THE NEUTRON MAGNETIC FORM FACTOR AT HIGH Q^2: EXPERIMENTAL STATUS, FUTURE MEASUREMENTS

W. K. BROOKS

Thomas Jefferson National Accelerator Facility
12000 Jefferson Ave, MS 12H
Newport News, VA, 23601, USA
E-mail: brooksw@jlab.org

Recent progress in improving our knowledge of the four nucleon form factors G_M^p, G_E^p, G_M^n, G_E^n at high momentum transfer is stimulating a new wave of theoretical efforts to describe these fundamental quantities. Both model calculations and lattice QCD can predict the elastic form factors; a definitive, stringent test of these efforts is to predict all of them simultaneously. However, the limited range and quality of the data for the neutron magnetic form factor G_M^n presently reduce the discriminating power of such a test. The present status of our knowledge of G_M^n is discussed, and prospects for future improvements are presented.

1. Introduction

The quest to understand the structure of protons and neutrons has been a major theme of hadronic physics over the last half century. Elastic scattering from the proton gave early indication of its composite nature[1], confirming the much earlier indications that its magnetic moment was not consistent with that of a point particle[2]. Over the intervening decades, knowledge of the *proton* elastic form factors has improved both in precision and in the range of momentum transfer (Q^2) spanned, including very recent progress[3]. The experimental determination of the *neutron* elastic form factors is more challenging for a variety of reasons, however, this problem is now being surmounted due to substantial technical advances. These include the development of continuous-wave electron accelerators that permit high-quality coincidence measurements, and the availability of high beam and target polarizations. The following discussion focuses on the present status and future prospects for measuring the neutron magnetic form factor G_M^n at $Q^2 > 1\ GeV^2$.

2. Significance of High-Q^2 Elastic Form Factors

Nucleon elastic form factors reflect the charge and magnetic moment distributions that arise from the intrinsic properties and motion of the nucleonic constituents. Therefore, they can typically be predicted by nucleon models and by lattice QCD calculations. While this is true at any momentum transfer, at higher momentum transfer a greater degree of sensitivity to the nucleonic constituents is achieved. In Figure 1 is shown the wavelength of the virtual photon as a function of Q^2 for the range $Q^2 = 1 - 15\ GeV^2$ under discussion. As may be seen, the wavelength itself ranges from approximately the nucleon radius to much smaller sizes, and one expects to be able to resolve structure to some fraction of a wavelength. Therefore, the elastic form factors in this range are very sensitive to the details of the sub-nucleonic constituents (classically, an average over their effective sizes and trajectories). The requirement to predict all four elastic nucleon form factors over a wide range in Q^2 is a powerful constraint for models of the nucleon.

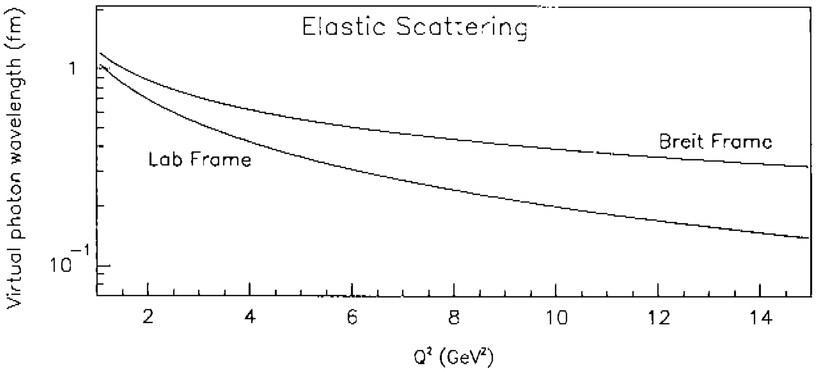

Figure 1. Wavelength of the virtual photon for elastic scattering in the Breit frame (upper curve) and the lab frame (lower curve).

Unfortunately, the quality of the world data set for these four fundamental functions varies widely. In Figure 2 is shown a comparison of representative data for the proton magnetic form factor and the neutron magnetic form factor, normalized to the dipole form $G_D(Q^2) \propto 1/(1+Q^2/Q_0^2)^2$, with $Q_0^2 = 0.71$ GeV^2. Both the extent of the Q^2 coverage and the size of the errors are poorer for the neutron. The lack of high-quality data for G_M^n clearly limits the degree to which these data can test our understanding in this range of momentum transfer.

Nucleon elastic form factors can be calculated in a wide variety of models; a number have attempted to describe the recent proton data[3]. In addition, there are predictions from pQCD, and lattice QCD efforts are underway[10]. It has been suggested that the form factors can be related to high-x structure functions using local duality[6]. Finally, these form factors are closely related to the generalized parton distributions[9,7,8], which are an important focus of the 12 GeV physics program at Jefferson Lab.

