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Nucleon electromagnetic form factor ratio at low Q^2: The JLab experimental Program

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The nucleon electromagnetic form factors encode information about their complex internal structure. At low Q^2 the form factors probe the peripheral structure of the nucleon and are related to the charge and magnetization distributions and radii.
Several experiments at JLab have probed the low Q^2 form factors, producing a wealth of data. In particular, new, very precise measurements of the proton form factor ratio at very low Q^2 have shown a strong deviation from unity at lower values than previously observed. This low Q^2 behavior is unanticipated by theoretical calculations. Even newer, more precise measurements are underway and are expected to provide results with unprecedented precision down to Q^2 *sim* 0.15 GeV^2.

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1. Review of Form Factors and Measurement Techniques

The cross section for electron-nucleon (eN) elastic scattering may be written in the Rosenbluth form [1]:

$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{Mott} \times \frac{1}{1+\tau}\left[G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2)\right] \tag{1.1}$$

where $\left.\frac{d\sigma}{d\Omega}\right|_{Mott}$ is the Mott cross section, τ=$Q^2/4M^2$, $\varepsilon = \left[1+2(1+\tau)\tan^2(\theta_e/2)\right]^{-1}$ is the virtual photon polarization, M is the nucleon mass, and G_M and G_E are the magnetic and electric form factors (FFs) respectively. The form factors are normalized such that at Q^2=0 they give the nucleon static properties:

$$\begin{aligned} G_M^p(0) = \mu_p \sim 2.793, \quad G_E^p(0) = 1, \\ G_M^n(0) = \mu_n \sim -1.91, \quad G_E^n(0) = 0. \end{aligned} \tag{1.2}$$

The FFs parametrize the complex internal structure of the nucleons and completely describe the EM structure of the nucleon ground state. Due to the relation between the FFs and the electric and magnetic distributions, a comparison of the form factors yields information of the difference between the nucleon electric and magnetic distributions and radii. Note however, that the relation is between the so-called Sachs form-factors (which are linear combinations of G_E and G_M and the *transverse* charge and magnetization distributions [2]. Furthermore, nucleon form factors are an important input to many calculations and experiments, including, but not limited too, extraction of the nucleon strange quark content [3], extraction of isoscaler and isovector form factors (relevant for comparison to lattice QCD calculations), and the calculation of the hydrogen hyperfine splitting via the Zemach radius [4, 5].

Two approaches have been developed in order to experimentally measure the nucleon form factors: *cross section based measurements* and *spin-correlation measurements*. Cross section based measurements (commonly known as "*Rosenbluth (or LT) separation*") rely on measuring the cross section at different values of ε but at the same Q^2 (changing the beam energy and scattering angle). The *reduced cross section* is then defined as:

$$\sigma_{red} \equiv (1+\tau)\frac{d\sigma/d\Omega}{d\sigma/d\Omega|_{Mott}} = G_E^2 + \frac{\tau}{\varepsilon} G_M^2. \tag{1.3}$$

A linear fit is then performed for $\varepsilon\sigma_{red}(\varepsilon)$ giving G_E^2 as the slope and τG_M^2 as the intercept.

Using the Rosenbluth separation method the three form factors G_M^p, G_E^p, and G_M^n were approximately found to follow the *dipole form*,

$$G_D(Q^2) = \frac{1}{\left(1+\frac{Q^2}{\Lambda}\right)^2}, \tag{1.4}$$

where $\Lambda \sim 0.71$ GeV^2. the neutron electric form factor has been found to approximately follow tthe *Galster parameterization* [6],

$$G_E^n(Q^2) \sim -\frac{\mu_n}{1+5.6\tau} G_E^p(Q^2) \tag{1.5}$$

It is worth noting that this method does not enable to determine the sign of the form factor. Also, for large (small) values of Q^2 the cross section is dominated by G_M (G_E) making the measurement relatively insensitive to the subdominant form factor. Finally, this type of measurement requires careful normalization between cross section measured at very different kinematical configurations (the cross section can typically change by several orders of magnitude over the measured ε range). Despite these drawbacks, the Rosenbluth separation method has been widely used for extracting the nucleon form factors for the past several decades.

