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 thirty 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, 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.

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 light quark masses in order to perform extrapolations to the continuum (zero lattice spacing) and chiral (physical mass of the up and down quarks) limits. Over the past ten years we have generated a large library of configurations using the improved staggered (Asqtad) action with lattice spacings as small as 0.045 fm, and light quark mass $m_l = (m_u + m_d)/2$ as small as 1/20 the strange quark mass. A table describing configurations with lattice spacings $a \leq 0.12$ fm is given at the link asqtad configurations. The Asqtad configurations are publicly available, and have been used by other groups to study a wide range of problems in high energy and nuclear physics. During the past year we have begun a program of generating gauge configurations using the highly improved staggered quark (HISQ) action developed by the HPQCD/UKQCD Collaboration. The HISQ action has two major advantages over Asqtad: 1) the taste symmetry violations, which are one of, if not the largest impediment to reducing errors in lattice calculations with staggered quarks, are significantly reduced relative to those of Asqtad; and 2) the HISQ action can be used to simulate charm sea and valence quarks, providing another significant reduction in errors for calculations involving charmed particles. We provide a description of our recent progress in gauge configuration generation with both Asqtad and HISQ quarks at the link recent results.

Our research is currently focused on four major areas: 1) the properties of light pseudoscalar mesons, 2) the decays and mixings of heavy-light mesons, 3) the mass spectrum of strongly interacting particles, and 4) the properties of strongly interacting matter at high temperatures. 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: Computation of the properties of light pseudoscalar mesons, in particular the π and K mesons, offers a unique opportunity to calculate phenomenologically important physical quantities that are difficult or impossible to obtain with controlled errors by other methods, and to check our lattice methods to high ($\approx$ 2 to 3%) precision. 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 leptonic decay constants at fixed lattice spacing and 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 continuum extrapolation followed by a controlled chiral extrapolation. Using the above methodology, we have computed the leptonic decay constants of the π and K mesons, f_π and f_K, and the CKM matrix element V_{us} with total errors of under 3%. The results agree with experiment at this level, providing good evidence that we understand and can control our errors.

These calculations, coupled with a perturbative determination of the mass renormalization constant, have allowed us to determine the light (u, d and s) quark masses, as well as their ratios, and several of the Gasser-Leutwyler low energy parameters L_i. The L_i in turn enable a determination of the $I = 0$ and 2 $\pi - \pi$ scattering lengths. Two of these quantities, in particular, urgently require precise lattice QCD evaluations: Uncertainty in m_s severely limits the theoretical precision of various phenomenological studies, including the determination of the important CP-violating quantity ε'/ε. Determination of m_u/m_d addresses the long standing proposal that $m_u = 0$. A massless up quark could have solved the “Strong CP Puzzle”; however, our results rule that possibility out at the 10σ level.

Our immediate objective is to improve our determinations of all of the above quantities by completing the analysis of the Asqtad configurations, and to improve our calculation of the quark masses through a non-perturbative determination of the mass renormalization constant. We expect the new HISQ configurations to provide further improvements.

The largest error in our current evaluation of the quark mass ratio m_u/m_d comes from uncertainties in the electromagnetic (EM) contributions to masses of π and especially K mesons. These effects also give significant errors to other quark mass ratios and to the quark masses themselves. At present, the EM contributions must be taken from continuum phenomenology. A conservative interpretation of the errors in the continuum calculations results in a 20% error on m_u/m_d, and even a rather aggressive interpretation leaves a 10% error. The importance of obtaining accurate determinations of the light quark masses makes it imperative to do better, and to be sure that the EM effects are under good control. This issue can be addressed directly on the lattice by including EM effects in the simulations. As a first step we are treating the EM field in the quenched approximation. We plan to extend our work to the study of the baryon spectrum which will allow us to address the long standing neutron-proton mass difference problem. A further extension to this project would be a fully dynamical treatment of both the $U(1)$ and $SU(3)$ gauge fields.

