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The role of the chiral phase transition in modelling the kaon to pion ratio

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The search of a quark-gluon plasma (QGP), where hadrons dissolve and quarks are supposed to be free and deconfined, is difficult due to the short QGP lifetime. Various signals were proposed for detection of the QGP phase, and the "horn", which appears in the ratio of positive charged kaon to pion, was supposed be one of them. Nowdays the picture of this peak becomes more clear from the experimental side: the peak appears in the ratio of positive charged kaons and pions at the collision energy $\sqrt{s_{NN}} \sim 7{-}10\,\mathrm{GeV}$ for the high-size systems in $\mathrm{Au}+\mathrm{Au}$ and $\mathrm{Pb}+\mathrm{Pb}$ collisions [1]. With decreasing system size, the sharp peak becomes lower and for $\mathrm{Be}+\mathrm{Be}$, $\mathrm{p}+\mathrm{p}$ collisions the ratio demonstrates smooth behaviour [2]. It is in agreement now, that the quick rise in K^+/π^+ ratio at low energies is associated with the phase transition in medium. The microscopic transport model with involving partial restoration of chiral symmetry at the early stages of the collision reproduces experimental data and predicts smoothing of the peak with decreasing system size [3]. The authors showed that the partial chiral symmetry restoration was responsible for a quick increase in the K^+/π^+ ratio at low energies. The jump in the ratio after reaching maximum could be explained as a result of a QGP formation during collision, as the deconfinement transition (the strangeness quark mass tends to its current value) makes the strangeness yield independent on energy [4].

In present work, we discuss the chiral phase transition and in-medium behaviour of the pseudo-scalar mesons in the framework of the SU(3) Polyakov loop exended Nambu–Jona–Lasinio model with vector interaction:

$$\mathcal{L} = \bar{q}\,(\,i\,\gamma^{\mu}\,D_{\mu}\,-\,\hat{m}-\gamma_0\mu)\,q\,+$$
$$+\,\frac{1}{2}\,g_S\,\sum_{a=0}^{8}\left[\,(\,\bar{q}\,\lambda^a\,q\,)^2\,+\,(\,\bar{q}\,i\,\gamma_5\,\lambda^a\,q\,)^2\,\right]-$$
$$-\,\frac{1}{2}g_{\mathrm{V}}\sum_{a=0}^{8}\,(\,\bar{q}\gamma_{\mu}\lambda^a\,q\,)^2+\mathcal{L}_{\mathrm{det}}-\mathcal{U}(\Phi,\bar{\Phi};T), \qquad (1)$$

with the Kobayashi–Maskawa–t'Hooft (KMT) interaction $L_{\mathrm{det}} = g_D\{\det[\bar{q}(1+\gamma_5)q] + \det[\bar{q}(1-\gamma_5)q]\}$ and the effective potential $\mathcal{U}(\Phi,\bar{\Phi};T)$, which describes the confinement/deconfinement properties [5–7].

In the model, the current quark propagating in the chiral condensate develops a quasi-particle mass that leads to spontaneous chiral symmetry breaking. At that time the quark is coupled to a homogeneous background field representing the Polyakov loop dynamics. At low chemical potential the chiral symmetry is restored when the dynamically generated quark mass drops as a function of temperature and chemical potentials in half of its value. At low chemical potential and high temperature the chiral symmetry restoration is soft and it is supposed to be a crossover. At high chemical potential and low temperature the gap equation has three solutions and the first order chiral phase transition is discussed.

This picture can be changed in the Polyakov loop extended Nambu–Jona–Lasinio (PNJL) model when the vector interaction is added. With increasing vector coupling g_{V}, the domain of the first order transition decreases until it completely disappears. Varying the vector coupling, we can check if the change of the type of the phase transition affects the behaviour of the kaon to pion ratio in the low temperature and high chemical potential (low energy) region.

