Hyperon–rich Matter and Kaons in Matter

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Abstract

We discuss the equation of state of neutron stars in the dense interior considering hyperons and the possible onset of kaon condensation within the relativistic mean field model. We find that hyperons are favoured in dense matter and that their appearance make the existence of a kaon condensed phase quite unlikely. Implications for the recent measurements of kaons in heavy ion collisions at subthreshold energy are also given.

1 Introduction

Nuclear matter at high densities and temperatures exhibits a new degree of freedom: strangeness, in neutron star matter hyperons and possibly kaons appear at a moderate density of about $2 \div 3$ times normal nuclear matter density $\rho_0 = 0.15$ fm$^{-3}$. These new species influence the properties of the equation of state of matter and the global properties of neutron stars.

The Relativistic Mean Field (RMF) model has been used first by Glendenning for describing the equation of state of matter with hyperons [1]. He founds that hyperons appear at $\rho \approx (2 - 3)\rho_0$ rather independent of the equation of state (EOS) used. Hyperons considerably soften the EOS and reduce the maximum mass of a neutron star. The appearance of kaons was discarded, as the chemical potential was saturating around 200 MeV while the kaon mass stayed constant with density, i.e. in-medium effects (as a decrease of the kaon energy) were not taken into account.

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On the other hand, chiral perturbation theory (ChPT) gives a rather robust prediction of the onset of antikaon condensation at \( \rho \approx (3 - 4)\rho_0 \) \cite{2} taking into account in-medium modifications of the antikaon energy with density. Antikaon condensation will soften the EOS and reduce the maximum mass of a neutron star similar to the case of hyperons. This will allow for the existence of low-mass black holes and implications have been discussed in \cite{3}. In \cite{4, 5} it was criticised that effects nonlinear in density were not taken into account which will shift the appearance of a kaon condensed phase to higher density. Moreover, hyperons were not considered in this approach.

Rather recently, antikaons and hyperons were considered on the same footing, where it was found that hyperons shift the onset of antikaon condensation to higher density \cite{6} or that it is very unlikely that it appears at all due to the rather strong hyperon-hyperon interactions \cite{7}. In the following we outline our recent work \cite{7} within the RMF model in more detail. Furthermore, we will discuss implications of in-medium effects of kaons and antikaons for the recent heavy ion experiments at subthreshold energy.

2 Strangeness in Neutron Stars

2.1 The RMF Model with Hyperons

The implementation of hyperons within the RMF approach is straightforward. SU(6)-symmetry is used for the vector coupling constants and the scalar coupling constants are fixed to the potential depth of the corresponding hyperon in normal nuclear matter \cite{8}. We choose

\[
U^{(N)}_\Lambda = U^{(N)}_\Sigma = -30 \text{ MeV} \quad , \quad U^{(N)}_\Xi = -28 \text{ MeV} .
\]

(1)

Note that a recent analysis \cite{9} comes to the conclusion that the \( \Sigma \) potential changes sign in the nuclear interior, i.e. being repulsive instead of attractive. In this case, \( \Sigma \) hyperons will not appear at all in our calculations. Nevertheless, our conclusion about the onset of kaon condensation remains unchanged.

The observed strongly attractive \( \Lambda \Lambda \) interaction is introduced by two additional meson fields, the scalar meson \( f_0(975) \) and the vector meson \( \phi(1020) \). The vector coupling constants to the \( \phi \)-field are given by SU(6)-symmetry and the scalar coupling constants to the \( \sigma^* \)-field are fixed by

\[
U^{(\Xi)}_\Xi \approx U^{(\Xi)}_\Lambda \approx 2U^{(\Lambda)}_\Xi \approx 2U^{(\Lambda)}_\Lambda \approx -40 \text{ MeV} .
\]

(2)

Note that the nucleons are not coupled to these new fields.

2.2 Neutron Stars with Hyperons

Fig. 1 shows the composition of neutron star matter for the parameter set TM1 with hyperons including the hyperon-hyperon interactions.
Figure 1: The composition of neutron star matter with hyperons which appear abundantly in the dense interior.

Up to the maximum density considered here all effective masses remain positive and no instability occurs. The proton fraction has a plateau at \((2 - 4)\rho_0\) and exceeds 11% which allows for the direct URCA process and a rapid cooling of a neutron star. Hyperons, first \(\Lambda\)'s and \(\Sigma^-\)'s, appear at \(2\rho_0\), then \(\Xi^-\)'s are populated already at \(3\rho_0\). The number of electrons and muons has a maximum here and decreases at higher densities, i.e. the electrochemical potential decreases at high densities. The fractions of all baryons show a tendency towards saturation, they asymptotically reach similar values corresponding to spin-isospin and hypercharge-saturated matter. Hence, a neutron star is more likely a giant hypernucleus [1]!

