Unpolarized nucleon structure studies utilizing polarized electromagnetic probes

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Abstract

By the mid-1980s, measurements of the nucleon form factors had reached a stage where only slow, incremental progress was possible using unpolarized electron scattering. The development of high quality polarized beams, polarized targets, and recoil polarimeters led to a renaissance in the experimental program. I provide an overview of the changes in the field in the last ten years, which were driven by the dramatically improved data made possible by a new family of tools to measure polarization observables.

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1. Introduction

Elastic electromagnetic form factors provide the most direct insight on the spatial distribution of the quarks in the proton and neutron. They encode information on the distribution of charge and magnetization, and are thus sensitive to both the distribution and the dynamics of quarks. Elastic lepton–nucleon scattering has been the preferred method to measure the form factors since the 1955 SLAC measurement that provided the first extraction of the proton radius [1]. Such measurements were extensively pursued for decades, both on the proton and on the neutron (using deuterium targets), and by the mid-1980s, this was considered to be a fairly mature field. Subsequent measurements in the late 1980s and early 1990s provided mainly incremental improvements to either the precision or the kinematic coverage of the data.

After four decades of effort, however, there were still large kinematic regions where only very limited measurements of the form factors were possible. There were two significant limitations to form factor measurements based on unpolarized electron scattering: the fact that the cross section is only sensitive to a specific combination of the form factors and the lack of a free neutron target.
The form factors represent the difference between scattering from a point-like object and from a spatially extended target. For a spin-1/2 target, the cross section for the exchange of a single virtual photon is sensitive to a specific combination of the form factors: $(Q^2/4M^2)G_M^2 + \varepsilon G_E^2$, where $G_E$ and $G_M$ are the electric and magnetic form factors, $-Q^2$ is the four-momentum squared of the virtual photon, $M$ is the mass of the target nucleon, and $\varepsilon$ is the virtual photon polarization parameter. The virtual exchange photon can have a longitudinal contribution in addition to the transverse contribution of real photons, and so $0 < \varepsilon < 1$, with $\varepsilon = 0$ corresponding to fully transverse photons (in the limit $\theta \to 180^\circ$), and $\varepsilon = 1$ corresponding to the maximal longitudinal component in the forward scattering limit. In a “Rosenbluth separation” of the form factors, cross sections are measured at fixed $Q^2$ over a range in $\varepsilon$. The $\varepsilon \to 0$ limit isolates the contribution from $G_M$, while the $\varepsilon$ (or $\theta$) dependence yields sensitivity to $G_E$. However, the $Q^2$ weighting on the magnetic form factor makes it difficult to isolate $G_M$ at low $Q^2$, except for scattering angles approaching $180^\circ$, while $G_E$ is difficult to isolate at high $Q^2$, where it has only a small contribution to the cross section.

For the neutron, there is an additional limitation, owing to the lack of a free neutron target. Early measurements of the neutron form factors came from inclusive quasielastic scattering from the deuteron, and so were a combination of the neutron and proton scattering cross sections, thus requiring a large correction to remove the proton contribution as well as corrections for the binding and motion of the nucleons. The proton corrections were eliminated in later experiments by measuring both the scattered electron and the struck neutron, but this introduces final state interaction corrections for the neutron in addition to the nuclear effects for the deuteron target.

Thus, even in the late 1990s, our knowledge of the form factors was still rather incomplete. The proton magnetic form factor, $G_{Mp}$, was well measured up to $Q^2 = 30$ GeV$^2$, while the electric form factor, $G_{Ep}$, was measured to $\sim 6$ GeV$^2$, with much lower precision for $Q^2 > 2$–3 GeV$^2$, as $G_M$ dominates the cross section at large $Q^2$. The neutron magnetic form factor, $G_{Mn}$, was relatively well measured up to $Q^2$ values of 5–6 GeV$^2$, while direct measurements of $G_{En}$ were mainly upper limits. Figure 1 gives an idea of the status of nucleon form factor measurements up to 5–6 GeV$^2$ as of the late 1990s.

