CHIRAL DENSITY WAVES IN QUARKYONIC MATTER

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We study the phase diagram of strongly interacting matter including the inhomogeneous phase of Chiral Density Waves (CDW) within the Polyakov loop extended Nambu–Jona-Lasinio (PNJL) model. We discuss the phase structure taking into account density and flavour dependence of the Polyakov loop potential parameter and temperature dependence of the four-point coupling constant of the NJL model. It is shown that the CDW phase exists and that can be interpreted as a special realisation of quarkyonic matter. This fact is of particular interest because the existence of homogeneous quarkyonic matter is strongly constrained. This also indicates that the study of inhomogeneous phases at finite temperatures and baryon densities are of special importance.

1. Introduction

An understanding of structure of the phase diagram of strongly interacting matter at finite baryon density is still an open problem despite many efforts that have been devoted to its study since the very beginning of the QCD era. The lack of experimental data and reliable tools of the direct QCD based calculations are the main culprits of this situation. Nevertheless, the progress is still possible and our experience must rely on the interplay between general arguments, models calculations and QCD lattice results accessible at the low chemical potential. A very good example of such approach is the PNJL model [1] which combines the chiral and the deconfinement order parameters linked to QCD at finite temperature through the parameter fits to the lattice data [2, 3, 4].

The new insight into the high baryon density domain based on large N_c expansion has been proposed by McLerran and Pisarski [5]. In the limit of a large number of colours $N_c \to \infty$ the QCD phase diagram simplifies substantially. The low baryon density and temperature region is occupied by the confined, chirally broken phase where the matter pressure scales with N_c as $P \sim O(1)$. The high temperature phase is deconfined and dominated by gluons with the $P \sim N_c^2$ scaling. Finally, at the low temperature and high baryon density there is a confined phase which scales as $P \sim N_c$. The latter phase has been named quarkyonic.

It is very natural to interpret the quarkyonic phase within the PNJL model as deconfined and chirally restored phase. This is based on the PNJL picture of the dense matter which consists of a degenerate Fermi sea of quarks with the colourless particle–hole excitations at the Fermi surface. Then the $P \sim N_c$ scaling at high density naturally arises. It was shown in paper [6] that at $N_c = 3$ the quarkyonic phase slightly precedes the chiral transition at finite density and low temperature. The existence of the quarkyonic phase within the PNJL model was also studied in Ref. [7].

Discussions of the QCD phase diagram frequently consider only homogeneous phases. However, at the high baryon density one also has to take into account the possibility of the crystal structures. The very well known examples are large N_c QCD [8], skyrmion crystals [9], LOFF phases [10], Overhauser effect [11] and chiral density waves [12]. The competition between chiral density waves and uniform colour superconductors were also discussed [13]. The chiral spirals have been already considered in the quarkyonic phase [14]. In this letter we would like to consider the chiral density waves in quarkyonic matter from the point of view of the PNJL model. It is an interesting problem to check how the chiral density waves are influenced by the presence of the Polyakov loop field and what kind of the feedback it generates. We also pay a particular attention to the relation between the inhomogeneous chiral phase and the quarkyonic matter.

2. Chiral density waves in the PNJL model

We consider the PNJL model with two light quarks and three colours with the parametrisation of the Polyakov loop based on paper [3] and the NJL part based on paper [15]

$$\mathcal{L} = \bar{\psi} i \gamma^\mu D_\mu \psi + G \left[\left(\bar{\psi} \psi \right)^2 + \left(\bar{\psi} i \gamma_5 \vec{\tau} \psi \right)^2 \right] - U(\Phi, T), \tag{1}$$

where ψ is a massless quark field and $D_\mu = \partial_\mu - i A_\mu$ is covariant derivative. The SU(3) gauge field $A_\mu = (A_0, \vec{0})$, $A_0 = g A_0^a \lambda_a / 2$ and λ_a are the Gell-

