

# The Proton Form Factor Ratio Measurements at Jefferson Lab

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**Abstract.** The ratio of the proton form factors,  $G_{Ep}/G_{Mp}$ , has been measured from  $Q^2$  of 0.5 GeV<sup>2</sup> to 8.5 GeV<sup>2</sup>, at the Jefferson Laboratory, using the polarization transfer method. This ratio is extracted directly from the measured ratio of the transverse and longitudinal polarization components of the recoiling proton in elastic electron-proton scattering. The discovery that the proton form factor ratio measured in these experiments decreases approximately linearly with four-momentum transfer,  $Q^2$ , for values above  $\approx 1$  GeV<sup>2</sup>, is one of the most significant results to come out of JLab. These results have had a large impact on progress in hadronic physics; and have required a significant rethinking of nucleon structure. There is an approved experiment at JLab, GEp(5), to continue the ratio measurements to 12 GeV<sup>2</sup>. A dedicated experimental setup, the Super Bigbite Spectrometer (SBS), will be built for this purpose. In this paper, the present status of the proton elastic electromagnetic form factors and a number of theoretical approaches to describe nucleon form factors will be discussed.

## 1 Introduction

In three experiments, GEp(1) [1, 2], GEp(2) [3, 4] and GEp(3) [5], in Halls A and C at JLab, the ratio of the proton's electromagnetic elastic form factors,  $G_{Ep}/G_{Mp}$ , was measured up to four momentum transfer  $Q^2$  of 8.5 GeV<sup>2</sup> with high precision, using the recoil polarization technique. The initial discovery that the proton form factor ratio measured in these three experiments decreases approximately linearly with four-momentum transfer,  $Q^2$ , for values above  $\approx 1$  GeV<sup>2</sup>, was modified by the GEp(3) results, which suggests a slowing down of this decrease.

Use of the double-polarization technique to obtain the elastic nucleon form factors has resulted in a dramatic improvement of the quality of two of the four nucleon electromagnetic form factors,  $G_{Ep}$  and  $G_{En}$ . It has also changed our understanding of the proton structure, having resulted in a distinctly different  $Q^2$ -dependence for both  $G_{Ep}$  and  $G_{Mp}$ , contradicting the prevailing wisdom of the 1990's based on cross section measurements, namely that  $G_{Ep}$  and  $G_{Mp}$  obey a "scaling" relation  $\mu G_{Ep} \sim G_{Mp}$ . A related consequence of the faster decrease of  $G_{Ep}$  revealed by the Jefferson Lab (JLab) polarization results was the disappearance of the early scaling of  $F_2/F_1 \sim 1/Q^2$  predicted by perturbative QCD.

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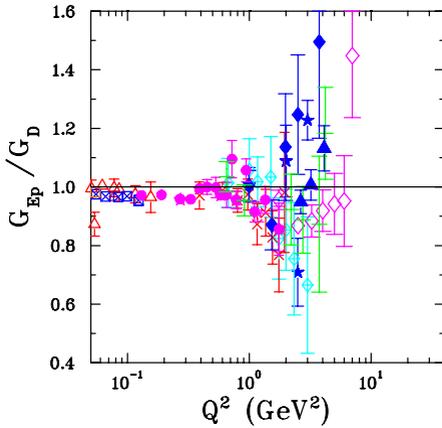
## 2 Elastic ep cross section and form factors

In terms of the electric and magnetic Sachs form factors,  $G_E$  and  $G_M$ , the lab cross section for elastic  $ep$  scattering can be written as:

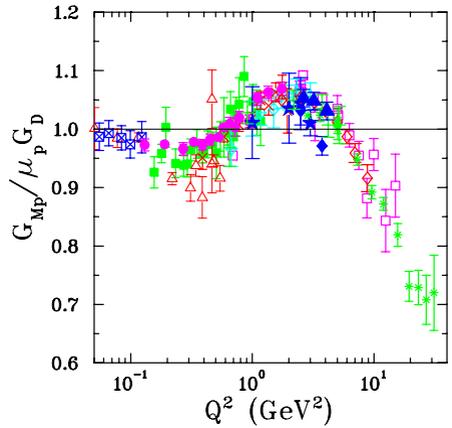
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_{Mott}} \frac{G_{Ep}^2 + \frac{\tau}{\varepsilon} G_{Mp}^2}{1 + \tau}, \quad (1)$$

where where  $\tau = \frac{Q^2}{4m_p^2}$  is the dimensionless 4-momentum transfer squared, and  $\varepsilon$  is the longitudinal polarization of the virtual photon,  $\varepsilon = [1 + 2(1 + \tau) \tan^2 \frac{\theta_e}{2}]^{-1}$ ;  $\theta_e$  is the lab electron scattering angle. Equation 1 leads to a simple separation method for  $G_{Ep}^2$  and  $G_{Mp}^2$ , referred to as Rosenbluth (or LT) separation [6].

