Chiral Model for Dense, Hot and Strange Hadronic Matter *

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1. Introduction

Until now it is not possible to determine the equation of state (EOS) of hadronic matter from QCD. One succesfully applied alternative way to describe the hadronic world at high densities and temperatures are effective models like the RMF-models [1], where the relevant degrees of freedom are baryons and mesons instead of quarks and gluons. Since approximate chiral symmetry is an essential feature of QCD, it should be a useful concept for building and restricting effective models. It has been shown [2,3] that effective $\sigma - \omega$-models including SU(2) chiral symmetry are able to obtain a reasonable description of nuclear matter and finite nuclei. Recently [4] we have shown that an extended $SU(3) \times SU(3)$ chiral $\sigma - \omega$ model is able to describe nuclear matter ground state properties, vacuum properties and finite nuclei satisfactorily. This model includes the lowest SU(3) multiplets of the baryons (octet and decuplet[5]), the spin-0 and the spin-1 mesons as the relevant degrees of freedom. Here we will discuss the predictions of this model for dense, hot, and strange hadronic matter.

2. Nonlinear chiral SU(3) model

We consider a relativistic field theoretical model of baryons and mesons built on chiral symmetry and scale invariance. The general form of the Lagrangean looks as follows:

$$\mathcal{L} = \mathcal{L}_{\mathrm{kin}} + \sum_{W=X,Y,V,\mathcal{A},u} \mathcal{L}_{\mathrm{BW}} + \mathcal{L}_{\mathrm{VP}} + \mathcal{L}_{\mathrm{vec}} + \mathcal{L}_0 + \mathcal{L}_{\mathrm{SB}}. \tag{1}$$

$\mathcal{L}_{\mathrm{kin}}$ is the kinetic energy term, $\mathcal{L}_{\mathrm{BW}}$ includes the interaction terms of the different baryons with the various spin-0 and spin-1 mesons. The baryon masses are generated by the non-strange ($< q\bar{q} >$) scalar condensate σ and the strange ($< s\bar{s} >$) scalar condensate ζ. $\mathcal{L}_{\mathrm{VP}}$ contains the interaction terms of vector mesons with pseudoscalar mesons. $\mathcal{L}_{\mathrm{vec}}$ generates the masses of the spin-1 mesons through interactions with spin-0 mesons, and $\mathcal{L}_0$ gives the meson-meson interaction terms which induce the spontaneous breaking of chiral symmetry. It also includes the scale breaking logarithmic potential. Finally, $\mathcal{L}_{\mathrm{SB}}$ introduces an explicit symmetry breaking of the $\mathrm{U}(1)_A$, the $\mathrm{SU}(3)_V$, and the chiral symmetry. All these terms have been discussed in detail in [4].

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To ingvestigate hadronic matter properties at finite density and temperature we adopt the mean-field approximation, i.e. the meson field operators are replaced by their expectation values and the fermions are treated as quantum mechanical one-particle operators [6]. After performing these approximations, the Lagrangean (1) becomes

$$\begin{aligned}
\mathcal{L}_{BM} + \mathcal{L}_{BV} &= -\sum_i \overline{\psi_i}[g_{i\omega}\gamma_0\omega^0 + g_{i\phi}\gamma_0\phi^0 + m_i^*]\psi_i \\
\mathcal{L}_{vec} &= \frac{1}{2}m_\omega^2\frac{\chi^2}{\chi_0^2}\omega^2 + \frac{1}{2}m_\phi^2\frac{\chi^2}{\chi_0^2}\phi^2 + g_4^4(\omega^4 + 2\phi^4) \\
\mathcal{V}_0 &= \frac{1}{2}k_0\chi^2(\sigma^2+\zeta^2) - k_1(\sigma^2+\zeta^2)^2 - k_2(\frac{\sigma^4}{2}+\zeta^4) - k_3\chi\sigma^2\zeta \\
&+ k_4\chi^4 + \frac{1}{4}\chi^4\ln\frac{\chi^4}{\chi_0^4} - \frac{\delta}{3}\ln\frac{\sigma^2\zeta}{\sigma_0^2\zeta_0} \\
\mathcal{V}_{SB} &= \left(\frac{\chi}{\chi_0}\right)^2\left[m_\pi^2 f_\pi\sigma + (\sqrt{2}m_K^2 f_K - \frac{1}{\sqrt{2}}m_\pi^2 f_\pi)\zeta\right],
\end{aligned}$$

