論文内容の要旨

論文題目 Ginzburg-Landau approach to color superconductivity

カラー超伝導のギンツブルグ・ランダウ理論による研究

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Single-gluon exchange between two quarks is attractive in the color-antitriplet channel. Therefore, at high baryon density and low temperature quark matter is expected to undergo a phase transition to a color superconductivity due to a Cooper instability. For three massless flavors (u, d, s), a ground state called the color-flavor-locked (CFL) phase is expected to realize. Theoretically, there has been a lot of work to make the nature of the high density quark matter clear and various new phases of color superconductor have been proposed so far. Such a high density quark matter is expected to exist in the cores of the neutron stars. Also, future experiments e.g. J-PARC (2007-) and GSI (2014-) try to reproduce and elucidate this state.

In this thesis, we describe the thermal phase transition in color superconductivity by model independent Ginzburg-Landau (GL) approach and study the features of the phase transition, the phase structure and the elementary excitations near the phase boundary. We also investigate the vortices which arise in color-flavor-locking (CFL) phase by use of the GL free energy and topological considerations.

To investigate the phase structure in color superconductivity, Ginzburg-Landau theory is one of the most powerful analytic tools, where the thermodynamic potential difference between the superfluid and normal phases is expanded in terms of the order parameter (the pairing gap). It is adequate near the phase transition temperature and its form is model independent, which means we can make some predictions even up to rather low density region. Moreover, we can determine the coefficients of the expansion by QCD itself in the asymptotically high density region.

In the beginning of this thesis, we construct the GL free energy in the case of massless

quarks with no chemical potential differences among quarks ($m = \delta\mu = 0$) in weak coupling (at high baryon density). The method we employ is the Cornwall-Jackiw-Tomboulis (CJT) approach in the rainbow-ladder approximation with the gluon propagator in the normal medium. The order parameter is just the pairing gap field with $J^P = 0^+$, color-flavor antisymmetric, and positive energy. We derive the coefficients in the GL free energy up to quartic order. Then the phase transition is found to be second order and the ordered phase is the CFL phase. To incorporate the inhomogeneity, gradient terms are included as well as color and electromagnetic gauge fields. The masses of color gauge fields and the order parameter fields are calculated.

Next, we incorporate the effects of quark mass m and chemical potential differences among quarks $\delta\mu$ perturbatively into the GL free energy and study how they affect the thermal phase transition. In the regime of realistic baryon density for quark matter in neutron stars ($\mu \sim 400$MeV), m and $\delta\mu$ play an important role since strange quark mass ($m_s \sim 100$MeV) cannot be neglected compared to the energy scale. $\delta\mu$ also enters if we impose the β equilibrium condition, color and electric charge neutrality conditions. Among these conditions, color neutrality condition turns out to be negligible near the phase transition temperature.

Generally, m and $\delta\mu$ shift the fermi momenta among flavors. The melting temperature of a Cooper pair, which is made of quarks with the mismatch in fermi momenta, turn out to depend only on the average of the fermi momenta of paired quarks and not the difference of the fermi momenta as in the case of $T = 0$. Namely, the larger the average fermi momenta among the paired quarks, the higher the melting temperature of the Cooper pair is. In realistic quark matter, the average fermi momenta among i, j quarks, p_F^{ij}, order such as $p_F^{ud} > p_F^{ds} > p_F^{su}$, thus the melting temperature of the Cooper pair of i, j quark, T_c^{ij}, follows like $T_c^{ud} > T_c^{ds} > T_c^{su}$. This ordering hierarchies the thermal phase transition. Namely, three successive phase transitions take place as the temperature increases: a modified color-flavor locked phase (ud, ds, and us pairings) $\rightarrow$ a dSC phase (ud and ds pairings) $\rightarrow$ an 2SC phase (ud pairing) $\rightarrow$ a normal phase (no pairing). Such picture is also confirmed by another effective theory of QCD.

Further we calculate the Meissner masses of the transverse gluons and the number of gapless quark modes analytically. The gapless quarks are found to appear near the phase boundaries where the gap is small compared to the mismatch in fermi momenta. Also, the Meissner masses turn out to be real and positive in those phases which include the gapless quarks. This indicates the existence of stable gapless phases in contrast to the unstable gapless phases, where the Meissner masses are imaginary, which are found away from the critical temperature.

Finally, we investigate the vortices which arise in the CFL phase by use of the GL free energy as well as the topological and dynamical considerations. Firstly, we show that the order parameter space of CFL phase is $U(3)$, which can generate the vortices classified by Z. In the construction of the vortices, we have shown that both generators of local $U(1)$ gauge symmetry (which is electromagnetic one and/or abelian subgroup of color $SU(3)_C$ symmetry) as well as global $U(1)_B$ baryon symmetry are required. The vortex consists of a large amount of the color gauge field and a small amount of electromagnetic gauge field. At the same time, it has a logarithmically divergent energy per unit length. Thus our vortex is named semi-superfluid vortex, which compromises the local (gauged flux tube) and global (superfluid) vortices. The profile of the semi-superfluid vortex is drawn by numerically solving the coupled Euler-Lagrange equations derived from the GL free energy. Dynamically, the vortices are stable in the Type II region of the color superconductor which is expected to exist in the low density region such as the cores in the neutron stars. We discuss the possible scenario of the evolution of the vortices in the CFL phase of the neutron star during the cooling process.

There remain several future problems:

1. In the construction of the Ginzburg-Landau free energy, we treat the CJT effective potential as the function of full fermion propagator. However, in principle, we should treat the full quark and gluon propagator together in a self-consistent way in the CJT formalism, which would make the picture of the phase transition more precise.

2. How the additional effect of thermal fluctuation of gauge fields affects the realistic quark matter is an important future problem.

3. QCD at high density seems to have various defects. The evolution mechanism of such defects is important since if such defects exist in the neutron stars, it may become one of the sources of the abnormal enhancement of rotation speed of the star (glitch), whose mechanism is not fully understood.