Ferromagnetism of Quark Matter

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Recently condensed matter physics of QCD has been an exciting area in nuclear physics. Many people have been expecting quark matter as a new form of matter in relativistic heavy-ion collisions and astrophysical phenomena. Very recently color superconductivity in quark matter has been extensively studied by many authors.
We consider here a possibility of ferromagnetism of quark matter, which may provide a macroscopic magnetic field. In ref. [1] it has been suggested that ferromagnetic phase exists at low densities in analogy with an electron gas first discussed by Bloch. With this idea the author also suggested that we can understand the superstrong magnetic field observed for magnetars if they are quark stars.
From a theoretical point of view, however, the framework there is not selfconsistent and simply based on the perturbation theory with one- gluon-exchange (OGE) interaction. So, it might be interesting to inquire into the possibility of ferromagnetism in quark matter more closely from elementary many-body theories. It should be also interesting to explore the phase diagram of quark matter in the temperature-density plane, especially the low density region, where chiral symmetry plays an important role. Spontaneous symmetry breaking (SSB) of chiral symmetry may be understood as a superconductivity of the vacuum. We consider here the coexistence of ferromagnetism and vacuum superconductivity at T=0. We prove that quark matter becomes unstable for a formation of a double chiral density wave (DCDW) above a critical density,

$$\begin{aligned} \langle \bar{q}q \rangle &= \Delta \cos \mathbf{q}\cdot\mathbf{r} \\ \langle \bar{q}i\gamma_5\tau_3 q \rangle &= \Delta \sin \mathbf{q}\cdot\mathbf{r}, \end{aligned}$$

using the Nambu-Jona-Lasinio (NJL) model [2]. We can see that the *amplitude* of the DCDW produces the dynamical mass of quarks due to the SSB of chiral symmetry, while the *phase* induces the magnetization. Thus a DCDW state is a ferromagnetic state. So there appears some coexistence region on the phase diagram of quark matter.
A DCDW instability in color superconducting phase might be another interesting subject to explore the phase diagram of quark matter, which may also lead to a coexistence of superconductivity and ferromagnetism. Some discussions about this subject will be also given.

References

[1] T. Tatsumi, Phys. Lett. **B489** (2000) 280.
[2] T. Tatsumi, submitted to Phys. Lett. B.