Mann matrices. The effective potential describing the traced Polyakov loop

$$\Phi = \frac{1}{N_c} \operatorname{Tr} \left[\mathcal{P} \exp \left(i \int_0^\beta d\tau A_4 \right) \right] ,$$

in the fundamental representation takes the form [3]

$$\frac{U(\Phi, T)}{T^4} = -\frac{1}{2} a(T) \Phi^2 + b(T) \ln \left[1 - 6\Phi^2 + 8\Phi^3 - 3\Phi^4 \right] ,$$

$$a(T) = 3.51 - 2.47 \frac{T_0}{T} + 15.2 \left(\frac{T_0}{T} \right)^2 , \quad b(T) = -1.75 \left(\frac{T_0}{T} \right)^3 , \quad (2)$$

where $A_4 = iA_0$ is a colour gauge field and the temperature $T_0 = 270$ MeV describes the deconfinement transition in a pure gauge sector. In equation (2) we already used the constraint that the expectation value of the Polyakov loops $\langle \Phi \rangle$, $\langle \Phi^* \rangle$ are real [16] which gives $\Phi = \Phi^*$ at the mean field level [3, 4]. The above treatment may be improved with fluctuations that lead to a difference between the expectation values of the traced Polyakov loops at non-zero baryon densities [17]. However, in the present work, as a practical procedure, we consistently keep $\Phi = \Phi^*$. In the literature, one may encounter also another approach. Fields Φ and Φ^* are treated as independent in the minimalization of the grand thermodynamic potential [18].

The coupling constant $G = 5.024$ GeV^{-2} and the three-dimensional momentum cut-off $\Lambda = 0.653$ GeV were used for regularization of the divergent vacuum contribution which reproduce the correct values of the pion decay constant and chiral condensate.

We are working at the mean field level with the chiral density wave ansatz [12]

$$\langle \bar{\psi}\psi \rangle = M \cos \vec{q} \cdot \vec{x} , \qquad \langle \bar{\psi} i \gamma_5 \tau_3 \psi \rangle = M \sin \vec{q} \cdot \vec{x} , \qquad (3)$$

where the third direction in isospin space was chosen arbitrarily. The colour field in a Polyakov gauge creates a constant background field $A_4 = \lambda_3 \phi$ which is related to the Polyakov loop through the equation $\Phi = (1 + 2\cos\phi)/3$.

The standard procedure of the mean-field calculation in the Matsubara formalism leads to the thermodynamic potential of the form

$$\frac{\Omega}{V} = \frac{M^2}{4G} + U(\Phi, T) - \frac{T}{2} \sum_n \int \frac{d^3 p}{(2\pi)^3} \operatorname{Tr} \ln \left[S^{-1}(i\omega_n, \vec{p}) \right] , \qquad (4)$$

where $\omega_n = (2n + 1)\pi T$. The inverse propagator in Nambu–Gorkov space reads

$$S_{\pm}^{-1}(i\omega_n, \vec{p}) = \begin{bmatrix} S_+^{-1} & 0 \\ 0 & S_-^{-1} \end{bmatrix}, \tag{5}$$

where $S_{\pm}^{-1}(i\omega_n, \vec{p}) = i\gamma_0(\omega_n \pm A_4 \pm i\mu) + \vec{\gamma}\left(\vec{p} - \frac{1}{2}\gamma_5\tau_3\vec{q}\right) + M$ and μ is a quark chemical potential. After diagonalization of the propagator one finally arrives at the formulae

$$\frac{\Omega}{V} = U(\Phi, T) + \frac{M^2}{4G} + \frac{M^2 F_\pi^2 \vec{q}^2}{2M_0^2} - 12\int^\Lambda \frac{d^3p}{(2\pi)^3} E_0$$

$$-2T\sum_{i=\pm}\int^\Lambda \frac{d^3p}{(2\pi)^3}\left\{\ln\left[1 + 3\Phi e^{-(E_i-\mu)/T}\left(1 + e^{-(E_i-\mu)/T}\right) + e^{-3(E_i-\mu)/T}\right]\right.$$

$$\left.+ \ln\left[1 + 3\Phi e^{-(E_i+\mu)/T}\left(1 + e^{-(E_i+\mu)/T}\right) + e^{-3(E_i+\mu)/T}\right]\right\}, \tag{6}$$

where $M_0 = 0.301$ GeV is a constituent quark mass at zero temperature and density. The regularization through the 3-dim momentum cut-off was introduced after paper [13]. The energy eigenvalues are given by the expressions

$$E_\pm = \sqrt{\vec{p}^2 + M^2 + \frac{\vec{q}^2}{4} \pm \sqrt{(\vec{q}\cdot\vec{p})^2 + M^2\vec{q}^2}}, \qquad E_0 = \sqrt{\vec{p}^2 + M^2}.$$

Let us notice that potential (6) reduces to NJL model prediction in the deconfined limit $\Phi = 1$.

