Open Charm mesons in magnetized nuclear matter
– effects of magnetic catalysis

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Abstract

We investigate the in-medium masses of the pseudoscalar ($D, \bar{D}$) and vector ($D^*, \bar{D}^*$) open charm mesons in isospin asymmetric magnetized nuclear matter. In the presence of an external magnetic field, there is mixing of the pseudoscalar and the vector mesons (PV mixing), leading to modifications to the masses of these mesons. There are additional contributions from the Landau energy levels for the charged open charm mesons in the presence of a magnetic field. The PV ($D - D^*$ and $\bar{D} - \bar{D}^*$) mixing effects are taken into account through a phenomenological interaction Lagrangian in the present study. The masses of the $D$ and $\bar{D}$ mesons in the magnetized nuclear matter are calculated from their interactions with the nucleons and scalar mesons within an effective chiral model, including the contributions of the Dirac sea through summation over nucleon tadpole diagrams. The Dirac sea contributions are observed to lead to magnetic catalysis effect, which is the enhancement of the chiral condensates with increase in magnetic field. The effects of the magnetic catalysis, in addition to the PV mixing and Landau level contributions (for charged mesons) are observed to lead to significant modifications to the masses of the open charm mesons. The modifications of the partial decay widths of the charmonium states to open charm mesons, e.g., $\psi(3770) \rightarrow D\bar{D}$, as well as $D^* \rightarrow D\pi$ (and $\bar{D}^* \rightarrow \bar{D}\pi$) due to the mass modifications of these mesons can affect the yield of the open charm and charmonium states produced in ultra relativistic peripheral heavy ion collision experiments, where the created magnetic field is huge.

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I. INTRODUCTION

The study of the hadron properties under extreme conditions of density, temperature and magnetic field is of relevance in the ultra-relativistic heavy ion collision experiments and in astrophysical objects like the magnetars, neutron stars etc. The topic of hadron properties in the presence of magnetic fields [1] has attracted a lot of attention in the recent past, due to its relevance in ultra relativistic peripheral heavy ion collision experiments. The magnetic fields produced are estimated to be huge in the heavy ion collision experiments at LHC in CERN and at RHIC in BNL.

The open heavy flavour mesons and the heavy quarkonium states are profusely produced in the early phase of these collisions, when the magnetic field can still be large. However, the time evolution of the magnetic field, which requires solutions of the magnetohydrodynamic equations, along with a proper estimate of the electrical conductivity in the medium, is still an open question. The experimental observables of the relativistic heavy ion collision experiments are affected by the medium modifications of the hadrons. In the presence of a magnetic field, there can be an enhancement of the light quark condensate with increase in the magnetic field, an effect called the magnetic catalysis [2–7]. The magnetic catalysis effect has been studied for the nuclear matter within Walecka model [8, 9], which arises from the Dirac sea contributions to the nucleon self energy calculated through the summation of nucleonic tadpole diagrams. The magnetic catalysis effect is observed as an increase in the scalar field, $\sigma(\sim \langle \bar{q}q \rangle)$, with a rise in the magnetic field at zero temperature and zero baryon density. As the magnetic field is raised, this effect leads to an increase in the nucleon mass given as $M_N^* = M_N - g_{\sigma N} \sigma$, where $M_N$ is the mass of the nucleon in vacuum (at zero magnetic field) and $g_{\sigma N}$ is the coupling of the nucleon with the scalar field, $\sigma$. In Ref. [9], the weak magnetic field approximation is used for the nucleon propagator, and, the effects of the anomalous magnetic moments (AMM) of the nucleons have also been considered. There is observed to be quite dominant contributions from the AMMs, as compared to when these are not taken into account. In the presence of a magnetic field, there is mixing of the pseudoscalar meson and the longitudinal component of the vector meson (PV mixing) leading to a drop (increase) in the mass of the pseudoscalar (longitudinal component of the vector) meson. The effects of the PV mixing have been studied for the open and hidden charm mesons [10–14] and have been observed to have appreciable modifications to the masses of
these mesons. For the charged mesons, there are additional contributions from the Landau levels in the presence of an external magnetic field. The open charm mesons, which are created at the early phase of the heavy ion collision experiments, when the magnetic field is still large, can hence be important tools in probing the effects of the magnetic field, e.g., the mass modifications due to mixing of pseudoscalar meson and the longitudinal component of the vector meson (PV mixing), Landau level contributions (for the charged mesons) as well as the magnetic catalysis.

