

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 consists of two quantum field theories: the Weinberg-Salam Theory of the electromagnetic and weak interactions, and QCD, the theory of the strong interactions. It has been enormously successful in explaining a wealth of data produced in accelerator and cosmic ray experiments over the past thirty years. However, our knowledge of the Standard Model is incomplete because it has been difficult to extract many of the most interesting predictions of QCD, those that depend on the non-perturbative regime of the theory. Although there is little doubt that QCD is the correct theory of the strong interactions, non-perturbative QCD calculations are crucial for testing the weak interaction part of the Standard Model: In the absence of such calculations the strong effects completely obscure the weak physics one is trying to study. 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. These simulations are needed to obtain a quantitative understanding of the physical phenomena controlled by the strong interactions, to determine a number of the basic 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, which unifies all four of the fundamental forces of nature, 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.

Our research is currently focused on four major areas: 1) the properties of light pseudoscalar mesons, 2) the decays of heavy-light mesons, 3) the properties of strongly interacting matter at high temperatures, and 4) the mass spectrum of strongly interacting particles. We briefly discuss each of these areas below. More detailed descriptions of recent progress can be found at the link [recent results](#).

Properties of light pseudoscalar mesons: Lattice computation of the properties of light pseudoscalar mesons (*i.e.*, π , K and η mesons) offers a unique opportunity to check our lattice methods to high (≈ 2 to 3%) precision, and to calculate phenomenologically important physical quantities that are difficult or impossible to obtain with controlled errors by other methods. The advantages of this system stem firstly from the fact that we are able to compute quantities such as the π and K masses and decay constants at fixed lattice spacing and (larger than physical) quark mass with extremely high statistical accuracy: 0.1% to 0.7% , depending on the quark masses. Secondly, the dependence of these quantities on quark masses is governed by the formalism of chiral perturbation theory, which enables us to fit the lattice data accurately, including the effects of $O(a^2)$ lattice spacing errors, and then make a controlled chiral extrapolation (extrapolation to the physical value of m_l) followed by a controlled continuum extrapolation. Using the above method, we are computing the leptonic decay constants of the π and K mesons, f_π and f_K , the CKM matrix element V_{us} and the masses of the light (u , d and s) quarks.

Weak decays of particles containing heavy quarks: At the SLAC and KEK B-factories, and facilities at Fermilab and Cornell, a concerted experimental effort is under way to study the mixing and decays of B mesons in order to determine elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which describes how quarks are coupled to the weak interactions. In addition, the properties of D mesons are being measured to high accuracy in the CLEO-c Program at Cornell. The CLEO-c measurements can provide powerful constraints on the CKM matrix, directly through measurements of matrix elements involving c quarks. Furthermore, comparisons of lattice and experimental results for the decays of D mesons offer an important opportunity to validate our approach, and ensure that we do, in fact, have full control over systematic errors. The successes of these comparisons to date indicate that we are in a position to carry out similar calculations for the b -quark system, where the corresponding quantities have not been measured, and are unlikely to be in the near future.

In most cases both an accurate experiment and lattice calculation are needed to determine a CKM matrix element, and in almost all cases for which experiments have been performed, the current lattice error is significantly larger than the experimental one. Our long term objective is to reduce the lattice errors so that they are less than or comparable to the experimental ones. The importance of doing so can be seen from the fact that a significant fraction of the \$750,000,000 per year that the United States spends on experimental high energy physics is devoted to the study of the weak decays of strongly interacting particles. It is clear that to fully capitalize on this investment, the lattice calculations must keep pace with the experimental measurements. As part of this effort, the MILC and Fermilab Lattice Collaborations have embarked on an extensive joint study of the decays of pseudoscalar mesons with one light and one heavy quark. The main objects of our work are B (with a heavy b quark and light u or d antiquark), B_s (b quark and s antiquark), D (c quark and u or d antiquark) and D_s (c quark and s antiquark). We are studying both leptonic and semi-leptonic decays. Strong interaction effects in leptonic decays are characterized by the decay constants f_B , f_{B_s} , f_D and f_{D_s} . Semileptonic decays are characterized by various form factors $F(q^2)$, where q is the momentum transfer carried by the leptons. It is these quantities which we and our Fermilab collaborators aim to calculate with increasing accuracy over the next few years. Lattice results for f_B and f_{B_s} of the precision already achieved for f_D and f_{D_s} would have a major impact on determination of the poorly known CKM matrix element V_{td} from experimental measurements of B - \bar{B} and B_s - \bar{B}_s mixing. Similarly, accurate lattice determinations of semileptonic form factors for B and B_s would provide a new window on the CKM matrix element V_{ub} . These calculations are in progress. Our goal in the next few years is to determine f_B and the corresponding semileptonic form factors to an accuracy of 5% to 10%. We are doing this with the same techniques that are being employed for our studies of the D mesons.

The mass spectrum of strongly interacting particles: The calculation of the mass spectrum of strongly interacting particles is one of the major goals of lattice gauge theorists. An accurate determination of the masses of the lightest of these particles is an essential test of lattice simulations. The nucleon and Ω^- masses are precisely known, and can be computed accurately on the lattice, making them trenchant tests of our techniques. Moreover, lattice computations can shed light on some of the open questions regarding the nature of the light strongly interacting particles. For example, the nature of the $a_0(980)$ is still somewhat controversial — to what extent is it a quark-antiquark state, and to what extent a $K - \bar{K}$ molecule? Also, the quark model assignments of many of the excited states are not well established, and lattice computations should be used to help nail them down. Lattice calculations are also important for understanding particles that are not explained by the naive quark model, namely hybrids and glueballs. These particles, especially those with exotic quantum numbers, are an important part of the experimental program at Jefferson Laboratory.

Strongly interacting matter under extreme conditions: Under ordinary laboratory conditions one does not directly observe quarks and gluons, the fundamental constituents of strongly interacting matter. Instead one sees their bound states: protons, neutrons and a host of unstable particles produced in accelerator or cosmic ray collisions. However, at high temperatures or densities one expects to observe a phase transition or crossover from ordinary strongly interacting matter to a plasma of quarks and gluons. A primary motivation for the construction of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven was to observe the quark-gluon plasma and determine its properties. The plasma was a dominant state of matter in the early development of the Universe, and may exist today in the cores of neutron stars. The behavior of strongly interacting matter in the vicinity of the phase transition or crossover is inherently a strong coupling problem, which can only be studied from first principles through lattice QCD calculations. Among the issues that can be uniquely addressed by lattice QCD calculations are the nature of the transition, the properties of the plasma, and the equation of state.

We have embarked on a long term study of these issues using the improved staggered action with three flavors of quarks: up, down and strange. The use of the improved action has a number of advantages. Our zero temperature simulations give significant improvement in the mass spectrum of the lightest strongly interacting particles, which is essential for getting the physics right on the low temperature side of the transition. Especially important here are the major improvements in the dispersion relations and taste symmetry of the pions over the conventional staggered action. On the high temperature side of the transition, the improvement in the dispersion relations of the quarks is particularly important. Our immediate goals are to determine the phase structure and equation of state of QCD at high temperature and zero baryon density. In the longer term, we plan to move these studies to finite densities appropriate to the heavy ion experiments in progress at RHIC and planned for CERN.