【Grant-in-Aid for Scientific Research (S)】

Revealing the mysteries of heavy-quark exotics from QCD

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Project Information	Project Number : 23H05439 Project Period (FY) : 2023-2027 Keywords : Exotics, Heavy-quark, Lattice QCD, Femtoscopy, Hadron theory

Purpose and Background of the Research

●Outline of the Research

Normal matter in the universe is made of elementary particles called quarks. Then, what kind of multi-quark systems can exist? What kind of structure do they have? Traditionally, multi-quark systems (=hadrons) have been classified to mesons (two-quark systems) and baryons (three-quark systems). However, recent large-scale accelerator experiments are reporting discoveries of new kinds of hadrons which contain heavy (large mass) quark(s), such as charm quark and bottom quark. They are considered as new exotic particles which consist of four or five quarks, in contrast to ordinary hadrons. Their structures remain to be mysterious, and it becomes an urgent task to develop a new theoretical framework based on the fundamental theory of quarks, Quantum Chromodynamics (QCD). In this research, we focus on interactions between heavy-quark hadrons, which play a crucial role to understand these exotics. We perform three key studies, first-principles calculations from QCD, research from hadron correlations in nuclear collision experiments and study from heavy-quark hadron theory. From the unification of these studies, we aim at comprehensive understanding of interactions and the nature of exotic new particles.

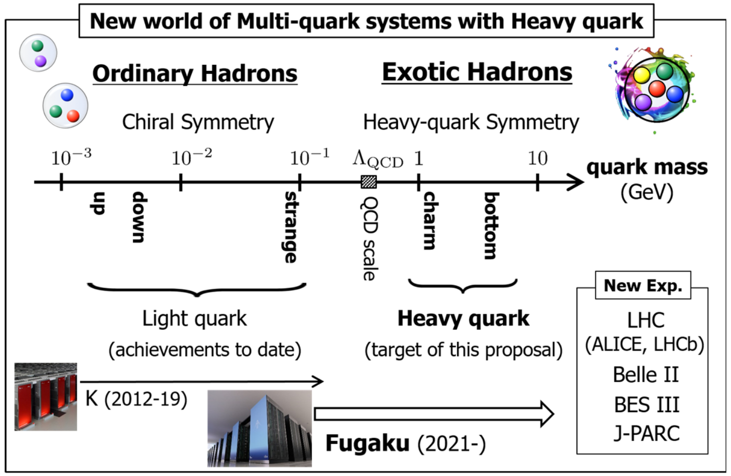

Figure 1. Overview of heavy-quarks and new multi-quark systems (exotic hadrons)

●Research plan and methods

We plan to study heavy-quark hadron interactions and exotic new hadrons through three pillars of research, where their mutual collaboration is the key in this project.

(1) First-principles calculation of heavy-quark hadron interactions
By performing large-scale numerical computations of QCD (Lattice QCD=LQCD), we systematically determine the interactions. Based on our novel "HAL QCD method", which successfully determined light-quark hadron interactions on K-computer, we determine heavy-quark hadron interactions on flagship supercomputer "Fugaku".

(2) Femtoscopic study of heavy-quark hadron interactions
In the femotoscopy, we can extract hadron interactions from hadron correlations in nuclear collision experiments. Triggered by our theoretical studies, large-scale femtoscopic experiments are on-going, e.g., at LHC. We will collaborate these experiments and perform experimental validation of hadron interactions.

(3) Study based on Heavy-quark Effective theory / Phenomenology
We employ approaches based on effective theory and phenomenology, where symmetries of QCD and physical degrees of freedom play an important role. We will single out important interactions to be calculated in LQCD. We also construct heavy-quark hadron theory based on QCD by using the information from LQCD.

Expected Research Achievements

●Revealing the properties of heavy-quark exotic hadrons based on QCD

In LQCD, we calculate heavy-quark hadron interactions on large volume with the physical quark masses using "Fugaku". In femtoscopy, we study interactions utilizing experimental data from, e.g., LHC ALICE RUN3. In addition, by combing LQCD outputs and experiments, we determine unknown interactions and/or parameters in nuclear collision experiments, which cannot be determined by LQCD or experiments alone. In heavy-quark hadron theory, we study effective theory based on heavy-quark symmetry/chiral symmetry of QCD, as well as phenomenological models based on hadron molecule models/quark models. In addition, we evolve a theory based on QCD by determining their unknown parameters using the results of LQCD/femtoscopy.

By coordinating these three studies, LQCD, femtoscopy and hadron theory, we perform mutual validation between theory and experiments, and quantitatively establish interactions as well as their physical picture. Based on the obtained interactions, we achieve comprehensive understanding of heavy-quark exotics.

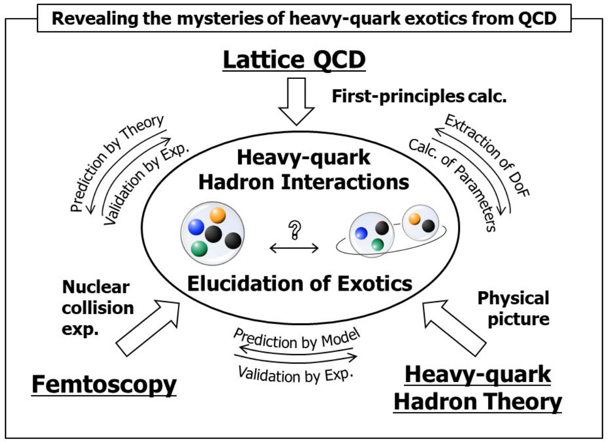

Figure 3. Comprehensive elucidation of heavy-quark hadron interactions and exotic new particles from coordinated studies of Lattice QCD, Femtoscopy and Heavy-quark hadron theory

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