The $D$($\bar{D}$) and $D^*$($\bar{D}^*$) mesons are the open heavy flavour mesons, which comprise of a heavy charm quark (antiquark) and a light (u,d) antiquark (quark). Within a chiral effective model, the in-medium masses of the $D$ and $\bar{D}$ mesons have been calculated. The in-medium properties of the open heavy flavour (charm and bottom) mesons and heavy quarkonium states in the absence of a magnetic field have been studied within the model [15–22]. In the presence of a magnetic field, the masses of the open and hidden heavy flavour mesons have been studied within the model in the ‘no sea’ approximation [23–25] and their effects on the partial decay widths of the charmonium states to $DD$ [26–28] and bottomonium states to $B\bar{B}$ [29].

In the present work, we investigate the masses of the open charm ($D$ and $\bar{D}$) mesons in isospin asymmetric magnetized nuclear matter using a chiral effective model, accounting for the Dirac sea contributions. The effects of the AMMs of the nucleons are also considered in the present work. The PV mixing effect is considered using a phenomenological Lagrangian interaction in the present work. The additional contributions from the lowest Landau level (LLL) are taken into account for the charged open charm mesons.

We organize the paper as follows: In section II, we discuss briefly the chiral effective model and the computation of the masses of the $D$ and $\bar{D}$ mesons in the isospin asymmetric magnetized nuclear matter. These are calculated including the contributions of the Dirac sea for the nucleon self-energy, which is observed to a rise in the magnitude of the light quark condensate with increase in the magnetic field, an effect called the magnetic catalysis, as well as, incorporating the effects of the PV mixing in the presence of a magnetic field. In section III, we describe the results for the masses of the open charm mesons due to the effects of the magnetic catalysis, PV mixing and for the charged mesons, contributions from the Landau level. In section IV, we summarize the findings of the present work.
FIG. 1: (Color online) The masses of the $D^+$, $D^-$, $D^{*+}$ and $D^{*-}$ mesons are plotted in (a), (b), (c) and (d) at $\rho_B=0$, including the magnetic catalysis (MC) effect, and, with and without PV ($D^+ - D^{*+}$ and $D^- - D^{*-}$) mixing effects accounting for the AMMs of the nucleons. These are compared with the cases when the AMMs of the nucleons are not considered (shown as dotted lines).

II. IN-MEDIUM MASSES OF OPEN CHARm MESONS

We describe the chiral effective model used to study the open charm $D$ and $\bar{D}$ mesons in magnetized nuclear matter. The model is based on a nonlinear realization of chiral symmetry. The breaking of scale invariance of QCD is incorporated into the model through the introduction of a scalar dilaton field, $\chi$. The Lagrangian of the model, in the presence
FIG. 2: (Color online) The masses of the $D^0$, $\bar{D}^0$, $D^{*0}$ and $\bar{D}^{*0}$ mesons are plotted in (a), (b), (c) and (d) at $\rho_B=0$, including the magnetic catalysis (MC) effect, and, with and without PV ($D^0 - D^{*0}$ and $\bar{D}^0 - D^{*0}$) mixing effects accounting for the AMMs of the nucleons. These are compared with the cases when the AMMs of the nucleons are not considered (shown as dotted lines).

