Charmonium decay widths in magnetized matter

A. Mishra\textsuperscript{a}, A. Jahan CS\textsuperscript{b}, S. Kesarwani\textsuperscript{c}, H. Raval\textsuperscript{d}, S. Kumar\textsuperscript{e}, and J. Meena\textsuperscript{f}

Department of Physics, Indian Institute of Technology, Delhi, Hauz Khas, New Delhi – 110 016, India

\textbf{Abstract.} We study the partial decay widths of the charmonium states ($J/\psi$, $\psi(3686)$, $\psi(3770)$, $\chi_{c0}$, $\chi_{c2}$) to $DD$ ($D^{*}D^{-}$ or $D^{0}D^{0}$) in isospin asymmetric nuclear matter, in the presence of strong magnetic fields. The in-medium partial decay widths of charmonium states to $DD$ are calculated within a light quark-antiquark pair creation model, namely the $^3P_0$ model, using the in-medium masses of the charmonia as well as $D$ and $\bar{D}$ mesons in the magnetized nuclear matter, obtained within a chiral effective model. The presence of a magnetic field leads to Landau quantization of the energy levels of the proton in the nuclear medium. The effects of magnetic field and isospin asymmetry on the charmonium decay widths into consideration for obtaining the in-medium masses of these heavy flavour mesons, used to calculate the partial decay widths of the charmonium states. The medium modifications of the charmonium decay widths can have observable consequences on the production of the charmed mesons in high energy asymmetric heavy ion collision experiments.

\textbf{1 Introduction}

The topic of in-medium properties of hadrons and more recently, of heavy flavour hadrons \cite{1}, is an important and challenging area of research in strong interaction physics, due to its relevance in the ultra relativistic heavy ion collision experiments. The estimated magnetic fields produced in noncentral ultra high energy nuclear collisions are huge ($eB \sim 2m_e^2$ at RHIC, BNL, and $eB \sim 15m_e^2$ at LHC, CERN) \cite{2–5}. This has initiated studies of the effects of strong magnetic fields on the in-medium properties of hadrons in the recent years. However, the time evolution of the magnetic field \cite{6–10} is still under debate, which needs the proper estimate of the electrical conductivity of the medium as well as solutions of the magnetohydrodynamic equations.

The properties of the heavy flavour mesons, e.g., the open charm and open bottom mesons \cite{11–15} as well as the charmonium states \cite{16–19} have been studied in the literature in the presence of strong magnetic fields. In the presence of a strong magnetic field, there can be mixing of the longitudinal components of the vector charmonium states, e.g., $J/\psi$, $\psi'(\equiv \psi(3686))$, with their pseudoscalar partners $\eta_c$, $\eta_c'$ \cite{20,21} which might show in the dilepton spectra as anomalous $\eta_c$ and $\eta_c'$ peaks, in addition to the $J/\psi$ and $\psi'$ peaks. In ref. \cite{20}, the formation times for the quarkonia have been studied and it is observed that with increasing magnetic field strength, the formation times of the vector quarkonia become larger, whereas the formation times of their pseudoscalar partners become faster \cite{20}. With a larger formation time, the $J/\psi$ could survive through the initial thermal effects, thus enhancing its survivability, whereas the $\eta_c$, $\eta_c'$ peaks in the dilepton spectra could probe an early magnetic field. The heavy ion collision experiments involve heavy nuclei which have much larger number of neutrons than protons, and hence the isospin asymmetry effects on the hadron properties are important to study. In the present work, we study in-medium decay widths of the charmonium states ($J/\psi$, $\psi(3686)$, $\psi(3770)$, $\chi_{c0}$ and $\chi_{c2}$) to $DD$, in isospin asymmetric nuclear matter in the presence of strong magnetic fields. These decay widths are computed using the $^3P_0$ model \cite{22–27}, from the mass modifications of the charmonium states as well as $D$ and $\bar{D}$ mesons calculated using a chiral effective model.

The heavy quarkonium states, e.g., the charmonium and bottomonium states have been studied extensively in the literature, using potential models \cite{28–35}. The effects of the gluonic fluctuations on the quarkonium states have been studied in refs. \cite{36–38}, with a color Coulomb poten-
tial for the interaction of the heavy quark, $Q$ and heavy antiquark, $\bar{Q}$, within the quarkonium state. Assuming the separation of $Q$ and $\bar{Q}$ to be small compared to the characteristic scale of the gluonic fluctuations, the leading order contribution of a multipole expansion of the quarkonium state to the gluonic field leads to the mass of the quarkonium state to be proportional to the gluon condensate. In ref. [39], the in-medium masses of the charmonium states have been studied using leading order QCD formula [36] and the linear density approximation for the gluon condensate in the nuclear medium. Within the QCD sum rule approach, the mass modifications of the charmonium states are due to the medium changes of the gluon condensate [40–42,19,43–46], whereas the open heavy flavour mesons are modified due to the interaction with the light quark condensates in the hadronic medium [47–55]. The heavy flavour mesons have also been studied in the literature, using quark meson coupling model [56–64], using heavy quark symmetry and interaction of these mesons with nucleons via pion exchange [65], using heavy meson effective theory [66], studying the heavy flavour meson as an impurity in nuclear matter [67] as well as using the coupled channel approach [68–74]. Within the chiral effective model [75–77], the in-medium charmonium masses are obtained from the medium changes of a scalar dilaton field, which mimicks the gluon condensates of QCD [78,79,27] and the mass modifications of the $D$ and $\bar{D}$ mesons arise due to their interactions with the baryons and scalar mesons in the hadronic medium [78,79,27,80,81]. The chiral effective model has been used extensively in the literature, for the study of finite nuclei [76], strange hadronic matter [77], light vector mesons [82], strange pseudoscalar mesons, e.g. the kaons and antikaons [83–86] in isospin asymmetric hadronic matter, as well as for the study of bulk matter of neutron stars [87]. The light vector mesons ($\omega$, $\rho$ and $\phi$) are modified in the hadronic medium, predominantly due to the medium changes in the light quark condensates [88] within the QCD sum rule approach. These vector mesons in (magnetized) hadronic matter have been studied using QCD sum rule calculations from the medium changes of the light quark condensates and gluon condensates calculated within the chiral SU(3) model [89,90]. The kaons and antikaons have been recently studied in the presence of strong magnetic fields using this model [91]. The model has been used to study the open heavy flavour (charm and bottom) mesons [78,79,27,80,81,92,93], the heavy quarkonium states [79,27,94], the partial decay widths of the heavy quarkonium states to the open heavy flavour mesons, in the hadronic medium [27] using a light quark creation model [26], namely the $^3P_0$ model [22–25] as well as using a field theoretic model for composite hadrons [95,96]. Recently, the effects of magnetic fields on these open and hidden heavy flavour mesons have been investigated [14,15,18,97] using the chiral effective model.

