In-medium decay widths of charm mesons in magnetized nuclear matter - effects of magnetic catalysis

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Abstract

We investigate the effects of magnetic catalysis on the hadronic decays of $D^* \rightarrow D \pi$ ($\bar{D}^* \rightarrow \bar{D} \pi$) and $\Psi(3770) \rightarrow D \bar{D}$ within the magnetized nuclear medium, by using the $^3P_0$ model. The in-medium masses of the open charm mesons are calculated within the chiral effective model in terms of the medium modified scalar and number densities of the nucleons, and the scalar fields fluctuations. Apart from the Landau quantization of the charged protons in the magnetized nuclear matter, the effects of the magnetized Dirac sea is also incorporated, which results in the phenomenon of magnetic catalysis. Magnetic catalysis leads to the enhancement of QCD condensates with increasing magnetic field. Anomalous magnetic moments of the nucleons are considered in the calculation of magnetic fields effects on the Fermi and Dirac sea of nucleons. Effects of magnetic fields are also taken into account through the lowest Landau level contribution of the charged open charm mesons. The strong magnetic field causes modifications to occur due to the mixing of the pseudoscalar $D$ ($\bar{D}$) and the longitudinal component of the vector $D^*_{||}$ ($\bar{D}^*_{||}$) mesons, with the additional contribution from the lowest Landau level for the charged $D$ mesons. For the charmonium state, $\Psi(3770)$, the effects of magnetic catalysis are incorporated on the mass modifications through the medium modified scalar dilaton field, $\chi$, which in turn mimics the gluon condensates of QCD, within the chiral effective model. The effects of pseudoscalar and vector mesons mixing are considered on the decay widths of $\Psi(3770) \rightarrow D \bar{D}$. There are observed to be significant modifications in the partial decay widths due to the effects of magnetic catalysis on the masses of initial and final state particles. The modifications in the decay widths can have impact on the production of the open charm and charmonium mesons in the non-central, ultra-relativistic heavy ion collision experiments, where produced magnetic field is very large.

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I. INTRODUCTION

Open charm mesons consist of a quark (antiquark) belonging to the charm (c) flavor and an antiquark (quark) from the light quark flavor sector. The estimation of the strong magnetic fields produced in the peripheral ultra-relativistic heavy ion collision experiments at LHC in CERN and at RHIC in BNL [1–5], has initiated the study of the hadron properties in the presence of magnetic fields [6]. The experimental observables from the relativistic heavy ion collision experiments are related to the medium modifications of the hadrons. There is a profuse production of the open heavy flavour mesons and the quarkonium in the early phase of these collisions. The increase of the chiral condensate with magnetic field is called the magnetic catalysis [7–9]. In the literature, there have been studies of the magnetic catalysis properties on quark matter in the Nambu Jona Lasinio model [10–14]. The effects of magnetic catalysis have been studied on the nuclear matter phase transition using the Walecka model and an extended linear sigma model in [15], resulting in the increasing nucleon mass with magnetic field at zero density, zero magnetic moments. There the magnetic catalysis effect was observed indirectly through the scalar field dependency of the nucleon mass \( M_N = m_N - g_{\sigma}\sigma \). In [16], the effects of magnetized Dirac sea have been studied under the weak-field approximation in presence of a constant, external background magnetic field. An increase of nucleon mass with magnetic field was observed in the Walecka model at zero density, with significant contribution from the anomalous magnetic moments of the Dirac sea of nucleons. At finite temperature, an inverse magnetic catalysis [17] effect was observed on the critical temperature of nuclear matter phase transition. In the literature, a few number of studies are there on the magnetized Dirac sea effects on the nuclear matter properties. The magnetized Dirac sea effects have been studied on the in-medium masses of the open charm (bottom) [18, 19] and the ground states of heavy quarkonia [20], in the magnetized nuclear matter. The masses of the heavy quarkonia were calculated in the QCD sum rule approach by using the medium modified quark and gluon condensates in terms of the scalar fields calculated within the chiral \( SU(3) \) model. On the other hand, the in-medium masses of the open heavy flavor mesons are obtained by solving their corresponding dispersion relations in terms of the number and scalar densities of the nucleons and the scalar fields fluctuations within the chiral effective model. The effects of magnetic catalysis are incorporated through summation over the nucleon tadpole diagrams with the magnetized
fermion propagators of the Dirac sea of nucleons. The scalar fields of the chiral effective model correspond to the QCD condensates (scalar, isoscalar, $\sigma \sim \langle \bar{u}u \rangle$, scalar, isovector, $\delta \sim (\langle \bar{u}u \rangle - \langle \bar{d}d \rangle)$ etc.) Thus, the increasing values of the scalar fields with the magnetic field, indicate indirectly a catalysis effect, which are studied on the masses of the heavy flavor mesons. Open charm mesons can be important tools in probing the magnetic catalysis, and other hadronic properties. $D$ and $D^*$ mesons are the pseudoscalar and vector open charm mesons, respectively, comprising of a charm quark (antiquark) and a light (u,d) antiquark (quark). We investigate the effects of a magnetic field on the decay widths of the vector meson ($D^*$) going to pseudoscalar mesons ($D$ and $\pi$) and the charmonium states $\Psi(3770)$ going to $D \bar{D}$, by using their masses in the magnetized nuclear matter, accounting for the magnetic field modified Dirac sea effects. 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. Time evolution of the produced field created in such high energy heavy ion collision is still an open question, needs further solutions of the magnetohydrodynamic equations with the proper estimation of the electrical conductivity of the medium [4]. Heavy quarkonia and open heavy flavor mesons (Open Charm mesons in this case) are produced in the early stages of the collisions, and as such are more sensitive to the magnetic field.

