

Preface

In the summer of 1986 I left Stanford University, after 26 years on the faculty, to assume the job of Scientific Director at the Continuous Electron Beam Accelerator Facility (CEBAF) now known as the Thomas Jefferson National Accelerator Facility (TJNAF). This facility, funded by the Department of Energy and located in Newport News, Virginia provides a high-energy, high-intensity, high-duty-factor electron accelerator for studying the internal structure of nuclei and nucleons. It has long been a top priority for the field of nuclear physics in the United States. Each year I gave a physics lecture series at the site. The initial series on electron scattering was based on a set of lectures I had given at Argonne National Laboratory in the winter of 1982–1983. As Scientific Director, I was continually called upon to make presentations on this topic. This book is based both on the lecture series on electron scattering, and on the many presentations I have given on this subject over the years.

The scattering of high-energy electrons from nuclear and nucleon targets essentially provides a microscope for examining the structure of these tiny objects. The best evidence we have on what nuclei and nucleons actually look like comes from electron scattering. An intense continuous electron beam with well-defined energy provides a powerful tool for structure investigations. Inclusive experiments, where only the final electron is detected, examine static and transition charge and current densities in the target. Coincidence experiments, where other particles are detected together with the scattered electron, provide valuable additional information.

In electron scattering experiments where the momentum of the initial and final electron are well-defined, a virtual quantum of electromagnetic radiation is produced which interacts with the target. The energy of this quantum is determined by the energy transfer from the electron, and the momentum of the quantum from the momentum transfer. The electromagnetic interaction is well-understood; the interaction is with the

local, static and dynamic charge and current densities. The scattering cross section is determined by the four-dimensional Fourier transform of these quantities. For a given energy transfer to the target, one can vary the three-momentum transfer by varying the momentum vector of the final electron. One then maps out the Fourier transform of the spatial densities, and by inversion of the Fourier transform, one determines the spatial distribution of the densities themselves. The wavelength with which the target is examined is inversely proportional to the three-momentum transfer. In electromagnetic studies in nuclear physics one focuses on how matter is put together from its constituents and on distance scales ~ 10 fm to ~ 0.1 fm where $1\text{fm} = 10^{-13}$ cm. Particle physics concentrates on finer and finer details of the substructure of matter with experiments at high energy which in turn explore much shorter distances. To carry out such studies, one needs electron accelerators of hundreds of MeV to many GeV.

A theoretical description of the nuclear and nucleon targets is required to interpret the experiments. The appropriate description employed depends on the distance scale at which one examines the target. Imagine that one looks at the earth from space. The appropriate quantities used to describe these observations, the appropriate *degrees of freedom*, are macroscopic ones, the location and shape of continents, oceans, clouds, etc. When one gets closer, finer details emerge, trees, houses, cars, people, and these must be included in the description. At the microscopic level of observations, it is the atomic and subatomic description which is relevant. It is thus self-evident that

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At the macroscopic level, one describes nuclei in terms of properties such as size, shape, charge, and binding energy. Further refinement describes, for example, the spatial distribution of the charge. A finer and more detailed description is obtained using nucleons, protons and neutrons, as the degrees of freedom. The *traditional* approach to nuclear physics starts from structureless nucleons interacting through static two-body potentials fitted to two-body scattering and bound-state data. These two-body potentials are then inserted in the non-relativistic many-body Schrödinger equation and that equation is solved in some approximation — it can be solved exactly for few-body systems using modern computing techniques. Electromagnetic and weak currents are then constructed from the properties of free nucleons and used to probe the structure of the nuclear system.

Although this traditional approach to nuclear physics has had a great many successes, it is clearly inadequate for an understanding of the nuclear system on a more microscopic level. A more appropriate set of

degrees of freedom then consists of the *hadrons*, the strongly-interacting mesons and baryons, where baryon number, a strictly conserved quantity, counts the number of nucleons that now exhibit internal structure and dynamics. There are many arguments that one can give in support of this picture. For example, the long-range part of all modern two-nucleon potentials consists of the exchange of mesons including π with $(J^\pi, T) = (0^-, 1), \sigma(0^+, 0), \omega(1^-, 0)$, and $\rho(1^-, 1)$. We know that at long range the force between two nucleons comes from meson exchange. Moreover, the first excited state of the nucleon, the $\Delta(1232)$ with $(J^\pi, T) = (3/2, 3/2)$, was first successfully described as a resonance arising from pion–nucleon dynamics. As a further example, one of the significant achievements in the field of electromagnetic nuclear physics in recent years has been the unambiguous identification of exchange currents, additional currents present in the nuclear system arising from the flow of charged mesons between the nucleons in the nucleus.

