Masses of Heavy Quarkonium states in magnetized matter  
- effects of PV mixing and magnetic catalysis

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Abstract

We study the in-medium masses of the heavy quarkonium (charmonium and bottomonium) states in isospin asymmetric nuclear matter in presence of an external magnetic field. The mass modifications of the heavy quarkonia are obtained from the medium modifications of a scalar dilaton field, χ, calculated within a chiral effective model. The dilaton field is introduced in the model through a scale invariance breaking logarithmic potential, and, simulates the gluon condensates of QCD. Within the chiral effective model, the values of the dilaton field along with the scalar (isoscalar, \(\sigma \sim \langle \bar{u}u \rangle + \langle \bar{d}d \rangle \)), \(\zeta \sim \langle \bar{s}s \rangle \)) and isovector \(\delta \sim (\langle \bar{u}u \rangle - \langle \bar{d}d \rangle)\)) fields, are solved from their coupled equations of motion. These are solved accounting for the effects of the Dirac sea for the nucleons. The Dirac sea contributions are observed to lead to enhancement of the quark condensates (through \(\sigma\) and \(\zeta\) fields) with increase in magnetic field, an effect called the magnetic catalysis. The magnetic field effects on the masses of the heavy quarkonia include the mixing of the pseudoscalar (spin 0) and vector (spin 1) states (PV mixing), as well as, the effects from magnetic catalysis. These effects are observed to be significant for large values of the magnetic field. This should have observable consequences on the production of the heavy quarkonia and open heavy flavour mesons, resulting from ultra-relativistic peripheral heavy ion collision experiments, where the created magnetic field can be huge.

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I. INTRODUCTION

The study of the in-medium properties of the heavy quarkonia is a topic of intense research work due to its relevance in heavy ion collision experiments [1]. The magnetic fields created in peripheral ultra-relativistic heavy ion collision experiments, e.g., at LHC, CERN and RHIC, BNL are estimated to be huge [2]. This has initiated a lot of work in the study of hadrons, in particular, of the heavy quarkonia as well as open heavy flavour mesons in the presence of magnetic fields, due to the reason that these heavy mesons are created at the early stage when the magnetic field can still be large. The heavy quarkonium (charmonium and bottomonium) states have been investigated in the literature using the potential models [3–13], the QCD sum rule approach [14–30], the coupled channel approach [31–37], the quark meson coupling (QMC) model [38–46], heavy quark symmetry and interaction of these mesons with nucleons via pion exchange [47], heavy meson effective theory [48], studying the heavy flavour meson as an impurity in nuclear matter [49].

Using leading order QCD formula [50–52], the mass modifications of the charmonium states were calculated in a linear density approximation in Ref.[53], due to the medium change of the scalar gluon condensate. The study showed much larger mass shifts for the excited states, $\psi(2S)$ and $\psi(1D)$, as compared to the mass shift of $J/\psi$. Within a chiral effective model [54–56], generalized to include the interactions of the charm and bottom flavoured hadrons, the in-medium heavy quarkonium (charmonium and bottomonium) masses are obtained from the medium changes of a scalar dilaton field, which mimics the gluon condensates of QCD [57–59]. The mass modifications of the open heavy flavour (charm and bottom) mesons within the chiral effective model have also been studied from their interactions with the baryons and scalar mesons in the hadronic medium [57, 58, 60–64]. The chiral effective model, in the original version with three flavours of quarks (SU(3) model), has been used extensively in the literature, for the study of finite nuclei [55], strange hadronic matter [56], light vector mesons [65], strange pseudoscalar mesons, e.g. the kaons and antikaons [60–69] in isospin asymmetric hadronic matter, as well as for the study of bulk matter of neutron stars [70]. Using the medium changes of the light quark condensates and gluon condensates calculated within the chiral SU(3) model, the light vector mesons ($\omega$, $\rho$ and $\phi$) in (magnetized) hadronic matter have been studied within the framework of QCD sum rule approach [71, 72]. The kaons and antikaons have been recently studied in the presence of strong...
magnetic fields using this model. The model has been used to study the partial decay widths of the heavy quarkonium states to the open heavy flavour mesons, in the hadronic medium using a light quark creation model, namely the $^3P_0$ model as well as using a field theoretical model for composite hadrons. Recently, the effects of magnetic field on the charmonium partial decay widths to $D\bar{D}$ mesons have been studied using the $^3P_0$ model and, charmonium (bottomonium) decay widths to $D\bar{D}$ ($B\bar{B}$) using the field theoretic model of composite hadrons.

