (MeV)	E (MeV)
$^{40}_{\Psi}$Ca	1s	-15.15	-17.42
	1p	-11.20	-13.32
	1d	-6.91	-8.85
$^{90}_{\Psi}$Zr	1s	-16.40	-18.69
	1p	-13.92	-16.14
	1d	-11.08	-13.21
$^{208}_{\Psi}$Pb	1s	-16.80	-19.06
	1p	-15.34	-17.57
	1d	-13.62	-15.81

SUMMARY AND CONCLUSION

We have estimated mass shift of the J/Ψ meson in nuclear matter arising from the modification of DD, DD^* and D^*D^* meson loop contributions to the J/Ψ self-energy, consistently including the in-medium masses of the D and D^* mesons calculated in the quark-meson coupling model. Then, we have calculated the J/Ψ-nuclear potentials using a local density approximation, where the nuclear density distributions are also calculated within the quark-meson coupling model. We emphasize that, in the model, all the coupling constants between the applied meson mean fields and the light quarks

in the nucleon, as well as those in the D and D^* mesons, are all equal and calibrated by the nuclear matter saturation properties. Using the J/Ψ-nuclear potentials obtained in this manner, we have solved the Klein-Gordon equation which is reduced from the Proca equation, and obtained the J/Ψ-nuclear bound state energies for ^{40}Ca, ^{90}Zr and ^{208}Pb nuclei, where possible center-of-mass corrections and in-medium width, which are expected to be small, are all neglected. Our results show that the J/Ψ meson is expected to form nuclear bound states.

In the future we need to study the case that the J/Ψ meson is produced with a finite momentum. In this case the J/Ψ self-energy in nuclear medium, applied to calculate the J/Ψ potential, will have an imaginary part. Then, J/Ψ meson will naturally get a momentum or energy dependent finite width. However, these issues, momentum and energy dependence of the effective mass or potential in nuclear medium, as well as the momentum and energy dependence of the width, are challenging problems which have not yet been studied well. In particular, when one considers the situation that the J/Ψ meson propagates in the nuclear medium (a nucleus), these issues are inevitable to be studied. All these are future challenging problems that we need to study.

ACKNOWLEDGMENTS

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