In any extrapolation away from the traditional nuclear physics approach, it is important to incorporate general principles of physics such as quantum mechanics, special relativity, and microscopic causality. The only consistent theoretical framework we have for describing such a relativistic, interacting, many-body system is relativistic quantum field theory based on a local lagrangian density. It is convenient to refer to relativistic quantum field theories of the nuclear system based on hadronic degrees of freedom as *quantum hadrodynamics* (QHD).

At a still finer level, we now know that the hadrons are themselves composite objects made up of quarks held together by the exchange of gluons. We now have a theory of the strong interactions binding quarks and gluons into the observed hadrons. This theory is based on an internal color symmetry and is known as *quantum chromodynamics* (QCD). The theory of QCD has two absolutely remarkable properties. The first is *asymptotic freedom*, which roughly states that at very high momenta, or very short distances, the renormalized coupling constant for the basic processes in the theory goes to zero; as a consequence, one can do perturbation theory in this regime. The second property is *confinement*. The basic underlying degrees of freedom in the theory, quarks and gluons, do not exist as asymptotic, free, scattering states in the laboratory. They exist and interact only inside hadrons. You cannot hold a single quark, or single gluon in your hand. There are strong indications from lattice gauge theory, where QCD is solved at a finite number of space-time points, that confinement is indeed a dynamic property of QCD arising from the nonlinear gluon couplings. Ultimately, nucleon and nuclear physics are the study of strong-coupling QCD.

As for the other basic forces in nature, surely one of the great intellectual achievements of our era is the unification of the theories of

electromagnetism and of the weak interactions. It is essential to continue to put this theory of the electroweak interactions to rigorous tests and fully explore its consequences. Nuclei and nucleons provide unique laboratories in which to conduct such tests and explorations.

The current picture of the nucleus in the *standard model* is that of a bound system of baryons and mesons, which are in turn confined triplets of quarks and of quark–antiquark pairs, respectively. The electroweak interactions of leptons (electrons and neutrinos) with the nucleus are mediated by the photon and the heavy weak vector bosons, the Z^0 and W^\pm . The electroweak interactions couple directly to the quarks; the gluons are absolutely neutral to the electroweak interactions. Thus every time one studies a nuclear gamma decay, for example, one is directly probing the quark structure of the nucleus. Once the quark is struck, it is not a quark that is emitted from the target, but a hadron. Nuclei are the ideal laboratories for studying this process of *hadronization*.

Another truly remarkable property of QCD is that the effective degrees of freedom at low energy and long wavelengths *are* the hadrons, the baryons and mesons.

In this book, the motivation for electron scattering is examined in some detail. The theoretical analysis of the process is developed, as is our current theoretical understanding of the underlying structure of nuclei and nucleons at appropriate levels of resolution and sophistication. Selected examples are given, present experimental capabilities are summarized, and future directions are previewed.

In part 1 of this book modern pictures of the nucleus and nucleon are surveyed. 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. The relativistic electrons of interest here are described by the Dirac equation, and the necessary tools are developed. A covariant analysis of the scattering of an electron by nuclear and nucleon targets 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 four-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, the role various laboratories throughout the world have played in these developments, and, quite frankly, the beauty of this branch of physics. Theoretical background in traditional nuclear physics, relativistic mean field theory, the quark model, QCD, and the standard model is developed in sufficient depth that the reader can indeed work through the examples in detail.

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

Nine appendixes are included which explore some of the more interesting and important technical aspects of this subject.

The book assumes only a working knowledge of quantum mechanics and special relativity and develops the theoretical analysis in a self-contained fashion up to current levels of sophistication. It is basically aimed at first-year graduate students and advanced undergraduates in physics, although it should be accessible to others in the natural sciences. Parts 1 and 5 can be read by a wider audience interested in understanding the essentials of the subject. The book should serve effectively as a text for special topics courses on this subject or as a supplemental text for nuclear or particle physics courses. It should also serve as a summary and reference for researchers already working in electron scattering as well as those in other areas.

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