The outline of the paper is as follows: in sect. 2, we describe briefly the quark pair creation model, namely the $^3P_0$ model [22–26] used to compute the in-medium partial decay widths of the charmonium states to $D\bar{D}$ in magnetized nuclear matter. The medium modifications of these decay widths are computed from the mass modifications of the charmonium states, $D$ and $\bar{D}$ mesons calculated within a chiral effective model. In sect. 3, we discuss the results obtained in the present investigation of these in-medium charmonium decay widths in asymmetric nuclear matter in presence of strong magnetic fields. In sect. 4, we summarize the findings of the present study.

2 Decay widths of charmonia to $D\bar{D}$ within $^3P_0$ model

In the present work, we compute the in-medium partial decay widths of the charmonium states ($J/\psi$, $\psi(3686)$, $\psi(3770)$, $\chi_{c0}$, $\chi_{c2}$) to $D\bar{D}$ ($D^+D^-$ or $D^0\bar{D}^0$) in magnetized nuclear matter, using the $^3P_0$ model. In this model, a light quark-antiquark pair is created in the $^3P_0$ state, and this light quark (antiquark) combines with the heavy charm antiquark (charm quark) of the decaying charmonium state at rest, resulting in the production of the open charm $D$ and $\bar{D}$ mesons.

The in-medium partial decay widths of charmonium states $\psi(3686)$, $\psi(3770)$, $\chi_{c0}$, $\chi_{c2}$ to $D\bar{D}$ were studied using $^3P_0$ model in ref. [26], where the masses of the $D$ and $\bar{D}$ mesons were assumed to have same medium modification, in addition to the degeneracy of the masses of the $D^+$ and $D^0$ within the $D$ doublet, and of $D^-$ and $D^0$ within the $\bar{D}$ doublet in symmetric nuclear matter. In the asymmetric strange hadronic matter, the partial decay widths of the charmonium states, $J/\psi$, $\psi(3686)$ and $\psi(3770)$ to $D\bar{D}$ pair were calculated within the $^3P_0$ model, using the mass modifications of these charmonium states, $D$ and $\bar{D}$ mesons calculated within the chiral effective model [27].

The mass modifications of the open charm meson are calculated from their interactions with the isoscalar scalar mesons ($\sigma$ and $\zeta$), isovector scalar meson, $\delta$, and the nucleons in the magnetized asymmetric nuclear matter [14], whereas the masses of the charmonium states are modified due to the medium change of the gluon condensates, simulated by the scalar dilation field, $\chi$ [18] within the chiral effective model. The in-medium masses of the $D$ and $\bar{D}$ mesons in the magnetized asymmetric nuclear matter were calculated in ref. [14], within the frozen glueball approximation, i.e., neglecting the medium modifications of the dilaton field, $\chi$. In the present work, we take into account the medium modification of the dilaton field, $\chi$, by solving the Euler Lagrange equations of motions for the scalar fields, $\sigma$, $\zeta$ and $\delta$, as well as $\chi$ self consistently, for given values of baryon density, isospin asymmetry parameter and magnetic field. Accounting for the medium modifications of the $\chi$ field, however, are observed to give rise to marginal modifications to the masses of the $D$ and $\bar{D}$ meson masses as compared to the case of frozen glueball approximation. The medium modifications of the charmonium decay widths to $D\bar{D}$ in the magnetized nuclear matter arise due to the mass modifications of the open charm and charmonium states, which depend on the medium changes of the scalar fields and the dilaton field. To understand the in-medium behaviour of these fields, which modify the masses of the charmonium and open
charm mesons, and hence the charmonium decay widths to $D\bar{D}$, we write explicitly the coupled equations of motion of the scalar fields ($\sigma, \zeta, \delta$) and the dilaton field, $\chi$. These are given as [97]

$$k_0\chi^2\sigma - 4k_1 (\sigma^2 + \zeta^2 + \delta^2) \sigma - 2k_2 (\sigma^3 + 3\sigma\delta^2) \sigma$$

$$- 2k_1\chi\sigma\zeta - \frac{d}{\chi} \left( \frac{2\sigma}{\sigma^2 - d^2} \right) + \left( \frac{\chi}{\chi_0} \right)^2 m^2_\pi f_\pi$$

$$- \sum g_{\rho i} \rho_i^* = 0$$

$$k_0\chi^2 - 4k_1 (\sigma^2 + \zeta^2 + \delta^2) \delta - 2k_2 (\delta^3 + 3\sigma^2\delta) + 2k_3\chi\delta$$

$$- \frac{d}{\chi} \left( \frac{\delta}{\sigma^2 - d^2} \right) - \sum g_{\sigma i} \rho_i = 0$$

$$k_0\chi (\sigma^2 + \zeta^2 + \delta^2) - k_1 (\sigma^2 - \delta^2) \zeta + \chi^3 \left[ 1 + \ln \left( \frac{\chi^4}{\chi_0^4} \right) \right]$$

$$+ 4k_1\chi^4 - 4 \chi^3 d\chi \left[ \sqrt{2m^2_\pi f_\pi - \frac{1}{\chi^2} m^2_\pi f_\pi} \right]$$

$$- \frac{\chi}{\chi_0} \left[ m^2_\pi f_\sigma + \left( \sqrt{2m^2_\pi f_\sigma - \frac{1}{\chi^2} m^2_\pi f_\sigma} \right) \zeta \right] = 0.$$

In the above, $\rho_i^*(i = p, n)$ are the scalar densities for the nucleons, and $\sigma_0$, $\zeta_0$ and $\chi_0$ are the vacuum values for these scalar fields.

