【Grant-in-Aid for Young Scientists(S)】

Science and Engineering (Mathematical and physical sciences)

Title of Project : Study of the topological vacuum structure of Quantum Chromodynamics using the lattice field theory with exact chiral symmetry

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Research Area : Physics and Mathematics

Keyword : Theoretical Particle Physics

【Purpose and Background of the Research】

Quantum Chromodynamics (QCD) has been established as the fundamental theory of strong interaction. Yet, solving the theory remains extremely difficult due to its non-perturbative nature at low energies. For the property of its ground state, which is the QCD vacuum, there were many studies in 1970s by t'Hooft, Witten, Gross and many others without full success. (But it was understood that the topology of gauge field and the quantum anomaly play an important role to form the QCD vacuum.)

The most powerful way of analyzing the non-perturbative aspect of QCD is to use the simulation of lattice field theory, which has been applied to the calculation of hadron spectrum and matrix elements. But an important restriction of this method is that the chiral symmetry cannot be preserved on the lattice (Nielsen-Ninomiya's theorem), so that the study of the topology or the axial-anomaly has been problematic. This problem was theoretically solved by Neuberger in 1998, when he proposed the so-called overlap fermion formulation, which preserves exact chiral symmetry on the lattice.

Numerical simulation with the overlap fermion was difficult for about 10 years since then, and became feasible only recently by 50 TFlops class supercomputer installed at KEK in 2006. We performed the lattice QCD simulation with exact chiral symmetry for the fist time. Through this work we now have a powerful tool to study the problems related to the vacuum structure of QCD, such as the U(1) problem and the strong CP problem.

This research project is an extension of our previous work. The purpose is to study (i) the relation between the chiral condensate and the quark near-zero modes associated with the topological excitation of gauge field, (ii) the physics of flavor-singlet sector, (iii) the pion-loop effects in QCD, which appears as an effect of spontaneous chiral symmetry breaking, and (iv) the problem of the theta vacuum, which is related to the topological structure of QCD.

【Research Methods】

The first task in this research project is to provide the data of QCD vacuum using the large-scale simulation. While using the data we have accumulated so far, we also carry out simulations on larger lattices for more detailed analysis. Improvement of the simulation algorithm is therefore an important subject of this project.

We then "measure" how quarks behave on the lattice in the QCD vacuum generated by our simulations. We are going to develop and use new analysis techniques, such as the analysis of the quark eigenmodes and the calculation of the disconnected quark loops.

【Expected Research Achievements and Scientific Significance】

The question of QCD vacuum is directly related to a more fundamental question, such as how the mass of matters is generated. It is a quite significant progress that we are now able to study such a question using numerical simulations. Through this research project, we expect to understand the nature of QCD vacuum and its phenomenological consequences.

【Publications Relevant to the Project】

- H. Fukaya et al. [JLQCD collaboration], "Two-flavor lattice QCD simulation in the epsilon-regime with exact chiral symmetry," Physical Review Letters, 98, 172001 (2007).
- J. Noaki et al. [JLQCD and TWQCD collaborations], "Convergence of the chiral expansion in two-flavor lattice QCD," Physical Review Letters, 101, 202004 (2008).

【Term of Project】 FY2009-2013

【Budget Allocation】 50,800 Thousand Yen

【Homepage Address and Other Contact Information】

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