Open charm and charmonium states in strong magnetic fields

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Abstract

The mass modifications of the open charm ($D$ and $D^*$) mesons, and their effects on the decay widths $D^* \rightarrow D\pi$ as well as of the charmonium state, $\Psi(3770)$ to open charm mesons ($\Psi(3770) \rightarrow D\bar{D}$), are investigated in the presence of strong magnetic fields. These are studied accounting for the mixing of the pseudoscalar ($P$) and vector ($V$) mesons ($D - D^*$, $\eta_c' - \Psi(3770)$ mixings), with the mixing parameter, $g_{PV}$ of a phenomenological three-point ($PV\gamma$) vertex interaction determined from the observed radiative decay width of $V \rightarrow P\gamma$. For charged $D - D^*$ mixing, this parameter is dependent on the magnetic field, because of the Landau level contributions to the vacuum masses of these mesons. The masses of the charged $D$ and $D^*$ mesons modified due to $PV$ mixing, in addition, have contributions from the lowest Landau levels in the presence of a strong magnetic field. The effects of the magnetic field on the decay widths are studied using a field theoretic model of composite hadrons with quark (and antiquark) constituents. The matrix elements for these decays are evaluated using the light quark–antiquark pair creation term of the free Dirac Hamiltonian for the constituent quark field, with explicit constructions for the the charmonium state $\Psi(3770)$, the open charm ($D, \bar{D}, D^*$) mesons and the pion states in terms of the constituent quark fields. The parameter for the charged $D - D^*$ mixing is observed to increase appreciably with increase in the magnetic field. This leads to dominant modifications to their masses, and hence the decay widths of charged $D^* \rightarrow D\pi$ as well as $\Psi(3770) \rightarrow D^+D^-$ at large values of the magnetic field. The modifications of the masses and decay widths of the open and hidden charm mesons in the presence of strong magnetic fields should have observable consequences on the production of the open charm ($D$ and $D^*$) mesons as well as of the charmonium states resulting from non-central ultrarelativistic heavy ion collision experiments.

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I. INTRODUCTION

The study of heavy flavour hadrons \[1\] is a topic of extensive research in high energy physics. The topic has relevance in the high energy heavy ion collision experiments, as the medium modifications of the properties of these hadrons can affect the experimental observables of heavy ion collision experiments. There have been extensive studies of the heavy flavour mesons in the literature using various frameworks. These include the potential models \[2-6\], the QCD sum rule approach \[7-10\], the coupled channel approach \[11\], a hadronic model using pion exchange \[12\], a chiral effective model \[13-17\] and the quark meson coupling (QMC) model \[18\]. There are studies which show attractive interactions of the open heavy flavour (\(\bar{D}, B\)) mesons, as well as \(J/\psi\) in nuclear matter, suggesting the interesting possibility of bound states of these mesons with nuclei \[18\]. A study of the heavy quarkonium state (with heavy quark and antiquark assumed to be bound by a Coulomb potential) in the presence of a gluon field \[19-21\] shows that its mass shift is proportional to the change in the gluon condensates in the medium. This is the result in the leading order approximation, with the distance between the heavy quark and antiquark assumed to be small as compared to the scale of gluonic fluctuations. The charmonium masses have been studied using the leading order formula using a linear density approximation for the gluon condensate \[22\].

The estimation of strong magnetic fields produced in the peripheral ultra relativistic heavy ion collision experiments \[23\] (of the order of \(eB \sim 2m_\pi^2\) at RHIC, BNL and \(eB \sim 15m_\pi^2\) at LHC, CERN) has initiated a lot of research activities in the study of the hadrons in the presence of magnetic fields. The heavy flavour mesons are produced in the very early phase of the heavy ion collision experiments, when the magnetic field can still be large. The effects of the magnetic field can thus have consequences on the observables of the heavy ion collision experiments. The open heavy flavour mesons as well as the heavy quarkonium states have been studied in the presence of a magnetic field \[24-33\]. In the presence of a magnetic field, the mixing of the pseudoscalar and the vector mesons has been shown to lead to dominant contributions to the masses of these mesons within a QCD sum rule approach \[24, 30, 31\] as well as within an effective potential approach \[32\].

Using a chiral effective model, the mass modifications of the heavy flavour mesons in a
hadronic medium have been studied [13–17]. The masses of the open charm (bottom) mesons are modified due to their interactions with the baryons and scalar mesons in the medium. On the other hand, the modifications of the charmonium (bottomonium) are studied from the modification of the gluon condensates in the hadronic medium using the leading order QCD formula [19–21]. This is calculated from the medium change of a dilaton field which simulates within the effective hadronic model. Using a light quark pair creation model, namely the $^{3}P_{0}$ model [34, 35], as well as using a field theoretical model of composite hadrons with quark (and antiquark) constituents [36–38], the decay widths of the charmonium (bottomonium) to $D \bar{D}$ ($B \bar{B}$) in (magnetized) hadronic matter have also been studied from the mass modifications of these mesons [15, 39–42]. In the presence of a magnetic field, the effects of the pseudoscalar meson - vector meson (PV) mixings been studied for the open and hidden charm sector [24, 30–32, 43] and the strange meson sector [44]. These effects are found to have the dominant contributions to the masses of these mesons. $\Psi(3770)$ is the lowest charmonium state which can decay to open charm mesons, $D \bar{D}$. In the presence of strong magnetic fields, the decay width of $\Psi(3770) \rightarrow D \bar{D}$ arising from the mass modifications of $\Psi(3770)$ due to PV ($\Psi(3770) - \eta'_{c}$) mixing and of the charged open charm mesons due to the contribution of Landau energy levels was studied in Ref. [43]. In the strange sector, the decay widths of $\phi \rightarrow K \bar{K}$ and $K^{*} \rightarrow K \pi$ in presence of strong magnetic fields [44], have been studied from the mass modifications of the $\phi$ and the open strange mesons arising from PV mixing ($\phi - \eta'$ and $K - K^{*}$ mixings) and, in addition, the Landau level contributions for the charged $K$, $K$ and $K^{*}$ mesons. In the present work, the decay widths of $D^{*} \rightarrow D \pi$ and $\Psi(3770) \rightarrow D \bar{D}$ are studied in the presence of a magnetic field from the mass changes of the initial and final state mesons accounting for the PV mixing ($\Psi(3770) - \eta'_{c}$, $D - D^{*}$) effects, as well as, accounting for the Landau level contributions for the charged open charm mesons. These decay widths are computed using a field theoretic model for composite hadrons with quark (and antiquark) constituents.

