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Lattice QCD for Nuclear Physics

Springer

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Foreword

The development of quantum chromodynamics over the past few decades as the accepted theory of the strong interactions has transformed almost every aspect of nuclear physics. Many major experimental nuclear physics programs being conducted today at national laboratories in the USA are directly related to QCD, including determination of the internal structure of hadrons and the nature of confinement at Jefferson Laboratory, the properties of the quark gluon plasma at Brookhaven, and the measurement of the neutron electric dipole moment at Oak Ridge National Laboratory. Even in more traditional nuclear structure studies, such as anticipated at the rare isotope beam facility (FRIB) under construction at Michigan State University, the theoretical framework often used today consists of overlapping techniques, with mean field and energy density functionals being used for the heaviest nuclei, shell models for the intermediate mass, numerical solutions of the Schrödinger equation for light nuclei—and underlying all that, the fundamental inter-nucleon interactions based on an effective field theory for QCD, which itself is increasingly informed by direct computation from lattice QCD.

There are various techniques for making theoretical progress in QCD: perturbation theory for high energy collisions, phenomenological effective field theories for low energy processes, and innovative models such as the color glass condensate for low-x physics. However, much of the physics of interest to nuclear physics must be computed nonperturbatively and so for many applications, lattice QCD is the ideal method.

We are now living in a "golden age" for lattice QCD as applied to nuclear physics. This is due to the confluence of increased hardware speed, as well as enormous progress in the past decade in improving computational algorithms. Just as important, though, is the increased awareness among nuclear physicists that we are on the threshold of finally being able to use lattice QCD to accurately answer many of the outstanding questions in nuclear physics. As lattice QCD becomes one of the most potent tools for theorists to unlock the secrets of the nucleus, it becomes increasingly important to train young scientists in the subject. Thus it is with great pleasure that the INT has hosted this summer school in lattice QCD, and with great anticipation of what this new generation of scientists will eventually teach us.

Seattle, WA, USA David B. Kaplan
April 2014

Preface

Perhaps the most fascinating aspect of the strong interaction of particle physics is the wealth of qualitatively different regimes it exhibits. Modern nuclear physics deals with phenomena typically occurring at energy, momentum, temperature, or density scales between a few MeV and a few GeV. A relatively new goal in the field is to connect nuclear phenomena directly to the fundamental theory of the strong interaction, quantum chromodynamics. QCD has only a few free parameters, and it is remarkable that so much can, in principle, be predicted from so little.

In certain regimes, such as low-energy nuclear few-body systems, effective field theories provide a systematic approach. QCD can then be used to determine their low-energy parameters and to test their range of validity. But certain observables, like the spectrum of excited hadrons and the charge distributions of the nucleon, or the transition from the hadronic phase of QCD to a plasma phase at high temperatures, have no obvious simpler description in terms of effective degrees of freedom. A systematic treatment then involves the full complexity of QCD.

Lattice QCD provides a framework to handle the theory of the strong interaction from first principles in a wide range of energies relevant to nuclear physics. It is a discretized formulation of QCD on a spacetime lattice which preserves its SU(3) gauge symmetry. The latter is key to its ability of handling the theory in its non-perturbative regime. Numerical techniques and high-performance computing are an essential part of lattice QCD. The success of lattice QCD calculations depends thus on its practitioners being proficient both in quantum field theory and in programming and numerical methods.

In the summer school held at the Institute for Nuclear Theory in Seattle, 6–24 August 2012 (http://www.int.washington.edu/PROGRAMS/12-2c/), a series of courses were delivered, aimed at giving graduate students not only an overall understanding of lattice gauge theory, but also at covering in detail how one applies lattice gauge theory to the calculation of key quantities in nuclear physics. The list of lectures held at the school is given hereafter. State-of-the-art algorithms for generating gauge ensembles and fermion propagators were covered. Students performed numerical exercises on using lattice QCD code, analyzing and fitting data, and on utilizing new hardware, such as graphics processing units (GPUs) and the CUDA environment. In this book you will find the contents of the lectures on the most central physics topics written up. We hope that they provide an accessible and solid introduction to nuclear physics applications in lattice QCD for graduate students and any interested physicist.

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April 2014

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