PROCEEDINGS OF SCIENCE

Effect of magnetic field on kaon and antikaon in neutron star matter

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Medium modification in the energies of kaon and antikaon in strongly magnetized neutron star matter are explored using the chiral SU(3) model. The parameters used in this calculation are fitted with nuclear matter saturation properties and the vacuum masses of baryons. We have investigated the probability of antikaon condensation in neutron star with charge neutrality and $\beta-$equilibrium condition. Considering the effect of strong magnetic field in present study, it is observed that the possibility of antikaon condensation almost diminish at large magnetic field strength in neutron star matter.

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1. Introduction

Much attention has been drawn towards the study of in-medium properties of kaon and antikaon because of their relevance in neutron star (NS) properties as well as in the relativistic heavy-ion collision experiments. It was demonstrated by Kaplan and Nelson [1] that antikaons can undergo Bose-Einstein condensation in dense matter formed in heavy-ion collision (HIC) experiments or in the interior of NSs. The occurrence of onset of s−wave K^- condensation is identified by equating the chemical potential of K^- (ω_{K^-}) and electron chemical potential (μ_e), whereas $\bar{K}^0$ condensation is determined by the condition, $\omega_{\bar{K}^0}(k=0)=0$. To maintain the charge neutrality condition, the K^- condensate replace the electrons. Nowadays, there has been a lot of research on the properties of kaons and antikaons in high magnetic field due to huge magnetic field generated in HIC experiments. The HIC experiments can create a magnetic field of order $eB \sim 5m_\pi^2$ in the Relativistic Heavy Ion Collider (RHIC) at BNL and $eB \sim 15m_\pi^2$ in the Large Hadron Collider (LHC) at CERN. The strong magnetic field can also exist in magnetars, where the magnetic field is of the order of $10^{15} - 10^{16}$ G at the surface and about 10^{18} G at the center of the NSs. The kaon and antikaon properties were studied in isospin symmetric and asymmetric nuclear matter within chiral SU(3) model in Ref. [2, 3] and in strange hadronic matter in Ref. [4, 5]. In the present study, we focus on the effect of magnetic field on the energies of kaons and antikaons in β-equilibrated neutron star matter using the hadronic chiral $SU(3)$ model.

2. The hadronic chiral $SU(3)$ model

We employed hadronic chiral SU(3) model to obtain the energies of kaons and antikaons in magnetized neutron star matter with β-equilibrium ($\mu_n - \mu_p = \mu_{K^-} = \mu_e$ and $\mu_{\bar{K}^0} = 0$) and charge neutrality condition ($\rho_v^p = \rho_{K^-} + \rho_v^e + \rho_v^\mu$). The model follows the concepts of broken scale invariance and non-linear realization of chiral symmetry. The Lagrangian density of chiral SU(3) model with mean field approximation can be inscribed as [6]

$$\mathcal{L}_{\rm chiral} = \mathcal{L}_{\rm kin} + \sum_{M=S,V} \mathcal{L}_{\rm NM} + \mathcal{L}_{\rm vec} + \mathcal{L}_0 + \mathcal{L}_{\rm SB} + \mathcal{L}_{\rm lep} + \mathcal{L}_{\rm mag} + \mathcal{L}_{\rm KN} \,. \tag{1}$$

The effect of magnetic field in number and scalar density of protons comes into picture through Landau energy levels, whereas in neutrons the contributions come from the anomalous magnetic moment [7]. The expressions for number and scalar density of proton and neutron are defined as [6]

$$\rho_v^p = \frac{|q_p|B}{2\pi^2}\left[\sum_{\nu=0}^{\nu_{max}^{(s=1)}} k^p_{f,\nu,1} + \sum_{\nu=1}^{\nu_{max}^{(s=-1)}} k^p_{f,\nu,-1}\right], \tag{2}$$

$$\rho_v^n = \frac{1}{4\pi^2}\sum_{s=\pm1}\Bigg[\frac{k^n_{f,s}}{3}\left(2{k^n_{f,s}}^2 - 3s\kappa_n\mu_N B(m_n^* - s\kappa_n\mu_N B)\right) - s\kappa_n\mu_N B E_f^{n2}\left(\arctan\left(\frac{(m_n^* - s\kappa_n\mu_N B)}{k^n_{f,s}}\right) - \frac{\pi}{2}\right)\Bigg], \tag{3}$$

$$\rho_s^p = \frac{|q_p|Bm_p^*}{2\pi^2}\Bigg[\sum_{\nu=0}^{\nu_{max}^{(s=1)}} \frac{\sqrt{m_p^{*2}+2|q_p|B\nu}-\kappa_p\mu_N B}{\sqrt{m_p^{*2}+2|q_p|B\nu}} \ln\left|\frac{k_{f,\nu,1}^p+E_f^p}{\sqrt{m_p^{*2}+2|q_p|B\nu}-\kappa_p\mu_N B}\right|$$
$$+\sum_{\nu=1}^{\nu_{max}^{(s=-1)}} \frac{\sqrt{m_p^{*2}+2|q_p|B\nu}+\kappa_p\mu_N B}{\sqrt{m_p^{*2}+2|q_p|B\nu}} \ln\left|\frac{k_{f,\nu,-1}^p+E_f^p}{\sqrt{m_p^{*2}+2|q_p|B\nu}+\kappa_p\mu_N B}\right|\Bigg], \tag{4}$$

$$\rho_s^n = \frac{m_n^*}{4\pi^2}\sum_{s=\pm1}\left[k_{f,s}^n E_f^n - (m_n^* - s\kappa_n\mu_N B)^2 \ln\left|\frac{k_{f,s}^n+E_f^n}{m_n^*-s\kappa_n\mu_N B}\right|\right]. \tag{5}$$

