Chapter 1

Physics of the Nucleon

1.1 Introduction to the Nucleon

In 1933 with the discovery that the magnetic moment of the proton (having mass M_N and charge e) was not simply that of a point particle, $\frac{e}{2M_N}$, nucleons were known to have internal structure [33]. This structure has been the object of interest to physicists for over 50 years. Nucleon structure may be examined with scattering experiments utilizing electromagnetic, hadronic or "weak" probes. The electromagnetic interaction, by scattering real or virtual photons off the nucleon, can be used to parametrize the unknown electromagnetic structure into effective form factors. One set of parametrizations for the electromagnetic form factors are the Sachs form factors, G_E and G_M, which relate to the charge and magnetism distributions of the nucleons. These form factors only depend on the square of the four-momentum transfer carried by the photon, Q^2.

However, the electromagnetic form factors provide more than just a relation to the charge and magnetization distributions of the nucleon. Any theory of the nucleon must explain the nucleon's structure, and the form factors provide an experimental test of this. The form factors are also important for the analysis of many other experiments, so having precise measurements can enable better determination of other quantities.

This thesis reports on a measurement of the neutron's electric (otherwise known as charge) form factor extracted from an asymmetry using polarized electron scattering from a polarized ^{3}He target. The structure of this thesis is as follows. In Chapter 1, the nucleon structure is introduced and discussed within the framework of various models. In Chapter 2, the formalism required for describing the form factors and the discussion of the measurement is developed. In Chapter 3, previous measurements of the electric form factor are presented in addition to selected previous fits within the framework of the models discussed in Chapter 1. In Chapter 4, the experiment is introduced, in addition to a description of the experimental apparatus. In Chapter 5, the analysis is presented along with the experimental values for G_E^n. Finally, in Chapter 6 new results are discussed in the context of the presented models, the flavor form factors are decoupled, and the quark orbital angular momentum is presented. The remainder of this chapter will have a short introduction to quantum chromo-dynamics (QCD) presented in section 1.2 and an introduction to the various models of nucleon structure in section 1.3.

1.2 QCD

The ground state structure of the nucleon can be investigated using momentum transfer in an elastic scattering experiment, where the initial state of the nucleon is not changed. In electron scattering, the electromagnetic properties of the nucleon are probed, and they are characterized by the aforementioned form factors. These form factors express the difference between scattering from an object with internal

structure and scattering from a point particle.

In the very successful theory of the strong interaction, quantum chromo-dynamics (QCD), the nucleon is the lowest energy three-quark bound state. QCD is similar in structure to quantum electro-dynamics (QED), but where in QED the strength of interaction is governed by electric charge and the exchange particle is photon, in QCD the exchange particles are gluons and the interaction strength is due to color charge. The nucleons are then made up of these gluons and quarks, with the individual quarks being resolved in the Bjorken limit. The three lightest quarks are identified in Table 1.1.

The notion of valence versus "sea" quarks, where it is the valence quarks that define the electromagnetic attributes of the hadron, is useful. For the proton, the valence quarks are two up quarks and one down quark, for the neutron the valence quarks are two down quarks and one up quark.

Protons and neutrons, as has been implied here, share many similar properties. Models and theories have been developed to explain both proton and neutron properties together, in terms of their shared properties as nucleons. Similar properties are expected because both nucleons are made up of the same constituents, and have the same types of valence quarks. Both also have the same spin, are very close in mass, and are long lived. This allows one to discuss the two nucleons as two states of a single object, differentiated by the additional quantum number "isospin". When the next lightest quark, the strange quark (with strangeness charge -1), is included an SU(3) symmetry group can be formed, although this symmetry is only approximate due to the larger mass of the strange quark.

The charge in QCD is color, with three colors instead of the single electromagnetic charge which is familiar from classical physics. A significant distinction of QCD is that, unlike the photon in QED, the exchange particles (gluons) hold the property of color themselves. As a result, the gluons can interact with each other, and a quark of a particular color will be "anti-screened", causing the force to increase as distance increases. This phenomenon is results in confinement. The three color charges of the quark form a SU(3) group as well. This confinement and the creation of the QCD vacuum implies the existence of "sea quarks" ($\bar{u}u$, $\bar{d}d$, $\bar{s}s$) and gluons within the nucleon [29].

name	electric charge	isospin	strangeness	mass
u (up)	$+\frac{2}{3}$	$\frac{1}{2}$	0	1.5 to 4 MeV
d (down)	$-\frac{1}{3}$	$-\frac{1}{2}$	0	4 to 8 MeV
s (strange)	$-\frac{1}{3}$	0	-1	80 to 130 MeV

Table 1.1: The three light quarks and their respective charges. Other quarks are the c (charm), b (beauty), and t (top) quark, but they are too heavy to play a large role in the experiments described here. These three light quarks form the SU(3) group.

