Research Objectives

The MILC Collaboration is engaged in a broad research program in Quantum Chromodynamics (QCD). This research addresses fundamental questions in high energy and nuclear physics and is directly related to major experimental programs in these fields. It includes studies of the mass spectrum of strongly interacting particles, the weak interactions of these particles, and the behavior of strongly interacting matter under extreme conditions.

The standard model of High Energy Physics encompasses our current knowledge of the fundamental interactions of subatomic physics. It consists of two quantum field theories: the Weinberg-Salaam theory of electromagnetic and weak interactions, and QCD, the theory of the strong interactions. The standard model has been enormously successful in explaining a wealth of data produced in accelerator and cosmic ray experiments over the past forty years; however, our knowledge of it is incomplete because it has been difficult to extract many of the most interesting predictions of QCD, those that depend on the strong coupling regime of the theory, and therefore require non-perturbative calculations. At present, the only means of carrying out non-perturbative QCD calculations from first principles and with controlled errors, is through large scale numerical simulations within the framework of lattice gauge theory. These simulations are needed to obtain a quantitative understanding of the physical phenomena controlled by the strong interactions, to determine a number of the fundamental parameters of the standard model, and to make precise tests of the standard model's range of validity. Despite the many successes of the standard model, it is believed by high energy physicists that to understand physics at the shortest distances, a more general theory will be required. The standard model is expected to be a limiting case of this more general theory, just as classical mechanics is a limiting case of the more general quantum mechanics. A central objective of the experimental program in high energy physics, and of lattice QCD simulations, is to determine the range of validity of the standard model, and to search for new physics beyond it. Thus, QCD simulations play an important role in efforts to obtain a deeper understanding of the fundamental laws of physics.

QCD is formulated in the four-dimensional space-time continuum; however, in order to carry out numerical calculations one must reformulate it on a lattice or grid. It should be emphasized that the lattice formulation of QCD is not merely a numerical approximation to the continuum formulation. The lattice regularization of QCD is every bit as valid as continuum regularizations. The lattice spacing a establishes a momentum cutoff π/a that removes ultraviolet divergences. Standard renormalization methods apply, and in the perturbative regime they allow a straightforward conversion of lattice results to any of the standard continuum regularization schemes.

Lattice QCD calculations proceed in two steps. In the first, one uses importance sampling techniques to generate gauge configurations, which are representative samples from the Feynman path integrals that define QCD. These configurations are saved, and in the second step they are used to calculate a wide variety of physical quantities. It is necessary to generate configurations with a range of lattice spacings and then perform extrapolations to the zero lattice spacing limit. Furthermore, the computational cost of calculations rises as the masses of the quarks, the fundamental constituents of strongly interacting matter, decrease. Until recently, it has been too expensive to carry out calculations with the masses of the two lightest quarks, the up and the down, set to their physical values. Instead, one has performed calculations for a range of up and down quark masses, and extrapolated to their physical values guided by chiral perturbation theory, an effective field theory that determines how physical quantities depend on the masses of the lightest quarks. The extrapolations in lattice spacing (continuum extrapolation) and quark mass (chiral extrapolation) are the major sources of systematic errors in QCD calculations, and both must be under control in order to obtain trustworthy results. In our current simulations, we are, for the first time, working at or near the physical masses of the up and down quarks. The gauge configurations produced in these simulations greatly reduce, and will eventually eliminate, the systematic errors associated with the chiral extrapolation.

A number of different formulations of QCD on the lattice are currently in use by lattice gauge theorists, all of which are expected to give the same results in the continuum limit. In recent years, major progress has been made in the field through the development of improved formulations (improved actions) which reduce finite lattice spacing artifacts. Approximately seventeen years ago, we developed one such improved action called asqtad [1], which significantly increased the accuracy of our simulations for a given amount of computing resources. We have used the asqtad action to generate an extensive library of gauge configurations with small enough lattice spacings and light enough quark masses to perform controlled calculations of a number of physical quantities. Computational resources provided by the DOE and NSF have enabled us to complete our program of generating asqtad gauge configurations. These configurations are publicly available and have been used by us and by other groups to study a wide range of physical phenomena of importance in high energy and nuclear physics. Ours was the first set of full QCD ensembles that enabled control over both the continuum and chiral extrapolations. We have published a review paper describing the asqtad ensembles and the many calculations that were performed with them up to 2009 [2].

Over the last decade, a major component of our work has been to use our asqtad gauge configurations to calculate quantities of importance to experimental programs in high energy physics. Particular emphasis was placed on the study of the weak decays and mixings of strongly interacting particles in order to determine some of the least well known parameters of the standard model and to provide precise tests of the standard model. The asqtad ensembles have enabled the calculation of a number of physical quantities to a precision of 1% – 5% and will enable many more quantities to be determined to this precision in the coming years [3]. These results are already having an impact on experiments in high energy physics; however, in some important calculations, particularly those related to tests of the standard model, higher precision is needed than can be provided by the existing asqtad ensembles. In order to obtain the required precision, we are now working with the Highly Improved Staggered Quark (HISQ) action developed by the HPQCD Collaboration [4]. We have performed tests of scaling in the lattice spacing using HISQ valence quarks with gauge configurations generated with HISQ sea quarks [5]. We found that lattice artifacts for the HISQ action are reduced by approximately a factor of 2.5 from those of the asqtad action for the same lattice spacing, and taste splittings in the pion masses are reduced by approximately a factor of three, which is sufficient to enable us to undertake simulations with the mass of the Goldstone pion at or near the physical pion mass. ("Taste" refers to the different ways one can construct the same physical particle in the staggered quark formalism. Although particles with different tastes become identical in the continuum limit, their masses can differ at finite lattice spacing.) Moreover, the improvement in the quark dispersion relation enables us to include charm sea quarks in the simulations. The properties of the HISQ ensembles are described in detail in Ref. [6], and the first physics calculations using the physical quark mass ensembles in Refs. [7, 8, 9]. The current status of the HISQ ensemble generation project is described at the link HISQ Lattice Generation and some initial calculations with them at Recent Results. The HISQ action also has advantages for the study of QCD at high temperatures, so we have started to use it in our studies of this subject. Projects using the HISQ action will be a major component of our research for the next several years.

Our research is currently focused on the properties of light pseudoscalar mesons, the decays and mixings of heavy-light mesons, the quarkonium spectrum, the anomalous magnetic moment of the muon, and the electromagnetic mass splittings of hadrons. We briefly discuss our research in each of these areas at the link Recent Results.

References

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