The in-medium masses of the heavy flavor mesons are calculated in the magnetized nuclear matter by using the chiral effective model approach in the absence of magnetic catalysis [21,23]. The hadronic decay widths have been calculated using the $^3P_0$ model [24,33]. In the $^3P_0$ model, a light quark-antiquark pair is created in the $^3P_0$ state (with quantum numbers similar to that of vacuum, $J^{PC} = 0^{++}$), and this light quark (antiquark) combines with the heavy charm antiquark (light quark (u or d)) of the decaying $D^*$ state at rest, resulting in the production of the open charm, $D$ meson and a light flavor meson, the $\pi$ meson [34,35]. The matrix element for the decay of the $D^*$ meson state depends on the momentum $|p|$ of the outgoing daughter meson states. The in-medium partial decay widths of charmonium (bottomonium) going to open charm (bottom) mesons (for e.g., $\Psi(3770) \rightarrow D \bar{D}$ and $\Upsilon(4S) \rightarrow B \bar{B}$ ) have been studied using a field theoretic model for composite hadrons with quark (and antiquark) constituents [36,38,45], as well as within a light quark-antiquark pair creation model or the $^3P_0$ model [37], in presence of an external magnetic field, without accounting for the Dirac sea effects. The PV mixing effects between
the longitudinal component of the vector and the pseudoscalar charm (bottom) mesons at finite magnetic field, have been studied \cite{36, 38, 48} without considering the magnetic catalysis effect and in \cite{18, 20} including the catalysis effect for the heavy quarkonia and open heavy flavor mixing. Effects of magnetic fields on the masses and hence on the decays, are seen to be dominant through the PV mixing effects. The in-medium hadronic decays of the vector open charm meson, $D^* \to D\pi$ ($\bar{D}^* \to \bar{D}\pi$) have also been studied incorporating the PV mixing effects between $D - D^{*\parallel}$ ($\bar{D} - \bar{D}^{*\parallel}$) and the lowest Landau level (LLL) contributions for the charged mesons at finite magnetic field, without considering the effects of magnetic catalysis on their masses \cite{36}.

We organize the paper as follows: In section II, we discuss in detail the lowest Landau level contribution on the masses of the charged mesons. The Pseudoscalar-Vector (PV) mixing in the presence of an external magnetic field is described by the effective Lagrangian approach in section III. In-medium masses of the open charm and charmonium, within the chiral effective model are discussed in section IV. In section V, using the $^3P_0$ model, the decays of the vector $D^*$ and $\Psi(3770)$ mesons are described. In section VI, we present the results of the current investigation. In section VII we summarize the findings of this work.

II. LOWEST LANDAU LEVEL CONTRIBUTION

We investigate the effects of a uniform magnetic field on the masses of the open charm ($D, D^*$) mesons. The charged $D$ ($D^\pm$) and $D^*$ ($D^{*\pm}$) mesons receive contributions from the lowest Landau level (LLL) at finite magnetic field. The external magnetic field contributes to the energy of the pseudoscalar and vector mesons as \cite{40},

$$E_P(n, p_z) = \sqrt{m_P^2 + (2n + 1)|eB| + p_z^2}$$ \hspace{1cm} (1)

$$E_V(n, p_z) = \sqrt{m_V^2 + (2n + 1)|eB| + p_z^2 + gS_z|eB|}$$ \hspace{1cm} (2)

Here the Landau levels are indicated by the integer ($n \geq 0$), $z$-component of momentum as $p_z$, $z$-component of the spin quantum number as $S_z$. We assume that the external magnetic field is along the $z$-direction (Momentum in the x-y plane is discretized, momentum along the z-direction is unaffected). We consider $g$, the Lande $g$-factor is equal to 2 (Not considering the case of Anomalous Magnetic Moment). For strong magnetic fields, and assuming $p_z$ is
very small, equations (1) and (2) modify into -

\[ E_P = \sqrt{m_P^2 + |eB|} \]  

for the pseudoscalar mesons, and

\[ E_{V_{\perp}} = \sqrt{m_V^2 + 3|eB|}, \quad S_z = +1 \]  
\[ E_{V_{\parallel}} = \sqrt{m_V^2 + |eB|}, \quad S_z = 0 \]  
\[ E_{V_{\perp-1}} = \sqrt{m_V^2 - |eB|}, \quad S_z = -1 \]

for the transverse \((V_{\perp1, -1})\) and longitudinal \((V_{\parallel})\) components of the vector mesons. In writing the above expressions for the LLL contribution, the internal structure of the charged mesons are neglected [45, 49]. Due to the strong external magnetic field, the triplet vector meson states which were degenerate, have now split into three distinct energy levels.