In the present work, we study the modifications of the masses of the charmonium ($J/\psi$, $\psi(2S)$ and $\psi(1D)$) and the bottomonium ($\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ and $\Upsilon(4S)$) states in magnetized (nuclear) matter, within a chiral effective model. The mass modifications of these states arise due to the medium change of a dilaton field, which is incorporated into the model to simulate the gluon condensates of QCD. In the presence of the magnetic field, the effects of the pseudoscalar meson-vector meson (PV) mixings on the charmonium and bottomonium states are taken into account in the present study. The Dirac sea contributions of the nucleons are also taken into consideration, by summing over the nucleon tadpole diagrams. Within the chiral effective model, the Dirac sea contributions are observed to lead to an enhancement of the quark condensates (through the scalar $\langle \bar{u}u + \bar{d}d \rangle$ and $\zeta(\sim \langle \bar{s}s \rangle)$ fields), with increase in the magnetic field, an effect called ‘magnetic catalysis’. The increase of the light quark condensates with magnetic field, has been studied in a large extent on the quark matter sector using the Nambu-Jona-Lasinio (NJL) model. In the Walecka model and an extended linear sigma model, the effects of magnetic field have been studied in the Walecka model by using a weak field approximation of the fermion propagator. The effect of the anomalous magnetic moment of the nucleons are important to study the contributions from the Dirac sea in presence of finite magnetic field. In the literature there are very few works on the magnetic catalysis effect in the nuclear matter. In the present work, we have incorporated the effects of the Dirac sea...
through summation of nucleonic tadpole diagrams within a chiral effective model. For the study of the heavy quarkonia masses, we also consider the mixing of the pseudoscalar and vector meson (PV mixing) in the presence of the external magnetic field.

The outline of the paper is as follows. In section II, we describe the mass modificaitons of the heavy quarkonium states in magnetized (nuclear) matter, using a chiral effective model. These masses are calculated within the model from the modification of the scalar dilaton, which mimics the scale symmetry breaking of QCD. The magnetic field effects considered are the pseudoscalar - vector meson (PV) mixing and the magnetic catalysis effects. The former corresponds to the mixing of the pseudoscalar (spin 0) and the vector (spin 1) mesons in the presence of a magnetic field. The latter, the magnetic catalysis effect, arises from the Dirac sea contributions of nucleons. In section III, the results of the medium modifications of the charmonium and bottomonium masses in magnetized matter are discussed and section IV summarizes the findings of this work.

II. MASS MODIFICATIONS OF HEAVY QUARKONIUM STATES IN MAGNETIZED MATTER

The in-medium masses of the charmonium ($J/\psi$, $\psi(2S)$ and $\psi(1D)$) and bottomonium states ($\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ and $\Upsilon(4S)$) are studied in magnetized (nuclear) matter. The effects of pseudoscalar - vector meson (PV) mixing ($J/\psi - \eta_c$, $\psi(2S) - \eta_c(2S)$, $\psi(1D) - \eta_c(2S)$ for charmonium states and $\Upsilon(1S) - \eta_b$, $\Upsilon(2S) - \eta_b(2S)$, $\Upsilon(3S) - \eta_b(3S)$, $\Upsilon(4S) - \eta_b(4S)$ for the bottomonium states), and magnetic catalysis are considered in the present study of mass modifications of these heavy mesons in the presence of a magnetic field.

