Phases of QCD ◇

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Recent years have seen an expansion of activities devoted to the study of the QCD phase diagram. The equation of state of strongly interacting matter is now at hand as a function of temperature T and in a limited range of quark chemical potential μ.

In our work [1] we have studied the thermodynamics of two-flavour QCD at finite quark chemical potential. Our investigation is based on a synthesis of a Nambu Jona-Lasinio (NJL) model and the non-linear dynamics involving the Polyakov loop [2,3]. In this Polyakov-loop-extended (PNJL) model, quarks develop quasiparticle masses by propagating in the chiral condensate, while they couple at the same time to a homogeneous background (temporal) gauge field representing Polyakov loop dynamics. The main aim of our work is to investigate whether results from lattice QCD thermodynamics can be understood and interpreted in terms of quasiparticle degrees of freedom.

The thermodynamic potential of the PNJL model is:

$$\begin{aligned}\Omega = &\,\mathcal{U}\left(\Phi,\bar{\Phi},T\right)+\frac{\sigma^2}{2G} \qquad (1)\\ &-2N_f\,T\int\frac{\mathrm{d}^3p}{(2\pi)^3}\left\{\mathrm{Tr}_c\ln\left[1+L\,\mathrm{e}^{-(E_p-\mu)/T}\right]\right.\\ &\left.+\mathrm{Tr}_c\ln\left[1+L^\dagger\,\mathrm{e}^{-(E_p+\mu)/T}\right]\right\}-6N_f\int\frac{\mathrm{d}^3p}{(2\pi)^3}E_p\,\theta\left(\Lambda^2-\vec{p}^{\;2}\right)\end{aligned}$$

where we have introduced the quark quasiparticle energy $E_p = \sqrt{\vec{p}^{\;2}+m^2}$, with a constituent quark mass given by their interaction with the chiral condensate (related to the σ scalar field): $m = m_0 - \langle\sigma\rangle = m_0 - G\langle\bar{\psi}\psi\rangle$. Φ and $\bar{\Phi}$ are the traced Polyakov loop and its conjugate: $\Phi = (\mathrm{Tr}_c\,L)/N_c$, $\bar{\Phi} = (\mathrm{Tr}_c\,L^\dagger)/N_c$. The Polyakov loop L is a matrix in colour space explicitly given by $L\left(\vec{x}\right) = \mathcal{P}\exp\left[i\int_0^\beta d\tau\,A_4\left(\vec{x},\tau\right)\right]$, with $\beta = 1/T$ the inverse temperature and $A_4 = iA^0$. The effective potential for the Polyakov loop, $\mathcal{U}(\Phi,\bar{\Phi},T)$, has a polynomial form reflecting the $Z(3)$ symmetry of pure-gauge QCD and its spontaneous breaking in the deconfined phase.

All parameters of the model are fixed a priori: the results are predictions of the model, which we will compare to the available lattice data. Minimizing the thermodynamic potential (1) gives the behaviour of Polyakov loop and chiral condensate as functions of temperature and chemical potential. We obtain the non-trivial result that chiral and deconfinement phase transitions take place at the same critical temperature, around 200 MeV (see Fig. 1). We have also evaluated the quark number density $n_q = -\partial\Omega(T,\mu)/\partial\mu$. We show an example in Fig. 2 in comparison with available lattice data [4], and with the results obtained in the standard NJL model. The improvement due to the inclusion of the Polyakov loop, resulting in a suppression of the quark degrees of freedom in the forbidden (confinement) region at $T < T_c$, is evident.

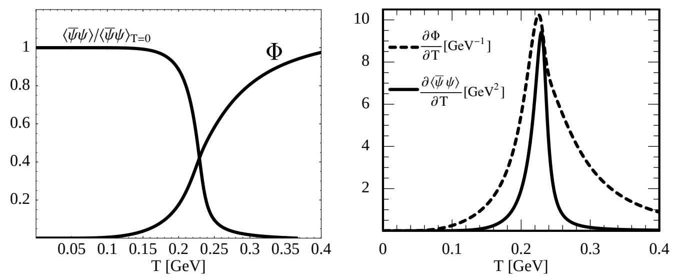

Fig. 1: Left: scaled chiral condensate and Polyakov loop $\Phi(T)$ as functions of temperature at zero chemical potential. Right: plots of $\partial\langle\bar{\psi}\psi\rangle/\partial T$ and $\partial\Phi/\partial T$.

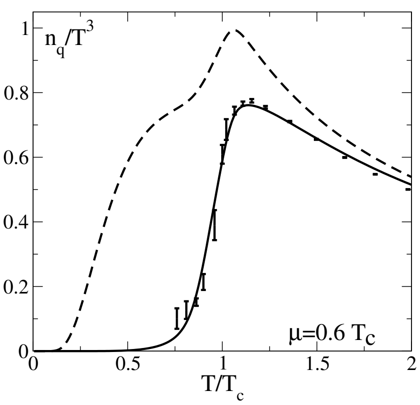

Fig. 2: Scaled quark number density calculated in the PNJL model as a function of temperature at finite chemical potential (continuous line), compared to lattice data [4], and to the standard NJL results (dashed line).

Considering the simplicity of the PNJL model, the conclusion that can be drawn at this point is promising: it appears that a relatively straightforward quasiparticle approach, with its dynamics rooted in spontaneous chiral symmetry breaking and confinement and with parameters controlled by a few known properties of the gluonic and hadronic sectors of the QCD phase diagram, can account for essential observations from two-flavour $N_c = 3$ Lattice QCD thermodynamics.

References

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