The outline of the paper is as follows. In section II, the effects of the magnetic field on the masses of the $D$ and $D^{*}$ mesons are studied. In the presence of a magnetic field, the mass modifications of these mesons arise due the mixing of the pseudoscalar, $D$ mesons with the longitudinal component of the vector, $D^{*}$ meson. The charged $D$ and $D^{*}$ mesons have
additional contributions from the Landau quantization in the presence of the magnetic field. In section III, the effects of the magnetic field on the $D^* \to D\pi$ as well as $\Psi(3770) \to DD$ decay widths are investigated using a field theoretic model of composite hadrons with quark (and antiquark) constituents. These decay widths are calculated using the light quark antiquark pair creation term of the free Dirac Hamiltonian and explicit constructions for these mesons. In section IV, we discuss the results of the effects of the magnetic field on the masses of the open charm ($D$ and $D^*$) mesons, and their subsequent effects on the decay widths $D^* \to D\pi$ and $\Psi(3770) \to D\bar{D}$. For the charmonium decay width, contributions to the masses of the $\Psi(3770)$ as well as open charm mesons due to $D - D^*$ and $\Psi(3770) - \eta'_c$ mixings are taken into account, and, in addition, the Landau level contributions for the charged open charm mesons. In section V, we summarize the findings of the present study.

II. MASSES OF $D$ AND $D^*$ MESONS IN PRESENCE OF A MAGNETIC FIELD

In this section, we investigate the effects of a uniform magnetic field on the masses of the open charm ($D$ and $D^*$) mesons. The modifications in the masses of these mesons arise from the mixing of the pseudoscalar ($D$) and the vector ($D^*$) mesons in the presence of an external magnetic field, with additional contributions from the Landau energy levels for the charged open charm mesons.

The mixing of the pseudoscalar ($D$) and vector ($D^*$) mesons in the presence of a magnetic field is taken into account through the interaction \cite{24, 31}

$$\mathcal{L}_{PV\gamma} = \frac{g_{PV}}{m_{av}} e \tilde{F}_{\mu\nu}(\partial^\mu P)^\nu, \quad (1)$$

where $m_{av} = (m_V + m_P)/2$, $m_P$ and $m_V$ are the masses for the pseudoscalar and vector charmonium states. In equation (1), the coupling parameter $g_{PV}$ is fitted from the observed radiative decay width $\Gamma(V \to P + \gamma)$, given as

$$\Gamma(V \to P\gamma) = \frac{e^2 g_{PV} p_{cm}^3}{12 \pi m_{av}^2}. \quad (2)$$

In the above, $p_{cm}$ is the magnitude of the center of mass momentum in the final state given as $p_{cm} = (m_V^2 - m_P^2)/(2m_V)$. The modified masses due to the mixing of the pseudoscalar
and the longitudinal component of the vector mesons, are given by

\[ m^{(PV)}_{V_{\parallel}, P} = \frac{1}{2} \left( M_+^2 + \frac{c^2_{PV}}{m_{av}^2} \pm \sqrt{M_+^4 + \frac{2c^2_{PV} M_+^2}{m_{av}^2} + \frac{c^4_{PV}}{m_{av}^4}} \right), \]  

(3)

where \( M_+^2 = m_P^2 + m_V^2, M_-^2 = m_V^2 - m_P^2 \) and \( c_{PV} = g_{PV} eB \).

In the presence of an external magnetic field, the masses of the charged \( D \) and \( D^* \) mesons have contributions from the Landau levels. In the present work, the mass of the charged open charm meson is taken to be the energy of the ground state (lowest Landau level) at \( p_z = 0 \), which is a valid approximation for strong magnetic fields. However, for weak magnetic fields, the Landau energy levels of the excited states of the charged mesons are quite close to the ground state and the mass of the charged meson has contributions also from the excited Landau levels. A consistent summation of all the Landau levels has been carried out in the study of the charged \( D \) mesons in the presence of a magnetic field using the QCD sum rule approach in Ref. [24]. In the present study, the masses of the charged open charm mesons are taken to be arising from the lowest Landau level \((n = 0)\) as

\[ m_{D_{\pm}}^{eff} = \sqrt{m_{D_{\pm}}^2 + eB}, \quad m_{D^*_{\pm}}^{eff} = \sqrt{m_{D^*_{\pm}}^2 - eB}, \]  

(4)

where the value of the gyromagnetic ratio of \( D^* \) meson has been taken to be 2. The mixing parameter for charged \( D - D^* \) mixing, determined from the observed decay width \( D^* \rightarrow D \gamma \), is magnetic field dependent, because of the lowest Landau level contributions to their vacuum masses. The masses of these charged mesons modified due to the mixing effect in the presence of a magnetic field, are obtained from equation [3], using the magnetic field dependent \( PV \) mixing parameter, and the values of the masses of the charged pseudoscalar and vector mesons \((m_P \text{ and } m_V)\) taken as the lowest Landau level contribution to their vacuum masses. The masses of the charged mesons modified due to \( PV \) mixing, in addition, have contributions from the lowest Landau levels.

The in-medium decay width of \( D^* \rightarrow D \pi \) arising from the mass modifications of the \( D \) and \( D^* \) mesons, and of \( \Psi(3770) \rightarrow D \bar{D} \), due to mass modifications of the \( \Psi(3770) \) as well as \( D \) and \( \bar{D} \) mesons, are investigated in the presence of strong magnetic fields. The \( PV \) mixing is observed to lead to a drop (rise) in the masses of the \( D \) (longitudinal \( D^* \)) mesons, and it is observed to be quite appreciable for the neutral open charm mesons [24], as
compared to the case of charged open charm mesons, when the $PV$ mixing parameter, $g_{PV}$ is kept at the zero magnetic field value. However, as we shall see later, the strong increase of this parameter with the magnetic field, is observed to lead to significant modifications to the masses of the charged open charm mesons, and hence to the decay widths of the charged $D^* \rightarrow D\pi$ as well as $\Psi(3770) \rightarrow D^+D^-$. There is substantial modification in the mass of the longitudinal component of $\Psi(3770)$ is due to mixing with $\eta'_c$ in the presence of a magnetic field, which was observed to lead to appreciable modification to the decay width of $\Psi(3770) \rightarrow D\bar{D}$ [43]. Due to the Landau level contributions for the charged open charm mesons the decay widths for the $D^+D^-$ and $D^0\bar{D}^0$ final states are observed to be quite different in the presence of a magnetic field [43]. In the present work, the decay widths of $\Psi(3770) \rightarrow D\bar{D}(D^+D^-,D^0\bar{D}^0)$ are studied accounting for the PV mixing contributions to the masses of the $D$ and $\bar{D}$ mesons (arising from the $D - D^*$ and $\bar{D} - \bar{D}^*$ mixings), and, in addition the Landau level contributions for the charged open charm mesons. The decay widths for $D^* \rightarrow D\pi$ and $\Psi(3770) \rightarrow D\bar{D}$ are calculated using a field theoretical model of composite hadrons with quark (and antiquark) constituents as described in the following section.