of a magnetic field, has the form

$$\mathcal{L} = \mathcal{L}_{kin} + \sum_{W} \mathcal{L}_{BW} + \mathcal{L}_{vec} + \mathcal{L}_0 + \mathcal{L}_{scalebreak} + \mathcal{L}_{SB} + \mathcal{L}_{mag}^{BW},$$  \hspace{1cm} (1)$$

where, $\mathcal{L}_{kin}$ corresponds to the kinetic energy terms of the baryons and the mesons, $\mathcal{L}_{BW}$ contains the interactions of the baryons with the meson, $W$ (scalar, pseudoscalar, vector, axialvector meson), $\mathcal{L}_{vec}$ describes the dynamical mass generation of the vector mesons
via couplings to the scalar fields and contains additionally quartic self-interactions of the vector fields, $L_0$ contains the meson-meson interaction terms, $L_{\text{scalebreak}}$ is a scale invariance breaking logarithmic potential given in terms of a scalar dilaton field, $\chi$ and $L_{SB}$ describes the explicit chiral symmetry breaking. The term $L^{B\gamma}_{\text{mag}}$, describes the interaction of the baryons with the electromagnetic field, which includes a tensorial interaction $\sim \bar{\psi}_i \sigma^{\mu\nu} F_{\mu\nu} \psi_i$, whose coefficients account for the anomalous magnetic moments of the baryons [23–25].

In the present work, we use the relativistic Hartree approximation where the meson fields are treated as classical fields. However, the nucleon is treated as a quantum field and the self energy of the nucleon includes the contributions of the Dirac sea through the summation of the nucleonic tadpole diagrams corresponding to the the non-strange isoscalar ($\sigma$), strange isoscalar ($\zeta$), and non-strange isovector ($\delta$) scalar fields. The masses of the baryons are generated by their interactions with the scalar mesons. The mass of baryon of species $i$ ($i = p, n$ in the present work of nuclear matter) is given as

$$M_i = -g_{\sigma i} \sigma - g_{\zeta i} \zeta - g_{\delta i} \delta.$$ (2)

The masses of the $D$ and $\bar{D}$ mesons are computed from solution of their dispersion relations, given as

$$-\omega^2 + \vec{k}^2 + m^2_{D(\bar{D})} - \Pi_{D(\bar{D})}(\omega, |\vec{k}|) = 0,$$ (3)

where $\Pi_{D(\bar{D})}$ denotes the self energy of the $D$ ($\bar{D}$) meson in the medium. These are given in terms of the scalar fields, the number and scalar densities of the nucleons [23] as For the $D$ meson doublet ($D^0, D^+$), and $\bar{D}$ meson doublet ($\bar{D}^0, D^-$), the self energies are given by

$$\Pi(\omega, |\vec{k}|) = \frac{1}{4f_D^2} \left[ 3(\rho_p + \rho_n) \pm (\rho_p - \rho_n) \right] \omega$$

$$+ \frac{m_D^2}{2f_D} (\sigma' + \sqrt{2} \zeta' \pm \delta')$$

$$+ \left[ -\frac{1}{f_D} (\sigma' + \sqrt{2} \zeta' \pm \delta') + \frac{d_1}{2f_D^2} (\rho_p^* + \rho_n^*) 
+ \frac{d_2}{4f_D^2} (\rho_p^* + \rho_n^*) \pm (\rho_p^* - \rho_n^*) \right] (\omega^2 - \vec{k}^2),$$ (4)
FIG. 3: (Color online) The masses of the $D^+$ and $D^{*+}$ mesons are plotted for $\rho_B = \rho_0$ in magnetized symmetric nuclear matter ($\eta = 0$) in (b) and (d) as functions of $eB/m^2_\pi$, including the magnetic catalysis (MC) effect, and, compared with the masses when without accounting for MC effect (shown in (a) and (c)). The masses are plotted with and without PV ($D^+ - D^{*+}$ mixing effect, accounting for the AMMs of the nucleons. These are compared with the cases when the AMMs of the nucleons are not considered (shown as dotted lines).
FIG. 4: (Color online) Same as fig 3 for $\eta=0.5$. 