III. PSEUDOSCALAR-VECTOR MIXING

The vector \(D^* [\Psi(3770)]\) and the pseudoscalar \(D [\eta_c(2S)]\) mesons interact via an effective interaction vertex. The z-component of the spin can exist as a good quantum number for the meson system [40] [41]. The vector meson, with the spin polarization along the direction of an external magnetic field, is called the longitudinal component of the vector meson state. Mixing occurs between the longitudinal component of the vector meson and the pseudoscalar meson. The effective interaction vertex accounting for this mixing effect is [18] [20] [36] [38] [40],

\[ \mathcal{L}_{PV\gamma} = \frac{g_{PV}}{m_{av}} e \tilde{F}_{\mu\nu}(\partial^\mu P) V^\nu. \]  

\(P\) and \(V^\mu\) represent the pseudoscalar and the vector fields, respectively. \(\tilde{F}_{\mu\nu}\) and \(m_{av}\) are the dual field strength tensor of the external magnetic field and the average mass \((m_{av} = (m_P + m_V)/2)\). The coupling constant, \(g_{PV}\) in equation (7), is fitted from the observed values of the corresponding radiative decay widths, given by,

\[ \Gamma_{V \rightarrow P + \gamma} = \frac{1}{12\pi} \frac{e^2 g_{PV}^2 \bar{p}^3}{m_{av}^2} \]

with \(\bar{p} = (m_V^2 - m_P^2)/2m_V\) is the magnitude of the center of mass momentum of the products in the final state. The masses of the pseudoscalar and the longitudinal component of the
vector mesons undergo a Pseudoscalar-Vector (PV) mixing, thereby causing a mass shift in the $[D - D^{*\parallel} (\bar{D} - \bar{D}^{*\parallel})]$ and $[\Psi(3770) - \eta_c(2S)]$ meson states as follows

$$m_{V,P}^2 = \frac{1}{2} \left( M_\pm^2 + \frac{c_{PV}^2 m_{av}^2}{m_{av}^2} \pm \sqrt{M_\pm^4 + \frac{2 c_{PV}^2 M_\pm^2}{m_{av}^2} + \frac{c_{PV}^4}{m_{av}^4}} \right)$$

(9)

with $M_\pm^2 = m_{V,\pm}^2 \pm m_{P}^2$ and $c_{PV} = g_{PV} eB$; with $m_{V,P}^*$ are the effective vector and pseudoscalar meson masses in the magnetized nuclear medium as will be explained in the next section, with the additional contribution from the lowest Landau level for the charged mesons, as given in equations (3)-(6). Equation (9) can also be written as

$$m_{V,P}^2 = m_{V,P}^* \pm \frac{c_{PV}^2}{M_\pm^2}$$

(10)

by considering the terms up to the second order in $c_{PV}$ and leading order in $(m_V - m_P)/2m_{av}$.

The total decay width for the neutral meson, viz. the $D^{*0}$ meson, has not been measured. However, the branching ratio for $\Gamma(D^{*0} \rightarrow D^0\pi^0): \Gamma(D^{*0} \rightarrow D^0\gamma) = 64.7 : 35.3$, is known [50]. Hence, the coupling constant involved in the radiative decay width can be obtained if the coupling constant of $(D^{*0} \rightarrow D^0\pi^0)$ is known. From isospin symmetry considerations, this coupling constant can be related to the corresponding charged mesons $(D^{*\pm})$ decay modes as follows [40],

$$g[D^{*0} \rightarrow D^0 + \pi^0] = \frac{1}{\sqrt{2}} g[D^{*+} \rightarrow D^0 + \pi^+]$$

(11)

$$g[D^{*0} \rightarrow D^0 + \pi^0] = g[D^{*+} \rightarrow D^+ + \pi^0]$$

(12)

Similarly for their charge conjugate modes. In this way, the coupling constant for the radiative decay width and the PV mixing parameter for the neutral D mesons can be obtained. The coupling constant $g$ is fitted from the measured decay width $\Gamma[D^* \rightarrow D\pi]$ in vacuum.

IV. IN-MEDIUM MASSES OF CHARMONIUM AND OPEN CHARM MESONS

An effective chiral model Lagrangian is applied to study the in-medium masses of charmonium and open charm mesons in asymmetric nuclear matter in the presence of strong magnetic field. The original version of the chiral $SU(3)_L \times SU(3)_R$ model is based on the non-linear realization of chiral symmetry [51–53] and broken scale invariance of QCD [54–56], which occurs through a logarithmic potential given in terms of a scalar dilaton field, $\chi$ [57]. The generalized Lagrangian density is written as [55]
\[ \mathcal{L} = \mathcal{L}_{\text{kin}} + \mathcal{L}_{BM} + \mathcal{L}_{\text{vec}} + \mathcal{L}_0 + \mathcal{L}_{SB} + \mathcal{L}_{\text{scalebreak}} + \mathcal{L}_{\text{mag}} \]  

\( \mathcal{L}_{\text{kin}} \) represents the kinetic energy of the baryons and the mesons. \( \mathcal{L}_{BM} \) gives the baryon-meson interaction, \( \mathcal{L}_{\text{vec}} \) refers to the interactions of the vector mesons, \( \mathcal{L}_0 \) is the meson-meson interaction, \( \mathcal{L}_{SB} \) is the explicit chiral symmetry breaking term. \( \mathcal{L}_{\text{scalebreak}} \) is a scale invariance breaking logarithmic potential given in terms of a scalar dilaton field. \( \mathcal{L}_{\text{mag}} \) is the contribution from the magnetic field \[21, 23, 58, 60\].

