LIGHT-FRONT QUANTUM CHROMODYNAMICS

A framework for analysis of hadron dynamics

Subcommittee of White Paper

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An outstanding goal of physics is to find solutions that describe hadrons in the theory of strong interactions, Quantum Chromodynamics (QCD). For this goal, the light-front Hamiltonian formulation of QCD (LFQCD) is an appealing approach that complements the well-established lattice gauge method. LFQCD offers unique access to the nonperturbative quark and gluon amplitudes for the hadrons which are directly testable in experiments at forefront facilities. We present an overview of the promises and challenges of LFQCD in the context of unsolved issues in QCD that require broadened and accelerated investigations. We identify specific goals of this approach.

I. INTRODUCTION

Quantum chromodynamics (QCD), the theory of strong interactions, is a part of the Standard Model of elementary particles that also includes, besides QCD, the electro-weak (EW) interactions. In view of the great difference in strength of these interactions, one may treat the EW interactions as a perturbation in systems consisting of hadrons, the composite particles that respond to the strong interactions. Perturbation theory has its place in QCD also, namely at large values of the transferred energy or momentum owing to the property of asymptotic freedom. The field of perturbative QCD is well developed and many phenomena have been discovered such as factorization, parton distributions, single-spin asymmetries, jets, etc. However, at low values of the energy and momentum transfer, the strong interaction must be treated in a nonperturbative manner since the interaction strength becomes large and the confinement of quarks and gluons, the partonic components of the hadrons, cannot be ignored. There is a wealth of data in this strong interaction regime that is waiting for explanation in terms of ab initio calculations proceeding directly from the underlying theory. As one prominent application of an ab initio approach to QCD, we mention that many extensive experimental programs either measure directly, or depend upon the knowledge of, the probability distributions of the quark and gluon components of the hadrons.

Two approaches have produced some success in the strong coupling area up to the present. First, hadronic models have been formulated in terms of the underlying quark and gluon degrees of freedom and applied successfully. This success comes at the price of introducing parameters whose origins in QCD are not understood. The second method, lattice QCD, is an ab-initio approach since it is directly linked to the Lagrangian of QCD. Based on the Euclidean formulation, lattice QCD provides an estimate of the QCD path integral and access to certain low-energy hadronic properties such as masses. On the other hand, physics involving timelike processes, those probed in many experiments, is difficult to access from a Euclidean approach. Moreover, although lattice QCD can estimate some observables directly, it does not provide the wave functions (WF) that are needed for the complete description of the structure and dynamics of hadrons.

Light-Front QCD (LFQCD) is an alternative ab initio approach for addressing non-perturbative or strongly interacting systems. It is, like perturbative and lattice QCD, directly connected to the QCD Lagrangian, but it is a Hamiltonian method, formulated in Minkowski space rather than Euclidean space. The essential ingredient is Dirac's front form of Hamiltonian dynamics where one quantizes the theory at fixed light-cone time $\tau = t + z/c$ rather than ordinary time t. Thus, initial conditions for a WF are set not at a single time t, but on the space-time hyperplane swept by the front of a plane wave of light. The solutions will be exact mass spectra and LF WFs capable of describing a wide range of experiments in a relativistically covariant manner. For example, one easily obtains the probability distributions of the quark and gluon components of the hadrons from the LF WFs. Hence, LFQCD exhibits the promise of accessing a much wider range of experimental situations than previously addressed.

There are many advantages of the light-front framework. On the technical side, LFQCD provides the largest number of kinematic (interaction-independent) generators of the Poincaré transformations in relativistic Hamiltonian dynamics. The eigenvalues of the LFQCD Hamiltonian provide the discrete masses and continuum hadronic spectra. The method yields the boost-invariant and process-independent light-front WFs needed for form factors, scattering amplitudes, correlations, spin effects, phases, decay rates, momentum space distributions, and other hadronic observables. The WFs contain information about novel QCD phenomena. These include effects suggested from other approaches such as color transparency, hidden color, intrinsic charm, sea-quark asymmetries, dijet diffraction, direct hard processes, and hadronic spin dynamics. In addition, unlike lattice QCD, there is no fermion doubling problem and no formulation-specific problem with light quarks in the theory. However, other subtle problems enter LFQCD that require thorough investigations. For example, the complexities of the vacuum in the usual instant-time formulation, such as the Higgs mechanism and condensates in ϕ^4 theory, have their counterparts in zero modes or, possibly, additional terms in the LFQCD Hamiltonian that are allowed by power counting.

The LF Hamiltonian formulation thus provides access to QCD at the amplitude level and is the foundation for a common treatment of spectroscopy and the parton structure of hadrons in a single covariant formalism, providing a unifying connection between low-energy and high-energy experimental data that so far have remained largely disconnected.

The LF quantization techniques can be applied not only to QCD in four dimensions but also to other theories of dimensions lower or greater than four, including the corresponding versions of QED, QCD, electroweak theories, gravity theories, string theories, and D-branes.