1.2.1 Perturbative QCD

Quantum electrodynamics is a highly successful and calculable theory, in part because it is perturbative. This is not the case for QCD. At large distances from the bare charge, the QED coupling is the familiar $\alpha(Q^2) = \frac{1}{137}$ while the QCD coupling, $\alpha_s(Q^2)$, is ≈ 1 at low momentum transfer making an expansion in $\alpha_s(Q^2)$ impossible. However, the coupling decreases with increasing Q^2, the theory is said

to be "asymptotically free". The renormalization scale, Λ, defines the energy at which the effective coupling becomes large. When Q^2 is well below this, quarks and gluons are bound into hadrons [29].

At sufficiently high momentum transfers ($Q^2 > \Lambda^2$), we would expect to be able to understand the nucleon structure using perturbative QCD. A virtual photon of high enough transferred momentum will see the nucleon as consisting of three massless quarks moving collinearly. In (quasi-)elastic scattering the momentum of the virtual photon is transferred among the three quarks through two hard gluon exchanges, with each gluon being proportional to Q^2. This gives the dominant scaling of $1/Q^4$ for the helicity conserving form factor (known as $F_1(Q^2)$). This power counting is justified by QCD factorization theorems[7].

1.3 Nucleon Structure

When the transferred momentum is below the scale Λ, the QCD interaction is strong and quarks are confined. In this parameter space there is no clear way to calculate quantities using QCD analytically. There is much promise for future calculations using direct computational techniques such as Lattice QCD. In the meanwhile, various models have been developed to describe the dominant features of nucleon structure.

1.3.1 Partons

In deeply inelastic scattering (DIS), where the proton breaks up, the final state of the interaction cannot be described by a particle in a single final state. Because of this, a tensor $W^{\mu\nu}$ is used to parametrize the unknown final state. In the Bjorken limit ($Q^2 \rightarrow$), apparent point particles known as quarks are resolved inside of the nucleon, each of which is carrying some fraction of the nucleon's four-momentum. The nature of the strong interaction is such that individual quarks are never seen; instead these "partons" exit the nucleon in jets of colorless hadrons; either qqq baryons or $q\bar{q}$ pairs (mesons). At lower momentum transfers where deep inelastic scattering is not applicable, mesons can also be produced through production and then decay of a nucleon excited state.

In the infinite momentum frame, where the momentum of the hadron is large and all masses can be neglected, and in the case that the invariant mass of the system is large, the tensors $W^{\mu\nu}$ can be represented in terms of dimensionless structure functions. It is useful for these to be expressed in terms of Bjorken x, a dimensionless kinematic variable of the virtual photon. This variable gives the component (xE) of the initial energy/momentum carried by the resulting "parton". In the limit $x \rightarrow 1$, all of the momentum is being carried by the parton, and so the valence quarks dominate the interaction. As x approaches 0, the sea quarks dominate. The momentum which is not carried by the quarks and antiquarks is carried by the gluons [29].

The analysis of partons and the constituents of the nucleon is made more

complicated because many energetic terms must be included. This means that relativistic effects should be considered. However, this makes the interpretation of the wave function unclear, because a Lorentz boost mixes the momentum states. If QCD is quantized at a fixed light-cone time, τ, where $\tau = t + \frac{z}{c}$, the challenges of mixing due to Lorentz boosts is removed along with the complexity of the vacuum in relativistic quantum field theory. The following models and interpretations of nucleon structure are mostly considered in such a quantization. Further discussion on this is in Section 6.1 [41][13][12][14].

In elastic scattering, where the nucleon neither breaks up nor is excited, there is a single final state. The tensor $W_{\mu\nu}$ then can be reduced to a form factor. Obviously, a complete model of the internal structure of the nucleon must include a description of form factors. In the case of a spin $\frac{1}{2}$ object like a nucleon, there are two independent form factors, which can be expressed in the form of Sachs electric and magnetic form factors (G_E and G_M) or as the Pauli and Dirac form factors, F_1 (helicity conserving) and F_2 (helicity-flip) (The relationship between these will be described in Chapter 2). In addition to elastic and deeply inelastic scattering other hard exclusive processes such as deeply virtual Compton scattering (DVCS), can also used to investigate nucleon structure (for a pictorial description see figure 1.1)[29] [15].