2.3 Kaon Condensation?

In the following we adopt the meson-exchange picture for the KN-interaction simply because we use it also for parametrizing the baryon interactions. We start from the following Lagrangian

\[
L_{KN}^{\text{RMF}} = D_\mu^* \bar{K} D^\mu K - m_K^2 \bar{K} K - g_{\sigma K} m_K \bar{K} K \sigma - g_{\sigma* K} m_K \bar{K} K \sigma^* \tag{3}
\]

with the covariant derivative

\[
D_\mu = \partial_\mu + ig_{\omega K} V_\mu + ig_{\rho K} \bar{\tau} R_\mu + ig_{\phi K} \phi_\mu . \tag{4}
\]
Figure 2: The effective energy of the kaon and the antikaon, and the electrochemical potential. Kaon condensation does not occur over the whole density region considered.

The scalar fields essentially decrease the kaon mass, while the vector fields will increase (decrease) the energy of the kaon (antikaon) in the dense medium. The scalar coupling constants are fixed by the s-wave KN-scattering lengths. The coupling constants to the vector mesons are chosen from SU(3)-relations. The onset of s-wave kaon condensation is now determined by the condition $-\mu_e = \mu_{K^-} \equiv \omega_{K^-}(k = 0)$.

The density dependence of the $K$ and $\bar{K}$ effective energies is displayed in Fig. 2. The energy of the kaon is first increasing in accordance with the low density theorem. The energy of the antikaon is decreasing steadily at low densities. With the appearance of hyperons the situation changes dramatically. The potential induced by the $\phi$-field cancels the contribution coming from the $\omega$-meson. Hence, at a certain density the energies of the kaons and antikaons become equal to the kaon (antikaon) effective mass, i.e. the curves for kaons and antikaons are crossing at a sufficiently high density. At higher densities the energy of the kaon gets even lower than that of the antikaon! Since the electrochemical potential never reaches values above 160 MeV here antikaon condensation does not occur at all. We have checked the possibility of antikaon condensation for all parameter sets and found that at least 100 MeV are missing for the onset of kaon condensation. This is in contrast to previous calculations disregarding hyperons but in line with the findings in where it was seen that hyperons shift the critical density for kaon condensation to higher density.
3 Kaons in Heavy Ion Collisions

Subthreshold production rates of K\(^{+}\) in heavy-ion reactions were recently measured at GSI \([10]\). The influence of rescattering and formation of resonance (Δ) matter was studied in the QMD model \([11]\), and the RBUU model \([12]\) and it was demonstrated that they are essential to explain the data. In-medium modifications of the effective energy of the kaon were studied in \([13]\) using again the RBUU model. The results are essential similar to the ones obtained without medium modifications \([12]\), because the in-medium kaon mass used is quite close to the respective vacuum mass. But there exist other observables which might be better suited for extracting in-medium effects: the flow of kaons might be a promising tool for measuring the kaon potential in dense matter \([14]\). And more pronounced in-medium effects are expected for the case of K\(^{-}\) \([15]\). Indeed, enhanced production rates for K\(^{-}\) have been seen at GSI recently \([16]\).

In the following we discuss the in-medium change of the threshold energy for kaon production. Details will be found in a forthcoming publication \([17]\).

3.1 RMF model for Kaons

The Lagrangian has been given above (eq. 3). From this one gets the following kaon self energy in the mean field approximation

\[
\Pi(\omega, k; \rho_N) = -g_{\sigma K} \sigma m_K + 2g_{\omega K} \omega V_0 + (g_{\omega K} V_0)^2 . \tag{5}
\]

Note that the scalar and vector fields depend on the nucleon density \(\rho_N\) and that the kaon self energy depends on the kaon energy itself. The antikaon energy is then given by

\[
\omega_K(k) = \sqrt{m_K^2 + m_K g_{\sigma K} \sigma + k^2 - g_{\omega K} V_0} \tag{6}
\]

and the coupling constants are fixed again to KN scattering lengths \([7]\).

3.2 Chiral Perturbation Theory for Kaons

We follow the procedure outlined in \([2]\) starting from the Nonlinear Chiral Lagrangian in next-to-leading order

\[
\mathcal{L}^{\text{ChPT}}_{KN} = -\frac{3i}{8f_K^2} \left[ N \gamma_\mu N \left( \bar{K} \partial^\mu K \right) \right] + \frac{\Sigma_{KN}}{f_K^2} \bar{N} NN \bar{K} K + \frac{D}{f_K} \bar{N} N \left( \partial_\mu \bar{K} \partial^\mu K \right) \tag{7}
\]