II. APPLICATIONS OF THE LIGHT-FRONT FORMALISM TO EXPERIMENT

A. Structure of Hadrons

Experiments that need a conceptually and mathematically precise theoretical description of hadrons at the amplitude level include investigations of: the structure of nucleons and mesons, heavy quark systems and exotics, hard processes involving quark and gluon distributions in hadrons, heavy ion collisions and many more. LFQCD offers, for example, the opportunity for an ab initio understanding of the microscopic origins of the spin content of the proton and how the intrinsic and spatial angular momenta are distributed among the partonic components. This is an outstanding unsolved problem as experiments to date have not yet found the largest components of the proton spin. The components previously thought to be the leading carriers, the quarks, have been found to carry a small amount of the total spin. As another example, LFQCD will predict the masses, quantum numbers and widths of yet-to-be observed exotics such as glueballs and hybrids. The experimental programs at JLAB are aimed to investigate these outstanding problems.

B. QCD at High Temperature and Density

There are major programs at accelerator facilities such as GSI-SIS, CERN SPS, BNL-RHIC to investigate the properties of a new state of matter, the quark-gluon plasma, and other features of the QCD phase diagram. In the early universe temperatures were high, while net baryon densities were low. In contrast, in compact stellar objects, temperatures are low, but the baryon density is high. QCD describes both extremes. However, reliable perturbative calculations can only be performed at asymptotically large temperatures and densities, where the running coupling constant of QCD is small due to asymptotic freedom. On the other hand, lattice QCD provides information only at very low chemical potential (baryon density). Thus, many frontier questions remain to be answered. What is the nature of the phase transitions? How does the matter behave in the vicinity of the phase boundaries? What are the observable signatures of the transition in transient heavy-ion collisions? LFQCD opens a new avenue for addressing these issues. In recent years a general formalism to directly compute the partition function in LF quantization has been developed and numerical methods are under development for evaluating this partition function in LFQCD.

C. Nuclear Reactions

In addition, there is a new appreciation that initial and final-state interaction physics, which is not intrinsic to the hadron or nuclear LF WFs, must be addressed in order to understand phenomena such as single-spin asymmetries, diffractive processes, and nuclear shadowing. This motivates extending LFQCD to the theory of reactions and to investigate high-energy collisions of hadrons in LFQCD. Parallel developments in the history of Hamiltonian frameworks for nuclear and atomic reaction theory provide valuable guides for developing LFQCD for high-energy reactions.

III. GOALS OF THE PROJECT

The purpose of the LFQCD program is to bring together experts in the field and attract new contributors who will together take advantage of the available theoretical and computational tools and develop them further in order to provide answers to the pertinent questions in an accelerated fashion.

The central issue addressed is the rigorous description of hadrons, nuclei, and systems thereof from first principles in QCD. The main goals of the research using light-front dynamics are

1. The rigorous evaluation of masses and wave functions of hadrons using the light-front Hamiltonian of QCD;

2. The analysis of hadronic and nuclear phenomenology based on fundamental quark and gluon dynamics taking advantage of the connections between quark-gluon and nuclear many-body methods.

3. A complete understanding of properties of QCD at finite temperature and densities as well as equilibrium and nonequilibrium, which is relevant for understanding the early universe as well as compact stellar objects.

4. Development of predictions for crucial experimental tests at the new hadron facilities – JLAB, RHIC, LHC, JPARC, GSI(FAIR).

To accomplish the nonperturbative analysis of QCD, we need to

1. Test the LF Hamiltonian approach in simple theories in order to gain understanding of its peculiarities and treacherous points vis ‘a vis manifestly-covariant quantization methods. This will include work on theories such as Yukawa theory and QED and on theories with unbroken supersymmetry, in order to understand the strengths and limitations of different methods. Much progress has already been made along these lines.

2. Construct symmetry-preserving regularization and renormalization schemes for light-front QCD, to include the Pauli–Villars-based method of the St. Petersburg group, Glazek–Wilson similarity renormalization-group procedure for Hamiltonians, Mathiot–Grangé test functions, and broken supersymmetry. Determine how to incorporate symmetry breaking in light-front quantization; this is likely to require analysis of zero modes.

3. Develop computer codes which implement the regularization and renormalization schemes. Provide a platform-independent, well-documented core of routines that allow investigators to implement different numerical approximations to field-theoretic eigenvalue problems. Consider various quadrature schemes and basis sets, including Discretized Light-Cone Qunatization (DLCQ), finite elements, function expansions, and the complete orthonormal wave functions obtained from AdS/QCD. This will build on the Lanczos-based MPI code developed for nonrelativistic nuclear physics applications and similar codes for Yukawa theory and lower-dimensional supersymmetric Yang-Mills theories.

4. Solve for hadronic wave functions and masses. Use these wave functions to compute form factors, GPDs, scattering amplitudes, and decay rates. Compare with perturbation theory, lattice QCD, and model calculations, using insights from AdS/QCD, where possible. Study the transition to nuclear degrees of freedom in light nuclei.

5. Develop numerical methods/computer codes to directly evaluate the partition function (viz. thermodynamic potential) as the basic thermodynamic quantity. Compare to lattice QCD, where applicable, and focus on a finite chemical potential, where reliable lattice QCD results are presently available only at very small (net) quark densities. There is also promise in using LF AdS/QCD to explore non-equilibrium phenomena such as transport properties during the very early state of a heavy ion collision. LF AdS/QCD opens the possibility to investigate hadron formation in such a non-equilibrated strongly coupled quark-gluon plasma.