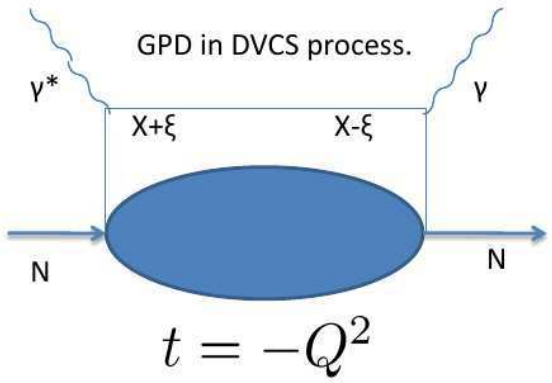

Figure 1.1: Shown is a schematic of the DVCS process, in the framework of generalized parton distributions (GPDs). Here ξ is the skewness, x is the longitudinal momentum fraction, N is the nucleon, $\gamma*$ is the virtual photon, and γ is the detected photon. The skewness gives the longitudinal momentum asymmetry, as shown in the figure.

1.3.2 The Constituent Quark Model

An early model of nucleon structure is the constituent quark model (CQM). In this case, the nucleon is a ground state of three massive quarks in a confining potential. The masses of these quarks are determined by SU(3) flavor symmetry and it is assumed that the mass of the hadron is held by just the valence quarks. While relativistic modifications of this model have had some descriptive success, the model does not satisfy the chiral symmetry of the QCD Lagrangian. Some modifications, such as goldstone-boson-exchange (GBE) where there is an additional quark-quark interaction, and the one-gluon exchange (OGE), provide a general fit to the data for the form factors and the radii of the nucleons.

The long distance behavior of hadronic wave functions should be able to described by the exchange of the lightest of the $q\bar{q}$ states, the pions. As a result, pion signatures should be seen in the low momentum behavior of hadrons, and the

addition of a this pion cloud to the constituent quark model is used to form a better model of the nucleon. An early model of this type is the cloudy bag model. Here the pion cloud interacts with the confined quarks such that chiral symmetry is restored. This cloudy bag model provides a good fit of low Q^2 nucleon form factors [50][45].

1.3.3 Generalized Parton Distributions

In a number of reactions, the scattering amplitudes factorize such that they can be described by a simple diagram known as the hand bag diagram. Here there is one valence quark interacting with the virtual photon, with the rest of the structure contained within a generalized parton distribution (GPD). An appealing feature of GPDs is that, depending on the kinematic limit selected, they can be related to a wide variety of scattering processes, such as deeply inelastic scattering, deeply virtual Compton scattering, wide angle compton scattering, and elastic scattering.

Currently, GPDs cannot be measured explicitly, and are instead expressed by models which are generally simple parametrizations constrained by the GPD relationship to the form factors, properties of the nucleon, and by the fact that the GPDs become parton densities in vanishing momentum transfer.

In this framework, hard exclusive reactions (like DVCS) result in an interaction between the probe and a single quark within the nucleon (see Figure 1.1). At leading order, the interaction that described by the traditional form factors can also be described by four Generalized Parton Distributions (GPDs), these GPDs depend on the longitudinal momentum fractions (light-cone and skewness), and the squared

four-momentum transfer (Q^2) to the nucleon. The four GPDs are H^v and E^v, where v indicates either an up quark or a down quark. [1]

These GPDs depend on Bjorken x, momentum transfer Q^2, scewness (ξ), and a scale parameter μ. The following sum rules, which are independent of ξ, relate the GPDs and the form factors:

$$\int_{-1}^{1} dx H_v(x, \xi, Q^2) = F_1^v(Q^2) \ , \tag{1.1}$$

$$\int_{-1}^{1} dx E_v(x, \xi, Q^2) = F_2^v(Q^2) \ . \tag{1.2}$$

$F_{1,2}^v(Q^2)$ are the flavor form factors, which describe the distribution of that flavor of quark within the nucleon. These can be expressed in terms of the electromagnetic form factors as $F_1^u = 2F_1^p + F_1^n + F_1^s$ and $F_1^d = 2F_1^n + F_1^p + F_1^s$, where F_1^s is the strangeness form factor of the nucleon. It is assumed, here as in most analyses, that the strange form factor is 0. Similar relationships exist for the Pauli form factor, F_2. The GPDs must still be modeled in order to predict form factors, and are usually done so using the sum rules [20][28][19].