and

$$
\Pi(\omega, |\vec{k}|) = -\frac{1}{4f_D^2} \left[ 3(\rho_p + \rho_n) \pm (\rho_p - \rho_n) \right] \omega 
+ \frac{m_D^2}{2f_D} (\sigma' + \sqrt{2}\zeta_c' \pm \delta') 
+ \left[ -\frac{1}{f_D} (\sigma' + \sqrt{2}\zeta_c' \pm \delta') + \frac{d_1}{2f_D^2} (\rho_p^s + \rho_n^s) 
+ \frac{d_2}{4f_D^2} \left( (\rho_p^s + \rho_n^s) \pm (\rho_n^s - \rho_p^s) \right) (\omega^2 - \vec{k}^2) \right], \tag{5}
$$

where the $\pm$ signs refer to the $D^0$ and $D^+$ respectively in equation (4) and to the $\bar{D}^0$ and $D^-$ respectively in equation (5). In equations (4) and (5), $\sigma'(= (\sigma - \sigma_0))$, $\zeta_c'(= (\zeta_c - \zeta_{c0}))$ and $\delta'(= (\delta - \delta_0))$ are the fluctuations of the scalar-isoscalar fields $\sigma$ and $\zeta_c$, and the third
component of the scalar-isovector field, \( \delta \), from their vacuum expectation values.

The values of the scalar meson fields \( \sigma \), \( \zeta \), \( \delta \) are obtained by solving their coupled equations of motion. In the present work, as has already been mentioned, the contribution of the Dirac sea to the self energy of the nucleon is taken into account through the summation of the nucleon tadpole diagrams, which are incorporated into the equations of motion of the fields \( \sigma \), \( \zeta \) and \( \delta \). These, along with the dilaton field, \( \chi \), are calculated for a given baryon density, \( \rho_B \), given isospin asymmetry, \( \eta = (\rho_n - \rho_p)/(2\rho_B) \), where \( \rho_{p,n} \) are the number densities of the proton and neutron respectively. Accounting for the lowest Landau level (LLL) contributions for the charged open charm mesons, the effective mass of \( D^\pm \) is given as

\[
m_{D^\pm}^{\text{eff}} = \sqrt{m_{D^\pm}^* + |eB|},
\]

whereas for the neutral \( (D^0 \text{ and } \bar{D}^0) \) mesons, the effective masses are given as

\[
m_{D^0(\bar{D}^0)}^{\text{eff}} = m_{D^0(\bar{D}^0)}^*.
\]

In equations (6) and (7), \( m_{D^\pm,D^0,\bar{D}^0}^* \) are the masses calculated using the chiral effective model, as the solutions for \( \omega \) at \( |\vec{k}| = 0 \), of the dispersion relations for these mesons given by equation (3).

The masses of the charged vector open charm \( (D^* \text{ and } \bar{D}^*) \) mesons, retaining the lowest Landau level contributions \( (n=0) \), depend on \( S_z \) (the z-component of the spin vector) and are given as

\[
m_{D^*\pm}^{\text{eff}} = \sqrt{m_{D^*\pm}^* + |eB| + gS_z|eB|},
\]

whereas for the neutral \( D^{*0} \) and \( \bar{D}^{*0} \), the in-medium masses are given as

\[
m_{D^*(\bar{D}^*)}^{\text{eff}} = m_{D^*(\bar{D}^*)}^*.
\]

