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Part 1

Introduction

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1
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

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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

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2
Pictures of the nucleus

We currently possess three levels of understanding of the nucleus within the following frameworks [Wa95]:

(I) *Traditional, Non-Relativistic, Many-Body Systems* [Fe71]. This approach uses static two-body potentials fit to two-nucleon scattering and bound-state data. These potentials are then inserted in the non-relativistic Schrödinger equation, and that equation is then solved in some approximation; with few-nucleon systems and large-scale computing capabilities, the equations can now be solved exactly. Electroweak currents constructed from the properties of free nucleons are then used to probe the nuclear system. Although this approach has had a great many successes [Bl52, Ma55, Bo69, Fe71, de74, Pr75, Fe91, Wa95], it is clearly inadequate for a more detailed understanding of the nuclear system.

(II) *Relativistic Many-Body Systems.* A more appropriate set of degrees of freedom for nuclear physics consists of the *hadrons*, the strongly interacting mesons and baryons. There are many arguments one can give for this. For example, the long-range part of the best modern two-nucleon potentials is given by meson exchange, predominantly π with $(J^{\pi}, T) = (0^{-}, 1)$, $\sigma(0^{+}, 0)$, $\rho(1^{-}, 1)$ and $\omega(1^{-}, 0)$ [La80, Ma89]. Furthermore, one of the successes of electromagnetic nuclear physics is the unambiguous demonstration of the existence of exchange currents, additional electromagnetic currents in the nucleus arising from the flow of charged mesons between nucleons. In addition, one daily sees copious production of mesons from nuclei in high-energy accelerators.

The only consistent theoretical framework we have for describing such a strongly-coupled, 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 theory models of the nuclear system based on hadronic degrees of freedom as *quantum hadrodynamics* (QHD).

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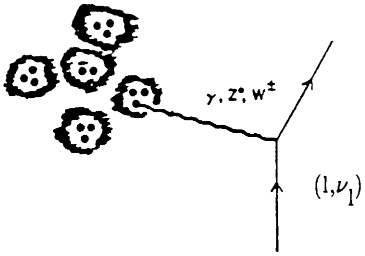

Fig. 2.1. Nucleus as a strongly-coupled system of colored quarks and gluons; electroweak interaction with a lepton.

More generally, one can view such field theories as *effective* field theories for the underlying theory of QCD [Se86, Se97].

(III) *Strongly-Coupled Colored Quarks and Gluons*. Our deepest level of understanding of nucleons, and the nucleus from which they are made, is as a strongly-coupled system of quarks and gluons (Fig. 2.1). Their interactions are described by a Yang–Mills theory [Ya54] based on an internal color symmetry (QCD). This theory has two remarkable properties: it is *asymptotically free*, which means that at very high momenta, or very short distances, the renormalized coupling constant becomes small. This has several consequences. For example, it implies that when in the appropriate kinematic regime, one scatters from essentially free point-like objects. In fact, it was the experimental observation of this phenomenon in deep inelastic scattering (DIS) that drove theorists to hunt for asymptotically free theories [Gr73a, Gr73b, Po73, Po74]. Furthermore, when the coupling is small, one can do perturbation theory. The many high-energy successes of *perturbative QCD* now provide convincing evidence that QCD is truly the underlying theory of the strong interactions.

When one scatters a lepton from a nuclear system, the electroweak interaction takes place through the exchange of one of the electroweak bosons ($\gamma, W^{\pm}, Z^0$), as illustrated in Fig. 2.1. These bosons couple directly to the quarks; the gluons are *absolutely neutral to the electroweak interactions*. Thus every time one observes a gamma decay or beta decay of a nucleus or nucleon, one is directly observing the quark structure of these systems!

The second remarkable property of QCD is *confinement*, which means that the underlying degrees of freedom, quarks and gluons, never appear as asymptotic, free scattering states in the laboratory. You cannot hold a free quark or gluon in your hand. Quarks and gluons, and their strong color interactions, are confined to the interior of the hadrons. At low momenta, or the large distances appropriate for nuclear physics, the renormalized coupling grows large. QCD becomes a strong-coupling theory in this limit.

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There are convincing indications from lattice gauge theory (LGT), where strong-coupling QCD is solved on a finite space-time lattice [Wi74], that confinement is indeed a dynamical property of QCD arising from the nonlinear gluon couplings dictated by local color gauge invariance in this non-abelian Yang–Mills theory.

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3
Some optics

To obtain insight into the electron scattering process, we appeal to some elementary optics, with which the reader is certainly familiar from an introductory physics course. If one looks through a telescope at a star, or shines a laser through a pinhole, one does not really observe a point of light, but actually a diffraction pattern with a bright disc at the center and a series of concentric rings with diminishing intensity. If the radius of the aperture through which the light passes is a, and the wavelength of the incident light is λ_1, then the angle θ to the first diffraction minimum of the central *Airy disc* is given by

$$a\theta \approx 0.61\lambda_1 \tag{3.1}$$

Here θ is measured from the central ray, starting at the aperture. Now introduce the incident wave number k_1 and "momentum transfer" κ

$$\begin{aligned} k_1 &\equiv \frac{2\pi}{\lambda_1} && ;\ \text{wave number} \\ \kappa &\approx k_1\theta && ;\ \text{momentum transfer} \end{aligned} \tag{3.2}$$