with m_i the effective mass of the baryon i ($i = N, \Lambda, \Sigma, \Xi, \Delta, \Sigma^*, \Xi^*, \Omega$). σ and ζ correspond to the scalar condenstates, ω and ϕ represent the non-strange and the strange vector field respectively and χ is the dilaton field. Now it is straightforward to write down the expression for the thermodynamical potential of the grand canonical ensemble Ω per volume V at a given chemical potential μ and temperature T

$$\frac{\Omega}{V} = -\mathcal{L}_{vec} - \mathcal{L}_0 - \mathcal{L}_{SB} - \mathcal{V}_{vac} - \sum_i \frac{\gamma_i}{(2\pi)^3}\int d^3k\left[\ln\left(1+e^{-\frac{1}{T}[E_i^*(k)-\mu_i^*]}\right) + \ln\left(1+e^{-\frac{1}{T}[E_i^*(k)+\mu_i^*]}\right)\right], \quad (2)$$

from which all thermodynamic quantites can be derived. γ_i denote the fermionic spin-isospin degeneracy factors. The single particle energies are $E_i^*(k) = \sqrt{k_i^2 + m_i^{*2}}$ and the effective chemical potentials read $\mu_i^* = \mu_i - g_{i\omega}\omega - g_{i\phi}\phi$. The mesonic fields are determined by minimizing Ω/V.

3. Excited hadronic matter

The parameters are fixed by hadronic vacuum masses and nuclear matter ground state properties [4,5]. For the following investigations we consider the two parameter sets C_1 and C_2, which satisfactorily describe finite nuclei [4]. The main difference between the two parameter sets is the coupling of the strange condensate to the nucleon and the Δ. While in C_2 this coupling is set to zero, in the case of C_1 the nucleon and the Δ couple to the ζ field. The equation of state for dense hadronic matter at vanishing strangeness without baryon resonances is shown in fig.1(left). In the middle and right picture the EOS including resonances is plotted for a varying ratio $r_v = g_{\Delta\omega}/g_{N\omega}$. One observes that for $r_v = 1$ the resulting EOS strongly depends on the way of the nucleon and Δ mass generation. For a pure σ-dependence of the masses of the nonstrange baryons (C_2) the equation of state is strongly influenced at high densities by the production of resonances, in contrast to the model where both masses are partly generated by the strange condensates (C_1). This is due to the different behaviour of the ratio of the effective masses m_Δ^*/m_N^* as a function of density. Furthermore one observes that the softening of the equation of state