The mass shift of the heavy quarkonium state is proportional to the change in the gluon condensate in the medium. This is the leading order result of a study of the heavy quarkonium state in a gluon field, assuming the distance between the heavy quark and antiquark (bound by a Coulomb potential) to be small as compared to the scale of gluonic fluctuations [50–52]. The chiral effective model as used in the present work, is based on a non-linear realization of chiral symmetry. The model also incorporates the broken scale invariance of QCD through a scalar dilaton field. The dilaton field $\chi$ of the scale breaking term $\mathcal{L}_{\text{scalebreak}}$ in the chiral effective model is related to the scalar gluon condensate of QCD and this relation is obtained by equating the trace of the energy momentum tensor in the chiral effective
FIG. 1: Masses (MeV) of $J/\psi$ and $\eta_c$ are plotted as functions of $eB/m_{\pi}^2$ for $\rho_B = \rho_0$ and $\eta = 0$, with and without the effects of PV mixing. These are shown in (a) and (c), when the Dirac sea contributions of nucleons (resulting in magnetic catalysis) are not included and in (b) and (d), while these effects are included. In (b) and (c), the masses are also shown for $\rho_B = 0$ due to the Dirac sea contributions. The results are for cases when the AMMs are included, which are compared with the cases when AMMs are not considered (shown as dotted lines).

model and in QCD [57-59]. The mass shift of the charmonium (bottomonium) state in the magnetized nuclear matter is hence computed from the medium change of the dilaton field from vacuum value, calculated within the chiral effective model, and is given as [57-59]

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

(1)
FIG. 2: Same as Figure 1 but with $\eta=0.5$.

where

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

In equation (2), $d$ is a parameter introduced in the scale breaking term in the Lagrangian, $\chi$ and $\chi_0$ are the values of the dilaton field in the magnetized medium and in vacuum respectively. The wave functions of the charmonium (bottomonium) states, $\psi(k)$ are assumed to be harmonic oscillator wave functions, $m_{c(b)}$ is the mass of the charm (bottom) quark, $\epsilon = 2m_{c(b)} - m$ is the binding energy of the charmonium (bottomonium) state of mass, $m$. The mass shifts of the heavy quarkonium states are thus obtained from the values of the dilaton field, $\chi$, (using equation (1)). For given values of the baryon density, $\rho_B$, the isospin...
FIG. 3: Masses (MeV) of \( \psi(2S) \) and \( \eta_c(2S) \) are plotted as functions of \( eB/m^2_\pi \) for \( \rho_B = \rho_0 \) and \( \eta = 0 \), with and without the effects of PV mixing. These are shown in (a) and (c), when the Dirac sea contributions of nucleons (resulting in magnetic catalysis) are not included and in (b) and (d), while these effects are included. In (b) and (c), the masses are also shown for \( \rho_B = 0 \) due to the Dirac sea contributions. The results are for cases when the AMMs are included, which are compared with the cases when AMMs are not considered (shown as dotted lines).

asymmetry parameter, \( \eta = (\rho_n - \rho_p)/(2\rho_B) \) (with \( \rho_n \) and \( \rho_p \) as the neutron and proton number densities), the magnetic field, \( B \) (chosen to be along z-direction), the values of the fields \( \chi, \sigma, \zeta \) and \( \delta \) are solved from their coupled equations of motion. The AMMs of the nucleons are considered in the present study \cite{91, 92}. There are contributions of the Landau
levels for the charged baryon, i.e., proton, whereas the neutron interacts with the magnetic field, due to its anomalous magnetic moment.

**A. Pseudoscalar meson-Vector meson (PV) mixing**

In the presence of a magnetic field, there is mixing between the pseudoscalar meson and vector mesons, which modifies the masses of these mesons [82, 84, 85, 94–98]. The PV mixing leads to a drop (rise) in the mass of the pseudoscalar (longitudinal component of the vector meson). The mass modifications have been studied using an effective Lagrangian.
FIG. 5: Masses (MeV) of $\psi(1D)$ and $\eta_c(2S)$ are plotted as functions of $eB/m^2_\pi$ for $\rho_B = \rho_0$ and $\eta = 0$, with and without the effects of PV mixing. These are shown in (a) and (c), when the Dirac sea contributions of nucleons (resulting in magnetic catalysis) are not included and in (b) and (d), while these effects are included. In (b) and (c), the masses are also shown for $\rho_B = 0$ due to the Dirac sea contributions. The results are for cases when the AMMs are included, which are compared with the cases when AMMs are not considered (shown as dotted lines).

