Strongly interacting hot and dense matter in background magnetic field

Nilanjan Chaudhuri[1,2*]
[1] *Variable Energy Cyclotron Centre, 1/AF Bidhannagar, Kolkata 700 064, India and*
[2] *Homi Bhabha National Institute, Anushaktinagar, Mumbai - 400085, India*

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. 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. 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. 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 in order to acquire a simultaneous description of the spontaneous breaking of chiral symmetry and confinement of the quarks. All the calculations are done considering finite values of the anomalous magnetic moment (AMM) of the quarks which are usually ignored in the literature. The possession of the AMM by a fermion, despite having no internal structure, due to quantum corrections, is a well-established phenomenon in the realm of gauge field theory. Quarks, being fermions themselves, also possess finite AMMs.

*Electronic address: n.chaudhri@vecc.gov.in

Thermodynamic properties

One of the key findings of our investigation is that the presence of AMM leads to inverse magnetic catalysis (IMC) of the transition temperature from chiral symmetry broken to the restored phase. This effect stands in contrast to the scenario without AMM, where the transition temperature increases, indicating magnetic catalysis (MC). Several thermodynamic quantities such as scaled pressure, entropy and energy density are studied as a function of temperature (T) and it is observed that they behave similarly as all the three curves increase smoothly in the vicinity of the phase transition owing to the liberation of degrees of freedom suggesting that the associated phase transition is a crossover. However, when finite values of AMM of the quarks are taken into consideration the transition occurs at lower temperatures.

Mesonic excitations

It is well known that, mesons are the bound state of quarks and antiquarks, so their propagation can be studied from the scattering of quarks/antiquarks in different channels employing the Bethe-Salpeter formalism within Nambu−Jona-Lasinio model. Mass, spectral function and dispersion relations are obtained in the scalar (σ) and pseudo-scalar (π^0) channels as well as in the vector (ρ^0) and axial vector (a_1) channels. This is accomplished by computing two-point thermo-magnetic correlation functions for various mesonic modes using the real-time formalism of thermal field theory and the Schwinger proper time formalism. The general Lorentz structures for the vector and axial-vector meson polarization functions have been considered in detail. The ultra-violet divergences have been regularized using a mixed regularization technique where the gamma functions arising in dimensional regularization are replaced with incomplete gamma functions as usually done in the proper time regularization procedure. The meson spectral functions obtained in the presence of magnetic field possess non-trivial oscillatory structure. Similar to the scalar and pseudo-scalar channel, the spectral functions for each of the modes of ρ^0 are observed to overlap with the corresponding modes of its chiral partner a_1 mesons in the chiral symmetry restored phase. We observe discontinuities in the masses of all the mesonic excitations for non-zero external magnetic field.

Dilepton production rate (DPR)

Considering finite values of AMM of the quarks dilepton production from magnetized quark matter is studied by evaluating the thermo-magnetic spectral function of the vector current correlator employing the real time formalism of finite temperature field theory and the Schwinger proper time formalism. The constituent quark mass, a crucial input in the expression for DPR, exhibits a significant dependence on temperature, density, magnetic field and the AMM of the quarks. This dependence captures the impact of 'strong' interactions, particularly in the vicinity of the (pseudo) chiral and confinement-deconfinement phase transition regions. The analytic structure of the spectral function in the complex energy plane has been analyzed in detail and a non-trivial Landau cut is found in the physical kinematic domains resulting from the scattering of the Landau quantized quark/antiquark with the photon which is purely a finite magnetic field effect. Due to the emergence of the Landau cut along with the usual unitary cut, the DPR is found to be largely enhanced in the low invariant mass region. Owing to the magnetic field and AMM dependence of the thresholds of these cuts, we find that the kinematically forbidden gap between the Unitary and Landau cuts vanishes at sufficiently high temperature, density and magnetic field leading to the generation of a continuous dilepton emission over the whole invariant mass region.

Collective Oscillations

The general structure of the self-energy at one loop order of a massive fermion is obtained in a magnetized medium considering the finite values of AMM. It is found that the self-energy of a thermo-magnetically modified massive fermion contains five non-trivial structure factors. These structure factors have been evaluated in a weak magnetic field within the HTL approximation using the real time approach of thermal field theory which has not been explored previously. Firstly we see that the presence of finite AMM modifies the magnetic mass. In such a scenario the most significant effect is observed in the dispersion relation of the excited states. For up quarks, which are positively charged, the states corresponding to the quantum numbers $\{n, s = 0, -1\}$ and $\{n, s = 1, 1\}$ are doubly degenerate in the absence of AMM. However, when finite values of AMM are taken into consideration, this degeneracy is lifted. The state with quantum numbers $\{n, s = 1, 1\}$ corresponds to the first excited state and has a slightly lower magnitude in energy compared to the doubly degenerate excited states observed in the absence of AMM. Similarly, the state represented by $\{n, s = 0, -1\}$ becomes the second excited state and its magnitude is slightly higher than that of the degenerate excited states. This effect is observed in both particle and hole-like excitations. Qualitatively similar effects are also observed in the dispersion of down quarks.

References

[1] N. Chaudhuri, S. Ghosh, S. Sarkar and P. Roy, Eur. Phys. J. A **56** 213 (2020).

[2] S. Ghosh, A. Mukherjee, N. Chaudhuri, P. Roy and S. Sarkar, Phys. Rev. D **101** 056023 (2020).

[3] N. Chaudhuri, S. Ghosh, S. Sarkar and P. Roy, Phys. Rev. D **103** 096021 (2021).

[4] N. Chaudhuri, S. Ghosh, P. Roy and S. Sarkar, Phys. Rev. D **108** 116006 (2023).