Measurements of $G_{Mp}$ extend up to 30 GeV$^2$, although with lower precision at higher $Q^2$, while the other form factors have only very low precision data at higher $Q^2$ values. For $G_{En}$, the only data above 1.5 GeV$^2$ was consistent with zero, with relatively large uncertainties. The dashed lines indicate the range as extracted from measurements of $e$–d elastic scattering, which yields a large model-dependent uncertainty. Details on these early form factor extractions can be found in recent reviews [2,3,4,5].

Except for $G_{En}$, all of the form factors were in approximate agreement with a dipole fit: $G_D = 1/(1 + Q^2/0.71)^2$, with $Q^2$ in GeV$^2$. In the textbook interpretation, this implies that the charge and magnetization distributions would be well described by an exponential distribution, corresponding to the Fourier transform of the dipole form. However, this picture is only valid in the limit of low $Q^2$, as it neglects model-dependent relativistic boost corrections. Nonetheless, the data suggest that the proton charge and magnetization distributions are similar, as is the neutron magnetization distribution. The neutron electric form factor is zero at $Q^2 = 0$, corresponding to the neutron charge. The positive value of $G_{En}$ at finite $Q^2$ implies a positive charge at the core of the neutron with a negative cloud of charge at larger distances. This is consistent with the “pion cloud” picture, where the neutron fluctuates into a proton and a negative pion.
2. Polarization Observables

During the last decade, the experimental program to measure form factors was completely reinvented, as it became possible to use polarization degrees of freedom to make dramatically improved extractions of the form factors. This concept was already well understood [6,7,8], but such measurements require high polarization, high intensity electron beams, as well as high figure-of-merit polarized targets or recoil polarimeters. The development of these tools made rapid progress in the 80s and 90s, spurred on initially by interest in nucleon spin structure. Once they were widely available, they were used to study a variety of topics unrelated to the spin structure studies that motivated much of the work.

In particular, polarization measurements dramatically improved the extraction of nucleon form factors. Over large kinematic regions, the Rosenbluth extractions were primarily sensitive to only one of the form factors, and so could not be used to separate $G_E$ and $G_M$. In polarization measurements, either the polarization transfer to the nucleon or the double spin asymmetry in scattering from a polarized nucleon, the observables depend only on the ratio of the electric to magnetic form factor: $G_E/G_M$. By themselves, polarization measurements cannot provide absolute measurements of either form factor, when coupled with cross section measurements, they allow for a precise extraction of both form factors, even in regions where the cross section is sensitive only to one of the form factors.
factors. In the last ten years, the new measurements utilizing polarization observables have almost entirely supplanted the previous measurements, and in some cases, yielded surprising new results.

3. Neutron Form Factors

The initial focus was on making improved measurements of the neutron. Polarization measurements not only allowed for a much better measurement of $G_{En}$, which is nearly impossible to access in a Rosenbluth separation, but also yielded reduced corrections for the nuclear effects in quasielastic scattering from the neutron in deuterium or $^3$He. Recoil polarization measurements typically use deuterium targets, while polarized target measurements have most frequently used $^3$He targets. While polarized $^3$He targets have a larger contamination from protons, the two protons spend most of the time with opposite spins, which means that the polarization of the neutron is very similar to the polarization of the $^3$He nucleus, and that the dilution due to scattering from the anti-aligned protons is the largest correction.

