Possibility of ferromagnetic neutron matter†

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Ferromagnetic order in nature always attracts interest for study as it manifests microscopic structure of matter and materials. Among observed magnetic fields in nature, perhaps the strongest stable magnetic field is on the surface of magnetars, which goes up to 10^{15} [G] and more. The mechanism for generating such a strong field is yet to be uncovered, and it is natural to resort the origin to the high density of neutrons of which the neutron stars consist. In fact, after the discovery of pulsars, the possibility of ferromagnetism at neutron stars was proposed. However, numerical simulations of neutron matter with realistic inter-nucleon potentials have not shown the ferromagnetic phase. So the possibility of the ferromagnetic phase at high density neutron matter, if exists in nature, waits for a new mechanism of the spontaneous magnetization.

In this paper, we study the possibility of the ferromagnetic phase at high density of neutrons, by using the simplest but general chiral effective action. Low energy dynamics of neutrons is governed by the chirally symmetric interactions through pions and the spin-magnetic coupling with magnetic fields. Our model consists of dense neutrons coupled with neutral pions and magnetic fields, together with the chiral anomaly term. These are indispensable ingredients, and we will see the outcome for the magnetic phase from this minimal model.

The reason for choosing the neutral pion is simply for the realization of the ferromagnetism, as other pion condensations such as charged pion condensation have not been shown to exhibit a ferromagnetism. In addition, with a neutral pion condensation of the form $\Pi_0(x) \propto \sin \boldsymbol{k}\cdot\boldsymbol{x}$, a neutron lattice is formed with an alternating layer structure (ALS)[1)], then the neutron spins cancel each other, and macroscopic magnetization would not emerge. In this paper, instead, we analyze a neutral pion condensation of the different form $\Pi_0(x) = \boldsymbol{q}\cdot\boldsymbol{x}$ following Dautry and Neyman[2)], and generalize the study to include magnetic fields and QCD anomaly.

Our study is motivated by the earlier work[3)] in which, together with M. Eto and T. Hatsuda, the author proposed a mechanism for a ferromagnetic phase at high density of neutrons. The mechanism utilizes a neutral pion domain wall coupled to the magnetic field through the QCD chiral anomaly. A spontaneous magnetization was shown in[3)] in the approximation of a single wall and one-loop neutrons. In this paper, we generalize the idea, and study in the simplest chiral model the Fermi energy of the dense neutrons and its back-reaction due to the pion condensation and the magnetic fields. A successive array of the domain walls can be approximated by the linear pion condensation of Dautry and Neyman.

Let us summarize what we find in this paper.

- Toy model of neutral fermions.
  First we provide a toy model of a neutral fermion with a Zeeman coupling to magnetic fields. Under the assumption of the spatial homogeneity, we calculate the energy density of the ferromagnetic phase and show that it is favored compared to the ordinary fermion matter.
- Simplest chiral model and ferromagnetic order.
  The toy model of the neutral fermions is the essential part of the chiral model of neutrons and pions. We analyze the simplest chiral effective model of dense neutrons and neutral pions, together with the magnetic field coupling and the QCD anomaly. We find that the neutral pion condensation of form proposed by Dautry and Neyman is precisely in the same place as the magnetization, under the assumption of the spatial homogeneity. The energy density of the ferromagnetic-pion-condensation phase is lower than the ordinary neutron matter at high density around $\rho > 5\rho_0$ where ρ_0 is The generated magnetic field is ~ 40 [MeV] $\sim \mathcal{O}(10^{17})$[G].
- Comparison to ALS.
  We compare our energy density with that of the inhomogeneous ALS phase (which does not exhibit a magnetization), and find that the ALS phase is favored. The energy gain of the ALS is by several times greater than that of our ferromagnetic phase.
- Axial vector meson condensation.
  To seek for the possibility of the ferromagnetism, we look at the *axial vector meson condensation* accompanied by our model. Indeed, any axial vector meson plays the same role as the neutral pions, and the axial vector meson condensation further reduces the energy density of the ferromagnetic phase significantly.

References
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