Quark matter under strong magnetic fields

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Simulations have shown that very strong magnetic fields $\sim 10^{15-18}$ Gauss may be produced in the highly relativistic heavy ion collision experiments being performed at the RHIC at Brookhaven and LHC at CERN. Fields of similar magnitude are expected to be present in the core of astrophysical objects such as magnetars and could have also existed during the electroweak phase transition in the early universe. Interestingly, the magnitude of this background field is of the same order as the scale of QCD causing an interplay of strong and electromagnetic interactions and leading to exotic phenomena involving the QCD vacuum such as magnetic catalysis of chiral symmetry breaking and its inverse, chiral magnetic effect etc.

In the recent past we have been involved in performing elaborate studies on various aspects of strong interactions in hot and dense matter in the presence of a magnetic field both in the hadronic as well as in the quark phase. We have used effective theories of strong interaction constructed with hadrons as the fundamental degrees of freedom such as the Walecka model as well as models with quark degrees of freedom such as the Nambu-Jona-Lasinio(NJL) model and its variants. In the latter case hadrons appear through a Bethe-Salpeter approach. In addition to the analyses of absorptive and dispersive properties of hadrons the latter models were also used to study the thermodynamics and phase structure of hot and dense quark matter. Almost all the calculations have been done without making any assumptions on the strength of the magnetic field thus entailing an infinite sum over Landau levels which characterize the quantized momenta in the direction transverse to the magnetic field appearing in the propagators of charged particles involved in the interactions.

We start with works based on hadronic models. We obtained the general Lorentz structure of the rho meson self-energy in hot and dense magnetized medium in terms of four form factors which were calculated using an improved regularization procedure. The decay channel of the rho into two pions was found to be blocked for certain critical values of the magnetic field depending upon the temperature and baryon chemical potential [1]. The pion and nucleon masses were also addressed in magnetized matter. It was found that the critical temperature corresponding to the vacuum to nuclear medium phase transition decreases with the external magnetic field which is inverse magnetic catalysis whereas the opposite is observed for vanishing nucleon magnetic moment indicating magnetic catalysis[2].

Our studies on quark matter in a magnetic field have been done using the NJL type of approach which involves a point-like four quark interaction. This renders the model nonrenormalizable. Thus proper regularization schemes need to be adopted to deal with the divergent integrals and the parameters associated with the model are fixed to reproduce some well-known phenomenological quantities such as the pion decay constant, quark condensate etc. The strength of this model is that it incorporates the global symmetries of QCD, especially chiral symmetry and enables one to "see" the dynamical breaking of this symmetry which is not possible with QCD because of its nonperturbative nature in the long wavelength region.

Most calculations dealing with quark matter in magnetic fields have ignored the effects brought about by inclusion of the anomalous magnetic moment(AMM) of quarks. Following Schwinger we have introduced the AMM through a spin-field interaction term in the Dirac Lagrangian which actually originates from radiative corrections to $\gamma\bar{q}q$ vertex. The numerical values of the AMM for u and d

quarks are fixed from the magnetic moments of the proton and neutron. Using the 2-flavour NJL model the constituent quark mass is obtained by solving the gap equation as a function of temperature for different values of baryon density and magnetic field. It is found [3] that the transition temperature from symmetry broken to restored phase increases with external magnetic field showing the enhancement of the quark condensate which can be identified as magnetic catalysis. The opposite behaviour is observed when AMM of quarks is taken into consideration, indicating inverse magnetic catalysis. The phase diagram of hot and dense magnetized quark matter is also obtained and the critical end point (CEP) is found to shift towards higher temperatures. On the contrary, when we include AMM of quarks the CEP follows an opposite trend. Interestingly for high fields the transition remains crossover for a larger range of temperature and chemical potential for finite values of AMM.

The masses of the σ and π^0 obtained in the NJL model using the RPA shows that with the increase in temperature, m_σ decreases while m_π increases followed by a merging of their masses at high temperature indicating partial restoration of the chiral symmetry. The external magnetic field affects the masses of these mesons in a non-trivial way; m_π decreases (increases) with the increase in magnetic field in the low (high) temperature region when the AMM of the quarks is turned off. However, in its presence m_π increases with the increase in magnetic field in the temperature range considered. These calculations have been also done using the NJL model with a Polyakov loop to include the effects of confinement [4].

We then go on to evaluate the current correlator in the vector channel in a thermomagnetic dense medium from which we obtain the dilepton production rate (DPR) [5]. The NJL model provides the temperature, density, magnetic field and AMM dependent effective quark mass which is used in the expression of DPR. The analytic structure shows that the thresholds of the unitary and Landau cuts have nontrivial dependence on the magnetic field as well as the AMM of the quarks. The DPR is largely enhanced in the low invariant mass region due to contribution from the Landau cut. Moreover, at lower temperatures there exists a kinematic region between the Landau and Unitary cuts where the DPR is zero if the AMM of the quarks is ignored irrespective of the value of the external magnetic field. For finite AMM this forbidden gap monotonically decreases to zero with the increase in external magnetic field resulting in a continuous spectrum of dilepton emission over the whole range of invariant mass. This is a novel finding not observed in earlier calculations. To study the effects of confinement and strangeness these results have also been done within a 3-flavour PNJL model [6].

It is expected that the AMM of the quarks will have a significant contribution coming from the QCD correction to the $\gamma\bar{q}q$ vertex. As an alternative to QCD we use the gauged NJL model to explicitly calculate [7] the effective vertex function and extract the AMM of the quarks which reproduces the measured values of the magnetic moment of the proton and neutron. The lowest order vertex diagram evaluated at finite temperature and external magnetic field provides us with the thermomagnetic modification of the AMM. We find that at sufficiently high temperature the AMM as well as the constituent mass of the quarks asymptotically go to zero.

References

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