Equation (3.1) can then be rewritten as

$$\kappa a \approx 1.22\,\pi \tag{3.3}$$

This relation has a marvelous consequence. Suppose one shines light from a laser of given wavelength on a pinhole, and projects the resulting diffraction pattern on a screen behind the pinhole. The angle to the first minimum can be determined by making *macroscopic measurements* of the distance of the screen from the aperture and the transverse distance on the screen out to the first minimum. Equation (3.3) then allows one to determine the radius a of the pinhole. *One can measure a radius of arbitrarily small size if only the momentum transfer is large enough!* The

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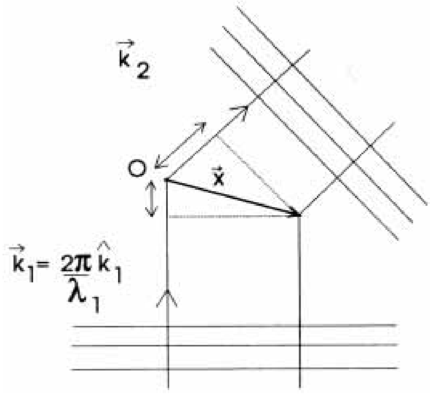

Fig. 3.1. Optical pathlength with respect to central ray in Fraunhofer diffraction.

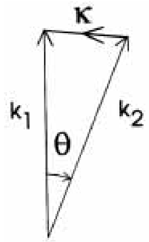

Fig. 3.2. The "momentum transfer" $\boldsymbol{\kappa} = \mathbf{k}_1 - \mathbf{k}_2$.

momentum transfer is inversely proportional to the wavelength. Thus to obtain large momentum transfer, one has to go to short wavelength. One evidently needs a wavelength comparable to the size of the aperture to make this measurement.

Let us extend these simple considerations. In Fraunhofer diffraction one has an incident plane wave and an outgoing plane wave in the direction of observation as illustrated in Fig. 3.1. The optical pathlength of an arbitrary ray with respect to the central ray is evidently given from this figure as

$$\Delta_{\text{opt}} = \frac{2\pi}{\lambda_1}(\hat{\mathbf{k}}_1 \cdot \mathbf{x} - \hat{\mathbf{k}}_2 \cdot \mathbf{x}) = \boldsymbol{\kappa} \cdot \mathbf{x} \tag{3.4}$$

where $\hat{\mathbf{k}}_1$ and $\hat{\mathbf{k}}_2$ are unit vectors in the incident and outgoing directions respectively. Here the momentum transfer $\boldsymbol{\kappa}$ is defined by (Fig. 3.2)

$$\boldsymbol{\kappa} = \mathbf{k}_1 - \mathbf{k}_2 \tag{3.5}$$

Since the lengths of the incoming and outgoing wave numbers are identical

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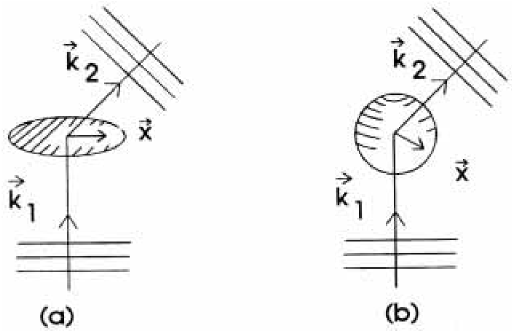

Fig. 3.3. (a) Fraunhofer diffraction of light from a circular aperture; and (b) Electron scattering through the Coulomb interaction from a spherical charge distribution.

$|\mathbf{k}_2| = |\mathbf{k}_1|$, the square of the momentum transfer is given by

$$\begin{aligned} \boldsymbol{\kappa}^2 &= 2k_1^2(1-\cos\theta) \\ &= 4k_1^2 \sin^2\frac{\theta}{2} \end{aligned} \tag{3.6}$$

Here θ is the angle between the incident and outgoing wave number vectors (Fig. 3.2). *Huygens Principle* says that each point on a wavefront serves as a new source of outgoing waves. The outgoing waves interfere. To determine the net outgoing wave from a circular aperture one must add the contributions from each little element of the disc weighted by $\exp\{i\Delta_{\rm opt}\}$ as illustrated in Fig. 3.3 (a). The resulting amplitude of the light wave far from the scatterer is thus given by

$$\mathscr{A}_\gamma = \int_{\rm Aperture} d^2x\, e^{i\boldsymbol{\kappa}\cdot\mathbf{x}} \tag{3.7}$$

The diffraction pattern evidently measures the two-dimensional Fourier transform of the aperture.

Now consider the scattering of an electron from a spherical charge distribution through the Coulomb interaction. de Broglie and quantum mechanics tell us that there is a wave associated with the electron of wavelength

$$\lambda_1 = \frac{h}{p_1} \qquad ;\ \text{electron} \tag{3.8}$$

Here $h \equiv 2\pi\hbar$ is Planck's constant and p_1 the incident electron momentum. The scattering amplitude from each little element will be proportional to the amount of charge there, or to the charge density $\rho_{\rm ch}(x)$. The resulting

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