Thermodynamic Behaviour of Magnetized QGP within the Self-Consistent Quasiparticle Model

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The self-consistent quasiparticle model has been successful in studying QCD thermodynamics. In this model, the medium effects are taken into account by considering quarks and gluons as quasiparticles with temperature dependent masses which are proportional to the plasma frequency. The present work involves the extension of this model in the presence of strong magnetic fields. We have included the effect of the magnetic field by considering relativistic Landau Levels. The quasiparticle masses are then found to be dependent on both temperature and magnetic field. The thermo-magnetic mass thus defined allows obtaining the thermodynamics of magnetised quark matter within the self-consistent quasiparticle model. The model then has been applied to the case of 2-flavor Quark-Gluon Plasma and the equation of state obtained in the presence of magnetic fields.

I. INTRODUCTION

High energy collisions have succeeded in recreating the state of matter called Quark Gluon Plasma (QGP) which is believed to have existed shortly after the big bang. It has been observed that QGP produced in high energy collisions behave very much like a nearly perfect fluid [1]. These collisions mostly occur with a finite impact parameter. During off central collisions, the charged ions thus can produce very large magnetic fields reaching up to $eB \approx (1 - 5)m^2$ [2, 3]. These magnetic fields may exist only for a short time but, depending on the transport coefficients, they may reach their maximum value and can be stationary during this time [4–7]. The magnetic field can cause different phenomena like magnetic catalysis [8, 9], chiral magnetic effect [10–12], etc. in the QGP. The equation of state is important for studying the particle spectra created in heavy-ion collisions. Very strong magnetic fields are estimated to have existed right after the big bang [13]. Effects of external magnetic fields are relevant in the context of strongly magnetised neutron stars too [14]. Therefore, it is of importance to investigate the behaviour of QGP under strong magnetic fields, in particular, the effect on the QCD thermodynamics [15–16]. There have been several investigations as to how these strong magnetic fields affect the transport coefficients [17, 18].

In this work, we intend to understand the effect of strong magnetic fields on QCD thermodynamics and obtain the equation of state by extending a quasiparticle model for QGP, called the self-consistent quasiparticle model. We incorporate the effect of the strong magnetic field by modifying the thermal mass using the relativistic Landau Levels. Such modified masses in the presence of strong magnetic fields can be used to calculate thermodynamic quantities like energy density, pressure, entropy density, etc. Besides, by applying this formalism to the 2-flavor system, we obtain its thermodynamics in the presence of strong background magnetic field and examine the qualitative behaviour of the equation of state.

II. THE SELF-CONSISTENT QUASIPARTICLE MODEL

In quasiparticle models, the thermal properties of interacting real particles are modelled by noninteracting quasiparticles. The quasiparticles have an effective mass which is determined by the collective properties of the medium [19, 20]. Such models include the Nambu-Jona-Lasinio and PNJL based quasiparticle models [21] or those that include effective mass with the Polyakov loop [22]. There are also quasiparticle models based on Gribov-Zwanziger quantisation [23]. Other effective mass quasiparticle models include self-consistent and single parameter quasiparticle models [24–28]. There are quasiparticle models which incorporate the medium effects by considering quasiparticles with effective fugacities too. Such models have been quite successful in describing the lattice QCD results [29–30].

The self-consistent quasiparticle model here considers QGP as consisting of non-interacting quasiparticles with effective masses which depend on thermodynamic quantities and encode all medium interactions [24–28]. Since the thermal mass depends on thermodynamic quantities which in turn depends on thermal mass, the whole problem is solved self-consistently. In the self-consistent model, following standard thermodynamics, all thermodynamic quantities are derived from the expressions for energy density and number density. The expression for energy density is,

$$\varepsilon = \frac{g_f}{2\pi^2} \int_0^\infty dk k^2 \frac{\omega_k}{z - 1 + e^{-\frac{\omega_k}{T}}},$$  \hspace{1cm} (1)$$

where $g_f$ is the degeneracy and $\mp$ refers to bosons and fermions. $z$ is the fugacity. The expression for number
Density is,
\[ n_{q/g} = \frac{gf}{2\pi^2} \int_0^\infty dk k^2 \frac{1}{z - ieT + 1}. \]  

