\textit{B and B$^*$ mesons in magnetized matter} \\
- effects of magnetic catalysis

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Abstract

The in-medium masses of the open bottom mesons ($B$, $\bar{B}$, $B^*$, and $\bar{B}^*$) are studied in the magnetized nuclear matter by considering the effects of magnetic catalysis within a chiral effective model. The mass modifications arise due to the interactions of the open bottom mesons with the nucleons and the scalar mesons of the medium, calculated in terms of the scalar and number densities of the nucleons and the fluctuations of the scalar fields from their vacuum expectation values in the chiral model. The effects of magnetized Dirac sea polarization is incorporated through the baryon tadpole diagram on the scalar fields which in turn represent the QCD condensates. The contribution of the magnetic field on the Fermi sea of nucleons are taken into account through the protons Landau energy levels and the nucleons anomalous magnetic moments. The additional contribution of the lowest Landau level for the charged mesons are taken into account. In the presence of an external magnetic field, the PV mixing effects between the longitudinal component of the vector mesons and the pseudoscalar mesons ($B - B^*\parallel$ and $\bar{B} - \bar{B}^*\parallel$) are studied, which lead to a level repulsion between their masses, increasing with magnetic field. The magnetic fields are observed to have significant contribution on the in-medium masses of the open bottom mesons through magnetic catalysis as compared to the no sea and hence no catalysis effect, in the magnetized nuclear matter. In the vacuum, the contribution of magnetic field is non-trivial through the magnetized Dirac sea and the nucleons anomalous magnetic moments have important effects via the magnetic field expansion of the fermion propagators, in the Dirac sea of nucleons.

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I. INTRODUCTION

The study of the in-medium properties of heavy flavor hadrons [1], has been an interesting topic of research in the studies of the hadron properties under extreme environment of matter. This topic has intense research interest due to its relevance in the high energy heavy ion collision experiments, where matter at very high temperature and/or density can be created from the collisions of heavy ions, at the ultra relativistic high energy. In the non-central heavy ion collision experiments, magnetic fields of very large magnitudes have been estimated by many works [2–6] ($eB \sim 2m_{\pi}^2$ at RHIC in BNL and $eB \sim 15m_{\pi}^2$ at LHC in CERN). The time evolution of the produced field is still an open question, needs to solve the magnetohydrodynamic equations, with the proper estimation of the electrical conductivity of the medium [6–9]. The magnetic field produced is weak in the (near) central collisions, due to the small impact parameter and the produced medium becomes dense. On the contrary, in the non-central heavy ion collisions, produced magnetic fields can be very large accompanied by a low density medium. The effects of magnetic fields on the heavy flavor mesons should have observable consequences in the high energy heavy ion collision experiments, since they formed at the early stages of collisions, when the produced magnetic field can still be large.