\[ \mathcal{L}_{\text{mag}} = -\bar{\psi}_i q_i \gamma_\mu A^\mu \psi_i - \frac{1}{4} \kappa_N \bar{\psi}_i \gamma_\mu \gamma_5 F^\mu_\nu \psi_i - \frac{1}{4} F^\mu_\nu F_{\mu\nu} \]  

where, \( \psi_i \) is the field operator for the \( i^{th} \) baryon (i = p, n, for nuclear matter, as considered in the present work). The values of \( \kappa_p \) and \( \kappa_n \) 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 (tensorial interaction with the electromagnetic field) respectively. In the magnetized nuclear medium, the magnetic field contribution occurs through the Landau energy levels of the charged particles and through the anomalous magnetic moment of the nucleons. The magnetic field dependent Dirac sea contribution to the self energy of the nucleons is incorporated through the scalar densities of the proton and the neutrons \[18, 20\] in the context of the chiral model.

The Lagrangian density is written as per the chiral SU(3) model in the mean field approximation. The scalar fields are solved from the coupled equations of motion, derived from the Lagrangian density under mean field approximation. In-medium masses of the open charm mesons in magnetized asymmetric nuclear matter in presence of strong magnetic field is obtained using the chiral effective model by generalizing the chiral SU(3) to chiral SU(4) and deriving interactions of the charmed mesons with the light hadronic sector \[18, 21, 62, 63\]. Dispersion relations for the open charm mesons viz., \( D \) (\( D^+, D^0 \)) and \( \bar{D} \) (\( D^-, D^0 \)) are obtained from the Fourier transform of the equation of motion of these mesons from the chiral effective Lagrangian \[18, 21\]. Besides, they also incur additional mass shifts from the lowest Landau levels (for the charged mesons). The medium modification of the dilaton field gives the modification in the gluon condensate, which causes modification in the charmonium mass in the presence of strong magnetic field \[22, 61, 62\].
\[ \Delta m_\Psi = \frac{4}{81} (1 - d) \int dk^2 \left\langle \left| \frac{\partial \psi(\vec{k})}{\partial \vec{k}} \right|^2 \right\rangle \frac{k}{k^2/m_c + \epsilon (\chi^4 - \chi_0^4)} \]  

\hspace{1cm} (15)

with

\[ \left\langle \left| \frac{\partial \psi(\vec{k})}{\partial \vec{k}} \right|^2 \right\rangle = \frac{1}{16\pi} \int \left| \frac{\partial \psi(\vec{k})}{\partial \vec{k}} \right|^2 d\Omega \]  

\hspace{1cm} (16)

Where, \( m_c \), the charm quark mass is taken to be 1.95 GeV \[22\], \( m_\Psi \) is the vacuum mass of the given charmonium state, and \( \epsilon = 2m_c - m_\Psi \) is the binding energy; \( \Psi(\vec{k}) \) is the wave function of the charmonium state in momentum space. The Gaussian form of the wave functions in coordinate space are given in \([22, 34, 62]\).

V. THE \( ^3P_0 \) MODEL

In this section we discuss the hadronic decay widths of \((D^* \rightarrow D\pi, \bar{D}^* \rightarrow \bar{D}\pi)\) and \((\Psi(3770) \rightarrow DD)\), by taking into account the internal structures of the parent and the outgoing mesons using the \( ^3P_0 \) model \[34\].

A. Decay of the Open Charm mesons

The uniform magnetic field results in the mass modification of the \((D, D^*)\) mesons. This modifies the resulting decay widths for the various channels. From the \( ^3P_0 \) model, the decay width of the vector open charm meson, \( D^* \) going to \( D\pi \) is given by \[31, 34, 37\]:

\[ \Gamma_{D^* \rightarrow D\pi} = \sqrt{\pi} E_D E_\pi \gamma^2 2^8 r^3 (1 + r^2)^2 x^3 \exp \left( - \frac{x^2}{2(1 + 2r^2)} \right) \]  

\hspace{1cm} (17)

In this expression, \( m_{D^*} \) is the mass of the parent \( D^* \) meson. \( E_D \) and \( E_\pi \) are the energies of the outgoing \( D \) and \( \pi \) mesons respectively;

\[ E_D = (p^2 + m_D^2)^{1/2}; \quad E_\pi = (p^2 + m_\pi^2)^{1/2} \]  

\hspace{1cm} (18)

with \( m_D \), the modified \( D \) meson mass and \( m_\pi \) as the \( \pi \) meson mass. \( p \) is the 3-momentum in the center of mass (c.o.m) frame.

\[ p = \left[ \frac{m_{D^*}^2}{4} - \frac{m_D^2 + m_\pi^2}{2} - \frac{(m_D^2 - m_\pi^2)^2}{4m_{D^*}^2} \right]^{1/2} \]  

\hspace{1cm} (19)
γ is the coupling constant related to the strength of the $^3P_0$ vertex [28, 31, 32]. It signifies the probability for creating a light quark-antiquark pair. The wave functions of the ($D^*, D$) mesons are assumed to be wave functions with harmonic oscillator potential. The ratio $r = \beta / \beta_{avg}$, where $\beta$ is the strength of the harmonic potential of the parent $D^*$ meson state and $\beta_{avg}$ is the average strength of harmonic oscillator potential of the daughter ($D - \pi$) mesons. The scaled momentum $x$ is defined as $x = p / \beta_{avg}$. The value of $\beta_D$ is taken as 310 MeV, consistent with the decay widths of $\psi(4040)$ to $D\bar{D}, D^*\bar{D}, D\bar{D}^*, D^*\bar{D}^*$ in vacuum [27, 35, 61]. Decay widths depend on the variable, $x$, which is the center of mass momentum, $p$ in units of $\beta_{avg}$, as a polynomial multiplied by an exponential term.

