Thermomagnetic modification of the anomalous magnetic moment of quarks

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Hot and/or dense 'strongly' interacting matter, when subject to an intense external magnetic field B can lead to various exotic and novel phenomenon owing to the rich vacuum structure of quantum chromodynamics (QCD) [1]. Such a scenario is conjectured to be existed during the electroweak phase transition in the early universe ($B \sim 10^{23}$ G), on the surface of *magnetars* ($B \sim 10^{15}$ G) and most importantly in non-central heavy ion collision (HIC) experiments at RHIC and LHC ($B \sim 10^{18}$ G or larger).

Owing to the non-perturbative nature of QCD especially in the low temperature region, one alternatively uses various QCD-based effective models to study the properties of nuclear matter under extreme condition. Nambu–Jona-Lasinio (NJL) model is one such model, which was built respecting the global symmetries of QCD [2] and has been extensively used to study phase structure of hot, dense and magnetized QCD medium. Recently, the effects of the anomalous magnetic moment (AMM) of the quarks on various properties of thermomagnetic dense quark matter have been studied in Ref. [3, 4, 5, 6, 7] where the AMM of quarks are taken as constant as calculated using the constituent quark model.

The appearance of AMM of an elementary particle, due to quantum corrections in Quantum Electrodynamics (QED) is a well known phenomenon; for example, the Landé g-factor of the electron comes out to be $2 + \alpha/\pi$ up to one-loop in QED where α is the fine structure constant. Now, QCD being the gauge theory of strong interactions, an anomalous contribution to the magnetic moment can therefore be associated with the quarks due to 'strong' corrections, along with the QED corrections. Using a gauged NJL model, it was shown in Ref. [8] that the AMM of quarks can be significant in theories where mass generation occurs through dynamical chiral symmetry breaking.

As the AMM of the quarks has dominant contribution from the QCD correction (to the photon-quark-antiquark ($\gamma q\overline{q}$) vertex function), we aim to use the gauged-NJL model to explicitly calculate the vertex function and extract the AMM of the quarks which reproduces the correct (large) values of the AMM of proton and neutron in the limit $T = 0$ and $B = 0$. This has been achieved by calculating the lowest order diagram which contributes to the magnetic form factor corresponding to the effective $\gamma q\overline{q}$ vertex at finite temperature in presence of arbitrary external magnetic field in the mean field approximation (MFA) employing the Schwinger proper time formalism and finite temperature field theory.

We use the two-flavor gauged NJL Lagrangian

$$\mathcal{L} = \overline{\psi}\left(i\gamma^\mu\partial_\mu - |e|\hat{Q}\gamma^\mu(A_\mu + A_\mu^{\rm ext}) - m\right)\psi + G\left\{(\overline{\psi}\psi)^2 + (\overline{\psi}i\gamma^5\boldsymbol{\tau}\psi)^2\right\} \quad (1)$$

where, G is the NJL coupling in the scalar channel, ψ is the quark iso-flavor doublet and the other details can be found in Ref. [9]. Using Eq. (1), the effective $\gamma q\overline{q}$ vertex function comes out to be,

$$\Gamma^\mu(k,p) = \gamma^\mu \otimes \hat{Q} \otimes \mathbb{1}_{\rm Color} - 2iG \sum\!\!\!\!\!\!\int \frac{d^4\tilde{p}}{(2\pi)^4}\Big[S_B(k+\tilde{p})\hat{Q}\gamma^\mu S_B(\tilde{p}) - \gamma^5\tau^i S_B(k+\tilde{p})\hat{Q}\gamma^\mu S_B(\tilde{p})\gamma^5\tau^i\Big] \quad (2)$$

in which $S_B(p)$ is the momentum space quark

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Schwinger propagator given by

$$S_B(p) = \begin{pmatrix} S_u^B(p) & 0 \\ 0 & S_d^B(p) \end{pmatrix} \quad (3)$$

where each of the diagonal flavor component becomes sum over discrete Landau levels and spin as

$$S_f^B(p) = \sum_{s\in\{\pm1\}} \sum_{n=0}^{\infty} \frac{-\mathcal{D}_{nfs}(p)}{p_\parallel^2 - M_{nfs}^2 + i\epsilon} \otimes \mathbb{1}_{\text{Color}}. \quad (4)$$

In the above equation, $f \in \{\text{u}, \text{d}\}$, $M_{nfs} = \left|M_{nf} - s\kappa_f Q_f B\right|$ where $M_{nf} = \sqrt{M^2 + 2n|Q_f eB|}$ with κ_f being the AMM of quark flavor f and M being the constituent quark mass. The quantity $\mathcal{D}_{nfs}(p)$ in the above equation contains the complicated Dirac structure of the propagator [9].

The vertex function can be decomposed in terms of the magnetic form factor F_2 (which is related to the AMM) as

$$\Gamma^\mu(k,p) = \left[F_1\hat{Q}\otimes\gamma^\mu + F_2\hat{Q}i\frac{\sigma^{\mu\nu}}{2M}k_\nu\right] \otimes \mathbb{1}_{\text{Color}},$$

from which the quantity F_2 can be easily extracted as

$$F_2(k,p) = -i\frac{M}{6N_c k^2}\hat{Q}^{-1}\text{Tr}_{\text{d,c}}\left(k_\nu\sigma^{\mu\nu}\Gamma_\mu\right) \quad (5)$$

where, N_c is the number of color. Detailed formalism, other technical details and model parameters can be found in Ref. [9].

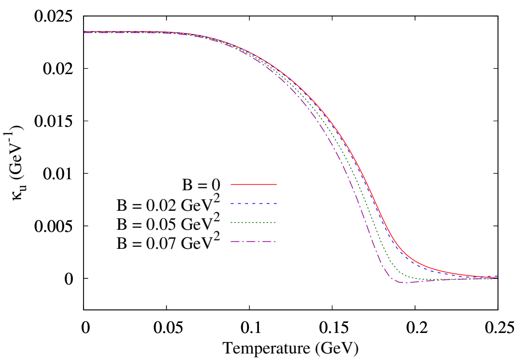

Figure 1: Variation of κ_u as a function of temperature.

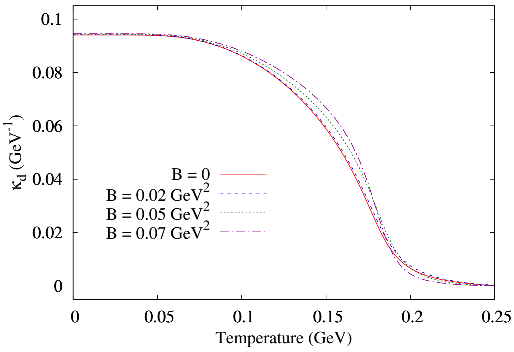

Figure 2: Variation of κ_d as a function of temperature.

In Fig. 1 we have depicted the T-dependence of κ_u for different values of magnetic field. It can be seen that, AMM of the up quark is large in the chiral symmetry broken phase. With the increase in temperature, κ_u first remain almost unchanged up to a certain value of temperature and then fall rapidly around the pseudo-chiral phase transition temperature. Finally, at sufficiently high temperature region approachs asymptotically to zero. The similar characteristics is also found in variation of κ_d as a function of temperature as can be seen from Fig. 2.

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