3. The phase diagram

The global minima of the potential (6) as a function of temperature and baryon density describe the phase diagram of the strongly interacting matter. This prescription leads to the self-consistent equations

$$\frac{\partial\Omega}{\partial M} = \frac{\partial\Omega}{\partial\Phi} = \frac{\partial\Omega}{\partial|\vec{q}|} = 0.$$

Fig. 1 shows the the PNJL model phase diagram including the inhomogeneous chiral density wave phase (CDW) marked with the grey colour. This phase is surrounded by the line of the first order phase transition where there are jumps in the values of the all order parameters M, Φ and $|\vec{q}|$. The jump in Φ is induced by the first order phase transition in M and it is not a mark of the transition to a deconfinement phase. One expects rather a crossover here and the exact place of this transition is not fixed unambiguously. We define the transition line as a place where the derivative $d\Phi/dT$ reaches its maximum unless stated otherwise (see Subsection 3.2). Using our definition

the lines of deconfinement phase transition are shown in Fig. 1 as dashed curves. For the Polyakov loop potential parameter $T_0 = 270$ MeV the chiral and deconfinement transitions almost perfectly coincide at zero density, however, they split around the point $(T, \mu) = (0.21, 0.12)$ GeV (left panel of Fig. 1). It is interesting to note that this is also the place where the quarkyonic phase appears. The boarder line for the quarkyonic matter is defined as a place where the value of the quark chemical potential exceeds the value of the constituent quark mass [6]. This line perfectly coincides with the first order phase transition line of the CDW phase for $\mu > 0.12$ GeV. It happens because at the first order phase transition there is a large jump in the value of the constituent quark mass M which drops below the value of μ. One can conclude that within the PNJL model the quarkyonic matter can be treated as confined, however, spatially inhomogeneous phase.
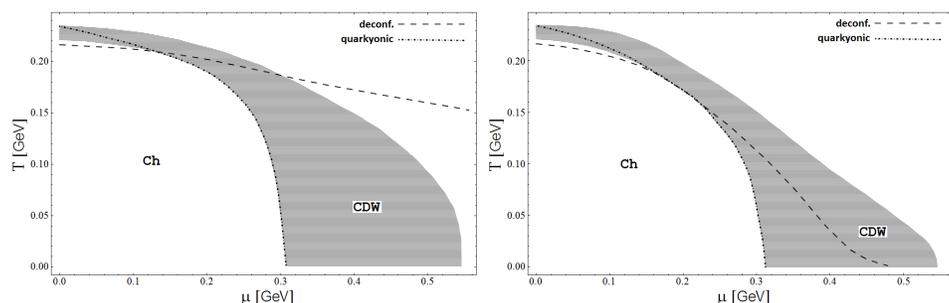

Fig. 1. The phase diagram of the PNJL model with inhomogeneous chiral wave. The dashed curves are lines of the deconfinement phase transition. The left panel shows the diagram for the constant Polyakov loop potential parameter $T_0 = 270$ MeV, whereas the right panel for the density dependent parameter $T_0(\mu)$ given by equation (7). The grey colour describes the inhomogeneous CDW phase. The dotted curves are lines of the transition to quarkyonic phase. These lines essentially coincide with the lines of the first order phase transition to CDW phase at higher density.