The expressions for the decay widths of the charmonium states in the asymmetric nuclear matter, considered in the present investigation, are given as [26]

$$\Gamma_{J/\psi \rightarrow D\bar{D}} = \sqrt{E_D E_{D\bar{D}}} \frac{\gamma^2}{2M_{J/\psi}} \frac{\rho^2\sigma^3 (1 + \rho^2)^2}{3(1 + 2\rho^2)^3} x^3$$

$$\times \exp \left( - \frac{x^2}{2(1 + 2\rho^2)} \right),$$

$$\Gamma_{D(3686) \rightarrow D\bar{D}} = \sqrt{E_D E_{D\bar{D}}} \frac{\gamma^2}{2M_{D(3686)}} \frac{2\sigma^2 (3 + 2\rho)^2 (1 - 3\rho\sigma)^2}{3^2(1 + 2\rho^2)^7} x^3$$

$$\times \left[ 1 + \frac{2\rho (1 + \rho^2)(3 + 2\rho^2)(1 - 3\rho\sigma)^2}{2(1 + 2\rho^2)} \right] \times \exp \left( - \frac{x^2}{2(1 + 2\rho^2)} \right),$$

$$\Gamma_{\psi(3770) \rightarrow D\bar{D}} = \sqrt{E_D E_{D\bar{D}}} \frac{\gamma^2}{2M_{\psi(3770)}} \frac{1}{3^2} \frac{r}{1 + 2\rho^2} x^7$$

$$\times x^3 \left[ 1 - \frac{1 + r^2}{5(1 + 2\rho^2)} x^2 \right] \times \exp \left( - \frac{x^2}{2(1 + 2\rho^2)} \right).$$

In the above, $M_{\psi}$ is the in-medium mass of the corresponding charmonium state ($\psi = J/\psi, \psi(3686), \psi(3770)$), $\chi_{c0}, \chi_{c2}, E_D, E_{D\bar{D}}$ are energies of the outgoing $D$ and $\bar{D}$ mesons given as

$$E_D = (p_D^2 + m_D^2)^{1/2}, \quad E_{D\bar{D}} = (p_{D\bar{D}}^2 + m_{D\bar{D}}^2)^{1/2},$$

with $m_D$ and $m_{D\bar{D}}$ as the in-medium masses of the $D$ and $\bar{D}$ mesons, and $p_D$ is the 3-momentum of the produced open charm mesons in the centre of mass frame given as

$$p_D = \left( \frac{M_{\psi}^2}{4} - \frac{m_D^2 + m_{D\bar{D}}^2}{2} + \frac{(m_D^2 - m_{D\bar{D}}^2)^2}{4M_{\psi}^2} \right)^{1/2}.$$
invariance [76,77,82]. The scale invariance breaking is through a logarithmic potential given in terms of a scalar dilaton field [102], and the medium modification of the dilaton field gives the medium modification of the gluon condensate, used to calculate the charmonium mass in the nuclear medium in the presence of an external magnetic field. The contribution of the magnetic field is incorporated [103–106] into the chiral effective model to study the mass modifications of the charmonium states [18] as well as open charm mesons [14] in the magnetized nuclear matter, including the effects of anomalous magnetic moments (AMM) of the nucleons [103–110]. The AMM effects are taken into consideration in the present study of the partial charmonium decay widths to $D\bar{D}$ in the magnetized nuclear matter, through the in-medium masses of the charmonium state as well as the open charm mesons. In the presence of the AMM effects, there are contributions to the nucleon fields, due to the tensorial interaction of the nucleons with the electromagnetic field ($-\frac{1}{2}g_i\mu x\bar{\psi}_i\sigma^\mu\nu F_{\mu\nu}\psi_i$), in addition to the vectorial interaction term ($-\bar{\psi}_i\gamma_\mu A^\mu\psi_i$), where, $\psi_i$ corresponds to the $i$-th baryon (proton and neutron for nuclear matter, as considered in the present work) [14,15,18,103–110]. The values of $\kappa_\sigma$ and $\kappa_\xi$ are given as 3.5856 and $-3.8263$ respectively, which are the values of the gyromagnetic ratio corresponding to the anomalous magnetic moments of the proton and neutron respectively. The scalar densities and number densities of the nucleons are modified with the AMM effects due to the tensorial interaction term. With inclusion of the AMM effects, the values for the scalar fields and dilaton field, which are obtained by solving the coupled equations of motion (1)–(4), are modified, as compared to when the AMM effects are not taken into consideration. Hence, the mass shifts of the charmonium states, as well as the $D$ and $D^*$ meson are modified, which in turn modify the charmonium decay widths to $D\bar{D}$.

As has already been mentioned, the mass shift in the charmonium state arises due to the medium modification of the scalar gluon condensate, and hence due to the change in the value of the dilaton field in the chiral effective model, and is given as [39,27,18]

$$\Delta m_{\psi} = \frac{4}{81}(1-d) \int dk^2 \left\langle \left(\frac{\partial \psi(k)}{\partial k}\right)^2 \right\rangle \frac{k}{k^2/m_c+\epsilon} \left(\chi^4 - \chi_0^4\right),$$

(12)

where

$$\left\langle \left(\frac{\partial \psi(k)}{\partial k}\right)^2 \right\rangle = \frac{1}{4\pi} \int \frac{\partial \psi(k)}{\partial k} \frac{k^2}{d\Omega}$$

(13)

In the above, $m_c$ is the mass of the charm quark, taken as 1.95 GeV, $m_{\psi}$ is the vacuum mass of the charmonium state and $\epsilon = 2m_c - m_{\psi}$ is the binding energy. $\psi(k)$ is the wave function of the charm quark state in the momentum space, which has been assumed to be Gaussian [26,27,39].