It is assumed that the mass shifts of the vector open charm \( (D^* \text{ and } \bar{D}^*) \) mesons (which have same quark-antiquark constituents as \( D \) and \( \bar{D} \) mesons) are identical to the mass shifts of the pseudoscalar mesons \( D \) and \( \bar{D} \) mesons, calculated within the chiral effective model [28]. This is in line with the QMC model where the masses of the hadrons are obtained from the modification of the scalar density of the light quark (antiquark) constituent of the hadron [1]. The in-medium mass of the vector open charm mesons are thus assumed to be

\[
m_{D^*(\bar{D}^*)}^* - m_{D^*(\bar{D}^*)}^{\text{vac}} = m_{D(\bar{D})}^* - m_{D(\bar{D})}^{\text{vac}},
\]
FIG. 5: (Color online) The masses of the $D^0$ and $D^{*0}$ mesons are plotted for $\rho_B = \rho_0$ in magnetized symmetric nuclear matter ($\eta=0$) in (b) and (d) as functions of $eB/m_{\pi}^2$, including the magnetic catalysis (MC) effect, and, compared with the masses when without accounting for MC effect (shown in (a) and (c)). The masses are plotted with and without PV ($D^0 - D^{*0}$ mixing effect, accounting for the AMMs of the nucleons. These are compared with the cases when the AMMs of the nucleons are not considered (shown as dotted lines).

for which there are additional Landau level contributions for the charged $D^{*\pm}$ mesons, as given by equation (8). In the presence of an external magnetic field, there is also mixing of the pseudoscalar and the longitudinal component ($S_z=0$) of the vector meson. Its effect on the masses of the open charm mesons is also studied in the present work.

The mixing between the pseudoscalar and the longitudinal component of the vector (PV
mixing) mesons in the presence of a magnetic field, is observed to lead to appreciable modifications to their masses [10–14, 27–30]. In the present work of the study of the in-medium masses of the open charm mesons, the PV mixing effects for the neutral open charm mesons ($D^0 - D^{0||}$ and $\bar{D}^0 - \bar{D}^{0||}$ mixings) as well as the charged mesons ($D^+ - D^{*+||}$ and $D^- - D^{*-||}$ mixings) are considered. The PV mixing is taken into account through a phenomenological Lagrangian, which was used to study the mixing ($J/\psi - \eta_c$ and $\psi(2S) - \eta_c(2S)$) of the charmonium states. The modifications of the masses of the charmonium states in magnetized nuclear matter, due to $J/\psi - \eta_c$, $\psi(2S) - \eta_c(2S)$ and $\psi(1D) - \eta_c(2S)$ [27]. The effects on the decay width $\psi(3770) \rightarrow D\bar{D}$ were observed quite appreciable due to the $\psi(1D) - \eta_c(2S)$ mixing [27], as well as due to the PV mixing of the open charm ($D(\bar{D}) - D^{*}(\bar{D}^*)$ mesons.
FIG. 7: (Color online) The masses of the $D^-$ and $D^{*-}$ mesons are plotted for $\rho_B = \rho_0$ in magnetized symmetric nuclear matter ($\eta = 0$) in (b) and (d) as functions of $eB/m_\pi^2$, including the magnetic catalysis (MC) effect, and, compared with the masses when without accounting for MC effect (shown in (a) and (c)). The masses are plotted with and without PV ($D^- - D^{*-}$ mixing effect, accounting for the AMMs of the nucleons. These are compared with the cases when the AMMs of the nucleons are not considered (shown as dotted lines).

[28]. The $PV\gamma$ interaction Lagrangian given as,

$$\mathcal{L}_{PV\gamma} = \frac{g_{PV\gamma}}{m_{av}} e \tilde{F}_{\mu\nu}(\partial^\mu P)V^\nu, \quad \text{(11)}$$

where P and $V^\mu$ represent the pseudoscalar and the vector fields, respectively, $\tilde{F}_{\mu\nu}$ is the dual field strength tensor of the external magnetic field and and $m_{av}$ is the average of the masses of the pseudoscalar and vector mesons, $(m_{av} = (m_P + m_V)/2)$. $g_{PV}$ is the coupling
constant for the radiative decay, $V \to P \gamma$. The value of the coupling parameter, $g_{PV, \gamma}$ is fixed from the observed decay width of $V \to P \gamma$. The masses of the pseudoscalar and the longitudinal component of the vector meson, due to the PV mixing are given as