1.3.4 Vector meson dominance models

Some of the earliest models of the nucleon were of a virtual photon coupling to the nucleon both through its internal structure and through exchange of intermediate vector mesons with a meson cloud. These vector mesons (the ρ, ω, and ϕ) have the same quantum numbers as the virtual photon and are the lightest hadrons in the

[1] There are other GPDs which aren't related to the electromagnetic form factors such as one to describe the polarized distribution.

time-like region ($Q^2 < 0$ in the standard definition), and so could potentially play a major role in nucleon structure at low Q^2. The form factors are commonly described by a dipole form, resulting from two nearby vector meson resonances (poles) that have opposite residue. This structure can be written in terms of a photon-meson coupling strength ($C_{\gamma V_i}$) and a meson-nucleon vertex ($F_{V_i N}$):

$$F^{iv,is} = \sum \frac{m_i C_{\gamma V_i}}{Q^2 + m_i^2} F_{V_i N}(Q^2). \tag{1.3}$$

These isovector and isoscalar form factors (F^{iv} and F^{is}) are then written as linear combinations of the electromagnetic form factors[50][51].

The internal structure coupling is sometimes identified with the three valence quarks. The initial models had only F_1 coupling with the internal structure, but some of those considered in this thesis include F_2 as well[10][42].

1.3.5 Chiral effective field theory

In chiral effective field theory, the electromagnetic form factors are computed using a chiral Lagrangian with pion, nucleon, and Δ fields. The short distance physics is determined by low-energy-constants, which are fit using the measured nucleon charge radius and moments. While this technique has had some success at low Q^2, by about 0.4 GeV^2 the predictions break down, due to an increasing role of vector mesons. Since this thesis deals with G_E^n at intermediate Q^2, such models can not reliably provide a description of the discussed data. Thus, the focus will be on models that are more appropriate to the energy regime investigated in this experiment [50].

1.3.6 Dyson-Schwinger Equations

As has been expressed earlier, there is a significant difference between the bare quark and the dressed (or "anti-screened") quark. All models of nucleon structure at intermediate Q^2 try to describe this difference. In a framework that uses Dyson-Schwinger equations, the primary cause of this parton behavior is a dense cloud of gluons which surround the low momentum quark, at low momentum transfer ($Q^2 < M_N^2$). This is a manifestation of dynamical chiral symmetry breaking (DCSB), and becomes a source for the nucleon's mass[17].

Describing the relativistic region in a framework that is consistent with this low energy description is difficult. In terms of these DSE, the nucleon appears as a pole in a six-point Green's function. Here, the three dressed quarks are described in terms of a bystander quark and a quark-quark correlation (diquark) pseudoparticle in a single color-$\bar{3}$ channel. The binding depends on the exchange of the bystander quark and quarks in the diquark pseudoparticle. This framework combines the descriptions of mesons and nucleons. It is the observation of this diquark description of the nucleon which is used to truncate the DSE and allow calculations using DSE.

An interesting prediction of models in this framework is that the radius of the "dressed" u-quark in the neutron is greater than that of the d-quark [9] [57] [17]. Another is that since the up and down current quark masses are thought to be small, the dominant mechanism for the helicity flip behavior in QCD comes from quark orbital angular momentum and an additional polarized gluon[17].

1.4 Experimental Investigation

These various models described above provide a description of the nucleon which is more complete than the simple constituent quark model or dynamical chiral symmetry breaking. Most of these models share in common as part of their description a non-zero current quark orbital angular momentum. In this regime, the constituents of the nucleus are dominated by the up and down quarks (with possibly a small strange quark component). The simplest probe available of this structure is the electron. The common experimental techniques used to study this behavior and to investigate the models are deep inelastic scattering (DIS), deeply virtual Compton scattering (DVCS), and (quasi-)elastic scattering. By expanding our knowledge of the nucleon form factors, the pieces needed to complete our picture of the neutron are brought together. The measurement described in this thesis is one important piece: the physics of electron scattering will be developed in the next section.