# Effects of Vector Coupling on Chiral and Color-superconducting Phase Transitions — interplay among the scalar, pairing and vector interaction—

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Although many works have been done for the problem of the so-called color superconductivity (CSC) in dense quark matter, one must say that the previous works are all incomplete because an important interaction in the vector channel $\mathcal{L}_V = -G_V(\bar{\psi}\gamma^\mu\psi)^2$ is missing, which is found to alter the nature of the transition from chiral-symmetry broken ($\chi$SB) to color-superconducting phase drastically, as we shall show.

The significance to incorporate $\mathcal{L}_V$ may be understood as follows: (1) First of all, the instanton-anti-instanton molecule model as well as the renormalization-group equation[1] show that $\mathcal{L}_V$ appear as a part of the effective interactions together with the ones in the scalar and the pseudo-scalar channels $\mathcal{L}_S = G_S\{(\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\tau\psi)^2\}$ responsible for $\chi$SB. (2) $\mathcal{L}_V$ gives a repulsive contribution, hence tends to suppress the formation of high-density system, because $\langle\bar{\psi}\gamma^0\psi\rangle = \rho$ is the density. (3) The chiral restoration at finite density is necessarily accompanied with a density jump to higher density state with a large Fermi surface, which in turn favors the formation of Cooper instability leading to CSC. Thus one expects naturally that $\mathcal{L}_V$ acts to postpone the chiral restoration and the formation of CSC to a higher density, which might be inaccessibly high.

To explore the effects of the vector interaction quantitatively, we take the following interaction Lagrangian of Nambu-Jona-Lasinio type with two flavors ($N_f = 2$) and determine the phase diagram in the mean-field approximation with the vector coupling $G_V$ varied by hand: $\mathcal{L}_I = \mathcal{L}_S + \mathcal{L}_V + G_C\{(\bar{\psi}i\gamma_5\tau_2\lambda_A\psi^C)(\bar{\psi}^C i\gamma_5\tau_2\lambda_A\psi) + (\bar{\psi}\tau_2\lambda_2\psi^C)(\bar{\psi}^C\tau_2\lambda_2\psi)\}$. The last term is responsible for CSC. The parameters $G_S$ and the cutoff $\Lambda$ are determined so as to reproduce the pion mass $m_\pi$ and the pion decay constant $f_\pi$ with the current quark mass $m_u = m_d = 5.5$ MeV. The $G_C$ is chosen so as to reproduce the results obtained with the instanton-induced interaction[2].

The numerical calculation shows the following: When $G_V/G_S$ is increased, (i) the first order phase transition between $\chi$SB and CSC is weaken and the transition point is postponed to larger chemical potential $\mu$ with a few tens MeV, and (ii) a 'coexisting phase', where massive quarks with dynamically generated quark mass is superconducting, appears in a wide range of $\mu$. We notice that the appearance of such a coexistence phase is robust in contrast to the case encountered in [2].

We emphasize that the effects (i) and (ii) of $\mathcal{L}_V$ are intuitively understandable and natural. Therefore all the previous works should be reexamined with $\mathcal{L}_V$ incorporated. Furthermore, since the effects does not depend on the number of the flavors, the so called color-flavor locking phase (CFL) with $N_f = 3$ can be also largely affected with $\mathcal{L}_V$.

## References

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