There have been a lot of studies in the literature, on the in-medium properties of the heavy flavor mesons (both the heavy quarkonia and open heavy flavor mesons) in the presence and absence of magnetic field, using the various approaches of chiral effective model [10–19], QCD sum rule approach [20–32], potential models [33–35], the coupled channel approach [36, 37], Quark meson coupling (QMC) model [38, 39], heavy meson effective theory [40], etc. The studies in the QMC model show attractive interactions of the $J/\Psi$ as well as of the open heavy flavor mesons ($\bar{D}, B$) in nuclear matter, suggesting the possibility of creating meson-nuclei bound states [38]. The in-medium masses of the heavy flavor mesons have been investigated within a chiral effective model. The chiral effective model in its original $SU(3)$ version [41, 42], generalized to incorporate the interactions of the heavy flavor (charm and bottom) hadrons with the baryons and scalar mesons in the hadronic medium. The masses of the heavy quarkonia (charmonia and bottomonia) are obtained from the medium modifications of a scalar dilaton field, $\chi$ which corresponds to the QCD gluon condensates [15, 16, 19]. The masses of the open heavy flavor mesons (open charm and open
bottom mesons) get modified in a hadronic medium by their interactions with the baryons and scalar mesons of the medium [14,15,17,19,43]. The effects of the magnetic field have been studied on the masses of the open charm [10,44] and open bottom mesons [11,45] in magnetized nuclear medium within the chiral effective model, without taking into account the effects from the magnetized Dirac sea. The magnetic field contributed through the Landau energy levels of the protons and the anomalous magnetic moments of the nucleons via scalar and number densities of the protons and neutrons in the nuclear matter [10,11,46–49]. The charged heavy flavor mesons ($D^\pm$ and $B^\pm$) have additional mass shifts due to the lowest Landau level (LLL) contribution at finite magnetic field [10,11,45,50]. In the QCD sum rule approach, the in-medium masses of the $1S$ and $1P$ wave states of charmonium and bottomonium have been calculated in the magnetized nuclear matter, from the medium modifications of the scalar and twist-2 gluon condensates calculated within a chiral SU(3) model [24,25], without including the effects of magnetic catalysis due to the magnetic field modifications of the Dirac sea of nucleons. In ref. [51] the contribution of the Dirac sea in the presence of an external magnetic field have been studied on the heavy quarkonia masses in magnetized nuclear matter by using the QCD sum rule approach. The magnetic catalysis effect lead to the increasing masses of the ground states of $\bar{c}c$ and $\bar{b}b$ mesons with magnetic field at zero ($\rho_B = 0$) and nuclear matter saturation density ($\rho_B = \rho_0$). The changes are appreciably visible with magnetic field variation in comparison to the case when only protons Landau energy level contribution were there. The in-medium partial decay widths of charmonium (bottomonium) going to open charm (bottom) mesons (for e.g., $\Psi(3770) \to DD$ and $\Upsilon(4S) \to BB$) have been studied using a field theoretic model for composite hadrons with quark (and antiquark) constituents [44,45,50], as well as within a light quark-antiquark pair creation model or the $^3P_0$ model [52]. The PV mixing effects between the longitudinal component of the vector and the pseudoscalar charm (bottom) mesons at finite magnetic field, have been studied in many works [24,25,44,45,50,51,53,57] and the magnetic fields are seen to have dominant contribution through the mixing effects on their masses and decay widths. The in-medium hadronic decays of the vector open charm meson, $D^* \to D\pi$ have also been studied incorporating the PV mixing effects between $D - D^{*\parallel}$ and LLL contributions for the charged mesons at finite magnetic field [50]. In these studies, the effects of magnetic catalysis have not been considered within the chiral effective model to study the masses of the open heavy flavor mesons and heavy quarkonia in the magnetized nuclear mat-
The rising of the QCD condensates with increasing magnetic field is known as magnetic catalysis \[58–61, 64\]. As the temperature and density dependence of the QCD condensates can modify the hadron properties, the magnetic field modifications of the condensates can contribute significantly on the hadronic properties. In ref.\[63\], the contribution of magnetic catalysis have been studied on the neutral open heavy flavor mesons (D) through the change in the light constituent quark mass with magnetic field. In the literature, there have been studies of the magnetized Dirac sea effects on the quark matter within the Nambu Jona Lasinio (NJL) model \[62, 65–68\]. In ref.\[69\], effects of magnetic catalysis have been studied on the nuclear matter phase transition using the Walecka model and the extended linear sigma model. The work shows a rise of nucleon mass with increasing magnetic field at zero density, zero magnetic moments, indicating the magnetic catalysis effect indirectly through the scalar field dependency of the nucleon mass. The authors of \[70\], have been studied the effects of magnetized Dirac sea in the weak-field approximation, by evaluating the modified fermion propagator in the magnetic field following the nucleon self-energy functions via tadpole diagrams. 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 \[71\] effect on the critical temperature of nuclear matter phase transition was observed. In the literature, there are very few studies of the magnetized Dirac sea effects on the nuclear matter properties.

In our present study, we have introduced the magnetic catalysis effect through the magnetized Dirac sea of nucleons, within the chiral effective model in terms of an additional contribution to the proton and neutron scalar densities via nucleon tadpole diagrams. Then, the in-medium masses of the pseudoscalar open bottom mesons \(B^+(\bar{b}u), B^- (\bar{u}b)\) and \(B^0 (\bar{b}d)\), \(\bar{B}^0 (\bar{d}b)\), and the vector open bottom mesons \(B^{++}, B^{*-}\) and \(B^{*0}, \bar{B}^{*0}\) mesons (with the same quark-antiquark constituents as their pseudoscalar partners) are studied in magnetized nuclear matter incorporating the effects of magnetized Dirac sea within the chiral effective model framework. The contribution of the lowest Landau level for the charged mesons are also considered at nonzero magnetic field. The PV mixing effects are studied on the pseudoscalar and vector (longitudinal component) open bottom mesons incorporating the contribution of the magnetized Dirac sea.

The present paper is organized as follows, in section \[11\] the in-medium masses of the open...
bottom mesons in magnetized nuclear matter are described using the chiral effective model. The sub-section II A illustrates the interaction Hamilton to find the PV mixing effects between the longitudinal component of the vector and the pseudoscalar mesons incorporating the Dirac sea effects in presence of an external magnetic field. The results of our study are discussed in section III. Section IV presents the summary of the present investigation.

II. IN-MEDIUM MASSES OF THE OPEN BOTTOM MESONS

The in-medium masses of the open bottom mesons, $B(B^+, B^0)$ and $\bar{B}(B^-, B^0)$ have been studied within a chiral effective model Lagrangian by generalizing the chiral $SU(3)$ model to incorporate the interactions between the open heavy flavor (bottom) mesons and the light hadrons $[11, 18, 45, 72]$. The original chiral $SU(3)_L \times SU(3)_R$ model with three light quark flavors, is based on the non-linear realization of chiral symmetry $[73–75]$ and the QCD broken scale invariance $[42, 43, 76]$. A logarithmic potential in terms of a scalar dilaton field, $\chi$ $[77]$ represents the scale symmetry breaking effect of QCD in the chiral model. The general form of the Lagrangian density is written as $[42]$