**B. Decay of $\Psi(3770)$ meson to $D\bar{D}$**

The hadronic decay width for the charmonium state, $\Psi(3770)$ going to $D\bar{D}$ mesons is calculated in this subsection, using the $^3P_0$ model. The in-medium masses of the parent and daughter particles are obtained from the chiral effective model calculations, with the additional contribution of LLL (for charged mesons only) and PV mixing effect, in the magnetized nuclear matter, including magnetic catalysis. The decay width expression is given by [34, 37]

$$
\Gamma_{\Psi(3770) \to D\bar{D}} = \frac{\gamma_{\Psi}^2 \sqrt{\pi} E_D E_{\bar{D}}}{2m_{\Psi(3770)}} \frac{2^{115}}{3^2} \left( \frac{r_{\Psi}}{1 + 2r_{\Psi}^2} \right)^7 \times x_{\Psi}^2 \left( 1 - \frac{1 + r_{\Psi}^2}{5(1 + 2r_{\Psi}^2)} x_{\Psi}^2 \right)^2 \exp \left( -\frac{x_{\Psi}^2}{2(1 + 2r_{\Psi}^2)} \right) \quad (20)
$$

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

$$
p_D = \left( \frac{m_{\Psi}^2}{4} - m_D^2 \right)^{1/2} \quad (21)
$$

Similar to the previous decay channel ($D^* \to D\pi$), $\gamma_{\Psi}$ signifies the probability for creating the light quark-antiquark pair. $\gamma_{\Psi}$ is chosen to be 0.33 [35], thus reproducing the observed decay widths of $\Psi(3770)$ to $D^+D^-$ and $D^0\bar{D}^0$ in vacuum. The ratio $r_{\Psi} = \beta_{\Psi} / \beta_D$ with $\beta_{\Psi} = 0.37$ and $\beta_D = 0.31$ (in GeV) are obtained from the mean squared radius for the D meson and the charmonium states. $\beta_D = 0.31$ GeV [61], is consistent with decay widths of $\Psi(4040)$ to $D\bar{D}, D^*\bar{D}, D\bar{D}^*$ and $D^*\bar{D}^*$ in vacuum. $x_{\Psi} = p_D / \beta_D$ is the scaled momentum.
VI. RESULTS AND DISCUSSIONS

In this section, we discuss the results on the in-medium hadronic decay widths for $D^* \rightarrow D \pi$ ($\bar{D}^* \rightarrow \bar{D} \pi$) and $\Psi(3770) \rightarrow D \bar{D}$ channels, in the magnetized nuclear matter, accounting the effects from the magnetized Dirac sea. The in-medium masses of the pseudoscalar open charm mesons $D (D^+, D^0)$, $\bar{D} (D^-, \bar{D}^0)$ are calculated within the chiral effective model. The magnetized Dirac sea contributions are taken through the additional terms of the scalar densities of protons and neutrons on the scalar fields of the model, which represent the chiral condensates. The effects of Landau quantization of the protons in the Fermi sea are considered along with the Dirac sea effects in the magnetized nuclear matter. The in-medium masses of the vector mesons $D^* (D^{*+}, D^{*0})$, $\bar{D}^* (D^{*-}, \bar{D}^{*0})$, are obtained from the mass shifts of the corresponding pseudoscalar partners (equation (10) of ref. [18]). The in-medium masses of the pseudoscalar mesons are solved from their dispersion relations (equation (3) of ref. [18]), which depend on the scalar and number densities of the nucleons and the scalar fields fluctuations from their vacuum expectation values (equations (4)-(5) of ref. [18]). However, the fluctuation in the charm (a heavy quark flavor) quark condensate is neglected in the mass calculations. Thus, the medium effects are incorporated in terms of the number and scalar densities and the scalar fields fluctuations on the open charm mesons masses within the chiral effective model. The magnetic field contributions are also considered due to the lowest Landau level of the charged meson state (being considered as particle entity) (equations (3)-(6)). There is no such additional effect for the neutral mesons. Although, the dominant magnetic field effects on the masses, are coming through the PV mixing between the pseudoscalar and the longitudinal component of the vector mesons. Using the fitted values of the coupling parameters from the observed radiative decay widths of the charmonium and open charm mesons, an effective Lagrangian approach is applied to find the PV mixing effect on the in-medium masses of $D - D^{*\|}$, $\bar{D} - \bar{D}^{*\|}$ and $\eta_c (2S) - \Psi(3770)^{\|}$ states (equation (10)), in the magnetized nuclear matter, by considering the effects from magnetic catalysis (MC). In the PV mixing calculations, the contribution from the lowest Landau level is considered in the case of electrically charged open charm mesons. However, the mass modifications of the excited charmonium state, $\Psi(3770)$ depend on the in-medium changes of the scalar dilaton field, $\chi$, which simulates the gluon condensate of QCD within the chiral model framework. The mass modification for the $\Psi(3770)$ is calculated using
equation (15), in the magnetized nuclear medium by accounting the effects of Dirac sea from the magnetized fermionic tadpole diagrams. The Landau quantization of protons in the nuclear medium are also considered along with Dirac sea effects at finite magnetic field. All along, the effects of anomalous magnetic moments of the nucleon are considered in the magnetized Fermi sea of nucleons and in the magnetized Dirac sea.

