Stable non-Abelian semi-superfluid vortices in dense QCD

Chandrasekhar Chatterjee[a] and Muneto Nitta[b]

Department of Physics, and Research and Education Center for Natural Sciences, Keio University,Hiyoshi 4-1-1, Yokohama, Kanagawa 223-8521, Japan

E-mail: chandra.chttrj@gmail.com[a], chandra@phys-h.keio.ac.jp[a], nitta(at)phys-h.keio.ac.jp[b]

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Color superconductivity is expected to be formed in high density quark matter where color symmetry is spontaneously broken in the presence of di-quark condensate. Stable non-Abelian vortices or color magnetic flux tubes exist in the color-flavor locked phase at asymptotically high density. $\mathbb{C}P^2$ Nambu-Goldstone(NG) bosons and Majorana fermions belonging to the triplet representation are localized around a non-Abelian vortex. We discuss the zero mode analysis and the low-energy effective world sheet theory of a non-Abelian vortex. We determine the interactions of these bosonic and fermionic modes by using the nonlinear realization method. We also discuss the Aharanov-Bohm (AB) phases of charged particles, such as, electrons, muons, and color-flavor locked mesons made of tetra-quarks encircling around a non-Abelian vortex in the presence of electro-magnetic fields. This is a review based on our recent works [1–3].

KEYWORDS: Color superconductor, CFL Phase, Non-Abelian vortices, Zero mode effective action, Majorana Fermion

1. Introduction

As it is well known that quantum chromodynamics (QCD) describes dynamics of interacting quarks and gluons. However free quarks and gluons are not detected in nature: they are confined to hadrons. The asymptotic freedom of SU(3) gauge theory describes QCD correctly at high energies by perturbative quantum field theory, where the coupling constant is small. At low energies the coupling constant becomes very strong and the mechanism of confinement remains unsolved. However if we increase the density sufficiently the system becomes asymptotically free and quarks condensate to color-superconductor due to existing attractive force among them. At asymptotically high densities the mass of the strange quark can be neglected and the system reaches to the most symmetric color-flavor locked (CFL) phase [4,5] (see Ref. [6] as a review). In this case, the baryon number symmetry along with the $SU(3)_c$ color $SU(3)_F$ flavor symmetries are spontaneously broken by forming di-quark condensates. This creates a color superconductor, and by an analogy with ordinary metallic superconductor, one would expect the formation of vortices here. Because the $U(1)_B$ baryon number symmetry is a global symmetry, stable vortices which can be created in this medium is superfluid vortices. These vortices carry color magnetic fluxes, so we may call them as chromo-magnetic flux tubes. The situation is dual to confining flux tubes in hadronic phase where quarks are confined by chromo-electric flux tubes. Beside these theoretical analogies, it is expected that a color superconductor can be found at the core of compact stars. The vortices in color superconductors then could effect the rotation dynamics of compact stars.

In this talk, based on our recent works [1–3], we review some developments of non-Abelian vortices in the CFL phase after the comprehensive review paper [7]. We discuss construction of vortices and their orientational zero modes using the Ginzburg-Landau (GL) formalism and Bogoliubov-de-Gennes (BdG) theory for fermions. We discuss interaction of fermion modes with bosonic orientational modes and write down effective interacting action. By introducing the electromagnetic interac-