![Fig. 2. Present status of neutron form factor extractions. For $G_{Mn}$, the cyan (light grey) points come from inclusive or coincident quasielastic scattering from deuterium. The hollow red triangles are measurements on polarized $^3$He [9], the solid black circles and solid magenta squares are from ratio measurements [10,11]. For $G_{En}$, the light gray (yellow and cyan) points are from elastic e–d scattering, while the other points are a variety of polarization measurements. Above 2 GeV$^2$, only upper limits on $G_{En}$ currently exist, but data on polarized $^3$He have been taken up to 3.4 GeV$^2$ at Jefferson Lab and are currently under analysis. Figures adapted from Ref. [4].](image)

Unpolarized measurements of the ratio of proton to neutron knockout were also used to improve our knowledge of $G_{Mn}$. Taking the ratio of the $^2$H(e,e’p) to $^2$H(e,e’n) cross sections removes the large proton contamination that is limits the inclusive measurements, while almost entirely cancelling the nuclear effects. The largest issue is then a precise measurement of the efficiency of the neutron detector, along with a correction for the difference between final state interactions of the proton and neutron. At large $Q^2$, the ratio measurements have provided much improved precision on the extraction of $G_{Mn}$, while at low $Q^2$, both techniques have been used. The extraction of $G_{Mn}$ is somewhat unusual, as the polarization observable for scattering from a nucleon are sensitive only to the ratio $G_E/G_M$, and nuclear targets are required to extract $G_{Mn}$. For a free neutron target, the asymmetry depends only on $G_E/G_M$, and by selecting the angle of the spin
relative to the beam polarization, one can choose a term that is roughly proportional to $G_E/G_M$, or a term that depends mainly on the kinematics, with only a small correction from $G_E/G_M$. In the latter case, the fact that $G_E/G_M$ is small for the neutron means that the asymmetry for scattering from a neutron is already known. Thus the resulting asymmetry for inclusive scattering, where the neutron is not tagged, is simply the neutron asymmetry diluted by scattering from the (nearly unpolarized) protons in $^3\text{He}$. This dilution depends only on the relative cross section for scattering from the neutron and the protons, and thus the asymmetry is actually used to extract the same cross section ratio that is directly measured in the ratio technique, but using an entirely different technique.

For $G_{En}$, a range of different measurements of $A(e,e'\nu)$ have been performed to verify the techniques and to test nuclear corrections. Measurements of recoil polarization in scattering from deuterium yield results that are consistent with measurements of double spin asymmetries made from polarized deuterium and $^3\text{He}$ targets. Figure 2 shows the present status of $G_{Mn}$ and $G_{En}$ extractions. The data sets included are described in more detail in Ref. [4]; the results from the CLAS high-$Q^2$ ratio measurement of $G_{Mn}$ are taken from a recent preprint [11].

It is clear from Fig. 2 that the polarization and ratio measurements had a huge impact, dramatically improving the precision for $G_{Mn}$, and providing essentially all of the high precision extractions of $G_{En}$. For the proton, the situation was expected to be improved, but not as dramatically, as the main limitation was the extraction of $G_{Ep}$ at high $Q^2$. However, the initial measurement of $G_{Ep}$ at high $Q^2$ didn’t just improve the precision for $G_{Ep}$, it also showed that the ratio $G_{Ep}/G_{Mp}$ fell with increasing $Q^2$. This surprising behavior motivated follow-up experiments meant to verify the results and extend the extraction of $G_{Ep}$ to higher $Q^2$.

4. Proton Form Factors and Two-Photon Exchange

While much of the effort went into the neutron measurements, the extraction of $G_{Ep}$ from Rosenbluth extractions was of limited precision at high $Q^2$. In addition, there were questions about the consistency of the results from different measurements. The initial proton measurements were aimed at clarifying the situation and improving the precision of $G_{Ep}$ extractions above 1–2 GeV$^2$.

Figure 3 shows the Rosenbluth and polarizations results for $G_{Ep}$. While the Rosenbluth measurements were of poorer quality, there appeared to be a real discrepancy with the new polarization measurements. A reexamination of the world’s cross section data showed that there were no significant inconsistencies within the set of previous data, and demonstrated that the discrepancy with polarization was well beyond the uncertainties of the data sets, even taking into account the normalization and correlated systematic uncertainties of the cross section data [12]. A new “Super-Rosenbluth” measurement, using proton rather than electron detection to provide extremely small relative systematic uncertainties verified the discrepancy [13]. The experiment yielded uncertainties comparable to the polarization data, as shown in Fig. 3 (solid stars).