density of the form $^{[95, 98]}$

$$L_{PV\gamma} = \frac{g_{PV}}{m_{av}} e\bar{F}_{\mu\nu}(\partial^\mu P)V^\nu, \quad (3)$$

for the heavy quarkonia $^{[82, 95]}$, the open charm mesons $^{[84]}$ and strange ($K$ and $\bar{K}$) mesons $^{[85]}$. In equation (3), $m_{av} = (m_V + m_P)/2$, $m_P$ and $m_V$ are the masses for the pseudoscalar
and vector charmonium states, \( \bar{F}_{\mu\nu} \) is the dual electromagnetic field. In equation (3), the coupling parameter \( g_{PV} \) is fitted from the observed value of the radiative decay width, \( \Gamma(V \rightarrow P + \gamma) \) given as

\[
\Gamma(V \rightarrow P\gamma) = \frac{e^2}{12} \frac{g_{PV}^2 p_{cm}^3}{\pi m_{av}^2},
\]

where, \( p_{cm} = (m_V^2 - m_P^2)/(2m_V) \) is the magnitude of the center of mass momentum in the final state. The masses of the pseudoscalar and the longitudinal component of the vector mesons including the mixing effects are given by

\[
m_{PV} (P,V)_{\parallel}^2 = \frac{1}{2} \left( M_{PV}^2 + \frac{c_{PV}^2}{m_{av}^2} \mp \sqrt{M_{PV}^4 + \frac{2c_{PV}^2 M_{PV}^2}{m_{av}^4} + \frac{c_{PV}^4}{m_{av}^4}} \right),
\]
FIG. 7: Masses (MeV) of Υ(1S) and ηb are plotted as functions of $eB/m^2_\pi$ for $\rho_B = \rho_0$ and $\eta = 0$, with and without the effects of PV mixing. These are shown in (a) and (c), when the Dirac sea contributions of nucleons (resulting in magnetic catalysis) are not included and in (b) and (d), while these effects are included. In (b) and (c), the masses are also shown for $\rho_B = 0$ due to the Dirac sea contributions. The results are for cases when the AMMs are included, which are compared with the cases when AMMs are not considered (shown as dotted lines).

where $M_+^2 = m_P^2 + m_V^2$, $M_-^2 = m_P^2 - m_V^2$ and $c_{PV} = g_{PV}eB$. By considering the terms in equation (5) up to the second order in $c_{PV}$ and leading order in $(m_V - m_P)/2m_{av}$, we obtain

$$m_{P,V \parallel}^2 = m_{P,V}^2 + \frac{c_{PV}}{M^2}$$

(6)
In Ref. [82], the effective Lagrangian term given by equation (3) has been observed to lead to appreciable mass modifications of the pseudoscalar and the longitudinal component of the vector charmonium states, due to the PV mixings \( (J/\psi - \text{eta}_c, \psi(2S) - \eta_c(2S) \) and \( \psi(1D) - \eta_c(2S) \)). This is observed to lead to substantial modification of the partial decay width of \( \psi(1D) \to D\bar{D} \) [82] due to \( \psi(1D) - \eta_c(2S) \) mixing, as well as, due to \( D(\bar{D}) - D^*(\bar{D}^*) \) mixing effects [84]. These mixing effects have been considered on the masses calculated using the chiral effective model. In the present work, the Dirac sea contributions are taken into account to compute the masses of the heavy quarkonium states, additionally, the PV mixing effects are considered for the masses of these mesons. The mixing parameter \( g_{PV} \) is determined from the observed decay widths of \( V \to P\gamma \) for the open and hidden charm
FIG. 9: Masses (MeV) of $\Upsilon(2S)$ and $\eta_b(2S)$ are plotted as functions of $eB/m^2_\pi$ for $\rho_B = \rho_0$ and $\eta = 0$, with and without the effects of PV mixing. These are shown in (a) and (c), when the Dirac sea contributions of nucleons (resulting in magnetic catalysis) are not included and in (b) and (d), while these effects are included. In (b) and (c), the masses are also shown for $\rho_B = 0$ due to the Dirac sea contributions. The results are for cases when the AMMs are included, which are compared with the cases when AMMs are not considered (shown as dotted lines).

sector. However, due to lack of data (radiative decay) for the bottomonium states, we estimate the modifications to the masses of the bottomonium pseudoscalar and vector mesons due to mixing of these states in the presence of a magnetic field, using the Hamiltonian
FIG. 10: Same as Figure 9, but with $\eta=0.5$.