Therefore, using the in-medium masses of the open charm and charmonium states, the effects of magnetic catalysis are studied on the possible hadronic decay channels of $D^* \to D\pi$ ($D^{*+} \to D^{+}\pi^0$, $D^{*+} \to D^{0}\pi^+$, $D^{*0} \to D^{0}\pi^0$); $\bar{D}^* \to \bar{D}\pi$ ($D^{*-} \to D^{-}\pi^0$, $D^{-*} \to \bar{D}^{0}\pi^-$, $\bar{D}^{*0} \to \bar{D}^{0}\pi^0$) and $\Psi(3770) \to D\bar{D}$. A light quark-antiquark pair creation model or the $^3P_0$ model is used in our present investigation, to study the hadronic decay widths for the vector open charm meson, $D^*$ going to two pseudoscalar mesons, $D$ and $\pi$ using equation (17). Due to the isospin considerations, the coupling constant related to the $^3P_0$ vertex for the various channels are different. For the channels $D^{*\pm} \to D^{\pm}\pi^0$, and $D^{*+} \to D^{0}\pi^+$ (with its charge conjugate mode, $D^{*-} \to \bar{D}^{0}\pi^-$), $\gamma$ is chosen to be 0.265 and 0.368 respectively. For $D^{*0} \to D^{0}\pi^0$ it is 0.264 (including the charge conjugate channel). The decay of $\Psi(3770)$ to $D\bar{D}$ can be possible by two decay modes, namely, $D^{+}D^{-}$ and $D^{0}\bar{D}^{0}$, which are calculated within the $^3P_0$ model to find the total decay width of $\Psi(3770)$, by equation (20).

In Fig.1, the hadronic decay widths for the neutral $D^{*0}$ ($\bar{D}^{*0}$) mesons to pseudoscalar mesons $D^{0}$ ($\bar{D}^{0}$) and $\pi^0$, are plotted for zero density matter, as a function of the magnetic field, $eB$ (in units of $m^2_{\pi}$). The magnetic catalysis effects are shown by accounting (and not) the anomalous magnetic moments of the Dirac sea of nucleons at $\rho_B = 0$. There is no Landau quantization effects of protons on the masses due to the absence of nuclear matter part. In the absence of Dirac sea polarizations, only the PV mixing effects between $D^{0} - D^{*0||}$ and $\bar{D}^{0} - \bar{D}^{*0||}$ on their vacuum masses, have impact on the decays at finite magnetic field. At zero density, decay widths are shown only up to $eB = 5.4 m^2_{\pi}$ in the case of with AMM, since the masses have been calculated till this range of magnetic field [18].