3.1. Deconfinement and the baryon density

It is important to remember that the critical temperature of the deconfinement phase transition decreases with increasing baryon number density. This results in T_0 parameter dependence on the quark chemical potential [19]. It can be intuitively understood in the picture of overlapping hadrons. At zero density the finite temperature causes fluctuations of mesons and baryon–antibaryon pairs up to some critical value of T_c. Above this temperature hadrons overlap with each other and there is a possibility of a colour flow in space which one can interpret as the process of deconfinement. At

higher baryon chemical potential there is already some number of hadrons present in a medium. Then a new critical temperature, lower then T_c, is sufficient to create appropriate number of hadrons which start to overlap. In paper [20] Fukushima tried to estimate such dependence from the statistical model data which we also adopted here

$$T_0(\mu) = T_0 - 9b\mu^2\,, \qquad (7)$$

where $b = 1.39 \times 10^{-4}$ MeV^{-1} and for $T_0(\mu) < 1$ MeV the phase is defined as deconfined. In the right panel of Fig. 1 the dashed curve describes the deconfinement phase transition for the density dependent parameter (7). As expected the line bends toward the density axis, but still, there is a place for the inhomogeneous phase in the quarkyonic region for temperatures below 0.16 GeV and chemical potential above 0.22 GeV. This needs to be confronted with the statement that the existence of homogeneous quarkyonic phase is inconsistent with the prediction of statistical model [20]. The introduction of non-uniform phases opens up a window for realisation of the quarkyonic matter (see also Fig. 4).

3.2. Deconfinement and the number of flavours

A value of the temperature parameter T_0 depends also on the number of active flavours. For the model which contains two degenerate flavours one should reduce the temperature parameter to $T_0 = 208$ MeV [2, 19]. The phase diagram for this parameter is shown in the left panel of Fig. 2. First of all one looses a good coincidence between the chiral and deconfinement phase transitions at zero density, nevertheless, the CDW phase remains intact. The confined (quarkyonic), inhomogeneous phase appears at chemical potential larger then $\mu = 0.21$ GeV and temperatures below $T = 0.16$ GeV. For lower baryon densities and higher temperatures the CDW phase still exists but it is deconfined.

The phase diagram at $T_0 = 208$ MeV is not satisfactory in a sense that at zero density there is a mismatch between the chiral and deconfinement phase transitions which contradicts the lattice results [21]. One can consider a possibility that this problem is a consequence of the wrong value of the coupling constant G at non-zero temperature. The effective coupling constant G is in principle a function of temperature and density. It contains contributions which follow from the integration of the gluonic degrees of freedom. At higher values of T gluons interaction with quarks weakens which in turn influences the effective four-quark interaction in the same way. Thus the coupling G decreases with increasing temperature which lowers the critical temperature of the chiral phase transition. If one attributes the whole mismatch between the chiral and deconfinement transitions at zero density
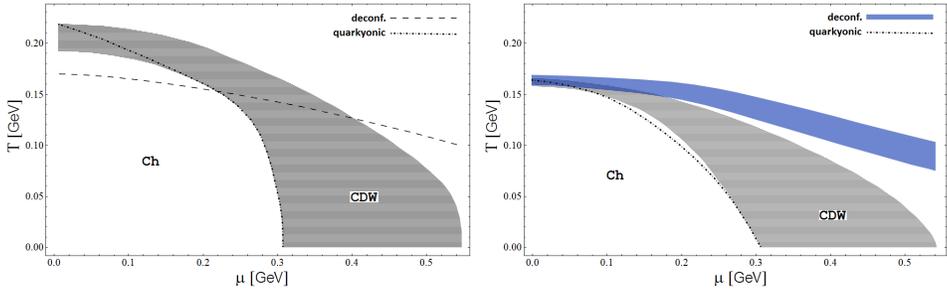
Fig. 2. The phase diagram of the PNJL model with inhomogeneous chiral wave for the Polyakov loop potential parameter $T_0 = 208$ MeV which corresponds to $N_f = 2$ active degenerate flavours. In the left panel the NJL parameter is set to $G = 5.024$ GeV^{-2}. In the right panel the temperature dependence of the NJL parameter $G(T)$ is taken into account according to equation (8). Behaviour of the Polyakov loop is disturbed by the first order transitions into the inhomogeneous phase and consequently deconfinement transition is determined with uncertainty within the blue band.