III. TWO BODY DECAY WIDTHS WITHIN A MODEL FOR COMPOSITE HADRONS

The decay width for a generic two body decay process of $A(0) \rightarrow B(p) + C(-p)$ is calculated within the field theoretic model of composite hadrons with explicit contructions for the initial and final states in terms of the quark (and antiquark) constituents and using the matrix element of free Dirac Hamiltonian as the light quark pair creation, between the initial and final states. In the present work, we calculate the decay widths for $D^* \rightarrow D\pi$ and $\Psi(3770) \rightarrow D\bar{D}$ accounting for the PV mixing contributions for the masses of the open charm mesons and charmonium states in the presence of a magnetic field.
A. Decay width of $D^* \rightarrow D\pi$

The effects of a uniform background magnetic field on the decay widths of $D^* \rightarrow D\pi$ are studied from the mass modifications of the $D$ and $D^*$ mesons in the presence of the magnetic field. The decay widths of the charged $D^{*+}$ meson ($D^{*+} \rightarrow D^{+}\pi^0$ and $D^{*+} \rightarrow D^0\pi^+$), and the neutral $D^{*0}$ meson ($D^{*0} \rightarrow D^0\pi^0$), are computed using a field theoretical model with composite hadrons [39], comprising of quark (and antiquark) constituents [36–38]. Using a Lorentz boosting, the constituent quark field operators of the hadron in motion are obtained from the constituent quark field operators of the hadron at rest. In the present model for the composite hadrons it is assumed that the quark (and antiquark) constituents carry fractions of the energy of the hadron [36, 37]. This is similar to the MIT bag model [45], where the quarks (antiquarks) occupy specific energy levels inside the hadron.

The decay width for $D^* \rightarrow D\pi$ is obtained from the matrix element of the quark-antiquark pair creation term of the free Dirac Hamiltonian in terms of the constituent quark field operators between the initial and final states. Assuming harmonic oscillator wave functions for these states, the explicit constructions for the decaying $D^*$ meson at rest and the produced states, $D$ and $\pi$ with finite momenta, are given as

$$|D^{*m}(0)\rangle = \frac{1}{\sqrt{6}} \left( \frac{R_{D}^2}{\pi} \right)^{3/4} \int d\mathbf{k} \exp \left( -\frac{R_{D}^2 k^2}{2} \right) c_r^i(\mathbf{k})^\dagger u_s^i \sigma^m \tilde{q}_s^i(-\mathbf{k}) v_s d\mathbf{k}|\text{vac}\rangle,$$  
$$|D(\mathbf{p})\rangle = \frac{1}{\sqrt{6}} \left( \frac{R_{D}^2}{\pi} \right)^{3/4} \int d\mathbf{k} \exp \left( -\frac{R_{D}^2 k^2}{2} \right) c_r^i(\mathbf{k} + \lambda_2 \mathbf{p})^\dagger u_s^i \tilde{q}_s^i(-\mathbf{k} + \lambda_1 \mathbf{p}) v_s d\mathbf{k}|\text{vac}\rangle (6)$$
$$|\pi^+(\mathbf{p})\rangle = \frac{1}{\sqrt{6}} \left( \frac{R_{\pi}^2}{\pi} \right)^{3/4} \int d\mathbf{k} \exp \left( -\frac{R_{\pi}^2 k^2}{2} \right) u_r^i(\mathbf{k} + \frac{\mathbf{p}}{2})^\dagger u_s^i \tilde{d}_s^i(-\mathbf{k} + \frac{\mathbf{p}}{2}) v_s d\mathbf{k}|\text{vac}\rangle,$$  
$$|\pi^0(\mathbf{p})\rangle = \frac{1}{2\sqrt{3}} \left( \frac{R_{\pi}^2}{\pi} \right)^{3/4} \int d\mathbf{k} \exp \left( -\frac{1}{2} R_{\pi}^2 k^2 \right) \left( u_r^i(\mathbf{k} + \frac{\mathbf{p}}{2})^\dagger u_s^i \tilde{d}_s^i(-\mathbf{k} + \frac{\mathbf{p}}{2}) v_s \right) |\text{vac}\rangle >,$$

In the above equations, $c_r^i(\mathbf{k})^\dagger(\tilde{c}_r^i(\mathbf{k}))$ is the creation operator of the heavy flavour charm quark (antiquark) with spin $r$, color $i$ and momentum $\mathbf{k}$, $q_r^i(\mathbf{k})^\dagger(\tilde{q}_r^i(\mathbf{k}))$ refer to the light $(q = (u, d))$ quark (antiquark), and $u_r$ and $v_s$ are the two component spinors. In equations (5) and (6), $q = d(u)$ correspond to $D^{*+}(D^{*0})$ and $D^+(D^0)$ states respectively. The parameters
$R_{D^*}$, $R_D$ and $R_\pi$ refer to the harmonic oscillator strengths for the states $D^*$, $D$ and $\pi$ respectively. In equation (6), $\lambda_1$ and $\lambda_2$ are the fractions of the mass (energy) of the $D$ meson at rest (in motion), carried by the constituent light (d,u) antiquark and the constituent heavy charm quark, with $\lambda_1 + \lambda_2 = 1$. These are calculated by assuming the binding energy of the hadron as shared by the quark (antiquark) to be inversely proportional to the quark (antiquark) mass \[37\]. For the pion states, $\pi^+$ and $\pi^0$, which are light quark-antiquark bound states, the fractions of energy carried by the quark and antiquark are the same, i.e., $\lambda_1 = \lambda_2 = 1/2$, as the masses of the $u$ and $d$ quarks are assumed to be the same.

The decay width for the process $D^*(0) \rightarrow D(p) + \pi(p')$, is obtained from the matrix element of the light quark pair creation term of the free Dirac Hamiltonian density

$$
\mathcal{H}_{q\bar{q}}(x, t = 0) = \bar{Q}^{\mu}_{q}(x)\left(-i\alpha \cdot \nabla + \beta M_q\right)Q_{q}(x)
$$

(9)

between the initial and the final states. In equation (9), $M_q$ is the constituent mass of the light quark, $q = (u,d)$, $\alpha$ and $\beta$ are the Dirac matrices, and, the subscript $q$ of the field operators in equation (9) refers to the fact that $\bar{q}$ and $q$ are the constituents of the $D$ and $\pi$ mesons with momenta $p$ and $p'$ respectively in the final state of the decay of the $D^*$ meson. The matrix element is evaluated using the explicit contructions for the initial and final states given by equations (5)–(8) and is obtained as

$$
\langle D(p) | \langle \pi(p') | \int \mathcal{H}_{q\bar{q}}(x, t = 0) dx | D^{*m}(0) \rangle = \delta(p + p') A_{D^*}(|p|) p^m,
$$

(10)

where,

$$
A_{D^*}(|p|) = 6c \left(\frac{\pi}{a}\right)^{3/2} \exp \left[ab^2|p|^2 - \frac{1}{2} \left(\lambda_2^2 R_D^2 + \frac{1}{4} R_\pi^2\right) |p|^2\right] \left[F_0 + F_1 \left(\frac{3}{2a}\right)\right].
$$