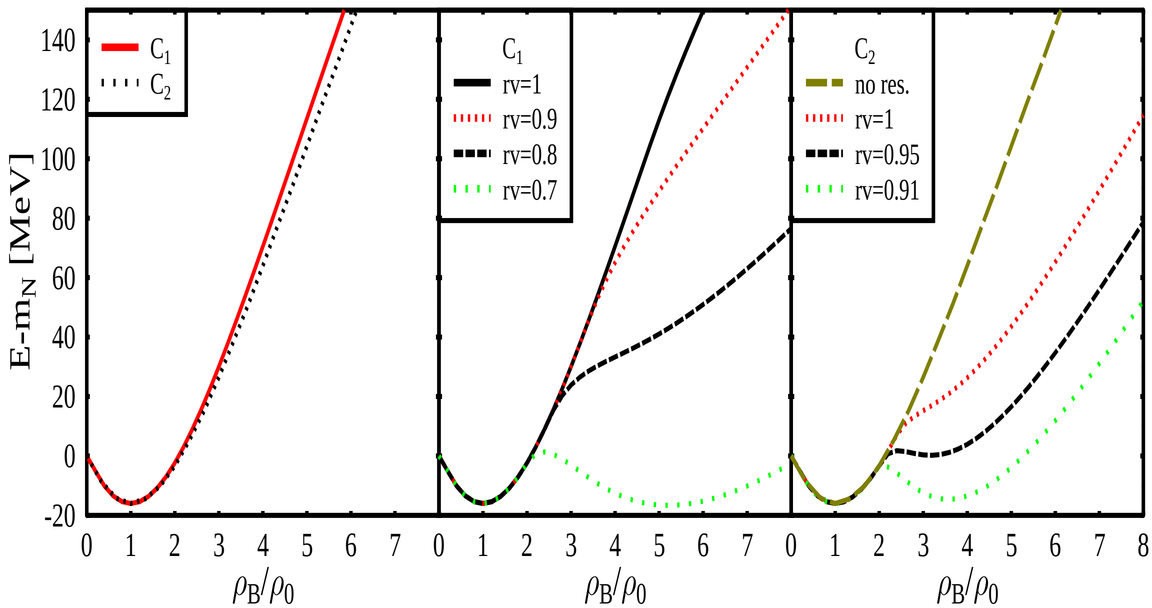

Figure 1. Nuclear matter equation of state for the parameter sets C_1 and C_2. (left: no baryon resonances, middle: C_1 including baryon resonances for different values of the quotient $r_v = \frac{g_{N\omega}}{g_{\Delta\omega}}$ right: same for C_2).

at high densities strongly depends on the vector coupling of the resonances. If we assume that there are no Δ's in the groundstate of nuclear matter and that density isomers are not absolutely stable, the minimal value for the vector coupling ratio r_v is 0.91 for a pure σ-coupling (C_1) of the nucleon and the Δ, while for the case of a partial ζ-coupling one obtains $r_v \geq 0.68$. In summary it can be seen that the inclusion of the baryon resonances may lead to a supersoft equation of state, but since this coupling cannot be fixed, the EOS cannot be predicted unambigiously from this chiral approach.
Fig.2 shows the behavior of the strange and non-strange condensates and the resulting baryon masses as a function of temperature for vanishing chemical potential with and without baryon resonances. The behaviour of the chiral condensates as a function of temperature depends on the significant contribution of the resonances at and above the transition temperature. In the case that no resonances are included, one observes a smooth transition to small expectation values of the condensates, while for the case with included resonances both scalar fields jump sequentially to lower values. This is due to the much larger number of degrees of freedom which accelerate the process of reducing the condensates and increasing the scalar density. This finally leads to a first order phase transition. In contrast the masses of the vector mesons are predicted to stay nearly constant, since there is no direct σ-ω coupling term included on the mean-field level [7,4]. The change of the hadronic masses in the hot and dense medium, as obtained from chiral arguments, shows that the assumptions of vacuum masses and also that of a universal linear drop with density are at least questionable because of the systems's strong nonlinear density behaviour. So the determination of freeze-out constants (T, μ_B, μ_S) have to be taken cautiously. To demonstrate this, we calculate the particle ratios in the chiral model, using the values of the freeze-out parameters for $S + Au$ collisions at 200 AGeV as obtained from an ideal gas model [8]. The results including the feeding from decays

of higher resonances are shown in figure 3. One observes that the change of the masses in the hot and dense medium (especially the baryon masses) leads to drastically altered particle ratios. Further examinations are under way.