to the wrong value of G then one can try, at least at the phenomenological level, to re-establish the agreement changing its value into the new one $G(T_c) = G_c$ in such a way, that both transitions have the same critical temperature T_c. We assume here that the coupling G is a linear function of temperature

$$G(T) = G(1 - (T/T_c)) + G_c(T/T_c)\,, \tag{8}$$
$$G = 5.024 \text{ GeV}^{-2}\,, \qquad G_c = 4.221 \text{ GeV}^{-2}\,, \qquad T_c = 167 \text{ MeV}\,.$$

According to our fit the change in the constant G between zero temperature and T_c is of the order of 15 per cent which is not much. Then one can treat equation (8) as a series expansion in the temperature around $T = 0$. The density dependence of G is neglected since it is less important at large N_c limit where quarks decoupled from the gluonic degrees of freedom.

The right panel of Fig. 2 describes the phase diagram where the NJL coupling constant G is given by the linear function from Eq. (8). It is clearly seen that the chiral and deconfinement phase transitions coincide at zero density to a good approximation. Let us mention that the usual definition of the deconfinement transition line as a place where the derivative $d\Phi/dT$ reaches its maximum is not quite useful in a situation where Φ is a discontinues function of temperature and the points of discontinuity are close to the expected maximum value of $d\Phi/dT$. In such situations we define the deconfinement transition as a place where the Polyakov loop Φ takes the value 0.31 ± 0.07. This is rather a modest value, however, such range is

suggested when one considers the deconfinement phase transition for the homogeneous phases where the transition line is defined in a standard way. Using our definition the line of deconfinement phase transition is shown in Fig. 2 (later in Fig. 4) as a dark (blue) band. At low temperature and high baryon density one recovers the results of the NJL model with a constant G coupling.

3.3. Triple point

The concept of a triple point in the QCD phase diagram refers to various situations. For instance, the existence of a triple point between hadronic, colour–superconducting and quark–gluon sectors was discussed in Ref. [22]. In the context of the present work, we refer to a very recent idea, namely, to the triple point in which hadronic, quarkyonic and quark–gluon phases meet together. Such a possibility was emphasized in paper [23]. Although in Figs. 1, 2 the CDW phase exists even at zero density region (there is no space for triple point), the location of the inhomogeneous phase depends on the regularization parameter Λ. In Figs. 1, 2 the cut-off parameter in the temperature dependent part of the potential (6) was sent to infinity. If one keeps this parameter at the constant value $\Lambda = 0.653$ GeV then the phase diagram changes and it is shown in Fig. 3. In this case the triple point actually appears at the point where the inhomogeneous phase ends $(T_3, \mu_3) = (0.22, 0.2)$ GeV, what is in agreement with the results of Ref. [24]. However, one has to remember that the location of this point is strongly dependent on the model parameters and the regularization method.
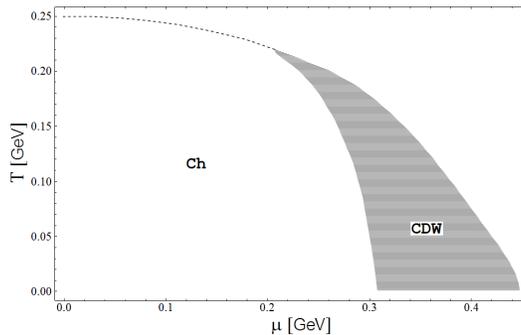

Fig. 3. The chiral phases of the PNJL model with inhomogeneous chiral wave. The NJL model parameters are $G = 5.024$ GeV^{-2} and $\Lambda = 0.653$ GeV. The temperature dependent part of the potential (6) is also regularized by the finite cut-off. In such a regularization the CDW phase is limited to the high density region of the diagram.

For the quark chemical potential below μ_3 the phase line describes the continuous phase transition whereas above μ_3 the line is of the first order. When a non-zero current quark mass is turned on then the continuous phase transition changes into a smooth crossover and only the island of CDW phase remains on the diagram.

