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Report on the thesis "Meson and diquark correlations in a chiral model for normal and superconducting quark matter" of Dipl.-Phys. Daniel Zablocki."

The investigation of strongly interacting dense and hot quark matter in Quantum Chromodynamics (QCD) and its "hadronization" is one of the fundamental problems in modern particle theory. An important task is here the exploration of the QCD phase portrait on the basis of the spontaneous breakdown and restoration of chiral and color symmetries in dependence on temperature and particle density. From the experimental side, present heavy ion collision experiments at RHIC (BNL Brookhaven) and the LHC-Collider (CERN) have already delivered important informations on the high temperature and low density region of strong interacting matter.

QCD, a non-abelian gauge theory of quarks and gluons, has for high energies a small running coupling constant ("asymptotic freedom"), allowing a perturbative treatment. On the other hand, at low and intermediate energies, the running coupling becomes large, and gluons and quarks become confined within observable hadrons. Clearly, the corresponding formation of hadronic bound states cannot be treated in perturbation theory, but requires non-perturbative methods like QCD lattice calculations, Dyson-Schwinger and Bethe-Salpeter equations or the method of effective chiral quark Lagrangians. As known, the very successful QCD lattice methods often suffer a lack of a clear physical interpretation of results, and, due to the fermion sign problem, are restricted to a vanishing or small chemical potential. On the other hand, "QCD-based" chiral quark models like the Nambu-Jona-Lasinio (NJL) model facilitate interpretations and allow larger values of the chemical potential. Such chiral NJL quark models typically arise by (approximately) "integrating out" the gluon fields and replacing the resulting non-local four-point interaction of quark color currents by a local one.

Subsequent Fierz transformations then project the interaction into various quark-antiquark and diquark channels, where bound state formation of mesons and diquarks occurs. Keeping global chiral and color symmetries of QCD intact, NJL models naturally incorporate the dynamical mechanism for spontaneous breakdown and restoration of symmetries and have been shown to give a successful description of masses and coupling constants of hadronic bound states. They thus provide an important guidance for a deeper understanding of the formation of quark and diquark condensates (mass gaps) and the formation and dissociation of hadronic bound states in hot and dense matter.

The present thesis is just devoted to the investigation of the QCD phase portrait on the basis of the NJL-model by considering quark and diquark condensates in dependence on temperature and chemical potential. The formation of these condensates just signals the spontaneous breaking of chiral and color symmetries. Moreover, the work contains a detailed analytical study of meson and diquark correlations beyond the mean field approximation.

Chapter 2 presents the considered NJL-type model with scalar, pseudoscalar, (singlet) vector and scalar diquark interaction channels. Next, the standard bosonization procedure for the path-integral of the partition function is performed by a Hubbard-Stratonovich transformation to composite (auxiliary) meson and diquark fields. This then allows to integrate out the Nambu-Gorkov quark bispinors and to arrive at a highly non-linear effective boson lagrangian including the determinant of the NG matrix quark propagator. Using clever sign operators, the candidate then derives in mean field approximation compact expressions for the normal and abnormal components of the matrix quark propagator in the 2SC phase depending on Matsubara frequencies and chemical potential. This chapter also contains the determination of the gap equations from the minima of the resulting thermodynamic potential and a numerical investigation of the gap equations for the quark condensate ("constituent" quark mass), diquark (Cooper pair) condensate and vector meson condensate (dynamical chemical potential).

Chapter 3 extends the mean field consideration by expanding the quark determinant up to quadratic order in field fluctuations. In this Gaussian approximation, the bosonic fields can be integrated out in the partition function. The resulting boson determinant leads to an additional boson correlation part in the thermodynic potential containing the two meson/diquark polarization matrix.

In Chapter 4 the imaginary parts of polarization functions are investigated in detail for the case of mesons and diquarks in the 2SC phase, the normal phase and for the case of sigma meson-diquark mixing.

Chapter 5 is the central part of the thesis. Here the modification of thermodynamic properties of hadronic matter under extreme conditions is studied in the region near the chiral symmetry restoration. Special attention is drawn to the question at which temperature a meson/diquark bound state may become a resonant state as result of a lowering of the two-quark threshold by chiral symmetry restoration ("Mott effect"). Such a Mott effect might explain the so-called BEC-BCS crossover. Clearly, such kind of investigations require a detailed understanding of the interplay of bound and continuum states and their relation to the Levinson theorem. The corresponding investigations in this chapter are based on an elaborated generalized Beth-Uhlenbeck (GBU) EoS which uses the scattering phase shift as central quantity. Its threshold value gives, according to Levison's theorem, just the number of bound states. Moreover, under the general condition of a vanishing phase shift at infinite energies, it also vanishes at zero energy. This are just the necessary conditions for the vanishing of the boundary term from partial integration in eq (5.6) (not discussed there) so that the Beth-Uhlenbeck formula for the pressure in eq(5.79) remains intact. Finally, the thesis includes a description of nucleons as quark-diquark bound state and a comparision of NJL-results with corresponding ones of the Walecka model. Obviously, such a comparision of expressions, obtained from quark loop calculations with non-confined quark propagators, with corresponding loop calculations using nucleon propagators, naturally rises the nontrivial question: How to take into account the effects of the neglected quark confinement in the NJL approach and how to avoid double counting ? A solution of this complicated problem is clearly outside the scope of the thesis. In this context, it is yet worth mentioning that there was found an interesting "quark-baryon" duality for fermion loops (see: D.E., M.K.Volkov, Fortsch.Phys. 29 (1981) 35). In fact, using the respective Goldberger-Treiman relations for meson-quark and meson-baryon coupling constants, the quark loop expressions were shown to be almost identical with the baryon loop results. (Additional meson loop contributions were generally small.) This remembers in some sense the concept of "quark-hadron duality", taken as basis of the "QCD sum rule" approach.

In conclusion, the present thesis contains important new results concerning the investigation of the QCD phase transition including restoration of chiral symmetry in hot and dense quark matter, Mott effect and color superconductivity. It is is written in an adequate form. Its results are published in 7 articles. The list of references is rather complete and reflects the existing literature on this topic. To my opinion, the thesis thus meets all necessary requirements and demonstrates the ability of the candidate for doing scientific work.

It is a pleasure to recommend the thesis of D.Zablocki to the faculty of physics of the Wroclaw university for defence.

Sincerely yours,

D. Ebert

Prof. Dr. D. Ebert