$$m^2_{V,\pm,P} = M^2_{\pm} + \frac{c_{PV}^2 m^2_{av}}{m^2_{av}} \pm \sqrt{M^4_{\pm} + \frac{2c^2_{PV} M^2_{\pm}}{m^2_{av}} + \frac{c^4_{PV}}{m^4_{av}}} \tag{12}$$

with $M^2_{\pm} = m^2_{V,\pm} \pm m^2_{P,\pm}$ and $c_{PV} = g_{PV,\gamma} eB$; with $m^2_{V,\pm,P}$ are the effective masses of the vector and pseudoscalar mesons. These effective masses, given by (6), (7), (8) and (9), include the effects of the Dirac sea calculated in the chiral effective model, with additional contributions due to the lowest Landau level contributions for the charged mesons.
FIG. 9: (Color online) The masses of the $\bar{D}$ and $\bar{D}^*$ mesons are plotted for $\rho_B = \rho_0$ in magnetized symmetric nuclear matter ($\eta=0$) in (b) and (d) as functions of $eB/m^2_\pi$, including the magnetic catalysis (MC) effect, and, compared with the masses when without accounting for MC effect (shown in (a) and (c)). The masses are plotted with and without PV ($\bar{D} - \bar{D}^*$ mixing effect, accounting for the AMMs of the nucleons. These are compared with the cases when the AMMs of the nucleons are not considered (shown as dotted lines).

III. RESULTS AND DISCUSSIONS

In the present work, we study the effects of magnetic field on the pseudoscalar ($D$ and $\bar{D}$) and vector ($D^*$ and $\bar{D}^*$) open charm mesons in magnetized (nuclear) matter. The in-medium masses are calculated using a chiral effective model for the $D$ and $\bar{D}$ mesons due to their
interactions with the nucleons and the scalar mesons, including the Dirac sea contributions, with additional Landau level contributions for the charged $D^\pm$ mesons. It might be noted here the neutron, which is electrically charge neutral, interacts with the magnetic field only due to its non-zero value of the anomalous magnetic moment. The effects of the magnetic field on the masses are computed for zero baryon density as well as, for $\rho_B = \rho_0$, the nuclear matter saturation density, The effects of isospin asymmetry as well as anomalous magnetic moments (AMMs) of the nucleons are also studied in the present work. The Dirac sea contributions lead to increase in the values of the scalar fields, $\sigma(\sim \langle \bar{u}u \rangle + \langle \bar{d}d \rangle)$ and $\zeta(\sim \langle \bar{s}s \rangle)$, leading to decrease in the nucleon self energy, i.e., enhancement of the light quark condensates (an effect called magnetic catalysis), as compared to when this effect
is not considered. The values (in MeV) of $\sigma$ and $\zeta$ are modified from the zero baryon density and zero magnetic values of $-93.3$ and $-106.6$ to $-96.7(-105.7)$ and $-108(-111.3)$ for $eB = 5m_\pi^2$, without (with) accounting for the AMMs of the nucleons. The masses are plotted for the cases of including (excluding) the PV mixing. The PV ($D - D^*$ and $\bar{D} - \bar{D}^*$) mixing result in a drop (increase) in the of the $D(D^*)$ as well as $\bar{D}(\bar{D}^*)$ meson.

In figures [1] and [2] at zero baryon density, the masses of the charged and neutral pseudoscalar and vector mesons are plotted accounting for the magnetic catalysis as well as PV mixing effects. These are plotted accounting for the AMMs of the nucleons and compared to the cases when the AMMs are not taken into account (shown as dotted lines). The masses for $D^\pm$ are observed to be identical to each other (so also for the neutral sector, $D^0$ and $\bar{D}^0$ mesons). This can be understood from the dispersion relations of the $D$ and $\bar{D}$ mesons given by (3), (4) and (5). For $\rho_B = 0$ (hence $\rho_p$ and $\rho_n$ are both zero), and the Weinberg-Tomozawa contribution is zero. The effective masses of $D^*(\bar{D}^*)$ mesons, which are calculated, using equation (10) are also identical within the charged as well as neutral sectors. The effects of the AMMs observed to be appreciable as compared to when these are not accounted for. It was difficult to find solutions for the scalar fields with AMM effects for $eB$ higher than around $5m_\pi^2$.