4. Summary and conclusions

We have discussed the phase diagram of the strongly interacting matter including the spatially dependent chiral density waves in the PNJL model. It was shown that the inhomogeneous CDW phase exists and dominates over the chirally restored phase in a large domain of the phase diagram. We have also pointed out that the chiral density wave can be interpreted as a special realisation of the quarkyonic matter. This is an interesting possibility, particularly, when the homogeneous quarkyonic phase was strongly constrained by the results of the statistical model [20]. Indeed in a case of two flavours the phase diagram with only homogeneous phases is shown in Fig. 4 (left panel) where the effects of flavour and density dependence of the Polyakov loop potential parameter $T_0(N_f, \mu)$ as well as the temperature dependence of the NJL coupling constant $G(T)$ were taken into account. This last dependence reflects the fact that at higher temperature the four-point quark interaction should weaken which in turn let the chiral and the deconfinement
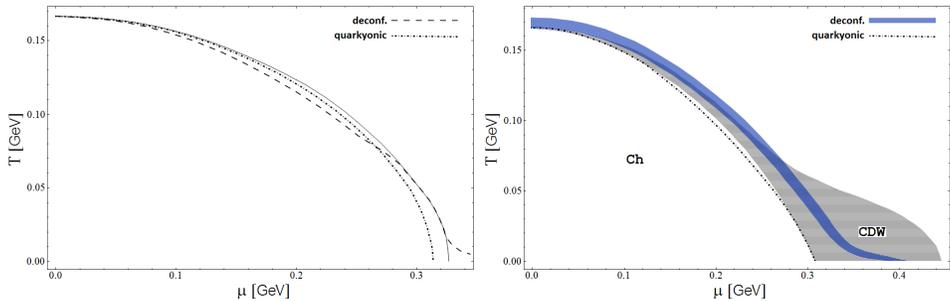

Fig. 4. Left panel: the phase diagram of the PNJL model with homogeneous phases only. Above the point $(T, \ \mu) = (0.085, \ 0.263)$, the nature of the chiral transition changes from first to second order. Right panel: the phase diagram of the PNJL model with inhomogeneous chiral density wave. The Polyakov loop potential parameter $T_0(\mu)$ is given by (7) with $T_0 = 208$ MeV. The finite 3-dim momentum cut-off $\Lambda = 0.653$ GeV regularized the potential (6) and the NJL coupling constant $G(T)$ depends on temperature through Eq. (8). The grey colour depicts the CDW phase. The dark (blue) band shows a location of the deconfinement phase transition.

transitions stay at the same critical temperature at zero baryon density. In the diagram the deconfinement phase transition precedes the chiral phase transition almost in all the domain. Only at high density and low temperature the transitions start to coincide. In such situation there is no space left for quarkyonic matter in accordance with the conclusion of paper [20]. The phase diagram in the right panel of Fig. 4 sums up all physical effects that we discussed in the previous sections and is the best candidate for the QCD phase diagram. The left panel of Fig. 4 should be compared with the right panel of the same figure. Let us notice a clear change in the order of the phase transitions. The phase transition to the CDW phase precedes the deconfinement phase transition. This fact also opens a window for the quarkyonic matter. The transition into the quarkyonic phase is close to or coincides with the first order phase transition into the CDW phase. Then the matter is spatially inhomogeneous but still confined. Let us remind that the details of the phase diagram depend on the temperature parametrisation of the NJL coupling constant $G(T)$. Nevertheless, at low temperatures one should expect the same pattern of phase transitions as given in Fig. 4.

For the model parameters we choose the CDW phase exists up to a zero density line. However, the low density and high temperature region is strongly affected by the temperature fluctuations which are neglected in the mean field approximation. These fluctuations probably melt the "crystal" structure of the CDW phase and the triple point is expected to appear on the phase diagram eventually.

It is an interesting task for the future work to compare the phases of the chiral density waves and the chiral spirals [14]. However, it requires the implementation of the chiral spirals within the NJL model in the first place. This is a subject of certain importance because the quarkyonic matter, if exists, would be most probably of an inhomogeneous nature. One should also check the dependence of the results against the regularization scheme and the influence of the finite current quark mass [25]. Finally, it is of great interest to consider more general ansatz then (3) to study the possibility of the creation of different crystal structures.

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