Crossover, fluctuation phenomena and Anderson transition at the onset of quark matter phase

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Abstract

We present the evidence that crossover, fluctuation phenomena and possible Anderson transition are the precursors of quark matter formation.

For several last years many investigators have joined the study of quark matter at finite density. The common lore is that at densities 3-5 times larger than the normal nuclear density matter becomes color superconductor. We argue that this is not the case. Transition from nuclear matter to quark matter phase ($NM \to QM$) is a "messy" and poorly understood process. First principle description of $NM \to QM$ transition is not currently available. However, we can point out three important features which characterize the region of moderate density where the $NM \to QM$ process occurs. These are:

(a) Crossover from strong coupling regime of composite nonoverlapping bosons (diquarks) to the weak coupling regime of macroscopic overlapping Cooper pair condensate (the BEC-BCS crossover).

(b) Drastic increase of fluctuations of both the order parameters and of the gluon field with the latter being the dominant ones.

(c) Possible Anderson localization phenomena.

All three phenomena are interrelated and may be described by a common set of parameters listed below.

The first parameter is $n^{1/3}\xi$, where n is the quark number density, ξ is the quark pair size. In the Bardeen-Cooper-Schrieffer (BCS) regime $n^{1/3}\xi \gtrsim 10^3$. At densities 3-5 times larger than the normal nuclear density $n^{1/3} \simeq 1$ fm^{-1} (the corresponding quark chemical potential is $\mu \simeq 0.3$ GeV). The root-mean square radius of the diquark at such density is $\xi \simeq 2$ fm, so that $n^{1/3}\xi \sim 1$. It is well known that at $n^{1/3}\xi \sim 1$ the system undergoes a crossover from the strong coupling/low density regime of independent bound state formation to the weak coupling/high density cooperative Cooper pairing (BEC-BCS crossover).

Another important parameter is the Ginzburg-Levanyuk number Gi which characterize the scale of the fluctuation region. It reads

$$Gi = \frac{27\pi^4}{28\zeta(3)} \left(\frac{T_c}{\mu}\right)^4 \simeq \frac{5 \cdot 10^{-2}}{(n^{1/3}\xi)^4}, \tag{1}$$

where $\zeta(3) = 1.2$, $T_c \simeq (0.04 - 0.05)$ GeV is the critical temperature, and $\mu \simeq (0.3 - 0.4)$ GeV. From (1) we obtain $Gi \gtrsim 10^{-2}$, while for the normal superconductors $Gi \simeq 10^{-12} - 10^{-14}$.

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The dominant fluctuations are that of the gauge field and they lead to the twofold effect. The first one is the fluctuation induced color diamagnetism, i.e., the lowering of the critical temperature, the second one is the modification of the order of the phase transition (first order instead of second). The critical temperature shifted due to gluon field fluctuations is given by

$$T_c' = T_c(1 - g^2\xi^2\langle \mathbf{A}^2\rangle), \tag{2}$$

where $g^2 = 4\pi\alpha_S$ is the strong coupling constant and $\langle \mathbf{A}^2\rangle$ is the expectation value of the gauge potential square in the fixed configuration of the diquark field. We can estimate $g^2\xi^2$ as $g^2 \simeq 4, \quad \xi \simeq 2$ fm, $g^2\xi^2 \simeq 400$ GeV^{-2}. The quantity $\langle \mathbf{A}^2\rangle$ is gauge-variant and (2) has been derived in the Coulomb gauge bringing a conjecturable minimum to $\langle \mathbf{A}^2\rangle$. Then very formal upper bound on $\langle \mathbf{A}^2\rangle$ following from (2) is $\langle \mathbf{A}^2\rangle < (50\ \text{MeV})^2$ which is more than an order of magnitude less than the lattice result at zero density. Such a significant mismatch can hardly be attributed to a moderate increase of density and at this point we arrive to the idea of possible Anderson localization (AL) phenomena.

If AL comes into play the coefficient in front of $\langle \mathbf{A}^2\rangle$ in (2), as well as a coefficient in front of the gradient term in Ginzburg-Landau functional, should depend on the quark mean free path l. The role of disordered background is attributed to random components of the gluon fields (may be partly to instantons). According to the Ioffe-Regel criterion the phase transition to the AL regime takes place at $k_F l \sim \mu l \lesssim 1$, i.e. at $l \sim 1$ fm for $\mu \sim 0.3$ GeV. This value of the quark mean free path seems quite reasonable. Calculation of the dynamical diffusion coefficient becomes a problem of utmost importance.

In order to keep this publication down to the required length we can not present the list of References which is rather extended. It can be found in our recent paper [1]. An important paper on this subject is Ref. [2].

References

[1] B. Kerbikov and E.V.Luschevskaya, arXiv: hep-ph/0607304.

[2] Y.Nishida and H.Abuki, Phys. Rev., **D72**, 096004 (2005).