(11)

In the above,

$$
a = \frac{1}{2} \left(R_{D^*}^2 + R_D^2 + R_\pi^2\right); \quad b = \frac{1}{2a} \left(R_D^2 \lambda_2 + \frac{1}{2} R_\pi^2\right), \quad c = \frac{1}{6} \cdot \frac{1}{2\sqrt{3}} \left(\frac{R_D^2 R_D^2 R_\pi^2}{\pi^3}\right)^{\frac{3}{2}}.
$$

(12)

and,

$$
F_0 = (b - 1) \left(1 - \frac{1}{8M_q^2}|p|^2 (\lambda_2^2 - \frac{1}{2})^2\right)
$$

$$
- (b - \lambda_2) \left(\frac{1}{2} + \frac{1}{4M_q^2}|p|^2 \left(\frac{3}{4} b^2 - \frac{5}{4} b + \frac{7}{16}\right)\right)
$$

9
\[-(b - \frac{1}{2}) \left[ \frac{1}{2} + \frac{1}{4M_{q}^{2}} |p|^2 \left( \frac{3}{4} b^2 - (1 + \frac{1}{2} \lambda_2) b + \lambda_2 - \frac{1}{4} \lambda_2^2 \right) \right] \]

\[ F_1 = -\frac{1}{4M_{q}^{2}} \left[ \frac{5}{2} b - \frac{9}{8} - \frac{11}{12} \lambda_2 \right]. \tag{13} \]

For the $D^*$ meson decaying at rest, the magnitude of the 3-momentum of the outgoing $D(\pi)$ meson is given as

\[ |p| = \left( \frac{1}{4} m_{D^*}^2 - \frac{m_{D}^2 + m_{\pi}^2}{2} + \frac{(m_{D}^2 - m_{\pi}^2)^2}{4m_{D^*}^2} \right)^{1/2}. \tag{14} \]

With $\langle f | S | i \rangle = \delta_4(P_f - P_i) M_{fi}$, we have

\[ M_{fi} = 2\pi (-i A^{D^* f} \langle |p| \rangle_p)^m. \tag{15} \]

The expression of the decay width of $D^* \rightarrow D\pi$ is obtained by taking the average over the initial spin components as

\[ \Gamma(D^*(0) \rightarrow D(p + \pi(-p))) = \gamma_{D^*}^2 \frac{1}{2\pi} \int \delta(m_{D^*} - p_D^0 - p_\pi^0) |M_{fi}|^2_{av} dp \]

\[ = \gamma_{D^*}^2 \frac{8\pi^2 p_D^0 p_\pi^0}{3m_{D^*}} |A^{D^* f}(|p|)|^2 |p|^3, \tag{16} \]

where $p_D^0 = (|p|^2 + m_D^2)^{1/2}$ and $p_\pi^0 = (|p|^2 + m_\pi^2)^{1/2}$ are the energies of the outgoing $D$ meson and pion respectively. In the above equation, $\gamma_{D^*}$ is the production strength of $D\pi$ from decay of $D^*$ meson, which is fitted from its vacuum decay width. In the presence of the magnetic field, the masses of the charged $D$ and $D^*$ mesons the lowest Landau level are given by equation \[14\]. The expression for the decay width of $D^* \rightarrow D\pi$ given by equation \[16\] does not account for the mixing of the $D$ and $D^*$ mesons in the presence of magnetic fields. The mixing of the pseudoscalar mesons and the vector mesons leads to a drop (increase) in the mass of the $D$ meson (longitudinal component of the $D^*$ meson) in the presence of a uniform magnetic field. When we include the mixing effect, the expression for the decay width of $D^* \rightarrow D\pi$ is modified to

\[ \Gamma^{PV}(D^*(0) \rightarrow D(p) \pi(-p)) = \gamma_{D^*}^2 \frac{8\pi^2}{3} \left[ \left( \frac{2}{3} |p| \beta_D^0 (|p|) p_\pi^0 (|p|) A^{D^* f}(|p|)^2 \right) \right. \]

\[ + \left( \frac{1}{3} |p| \beta_D^0 (|p|) p_\pi^0 (|p|) A^{D^* f}(|p|)^2 \right) \left( |p| \rightarrow |p| (m_{D^*} = m_{D^*}^{PV}, m_D = m_D^{PV}) \right) \right]. \tag{17} \]

In the above, the first term corresponds to the transverse polarizations for the vector $D^*$ meson, which remain unaffected by the mixing of the $D$ and $D^*$ states. However, the masses
of the charged $D^*$ (and $D$) mesons are modified due to the lowest Landau level as given by equation (4). The second term in (17) corresponds to the longitudinal component of the $D^*$ meson, where the pseudoscalar-vector meson mixing leads to the modifications of the masses of the longitudinal component of the $D^*$ meson as well as the $D$ mesons, as given by equation (3). In the presence of the magnetic field, these mixing effects are taken into account in addition to the Landau level contributions for the charged $D$ and $D^*$ mesons in the presence of the magnetic fields. For the charged mesons the transverse components are also modified in the presence of the magnetic field, whereas, the mixing effects modify only the masses of the longitudinal component of the $D^*$ meson.

**B. Decay width of $\Psi(3770) \rightarrow D\bar{D}$**

The decay width of $\Psi(3770) \rightarrow D\bar{D}$ in (magnetized) matter was investigated using the field theoretical model for hadrons with quark (and antiquark) constituents [39, 43]. The expression of the decay width of $\Psi(3770) \rightarrow D\bar{D}$ including the PV ($\Psi(3770) - \eta_c$) mixing in the presence of a magnetic field is given as [43]

$$\Gamma^{PV}(\Psi \rightarrow D(P)\bar{D}(-P)) = \frac{\gamma^2}{3} \frac{8\pi^2}{3} \left[ \left( \frac{2}{3} |P|^2 \frac{P_D^0(|P|)P_D^0(|P|)}{m_\Psi} A^\Psi(|P|) \right)^2 \right]$$

$$+ \left( \frac{1}{3} |P|^2 \frac{P_D^0(|P|)P_D^0(|P|)}{m_\Psi} A^\Psi(|P|)^2 \right) \left( |P| \rightarrow |P|(m_\Psi = m_{PV}) \right),$$

where,

$$A^\Psi(|P|) = 6c_\Psi \exp[(a_\psi b_\Psi^2 - R_D^2 \lambda_\Psi^2)|P|^2] \cdot \left( \frac{\pi}{a_\Psi} \right)^{3/2} \left[ F_0^\Psi + F_1^\Psi \frac{3}{2a_\Psi} + F_2^\Psi \frac{15}{4a_\Psi^2} \right].$$