$$\mathcal{L} = \mathcal{L}_{\text{kin}} + \sum_W \mathcal{L}_{BW} + \mathcal{L}_{\text{vec}} + \mathcal{L}_0 + \mathcal{L}_{SB} + \mathcal{L}_{\text{scalebreak}} + \mathcal{L}_{\text{mag}}$$

where, $\mathcal{L}_{\text{kin}}$ represent the kinetic energy terms of baryons and mesons; $\mathcal{L}_{BW}$ gives the baryon-meson interactions for $W = \text{both spin-0 (scalar, pseudoscalar) and spin-1 (vector, axial-vector) mesons; \mathcal{L}_{vec}}$ contains the dynamical mass generation of the vector mesons mass through the interactions with the scalar fields and the vector mesons quartic self-interactions terms; $\mathcal{L}_0$ corresponds to the meson-meson interactions; $\mathcal{L}_{SB}$ is the explicit chiral symmetry breaking term; $\mathcal{L}_{\text{scalebreak}}$ corresponds to a scale invariance breaking logarithmic potential given in terms of the scalar dilaton field, $\chi$. Finally, the magnetic term, $\mathcal{L}_{\text{mag}}$ gives the interaction of the baryons with an external electromagnetic field, of field strength tensor $F^{\mu\nu}$. This last term includes apart from the photon kinetic energy, baryon vector current-photon vector potential interactions, a tensorial interaction term of the baryon and electromagnetic field which incorporates the effects of the anomalous magnetic moments of the baryons in presence of a finite magnetic field $[10, 12, 24, 25, 45]$. The Euler Lagrange’s equations motion are solved for the scalar isoscalar fields, $\sigma$ (non-strange), $\zeta$ (strange), scalar isovector field, $\delta$ (non-strange) and scalar dilaton field, $\chi$ under the mean-field approximations of the fields.
In this approximation, the scalar fields are treated as classical fields and they are related to the QCD condensates \[ \sigma(\sim \langle \bar{u}u \rangle), \zeta(\sim \langle \bar{s}s \rangle) \text{ and } \delta(\sim (\langle \bar{u}u \rangle - \langle \bar{d}d \rangle)) \].

In our present work, we have studied the in-medium masses of the open bottom mesons in the magnetized, isospin asymmetric, nuclear matter accounting the effects from the magnetized Dirac sea. At the given values of baryon density, \( \rho_B \), magnetic field, \( |eB| \) and isospin asymmetry parameter, \( \eta = \frac{\rho_n - \rho_p}{2\rho_B} \) (where \( \rho_n \) and \( \rho_p \) are the number densities of the neutron and proton, respectively) of the nuclear medium, the coupled equations of motion in these scalar fields are solved. The contributions of the magnetic fields due to the Fermi sea of nucleons in the magnetized nuclear matter, are incorporated through the scalar and number densities of protons \( (\rho^s_p, \rho_p) \) and neutrons \( (\rho^s_n, \rho_p) \) in terms of the Landau energy levels of the charged protons and the anomalous magnetic moments of the nucleons in the Fermi sea \[10\,12\,47\,48\]. Additionally, the effects of the magnetized Dirac sea on the scalar fields in the chiral effective model, are included through the scalar densities of the protons \( \Delta \rho^s_p \) and neutrons \( \Delta \rho^s_n \) via nucleon tadpole diagrams with the magnetic field modified fermion propagators in the Dirac sea of nucleons \[69\,70\].

To obtain the in-medium masses of the open bottom mesons \( (B \text{ and } \bar{B}) \), the dispersion relations as obtained from the Fourier transformations of the equations of motion of these mesons from the chiral effective Lagrangian \[11\,45\], are solved

\[
-\omega^2 + \vec{k}^2 + m^2_{B(\bar{B})} - \Pi_{B(\bar{B})}(\omega, |\vec{k}|) = 0
\]

(2)

Where \( \Pi_{B(\bar{B})}(\omega, |\vec{k}|) \) represent the self-energy functions of the \( B(\bar{B}) \) mesons doublet \([B(B^+, B^0) \text{ and } \bar{B}(B^-, \bar{B}^0)]\) in magnetized nuclear medium. The expressions for the self-energy functions of the \( B(\bar{B}) \) mesons doublet are given in terms of the proton and neutron number densities \( (\rho_p, \rho_n) \) and scalar densities \( (\rho^s_p, \rho^s_n) \) in the magnetized nuclear matter; some fitted parameters of the effective Lagrangian (the \( B \) meson decay constant, \( f_B \) and two other parameters, \( d_1, d_2 \) fitted from the low-energy kaon-nucleon scattering lengths for isospin \( I = 0 \) and \( I = 1 \) channels \[13\]), and the fluctuations of the scalar fields, \( \sigma'(= \sigma - \sigma_0) \), \( \zeta'(= \zeta - \zeta_0) \) and \( \delta'(= \delta - \delta_0) \) from their vacuum expectation values \( (\sigma_0, \zeta_0, \delta_0) \). Due to the small fluctuations of the heavy quark condensates within the medium, the fluctuation of \( \zeta_b \) \((\sim \langle \bar{b}b \rangle)\), is neglected in our work. The medium modifications of other scalar fields are obtained from the coupled equations of motion at given values of the baryon density \( (\rho_B) \), isospin asymmetry parameter \( (\eta) \) of the nuclear medium in presence of an external magnetic
field (|eB|), by including the effects of the protons Landau quantization and the magnetized Dirac sea contribution. In our present work, the effects of the nucleons anomalous magnetic moments are considered on the Fermi sea via the tensorial interaction term in $L_{\text{mag}}$ and also on the magnetized Dirac sea through the baryonic tadpole diagrams at finite magnetic field. The charged $B^\pm$ mesons have additional contribution from the Landau energy levels in the presence of magnetic field. Considering the contribution from the lowest Landau level ($n = 0$) only, the effective masses of the charged mesons are given by [45, 78, 79]