\[ H_{\text{spin-mixing}} = -\sum_{i=1}^{2} \mu_i \cdot B, \] (7)

which describes the interaction of the magnetic moments of the quark (antiquark) with the external magnetic field. In the above, $\mu_i = g|e|q_i S_i/(2m_i)$ is the magnetic moment of the $i$-th particle, $g$ is the Lande g-factor (taken to be $2(-2)$ for the quark(antiquark)), $q_i, S_i, m_i$ are the electric charge (in units of the magnitude of the electronic charge, $|e|$), spin and mass of the $i$-th particle [95,98]. This interaction leads to a drop (increase) of the mass of the pseudoscalar (longitudinal component of the vector meson) given as [97]

\[ \Delta M^{PV} = \frac{\Delta E}{2} \left( 1 + \Delta^2 \right)^{1/2} - 1, \] (8)
FIG. 11: Masses (MeV) of Υ(3S) and ηb(3S) are plotted as functions of $eB/m_{\pi}^2$ for $\rho_B = \rho_0$ and $\eta = 0$, with and without the effects of PV mixing. These are shown in (a) and (c), when the Dirac sea contributions of nucleons (resulting in magnetic catalysis) are not included and in (b) and (d), while these effects are included. In (b) and (c), the masses are also shown for $\rho_B = 0$ due to the Dirac sea contributions. The results are for cases when the AMMs are included, which are compared with the cases when AMMs are not considered (shown as dotted lines).

where $\Delta = 2g|eB|((q_1/m_1) - (q_2/m_2))/\Delta E$, $\Delta E = m_V - m_P$ is the difference in the masses of the pseudoscalar and vector mesons. Here, the masses $m_V$ and $m_P$ refer to those calculated from the medium change of the dilaton field within the chiral effective model, using equation (1). These masses are calculated considering the Dirac sea contributions. We study the PV
mixing effects and consequently, the modifications to the masses of the pseudoscalar and the longitudinal component of the vector bottomonium states, arising due to the $\Upsilon(1S)^\| - \eta_b$, $\Upsilon(2S)^\| - \eta_b(2S)$, $\Upsilon(3S)^\| - \eta_b(3S)$, and $\Upsilon(4S)^\| - \eta_b(4S)$ mixing effects.

**III. RESULTS AND DISCUSSIONS**

We discuss the results obtained due to the effects of Dirac sea contributions for the nucleons, as well as, PV mixing on the masses of the charmonium and bottomonium states in magnetized isospin asymmetric nuclear matter. These are studied considering the AMMs of the nucleons and compared to the cases when AMMs are not taken into account. There
FIG. 13: Masses (MeV) of Υ(4S) and η_b(4S) are plotted as functions of $eB/m_{\pi}^2$ for $\rho_B = \rho_0$ and $\eta = 0$, with and without the effects of PV mixing. These are shown in (a) and (c), when the Dirac sea contributions of nucleons (resulting in magnetic catalysis) are not included and in (b) and (d), while these effects are included. In (b) and (c), the masses are also shown for $\rho_B = 0$ due to the Dirac sea contributions. The results are for cases when the AMMs are included, which are compared with the cases when AMMs are not considered (shown as dotted lines).

is enhancement of the quark condensates (through scalar fields $\sigma$ and $\zeta$) due to Dirac sea contributions even for zero density. The scalar fields and the dilaton field are solved from their coupled equations of motion within the chiral effective model, for given values of the baryon density, $\rho_B$, isospin asymmetry parameter, $\eta$ and the magnetic field, $B$. 
In figures 1 and 2, the masses of $J/\psi$ and $\eta_c$ are plotted for isospin symmetric nuclear matter ($\eta=0$) and asymmetric nuclear matter (with $\eta=0.5$) with and without PV ($J/\psi - \eta_c$) mixing effects. These are shown in (a) and (c), when the Dirac sea contributions are not considered. In the absence of PV mixing, there is observed to be almost no change in the masses of $J/\psi$ and $\eta_c$ mesons. The PV mixing is observed to lead to substantial rise (drop) in the mass of $J/\psi$ ($\eta_c$) meson. The effects of magnetic catalysis (through Dirac sea contributions) are shown in (b) and (d) respectively. There is observed to be an increase in the mass of $J/\psi$ as well as $\eta_c$, of the order of around 3-4 MeV. However, the effects due to PV mixing is observed to be much more dominant as compared to the contributions due to the magnetic catalysis for $J/\psi$ and $\eta_c$ mesons. These are plotted considering the AMMs.
of the nucleons and compared with the cases when the AMMs are not taken into account (shown as dotted lines). The effects of AMMs are observed to be negligible. In (b) and (c), the masses are shown for the zero baryon density. The effects of magnetic catalysis for $\rho_B = 0$ are observed to be marginal. The plots for $\eta = 0.5$ shown in figure 2 show that the masses of $J/\psi$ and $\eta_c$ have very small variation with the siospin asymmetry of the nuclear matter.