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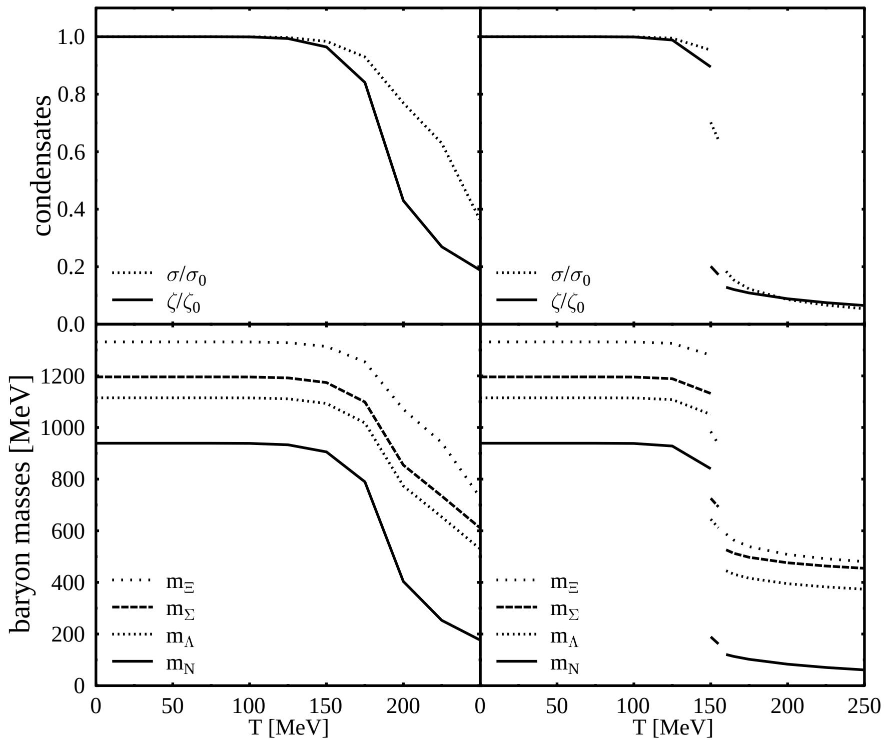

Figure 2. Chiral condensates (top) and resulting baryon masses (bottom) as a function of temperature for vanishing chemical potential (Left: no resonances included, right: baryon decuplet included).

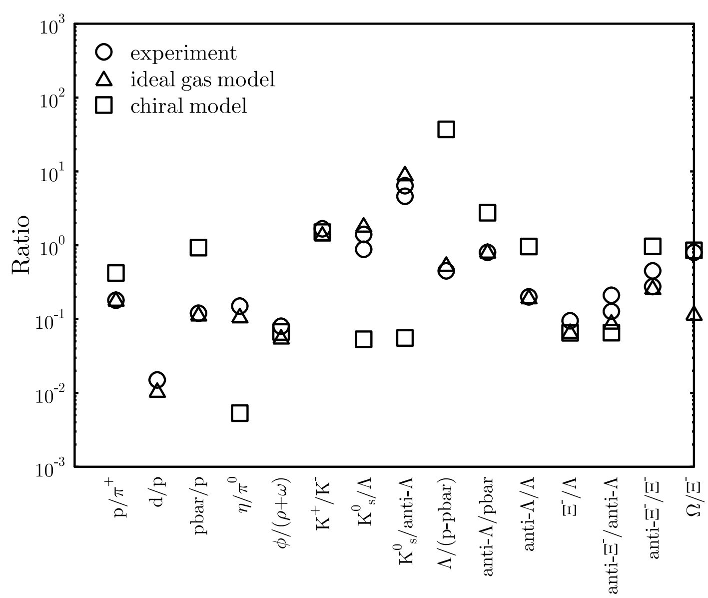

Figure 3.
Particle ratios for 200 A GeV/c S+Au collisions. Experimental yields are compared to ideal gas and chiral model calculations using $T = 160 MeV$, $\mu_q = 57 MeV$ and $\mu_s = 20 MeV$, as obtained from ideal gas fits.