$$m_{B^\pm}^{\text{eff}} = \sqrt{m_{B^\pm}^* + |eB|}$$ (3)

This formula refers to the contribution of the lowest Landau level on a charged pseudoscalar particle, ignoring its internal structure [45, 78]. Whereas, the masses of the neutral mesons ($B^0, \bar{B}^0$) have no such Landau level contribution due to their charge neutrality. Their effective masses are, therefore, given by [45]

$$m_{B^0(\bar{B}^0)}^{\text{eff}} = m_{B^0(\bar{B}^0)}^*$$ (4)

In equations (3) and (4), the masses, $m_{B^\pm, B^0, \bar{B}^0}^*$ are calculated within the chiral effective model by solving their dispersion relations for $\omega$ at $\vec{k} = 0$, as given by equation (2).

The masses of the vector open bottom mesons $B^*$ ($B^{*+}, B^{*0}$) and $\bar{B}^*$ ($B^{*-}, \bar{B}^{*0}$) mesons, which have the same quark-antiquark constituents as $B$ and $\bar{B}$ mesons, are assumed to have identical mass shifts as the shifts in the masses of the $B$ and $\bar{B}$ mesons calculated within the chiral effective model. This is in line with the mass modifications of hadrons within the Quark meson coupling (QMC) model, which arise due to the modification of the scalar density of the light quark (antiquark) constituent of the hadron [11]. Thus the mass shifts of the $B^*$ and $\bar{B}^*$ mesons, in the magnetized nuclear matter, are assumed to have the form [45]

$$m_{B^*,(\bar{B}^*)}^* - m_{B^*,(\bar{B}^*)}^{\text{vac}} = m_{B^*,(\bar{B}^*)}^* - m_{B^*,(\bar{B}^*)}^{\text{vac}}$$ (5)

For the charged $B^{*\pm}$ mesons there will be the lowest Landau level ($n = 0$) contribution on the masses obtained from equation (5) [45, 78]

$$m_{B^{*\pm}}^{\text{eff}} = \sqrt{m_{B^{*\pm}}^* + (-gS_z + 1)|eB|}$$ (6)

The neutral mesons receive no LLL contribution. From equation (5) their effective masses are given by [45]

$$m_{B^0,\bar{B}^0}^{\text{eff}} = m_{B^0,\bar{B}^0}^*$$ (7)
Equation (5) gives the contribution of the lowest Landau level of a charged vector particle ignoring its internal structure [78]. As it is noted from equation (6), the effective masses of the charged mesons depend on the spin-projection along the direction of the external magnetic field, \( \vec{B} = B \hat{z} \), namely on the \( S_z \) component of the intrinsic spin of the vector bottom mesons with \( S = 1 \). For transverse component with \( S_z = -1 \), square of the vector particle mass increases by \( 3|eB| \) amount and of the \( S_z = 1 \) component decreases by \( |eB| \) amount, with magnetic field for the gyromagnetic ratio \( g = 2 \) [45, 50, 78]. However, in the presence of an external magnetic field, there is PV mixing between the longitudinal component \( (S_z = 0) \) of the vector mesons \( B^* (\bar{B}^*) \) with the pseudoscalar meson \( B (\bar{B}) \). This is described in the next subsection. Therefore, we consider only the effective mass of the longitudinal component \( (S_z = 0) \) of the charged \( B^{*\pm} \) mesons, to be used in the PV mixing calculation [45]

\[
m_{\text{eff}}^{B^{*\pm}(\parallel)} = \sqrt{m_{B^{*\pm}}^2 + |eB|} \tag{8}
\]

In equations (7)-(8), the in-medium masses \( m_{B^*, \bar{B}^*} \) of the vector mesons are obtained from the in-medium masses of the corresponding pseudoscalar partners [using equation (5)], as calculated within the chiral effective model incorporating the magnetized Dirac sea effects.

