Anisotropic pressure of magnetized quark matter

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Study of hot and/or dense matter in the presence of strong magnetic field has gained a significant research interest in last few decades. Recent studies suggest that, very strong magnetic fields of the order $\sim 10^{18}$ G or larger might be momentarily generated in non-central collisions of two heavy nuclei. The presence of finite electrical conductivity of the medium is expected to substantially delay the decay process of these time dependent fields. Beside this, there are other physical systems where such strong magnetic fields can be present. For example, in the interior of magnetars, the magnitude of magnetic field may reach up to $\sim 10^{15}$ G. Moreover, during the electroweak phase transition in the early universe, it is conjectured that, primordial magnetic fields as high as $\sim 10^{23}$ G might have been produced. Since the strength of these magnetic fields is equivalent to the typical Quantum Chromodynamics (QCD) energy scale ($eB \sim \Lambda^2_{\rm QCD}$), it is expected that, various microscopic and bulk properties of the strongly interacting matter can undergo significant modifications due to the presence of background field (see [1] for a broad overview).

It is well known that, the energy-momentum tensor (EMT) shows anisotropies owing to the breaking of the spatial rotational symmetry in the presence of a magnetic field (eB). Now, in the local rest frame, if the spatial elements of the EMT are interpreted as the pressures, then there is a difference induced by the orientation of the magnetic field. These different elements along and perpendicular to eB are called longitudinal ($P_{\parallel}$) and transverse ($P_{\perp}$) pressures respectively. These quantities can in turn modify the equation of state (EoS) of the strongly interacting matter which goes as input in magneto-hydrodynamical evolution of the hot and dense matter created in heavy ion collisions which is a topic of current research. Incorporating the anisotropic nature of the pressure on the EoS of certain compact stars such as neutron star, quark star, hybrid star and so on also leads to many important consequences.

However, detailed first principle calculations involve a great deal of complexities as the large coupling strength of QCD in low energy regime restricts the use of perturbative approach. Most of our current knowledge of these non-perturbative features is obtained from Latiice QCD simulations at zero chemical potential. The situation is less explored at finite baryon density due to the (in)famous sign problem. Thus, one has to rely on the phenomenological models, which capture the basic aspects of QCD and are useful to evaluate the constituent quark mass, the pion mass, and so on at arbitrary temperature and chemical potential. Here we have used the Polyakov loop extended Nambu−Jona-Lasinio (PNJL) model model in order to acquire a simultaneous description of the spontaneous breaking of chiral symmetry and confinement of the quarks. In this work we have evaluated the longitudinal and transverse pressures of magnetized strongly interacting matter for three different stages of chiral phase transition without making any approximation on the strength of the magnetic field (more de-

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tail can be found in [2]). These are as follows:

1. $T < T^{\text{ch}}_{eB=0}$: This will represent the scenario when chiral symmetry is broken.
2. $T \approx T^{\text{ch}}_{eB=0}$: This corresponds to the situation in the vicinity of chiral phase transition.
3. $T > T^{\text{ch}}_{eB=0}$: This will represent the (partial) restoration of the chiral symmetry.

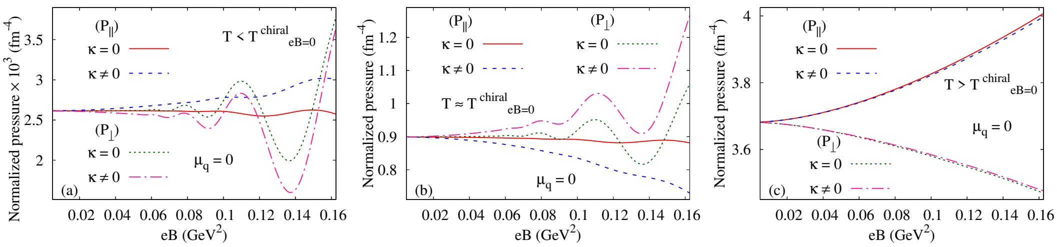

FIG. 1: Normalized longitudinal ($P_{\|}$) and transverse ($P_{\perp}$) pressure as a function of eB for (a) $T < T^{\text{ch}}_{eB=0}$ (b) $T \approx T^{\text{ch}}_{eB=0}$ and (c) $T > T^{\text{ch}}_{eB=0}$ with and without the AMM of the quarks at $\mu_q = 0$.

Normalization of any thermodynamic quantity $\Xi(T, \mu_q, eB)$ is done in the usual manner:

$$\Xi_N\,(T, eB) \equiv \Xi\,(T, eB) - \Xi\,(T = 0, eB)\,.$$

For convenience, we will omit the subscript N. In Figs. 1 (a), (b) and (c) we have presented the variation of normalized longitudinal ($P_{\|}$) and transverse ($P_{\perp}$) pressures as a function of eB with and without considering the AMM of quarks illustrating distinct phases of chiral symmetry breaking and its restoration. Concentrating on Fig. 1(a), it can be observed that for small values of eB, the $P_{\|}$ almost coincides with $P_{\perp}$ independent of the consideration of the AMM of the quarks. But for $eB > 0.03$ GeV^2, the pressures along the magnetic field and transverse to it, begin to be different revealing the anisotropic nature. At higher values of magnetic field, $P_{\|}$ shows slight oscillation although its magnitude remains almost unchanged when the AMM of the quarks is no taken into consideration. However, an overall increase in the magnitude of longitudinal pressure can be observed in nonzero AMM case. On the other hand, the transverse pressure, becomes highly oscillatory for large values of eB and the amplitude of oscillation is higher when finite values of AMM of the quarks are taken into consideration. From Fig. 1(b), it is evident that, the eB-dependence of $P_{\|}$ and $P_{\perp}$ in the vicinity of chiral phase transition is quite similar to the previous case. However, the overall magnitude is $\sim 10^3$ times higher compared to Fig. 1 (a). From Fig. 1(c), it can be seen that, at a temperature where chiral symmetry is restored, the anisotropic effects in $P_{\|}$ and $P_{\perp}$ are noticeable for all values of background magnetic field and the inclusion of AMM of the quarks bring negligible changes. Moreover, the oscillations observed in both $P_{\|}$ and $P_{\perp}$ in the preceding cases are absent and the longitudinal (transverse) pressure increases (decreases) monotonically as a function of eB.

References

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