3 Results and discussions

We investigate the in-medium partial decay widths of the charmonium state $\psi (J/\psi, \psi(3686), \psi(3770)$, $\chi_{c0}$ and $\chi_{c2}$) to $D\bar{D}$ pair in the magnetized nuclear matter. The medium modifications of these decay widths are calculated from the medium modifications of their masses. The in-medium masses of the charmonium states, $J/\psi$, $\psi(3686)$ and $\psi(3770)$ in asymmetric nuclear matter in the presence of strong magnetic fields, have already been studied using a chiral effective model in ref. [18]. These masses were calculated from the medium changes of a scalar dilaton field, which simulates the gluon condensates of QCD, within the effective hadronic model through broken scale invariance. In the present work, the mass modifications of the 1P charmonium states, $\chi_{c0}$ as well as $\chi_{c2}$ have been studied, which are obtained from the medium modifications of the scalar dilaton field, $\chi$, from eq. (12), using the wave function for the charmonium state to be of harmonic oscillator wave function for 1P state. The values of the strength of the harmonic oscillator potential, $\beta$ for $J/\psi$, $\psi(3686)$ and $\psi(3770)$ (assuming these states to be 1S, 2S and 1D states) are calculated from their rms radii ($\langle r^2 \rangle$) of 0.47 fm$^2$, 0.96 fm$^2$ and 1 fm$^2$ respectively [39,27]. The mass modifications of the 1P states as well as the $\psi(3686)$ and $\psi(3770)$. The values of $\beta$ for $\chi_{c0}$ (vacuum mass of 3414.7 MeV) and $\chi_{c2}$ (vacuum mass of 3556.17 MeV) are obtained as 0.44 GeV and 0.41 GeV respectively.

The masses of the $D$ and $D^*$ mesons are obtained in the present work, from their interactions with the nucleons and the scalar mesons, $\sigma$, $\zeta$ and $\delta$ in the isospin asymmetric magnetized nuclear matter. The values of these meson fields are solved from the coupled equations of these fields as well as of the scalar dilaton field in the mean field approximation. The study of $D(D^*)$ mesons in asymmetric nuclear matter in the presence of a strong magnetic field in ref. [14], used the frozen glueball approximation, i.e., $\chi$ to be fixed at the vacuum value of $\chi$ as 409.77 MeV. The masses of the $D$ and $D^*$ mesons in the magnetized nuclear matter in the present work are observed to have modifications (though small) as compared to the masses obtained in ref. [14], due to the medium dependence of the dilaton field $\chi$ considered in the present investigation.

The masses of the $D(D^*, D^0)$ and $D(D^*, D^0)$ mesons are shown in figs. 1 and 2, as functions of the baryon density (in units of nuclear matter saturation density) for the values of magnetic field as $eB = 4m_\pi^2$ and $eB = 8m_\pi^2$, with the values of the isospin asymmetry parameter as $\eta = 0, 0.3$ and 0.5, with the anomalous magnetic moments (AMM) of the nucleons taken into consideration. These results are compared with the case when the AMM of the nucleons are neglected. In the isospin symmetric nuclear matter, the masses (in MeV) of the $D^+$ and $D^0$ are observed to be 1813.6 (1811.8) and 1787 (1785.5) at the nuclear matter saturation density for magnetic field (in units of $1/e$) of $4m_\pi^2$ with (without) AMM effects. With the larger density of $4\rho_0$, these are modified to 1557 (1542.6) and 1526.5 (1510.4). These values may be compared to 1809.7 (1807.8) and 1782.9 (1781.4) at $\rho_\pi = \rho_0$ and 1539.9 (1524.9) and 1508.5 (1492.7) at $\rho_\pi = 4\rho_0$, in the frozen glueball approximation [14]. The modifications of the masses of the $D$ mesons are thus observed to be
rather small, when the medium modifications of the dilaton field are taken into account, as compared to the frozen glueball approximation. For the \( D \) mesons, in isospin symmetric nuclear matter, the masses of \( D^- \) and \( D^0 \) mesons are obtained as 1864 (1862.2) and 1837.8 (1836.4) at \( \rho_0 \) and 1740.2 (1722.7) and 1711.5 (1692.6) at 4\( \rho_0 \) with (without) AMM effects. The isospin asymmetry as well as AMM effects are observed to be larger at the higher magnetic field of \( eB = 8m_\pi^2 \) for \( D^0 \) meson, whereas \( D^+ \) is rather insensitive to these effects, as can be seen from fig. 1. For \( D^- \) as well as \( D^0 \) mesons, the asymmetry as well as AMM effects are appreciable for the larger value of the magnetic field \( (eB = 8m_\pi^2) \), as can be seen from fig. 2.

The in-medium masses of the charmonium states, \( J/\psi, \psi(3686) \) and \( \psi(3770) \) in the magnetized asymmetric nuclear matter have been studied within the chiral effective model [18]. In the present work, we study the mass modifications of the P-wave charmonium states, \( \chi_{c0} \) and \( \chi_{c2} \), and investigate the partial decay widths of the charmonium states \( J/\psi, \psi(3686), \psi(3770), \chi_{c0}, \chi_{c2} \) to \( DD \) in the magnetized nuclear matter.