The parameters $a_\Psi$, $b_\Psi$ and $c_\Psi$ are given in terms of $R_D$ and $R_\Psi$, which are the strengths of the harmonic oscillator wave functions for the $D(\bar{D})$ and the charmonium states, and $F_i^\Psi(i = 0, 1, 2)$ are polynomials in $|P|$, the magnitude of the momentum of the outgoing $D(\bar{D})$ meson given by [39]

$$|P| = \left( \frac{m_\Psi^2}{4} - \frac{m_D^2 + m_D^2}{2} + \frac{(m_D^2 - m_D^2)^2}{4m_\Psi^2} \right)^{1/2}. $$

The first term in equation (18) corresponds to the transverse polarizations for the charmonium state, $\Psi \equiv \Psi(3770)$, whose masses remain unaffected by the mixing of the pseudoscalar
and vector charmonium states. The second term in Eq. (18) corresponds to the longitudinal component of the charmonium state whose mass is modified due to mixing with the pseudoscalar meson in the presence of the magnetic field. In Ref. [43], the mass modification of Ψ(3770) due to mixing with η_c and the Landau level contributions for D and D̄ were considered for the computation of the the in-medium decay width in the presence of a magnetic field. In the present work, we compute the decay width accounting also for mass modifications of D and D̄ due to mixings with the vector D* and D̄* mesons in the presence of a magnetic field.

IV. RESULTS AND DISCUSSIONS

The masses of the D and D* are calculated in the presence of a uniform magnetic field arising due to the mixing of the pseudoscalar and vector mesons, with additional Landau level contributions for the charged open charm mesons. The mixing is taken into account through a phenomenological Lagrangian interaction given by equation (1). This is observed to lead to substantial drop (rise) in the pseudoscalar (longitudinal component of the vector) meson. The coupling parameter g_{PV} is calculated from the radiative decay width of the vector meson, V to pseudoscalar meson, P, V \to P\gamma. There is observed to be mass splitting of the D^0 and D^*0, as well as, for D^+ and D^*+ due to the mixing. As we shall see later, the effect is observed to be much more prominent for the neutral mesons as compared to the charged open charm mesons, when the g_{PV} is fixed at its the zero magnetic field value. This is due to the much larger value of the mixing strength parameter, g_{PV} for the neutral mesons (D^*0 and D^0) as compared to g_{PV}(eB = 0) for the charged mesons (D^*+ and D^+). However, as has been mentioned earlier, the mixing parameter for the charged mesons is magnetic field dependent, because of the Landau level contributions to the vacuum masses of these mesons. The value of the mixing parameter for the charged open charm mesons is observed to increase appreciably at high magnetic fields, which leads to significant modifications to the masses of these mesons for large magnetic fields.

In the present work, we investigate the effects of the magnetic field on the decay widths D* \to D\pi from the mass modifications of the D* and D mesons in the presence of a magnetic field. The decay widths for the charged D* meson (D^{*+} \to D^+\pi^0 and D^{*+} \to D^0\pi^+) and
FIG. 1: (Color online) The masses of the $D$ meson and the longitudinal component of the $D^*$ mesons are plotted as functions of $eB/m_{\pi}^2$. The masses of the charged mesons $D^{++}$ and $D^+$ are compared with the masses for the case when the PV mixing parameter is fixed at the zero magnetic field value (shown as long dash-dotted lines). The effects of the pseudoscalar–vector (PV) mixing on these masses are shown for the charged (for $g_{PV} = g_{PV}(eB = 0)$) and neutral mesons. The Landau contributions to the masses of the charged mesons are also shown as the short dash-dotted lines. The dotted lines show the masses when the mixing effects as well as the Landau level contributions (for charged mesons) are not included.
FIG. 2: (Color online) The logarithm of the decay widths for $D^* \rightarrow D\pi$ (in KeV) for the charged $D^{*+}$ and neutral $D^{*0}$ are plotted as functions of $eB/m_\pi^2$ in panels (a) and (b) respectively. The PV mixing parameter of the charged mesons is magnetic field dependent due to Landau level contributions to their masses. The decay widths, $D^{*+} \rightarrow D^0\pi^+$ as well as $D^{*+} \rightarrow D^+\pi^0$ are shown accounting for the magnetic field dependence of this parameter, and compared with the cases when this parameter is fixed at the zero magnetic field value (shown as the short dash-dotted lines). The decay widths are also plotted for the case with only the PV mixing effects (with $g_{PV} = g_{PV}(eB = 0)$).
FIG. 3: (Color online) The partial decay widths for $\Psi(3770) \to D\bar{D}$ (in MeV) plotted as functions of $eB/m^2_\pi$ for the final states (I) $D^+D^-$, (II) $D^0\bar{D}^0$ and total of these two contributions (I+II). These are plotted without and with the pseudoscalar-vector meson (PV) mixing effects on the masses of the initial and final state mesons in panels (a) and (b) respectively. In panel (b), the results are compared with the case (shown as dotted lines) when the mass modifications of the $D$ and $\bar{D}$ mesons do not include the contributions from the PV mixing. The decay width for (I) $\Psi(3770) \to D^+D^-$ as well as the total (I+II) are compared to the case when the $D^{\pm} - D^{\ast\pm}$ mixing parameter is fixed at the zero magnetic field value (shown as dot-dashed lines).
the neutral $D^{*0}$ meson ($D^{*0} \rightarrow D^{0}\pi^{0}$) are calculated using a field theoretical model for composite hadrons as described in the previous section. The values of the constituent light quark ($q = u, d$) masses are taken to be $M_u = M_d = 330$ MeV and that of the heavy charm quark as 1600 MeV \[39\]. The vacuum values for the masses (in MeV) of these mesons are taken to be $m_{D^{*+}} = 2010.26$, $m_{D^{*0}} = 2006.85$, $m_{D^{+}} = 1869.65$, $m_{D^{0}} = 1864.8$, $m_{\pi^+} = 139.57$, $m_{\pi^0} = 135$ \[46\]. As has already been mentioned, the parameters $\lambda_1$ and $\lambda_2$ in equation (6), are the fractions of the mass (energy) of the $D$ meson at rest (in motion), carried by the constituent light antiquark and the constituent heavy charm quark. For the quark-antiquark bound states, these fractions add up to 1, i.e., $\lambda_1 + \lambda_2 = 1$, yielding the sum of the masses (energies) of the quark and antiquark constituents to be the mass (energy) of the heavy flavour meson. The value of $\lambda_2$ is calculated to be 0.85 \[39\], by assuming the binding energy of the hadron as shared by the quark (antiquark) to be inversely proportional to the quark (antiquark) mass \[37\]. The harmonic oscillator strength parameter for $D$ meson is taken as $R_D=(310 \text{ MeV})^{-1}$ which is consistent with the experimental values of the vacuum decay widths of $\Psi(3770) \rightarrow D\bar{D}$, and, $\Psi(4040)$ to $D\bar{D}$, $D\bar{D}^*$, $D^*\bar{D}$ and $D^*\bar{D}^*$ \[22, 39\]. In the present work of computation of the decay width, $\Gamma(D^* \rightarrow D\pi)$, the value of the harmonic oscillator strength for $D^*$ meson, $R_{D^*}$ has been taken to be the same as that of the $D$ meson, $R_D$ and the value of $R_\pi$ of the pion wave function is fitted to the square of the charge radius of pion as 0.4 fm$^2$, which yields $R_\pi=(211 \text{ MeV})^{-1}$ \[37, 39\].