Weak decays of particles containing heavy quarks: At SLAC, KEK and Fermilab, a concerted experimental effort is underway to determine elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix through studies of the mixings and decays of B mesons. Of particular note is the recent observation of B_s-$\underline{B}_s$ mixing by the CDF and D0 collaborations at Fermilab. In addition, the properties of D mesons have been measured to high accuracy in the CLEO-c Program at Cornell. One hopes that by tightly over–constraining the CKM matrix elements, the range of validity of the Standard Model will be determined, and new physics beyond it will be discovered. However, the experimental results do not, in general, determine the CKM parameters without lattice calculations of the effects of the strong interactions, 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 contributions to errors in CKM matrix elements so that they are less than or comparable to the experimental ones. To this end, our group and the Fermilab Lattice Collaboration are involved in 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, B_s, D and D_s mesons. We are studying both leptonic and semileptonic decays, and the mixing between the neutral B and B_s mesons and their antiparticles. 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 transferred to the leptons, and the mixing of B and B_s mesons with their antiparticles by the bag parameters B_B and B_{B_s}. CLEO-c is providing precise measurements of the D and D_s leptonic and semileptonic decays. Comparisons of lattice and experimental results have provided an opportunity to validate our approach, and insure that we do, in fact, have full control over systematic errors.

Our objective for the next few years is to calculate the leptonic decay constants, semileptonic form factors and bag constants for B mesons to an accuracy such that the lattice errors would no longer be the limiting factor in the determination of the corresponding CKM matrix elements. In particular, lattice results for f_B and f_{B_s} of the precision already achieved for f_D and f_{D_s}, along with the $B^0-\bar{B}^0$ and $B_s^0-\bar{B}_s^0$ mixing parameters B_B and B_{B_s} would have a major impact on the determination of the poorly known CKM matrix element V_{td} from experimental measurements of B-$\bar{B}$ and B_s-$\bar{B}_s$ mixing. In fact, after the latest experimental results on B_s-$\bar{B}_s$ mixing, an important ratio of CKM matrix elements $|V_{td}|/|V_{ts}|$ now has a theoretical error almost ten times the experimental error, so improved lattice results are crucial. Our calculations of the semileptonic form factors for $B \rightarrow \pi l \nu$ and $B \rightarrow D^* l \nu$ during the past year have lead to the most accurate lattice determinations to date of the CKM matrix elements V_{ub} and V_{cb}, respectively.

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 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. Heavy baryons, which contain one or more charm or bottom quarks, are much less studied than heavy mesons, both experimentally and theoretically. We have recently begun to study a large number of such states containing one or two heavy quarks.

Heavy quarks and anti-quarks (charm, bottom, and top) form bound states analogous to positronium — hence the name “quarkonium”. Since their discovery in the 1970’s, many dozens of states of charmonium and bottomonium have been studied experimentally. Below the so-called open charm or open bottom threshold energy — the threshold for decay into pairs of mesons consisting of a heavy quark and light antiquark, the states have small measured widths, and provide exacting tests of our theoretical ability to do high precision predictions of the properties of states involving heavy quarks. Even above threshold theoretical guidance is needed for the classification of observed states. A variety of new charmonium states have been found in recent experiments, but their interpretation in terms of standard potential model states is uncertain. Numerical simulation should help in classifying these states.

Strongly interacting matter under extreme conditions: At very high temperatures 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 National Laboratory was to observe the quark–gluon plasma and determine its properties. The plasma was the state of matter in the early development of the Universe, and may be a central component of neutron stars today. 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 gauge theory calculations. Among the issues that can uniquely be addressed by lattice calculations are the nature of the transition, the properties of the plasma, including strange quark content, and the equation of state. We are currently seeking to significantly improve our determinations of the transition temperature and the equation of state, which are critical inputs to hydrodynamic modeling of heavy-ion collisions. A project using the Asqtad action is being carried out as part of the work of the recently formed HotQCD Collaboration, of which we are members, along with colleagues at Brookhaven National Laboratory, Columbia University Los Alamos National Laboratory, and Lawrence Livermore National Laboratory.

During the past year we have begun a study of high temperature QCD using the HISQ action. This action has several advantages for thermodynamics studies. First, in calculations of the equation of state it is necessary to subtract the gauge action and the chiral order parameter $\bar{\psi}\psi$ calculated on a high temperature ensemble from the same quantities calculated at zero temperature. Since these quantities are highly divergent in the ultraviolet, this subtraction becomes extremely difficult as the lattice spacing is reduced. Since the HISQ action allows one to work at larger lattice spacing than Asqtad for similar sized lattice artifacts, it appears that the equation of state could be computed with far fewer Monte Carlo samples, or shorter runs. Furthermore, the reduction in taste symmetry violations leads to a more realistic hadron spectrum, which is particularly important in the low temperature regime. Finally, the HISQ action allows us to include charm quarks as dynamical sea quarks in high temperature simulations for the first time. Since charm quarks are thought to have had an important effect on the transition between the quark-gluon plasma and ordinary hadronic matter that took place during the early development of the universe, their inclusion opens an interesting new area of study.