(2)

The single particle energy \( \omega_k \) is approximated to a simple form,
\[ \omega_k = \sqrt{k^2 + m_g^2} \]  

(3)

and
\[ \omega_k = \sqrt{k^2 + m_q^2}, \]  

(4)

for gluons and quarks respectively. This approximation is valid at high temperatures only. In the model that we study here, the thermal masses are defined in terms of the plasma frequencies as,
\[ m_g^2 = \frac{3}{2} \omega_p^2 \quad \text{and} \quad m_q^2 = 2m_f^2, \]  

(5)

for massless particles. For massive quarks \( m_q^2 \) is written as,
\[ m_q^2 = (m_0 + m_f)^2 + m_f^2. \]  

(6)

The plasma frequencies are calculated from the density dependent expressions
\[ \omega_p^2 = a_p^2 \frac{2n_g}{T}, \quad \omega_q^2 = a_q^2 \frac{2n_q}{T}, \]  

(7)

for gluons and,
\[ m_f^2 = e^2 g^2 \frac{2n_q}{T}, \]  

(8)

for quarks. Here \( n_q \) is the quark number density and \( n_g \) is the gluon number density. \( g^2 = 4\pi a_s \) is the QCD running coupling constant. The coefficients \( a_g, a_q, kg \) are determined by demanding that as \( T \to \infty \), \( \omega_p \) and \( m_f \) both go to the corresponding perturbative results. The motivation for choosing such an expression for plasma frequency is that the plasma frequency for electron-positron plasma is known to be proportional to \( n/T \) in the relativistic limit \[31,32\]. Since the thermal masses appear in the expression for the density, we need to solve the density equation self-consistently to obtain the thermal mass, which may be used to evaluate the thermodynamic quantities of interest. The result obtained have shown a good fit with lattice data even at temperatures near \( T_c \) \[33\].

### III. Extension of the Self-Consistent Model in Strong Magnetic Field

The quantisation of fermionic theory in strong magnetic fields has been known. The energy eigenvalues are obtained as Landau levels and have been subject to several investigations \[34,35\]. In the Landau gauge \( A_\mu = B x \) so that \( B = B \hat{z} \) and the energy eigenvalues are obtained as,
\[ E_j = \sqrt{m^2 + k_z^2 + 2j \left| q_f eB \right|}. \]  

(9)

Here, \( q_f e \) is the charge of the fermion and \( j = 0, 1, 2, . \) are the Landau energy levels. In strong magnetic fields, the magnetic field constrains the motion of a particle in the direction of the magnetic field. Studies related to magnetic catalysis have explored this impact of dimensional reduction \( (D - D - 2) \) \[36,37\]. The integration of phase factor due to the dimensional reduction becomes \[38,39\],
\[ \int \frac{d^3k}{(2\pi)^3} \to \left| q_f eB \right| \sum_{j=0}^\infty \int \frac{dk_z}{2\pi} (2 - \delta_{0j}) \]  

(10)

### A. Thermo-Magnetic Mass for Quarks

Making use of equations (9) and (10), we can write the expression for number density in the presence of strong magnetic fields as,
\[ n_q = \frac{gfq_f eB}{(2\pi)^2} \sum_{j=0}^\infty \left[ 2 \int_0^\infty dk_z \frac{1}{e^{(\frac{k_z^2}{2})} + (\frac{m_f}{2})^2 + 1} - \int_0^\infty dk_z \frac{1}{e^{(\frac{k_z^2}{2})} + (\frac{m_f}{2})^2 + 1} \right] \delta_{0j}, \]  

(11)

where, we have assigned for simplicity,
\[ m_q^2 = m_q^2 + 2j \left| q_f eB \right|. \]  

