Weak magnetic field effect on neutrino emissivity

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I. Introduction

Recent years have witnessed significant progress in understanding the properties of hot and/or dense matter produced at relativistic heavy ion collider (RHIC) at BNL and at the large hadron collider (LHC) at CERN. Such studies are important in determining the thermodynamic and transport properties of quark component of astrophysical compact objects like neutron stars and pulsars. It is known that when a new star is born following a supernova explosion, large amount of neutrinos and antineutrinos are emitted immediately from the core involving the direct or the modified URCA processes, resulting in colder core and a hotter crust, thus a temperature gradient is set up [1]. Then the thermal energy gradually flows inward by heat conduction which alternatively might be viewed as the propagation of the cooling waves from the center towards the surface leading to thermalization.

It is well known that the matter density in the core of the neutron stars could well exceeded up to a few times the nuclear matter saturation density. Thus, in this context we can expect comparable proportions of up, down and strange quarks which are quite truly the ground state of QCD at finite baryon density. At such high densities, the constituents of matter are relativistic which compels one to describe such matter in the frame work of the non-Fermi liquid (NFL) behavior [2–4]. It has been known that a fermionic system interacting via the exchange of transverse gauge bosons exhibit deviations from the normal Fermi liquid behavior, the correction to the leading-order contribution involves non-analytic terms, known as NFL corrections. This is a consequence of the long range behavior of the magnetic interaction due to the absence of magnetostatic screening. However, the magnetic interaction in non-relativistic systems is suppressed in powers of $(v/c)^2$. The scenario changes as one enters into the relativistic domain, where it becomes important. Hence, in dealing with relativistic plasma one has to retain both electric and magnetic interactions mediated by the exchange of longitudinal and transverse gauge bosons like photons or gluons. More interestingly, it is observed that for ultradegenerate case, both in QCD and QED, the transverse interactions not only become important but it dominates over its longitudinal counterpart; a characteristic behavior having a non-trivial origin residing in the analytical structure of the Fermion-self energy close to the Fermi surface [3]. Actually, the fermion self-energy close to the Fermi surface receives a logarithmic enhancement due to the exchange of magnetic gluons. Such calculations were performed one in [2] and the other in [4] where it was shown how the emissivity and the mean free path receives logarithmic corrections, respectively. In the present work we compute the weak magnetic field effect to the neutrino emissivity over the NFL corrections.

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II. Emissivity in presence of weak magnetic field

The dominant contribution to the emission of neutrinos is given by the quark analogus of β decay (β) and the electron capture (ec)

$$d \rightarrow u + e^- + \overline{\nu_e} \tag{1}$$

$$u + e^- \rightarrow d + \nu_e \tag{2}$$

In presence of high magnetic fields modifies the energy of charged particles confining them to low Landau levels. This quantization effect is important when the magnetic strength is equal to or larger than some critical value. However, in the present context, we consider the magnetic field is not strong enough to force the electrons in the lowest Landau level. In this situation, the matrix element for the process remains unaffected and the modification comes from the phase space factor. The quark energies are essentially independent of spin states and we can sum over quark spins [5]. The weak matrix element squared for the β and ec processes is given by

$$
\begin{aligned}
|M_{\beta/ec}|^2 &= \frac{1}{2}\sum_{\sigma_u,\sigma_d,\sigma_e}|M_{fi}|^2 \\
&= 64G^2\cos^2\theta_c(P_d\cdot P_\nu)(P_u\cdot P_e) \qquad (3)
\end{aligned}
$$

where the weak coupling constant $G \simeq 1.166\times 10^{-11}\ MeV^{-2}$, θ_c is the Cabibbo angle. The dependence on the Cabbibo angle suppresses the processes involving the strange quark.

The neutrino emissivity is given by [2]

$$
\begin{aligned}
\epsilon &= g\int\frac{d^3p_d}{(2\pi)^3}\frac{1}{2E_d}\int\frac{d^3p_u}{(2\pi)^3}\frac{1}{2E_u}\int\frac{d^3p_e}{(2\pi)^3}\frac{1}{2E_e} \\
&\int\frac{d^3p_\nu}{(2\pi)^3}\frac{1}{2E_\nu}E_\nu\{|M_\beta|^2(2\pi)^4\delta^4(P_d-P_u \\
&-P_e-P_\nu)n(p_d)[1-n(p_u)][1-n(p_e)] \\
&+|M_{ec}|^2(2\pi)^4\delta^4(P_u+P_e-P_d-P_\nu) \\
&n(p_u)n(p_e)[1-n(p_d)]\} \qquad (4)
\end{aligned}
$$

where, g is the spin and color degeneracy. Now, we evaluate the emissivity in the limit of extreme degeneracy, a situation appropriate in neutron star cores by replacing the electron phase space factor

$$
\int\frac{d^3p_e}{(2\pi)^3} \rightarrow \frac{eB}{(2\pi)^2}\sum_{\nu=0}^{\nu_{max}}(2-\delta_{\nu,0})\int dp_z \qquad (5)
$$

and using the standard techniques to perform the phase space integral [1, 2, 4], we have

$$
\begin{aligned}
\epsilon &= \frac{457}{1260}G^2\cos^2\theta_c\alpha_s\mu_d\mu_u eBT^6 \\
&\left[1+\frac{C_F\alpha_s}{3\pi}\ln\left(\frac{m_D}{T}\right)\right]^2 \\
&\sum_{\nu=0}^{\nu_{max}}(2-\delta_{\nu,0})\frac{1}{\sqrt{\mu_e^2-m_e^2-2\nu eB}} \qquad (6)
\end{aligned}
$$

$$
\text{and} \qquad \nu_{max} = \text{Int}\Big(\frac{\mu_e^2-m_e^2}{2eB}\Big) \qquad (7)
$$

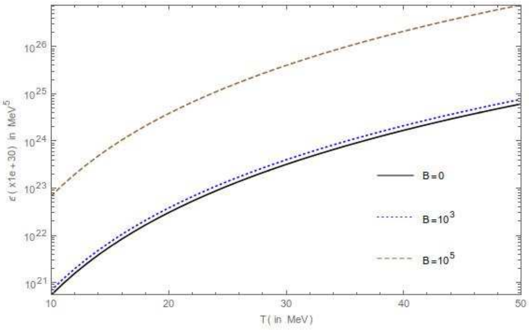

FIG. 1: Neutrino emissivity with different values of magnetic field.

In the limit of vanishing magnetic field ($B = 0$), the sum can be replaced by an integer and we recover the usual expression as given in [2].

III. Results and Discussions

In Fig.(1), we show the temperature dependence of neutrino emissivity for different values of the magnetic field. With the increase in magnetic field, emission of neutrino from degenerate quark matter enhances. This enhancement effects lead to faster cooling of neutron star.

References

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