Kaon condensation in quark meson coupling model at finite temperature

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The understanding of the properties of hot dense nuclear matter is an important problem in theoretical physics in the context of neutron stars as well as in high-energy heavy ion collisions experiments where nuclei undergo violent collisions. Kaplan and Nelson have suggested that, above some critical density, the ground state of baryonic matter might contain a Bose-Einstein condensate of negatively charged kaons. There is a strong attraction between K mesons and baryons that increases with density and lowers the energy of the zero-momentum state. A condensate is formed when this energy equals the kaon chemical potential. Hence, in neutron stars, charge neutrality favors kaon condensation because the neutrons at the top of the Fermi sea decay into protons plus electrons, which in turn have an increase in the energy as the density increases. In the present work, we investigate the phase transition from a hadronic phase to a phase with nucleon and kaon condensate by using the quark-meson-coupling (QMC) model.

In the QMC model, the nucleon in nuclear medium is assumed to be a static spherical MIT bag in which quarks interact with the scalar and vector fields and these fields are treated as classical fields in the mean-field approximation. The equation of motion for the quark field $\psi_q(\vec{r},t)$ inside the bag satisfies [1]

$$\begin{aligned}[i\gamma_\mu\partial^\mu \;&-\; (m_q^0 - g_\sigma^q\sigma_0) - \gamma^0(g_\omega^q\omega_0 \\ &+\; \frac{1}{2}g_\rho^q\tau_{3q}b_{03})]\psi_q(\vec{r},t) = 0 \qquad (1)\end{aligned}$$

where ${m^0}_q$ is the current quark mass and τ_{3q} is the third component of the Pauli matrices. $g_\sigma^q, g_\omega^q, g_\rho^q$ are the quark coupling constants for σ, ω, ρ mesons.

The equilibrium condition for the bag is obtained by minimizing the effective mass ${M_B}^*$ with respect to the bag radius R_B as in Ref. [2]

$$\frac{\partial M_B^*}{\partial R_B^*} = 0 \qquad (2)$$

Once the bag radius is obtained, the effective baryon mass is immediately determined. Also, we assume that the kaons are described by the static MIT bag in the same way as the nucleons. Bag constant for kaons, B_K is taken to be same as for the nucleons. The effective mass of the kaons is calculated in the same way as that of nucleons. σ, ω and ρ mesons are only mediators of the u and d quarks inside the kaons . The energy of the static bag describing kaon bag can be expressed as

$$E_K^{bag} = \frac{\Omega_q + \Omega_s}{R_K} - \frac{Z_K}{R_K} + \frac{4}{3}\pi R_K^3 B_K \qquad (3)$$

Pressure for the kaonic sector at finite temperature T is ,

$$\begin{aligned}P_K \;&=\; \zeta^2\Big[{M_K^*}^2 - (\mu + X_0)^2\Big] \\ +T\int_0^\infty \frac{d^3p}{(2\pi)^3} \;&\Big\{\; \ln[1 - e^{-\beta(\omega^- - \mu)}] \\ &+\; \ln[1 - e^{-\beta(\omega^+ + \mu)}]\Big\} \qquad (4)\end{aligned}$$

where $X_0 = g_{\omega K}\omega_0 + g_{\rho K}\rho_{03}$, Bose occupation probability $f_B = (e^{-\beta x} - 1)^{-1}$, $\omega^\pm = \sqrt{p^2 + {M_K^*}^2} \pm X_0$, ζ is the condensate factor for the kaons. The total energy density of the baryonic and the kaonic contribution at finite density ρ_B and ρ_K is

$$\epsilon = \epsilon_B + \epsilon_K \qquad (5)$$

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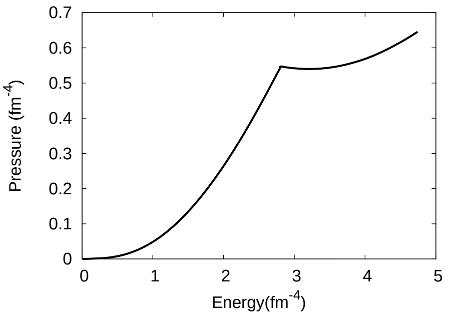

FIG. 1: Pressure versus energy density for nuclear matter at T=10 MeV.

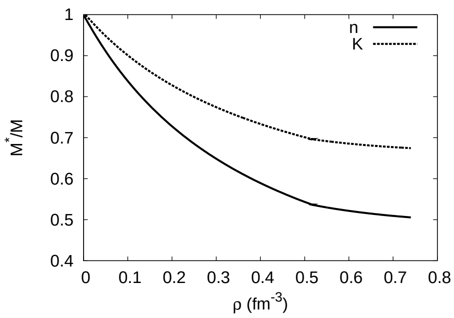

FIG. 2: Effective nucleon and kaon masses versus density obtained with the QMC model at T=10 MeV.

The baryon energy density is same as in Ref [3] and the kaon energy density becomes

$$\varepsilon_K = \zeta^2 \Big[{M_K^*}^2 - \mu^2 + X_0^2 \Big] + \int_0^\infty \frac{d^3p}{(2\pi)^3} \Big[\omega^-(p) f_B(\omega^- - \mu) + \omega^+(p) f_B(\omega^+ + \mu) \Big] \quad (6)$$

The values of σ, ω and ρ can be obtained as in ref [2]. In Fig. 1, we show the equation of state obtained in a QMC model for nucleons plus kaon phase. A kaon condensation is possible for densities greater than around $3.5\rho_0$, where ρ_0 is the saturation density. In Fig. 2, we show the kaon and nucleon effective masses. Note that the mass of the nucleons is more affected by the medium than

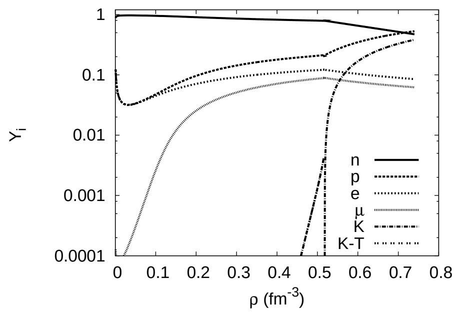

FIG. 3: Particle population of nucleons, kaon and leptons versus baryon density at T=10 MeV. K-T is the contribution due to thermal part.

that of the kaons, but both decrease quite a lot at the high densities. In Fig. 3, we display the particle population for different densities including the possibility of kaon condensation. In summary, we have investigated within the QMC model the consequences of including kaon condensation on the equation of state and related compact star properties. Within the QMC the kaon-σ coupling constant is obtained self-consistently. This definition of the kaon-meson couplings gives rise to a K^+ optical potential. Kaon condensation makes the equation of state softer and reduces the maximum allowed stellar masses

References

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