### A. Interaction Hamilton for the Pseudoscalar-Vector Mesons (PV) Mixing

In this sub-section, we present the formulation to evaluate the mass modifications of the pseudoscalar and the longitudinal component of the vector meson due to the mixing effect between these states in presence of magnetic field. The Hamilton accounting for the spin-magnetic field interaction is given by [45, 56, 63, 80]

\[
H_{\text{spin-mix.}} = -\sum_{i=1}^{2} \bar{\mu}_i \vec{B} \tag{9}
\]

Where, \( \bar{\mu}_i = g q_i \vec{S}_i / 2 m_i \) is the quark magnetic moment for the \( i^{th} \) flavor, presented in the bound states of open bottom mesons \( (q_2 q_1) \). In this equation, \( g \) is the Lande g-factor, is taken to be 2. \( q_i \) is the electric charge (in units of the electron charge \( |e| \)), \( \vec{S}_i \) denotes the spin and \( m_i \) is the mass of the \( i^{th} \) flavor of quark. This interaction Hamilton equation (9) leads to a rise (drop) in the mass of the longitudinal component of the vector (pseudoscalar) meson in the following way

\[
m_{V}^{PV} = m_{V}^{\text{eff}} + \Delta m_{sB} \quad m_{P}^{PV} = m_{P}^{\text{eff}} - \Delta m_{sB}; \tag{10}
\]
with $\Delta m_{sB} = \frac{\Delta E}{2}((1 + x^2)^{1/2} - 1)$; $x = \frac{2}{\Delta E} \left( \frac{-g[eB]}{4} \right) \left( \frac{n_1 - n_2}{m_1 - m_2} \right)$; $\Delta E = m_{eff}^V - m_{eff}^P$ is the mass difference between the vector and pseudoscalar mesons calculated within the chiral effective model. In this work, we will be studying the PV mixing effects between the $(B - B^*)$ and $(\bar{B} - \bar{B}^*)$ mesons accounting for the additional effects of the magnetic catalysis on their masses in magnetized nuclear matter in terms of the enhanced values of the scalar fields with magnetic field.

III. RESULTS AND DISCUSSION

In the present study, the in-medium masses of the open bottom pseudoscalar mesons $B^+, B^-$ and $B^0, \bar{B}^0$, are calculated in the magnetized nuclear matter by incorporating the effects of magnetic catalysis through the magnetized Dirac sea, within the chiral effective model. The medium modifications of masses arise due to their interactions with the scalar mesons and the nucleons in nuclear medium. The in-medium masses are obtained by solving equation (2) with the self-energies for all four pseudoscalar mesons calculated in terms of the number and scalar densities of the nucleons and the scalar fields fluctuations with respect to their vacuum expectation values [11, 18]. The scalar and number densities ($\rho^s_p$, $\rho^s_n$ and $\rho_p$, $\rho_n$) have magnetic field effects through the Landau energy levels of the positively charged protons and the nucleons anomalous magnetic moments in the Fermi sea of nucleons. In the current study, the contribution of the vacuum corrections at finite magnetic fields, are studied on the mass modifications in terms of the scalar fields fluctuations and the scalar densities presented in the self-energy functions of the open bottom mesons. The masses of the $B$ and $\bar{B}$ mesons in the chiral effective model are obtained in the mean field approximation, in which the scalar fields are treated as classical fields. Then, there is additional contribution added to the proton and neutron scalar densities due to the magnetic field effects on the nucleons tadpole diagrams, which impose the effects of the magnetized Dirac sea on the scalar fields of the chiral effective model. In our study, the scalar fields solved from the coupled equations of motion of the chiral effective Lagrangian, tend to increase with magnetic field at the nuclear matter saturation density, $\rho_0$, both considering and not considering the anomalous magnetic moments (AMM) of the nucleons. These fields correspond to the QCD vacuum condensates as described in section (II). The enhanced values of the scalar fields due to the magnetic catalysis effect, give rise to significant modifications on the open bottom mesons masses with
magnetic field, as compared to only the magnetized Fermi sea effects. The magnetized Dirac
sea also have important effects on the masses of the open bottom mesons in the vacuum,
in presence of an external magnetic field, while there is no contribution from the protons
Landau energy levels, in the absence of matter part. Due to the presence of a light quark
flavor (u or, d) in the B mesons quark contents, there are significant changes in their masses
with magnetic field, accounting the effects of magnetic catalysis. The anomalous magnetic
moments of the protons and neutrons have considerable effects on the magnetized Dirac sea
via the magnetic field expansion of the fermion propagators.

In Fig.1, the effective masses of the $B^\pm$, $B^0$, and $\bar{B}^0$ are plotted as a function of $|eB|/m_\eta^2$, at
zero density, by taking into account the effects of the anomalous magnetic moments (AMM)
on the Dirac sea of nucleons, in the presence of an external magnetic field. The solutions of
fields are done up to $|eB| = 5.5 \ m_\eta^2$, in presence of the nucleons AMM. At $\rho_B = 0$, there is
striking difference between the two cases of with AMM and without AMM of the Dirac sea
of nucleons. For the charged mesons ($B^\pm$), an additional contribution of the lowest Landau
level (LLL) at finite magnetic field is taken into account. However, without incorporating
the catalysis effects, mass of the neutral mesons remain unaffected with changing magnetic
field, but the charged mesons do have positive mass shifts due to the lowest Landau level
contribution at finite magnetic field [from equation (3)], as shown by the (short) dashed
increasing straight lines in plots (c) and (d) of Fig.1.