Figures [3] and [4] show the effects of the magnetic catalysis as well as the PV mixing on the masses of $D^+$ and $D^{*+}$ mesons for the isospin symmetric and asymmetric (with $\eta=0$) nuclear matter in (b) and (d) and compared with the case when the Dirac sea effect is not taken into account (shown in (a) and (c) respectively). In the ‘no sea’ approximation, the mass calculated within the chiral effective model is observed to be extremely insensitive to the change in magnetic field in the absence of Landau level contributions. The increase in the masses of $D^+$ and $D^{*+\parallel}(S_z=0)$ are due to the positive Landau contributions. The effect of Dirac sea is observed to be quite large, as compared to the effects from the PV mixing, at high values of the magnetic field. With PV mixing, but in the ‘no sea’ approximation, the mass (in MeV) of $D^+(D^{*+})$ is modified from 1824.3 (1989) to around 1949 (2111) at $eB = 10m_\pi^2$, when the Dirac sea contributions are considered. The in-medium mass (in MeV) of $D^+(D^{*+})$ at $\eta = 0.5$, plotted in fig [4] is observed to be around 2164 (2322.7) at $eB = 10m_\pi^2$, which is much larger than the $\eta = 0$ value, with the MC as well as PV mixing effects. The effects of AMM are observed not as much appreciable.

In figures [5] and [6] the effects of the MC and PV mixing are shown on the masses are
plotted for $D^0$ and $D^{*0}$ mesons for $\rho_B = \rho_0$ and for $\eta = 0$ and $\eta = 0.5$ respectively. Similar to
the case of $D^+$ and $D^{*+}$, the Dirac sea contributions have a significant effect on the masses
of these neutral open charm mesons.

The masses of the $\bar{D}$ and $\bar{D}^*$ mesons are plotted for the charged sector in figures [7] and [8] and for the neutral sector in figures [9] and [10] for $\eta = 0$ and $\eta = 0.5$ respectively. It is
observed that the most dominant contribution due to the magnetic field on the masses of
the open charm mesons arise from the effects of the Dirac sea.

IV. SUMMARY

To summarize, we have investigated the effects of magnetic field on the masses of the
open charm pseudoscalar ($D$ and $\bar{D}$) and vector ($D^*$ and $\bar{D}^*$) in magnetized (nuclear) mat-
ter, accounting for the effects from the Dirac sea, PV mixing and additional Landau level contributions for the charged mesons. The effects of the Dirac sea is observed to lead to
an enhancement of the quark condensates, an effect called magnetic catalysis, which is ob-
served as an increase in the magnitude of the scalar fields, $\sigma$ and $\zeta$. The effects of isospin
asymmetry as well as AMMs of the nucleons are also studied in the present work. The
effects of the Dirac sea contribution on the masses of the open charm mesons is observed
to be the most dominant effect due to the magnetic field, the effect being much larger than
the PV mixing. The effect should modify the yields pf the open and hidden charm mesons
arising from ultra-relativistic peripheral heavy ion collision experiments, where the created
magnetic field is huge.

[1] A. Hosaka, T. Hyodo, K. Sudoh, Y. Yamaguchi, S. Yasui, Prog. Part. Nucl. Phys. 96, 88
(2017).

[2] D. Kharzeev, K. Landsteiner, A. Schmitt, and H.-U. Yee, Lect. Notes Phys. 871, 1 (2013).

[3] D. Kharzeev, Ann. Phys. (N.Y.) 325, 205 (2010); K. Fukushima, M. Ruggieri, and R. Gatto,
Phys. Rev. D 81, 114031 (2010).