With the advent of polarized electron beams and polarized targets a second approach, suggested by various authors [7, 8, 9] is also being employed. In a *recoil polarization* measurement, longitudinally polarized electrons are elastically scattered off unpolarized nucleons (typically deuterons are used for unpolarized neutrons) and the polarization components of the recoiling nucleon are measured. The longitudinal and transverse transferred polarization components are, respectively:

$$\sigma_{red} C_z = h \frac{E+E'}{M} \sqrt{\frac{\tau}{1+\tau}} G_M^2, \tag{1.6}$$

and

$$\sigma_{red} C_x = -2h \cot \frac{\theta_e}{2} \sqrt{\frac{\tau}{1+\tau}} G_E G_M, \tag{1.7}$$

where E and h are the beam energy and degree of polarization, E' the scattered electron energy, and θ_e the electron scattering angle. A simultaneous measurement of both polarization components allows one to directly measure the form factor ratio (without requiring a measurement of the cross section):

$$\mu_N \frac{G_E}{G_M} = -\mu_N \frac{E+E'}{2M} \frac{C_x}{C_z} \tan \frac{\theta_e}{2} \tag{1.8}$$

Analogously, in a *beam-target asymmetry* measurement, a longitudinally polarized electron beam is elastically scattered off a polarized target (typically polarized ND_3 or ^{3}He is used for neutrons and polarized NH_3 or a polarized atomic hydrogen gas jet is used for protons). The cross section asymmetry is then related to the nucleon form factors as:

$$A \equiv \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = -\frac{2\sqrt{\frac{\tau}{1+\tau}} \tan \frac{\theta}{2} \left\{ \sqrt{\tau \left(1+(1+\tau)\tan^2 \frac{\theta}{2}\right)} cos\theta^* G_M^2 + \sin \theta^* \cos \phi^* G_M G_E \right\}}{\left(\frac{G_e^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2(\theta/2) \right)} \tag{1.9}$$

where θ^* (ϕ^*) is thet target spin polar (azimuthal) angle with respect to the momentum transfer vector. Performing an asymmetry measurement at two different target spin settings then allows one to extract the form factor ratio.

2. JLab Neutron Form Factor Measurements

Polarization measurements for the neutron not only allow for a better determination of G_E^n, which is difficult to measure using Rosenbluth separation due to it's smallness, but also allowed for reduced corrections for the nuclear effects in the quasielastic scattering from ^{3}He or deuterium, used as a source of *quasi-free* neutrons. Typically, polarized ^{3}He targets are used for beam target asymmetry measurements, since the two protons are mostly with anti-parallel spins and the polarization of the neutron is quite similar to that of a free neutrons. Recoil polarization measurements have typically used a deuterium target due to the easier nuclear corrections for the lightly bound deuterium.

An alternative techinque, applicable for neutron form factor measurements and also applied at JLab [10] relies of the measurement of the ratio of neutron to proton knockout from deuterium. The measured ratio can be written as:

$$R_D = \frac{\frac{d\sigma}{d\Omega}\left[{}^2H(e,e'n)_{QE}\right]}{\frac{d\sigma}{d\Omega}\left[{}^2H(e,e'n)_{QE}\right]} = a\cdot\frac{\frac{(G_E^n)^2+\tau(G_M^n)^2}{1+\tau}+2\tau(G_M^n)^2\tan^2\left(\frac{\theta_e}{2}\right)}{\frac{(G_E^p)^2+\tau(G_M^p)^2}{1+\tau}+2\tau(G_M^p)^2\tan^2\left(\frac{\theta_e}{2}\right)}, \tag{2.1}$$

where a is a purely kinematical factor. Figures 1 & 2 show the world data for G_E^n and G_M^n at low Q^2.