The nuclear matter saturation density taken to be $\rho_0 = 0.15 \ fm^{-3}$ in our work. The
constituent quark masses are taken as $m_u = m_d = 330 \ MeV$ and $m_b = 5360 \ MeV$ to be used
in the calculation of PV mixing effects.

At nuclear matter saturation density, $\rho_0$, considering the isospin asymmetry parameter values
of $\eta = 0$, 0.5 of the nuclear matter, the effective masses of the neutral mesons $B^0$ and $\bar{B}^0$
are plotted as a function of magnetic field in Fig.2. The contribution of the magnetic field is
significant on the effective masses through the magnetized Dirac sea effects as it is compared
with the no sea situation. The cases of with and without AMM effects both on the Dirac
and Fermi sea of nucleons are compared here. Similarly, in Fig.3, it is shown for the charged
mesons $B^\pm$ with an additional contribution of the lowest Landau level in the presence of
magnetic field. Here also the significant contribution of magnetic field is coming through
the magnetic catalysis effect as compared to only the Landau quantization of the protons in
nuclear matter.
As it is argued in section II, the mass shifts of the vector open bottom mesons are the same with that of the pseudoscalar partners within the chiral effective model, given by equation (5). The vacuum mass of all four vector mesons $B^{*0}, \bar{B}^{*0}, B^{*\pm}$ are taken to be 5324.7 MeV \cite{81}. From the mass shifts of the pseudoscalar mesons, using equation (5), the in-medium effective masses of the vector open bottom mesons are obtained at different values of the medium parameters. In Fig. (4), the masses of the $B^{*0}, \bar{B}^{*0}, B^{*\pm}$ are shown as a function of the magnetic field $|eB|/\pi m_{\pi}^2$ at $\rho_B = 0$. The anomalous magnetic moments in the Dirac sea of nucleons have significant effects on the masses through the magnetized Dirac sea which is the only part in play at zero density, in presence of an external magnetic field. In the absence of any catalysis effect, there is no changes in the neutral mesons masses whereas there are observed to be positive shifts in the vector charged particles masses with magnetic field due to the LLL contribution only, as given by equation (6). In Fig.\ref{fig:4} it is shown for the longitudinal component of the charged vector particles by the (short) dashed lined in plots (c) and (d). In the plots for the charged vector particles, wherever the LLL contribution is considered it is for the longitudinal part only with $S_z = 0$ in equation (6), as it will be used in the PV mixing calculation later. At $\rho_B = \rho_0$, the effective masses are calculated accounting the contribution of the magnetic catalysis from equation (5). These are shown in Figs. [(5) − (6)] for the neutral ($B^{*0}, \bar{B}^{*0}$) and charged ($B^{*\pm}$) vector open bottom mesons, respectively. The appreciable difference between the catalysis effects and no catalysis effects on the masses of the vector mesons are observed in the plots. In the presence of anomalous magnetic moments of the Dirac sea of nucleons, the masses are observed to decrease with magnetic field till $|eB| = 8m_{\pi}^2$, after that there is observed to be a sudden rise with further increase of the magnetic fields. For the charged mesons, contribution of the lowest Landau level is there, which lead to a steeper change in the effective masses as compared to the neutral mesons masses. These are due to the similar trends observed in the pseudoscalar mesons masses Figs. [(2)-(3)] at $\rho_B = \rho_0$. Although, at zero baryon density, the effect of nucleons AMM is observed to lead to a rise in the pseudoscalar [Fig.\ref{fig:1}] and vector [Fig.\ref{fig:2}] open bottom mesons masses with magnetic field. In vacuum, there is only Dirac sea polarization effects at finite magnetic field, contribution from the matter part is zero. On the other hand, at $\rho_B = \rho_0$, there is an interplay between the effects of the scalar densities due to the magnetized Dirac sea and due to the Landau quantization of the Fermi sea of protons. The effects of the protons Landau energy levels in the magnetized nuclear matter is seen to
be negligible in comparison to the case of an additional Dirac sea effect at finite magnetic field, in all of these figures. Thus, accounting the anomalous magnetic moments of the Dirac sea of nucleons to find the vacuum corrections on the masses, lead to strikingly different behavior in the masses, in comparison to the case when it is not taken into account.

