Kaon condensation in neutron stars studied with recent RMF models

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Introduction

In neutron stars (NS), kaon (K^-) condensation is one of the several possible transitions that could exist at high density. As the density of NS increases, the chemical potential of the negative electric charge (μ_e) also increases with the same rate of proton number density. Simultaneously, the effective mass of an in-medium K^- will decrease, due to the attractive interaction between K^- and nuclear matter. Therefore at a particular density (when μ_e is greater than energy of K^-), K^- replaces electron as neutralizing agent in charge neutral matter. This will soften the equation of state (EoS) and hence lower the maximum mass of NS. In this work we discuss the role higher order couplings in conjunction with kaon condensation using recent versions of relativistic mean field models.

Formalism

The details of the Lagrangian for the nucleon part and the notations followed here are explained explicitly in Refs. [1, 2]. The Lagrangian for the kaon part reads

$$\mathcal{L}_K = D^*_\mu K^* D^\mu K - m^{*2}_K K^* K, \tag{1}$$

where the vector fields are coupled to kaons via the relation

$$D_\mu = \partial_\mu + i g_{\omega K} V_\mu + i g_{\rho K} \tau_3 \cdot R_\mu, \tag{2}$$

and m^*_K is the effective mass of kaon. The scalar field is coupled to kaons in a way analogous to the minimal coupling scheme [3] of the vector fields

$$m^*_K = m_K - g_{\sigma K}\sigma. \tag{3}$$

The interaction of omega and rho mesons with kaon ($g_{\omega K}$ and $g_{\rho K}$) can be determined using a simple quark and isospin counting argument [3] given by,

$$g_{\omega K} = \frac{1}{3} g_\omega \text{ and } g_{\rho K} = \frac{1}{2} g_\rho \,. \tag{4}$$

We can specify interaction of sigma meson with kaon ($g_{\sigma K}$) using its relation with optical potential of a single kaon in infinite matter (U_K):

$$U_K = -g_{\sigma K}\sigma(\rho_0) - g_{\omega K} V_0(\rho_0), \tag{5}$$

where typically we have -80 MeV $\lesssim U_K \lesssim$ -180 MeV.The dispersion relation for s-wave condensation ($\vec{k} = 0$), for (K^-) is

$$\omega_K = m_K - g_{\sigma K}\sigma - g_{\omega K} V_0 - g_{\rho K} R_0, \tag{6}$$

with K^- mesons having isospin projection $-1/2$. ω_K represents the K^- energy and is linear in the meson field. One can note that with the increase in density, ω_K decreases. The total charge in the pure nucleon and kaon phases are respectively

$$\begin{aligned} q_N &= \rho_p - \rho_e - \rho_\mu, \\ q_K &= \rho_p - \rho_e - \rho_\mu - \rho_K. \end{aligned} \tag{7}$$

The K^- density is given by

$$\rho_K = 2m^*_K K^* K = 2(\omega_K + g_{\omega K} V_0 + g_{\rho K} R_0) K^* K. \tag{8}$$

and the energy density contributed by K^- condensation is

$$\epsilon_K = 2m^{*2}_K K^* K = m^*_K \rho_K. \tag{9}$$

Unlike the energy density, pressure is not directly affected by the inclusion of K^-, but the inclusion of K^- affect the fields and hence the pressure.

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Results

The EoS obtained from different interactions are given in Fig. 1. The onset of kaon condensation in NS strongly depend on the parameters of Lagrangian, apart from the usual dependence on the kaon optical potential (U_K). For most common values of U_K ($\lesssim -160$ MeV), the transition from a non-kaonic phase to kaonic phase has a character of second order, which rules out the possibility of having a mixed phase of kaonic and non-kaonic matter. This justifies the neglection of mixed phase in our calculations, done with $U_K = -120$ MeV. Earlier the onset of K^- condensation, larger is the difference between EoS calculated with and without kaons. The higher order couplings have a role to play, despite kaons playing dominant role in that regime.

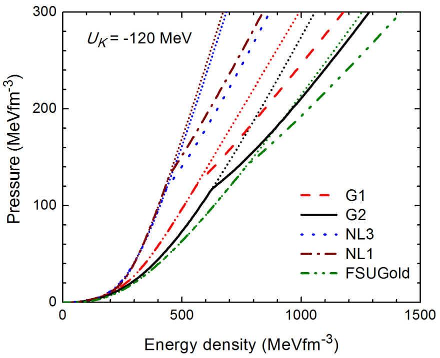

FIG. 1: The EoS for a pure nucleon and pure kaon matter change with different parameter sets. The calculations done without considering kaons are represented by the small-dotted lines.

The results for mass-radius relation in NS are given in Fig. 2 where the calculations were done using different interactions, without and with the K^- ($U_K = -120$ MeV). The RMF models NL3 and NL1 suggest very large and massive NS. Though G1 and G2 are from the same E-RMF model with same terms in the Lagrangian, their results for NS are quite different with G1 suggesting a larger and heavier NS. The result for G2 and FSUGold are the closest ones. Very interestingly, inspite of their difference when K^- are not considered, the presence of K^- brings these two results very closer. Overall, in the presence of K^-, the mass decreases and the radius corresponding to maximum mass increases marginally.

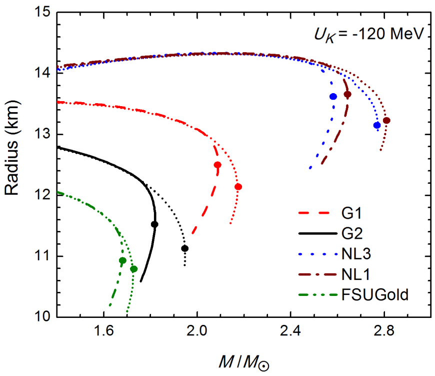

FIG. 2: The mass-radius relation for pure nuclear and kaon condensed phases using different parameter sets. The calculations done without considering kaons are represented by the small-dotted lines. The solid circles represent the maximum mass in every case. Mass is given in units of sun's mass $M_\odot$.

References

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