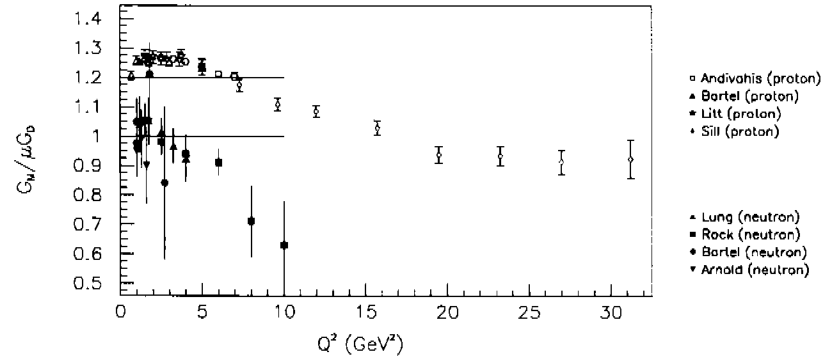

Figure 2. The normalized proton and neutron magnetic form factors ($G_M^n/G_D\mu_n$, $G_M^p/G_D\mu_p$) out to high Q^2. The proton data has been shifted upwards by 0.2 for clarity. Note the lack of high-quality data for the neutron at large Q^2. See text for further discussion.

3. Measurement Methods for the Neutron

The previous data for the neutron at large Q^2 are dominated by inclusive electron scattering measurements. This method is straightforward for measurement of G_M^p in this kinematic regime, however, to measure G_M^n there are further complications associated with the necessity of using a bound neutron as a target. The state-of-the-art for this technique may be illustrated by the NE11 experiment at SLAC [4]. In this experiment, a Rosenbluth separation of quasielastic scattering on deuterium was performed; the response functions obtained were fitted with model curves for the quasielastic process and for the inelastic background. Assuming PWIA expressions for the response functions, the contribution from the proton form factors (which were also measured in the experiment) were then subtracted from the deuteron response functions, yielding the neutron form factors G_M^n and G_E^n. Extensive studies of the model dependence of the results were performed. This method has the advantage that it only requires the detection of the electron, however, it relies heavily on modelling of the deuteron wave function and the inelastic background. A limitation in extending this method to higher Q^2 is that the peak-to-background ratio in the W^2 spectrum decreases as Q^2 increases, primarily due to kinematic broadening. In the NE11 experiment, it was estimated that the background was 15% of the signal at the quasielastic peak for the $Q^2 = 4\ GeV^2$ point.

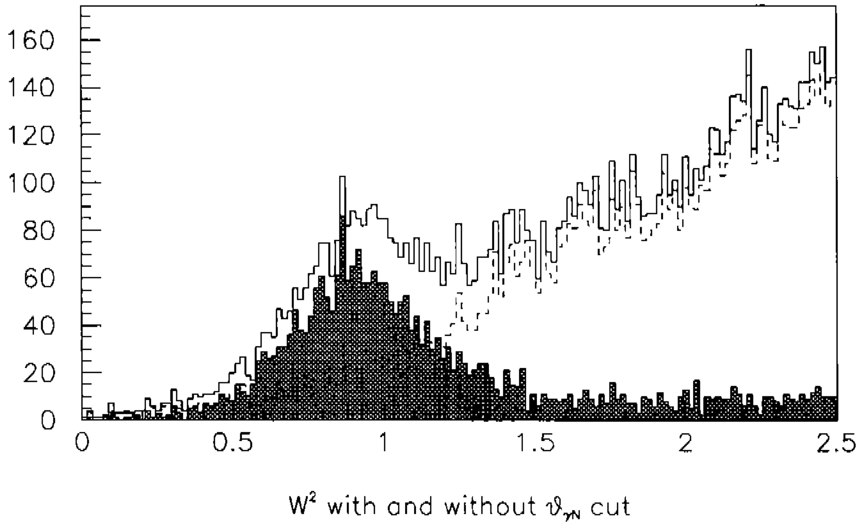

Figure 3. A plot from the CLAS E5 data of the W^2 spectrum with a cut on $\theta_{\gamma^* N} < 2.6^o$ for $Q^2 > 3\ GeV^2$. Approximately 7% of the data sample is shown. The uppermost solid line shows the W^2 spectrum for events in which a nucleon candidate was detected; the shaded peak shows the quasielastic events identified using the cut on $\theta_{\gamma^* N}$; the dashed line shows the inelastic background contribution that was removed using this cut.