In the presence of an external magnetic field, there is mixing phenomenon between the pseudoscalar and the longitudinal component of the vector mesons. The pseudoscalar meson-vector meson (PV) mixing gives rise to modifications to their masses, with a drop (rise) in the mass of the pseudoscalar (longitudinal component of the vector) meson. In the field theoretical model of composite hadrons with quark (and antiquark) constituents, the in-medium charmonium decay widths have been studied accounting for the PV mixing effects of \((J/\Psi^{||} - \eta_c)\) and \(\psi(3770)^{||} - \eta'_c\) using a phenomenological effective Lagrangian, in the magnetized nuclear matter with no sea contribution on their masses. The decay widths of \(\psi(3770) \to D\bar{D}\) were observed to be modified significantly due to the contributions of the \(\psi(3770)^{||} - \eta'_c\) mixing to the mass of the charmonium state \(\psi(3770)\), as well as due to the PV \(((D - D^{*||})\) and \((\bar{D} - \bar{D}^{*||})\) mixing contributions to the masses of the open charm mesons \(D\bar{D}\) [44]. The parameter \(g_{PV}\) of the phenomenological Lagrangian density was calculated from the observed decay width of \(V \to P\gamma\) in vacuum. Due to the lack of experimental data on the radiative decays \((V \to P\gamma)\) in the bottom sector, an interaction Hamiltonian approach is adopted to account for the spin-magnetic field interaction on the bottom mesons, as given by equation (9). In ref.[45], an interaction Hamiltonian approach was used to study the PV mixing effects on the \(\Upsilon(4S)^{||} - \eta_b(4S), B - B^{*||}\) and \(\bar{B} - \bar{B}^{*||}\) mesons, with the masses calculated within the chiral effective model, without considering the Dirac sea effects in the magnetized nuclear matter. The magnetic fields were seen to have dominant contribution through the PV mixing effects, on the in-medium partial decay widths of \(\Upsilon(4S) \to B\bar{B}\), using a field theoretical model of composite hadrons with quark (and antiquark) constituents. As there are very important modifications on the open bottom mesons masses due to the magnetic catalysis effects, as discussed above. It is important to investigate the PV mixing effects on the open bottom mesons by considering the contribution of Dirac sea at finite magnetic field, as they can have significant impact on the in-medium decay widths. In the present study, the PV mixing effects are investigated, in addition to the lowest Landau level (LLL) contribution for the charged open bottom mesons, accounting for the additional effects of the magnetized Dirac sea within the magnetized nuclear matter.
In Figs.[(7)-(9)], the masses of the longitudinal component of the vector and the pseudoscalar mesons are plotted with the variation in magnetic field, $|eB|$ (in units of $m_{\pi}^2$) at $\rho_B = 0$ and $\rho_B = \rho_0$ by imposing the effects of magnetic catalysis on the masses within the chiral effective model. Comparisons are shown between the cases of with and without AMM effects for both the symmetric ($\eta = 0$) and asymmetric ($\eta = 0.5$) nuclear matter, at $\rho_B = \rho_0$. The level repulsion between the masses of $V^\parallel$ and $P$ mesons are seen to be enlarged with increasing magnetic field. At $\rho_B = \rho_0$, the rise (drop) in the mass of the $B^{*0\parallel}$ ($B^0$) [plots (a)-(b) of Fig.(8)], $\bar{B}^{*0\parallel}$ ($\bar{B}^0$) [plots (c)-(d) of Fig.(8)] are shown with and without considering the effects of magnetic catalysis on their masses. Similar effects are shown for the charged mesons masses of $B^{*+\parallel}$ ($B^+$) [plots (a)-(b) of Fig.(9)], $B^{*-\parallel}$ ($B^-$) [plots (c)-(d) of Fig.(9)].
FIG. 1: The effective masses of the pseudoscalar open bottom mesons, neutral: $B^0$ [plot (a)], $\bar{B}^0$ [plot (b)] and charged: $B^+$ [plot (c)], $B^-$ [plot (d)], are plotted as a function of magnetic field $|eB|$ (in units of $m^2$), at zero density matter, $\rho_B = 0$, taking into account the effects of magnetized Dirac sea. The contribution of the lowest Landau level is considered for the charged mesons. Effects of nucleons anomalous magnetic moments (AMM) are compared with the no moments condition.
FIG. 2: In-medium effective masses of the $B^0$ [plots (a)-(b)] and $\bar{B}^0$ [plots (c)-(d)] mesons are shown as a function of the magnetic field, $|eB|$ (in units of $m_{\pi}^2$), at baryon density, $\rho_B = \rho_0$ and isospin asymmetry parameter, $\eta = 0, 0.5$, respectively. Comparison between the cases when magnetic catalysis considered and not considered are shown. The cases with nucleons AMM and without AMM are also compared in the plots.
FIG. 3: In-medium effective masses of the $B^+$ [plots (a)-(b)] and $B^-$ [plots (c)-(d)] mesons are shown as a function of the magnetic field, $|eB|$ (in units of $m^2$), at baryon density, $\rho_B = \rho_0$ and isospin asymmetry parameter, $\eta = 0$, 0.5, respectively. Comparison between the cases when magnetic catalysis considered and not considered are shown. Contribution of the lowest Landau level are taken into account for the charged meson particles. The cases with nucleons AMM and without AMM are also compared in the plots.
FIG. 4: The effective masses of the vector open bottom mesons, neutral: $B^*^0$ [plot (a)], $\bar{B}^*^0$ [plot (b)] and charged: $B^{*+}$ [plot (c)], $B^{*-}$ [plot (d)], are plotted as a function of magnetic field $|eB|$ (in units of $m_π^2$), at zero density matter, $\rho_B = 0$, taking into account the effects of magnetized Dirac sea. The contribution of the lowest Landau level is considered for the charged mesons (longitudinal part is shown here). Effects of nucleons anomalous magnetic moments (AMM) are compared with the no moments condition.
FIG. 5: In-medium effective masses of the $B^{*0}$ [plots (a)-(b)] and $\bar{B}^{*0}$ [plots (c)-(d)] mesons are shown as a function of the magnetic field, $|eB|$ (in units of $m^2$), at baryon density, $\rho_B = \rho_0$ and isospin asymmetry parameter, $\eta = 0, \ 0.5$, respectively. Comparison between the cases when magnetic catalysis considered and not considered are shown. The cases with nucleons AMM and without AMM are also compared in the plots.
FIG. 6: In-medium effective masses of the $B^{*+}$ [plots (a)-(b)] and $B^{*-}$ [plots (c)-(d)] mesons are shown as a function of the magnetic field, $|eB|$ (in units of $m_{\pi}^2$), at baryon density, $\rho_B = \rho_0$ and isospin asymmetry parameter, $\eta = 0, 0.5$, respectively. Comparison between the cases when magnetic catalysis considered and not considered are shown. Contribution of the lowest Landau level (for the longitudinal part only) are taken into account for the charged meson particles. The cases with nucleons AMM and without AMM are also compared in the plots.
FIG. 7: The PV mixing effects between the pseudoscalar and (longitudinal part of) vector mesons \([B^0 - B^{*0}]\) [plot (a)], \(\bar{B}^0 - \bar{B}^{*0}\) [plot (b)], \(B^+ - B^{*+}\) [plot (c)], \(B^- - B^{-}\) [plot (d)] are shown on their effective masses as a function of magnetic field, \(|eB|/m_{\pi}^2\). Comparison on the basis of nucleons anomalous magnetic moments, magnetic catalysis effect at finite magnetic field are shown in the plots at zero density matter, \(\rho_B = 0\). For the charged meson particles, LLL contribution at finite magnetic field are considered.
FIG. 8: The PV mixing effects between the pseudoscalar and (longitudinal part of) vector mesons ($B^0 - B^{*0}$) [plots (a)-(b)], $\bar{B}^0 - \bar{B}^{*0}$) [plots (c)-(d)] are shown on their effective masses as a function of magnetic field, $|eB|/m^2$. Comparison on the basis of nucleons anomalous magnetic moments, magnetic catalysis effect at finite magnetic field, and isospin asymmetry parameter, $\eta = 0, 0.5$ are shown in the plots at $\rho_B = \rho_0$. 