Today, it is believed that the discrepancy is due to two-photon exchange corrections to the Born cross section. While early calculations had suggested these corrections were very small, a reexamination of two-photon exchange (TPE) in light of the new experimen-
Fig. 3. Present status of the proton form factor extractions. The left plot shows measurements of $G_{Ep}$, with the cyan (light gray) symbols showing results from previous Rosenbluth extractions, the solid red diamonds showing the high $Q^2$ polarization measurements [14,15], and the solid blue stars showing the new “Super-Rosenbluth” extractions [13]. The right plot shows the extractions of $G_{Mp}$ from Rosenbluth extractions before (blue open circles) and after (red filled circles) corrections for two-photon exchange [16].

Initial results showed that a relatively small correction, with a strong angular dependence, could significantly modify the Rosenbluth extraction of $G_{Ep}$ and explain the discrepancy [17,18,19,20]. This led to a significant effort to examine the impact TPE corrections could have on both nucleon form factors and a range of other observables [20,21,22,23]. With the assumption that TPE corrections explain the entire discrepancy, it has been possible to make updated extractions of the proton form factors [16] using hadronic calculations of the TPE corrections [24]. The additional uncertainty associated with these corrections does not appear to be a limiting factor in the form factor extractions, and effects on the neutron form factors, especially for polarization measurements, appear to be negligible. However, this conclusion is based on the assumption that these TPE corrections fully resolve the difference. While some calculations indicate that TPE corrections are sufficient, direct experimental evidence for TPE effects of the necessary magnitude is very limited.

Two-photon exchange corrections have the opposite sign in positron and electron scattering. While early comparisons of positron and electron scattering generally showed very small effects, a reexamination of these data focusing on the angular dependence of the correction found some evidence for TPE corrections of the kind needed to resolve the discrepancy [25]. There are currently several experiments whose goal is to study TPE corrections, either through direct comparisons of positron and electron scattering, or through detailed examination of the angular dependence of cross section or polarization observables. Other experiments aim to extract polarization observables that are forbidden in the Born approximation. These observables relate to the imaginary part of the TPE amplitude, while the form factor extractions are affected by the real part, but these measurements will provide a clean way to test calculations of the TPE effects. A detailed review of our current understanding and the ongoing experimental program designed to isolate these contributions can be found in Ref. [23,4].
5. Impact of the New Data

The new high $Q^2$ data for the proton, with the dramatically different $Q^2$ dependence for $G_{Ep}$ and $G_{Mp}$, led to a significant reevaluation of the high $Q^2$ region. It was realized that while the $Q^2$ dependence of $G_{Ep}$ was not consistent with the leading term of the pQCD prediction, the inclusion of orbital angular momentum introduced an additional falloff which may explain the high $Q^2$ data \[20\,27\].

In addition, the difference in the electric and magnetic form factors implies a difference in the spatial charge and magnetization distributions. In the textbook picture, the spatial distribution is related to the Fourier transform of the form factors. However, these spatial distributions are in the Breight frame, and so each $Q^2$ value requires a different boost to get to the rest frame, thus requiring model dependent relativistic boost corrections which become large at high $Q^2$. A comparison of the difference between charge and magnetization distributions, applying one model of the boost corrections, showed that the central magnetic density was roughly 50% larger than the electric density \[28\]. Other works have looked beyond the overall density, and found non-spherical, highly complex structures in the spatial distribution of the charge when examining quarks of specific moment, or specific spin \[29\,30\]. These provide additional information on the correlation of the quark space, spin, and momentum degrees of freedom, but require a model of the full generalized parton distribution, rather than simply the form factors.