In above, $k_{f,\nu,\pm1}^p$ and $k_{f,s}^n$ represents the Fermi momenta of protons and neutrons, respectively, for the Landau level, $\nu = 0, 1, 2...\nu_{max}$, $s = \pm1$. These Fermi momenta are related to the Fermi energy of the proton and neutron as

$$k_{f,\nu,s}^p = \sqrt{E_f^{p2} - \left(\sqrt{m_p^{*2} + 2|q_p|B\nu} - s\kappa_p\mu_N B\right)^2}, \tag{6}$$

$$k_{f,s}^n = \sqrt{E_f^{n2} - (m_n^* - s\kappa_n\mu_N B)^2}. \tag{7}$$

The Fourier transformation of the equations of motion for kaons (antikaons) leads to the dispersion relation as

$$-\omega^2 + |\vec{k}|^2 + m_{K(\bar{K})}^2 - \Pi_{K(\bar{K})}(\omega, |\vec{k}|) = 0 \tag{8}$$

where $\Pi_{K(\bar{k})}$ stands for the kaon (antikaon) self energy in the medium.

Finally, the effective masses of the charged $K^\pm$ meson and neutral kaons (antikaons), $K^0(\bar{K^0})$ in the magnetized neutron star matter are given as [6]

$$m_{K^\pm}^{eff} = \sqrt{(m_{K^\pm}^*)^2 + q_{K^\pm}B}, \tag{9}$$

$$m_{K^0(\bar{K^0})}^{eff} = m_{K^0(\bar{K^0})}^*. \tag{10}$$

3. Numerical Results and summary

The effect of magnetic field on the energies of kaons (K^+, K^0) and antikaons (K^-, $\bar{K}^0$) is studied as a function of baryonic density in magnetized neutron star matter with hadronic chiral SU(3) model as shown in Fig. 1. The free model parameters and meson masses used in this calculation are provided in Ref. [8]. The energies of K^+ and K^0 mesons increases with increase in density; whereas the energies of K^- and $\bar{K}^0$ mesons decreases. This is due to the dominating behavior of Weinberg-Tomozawa term over the attractive scalar exchange and two range terms of the model [6]. The interaction of Weinberg-Tomozawa term is repulsive for kaons and attractive for antikaons. Then, we consider the effect of magnetic field on kaon-nucleon Lagrangian density, $\mathcal{L}_{\text{KN}}$ at finite baryonic density. The effective masses of $K^\pm$ increases with magnetic field; whereas effective masses of K^0 and $\bar{K}^0$ decreases at lower density, due to direct contribution of magnetic field in $K^\pm$ masses. At higher density, a small change in mass of K^0 is observed as shown in Fig. 1(c). At $\rho_B = 0$, the energies of $K^\pm$ mesons increased by 50 MeV and K^0, $\bar{K}^0$ meson decrease by 35 MeV, respectively, with increase magnetic field from $eB = 2m_\pi^2$ to $6m_\pi^2$. Below $2\rho_0$, with an increase in the magnetic field, the energies of $\bar{K}^0$ decreases whereas, at high ρ_B an increase in effective mass is observed. From Fig. 1, it is also concluded that the possibility of antikaon condensation reduces with increase the magnetic field in neutron star matter.

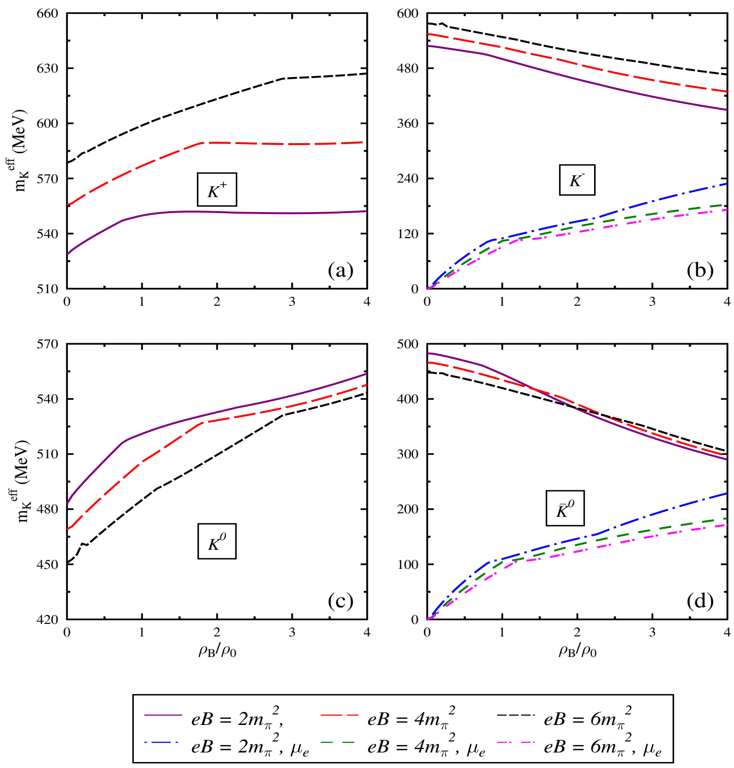

Figure 1: The effective masses of kaon and antikaon as well as electron chemical potential are plotted as a function of baryonic density, ρ_B (in units of nuclear saturation density ρ_0) with $eB = 2m_\pi^2$, $4m_\pi^2$ and $6m_\pi^2$.

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