An alternative approach, often referred to as the 'ratio method,' has been used at lower Q^2 for precision determinations[5] of G_M^n. Recent measurements[11] with CLAS at Jefferson Lab are extending this method to Q^2 of nearly 5 GeV^2. In the ratio method, protons and neutrons are detected in coincidence with scattered electrons from a deuterium target. The ratio of e-n scattering to e-p scattering is measured for quasielastic kinematics. Using the known values of the other three nucleon form factors, one can then use the ratio to calculate G_M^n. For larger Q^2, the method is largely insensitive to the precision of both electric form factors. In this method it is possible to suppress the inelastic background by using the additional information from the detected protons and neutrons. For instance, the angle between the emitted nucleon and the virtual photon, $\theta_{\gamma^* N}$, is small for quasielastic events and larger for the inelastic events. In Figure 3 is shown the effect of a cut in $\theta_{\gamma^* N}$ on the W^2 spectrum for $Q^2 > 3\, GeV^2$. The inelastic background is well-separated from the quasielastic peak with this simple kinematic cut, which can be applied to both proton and neutron. Since the distribution in $\theta_{\gamma^* N}$ narrows with increasing Q^2, this cut remains effective at high momentum transfer. Additional suppression of inelastic final states can be obtained by vetoing events with additional charged tracks, and this technique also continues to be effective at high momentum transfer, particularly for spectrometers with substantial hermiticity. This method has the advantage that the reaction of interest is identified via experimental information with little model input, and numerous sources of error cancel or are reduced due to the use of the ratio. The experimental challenges include the requirement of a precise measurement of the neutron detection efficiency, and the equivalency of the neutron and proton solid angles. The primary technique in this measurement that addresses those challenges was to have a hydrogen target in the beam simultaneously with the deuterium target. This allows measurement of tagged neutrons in exclusive reactions on the hydrogen target as well as many cross-checks of neutral and charged particle angles and reconstruction efficiencies.

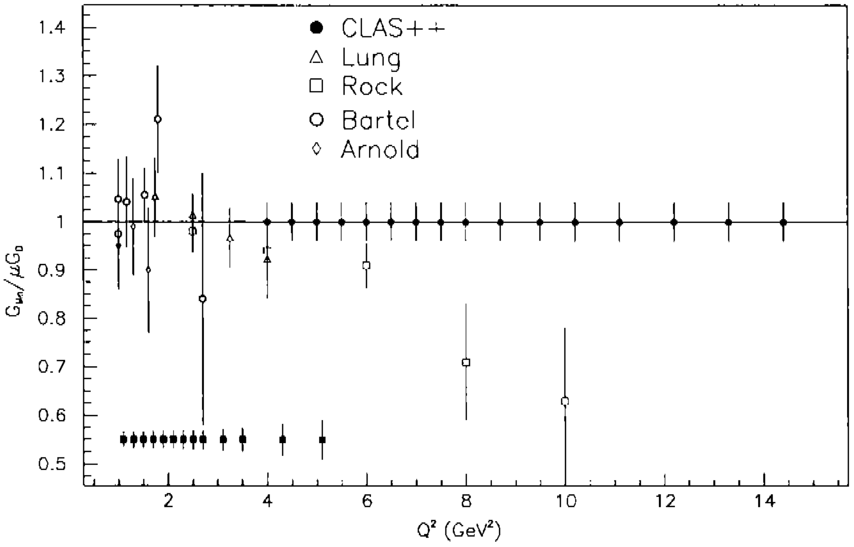

Figure 4. Measurements of G_M^n that will be feasible with an upgraded CLAS, with the 12 GeV upgrade of Jefferson Lab. See text for further discussion. An indication of the coverage of the CLAS E5 data that is currently under analysis is plotted at 0.55 in solid squares.

4. Future Prospects

New, high-precision data for the neutron magnetic form factor for $Q^2 < 5\ GeV^2$ will be forthcoming in the near future[11], derived using the ratio method as described in the previous section. The approximate coverage for these data is indicated in solid squares plotted at 0.55 in Figure 4. To go to higher Q^2 using the same technique requires an upgraded CLAS and Jefferson Lab. After the 12 GeV upgrade of CLAS and Jefferson Lab, CLAS will be capable of measuring G_M^n out to 14 GeV^2; at a luminosity of $10^{35} cm^{-2} s^{-1}$, the uncertainties are expected to be due entirely to systematic errors for reasonable run times. Figure 4 shows the expected quality and coverage of the data accessible after the 12 GeV upgrade.

Acknowledgments

This work was supported by the U. S. Department of Energy. The Southeastern Universities Research Association (SURA) operates the Thomas Jefferson National Accelerator Facility for the United States Department of Energy under contract number DE-AC05-84ER40150.

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