(12)

Equation (11) can be further simplified to
\[ T^2 F_q^2 = \sum_{j=0}^\infty \left( 2 \sum_{l=1}^{\infty} (-1)^{(l-1)} \frac{m_q}{T} K_1 \left( \frac{m_q}{T} \right) \right. \]  

(13)

Here we have defined for later convenience,
\[ F_q^2 = \frac{(2\pi)^2 n_q}{gfq_f eB T^3}. \]  

(14)

For massive quarks, \( m_q \) is given by,
\[ m_q^2 = (m_0 + m_f)^2 + m_f^2, \]  

(15)

where we take just as in \[28\],
\[ m_f^2 = \frac{e^2 g^2}{2} \frac{2n_q}{T}. \]  

(16)

Or,
\[ \left( \frac{m_f}{T} \right)^2 = \frac{e^2 g^2}{2} \frac{2n_q}{T^3} = \frac{e^2}{q_f^2}. \]  

(17)
where,

\[ c_g^2 = c_g^2 q^2 g_f |q_f e B| \left( \frac{2\pi}{T} \right)^2. \]  

(18)

Combining equations (12), (15), (17), we can write,

\[ \left( \frac{m_g}{T} \right)^2 = \left[ \frac{m_0}{T} + \bar{c}_g F_q \right]^2 + \bar{c}_g^2 F_q^2 + 2j |q_f e B| \]  

(19)

Using (19) in equation (13), and simplifying the Krenecker delta we get,

\[ T^2 F_q^2 = \sum_{l=1}^{\infty} \sum_{j=0}^{\infty} \left[ 2 \sum_{j=0}^{\infty} \sqrt{\left( \frac{m_0}{T} + \bar{c}_q F_q \right)^2 + \bar{c}_q^2 F_q^2 + 2j |q_f e B| \left( \frac{T}{T^2} \right)^2} \right] K_1 \left( l \sqrt{\left[ \frac{m_0}{T} + \bar{c}_q F_q \right]^2 + \bar{c}_q^2 F_q^2} - \sqrt{\left( \frac{m_0}{T} + \bar{c}_q F_q \right)^2 + \bar{c}_q^2 F_q^2} \right) K_1 \left( l \sqrt{\left[ \frac{m_0}{T} + \bar{c}_q F_q \right]^2 + \bar{c}_q^2 F_q^2} + \bar{c}_q^2 F_q^2 \right). \]  

(20)

where \( K_n(x) \) are the modified Bessel functions of the second kind. Solving this equation for \( F_q \) and using equation (19) we get the thermo-magnetic mass which depends both on temperature and magnetic field. This thermo-magnetic mass can be used to obtain the thermodynamics of the system considering it as a collection of non-interacting quasiparticles with mass depending on temperature and magnetic field.

**B. Thermo-Magnetic Mass for Gluons**

The density-dependent expression for plasma frequency for gluons is given by equation (7). The expression for gluon number density \( n_g \) remains unchanged because gluons are chargeless. But the term \( n_g \) changes as explained and so the gluons also acquire a thermo-magnetic mass. We have,

\[ n_g = \frac{g_g}{2\pi^2} \int_0^\infty dk k^2 \frac{1}{e^{\omega_k/T} - 1} \]  

(21)

Following (7), we define the plasma frequency as,

\[ \omega_p^2 = \bar{a}^2 g^2 \frac{2n_g}{T} + \bar{d}^2 q^2 \frac{2n_q}{T}. \]  

(22)

Making use of (5) and simplifying equation (21),

\[ f_g^2 = \left( \bar{a}^2 f_g^2 + \bar{d}^2 q^2 F_q^2 \right) \sum_{l=1}^{\infty} K_2 \left(l \left( \bar{a}^2 f_g^2 + \bar{d}^2 q^2 F_q^2 \right)^{1/2} \right). \]  

(23)

where,

\[ f_g^2 = \frac{2\pi^2 n_g}{g_g T^3}. \]  

(24)

and \( F_q \) is obtained as solution to (20). Now, solving equation (23) for \( f_g \) using the above, we obtain the thermo-magnetic mass using,

\[ \left( \frac{m_g}{T} \right)^2 = \bar{a}^2 f_g^2 + \bar{d}^2 q^2 F_q^2. \]  

(25)

The coefficients \( c_q, a_g \) and \( d_q \) are determined by demanding that as \( T \to \infty \) the expression for frequency approaches the corresponding perturbative QCD results.