In figs. 3 and 4, the masses of the 1P states are plotted as functions of the baryon density (in units of nuclear matter saturation density) for the values of magnetic field as \( eB = 4m_\pi^2 \) and \( eB = 8m_\pi^2 \), with the values of the isospin asymmetry parameter as \( \eta = 0, 0.3 \) and 0.5, with the anomalous magnetic moments (AMM) of the nucleons taken into consideration. These results are compared with the case when the AMM of the nucleons are neglected. The mass of \( \chi_{c0} \) (in MeV) is observed to be modified from its vacuum value of 3414.7 to 3385.57 (3309) at a density of \( \rho_0(4\rho_0) \) for \( eB = 4m_\pi^2 \) for symmetric nuclear matter, with AMM effects, and 3384.8 (3303.7) when AMM of nucleons are not taken into consideration. The mass shifts are observed to be smaller with isospin asymmetry effects, as well as with increase in the magnetic field. The mass shifts are observed to be larger when the AMM of the nucleons are not considered. The mass of \( \chi_{c2} \) is plotted in fig. 4. For symmetric nuclear matter, at a density of \( \rho_0(4\rho_0) \) for \( eB = 4m_\pi^2 \), the mass of \( \chi_{c2} \) (in MeV) is observed to be modified from its vacuum value of 3556.17 to 3511 (3393) with AMM effects, and 3509.9 (3382.9) when AMM of nucleons are not taken into consideration. The effects of isospin asymmetry as well as magnetic fields on the mass of \( \chi_{c0} \) plotted in fig. 4 are observed to be similar to that of \( \chi_{c0} \) in the present work as well as to the mass modifications of the charmonium states \( J/\psi, \psi(3686) \) and \( \psi(3770) \) already studied in ref. [18]. This is due to the fact that the mass modifications of the charmonium states are determined by the medium change of the scalar dilaton field in the magnetized nuclear matter. The medium change of the mass of the charmonium state is observed to be quite insensitive to the isospin asymmetry in the medium. This can be understood in the following manner.

![Fig. 1. (Color online) The masses of \( D^+ \) and \( D^0 \) mesons plotted as functions of the baryon density in units of nuclear matter saturation density, for different values of the magnetic field and isospin asymmetry parameter, \( \eta \), including the effects of the anomalous magnetic moments of the nucleons. The results are compared to the case when the effects of anomalous magnetic moments are not taken into consideration (shown as dotted lines).](image1)

![Fig. 2. (Color online) The masses of \( D^- \) and \( D^0 \) mesons plotted as functions of the baryon density in units of nuclear matter saturation density, for different values of the magnetic field and isospin asymmetry parameter, \( \eta \), including the effects of the anomalous magnetic moments of the nucleons. The results are compared to the case when the effects of anomalous magnetic moments are not taken into consideration (shown as dotted lines).](image2)
The mass shift of the charmonium state is obtained from the shift of the dilaton field, $\chi$ and is proportional to the shift in the fourth power of $\chi$ from the vacuum value (as can be seen from eq. (12)), in the limit of massless quarks in the trace anomaly [18] as considered in the present investigation. In the mean field approximation, the meson fields are replaced by their expectation values and as has already been mentioned, the value of $\chi$ is obtained through the solution of coupled equations of the scalar fields, $\sigma, \zeta, \delta$ and $\chi$ given by eqs. (1)–(4). In the presence of the isospin asymmetry in the medium, i.e. for nonzero values of the isospin asymmetry parameter, $\eta = (\rho_0 - \rho_p)/(2\rho_0)$, the number density of the neutron is larger than the proton density and the scalar densities of the proton and neutron become different, with the value of $\delta$ being proportional to their difference. The magnitudes of $\sigma$ and $\zeta$, become larger in the asymmetric nuclear matter than in the symmetric nuclear matter case, due to the contributions from $\delta^2$ term, as can be seen from the equations for $\sigma$ and $\zeta$ fields given by (1) and (2). However, due to the much smaller magnitude of $\delta$ as compared to $\sigma$ and $\zeta$ (e.g., $\delta \sim 2\text{ MeV}, \sigma \sim 45\text{ MeV}, \zeta \sim 94\text{ MeV}$ at $\rho_B = 2\rho_0$ for $eB = 8m_\pi^2$ and $\eta = 0.3$), the modifications for $\sigma$ and $\zeta$ are very small in the asymmetric nuclear matter as compared to symmetric nuclear matter. It might be noted here that in the absence of a magnetic field, the scalar densities for the proton and neutron remain the same and the value of $\delta$ is zero, whereas, in the presence of a magnetic field, even for the case of isospin symmetry in the medium ($\rho_p = \rho_n$), the scalar densities are different for the proton...
and neutron (due to contribution of Landau energy levels for proton in the presence of a magnetic field), which gives rise to a nonzero value (though small, with a maximum value of about 0.5 MeV for \( eB = 8m^2_\pi \)) for the isovector scalar meson, \( \delta \). The dependence of \( \chi \) on \( \sigma \) and \( \zeta \) (as can be seen from eq. (4)) in the leading order, is proportional to \((\sigma^2 + \delta^2 + \zeta^2)\). The magnitude of the isovector scalar field \( \delta \) remains small (\( \sim \) few MeV) as compared to the magnitudes of \( \sigma \) or \( \zeta \). This is the reason why the modification of the dilaton field \( \chi \) due to isospin asymmetry remains small, and subsequently the mass shifts of the charmonium states (which are proportional to \((\chi^4 - \chi^2 \delta^2)\)) remain insensitive to isospin asymmetry of the medium.

We investigate the in-medium decay widths of the charmonium states to \( DD \) in the magnetized nuclear matter, for the values of the isospin asymmetry parameter \( \eta \) as 0, 0.3 and 0.5 and magnetic fields \( eB = 4m^2_\pi \) and \( eB = 8m^2_\pi \). For \( eB = 8m^2_\pi \) and in the case when the AMM effects of the nucleons are neglected, the decay width of \( \psi \rightarrow D^0\bar{D}^0 \) is observed to be possible above a density of around 5\( \rho_0 \) in symmetric nuclear matter. There is observed to be an increase in this decay width with density, reaching a value of around 27.9 MeV at 6\( \rho_0 \). The decay \( \psi \rightarrow D\bar{D} \) is not observed in any other case considered in the present work.