The mixing of the $D$ and $D^*$ in the presence of a magnetic field is described by the interaction Lagrangian given by equation (1). The coupling constant, $g_{PV}$ is obtained from the observed decay width for the process $V \rightarrow P\gamma$. For the process $D^{*+} \rightarrow D^+\gamma$, the observed value of 1.33 keV (1.6% of the total width of $D^{*+}$ of 83.4 KeV) (which is the same as the decay width of $D^{*-} \rightarrow D^-\gamma$) gives the value of the coupling constant, $g_{D^{\pm}D^{*\pm}}$ as 0.9089, when the vacuum masses for the charged open charm vector and pseudoscalar mesons ($D^{*\pm}$ and $D^{\pm}$) are used in equation (2). However, in the presence of a magnetic field, the masses of these charged mesons have contributions from the Landau levels (dominantly from the lowest Landau level in the presence of strong magnetic fields) and are given by $m_{D^\pm}(eB) = \sqrt{m_{D^{*\pm}}^2 + eB}$, $m_{D^{*\pm}}(eB) = \sqrt{m_{D^{*\pm}}^2 - eB}$. The coupling parameter $g_{PV} \equiv g_{D^{\pm}D^{*\pm}}$, as obtained from the decay width of the process $D^{*\pm} \rightarrow D^{\pm}\gamma$, thus turns out to
be dependent on the magnetic field. The value of this parameter for $D^\pm - D^{*\pm}$ mixings is modified from the value of 0.9089 for zero magnetic field to around 1.484, 2.0587 and 5.7337 for the values of $eB/m^2_\pi$ of 4, 6 and 10 respectively. The value of this coupling parameter for a given magnetic field and the masses of $D^\pm$ and $D^{*\pm}$ mesons including the lowest Landau level contributions, are used in equation (5) to compute the masses $m_{V_{||}}^{(PV)}$, due to the pseudoscalar-vector meson mixing, of the pseudoscalar meson $P \equiv D^\pm$ and longitudinal component of the vector meson $V \equiv D^{*\pm}$, in the presence of the magnetic field. The masses for these charged mesons obtained from the PV mixing in the presence of a magnetic field, have in addition the lowest Landau level contributions, as given by equation (4). The large increase in the value of the $D^\pm - D^{*\pm}$ mixing parameter at high magnetic fields, as we shall see later, is observed to modify appreciably the masses of the charged open charm mesons (and hence the decay widths involving these charged mesons), as compared to the case when the mixing parameter is taken to be fixed at the zero magnetic field value.

We next consider the mixing effect between the neutral $D$ and $D^*$ mesons in the presence of a magnetic field. The value of $g_{D^0 D^{*0}}$ is needed to study the mixing of the $D^{*0}$ and $D^0$ mesons, which can be obtained from the decay width of $D^{*0} \rightarrow D^0 \gamma$. This partial decay width is 35.3 % of the total width of $D^{*0}$ [46]. However, its value is not known, as the total width of $D^{*0}$ is still not measured experimentally with accuracy [46]. The decay of $D^{*0}$ comprises of the decay modes $D^{*0} \rightarrow D^0 \pi^0$ and $D^{*0} \rightarrow D^0 \gamma$ with the branching ratio of 64.7:35.3 [46]. In the present work, the value of the radiative decay width of $D^{*0}$ is estimated in a similar manner as was done in Ref. [24]. The coupling constant for $D^{*0} \rightarrow D^0 \pi^0$ is assumed to be the same as that of the decay $D^{*+} \rightarrow D^+ \pi^0$, the latter as calculated from its observed decay width. This value of the coupling constant is used to calculate the decay width of $D^{*0} \rightarrow D^0 \pi^0$, and the decay width of $D^{*0} \rightarrow D^0 \gamma$, is then obtained from the observed branching ratio of these two decay modes. It might be noted here that in Ref. [24], the decay width of the process $D^* \rightarrow D \pi$ was calculated using a phenomenological Lagrangian interaction $L_{int} \sim g_\pi (\partial^\mu D) D_{\mu}$ and the value of the coupling constant, $g$, was assumed to be same for the processes, $D^{*0} \rightarrow D^0 \pi^0$ and $D^{*+} \rightarrow D^+ \pi^0$, using isospin symmetry. In the present work, we use the values of the coupling strength $\gamma_{D^*}$ as given in the expression for the decay width of $D^* \rightarrow D \pi$ (given by equation [16]) calculated within
the field theoretic model of composite hadrons, to be same for these two processes. The observed decay width of \( \Gamma(D^{*+} \rightarrow D^+\pi^0) \) as 25.6 KeV \cite{16} yields the value of \( \gamma_{D^*} \) to be 4.27. Using this value for \( \gamma_{D^*} \), the decay width of \( \Gamma(D^{*0} \rightarrow D^0\pi^0) \) is obtained as 35.9 keV. This gives the value of the decay width \( \Gamma(D^{*0} \rightarrow D^0\gamma) \) as 19.593 keV, using the measured branching ratio of \( \Gamma(D^{*0} \rightarrow D^0\gamma) : \Gamma(D^{*0} \rightarrow D^0\pi^0) \) to be 64.7:35.3 \cite{16}. Using equation (2), the value of the coupling parameter, \( g_{VP} = g_{D^{*0}D^0} \) is obtained as 3.426. This value of the coupling parameter may be compared to the value of 3.6736 Ref. \cite{24}, evaluated using the phenomenological Lagrangian interaction \( \sim g\pi(\partial^\mu D^\ast)D_{\mu} \) and using the branching ratio of \( \Gamma(D^{*0} \rightarrow D^0\pi^0) : \Gamma(D^{*0} \rightarrow D^0\gamma) \) as 61.9:38.1. The value of the mixing strength parameter, \( g_{D^{*0}D^0} = 3.426 \) as estimated in the present work, is used to study the effects of the mixing on the masses of the \( D^0 \) and \( D^{*0} \) mesons in the presence of a magnetic field. The effect of the magnetic field on the decay \( D^{*+} \rightarrow D^0\pi^+ \) is also studied in the present work. The value for \( \gamma_{D^*} \) for this channel is obtained to be 5.94, from the measured value of the vacuum decay width of \( D^{*+} \rightarrow D^0\pi^+ \) as 56.46 keV \cite{16}.

