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Motivation

This monograph is concerned with the study of nuclear and nucleon structure through the scattering of high energy electrons. The history of this field is well summarized in the proceedings of the *Conference on 35 Years of Electron Scattering* held at the University of Illinois in 1986 to commemorate the 1951 experiment of Lyman, Hanson, and Scott; this experiment provided the first observation of the finite size of the nucleus by electron scattering [Ly51, Il87]. Hofstadter and his colleagues, working in the High Energy Physics Laboratory (HEPL) at Stanford University in the late 1950's, beautifully and systematically exhibited the shape of the charge distributions of nuclei and nucleons through experiments at higher momentum transfer [Ho56, Ho63]. Subsequent experimental work at HEPL, the Bates Laboratory at M.I.T., Saclay in France, NIKHEF in Holland, and both Darmstadt and Mainz in Germany (as well as other laboratories), utilizing parallel theoretical analysis [Gu34, Sc54, Al56, de66, Ub71], clearly exhibited more detailed aspects of nuclear structure. Experiments at higher electron energies and momentum transfers at the Stanford Linear Accelerator Center (SLAC) by Friedman, Kendall, and Taylor, together with theoretical developments by Bjorken, for the first time demonstrated the pointlike quark–parton substructure of nucleons and nuclei [Bj69, Fr72]. This work played a key role in the development of modern theories of the strong interaction. Major efforts today at CEBAF, the Continuous Electron Beam Accelerator Facility (now known as TJNAF, the Thomas Jefferson National Accelerator Facility) in the U.S., Bates, Mainz, SLAC, DESY in Germany, and CERN in Geneva (using muons) contribute to the development of our understanding of nuclei and nucleons.

In part 1 we discuss modern pictures of the nucleus and nucleon, starting with non-relativistic nucleons interacting through static potentials and proceeding to quarks and gluons with interactions described

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by strong-coupling *quantum chromodynamics* (QCD). As an introduction to electron scattering, the optical analogy is developed. The virtues of electron scattering are described and a qualitative overview of the nuclear response surfaces in inclusive electron scattering presented. The arguments for coincidence experiments are then given.

In part 2, a general theoretical analysis of electron scattering is developed, starting from a discussion of the electromagnetic interaction with an arbitrary localized quantum mechanical system. This includes a multipole decomposition. Since electrons are relativistic here, they are described by the Dirac equation and the necessary tools are developed. A covariant analysis of the scattering of an electron by a nuclear target is then carried out. Both the excitation of discrete target states and one-particle emission coincidence experiments are analyzed. An analysis of deep-inelastic scattering (DIS) experiments, where the momentum transfer squared and energy transfer both grow large, but with a fixed ratio, is presented. This section ends with a general analysis of parity violation in inclusive polarized electron scattering.

Since electrons are charged and light, they by necessity radiate during the scattering process. This is one of the technical complications of electron scattering. This radiation as well as the accompanying virtual electromagnetic effects are described by *quantum electrodynamics* (QED); part 3 presents a brief review of the essentials of QED.

Part 4 presents experimental and theoretical results for selected examples. These examples are chosen to illustrate the wide variety of incisive information that can be obtained about the structure of nuclei and nucleons, the influence electron scattering has had on the development of our pictures of these systems, and the role various laboratories throughout the world have played in these developments.

In part 5, future directions for the field are discussed, building on the evolving TJNAF program [Wa93, Wa94], but including other world-wide developments at both intermediate and very high energy.

One of the most attractive and powerful aspects of the field of electron scattering for the structure of nuclei and nucleons is that experimental and theoretical developments have always progressed hand in hand, with each reinforcing the other.

We start this monograph with a more detailed discussion of the motivation for studying the structure of nuclei and nucleons through the scattering of high energy electrons.

Let us go back to the beginning. Why do we do nuclear physics? Why is nuclear physics interesting? First of all, the nucleus is a unique form of matter consisting of many baryons in close proximity. All the forces of nature are present in the nucleus — strong, electromagnetic, weak, and even gravity if one includes condensed stellar objects which are nothing more than enormous nuclei held together by the gravitational attraction. The nucleus provides a microscopic laboratory to test the structure of the fundamental interactions. Furthermore, the nucleus manifests remarkable properties as a strongly interacting, quantum mechanical, relativistic, many-body system. In addition, most of the mass and energy in the visible universe comes from nuclei and nuclear reactions. Also, we now know there are new underlying degrees of freedom in the nucleus, quarks and gluons, interacting through remarkable new forces described by quantum chromodynamics (QCD). The single nucleon itself is now a complicated nuclear many-body system. The electromagnetic properties of nucleons and nuclei provide benchmarks with which to test our understanding of strong-coupling QCD and the quark substructure of matter. Moreover, nuclear physics is crucial to the understanding of the universe, for example: the early universe, formation of the elements, supernovae, and neutron stars. In sum, nuclear physics is really the study of the *structure of matter*.

Where is nuclear physics going? The nuclear science community in the U.S. recently underwent one of its periodic long-range planning exercises under the leadership of the Nuclear Science Advisory Committee (NSAC) and the Division of Nuclear Physics (DNP) of the American Physical Society (APS). In the report entitled *Nuclear Science:A Long-Range Plan* [NS96] the headings in part II on *The Scientific Frontiers* capture the present frontiers:

1. Nuclear Structure and Dynamics: Exploring the Limits
2. To the Quark Structure of Matter
3. The Phases of Nuclear Matter
4. Fundamental Symmetries and Nuclear Astrophysics