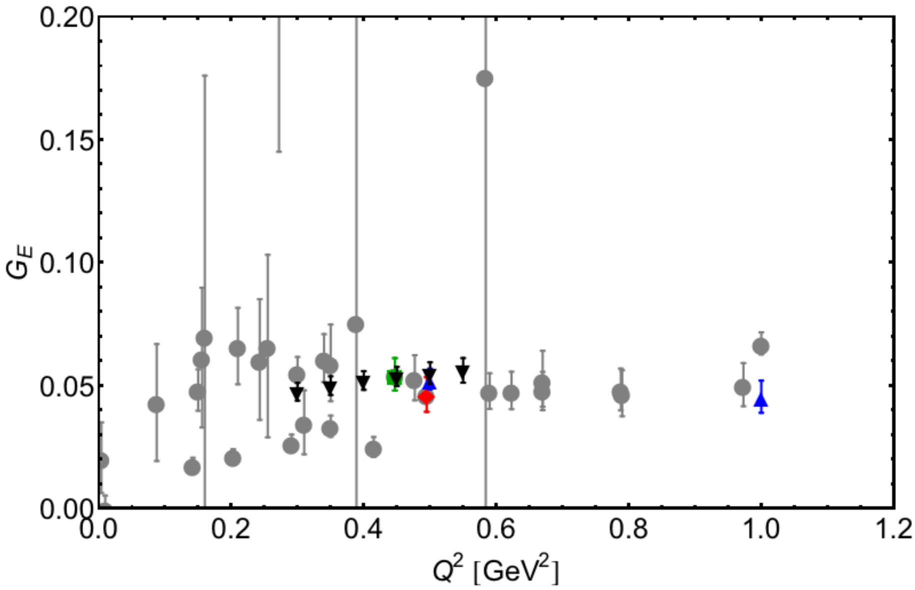

Figure 1: World data for G_E^n at low Q^2. Circles are non-JLab data. Squares are recoil polarization measurement [11], Rhomboids are beam target asymmetry measurements on polarized deuterium [12], triangles are beam target asymmetry measurements on polarized ^{3}He [13, 14].

3. JLab Proton Form Factor Measurements

Several proton form factor experiments have been performed at JLab, using the recoil polarization technique, mid-high Q^2 measurements [17, 18, 19, 20] have shown a steep decline of the proton form factor ratio ($\mathscr{R} \equiv \mu_p G_E^p/G_M^p$) from the ratio of near unity measured using Rosenbluth separation techniques. A later, high-precision Rosenbluth measurement at JLab [21] has confirmed the previous results of $\mathscr{R} \sim 1$. This discrepancy has been explained to some degree by correcting

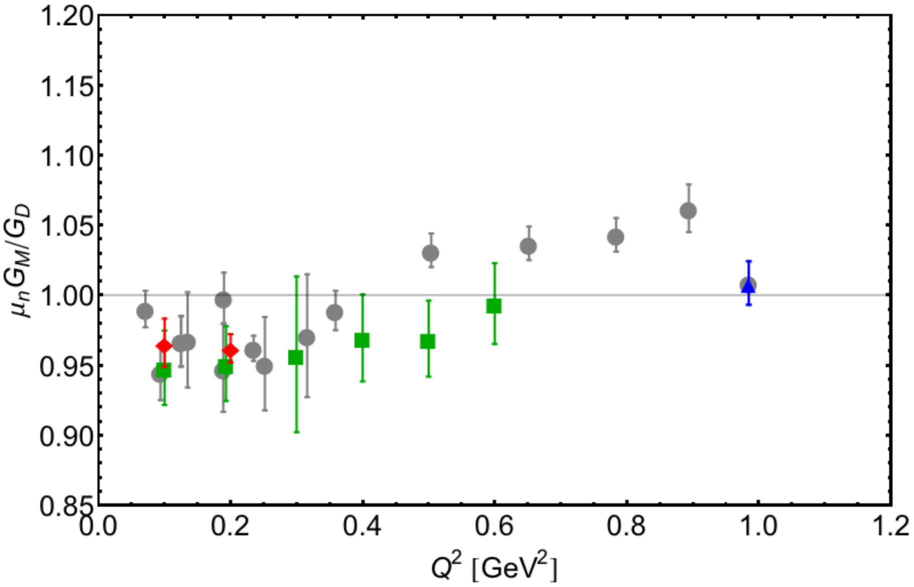

Figure 2: World data for G_M^n at low Q^2. Circles are non-JLab data. Rhomboids [13] and squares [15] are beam target asymmetry measurements on polarized ^{3}He, triangles are from ratio measurements of neutron to proton knockout from deuterium [16].

the Rosenbluth results to take into account 2γ exchange diagrams [22], which can be shown to affect the polarization results to a lesser degree.

