In-medium $J/\psi$ mass shift by the $D$ meson loop effect

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Abstract. The mass shift of the $J/\psi$ state in-medium in symmetric nuclear matter with zero and finite temperature and cold strange matter was investigated by an effective Lagrangian plus QCD sum-rule approach. The in-medium mass of the $J/\psi$ state is evaluated through the intermediate pseudoscalar $D$-meson loop for the $J/\psi$ self-energy. The effect of medium is incorporated through the in-medium mass of $D$ meson calculated using chiral SU(3) model plus QCD sum-rule approach. The self energy loop integral is regularized using the phenomenological form factor of the dipole form. We compare our results with some of the results in the literature. The present results should be helpful to better understand the expected data from heavy ion collision experiments, such as CBM and PANDA.

1. Introduction

The study of in-medium hadron properties is very important for better understanding of data from heavy ion collision (HIC) experiments. For example, at Facility of antiproton and ion research (FAIR) charmed hadrons will be produced in large numbers during the annihilation of antiprotons and nuclei. The studies of charmed hadron, as well as charmonium properties in-medium, will advance in understanding the interaction of these mesons with the nucleons. In particular, their properties in a strange hadronic medium will add interesting and new information. For example, the $J/\psi$ ($c\bar{c}$) suppression is known as one of the signatures of the quark gluon plasma (QGP) production in HICs. It was initially suggested by Matsui and Satz that the drop in the yield of the $J/\psi$ state in HICs appears due to the color screening effect and this should be considered as a signature of the production of QGP [1]. Important results in favor of the $J/\psi$ suppression were indeed observed at CERN SPS and RHIC experiments [2–4]. However, in [5–7] it was observed that the heavy quark bound states can survive in the deconfined QGP phase. Therefore, further studies of the modification of the $J/\psi$ state in-medium will add extra important information on the production of QGP in heavy ion experiments. Moreover, the charmonium interaction with the nucleon and hadronic medium was investigated in [8–10] and there the negative shift in the mass (around 7-8 MeV) of $J/\psi$ meson was predicted by using the QCD sum-rule approach. Also, the charmonium nucleon interaction and dissociation cross section of the $J/\psi$ state were studied using one-boson exchange model [11], quark model [12], and effective Lagrangian approach [13,14]. In this study, we consider the impact of the pseudoscalar $D$-meson loop contribution on the mass shift of the $J/\psi$ state in hot and strange hadronic
medium. The medium effects are incorporated through the in-medium modified mass of $D$ meson, calculated using chiral $SU(3)$ model plus QCD sum-rule approach [15].

2. Methodology
We use the following phenomenological effective Lagrangian density at hadronic level for the $J/\psi$-$DD$ vertices [16][17]:

$$L_{\text{int}} = ig_{J/\psi DD}(J/\psi)\mu[\bar{D}(\partial_{\mu}D) - (\partial_{\mu}\bar{D})D] + g_{J/\psi DD}^2J/\psi_{\mu}(J/\psi)^{\mu}D D,$$

with conventions $D = \begin{pmatrix} D^+ \\ D^0 \end{pmatrix}$ and $\bar{D} = \begin{pmatrix} D^0 \\ D^- \end{pmatrix}$.

Here, the Lagrangian density is an $SU(4)$ extension of the light-flavor chiral-symmetric Lagrangians of the pseudoscalar mesons. However, $SU(4)$ flavor symmetry is strongly broken in nature. Therefore, we use experimental masses of the open charmed mesons and the $J/\psi$ meson. In addition, we employ the empirically extracted coupling constants of mesons. The shift in the mass of the $J/\psi$ meson is defined as $\Delta m_{J/\psi} = m_{J/\psi}^* - m_{J/\psi}$, where $m_{J/\psi}^*$ represents the in-medium mass of the $J/\psi$ meson, while $m_{J/\psi}$ is the free-space mass.

Furthermore, using the non-gauged Lagrangian density for the $J/\psi$-$DD$ vertices, we get the expression for the $J/\psi$ self-energy by the $D$-meson loop contribution [18]:

$$\Sigma_{DD}(m_{J/\psi}^2) = \frac{-g_{J/\psi DD}^2}{3\pi^2} \int dq \frac{q^2}{(q^2 + m_D^2)^{1/2}} \frac{q^2}{(q^2 + m_D^2)^2 - m_{J/\psi}^2/4} F_{DD}(q^2).$$

In the above expression, $q \equiv |\vec{q}|$ and $F_{DD}(q^2)$ represent the square of vertex form factor $(u(q^2))$ multiplied by the two vertices. We also use a dipole form [18] with $\omega_D(q) = (q^2 + m_D^2)^{1/2}$,

$$F_{DD}(q^2) = u^2(q^2) = \left(\frac{\Lambda_D^2 + m_{J/\psi}^2}{\Lambda_D^2 + 4\omega_D^2(q)}\right)^4,$$

where $\Lambda_D$ is the cut off mass and $\Lambda_D = 1000$ MeV is used in this study. The bare mass $(m_{J/\psi}^0)$ is calculated from the free-space values of the $J/\psi$ and $D$ mesons as:

$$m_{J/\psi}^2 = (m_{J/\psi}^0)^2 + \Sigma(k^2 = m_{J/\psi}^2),$$

where $m_{J/\psi}^0$ is the bare mass and $\Sigma(k^2 = m_{J/\psi}^2)$ is the total $J/\psi$ self-energy obtained from the contribution from the $DD$ loop. To study the in-medium mass of the $J/\psi$, we use the in-medium mass of $D$ meson calculated using chiral $SU(3)$ model plus QCD sum-rule approach [15] as input in the in-medium $J/\psi$ self-energy, where the bare mass is fixed in free space.