The masses for the charged and neutral open charm mesons are plotted as functions of \( eB/m_{\pi}^2 \) in figure 1. As has already been mentioned, the parameter for \( D^+ - D^{*+} \) mixing is calculated using equation (2), from the observed value of the radiative decay width of \( D^{*+} \rightarrow D^+\gamma \) and, this parameter is dependent on the magnetic field, due to the Landau level contributions to the masses for these charged mesons in the presence of a magnetic field. The effects of the pseudoscalar-vector meson mixing (marked as PV) on the masses of these mesons are shown for the charged and neutral mesons in panels (a) and (b) respectively, when the \( D^+ - D^{*+} \) mixing parameter is fixed at the zero magnetic field value. For this case, the mixing is observed to lead to a monotonic decrease (increase) in the mass of the \( D \) (longitudinal component of \( D^* \)) meson. For the neutral \( D \) and \( D^* \) mesons, the shifts in the masses are observed to be much larger due to the mixing effects, as compared to the case of the charged mesons. This is due to the much larger value of the coupling parameter, \( g_{VP} \) of 3.426 for \( D^0D^{*0} \) mixing as compared to the value of 0.9089 (for zero magnetic field case) for the \( D^+ - D^{*+} \) mixing. In the present work, the masses of the charged \( D \) and \( D^* \) mesons have contributions from the lowest Landau level, as given by equation [4]. These contributions, shown as the dot-dashed lines, lead to a rise (drop) in the mass of the \( D^+ \) (\( D^{*+} \)) meson.
In panel (a), the masses due to the combined effects of including the Landau level as well as the mixing contributions are shown for the $D^+$ and $D^{*+}$ respectively. These masses are observed to lead to an initial increase (drop) for the $D^+$ ($D^{*+}$ $||$) up to around $eB = 5m^2_{\pi}$, followed by a slow decrease (increase) as the magnetic field is further increased, when the mixing effects dominate over the Landau level contributions. When the mixing parameter for the charged open charm mesons is fixed at the zero magnetic field value of $0.9089$, the mass of the $D^{*+} || (D^+)$ (in MeV) is modified from its vacuum value 2010.26 (1869.65) to 2014 (1866) and 2024 (1856.8) at $eB = 5m^2_{\pi}$ and $eB = 10m^2_{\pi}$ respectively in the presence of only mixing effect and to 1991.4 (1890.3) and 1991.2 (1892.1), when the Landau level contributions are also taken into account. The masses of the charged open charm mesons are thus observed to vary only marginally for $eB$ larger than $5 m^2_{\pi}$. On the other hand, the mass of neutral $D^{*0} || (D^0)$ (in MeV) is observed to be modified from the vacuum value of 2006.9 (1864.83) to 2049.4 (1826.1) and 2129.9 (1757) at $eB = 5m^2_{\pi}$ and $eB = 10m^2_{\pi} (\sim 0.1\text{GeV}^{-2})$ respectively in the presence of the mixing effect. The shifts in the masses of the neutral open charm mesons are thus observed to be much larger than for the charged $D^{*+}$ and $D^+$ mesons, as is observed in figure 1 when the charged $D^* - D$ mixing parameter is fixed at its value at $eB = 0$. However, there are observed to be dominant modifications when the magnetic field dependence of this parameter is considered. Above a value of the magnetic field of around $4 m^2_{\pi}/e$, there is observed to large increase (drop) in the mass of the $D^{*+}(D^+)$ meson. The values of the mass of the $D^{*+}(D^+)$, accounting for both the PV mixing as well as Landau quantization effects, are observed to be modified from 1989.5 (1892.5) and 1991.2 (1892.1) to 2015.7 (1867.9) and 2250.7 (1673.9) for $eB = 6m^2_{\pi}$ and $eB = 10m^2_{\pi}$, when the magnetic field dependence of the $D^{*+} - D^+$ mixing parameter is taken into account. These are observed to modify the decay widths of the charged $D^*$ meson as well as $\Psi(3770) \to D^+D^-$, as we shall later.

The decay widths of $D^* \to D\pi$ are computed using a field theoretic model of composite hadrons. The Landau level contributions modify the masses of the charged $D$ and $D^*$ mesons, whereas, the pseudoscalar vector meson mixing modifies the masses of the longitudinal component of the $D^*$ meson as well as of the $D$ mesons. The decay width of $D^* \to D\pi$ is given by equation [17], which has contributions from mixing effects from the longitudinal...
$D^*$ meson. The dependence of the decay width given by equation (17) on the masses of the $D$, $D^*$ and $\pi$ are through the center of mass momentum $|\mathbf{p}|$ given in terms of the masses of the $D$ and $D^*$ mesons, including the Landau level contributions for the charged mesons, whereas, the second term has the masses of these mesons including the mixing effects as well. The center of mass momentum, $|\mathbf{p}|$ is given by equation (14), in terms of the masses of the decaying, $D^*$ meson and the produced mesons, $D$ and $\pi$.

The effects of the magnetic field on the decay widths of the charged $D^{*+}$ and $D^{*0}$ are shown in panels (a) and (b) in figure 2. When the $PV$ mixing parameter is fixed at its zero magnetic field value for the charged open charm mesons ($g_{PV} = g_{PV}(eB = 0)$), in the presence of only the pseudoscalar-vector meson mixing (marked as PV), the decay width of $D^{*+} \to D^{+}\pi^0$ is observed to be modified only marginally as compared to the case when these effects are not taken into account (the decay widths remain at their vacuum values as shown by the dotted line). This is because the small value of the coupling parameter, $g_{PV}(eB = 0)=0.9089$ for the $D^+ - D^{*+}$ mixing, leads to moderate modifications in the masses of the $D^{*+}$ and $D^+$ mesons. However, the decay width of $D^{*+} \to D^0\pi^+$ is observed to increase appreciably with the magnetic field, when we consider only the mixing effect, from its vacuum value of 56.46 keV to a value of 0.6569 (3.991) MeV at the value of $eB$ as 5$m^2_\pi$ (10 $m^2_\pi$). In the presence of $PV$ mixing effects as well as Landau level contributions, when the magnetic field dependence of the $D^{*+} - D^+$ mixing parameter is taken into account, there is observed to be steeper rise of the decay width $D^{*+} \to D^0\pi^+$, as compared to the the case when this parameter is fixed at the zero magnetic field value, as can be seen from figure 2. However, the decay width of $D^{*+} \to D^+\pi^0$ remains almost unchanged, for the cases of $g_{PV}(eB)$ and $g_{PV}(eB = 0)$, due to the marginal magnetic field dependence of this parameter for upto $eB \sim 0.5m^2_\pi$ (beyond which the decay width drops appreciably). In the presence of Landau effects, there is observed to be an initial drop in the width of $D^{*+} \to D^0\pi^+$ followed by a rise as the magnetic field is further increased. In the panel (b), the logarithm of the decay width of $D^{*0} \to D^0\pi^0$ is plotted as a function of $eB/m^2_\pi$. The decay width of $D^{*0} \to D^0\pi^0$ is observed to have large contribution from the mixing effects. This is due to the large positive (negative) shifts in the mass of the neutral vector $D^{*0}$ ($D^0$) in the presence of a strong magnetic field. The decay widths for the modes $D^{*+} \to D^0\pi^+$ as
well as $D^{*0} \rightarrow D^{0}\pi^{0}$ are observed to have significant contributions for large values of the magnetic fields. These should have implications in the enhancement of the neutral $D$ mesons as compared to the charged $D^+$ meson.