Recently, an analysis of all four nucleon form factors [23] has suggested evidence for a narrow structure at Q^2 ~ 0.3 GeV^2 exhibited for all four form factors, also high precision data from the Bates BLAST experiment [24] has also shown indication of such a structure. A high precision investigation of the proton form factor ratio at Q^2 $\sim 0.25 - 0.5$ GeV^2 was carried out at JLab in order to better examine the low Q^2 region [25]. Results from [25] have conclusively shown a deviation of the form factor ratio from unity at low Q^2, furthermore, the deviation was attributed to a decrease of the electric form factor ratio from standard calculations and fits, as seen by using high precision cross section data together with the measured form factor ratio to extract the individual form factors. The experiment was unable, however, due to lack of statistics, to conclusively confirm or refute the existence of a narrow structure in the data. An analysis of high precision world low Q^2 data was able to show that the reduction of the form factor ratio from unity at low Q^2 can be attributed to a larger RMS radius of the proton transverse magnetic distribution than the transverse electric charge distribution [2].

In order to settle the question of the existence, or non existence, of such structures, as well as extend the range of high precision, low Q^2 measurements, a two part, high precision survey of the proton form factor ratio at JLab (experiment E08-007) was proposed and approved [26]. The first part of the experiment, using recoil polarization has already taken data for Q^2 $\sim 0.3 - 0.7$ GeV^2. The second part of the experiment, scheduled for 2012, will use the two identical Hall A spectrometers to simultaneously measure a beam target asymmetry off a polarized NH_3 target, for two different target spin orientations (with respect to $\vec{q}$) thus eliminating almost all systematic uncertainties stemming from beam and target polarization uncertainties.

Figure 3 shows the world data for the proton form factor ratio, along with the total (syst.+stat.) achieved in part I of E08-007 and the projected total uncertainties for part II of the same experiment. The extremely high precision achieved and planned, as well as the wide range of expected data points is evident.

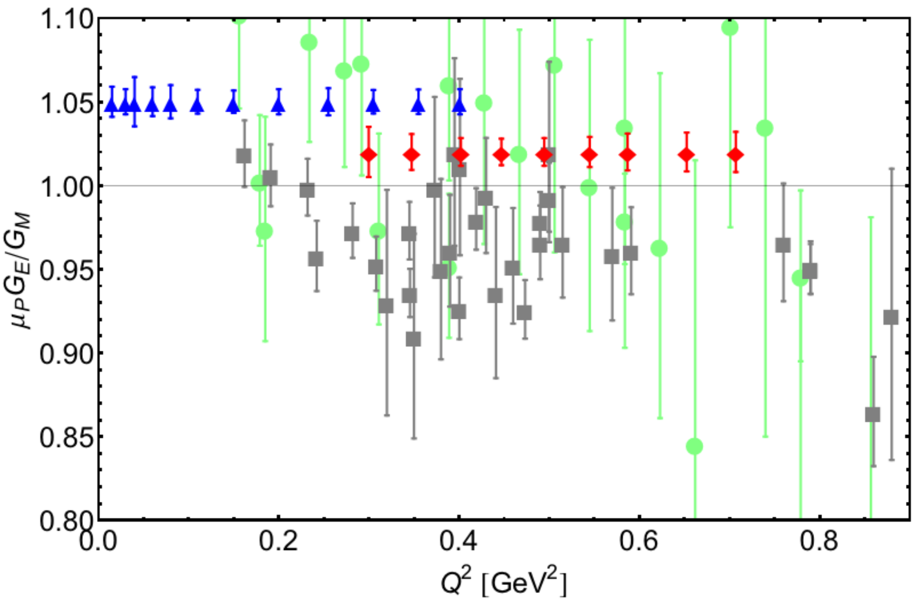

Figure 3: World data on the proton form factor ratio at low Q^2 together with achieved and projected uncertainties for JLab experiment E08-007. Rosenbluth, polarization, achieved uncertainties for E08-007 part I, and projected uncertainties for E08-007 part II are represented by circles, squares, rhomboids, and triangles, respectively.

4. Summary

In summary, the JLab low Q^2 experimental program has provided a rich data set on the nucleon form factors with unprecedented precision. Utilizing the unique features of the JLab experimental setup, namely, high beam polarization, polarized target setups, and high precision detectors we have been able to probe the nucleon structure to great precision. While the imminent JLab 12 GeV upgrade will present exciting new opportunities for high Q^2 measurements, it is expected that an even more precise, low Q^2, dataset will be achieved before the planned upgrade.

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