The decay widths of \( \psi(3686) \) to \( DD \) in magnetized isospin asymmetric nuclear matter are plotted as functions of the baryon density in units of nuclear matter saturation density in fig. 5 for different values of the magnetic field and isospin asymmetry parameter. These are plotted for the channels (i) \( D^+D^- \), (ii) \( D^0\bar{D}^0 \) as well as (iii) the sum of these two channels. The decay of \( \psi(3686) \) is not possible in vacuum since the mass of this charmonium state is smaller than the combined mass of \( D \) and \( D \) in vacuum. However, at certain densities, these decays become possible, when the center of mass momentum, \( p_D \) becomes nonzero with the medium modifications of the masses of the charmonium as well as the outgoing \( D \) and \( \bar{D} \) mesons [26, 27]. In symmetric nuclear matter (\( \eta = 0 \)), in the presence of magnetic field, \( eB = 4m^2_\pi \), shown in panel (a) of fig. 5, the threshold densities above which the decays \( \psi(3686) \) to \( D^+D^- \) and \( \psi(3686) \) to \( D^0\bar{D}^0 \) become possible are 4.5\( \rho_0 \) and 2.54\( \rho_0 \) respectively when the AMM of the nucleons are taken into account, and 4.1\( \rho_0 \) and 2.37\( \rho_0 \) when the AMM of nucleons are not considered. The higher value for the threshold density for the decay width of \( \psi(3686) \) to \( D^+D^- \) as well as \( \psi(3686) \) to \( D^0\bar{D}^0 \) is due to the reason that the masses of the charged \( D \) as well as charged \( \bar{D} \) mesons have positive shifts due to the contributions from the lowest Landau levels [14], which makes the mass of \( D^+D^- \) to be larger than \( D^0\bar{D}^0 \). For the magnetic field \( eB = 8m^2_\pi \) in symmetric nuclear matter, as shown in panel (b), the decay of \( \psi(3686) \) to \( D^0\bar{D}^0 \) becomes possible at a density of 2.4\( \rho_0 \) (2.2\( \rho_0 \)) for the cases of with (without) AMM effects. The decay of \( \psi(3686) \) to \( D^+D^- \) is not observed even up to a density of 6\( \rho_0 \).

In the isospin asymmetric nuclear medium with \( \eta = 0.3 \), the densities above which the decays of \( \psi(3686) \) to \( D^+D^- \) and \( \psi(3686) \) to \( D^0\bar{D}^0 \) become possible are observed to be 3.3\( \rho_0 \) and 3.7\( \rho_0 \) respectively for \( eB = 4m^2_\pi \) as can be seen from panel (c) of fig. 5 when the AMM of the nucleons are taken into account. These densities are modified to 3.12\( \rho_0 \) and 3.5\( \rho_0 \), when the AMM effects are not taken into consideration. The contrasting behaviour of the threshold density for \( \psi(3686) \rightarrow D^+D^- \) to be smaller than the channel \( \psi(3686) \rightarrow D^0\bar{D}^0 \) for the isospin asymmetric case with \( \eta = 0.3 \), as compared to the isospin symmetric case for \( eB = 4m^2_\pi \) is due to the reason that the center of mass momentum of the outgoing \( D \) and \( \bar{D} \) mesons, \( p_D \), has larger contribution from the last term of eq. (11) for the case of outgoing mesons as \( D^+D^- \) as compared to \( D^0\bar{D}^0 \), since the difference in the masses of \( D^+ \) and \( D^- \) is much bigger than the difference in \( D^0 \) and \( \bar{D}^0 \) masses. When the magnetic field is increased to \( eB = 8m^2_\pi \), for asymmetric nuclear matter with \( \eta = 0.3 \), as can be seen from panel (d) of fig. 5, the values for the threshold densities for decay to \( D^+D^- \) and \( D^0\bar{D}^0 \) are 4.6\( \rho_0 \) and 3.6\( \rho_0 \) respectively for the case
without AMM effects. The higher threshold density for the charged $D \bar{D}$ decay as compared to neutral $D \bar{D}$ decay is similar to the case of the isospin symmetric case. This is because the masses of the charged mesons have larger positive mass shifts with increase in the magnetic field to $eB = 8m_\pi^2$. When the AMM effects are taken into account, the threshold density for $\psi(3686)$ to $D^0\bar{D}^0$ is about $4\rho_0$ and the decay of $\psi(3686)$ to $D^+\bar{D}^-$ does not become possible even up to a density of $6\rho_0$.

At the maximum value of the isospin asymmetry parameter of $\eta = 0.5$, only the decay channel of $\psi(3686)$ to $D^+\bar{D}^-$ is possible, above a density of $2.9\rho_0$ and $5\rho_0$ for $eB = 4m_\pi^2$ and $eB = 8m_\pi^2$ respectively, when AMM of the nucleons are considered. In the case when the AMM effects are not taken into account, there is no dependence on the magnetic field, for the decay to $D^0\bar{D}^0$, as the system consists of only neutrons for $\eta = 0.5$ and the only effect of magnetic field can be through the AMM of neutron. However, in the presence of a magnetic field, the masses of the charged $D^\pm$ mesons are modified due to the contribution from the lowest Landau level. For the case of without AMM effects and for $\eta = 0.5$, the decay of $\psi(3686)$ to $D^+\bar{D}^-$ is possible above a density of about $2.7 \, (4) \, \rho_0$ for $eB = 4(8)m_\pi^2$, and the decay to the neutral $D\bar{D}$ pair is not observed even up to a density of $6\rho_0$.

