\section*{J/\Psi in nuclear matter}

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\textbf{Abstract.} We report on recent estimates of the $J/\Psi$ mass shift in infinite nuclear matter and finite nuclei arising from in-medium $D$ and $D^*$ meson loops. The density dependence of the $J/\Psi$ mass shift is evaluated employing medium-modified $D$ and $D^*$ meson masses derived within the quark-meson coupling model. Using a local density approximation, $J/\Psi$-nuclear bound state energies are calculated for a range of nuclei. We predict that $J/\Psi$-nuclear bound states should be observed with a clear signal in experiments, provided the $J/\Psi$ meson is produced in recoilless kinematics.

\section{1. Introduction}

New opportunities will be opened for studying properties of charmonia and charmed mesons in the nuclear medium 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 potential of implanting low-momentum charmed mesons like $J/\Psi$, $\eta_c$, $D$ and $D^*$. Particularly exciting perspectives are the possibility of creating new exotic nuclear bound states by nuclei capturing charmonia states like $J/\Psi$ and $\eta_c$ [1, 2, 3, 4], or heavy-light $D$ and $D^*$ mesons [5, 6, 7]. Capture of $J/\Psi$ (and other charmonia) by nuclei is particularly interesting because a charmonium state does not have quarks in common with the nuclear medium and therefore 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, and the excitation of charmed hadronic intermediate states with light quarks created from the vacuum.

In the present communication we present recent results for the mass shift of $J/\Psi$ in terms of the excitation of intermediate charmed mesons using effective Lagrangians. In addition to the $DD^*$ loops, we also include $DD^{*}\bar{D}$ and $D^*\bar{D}^*$ loops. The medium dependence of the $D$ and $D^*$ masses in nuclear matter is obtained by an explicit calculation using the quark-meson coupling (QMC) model – for a review of the model see Ref. [8]. 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. We also present predictions for $J/\Psi$ energy levels in selected nuclei, obtained by solving a Klein-Gordon for the $J/\Psi$ wave function in presence of an effective local potential derived in a local density approximation from the mass shift in infinite nuclear matter.
2. The model

Initially we specify the phenomenological Lagrangian densities for the vertices $J/\Psi-D$ and $J/\Psi-D^*$ ($\psi$ denotes the field representing $J/\Psi$):

$$\mathcal{L}_{\psi DD} = if^{\mu\nu} \bar{\psi} D (\partial_\mu D) - (\partial_\mu \bar{D}) D,$$

$$\mathcal{L}_{\psi DD^*} = \frac{g_{\psi DD^*}}{m_\psi} \varepsilon_{\alpha\beta\mu
u} \left( \partial_\alpha \psi \right) \left[ (\partial_\mu \bar{D}) \psi - D (\partial_\mu \psi) \right],$$

$$\mathcal{L}_{\psi D* D^*} = if^{\mu\nu} \left\{ \bar{\psi} \left[ (\partial_\mu \bar{D}) \psi - D (\partial_\mu \psi) \right] + \left[ (\partial_\mu \bar{D}) \psi - D (\partial_\mu \psi) \right] \right\}.$$

These Lagrangians are an $SU(4)$ extension of light-flavor chiral-symmetric Lagrangians of pseudoscalar and vector mesons. Note that we are not using a local gauge symmetry principle for vector mesons [2] which would introduce contact interactions involving two pseudoscalar and two vector mesons – this would introduce an additional contact interaction of the form $2g_{\psi DD} \bar{\psi}_\mu D_{\mu} DD$ in Eq. (1), leading to a small positive (instead of a small negative) mass shift due to the $DD$ loop [3]. Given the Lagrangians, the mass-difference $m = m_{D^*} - m_\psi$, where $m_\psi$ and $m_{D^*}$ are respectively the vacuum and in-medium masses of $J/\Psi$, defined as:

$$m_\psi^2 = (m_0^2)^2 + \Sigma(k^2) \quad \text{and} \quad m_{D^*}^2 = (m_0^2)^2 + \Sigma^*(k^2) = m_{D^*}^2,$$

where $m_0^2$ is the bare mass and $\Sigma(k^2)$ is the total $J/\Psi$ self-energy obtained by summing the contributions from the $DD$, $DD^*$ and $D^*D^*$ loops (we take $m_{DD} = m_{D^*} = m_{D^*} = m_{D^*}$):

$$\Sigma_i(m_\psi^2) = -\frac{g_{\psi i}^2}{3\pi^2} \int dq q^2 F_i(q^2) K_i(q^2),$$

where $F_i(q^2)$ is the product of vertex form-factors and the $K_i(q)$ for each loop contribution are given by

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

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

where $\omega_D = (q^2 + m_\psi^2)^{1/2}$, $\omega_{D^*} = (q^2 + m_{D^*}^2)^{1/2}$, $\omega_{DD^*} = (\omega_D + \omega_{D^*})/2$, $\xi = 0$ for the non-gauged Lagrangian of Eq. (1) and $\xi = 1$ for the gauged Lagrangian of Ref. [2], and $A(q^2) = \sum_{i=1}^4 A_i(q)$, with

$$A_1(q) = -4q^2 \left\{ 4 - \frac{q^2 + (q - k)^2}{m_{D^*}^2} + \frac{q \cdot (q - k)^2}{m_{D^*}^2} \right\},$$

$$A_2(q) = 8 \left[ q^2 - \frac{q \cdot (q - k)}{m_{D^*}^2} \right] \left[ 2 + \frac{(q_0)^2}{m_{D^*}^2} \right],$$

$$A_3(q) = 8 \left\{ (2q_0 - m_\psi) \frac{q^2 + q \cdot (q - k)}{m_{D^*}^4} + q_0 \frac{q \cdot (q - k)^2}{m_{D^*}^4} \right\},$$

$$A_4(q) = -8 \left[ (q_0 - m_\psi) \frac{q \cdot (q - k)}{m_{D^*}^4} \right] \left[ (q_0 - m_\psi) - q_0 \frac{q \cdot (q - k)}{m_{D^*}^4} \right].$$
Here, \( q \) and \( k \) are four-vectors given by \( q = (q^0, \mathbf{q}) \) and \( k = (m_\psi, 0) \). The expression for \( \Sigma^* \) is identical to \( \Sigma \), but calculated with in-medium \( D \) and \( D^* \) masses.

The medium dependence of the masses of the \( D \) and \( D^* \) mesons are obtained using the QMC model. Explicitly, the masses are given by

\[
m_{D,D^*}^* = \sum_{j=q,\bar{q},c,\bar{c}} n_j \Omega_j^* - z_{D,D^*} R_{D,D^*}^* + \frac{4}{3} \pi B R_{D,D^*}^3,
\]

where \( B \) is the bag constant, \( \Omega_q^* = \Omega_{\bar{q}}^* = \sqrt{x_q^2 + (R_{D,D^*}^* m_q^*)^2} \), \( \Omega_c^* = \Omega_{\bar{c}}^* = \sqrt{x_c^2 + (R_{D,D^*}^* m_c^*)^2} \), \( x_{q,c} \) are the bag eigenfrequencies, and \( n_q(n_{\bar{q}}) \) 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. The bag radii \( R_{D}^* \) and \( R_{D^*}^* \) are obtained from the minimization of the masses, \( \partial m_{D,D^*}^*/\partial R_{D,D^*}^* = 0 \).