[4] M.N. Chernodub, Lect. Notes Phys. 871, 143 (2013); A. J. Mizher, M.N. Chenodub, and E.
Fraga, Phys. Rev. D 82, 105016 (2010).

[5] F. Preis, A. Rebhan, and A. Schmitt, Lect. Notes Phys. 871, 51 (2013).
[6] D. P. Menezes, M. Benghi Pinto, S. S. Avancini, and C. Providencia, Phys. Rev. C 80, 065805 (2009); D.P. Menezes, M. Benghi Pinto, S. S. Avancini, A. P. Martinez, and C. Providencia, Phys. Rev. C 79, 035807 (2009).

[7] Igor Shovkovy, arXiv:1207.5081 [hep-ph] (2012).

[8] Alexander Haber, Florian Preis, and Andreas Schmitt, Phys. Rev. D 90, 125036 (2014).

[9] Arghya Mukherjee, Snigdha Ghosh, Mahatsab Mandal, Sourav Sarkar, and Pradip Roy, Phys. Rev. D 98, 056024 (2018).

[10] P. Gubler, K Hattori, S.H. Lee, M. Oka, S. Ozaki and K. Suzuki, Phys. Rev. D 93, 054026 (2016).

[11] S. Cho, K. Hattori, S. H. Lee, K. Morita and S. Ozaki, Phys. Rev. Lett. 113, 122301 (2014).

[12] S. Cho, K. Hattori, S. H. Lee, K. Morita and S. Ozaki, Phys. Rev. D 91, 045025 (2015).

[13] K. Suzuki and S. H. Lee, Phys. Rev. C 96, 035203 (2017).

[14] J. Alford and M. Strickland, Phys. Rev. D 88, 105017 (2013).

[15] A. Mishra, E. L. Bratkovskaya, J. Schaffner-Bielich, S.Schramm and H. Stöcker, Phys. Rev. C 69, 015202 (2004).

[16] Amruta Mishra and Arindam Mazumdar, Phys. Rev. C 79, 024908 (2009).

[17] Arvind Kumar and Amruta Mishra, Phys. Rev. C 81, 065204 (2010).

[18] Arvind Kumar and Amruta Mishra, Eur. Phys. A 47, 164 (2011).

[19] Divakar Pathak and Amruta Mishra, Adv. High Energy Phys. 2015, 697514 (2015).

[20] Divakar Pathak and Amruta Mishra, Phys. Rev. C 91, 045206 (2015).

[21] Divakar Pathak and Amruta Mishra, Int. J. Mod. Phy. E 23, 1450073 (2014).

[22] Amruta Mishra and Divakar Pathak, Phys. Rev. C 90, 025201 (2014).

[23] Sushruth Reddy P, Amal Jahan CS, Nikhil Dhale, Amruta Mishra, J. Schaffner-Bielich, Phys. Rev. C 97, 065208 (2018).

[24] Nikhil Dhale, Sushruth Reddy P, Amal Jahan CS, Amruta Mishra, Phys. Rev. C 98, 015202 (2018).

[25] Amal Jahan CS, Nikhil Dhale, Sushruth Reddy P, Shivam Kesarwani, Amruta Mishra, Phys. Rev. C 98, 065202 (2018).

[26] A. Mishra , A. Jahan CS , S. Kesarwani , H. Raval , S. Kumar, and J. Meena , Eur. Phys. J. A 55,99 (2019).

[27] Amruta Mishra, S.P. Misra, Phys. Rev. C 102, 045204 (2020).
[28] Amruta Mishra and S. P. Misra, Int. Jour. Mod. Phys. E 30, 2150064 (2021).
[29] Amruta Mishra, S.P. Misra, Int. Jour. Mod. Phys. E 31, 2250060 (2022).
[30] Sachio Iwasaki, Makoto Oka, Kei Suzuki, Eur. Phys. J. A 57 222 (2021).