In the decay calculations, PV mixing effects are considered on the masses of the longitudinal ($S_z = 0$) component of the vector mesons, to find the decay width of the corresponding polarization state of the vector meson, $D^{*||}$ ($\bar{D}^{*||}$). In this case, the final state decay product, pseudoscalar meson, $D$ ($\bar{D}$), mass is taken to be its corresponding PV mixed value. The decay widths for the non-PV mixed, transverse components ($S_z = \pm 1$) of the vector mesons, $D^{*\perp}$ ($\bar{D}^{*\perp}$), are calculated separately for their decays into the corresponding non-PV mixed,
pseudoscalar state, $D(\bar{D})$ and a $\pi$ meson. The lowest Landau level (LLL) contribution for the transverse components of vector mesons are different for charged particles, as it is given by equation (4) for $S_z = +1$ component and equation (6) for $S_z = -1$ component of spin-polarizations. However, there is no LLL contribution at finite magnetic field for the neutral vector as well as neutral pseudoscalar mesons. In Fig.2, in-medium decay widths are shown for the charged open charm mesons at zero density. For the charged mesons there are two decay modes for the $D^{*+}$ meson, $D^{*+} \rightarrow D^+\pi^0$ (denoted as I.a), $D^{*+} \rightarrow D^0\pi^+$ (denoted as II.a) and two for the $D^{*-}$ meson, $D^{*-} \rightarrow D^-\pi^0$ (denoted as I.b), $D^{*-} \rightarrow \bar{D}^0\pi^-$ (denoted as II.b). The decay widths are also calculated for nuclear matter saturation density, $\rho_0$ both in case of symmetric (with $\eta = 0$) and asymmetric (with $\eta = 0.5$) nuclear matter, in Figs. [(3)-(4)] for the neutral and in Figs. [(5)-(6)] for the charged open charm mesons. Next, the decay widths for the charmonium state, $\Psi(3770) \rightarrow D\bar{D}$ are shown in the magnetized nuclear matter taking into account the magnetic catalysis effects on the respective parent and daughter particle masses within the chiral effective model. The zero density calculation are shown in Fig.(7). The finite density, decay widths are shown in Figs.[(8)-(9)], at $\rho_0$ and $\eta = 0, 0.5$, respectively. The two decay modes of $\Psi(3770)$ to $D^+D^-$ (denoted as I) and $D^0\bar{D}^0$ (denoted as II) are shown separately in the plots, along with their total values (I+II). The effects of PV mixing are also considered on the masses of the initial and final states particles, including the catalysis effect in presence of magnetic field. The effects of magnetic catalysis on the in-medium decay widths are seen to be important through the incorporation of nucleons anomalous magnetic moments. The effects of magnetic catalysis are appreciably visible on the decays of charged vector charm mesons in comparison to their neutral partners decay widths. However, the in-medium decay widths of $\Psi(3770) \rightarrow D^0\bar{D}^0$ channel get significant modifications over the $\Psi(3770) \rightarrow D^+D^-$ mode, by the magnetized Dirac sea polarizations accounting the anomalous magnetic moments of the nucleons, as compared to the no catalysis case. As in the case of charged vector charm meson decay widths, containing two decay modes, the dominant contribution is coming from the $D^{*+} \rightarrow D^0\pi^+$ ($D^{*-} \rightarrow \bar{D}^0\pi^-$) as compared to the $D^{*+} \rightarrow D^+\pi^0$ ($D^{*-} \rightarrow D^-\pi^0$) decay mode. There is observed to be important difference in the partial decay widths of $\Psi(3770) \rightarrow D\bar{D}$ through the PV mixing effects of $\eta_c(2S) - \Psi(3770)||$ and $D - D^*|| (\bar{D} - \bar{D}^*||)$, as compared to the no mixing case, both in presence and absence of the magnetic catalysis effect.
FIG. 1: The decay widths of $D^{*0} \to D^0 \pi^0$ (I) and $\bar{D}^{*0} \to \bar{D}^0 \pi^0$ (II) are plotted as a function of magnetic field $|eB|$ (in units of $m^2_\pi$), at zero density matter, $\rho_B = 0$, taking into account the effects of magnetized Dirac sea. The decays incorporate the PV mixed masses for the $D^0 - D^{*0}$ and $\bar{D}^0 - \bar{D}^{*0}$, along with the non-PV mixed, transverse components mass. The magnetic catalysis effects [plot (a) for I, plot (c) for II] are compared with no catalysis effect [plot (b) for I, plot (d) for II]. Effects of nucleons anomalous magnetic moments (AMM) are compared with the case when AMM is not considered.
FIG. 2: The decay widths of $D^{*+} \to D^{+}\pi^0$ (I.a), $D^{*+} \to D^{0}\pi^+$ (II.a) and $D^{*-} \to D^{-}\pi^0$ (I.b), $D^{*-} \to \bar{D}^{0}\pi^-$ (II.b) are plotted as a function of magnetic field $|eB|$ (in units of $m^2_\pi$), at zero density matter, $\rho_B = 0$, taking into account the effects of magnetized Dirac sea. The decays incorporate the PV mixed masses for the $D^{+} - D^{*+}$ and $D^{-} - D^{*-}$, along with the non-PV mixed (only LLL contributed) transverse components masses for the charged vector mesons. The magnetic catalysis effects [plot (a) for I.a and II.a, plot (c) for I.b and II.b] are compared with no catalysis effect [plot (b) for I.a and II.a, plot (d) for I.b and II.b]. Effects of nucleons anomalous magnetic moments (AMM) are compared with the case when AMM is not considered.
FIG. 3: The decay widths of $D^*0 \to D^0\pi^0$ (I) and $\bar{D}^*0 \to \bar{D}^0\pi^0$ (II) are plotted as a function of magnetic field $|eB|$ (in units of $m^2_{\pi}$), at $\rho_B = \rho_0$ and $\eta = 0$, taking into account the effects of magnetized Dirac sea. The decays incorporate the PV mixed masses for the $D^0 - D^{*0\|}$ and $D^0 - \bar{D}^{*0\|}$, along with the non-PV mixed, transverse components mass. The magnetic catalysis effects [plot (a) for I, plot (c) for II] are compared with no catalysis effect [plot (b) for I, plot (d) for II]. Effects of nucleons anomalous magnetic moments (AMM) are compared with the case when AMM is not considered.
FIG. 4: The decay widths of $D^{*0} \rightarrow D^0\pi^0$ (I) and $\bar{D}^{*0} \rightarrow \bar{D}^0\pi^0$ (II) are plotted as a function of magnetic field $|eB|$ (in units of $m_\pi^2$), at $\rho_B = \rho_0$ and $\eta = 0.5$, taking into account the effects of magnetized Dirac sea. The decays incorporate the PV mixed masses for the $D^0 - D^{*0}$ and $\bar{D}^0 - \bar{D}^{*0}$, along with the non-PV mixed, transverse components mass. The magnetic catalysis effects [plot (a) for I, plot (c) for II] are compared with no catalysis effect [plot (b) for I, plot (d) for II]. Effects of nucleons anomalous magnetic moments (AMM) are compared with the case when AMM is not considered.
FIG. 5: The decay widths of $D^{*+} \to D^+ \pi^0$ (I.a), $D^{*+} \to D^0 \pi^+$ (II.a) and $D^{*-} \to D^- \pi^0$ (I.b), $D^{*-} \to \bar{D}^0 \pi^-$ (II.b) are plotted as a function of magnetic field $|eB|$ (in units of $m^2_{\pi}$), at $\rho_B = \rho_0$ and $\eta = 0$, taking into account the effects of magnetized Dirac sea. The decays incorporate the PV mixed masses for the $D^+ - D^{*+||}$ and $D^- - D^{*-||}$, along with the non-PV mixed (only LLL contributed) transverse components masses for the charged vector mesons. The magnetic catalysis effects [plot (a) for I.a and II.a, plot (c) for I.b and II.b] are compared with no catalysis effect [plot (b) for I.a and II.a, plot (d) for I.b and II.b]. Effects of nucleons anomalous magnetic moments (AMM) are compared with the case when AMM is not considered.
FIG. 6: The decay widths of $D^{*+} \to D^+\pi^0$ (I.a), $D^{*+} \to D^0\pi^+$ (II.a) and $D^{*-} \to D^-\pi^0$ (I.b), $D^{*-} \to \bar{D}^0\pi^-$ (II.b) are plotted as a function of magnetic field $|eB|$ (in units of $m^2_{\pi}$), $\rho_B = \rho_0$ and $\eta = 0.5$, taking into account the effects of magnetized Dirac sea. The decays incorporate the PV mixed masses for the $D^+-D^{*+||}$ and $D^--D^{*-||}$, along with the non-PV mixed (only LLL contributed) transverse components masses for the charged vector mesons. The magnetic catalysis effects [plot (a) for I.a and II.a, plot (c) for I.b and II.b] are compared with no catalysis effect [plot (b) for I.a and II.a, plot (d) for I.b and II.b]. Effects of nucleons anomalous magnetic moments (AMM) are compared with the case when AMM is not considered.
FIG. 7: The decay widths of $\Psi(3770) \rightarrow D^+D^- \ (I)$ and $\Psi(3770) \rightarrow D^0\bar{D}^0 \ (II)$ and their total \ (I+II), are plotted as a function of magnetic field $|eB|$ (in units of $m^2_\pi$), at $\rho_B = 0$, taking into account the effects of magnetized Dirac sea. The PV mixing effects on the masses of the parent and daughter particles [plot (b)] are compared with the no PV mixing effect [plot (a)]. The contribution of the lowest Landau level is considered for the charged mesons. Effects of nucleons anomalous magnetic moments (AMM) is compared with the case when AMM is not considered.