3. Results and discussion
In the present study, we use the value of the coupling constant $g_{J/\psi DD} = 7.64$ [18]. The considered free-space values of $m_{J/\psi}$ and $m_D$ are 3096 MeV and 1867 MeV, respectively. In figure [1] we show the calculated in-medium mass of $J/\psi$ as a function of baryonic density ratio, $\rho_B/\rho_0$ ($\rho_0 = 0.15$ fm$^{-3}$). In cold nuclear matter ($T = 0$ and $f_s = 0$) the mass shift $\Delta m_{J/\psi}$ is equal to $-3.5$ MeV at $\rho_B/\rho_0 = 1.0$ (normal nuclear matter density). The density dependence of the $J/\psi$ mass is directly related to the drop of the $D$ meson mass, calculated by using chiral $SU(3)$ plus QCD sum-rule approach [15].
Figure 1. In-medium $J/\psi$ meson mass, calculated based on the $D$-meson loop effect, as a function of baryonic density $\rho_B/\rho_0$ ($\rho_0 = 0.15$ fm$^{-3}$) at finite temperature $T = 100$ MeV and strangeness fraction $f_s = 0.5$.

For a given baryonic density and at finite temperature, the magnitude of downward shift in the $J/\psi$ mass increases as a function of strangeness fraction of the medium. This effect can be understood if we proceed from the fact that the mass of a pseudoscalar $D$-meson in a strange hadronic medium decreases the more the fraction of strangeness $f_s$ increases (along with nucleons), as discussed in [15]. The drop in the mass of the $J/\psi$ meson as $f_s$ increases indicates that the strange hadronic medium provides an attraction to the $J/\psi$ state. Furthermore, an impact of finite temperature gives opposite effect to that of the strangeness fraction. Namely, finite temperature causes an increase of the $J/\psi$ mass. For example, for $T = 100$ MeV at normal nuclear matter density ($\rho_B/\rho_0 = 1.0$ and $f_s = 0$), the value of $\Delta m_{J/\psi}$ is equal to $-2.9$ MeV, while at $T = 0$ it is equal to $-3.5$ MeV. The effects discussed above can be understood in terms of the temperature dependence of pseudoscalar $D$ meson as follows. Since the mass of the $D$ meson increases as temperature of the medium increases [15], this, in turn, provides less impact on the $D$-meson loop contribution to the $J/\psi$ self-energy than the one in free space, which results to increase the mass of the $J/\psi$ state. This indicates that hot medium with zero baryon density ($T = 100$ MeV and $\rho_B = 0$) provides repulsive potential, whereas the cold medium ($T = 0$) provides attractive potential for the $J/\psi$ state.

In the literature, the $J/\psi$ mass shift was evaluated by using various methods. For example, in [16] the authors observed a small positive mass shift at normal nuclear matter density when only the effect of the $D$-meson loop was taken into account, where the in-medium mass of the $D$ meson was used to include the medium effect using the momentum-dependent $J/\psi$-$DD$ coupling. On the other hand, they obtained a negative mass shift in case of leading order QCD calculation. As the total sum of them, the results from a paper described above demonstrate a slight negative mass shift of the $J/\psi$ meson. In [18], authors also observed a relatively larger negative mass shift of the $J/\psi$ state by considering the in-medium mass of the $D$ meson, calculated within
the quark-meson coupling (QMC) model. Although these studies were performed for the cold nuclear matter, we have studied the $J/\psi$ mass shift further in hot and strange hadronic medium in addition to the existing studies made for the cold nuclear matter. The observed in-medium mass of the $J/\psi$ state in this study is useful to understand the $J/\psi$ suppression, observed by the NA50 collaboration at 158 GeV/nucleon in Pb-Pb collisions. We have obtained a moderate negative mass shift of the $J/\psi$ state, relative to that observed for the pseudoscalar $D$ meson \cite{15}. The negative mass shift of the $D$ meson is more pronounced than the shift of the $J/\psi$ mass.

4. Conclusion
We have observed a moderate negative mass shift of the $J/\psi$ state using an effective Lagrangian approach focusing on the effect of the $D$ meson loop contribution on the $J/\psi$ self-energy both in medium and in free space. The medium effect was taken into account through the in-medium mass modification of the $D$ meson. The observed negative mass shift of the $J/\psi$ meson, that is relatively smaller than that of the $D$ ($\bar{D}$) meson, suggests that $J/\psi$ suppression will be increased by the enhanced dissociation into the $D\bar{D}$ meson pair in hadronic medium due to the downward shift of the threshold. The results of the present study, together with other detailed studies, should be helpful for better understanding the future of HICs experiments, such as CBM and PANDA under FAIR facility. In particular, further studies of the effects of temperature and strangeness fraction will bring additional, important information. We plan to do an elaborated study focusing on these issues in the future.

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