In fig. 6, the partial decay widths of $\psi(3770)$ to $D\bar{D}$ are shown for different values of the isospin asymmetry parameter and magnetic fields, accounting for the effects of AMMs of nucleons. These results are compared with the case when the AMMs of nucleons are not taken into consideration. For symmetric nuclear matter ($\eta = 0$), an initial decrease of the decay width is observed up to a density of around $1.5\rho_0$ followed by an increase at high densities both for the cases of $eB = 4m_\pi^2$ and $eB = 8m_\pi^2$, as can be seen from panels (a) and (b) of fig. 6. For $eB = 4m_\pi^2$, the decay is solely through the channel $\psi(3770) \to D^0\bar{D}^0$ up to a density of around $4.8\rho_0$ ($5.3\rho_0$), above which the decay to the charged $D\bar{D}$ mesons also becomes possible. For the higher magnetic field of $eB = 8m_\pi^2$, as can be seen from panel (b) of fig. 6, the decay to the charged $D\bar{D}$ mesons does not become possible even up to a density of $6\rho_0$. For isospin asymmetric nuclear matter with $\eta = 0.3$, there is observed to be an initial drop in the partial decay width of $\psi(3770) \to D\bar{D}$ (solely due to contribution from the channel $\psi(3770) \to D^0\bar{D}^0$) with density, which becomes very small ($\sim 0.28 \, (0.11) \text{ MeV}$) at around $1.05\rho_0$ ($0.9\rho_0$) with (without) the AMM effects of the nucleons. The value of the decay width for $\psi(3770) \to D^0\bar{D}^0$ remains similar up to a density of around $3.75\rho_0$ ($3.6\rho_0$), with (without) AMM effects, above which there is observed to be an increase in this decay width with density. The decay channel $\psi(3770) \to D^+\bar{D}^-$ is observed to become possible above a density of around $3.1\rho_0$ ($2.9\rho_0$) when the AMM effects are considered (neglected). For the magnetic field $eB = 8m_\pi^2$, the behaviour is similar to case of $eB = 4m_\pi^2$, for the case when the AMMs of the nucleons are not taken into account. On the other hand, for the case when AMM effects are considered, there is no decay to charged $D\bar{D}$ pair observed even up to a density of $6\rho_0$.

For the isospin asymmetry parameter, $\eta = 0.5$, the decay is only through the channel $\psi(3770) \to D^+\bar{D}^-$, for both $eB = 4m_\pi^2$ and $eB = 8m_\pi^2$.

In fig. 7, the effects of isospin asymmetry, magnetic field and density on the partial decay widths of $\chi_{c2} \to D\bar{D}$ are shown. There is observed to be a threshold density above which the decay is observed to be possible for both the charged and neutral $D\bar{D}$ channels. An initial increase with density is observed, followed by a drop when the density is further increased. The AMM effects are observed to be large for higher value of magnetic field.

In fig. 8, the partial decay widths of $\chi_{c2} \to D\bar{D}$ is plotted as functions of the baryon density for different values of isospin asymmetry parameter and magnetic fields, both with and without AMM effects of the nucleons. A threshold density is observed for both the charged and neutral $D\bar{D}$ pair channels, and the decay width is observed to increase monotonically with density. This behaviour can be understood looking at the polynomial part (in $p_D$) of

\[ (\rho_0/\rho) = \text{threshold density} \]

\[ (\eta) = \text{isospin asymmetry parameter} \]

\[ (eB) = \text{magnetic field} \]
the partial decay width which increases with \( p_D \), which in turn is an increasing function of the baryon density. This behaviour of monotonic increase in the decay width of \( \chi_{c2} \) was also observed in ref. [26], as a function of the mass drop in \( D \) and \( \bar{D} \) mesons in the nuclear medium.

The partial decay widths of the charmonium to \( D\bar{D} \) depend on the center of mass momentum of the \( D(\bar{D}) \) meson, \( p_D \) (given by eq. (11)), through a polynomial part multiplied by an exponential part, as can be seen from eqs. (5)–(9). The stark difference of the \( \chi_{c0} \) and \( \chi_{c2} \) decay widths is due to the difference in the forms of the polynomial part, which has a monotonic increase with density in the case of \( \chi_{c0} \) above a threshold density when the decay to \( D\bar{D} \) becomes possible. On the other hand, the decay width for \( \chi_{c0} \) (above the threshold density when the decay becomes possible) shows an initial increase followed by a drop with further increase in the density. Similar behaviours for the decay widths of \( \chi_{c0} \) and \( \chi_{c2} \) to \( D\bar{D} \) were also observed in ref. [26]. The medium modifications of these decay widths were calculated from the mass modifications of the \( D \) and \( \bar{D} \) mesons, which were assumed to be same in the symmetric nuclear matter in ref. [26]. The \( \psi(3686) \) decay width shows a monotonic increase, whereas \( \psi(3770) \to D\bar{D} \) decay width has an initial drop followed by a rise with further increase in the density. As has already been mentioned, the dependence of the charmonium decay width to \( D\bar{D} \) on density is determined by the form of the polynomial and the exponential parts in terms of the center of mass momentum, \( p_D \).

4 Summary

We have studied the effects of magnetic field on the partial decay widths of the charmonium states, \( J/\psi(3097) \), \( \psi(3686) \), \( \psi(3770) \), \( \chi_{c0}\) and \( \chi_{c2} \) to \( D\bar{D} \) in isospin asymmetric nuclear matter. These are obtained using the mass modifications of the \( D \) and \( \bar{D} \) mesons as well as the charmonium states, calculated within a chiral effective model. The mass modifications of the open charm mesons, \( D \)
and $D^- (D^0, D^-)$ arise due to their interactions with the nucleons and the scalar mesons, whereas the intermediate masses of the charmonium states are calculated from the medium changes of the scalar dilaton field, which simulates the gluon condensates of QCD within the chiral effective model. In the presence of the magnetic field, the proton has contributions from the Landau energy levels. Unequal masses are observed for the $D^0$ and $D^+$ within the $D$ meson doublet, as well as for $D^0$ and $D^-$ within the $D$ doublet, even in isospin symmetric nuclear matter, due to difference in the interactions with the proton and neutron, as well as due to contributions from the Landau energy levels for the charged $D$ and $D$ mesons, in the presence of magnetic field. In symmetric nuclear matter, the threshold densities for which the decay widths of the masses of the charmonium state to $DD$ turn out to be smaller for the $D^0D^0$ channel as compared to for $D^+D^-$ channel, as the masses of the $D^+$ as well as $D^-$ have positive shifts in the presence of magnetic field. The effects of isospin asymmetry, magnetic fields are observed to be quite appreciable on the partial decay widths for the charged and neutral $DD$ pair channels, which will affect the production of these mesons in high energy asymmetric heavy ion collision experiments.