where \(f_K = 93\) MeV is the kaon decay constant and \(\Sigma_{KN} = 2m_\omega\) is the sigma term. The first two terms comes from the Tomozawa–Weinberg term and is in leading order of the chiral expansion. This is a vector interaction and is repulsive (attractive) for kaons (antikaons). The other terms are in next-to-leading order. The second term involves the sigma term which is of scalar type and will decrease.
the mass of the kaon and antikaon in the medium. The last term is the so called off-shell term which will modify the scalar attraction. It is essential to get a correct scattering length [2]. The kaon self energy $\Pi(\omega, k; \rho_N)$ is given in the mean field approximation by

$$
\Pi(\omega, k; \rho_N) = -\frac{\Sigma_{KN}}{f_K^2} \rho_s - \frac{\tilde{D}}{f_K^2} \rho_s \omega^2 + \frac{3}{4 f_K^2} \omega \rho_N
$$

which depends in general also on the kaon energy. This has to be taken into account to get the energy of a kaon or antikaon in the nuclear medium correctly.

### 3.3 Subthreshold Production of Kaons

In the following we discuss the shift of the threshold energy of various processes for heavy ion collisions due to medium modifications.

Kaons are mainly produced at threshold via the process $NN \rightarrow N\Lambda K$. The minimum energy needed is $Q(NAK) \approx 671$ MeV in vacuum. In the medium, the threshold is shifted to

$$
Q(NAK) = E_{\Lambda}(p = 0) + \omega_K(k = 0) - E_N(p = 0)
$$
where we assume that the outgoing nucleon is not Pauli-blocked in the hot zone of the collision. Hence, the subthreshold production of kaons is sensitive to three different in-medium effects: the EOS ($E_N$), the $\Lambda$ potential ($E_\Lambda$) and the kaon energy ($\omega_K$) in medium. These effects will partly cancel each other as the kaon feels a repulsive potential of 29 MeV due to the low density theorem while the $\Lambda$ sees an attractive potential of $-30$ MeV (see e.g. [8]). Therefore, subthreshold kaon production seems to probe mainly the nuclear EOS. As the nucleons feel an attractive potential of about 60 MeV the threshold will be shifted upwards at normal nuclear density by this amount and the production of kaons is reduced in the medium. This is indeed the case as can be seen from the middle curves of Fig. 3 which shows the threshold energy $Q(N\Lambda K)$ as a function of density. The similar behaviour of the different curves at low density is due to the low-density theorem. At $\rho = 3\rho_0$ the value of $Q(N\Lambda K)$ reaches about 800 MeV for the RMF model and about 860 MeV for ChPT. Without off-shell terms, the threshold energy is underestimated in medium, and we expect that the production rates for kaons calculated in [13] are overestimated. Note, that all calculations ignoring in-medium effects [11, 12] will also give a too high production rate for kaons. Note that the threshold energy for the secondary process $\pi N \rightarrow \Lambda K$ will be also shifted upwards with density (lower curves in Fig. 3).

Antikaons are created in heavy ion collisions first by the process $NN \rightarrow NNK\bar{K}$. The threshold value of $Q(K\bar{K}) \approx 988$ MeV is modified in the medium and given by the sum of the kaon and antikaon energy $Q(K\bar{K}) = \omega_K(k = 0) + \omega_{\bar{K}}(k = 0)$. Therefore, subthreshold antikaon production probes the in-medium property of kaons and antikaons solely. As the vector potential cancels out approximately, it will mainly depend on the scalar potential the kaon feels in the medium. The upper curves in Fig. 3 show that indeed $Q(K\bar{K})$ is reduced in the medium in all models discussed here. ChPT predicts an in-medium reduction of about $-56$ MeV at maximum compared to the vacuum and then the curves go up again for higher density. On the other side, the RMF model gives a reduction of about $-140$ MeV at $\rho = 3\rho_0$. The $Q$-value is steadily decreasing. The curve used in RBUU calculations neglecting off-shell terms [13] is lying even lower and hence, the in-medium production rates of antikaons seems to be overestimated.

As an interesting fact, the $Q$-values for kaon and antikaon production are lying close together for the RMF model. Note that this does not mean that the numbers of produced kaons and antikaons are the same. The kaons will be produced at different density and the average $Q$-value over the density profile will give a measure for the total number of produced kaons and antikaons in the medium.
4 Conclusions

We discussed medium modifications of the kaon and antikaon on the mean field level and applied it for neutron star matter and heavy ion reactions. We have shown that kaon condensation is unlikely to happen inside a neutron star within the RMF model due to the presence of hyperons. Relativistic heavy ion reactions at subthreshold energy might see in-medium modifications of the kaon or antikaon. The threshold energy for kaon production goes up with density. Hence, rescattering effects and resonance decays are mainly responsible for the enhanced $K^+$ production seen. On the other hand, the antikaon production is enhanced in dense matter due to a decreased antikaon energy. This attractive potential will be visible in e.g. the antikaon flow or the excitation function of the produced $K^−$.

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