More recently, a model-independent method was found to extract the transverse charge distribution in the infinite momentum frame (IMF) \[31\], the same frame in which the longitudinal momentum distributions of the quarks can be extracted from the parton distribution functions. In the IMF, the transverse charge density at the center of the nucleon is dominated by the high-$x$ pdfs, i.e. the high momentum quarks in the nucleon, corresponding to a positive core for the proton and negative core for the neutron. This differs from the rest frame distributions, where the neutron has a positive core. Further details of the interpretation are available for the proton \[32\] and neutron \[33\].

The neutron data were limited to a lower $Q^2$ region, but have been of equal importance in improving our understanding of the nucleon structure. Calculations of the nucleon structure have historically been able to do a fair job of reproducing $G_{Mp}$, which was well known over a large $Q^2$ range, but the data on the other form factors has been of much lower quality, and thus not been able to really challenge the assumptions of the models in a global and systematic fashion. Calculations must now explain both $G_{Mp}$ and the dramatically improved data on $G_{Ep}$ and $G_{Mn}$. The neutron electric form factor is a special case, as one would have $G_{En} = 0$ if the up and down quark spatial distributions were identical, and thus it is sensitive to difference in the flavor distributions. Thus, the “pion cloud” contributions, coming from fluctuations of the neutron into a virtual proton and negative pion, yield a leading contribution to $G_{En}$. Such fluctuations are small perturbations to the distributions for the other form factors, although an intriguing analysis \[34\] suggested that there were common features in all four form factors that may be attributable to the pion cloud contributions. Nonetheless, $G_{En}$ provides a unique sensitivity to pion contributions, which are difficult to include in constituent quark models of the nucleon, and it is therefore difficult to simultaneously describe all of the form factors within a single model.

Interest in low $Q^2$ form factors has also led to efforts to make higher precision mea-
measurements of the proton form factors at low $Q^2$ \[35,36\]. The data, along with recent experiments that are still being analyzed, will improve the precision in the region where the pion cloud contributions are believed to be the largest. In addition, high precision measurements, utilizing these new polarization techniques and applying new corrections for two-photon exchange terms, have an impact on other experiments. Calculations of the hydrogen hyperfine splitting, measured to 12 decimal places, are limited by hadronic corrections relating to the proton size, and thus the low $Q^2$ form factors \[37\]. Precise knowledge of these low $Q^2$ form factors is also important in extracting the contribution of strange quarks to the form factors. The nucleon form factors are the sum of up, down, and strange quark contributions, and by measuring the proton and neutron form factors, along with a third set of form factors, we can extract the up, down, and strange quark contributions. That third set is the form factor associated with Z-boson exchange, which can be measured in parity violating electron scattering \[38,39,40\]. In the case of no strangeness, the parity violating asymmetry can be calculated from just the proton and neutron form factors, and thus provides the baseline for extracting strange quark contributions. As with the form factor program, this has also relied on the development of high polarization, high intensity electron beams, and has made dramatic progress in the last ten years.

6. Future Plans

The energy upgrade at Jefferson Lab will allow for dramatic extensions of these form factor measurements to higher $Q^2$, and providing a complete set of high-precision measurements up to relatively high $Q^2$. In addition, the are new measurements pushing the level of precision at low $Q^2$, which provide useful information on the proton structure and complement the low $Q^2$ parity violating elastic scattering measurements. Rapid progress is still being made in modeling form factors, and in QCD-based calculations of the nucleon form factors. The data acquired over the past decade led to a dramatic resurgence in these efforts, and the promise of future data, and the ability to apply these models to a range of form factors and related observables, have made this an exciting and rapidly progressing field.

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References

[1] R. Hofstadter, R. W. McAllister, Phys. Rev. 98 (1955) 217–218.
[2] H. Gao, Int. J. Mod. Phys. E12 (2003 [Erratum-ibid., 567, 2003]) 1–40.
[3] C. E. Hyde-Wright, K. de Jager, Ann. Rev. Nucl. Part. Sci. 54 (2004) 217–267.
[4] J. Arrington, C. D. Roberts, J. M. Zanotti, J. Phys. G34 (2007) S23–S52.