In figure 3, the dependence of the decay widths of $\Psi(3770) \rightarrow D\bar{D}$ on the magnetic field are shown, for the cases when the contributions from PV mixing to the masses of the charmonium as well as $D$ and $\bar{D}$ mesons are considered. These are compared with the case shown as dotted lines) when the mass modifications from the pseudoscalar-vector meson mixing are not taken into account for the open charm mesons in panel (b) of figure 3 [43].

In panel (a), the decay widths of $\Psi(3770)$ to the charged and neutral $D\bar{D}$ pair are shown for the case when the PV mixing contributions are not taken into account for the charmonium as well as open charm mesons, but only the Landau level contributions are considered for the charged $D^{\pm}$ mesons. Due to the positive Landau level contributions to the masses of the charged pseudoscalar mesons, there is observed to be a decrease of the decay width for the $D^+D^-$ final state, which is observed to vanish for $eB \geq 3m^2_\pi$. On the other hand, the final state $D^{0}\bar{D}^{0}$ decay width remains unaffected by the magnetic field (as there are no Landau level contributions for the neutral open charm mesons). Fig 3(b) shows the results for the decay widths of $\Psi(3770)$ accounting for the PV mixing contributions for the masses of the charmonium state as well as open charm mesons, in addition to the Landau level contributions for the charged open charm mesons. It is observed that the PV mixing contributions to the masses of the final state open charm mesons, along with the PV mixing contributions to the mass of $\Psi(3770)$ (due to mixing with $\eta_c'$) lead to larger values of the decay widths. As has already been mentioned, the Landau level contributions are considered for the charged open charm mesons in the presence of the magnetic field. As may be seen from figure 1(a), while accounting for the PV mixing contributions along with the Landau level contributions, there is observed to be an initial increase (drop) in the mass of the charged $D^+$ ($D^{*+||}$) with increase in the magnetic field, due to the Landau level contribution dominate over the PV mixing contributions. This leads to a decrease in the mass difference between the $D^+$ and $D^{*+||}$ with rise in the magnetic field, due to which the PV mixing effects start becoming more important since the mass splitting between the pseudoscalar and longitudinal component of the vector mesons from PV mixing is inversely proportional to the mass.
difference of the mesons [24, 43]. As the magnetic field is further increased, the PV mixing contributions dominate over the Landau level contributions. At higher values of the magnetic field, the mass of the charged pseudoscalar meson is observed to drop. This is observed as enhancement of the decay width of $\Psi(3770) \to D^+ D^-$ when the PV mixing effects are also taken into account for the open charm mesons, as compared to when the PV mixing effects are considered only for the charmonium state (due to $\Psi(3770) - \eta'_c$ mixing). The decay width of $\Psi(3770) \to D^0 \bar{D}^0$ is observed to have a positive contribution from the $D - D^*$ mixing, as may be seen from the panel (b) of figure [43]. There is observed to be a drop in the decay width with the neutral $D \bar{D}$ final state, with further increase in the magnetic field. The decay width (in MeV) of $\Psi(3770)$ to the neutral $D \bar{D}$ is observed to be around 39.1 (33.2) for $eB = 6 (10) m^2_\pi$, which is much larger as compared to the values of 6.4 (10.2) for the $D^+ D^-$ final state, when the $D^{*\pm} - D^{\pm}$ mixing parameter is fixed at its zero magnetic field value, and 10.8 (3.1) when the magnetic field dependence of the charged $D^* - D(\bar{D}^* - \bar{D}$ mixing is taken into account. The much larger value of the decay width to the neutral $D \bar{D}$ pair as compared to the $D^+ D^-$ final state, may be observed as the neutral $D \bar{D}$ mesons to be much more profusely produced from decay of charmonium states as compared to the charged $D \bar{D}$ mesons in the presence of strong magnetic fields.

V. SUMMARY

The masses of the $D$ and $D^*$ mesons are studied in the presence of magnetic fields, taking the effects of the mixing of the pseudoscalar and vector mesons into consideration. The charged open charm mesons have additionally the Landau level contributions. The masses of the $D$ (and $\bar{D}$) and the vector $D^*$ mesons in the presence of a magnetic field are used to study the decays of the charged and neutral $D^*$ mesons to $D\pi$, as well as to study the decay width of $\Psi(3770) \to D \bar{D}$. For the charmonium decay width, the mass modification of $\Psi(3770)$ in the presence of a magnetic field is due to its mixing with the pseudoscalar mesons, $\eta'_c$. The decay widths are computed by using a composite model for the hadrons with quark and antiquark constituents, using the light quark-antiquark pair creation term of the free Dirac Hamiltonian for the constituent quarks. The matrix element of this term between the initial and final states is used to calculate the decay width. The
matrix element is multiplied with a strength parameter for the quark pair creation, which is fitted from the observed vacuum decay widths for the specific decay process ($D^* \rightarrow D\pi$ and $\Psi(3770) \rightarrow D\bar{D}$). For the charged $D^* - D$ mixing, the parameter $g_{PV}$ depends on the magnetic field, because of the Landau contributions to the masses of these charged mesons in the presence of a magnetic field. The $D^{*\pm} - D^\pm$ mixing parameter is observed to increase appreciably with increase in the magnetic field. This leads to dominant modifications of the charged open charm mesons, and hence on the decay widths of the charged $D^* \rightarrow D\pi$, as well as of $\Psi(3770) \rightarrow D^+D^-$ at large values of the magnetic field. The $\Psi(3770)$ decays dominantly to the neutral open charm mesons as compared to $D^+D^-$ mesons, in the presence of strong magnetic fields. The created magnetic fields in the peripheral ultra-relativistic heavy ion collision experiments, e.g., at RHIC and LHC, are huge, and the matter resulting from the high energy collision is of (extremely) low density. For zero (extremely small) density, the lowest charmonium state which can decay to $D\bar{D}$ is $\Psi(3770)$. The present work of the study of the effects of magnetic field on the masses of the open charm mesons, $D$, $\bar{D}$, $D^*$ and $\psi(3770)$, and their subsequent effect on the decay widths of $D^* \rightarrow D\pi$ and $\Psi(3770) \rightarrow D\bar{D}$ can be of relevance to the observables, e.g., the production of the open charm mesons and charmonium states in peripheral ultra-relativistic heavy ion collision experiments.

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