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Inhomogeneous Chiral and Coulomb Crystal in Neutron Stars

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Abstract. We study the possibility of two types of inhomogeneous phases in core of neutron stars: one is the Coulomb crystal, which is known as quark-hadron pasta structures, and another one is chiral crystal. In the Coulomb crystal, the inhomogeneous phase appears as the result of the balance between the surface tension and the Coulomb interaction. In chiral crystal, we study the inhomogeneous chiral condensate, which has spatial modulation. In the simple model in 1+1 dimensions, this condensate has the same feature with the FFLO state, which is well known in the condensed matter physics.

Keywords. equation of state, phase diagram, neutron stars, etc.

1. Introduction

Recent pulsar observations have presented useful information to understand the physics of highly dense matter. The observations of J1614-2230 and J0348-0432 suggested the maximum mass of NSs should exceed $\sim 2M_\odot$ (Demorest *et al.* (2010), Antoniadis *et al.* (2013)). The gravitational wave observations and/or NICER will provide new constraints on mass-radius relation of NSs in the future.

A possibility of the inhomogeneous chiral transition has been suggested in dense matter, and extensively studied by using the effective models of QCD such as Nambu-Jona-Lasinio (NJL) model or Gross-Neveu model (For a review, Buballa & Cagrinano (2015)). The inhomogeneous chiral phase has a spatial modulation, which may give rise to a kind of crystal in the core of neutron stars. Actually it is known that some solutions in the 1+1 dimensional NJL model have duality with the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state in condensed matter physics (Thies (2003)). The FFLO state is a superconducting phase with a spatial modulation, and is a hot topic in condensed matter physics.

Superconductivity plays a critical role for glitch phenomena and thermal evolution of pulsars. In many studies on such topics, it is assumed that the BCS phase appears at low temperature under weak magnetic field, and normal phase does at high temperature and/or under strong magnetic field. This understanding, however, is not enough. The recent experiment suggests that there exists a new phase with spatial modulation — namely the FFLO state, although it was theoretically proposed more than 40 years ago.

In this study, we focus on inhomogeneous chiral phase transition which corresponds to the FFLO state in condensed matter physics, as we described. We also consider the finite size effects, the pasta structures between quarks and hadrons.

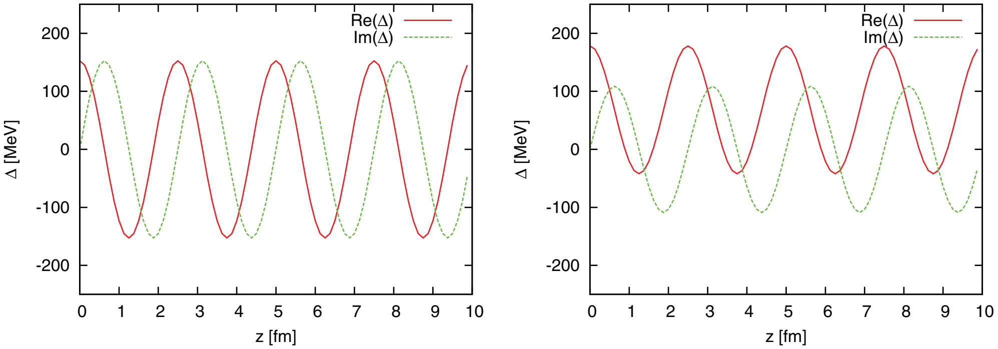

Figure 1. Numerical results of the inhomogeneous chiral condensates. Left panel is for the case without the current mass, right one is with the mass.

2. Overview

The Dirac equation for the 1+1 dimensional NJL model has the same structure with Bogoliubov-de Gennes (BdG) equation, which describes superconductivity. That is why some inhomogeneous chiral-phases have a duality with the FFLO state. Our purpose is to solve the Dirac equation numerically to obtain the inhomogeneous chiral phase without any *ansatz*, as shown in Heinz *et al.* (2016). We also check the self-consistency: the chiral condensate should be reconstructed by the solutions of the BdG equation with the condensate. Although the detailed results will be presented in a full paper, we only show a preliminary result here. We demonstrate how our procedure works in 1+1 dimensions by showing the chiral condensate for chiral spiral with and without the current mass. Note that the former case has not been obtained yet.

In Fig. 1, we show the inhomogeneous chiral condensates, which satisfy the self-consistentency. Left panel is for the condensate without the current mass, right one is with the mass of 30 MeV. The chemical potential, the dynamical mass, and cutoff are set as 200 MeV, 120 MeV, and 5 GeV. Note that the energy minimum has not been taken for these configurations yet, although they are the self-consistent solutions. We hence have to compare the energies for various types of the self-consistent solutions, and find the optimal modulations for the chiral condensate.

Our goal is to solve the Dirac equation in 3+1 dimensions to obtain the optimal structures of inhomogeneous chiral phase. However, the numerical cost will be extremely heavy: if we discretize the space and/or the momentum space to 100 for each direction, we have to solve the eigen value problem against the matrix with the size $\sim O(10^6)$, repeatedly.

If the density has the spatial modulation as the result of inhomogeneous chiral condensation, the Coulomb crystals may appear (Yasutake *et al.* (2014)). We will report the correlation between these crystals in some papers in near future.

References

Buballa, M. & Cagrinano, S. 2015, *Prog. Part. Nucl. Phys.*, 81, 39

Demorest, P. B., Pennucci, T., Ransom, S. M., Roberts, M. S. E., & Hessels, J. W., 2010, *Nature* 467, 1081 ; Antoniadis *et al.* 2013, *Science* 340, 6131

Heinz, A., Giacosa, F., Wagner, M., & Rischke, D. H. 2016, *Phys. Rev. D*, 93, 014007

Thies, M. 2003, *Phys. Rev. D*, 68, 047703

Yasutake, N., Łastowiecki, R., Benić, S., Blaschke, D., Maruyama, T., & Tatsumi, T. 2014, *Phys. Rev. C*, 89, 065803, and the reference there in.