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References
1. A. Hosaka, T. Hyodo, K. Sudoh, Y. Yamaguchi, S. Yasui, Prog. Part. Nucl. Phys. 96, 88 (2017).
2. V. Skokov, A.Y. Illarionov, V. Toneev, Int. J. Mod. Phys. A 24, 5925 (2009).
3. W.T. Deng, X.G. Huang, Phys. Rev. C 85, 044907 (2012).
4. D. Kharzeev, L. McLerran, H. Warringa, Nucl. Phys. A 803, 227 (2008).
5. K. Fukushima, D.E. Kharzeev, H.J. Warringa, Phys. Rev. D 78, 074033 (2008).
6. K. Tuchin, Phys. Rev. C 83, 017901 (2011).
7. K. Marasinghe, K. Tuchin, Phys. Rev. C 84, 044908 (2011).
8. K. Tuchin, Phys. Rev. C 82, 034904 (2010) 83, 039903(E) (2011).
9. K. Tuchin, Phys. Rev. C 88, 024911 (2013).
10. Arpan Das, S.S. Dave, P.S. Saumia, A.M. Srivastava, Phys. Rev. C 96, 034902 (2017).
11. P. Gabler, K. Hattori, S.H. Lee, M. Oka, S. Ozaki, K. Suzuki, Phys. Rev. D 93, 054026 (2016).
12. C.S. Machado, F.S. Navarra, E.G. de Oliveira, J. Noronha, M. Strickland, Phys. Rev. D 88, 034009 (2013).
13. C.S. Machado, R.D. Matheus, S.I. Finazzo, J. Noronha, Phys. Rev. D 89, 074027 (2014).
14. Sushruth Reddy P, Amal Jahan CS, Nikhil Dhale, Amruta Mishra, J. Schaffner-Bielich, Phys. Rev. C 97, 065208 (2018).
15. Nikhil Dhale, Sushruth Reddy P, Amal Jahan CS, Amruta Mishra, Phys. Rev. C 98, 015202 (2018).
16. S. Cho, K. Hattori, S.H. Lee, K. Morita, S. Ozaki, Phys. Rev. Lett. 113, 172301 (2014).
17. S. Cho, K. Hattori, S.H. Lee, K. Morita, S. Ozaki, Phys. Rev. D 91, 045025 (2015).
18. Amal Jahan CS, Nikhil Dhale, Sushruth Reddy P, Shivam Keswarani, Amruta Mishra, Phys. Rev. C 98, 065202 (2018).
19. Pallabi Parui, Ankit Kumar, Sourodeep De, Amruta Mishra, arXiv:1811.04622 [nucl-th].
20. K. Suzuki, S.H. Lee, Phys. Rev. C 96, 035203 (2017).
21. J. Alford, M. Strickland, Phys. Rev. D 88, 105017 (2013).
22. A. Le Yaouanc, L. Oliver, O. Pene, J.C. Raynal, Nucl. Phys. A 8, 2223 (1973).
23. A. Le Yaouanc, L. Oliver, O. Pene, J.C. Raynal, Phys. Rev. D 9, 1415 (1974).
24. A. Le Yaouanc, L. Oliver, O. Pene, J.C. Raynal, Phys. Rev. D 11, 1272 (1975).
25. T. Barnes, F.E. Close, P.R. Page, E.S. Swanson, Phys. Rev. D 55, 4157 (1997).
26. B. Friman, S.H. Lee, T. Song, Phys. Lett. B 548, 153 (2002).
27. Arvind Kumar, Amruta Mishra, Eur. Phys. J. A 47, 164 (2011).
28. E. Eichten, K. Gottfried, T. Kinoshita, K.D. Lane, T.M. Yan, Phys. Rev. D 17, 3090 (1978).
29. E. Eichten, K. Gottfried, T. Kinoshita, K.D. Lane, T.M. Yan, Phys. Rev. D 21, 203 (1980).
30. L. Kluberg, H. Satz, in Relativistic Heavy Ion Physics, edited by R. Stock, Landolt-Börnstein - Group I Elementary Particles, Nuclei and Atoms, Vol. 23 (Springer, Berlin, Heidelberg, 2010).
31. F. Karsch, M.T. Mehr, H. Satz, Z. Phys. C 37, 617 (1988).
32. A. Bazavov, P. Petreczky, A. Velytsky, Quark-Gluon Plasma 4, edited by R.C. Hwa, Xin-Nian Wang (World Scientific Publishers, 2010) p. 61.
33. S. Digal, P. Petreczky, H. Satz, Phys. Lett. B 514, 57 (2001).
34. A. Mocsy, P. Petreczky, Phys. Rev. D 73, 074007 (2006).
35. S.F. Radford, W.W. Repko, Phys. Rev. D 75, 074031 (2007).
36. M.E. Peskin, Nucl. Phys. B 156, 365 (1979).
37. G. Bhanot, M.E. Peskin, Nucl. Phys. B 156, 391 (1979).
38. M.B. Voloshin, Nucl. Phys. B 154, 365 (1979).
39. Su Hong Lee, Che Ming Ko, Phys. Rev. C 89, 054026 (2016).
40. Sugis Kim, Su Hong Lee, Nucl. Phys. A 759, 517 (2001).
41. F. Klingl, S. Kim, S.H. Lee, P. Morath, W. Weise, Phys. Rev. Lett. 82, 3396 (1999).