**C. QCD Thermodynamics in Strong Magnetic Field Background**

We start with the energy density. Using equations (10) and (9), the expression for energy density for quarks, equation (1) becomes,

\[ \varepsilon_q = \frac{12n_q |q_f e B|}{4\pi^2} \sum_{j=0}^{\infty} \left[ 2 \int_0^\infty dk_z \frac{\omega_{k_z j}}{e^{\varepsilon_{k_z j} T} + 1} - \int_0^\infty dk_z \frac{\omega_{k_z j}}{e^{\varepsilon_{k_z j} T} + 1} \right], \]  

(28)

where,

\[ \omega_{k_z j} = \sqrt{m_{q_j}^2 + k_z^2} + 2j |q_f e B| \]  

(29)

where, we have defined, \( m_{q_j}^2 = m_q^2 + 2j |q_f e B| \)
Equation (28) becomes, after some algebra,

\[
\varepsilon_q = \frac{12n_q|q_f B| T^2}{4\pi^2} \sum_{l=0}^{\infty} \frac{(-1)^{(l+1)}}{l^2} \left\{ \sum_{j=0}^{\infty} \left[ \left( \frac{l m_q}{T} \right) K_1 \left( \frac{l m_q}{T} \right) + 2 \left( \frac{l m_q}{T} \right)^2 K_0 \left( \frac{l m_q}{T} \right) \right] \\
- \left[ \left( \frac{l m_g}{T} \right) K_1 \left( \frac{l m_g}{T} \right) + 2 \left( \frac{l m_g}{T} \right)^2 K_0 \left( \frac{l m_g}{T} \right) \right] \right\}
\]

\[(30)\]

The expression for energy density of gluons is,

\[
\varepsilon_g = \frac{g_g T^4}{2\pi^2} \sum_{l=1}^{\infty} \frac{1}{l^4} \left[ \left( \frac{l m_g}{T} \right)^3 K_1 \left( \frac{l m_g}{T} \right) \right] + 3 \left( \frac{l m_g}{T} \right)^2 K_2 \left( \frac{l m_g}{T} \right)
\]

\[(31)\]

The total energy density is obtained as

\[
\varepsilon = \varepsilon_g + \sum_q \varepsilon_q.
\]

\[(32)\]

The pressure can be obtained from the thermodynamic relation,

\[
\varepsilon = T \frac{\partial P}{\partial T} - P,
\]

\[(33)\]

as,

\[
P = \frac{P_0}{T_0} + \int_{T_0}^{T} dT \frac{\varepsilon(T)}{T^2}.
\]

\[(34)\]

Here, \(P_0\) and \(T_0\) are pressure and temperature at some reference points [26]. The entropy density can be calculated from,

\[
s = \frac{\varepsilon + P}{T}.
\]

\[(35)\]

D. Equation of State for 2-flavor System in the Presence of Strong Magnetic Fields

Using the above formalism, we obtain the equation of state for the 2-flavor system in the presence of strong magnetic fields. To this end, we need a running coupling constant that depends both on temperature and magnetic field. The running coupling constant needs modification in the presence of magnetic fields. It has been well known that the coupling constant shows a decreasing behaviour in the presence of magnetic field [20]. Different ansatz for the dependence of coupling constant on magnetic fields, in the presence of strong magnetic fields, have been proposed [41][42]. In [44] the coupling constant depending on both temperature and magnetic fields was introduced in the SU(2) NJL models as,

\[
G(B,T) = c(B) \left[ 1 - \frac{1}{1 + e^{\beta(B)(T_s(B) - T)}} \right] + s(B), \quad (36)
\]

where, the four parameters \(c, \beta, T_s,\) and \(s\) were obtained by fitting the lattice data. It was shown that the thermodynamic quantities showed correct qualitative behaviour, in the presence of strong magnetic fields, with this parametrisation.