Figures 3 and 4 show the plots of masses of $\psi(2S)$ and $\eta_c(2S)$ with and without the PV mixing effects, for $\eta = 0$ and $\eta = 0.5$ respectively. The contributions from magnetic catalysis is observed to lead to appreciable increase in the masses of these mesons. Along with the PV effect, the mass of $\psi(2S)$$^\parallel$ is much larger as compared to when the effect of Driac sea is not considered. The effect of magnetic catalysis is observed to dominate over the PV mixing contributions. The modifications due to the isospin asymmetry, AMMs of the nucleons are observed to be marginal as compared to the effects of magnetic catalysis and PV mixing.

In figures 5 and 6 we plot the masses of $\psi(1D)$ and $\eta_c(2S)$ for $\eta = 0$ and $\eta = 0.5$ for $\rho_B = \rho_0$. The mixing effect for $\psi(1D) - \eta_c(2S)$ is observed to be much more pronounced as compared to for $\psi(2S) - \eta_c(2S)$ mixing. One might observe that the mass drop of $\eta_c(2S)$ is much larger with $\psi(1D) - \eta_c(2S)$ as compared to with $\psi(2S) - \eta_c(2S)$ mixing. The effect of magnetic catalysis is observed to be quite significant for $\psi(1D)$, with further appreciable increase due to PV mixing, can modify the partial decay width of $\psi(1D) \rightarrow D\bar{D}$, and can have consequences in the production of the charmonia and open charm mesons in non-cestral ultra-relativistic heavy ion collisions, where the created magnetic field can be large.

In figures 7 and 8, the effects of the PV mixing and magnetic catalysis on the masses of $\Upsilon(1S)$ and $\eta_b$ are shown at $\rho_B = \rho_0$ and for $\eta = 0$ and $\eta = 0.5$ respectively. These are compared with the case of $\rho_B = 0$ with the magnetic catalysis effect. Similar to the charmonium sector, the effects of magnetic catalysis are observed to be quite significant for the excited bottomonium states ($\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(4S)$) as might be seen from the figures 9, 11 and 13 for $\eta = 0$, and, from the figures 10, 12 and 14 for $\eta = 0.5$. The further (appreciable) increase due to PV effects lead to much larger masses for the excited states in presence of high magnetic fields. These should have observable consequences in the production of the bottomonium and open bottom mesons.
IV. SUMMARY

To summarize, we have studied the masses of the heavy quarkonium states in magnetized nuclear matter. The masses are calculated within a chiral effective model from the medium change of a scalar dilaton field, which mimics the gluon condensates of QCD. The effects if Dirac sea of nucleons are taken into consideration, which lead to increase of the magnitudes of the scalar fields (thus leading to increase in the light quark condensates), with rise in the magnetic field, an effect called magnetic catalysis. In the presence of the magnetic field, there are further modifications to the masses of the chamronium and bottomonium states due to PV mixing. The effects from AMMs of nucleons, isospin asymmetry on the in-medium masses of heavy quarkonia are observed to be marginal and the dominant contributions due to magnetic field effects are observed to be arising from the effects of PV mixing as well as magnetic catalysis. These should have observable consequences on the production of heavy quarkonium states and open heavy flavour mesons, as these are created at the early stage of the non-central ultra-relativistic heavy ion collision experiments, when the magnetic field can be large.

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