The study of pseudo-scalar mesons is interesting since they due to their Goldstone boson nature are associated with the breaking of the chiral symmetry and are sensible to the medium. Meson masses are defined by the Bethe–Salpeter equation at $\mathbf{P}=0$

$$1 - P_{ij}\Pi^P_{ij}(P_0 = M, \mathbf{P} = \mathbf{0}) = 0. \qquad (2)$$

When the meson mass exceeds the sum of masses of its constituents ($P_0 > m_i + m_j$), the meson turns into

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the resonance state and the Mott transition occurs. In this case, the complex properties of the integrals have to be taken into account and the solution has to be defined in the form $P_0 = M_M - \frac{1}{2}i\Gamma_M$. Though at the zero chemical potential pions and kaons are degenerated, their masses split with increasing density. At the nonzero chemical potential and low T, the mass splitting in charged multiplets appears due to the excitation of the Dirac sea is modified by the presence of the medium [8–10].

For the effective models the ratio of the particle number can be calculated in terms of the ratio of the number densities of mesons ($n_{K^\pm}/n_{\pi^\pm}$) with

$$n_{M^\pm} = \int_0^\infty p^2 dp \frac{1}{e^{\beta(\sqrt{p^2+m_{M^\pm}} \mp \mu_{M^\pm})} - 1}, \tag{3}$$

the chemical potential for pions is a phenomenological parameter $\mu_\pi = 0.135$ GeV, and the chemical potential for kaons can be defined as $\mu_K = \mu_u - \mu_s$.

The experimental data are shown as a function of the collision energy $\sqrt{s_{NN}}$ which never appears as a parameter in effective models. We introduced the parameter T/μ_B, where (T, μ_B) are taken on the phase diagram along the phase transition curve assuming that chiral phase transition can be considered as chemical freeze-out, and rescaled both experimental and theoretical results (see [8, 11]). The main difference between the choice of T and μ_B along the phase transition line is whether we are in the crossover region or in the first-order transition region. In the region of the first-order transition (low T/μ_B) the value of $\Phi \to 0$ and the matter is confined. In the region of the crossover deconfinement transition takes place.

We used the PNJL model with $\mu_s = 0.5\mu_u$ and considered the cases with different values of g_V which moves the critical end point to lower T till it disappears and shifts the crossover pattern to higher chemical potentials. It can be seen in the Fig. 1 that the absence of the first order phase transition domain leads only to a changing in the peak hight in the $K^+\pi^+$ ratio.

In the PNJL model we can show how K/π ratio changes as function T/μ_B, when T and μ_B are chosen on the phase diagram along the chiral phase transition curve and discuss in this way how the chiral phase transition can affect to the K/π behaviour. Using our previous study we can conclude that the peak appears in the range of low temperatures and high baryon chemical potential (which corresponds to low energy of the collision). The appearance of the peak is weakly sensitive to the type of phase transition in the high density region, as the replacement of the the first order transition to the soft crossover only leads to a changing in the peak hight. The structure is more sensitive to the slope of the phase transition curve (see [11]) and the matter properties. For example, when the strange chemical potential is zero $\mu_S(\mu_K) = 0$, the K^+/π^+ ratio shows smooth behaviour. When the strangeness neutrality is introduced, the K^+/π^+ ratio does not show a peak structure [8, 11].

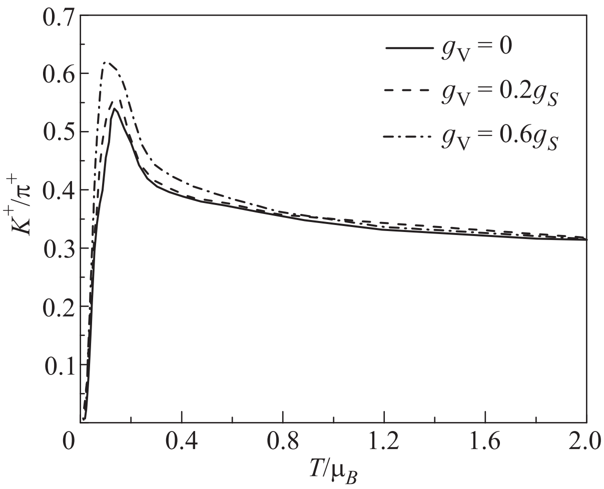

Fig. 1. The K^+/π^+ ratios for different values of g_V

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