VII. SUMMARY

We have investigated the in-medium hadronic decays of $D^{*\pm} \rightarrow D^{\pm}\pi^0$, $D^{*+} \rightarrow D^0\pi^+$, $D^{*-} \rightarrow \bar{D}^0\pi^-$, $D^{*0} \rightarrow D^0\pi^0$, $\bar{D}^{*0} \rightarrow \bar{D}^0\pi^0$ and $\Psi(3770) \rightarrow D\bar{D}$, in the magnetized nuclear matter incorporating the effects of the magnetic catalysis through the Dirac sea polarization, within the chiral effective model. For the charged mesons, the contribution of the lowest Landau level has been considered. Pseudoscalar-Vector (PV) mixing has also been incorporated through the effective Lagrangian approach. The Landau level lifts the degeneracy of the energy levels of the vector ($D^{*\pm}$) mesons as the transverse components of the charged vector mesons undergo energy shifts. The coupling parameter $g_{PV}$ is fitted from the observed radiative decay widths, $\Gamma(V \rightarrow P\gamma)$. The decay width for the $D^{*0} \rightarrow D^0\pi^0$ channel, is cur-
FIG. 8: The decay widths of $\Psi(3770) \rightarrow D^+ D^- \ (I)$ and $\Psi(3770) \rightarrow D^0 \bar{D}^0 \ (II)$ and their total (I+II), are plotted as a function of magnetic field $|eB|$ (in units of $m^2_\pi$), at $\rho_B = \rho_0$ and $\eta = 0$, taking into account the effects of magnetized Dirac sea. The PV mixing effects on the masses of the parent and daughter particles [plot (c) and plot (d)] are compared with the no PV mixing effect [plot (a) and plot (b)]. The effects of magnetic catalysis (MC) [plot (a) and plot (c)] are compared with the no catalysis effect [plot (b) and plot (d)]. The contribution of the lowest Landau level is considered for the charged mesons. Effects of nucleons anomalous magnetic moments (AMM) is compared with the case when AMM is not considered.
FIG. 9: The decay widths of $\Psi(3770) \rightarrow D^+ D^-$ (I) and $\Psi(3770) \rightarrow D^0 \bar{D}^0$ (II) and their total (I+II), are plotted as a function of magnetic field $|eB|$ (in units of $m^2_\pi$), at $\rho_B = \rho_0$ and $\eta = 0.5$, taking into account the effects of magnetized Dirac sea. The PV mixing effects on the masses of the parent and daughter particles [plot (c) and plot (d)] are compared with the no PV mixing effect [plot (a) and plot (b)]. The effects of magnetic catalysis (MC) [plot (a) and plot (c)] are compared with the no catalysis effect [plot (b) and plot (d)]. The contribution of the lowest Landau level is considered for the charged mesons. Effects of nucleons anomalous magnetic moments (AMM) is compared with the case when AMM is not considered.
rently seen but not measured. However, from isospin considerations, we can estimate the variation of this decay width with varying magnetic field. The effects of magnetic catalysis on the in-medium partial decay widths of open charm and charmonium states can affect the yield of open charm and charmonia produced in the non-central, ultra-relativistic, heavy ion collision experiments, where produced magnetic field is very large.

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