$\text{meff (MeV)}$

$\eta = 0$

$\eta = 0.5$

$\rho_B = \rho_0$
FIG. 9: The PV mixing effects between the pseudoscalar and (longitudinal part of) vector mesons ($B^+ - B^{*-\parallel}$ [plots (a)-(b)], $B^- - B^{*-\parallel}$ [plots (c)-(d)]) are shown on their effective masses as a function of magnetic field, $|eB|/m^2$. Comparison on the basis of nucleons anomalous magnetic moments, magnetic catalysis effect at finite magnetic field, and isospin asymmetry parameter, $\eta = 0, 0.5$ are shown in the plots at $\rho_B = \rho_0$. The effects of LLL contribution on the charged particles are taken into account at finite magnetic field.
IV. SUMMARY

In the summary, the in-medium masses of the pseudoscalar and vector open bottom mesons ($B^0, \bar{B}^0, B^+, B^-$) and ($B^{*0}, \bar{B}^{*0}, B^{*+}, B^{*-}$) are studied in the magnetized nuclear matter incorporating the effects of the magnetic catalysis through the Dirac sea polarization within the chiral effective model. The contribution of the lowest Landau level are considered by neglecting the internal structure of the charged meson particles. There is seen to be significant modifications on the masses incorporating the magnetized Dirac sea effects as compared to the no sea effects in the magnetized nuclear matter environment. In the vacuum, the magnetic fields are seen to have a no-trivial contribution on the masses through the magnetized Dirac sea effects and the anomalous magnetic moments of the nucleons are seen to have important effects at zero as well as nuclear matter saturation density via magnetic catalysis. The PV mixing effects including the magnetic catalysis are also studied, which lead to a level repulsion between the masses of the longitudinal component of the vector and the pseudoscalar mesons. The level repulsion increases with rising magnetic field. The visibly large effects of the magnetic catalysis on the masses of the open bottom mesons at finite magnetic field should thus have important observable consequences in the high energy, heavy-ion collision experiments where produced magnetic fields are very large.

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