Using a local density approximation, one can identify \( m_{\psi}^*(\rho_B) - m_{\psi} \equiv U_\psi(r) \), with \( \rho_B = \rho_B(r) \) being the nuclear density, as an effective potential for the \( J/\Psi \) in a nucleus. Energy levels are then obtained solving a Klein-Gordon equation for the \( J/\Psi \) wave function \( \phi_\psi(\mathbf{r}) \):

\[
[\nabla^2 + E_\psi^2 - \mu^2 - 2\mu U_\psi(r)] \phi_\psi(\mathbf{r}) = 0,
\]

where \( E_\psi \) is the total energy of the \( J/\Psi \) meson, and \( \mu = m_\psi m_A/(m_\Psi + M) \) with \( m_\Psi \) \((M)\) being the vacuum mass of the \( J/\Psi \) meson (nucleus). Further details can be found in Ref. [4].

![Figure 1](image.png)

**Figure 1.** \( J/\Psi \) mass difference as a function of nuclear matter density. Figure from Ref. [3].

### 3. Results

We choose the values \((m_q, m_c) = (5, 1300) \) MeV for the current quark masses, \( B = 170 \) MeV\(^4 \) and \( R_N = 0.8 \) fm for the bag radius of the nucleon in free space. The quark-meson coupling constants, \( g_\sigma^q, g^q_\omega \) and \( g^q_\rho \), are adjusted to fit the nuclear saturation energy and density of symmetric nuclear
matter, and the bulk symmetry energy [8]. Exactly the same coupling constants, \( g^q_\sigma \), \( g^q_\omega \) and \( g^q_\rho \), are used for the light quarks in the \( D \) and \( D^* \) mesons and baryons as in the nucleon. The nuclear densities \( \rho_B(r) \) are calculated within the QMC with the same set of parameters. Another ingredient of the calculation are form factors, necessary to regularize the loop integrals. We parametrize them as dipoles with a cutoff mass \( \Lambda \) - we use the same \( \Lambda \) in all vertices. In our estimates we vary \( \Lambda \) over a wide range of values to test sensitivity of results to this crucial input.

In Fig. 1 we present results for the mass shift as a function of the nuclear matter density. Clearly seen, is a negative shift in the mass of \( J/\Psi \) in nuclear matter, of the order of \( 10^{-20} \) MeV. As estimated in Ref. [3], such an attraction is more than enough to bind a \( J/\Psi \) meson to a nucleus. Indeed, solving the Klein-Gordon equation of Eq. (13) for a series of nucleus, ranging from small nuclei like \(^4\text{He} \) and \(^{12}\text{C} \) to large ones like \(^{90}\text{Zr} \) and \(^{208}\text{Pb} \), one finds [4] single-particle energy levels with sizable binding energies, as shown in Table 1 for selected nuclei. Such \( J/\Psi \)-nuclear bound states should be observed experimentally, provided, of course, the \( J/\Psi \) meson is produced in recoilless kinematics. The model leaves room for improvements, like a systematic study of the interaction of the \( D \) mesons with nucleons [9, 10].

| \( \Lambda_{D,D^*} = 1500 \) MeV | \( \Lambda_{D,D^*} = 2000 \) MeV |
|----------------|----------------|
| \(^4\text{He}\) | \(^{40}\text{Ca}\) | \(^{208}\text{Pb}\) | \(^4\text{He}\) | \(^{40}\text{Ca}\) | \(^{208}\text{Pb}\) |
| \( 1s \) | \( 1s \) | \( 1s \) | \(-4.19 \) | \(-14.96 \) | \(-16.83 \) | \(-5.74 \) | \(-17.24 \) | \(-19.10 \) |
| \( 1p \) | \( 1p \) | \( 1p \) | \(-10.81 \) | \(-10.81 \) | \(-15.36 \) | \(-12.92 \) | \(-12.92 \) | \(-17.59 \) |
| \( 1d \) | \( 1d \) | \( 1d \) | \(-6.29 \) | \(-6.29 \) | \(-13.61 \) | \(-8.21 \) | \(-8.21 \) | \(-15.81 \) |
| \( 2s \) | \( 2s \) | \( 2s \) | \(-5.63 \) | \(-5.63 \) | \(-13.07 \) | \(-7.48 \) | \(-7.48 \) | \(-15.26 \) |

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