We make use of this ansatz for the coupling constant with the parameters as obtained in [44], to calculate the thermo-magnetic mass according to (7) and (8) and hence obtain the equation of state.

Calculation of \(P(T)\) requires the value of pressure at some fixed temperature \(T_0\). If lattice data is available \(P_0\) can be chosen as the value of pressure at transition temperature \(T_c\). Here we have chosen the value of pressure at \(T_c\) from [44].

For all calculations, we have taken the physical masses of quarks as in [33]. We have shown the temperature dependence of different thermodynamic quantities at different values of magnetic fields in Figs. 1-3. Fig.1 shows that the energy density increases, at a given temperature, as the magnetic field increases. This is expected as, in the presence of magnetic field the total energy density goes as \(\varepsilon_{total} = \varepsilon + qM \cdot B\), where \(M\) is the magnetization [44]. We notice that the plots show correct qualitative behaviour. The values of pressure, energy density, and entropy density increase with the increase in \(eB\). This behaviour is consistent with that obtained using lattice QCD simulations [46] and [47]. The same behaviour has been obtained using an effective fugacity quasiparticle model in [48] and within SU(2) NJL model in [44]. There are several other studies which study magnetised quark matter. The QCD equation of state in the presence of magnetic field has been studied numerically in [48] [49].
The effect of magnetic field on QCD thermodynamics has been studied using the HTL perturbation theory both at strong [50] and in weak [51] magnetic fields. 

$\Delta \varepsilon$ is the difference between energy density in the presence of magnetic fields with that in the absence of any magnetic field. This depicts the increment of energy density in the presence of the magnetic field. The temperature dependence of $\Delta \varepsilon/T$ has been plotted in Fig.3. In addition, we have plotted $\Delta P/T^4$ and $\Delta s/T^3$ as functions of temperature. As expected, higher the magnetic field, higher are their values too.

IV. CONCLUSIONS

We have extended the self-consistent quasiparticle model for hot QCD in the presence of strong magnetic fields to understand the behaviour of magnetised quark matter. The effect of magnetic fields has been included
by redefining the thermal mass of quasiparticles. The definition of thermal mass in the self-consistent model has been extended to define a thermo-magnetic mass through Landau Level quantisation for fermions. The thermodynamic quantities are evaluated by starting with the modified momentum distributions and the energy dispersion relations. The modification of these quantities has been brought about by incorporating relativistic Landau Levels and the effect of dimensional reduction.

Using this modified quasiparticle model, we have studied the 2-flavor system in the temperature range 170-400 MeV, in the presence of strong magnetic fields. To this end, we made use of a parametrisation of the coupling constant that depends both on temperature and magnetic field, obtained in the context of SU(2) NJL model. We found that the energy density, pressure and entropy density increase in the presence of a magnetic field as expected. Our results are qualitatively consistent with the results obtained using other approaches including lattice QCD simulations.

The correct behaviour of the equation of state shows that the self-consistent quasiparticle can be extended to study the thermodynamics of quark-gluon plasma in the presence of magnetic fields. For a quantitative study that can be compared with the lattice data, we need a coupling constant depending both on temperature and magnetic field. With a proper parametrisation of the coupling constant for 2 + 1 flavor, we can easily extend this work to obtain the equation of state for 2 + 1 flavor QGP in the presence of strong magnetic field and compare it with the other works in this area. We intend to do this in our future work. Another area that we plan to investigate further is how the modified equation of state affects the transport coefficients of QGP.

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