論文内容の要旨

論文題目: Hadron-quark continuity and duality in dense QCD (高密度 QCD におけるハドロン・クォーク連続性と双対性)

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We study the quantum phase transition between hadronic matter and color superconducting quark matter with three-flavors (up, down, and strange quarks). We demonstrate the continuity between them from a variety of perspectives such as the phase structure, elementary excitations, and topological excitations.

First, we classify the possible QCD phase structures by using the Ginzburg-Landau theory based only on the QCD symmetry. We find that an interplay between the chiral condensate and the diquark condensate induced by the axial anomaly leads to a new critical point and a crossover between hadronic matter and quark matter. We then study the location of this new critical point with an effective model of QCD, the Nambu-Jona-Lasinio model. A novel crossover triggered by the axial anomaly between a Bose-Einstein condensation of the diquark pairing and a Bardeen-Cooper-Schrieffer-type pairing is found in this model.

Secondly, we study the collective excitations in dense QCD and derive formulas relating the masses of Nambu-Goldstone modes and vector mesons to chiral and diquark condensates. For the Nambu-Goldstone modes, we show the continuity between the pions ($\bar{q}q$-states) at low density and the generalized pions ($\overline{qq}qq$-states) at high density within the framework of the effective Lagrangian. For the vector mesons, we find the spectral continuity between the flavor-octet vector mesons at low density and the color-octet gluons at high density using the in-medium QCD sum rules.

Thirdly, we constitute a dynamical demonstration of the crossover found above in terms of the QCD topological excitations, the instantons. We show that instantons always behave as a unpaired plasma at high density using the renormalization group approach, which accounts for a nonvanishing chiral condensate at high density. This crossover can also be interpreted as a four-dimensional analogue of the Berezinskii-Kosterlitz-Thouless phase transition of vortices in two dimensions.

Finally, we formulate an exact duality between hadronic matter and quark matter in a finite volume: Their partition functions are mapped to each other via a transformation between the chiral condensate and the color superconducting gap.

These studies on dense QCD from different points of view strongly indicate a novel notion of "hadron-quark continuity and duality" which has close relevance to the physics in the interiors of neutron stars and in the future heavy ion collision experiments.