In the Rosenbluth method, the separation of  $G_{Ep}^2$  and  $G_{Mp}^2$  is achieved by fitting data with a straight line fit at a given  $Q^2$  over a range of  $\varepsilon$  obtained by changing the beam energy,  $E_e$  and electron scattering angle,  $\theta_e$ . The form factors,  $G_{Ep}$  and  $G_{Mp}$ , obtained from all cross section measurements are shown in Fig. 1 and 2; they have been divided by the dipole form factor  $G_D = (1 + \frac{Q^2}{0.71})^{-2}$ . Evidently the form factors divided by  $G_D$  appear to remain close to 1. This behavior suggested that  $G_{Ep}$ , and  $G_{Mp}$  have similar spatial distributions.



**Figure 1.** World data base for  $G_{Ep}$  obtained by the Rosenbluth method.



**Figure 2.** World data base for  $G_{Mp}$  obtained by the Rosenbluth method.

## 3 Recoil Polarization Method

The relationship between the Sachs electromagnetic form factors and the polarization transfer to the recoil proton in  $^1H(\vec{e}, e'\vec{p})$  scattering was first developed by Akhiezer and Rekalov [7], and later discussed in more detail by Arnold, Carlson, and Gross [8]. For single photon exchange, the 3 components of the transferred polarization are:

$$P_n = 0 \quad (2)$$

$$hP_e P_\ell = hP_e \left( \frac{E_e + E'_e}{m_p} \right) \frac{\sqrt{\tau(1+\tau)} G_{Mp}^2(Q^2) \tan^2 \frac{\theta_e}{2}}{G_{Ep}^2(Q^2) + \frac{\tau}{\varepsilon} G_{Mp}^2(Q^2)} \quad (3)$$

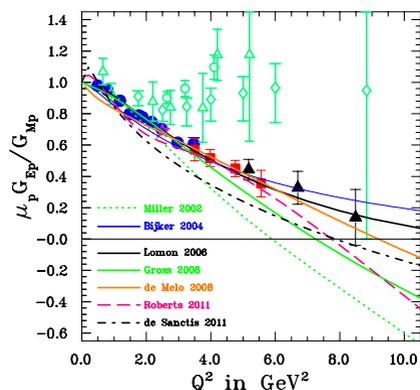
$$hP_e P_t = hP_e \frac{2\sqrt{\tau(1+\tau)} G_{Ep} G_{Mp} \tan \frac{\theta_e}{2}}{G_{Ep}^2(Q^2) + \frac{\tau}{\varepsilon} G_{Mp}^2(Q^2)} \quad (4)$$

for the normal, in-plane longitudinal and transverse polarization components  $P_n$ ,  $P_\ell$  and  $P_t$ , respectively; the  $h = \pm$  stands for the electron beam helicity, and  $P_e$  for the electron beam polarization.

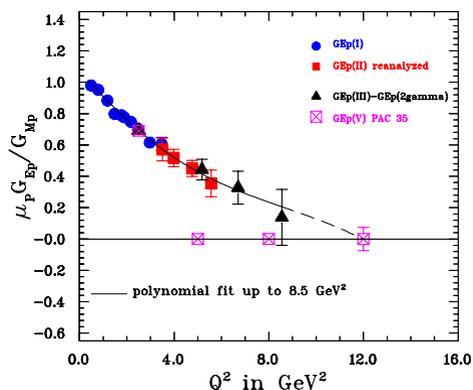
For each  $Q^2$ , a single measurement of the azimuthal angular distribution of the proton scattered in a secondary target gives both the longitudinal and transverse polarizations. Combining Eqs. 3 and 4 directly provides:

$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_\ell} \frac{(E_e + E'_e)}{2m_p} \tan \frac{\theta_e}{2}; \quad (5)$$

The striking disagreement of the polarization data with the Rosenbluth results is illustrated in Fig. 3; the Refs. to the various curves are [9–15].



**Figure 3.** The ratio  $\mu_p G_{Ep}/G_{Mp}$  obtained in polarization transfer experiments shown as filled symbols, refs. [1–5, 16]. Empty symbols: Rosenbluth results of refs. [17–19].



**Figure 4.** The three data points to be obtained in the GEp(5) experiment [20]. The solid line is a polynomial fit to the existing data, extrapolated as dashed line.

## 4 The Super Bigbite Spectrometer

Measurements of  $G_{Ep}/G_{Mp}$  and  $G_{En}$  from elastic **ep** or **en** scattering, to yet larger  $Q^2$ , requires a new approach, largely because of the rapid decrease of both the elastic scattering cross sections and of the  $p\text{CH}_2$  analyzing power  $A_y$  with increasing  $Q^2$ .

The approved Super Bigbite Spectrometer project at JLab Hall A [21], or SBS was originally conceived to allow measurement of  $G_{Ep}/G_{Mp}$  to up to  $15 \text{ GeV}^2$  (GEp(5))[20]. On the proton side it consists of a dipole with horizontal B-field and very large aperture. The resulting high flux of low energy photons will be overcome by using GEM detectors. For GEp(5) (currently approved to  $12 \text{ GeV}^2$ ), a double polarimeter with 2  $\text{CH}_2$  analyzers and 2 GEM detector clusters, is being built. The trigger for the proton arm will be generated in the hadron calorimeter downstream from the polarimeter.

The electron will be detected in a new electromagnetic calorimeter, preceded by a GEM coordinate detector. The anticipated error bars and  $Q^2$  values are shown in Fig. 4.

## 5 Conclusions

Much has happened since the results of the first JLab **ep** form factor double-spin experiment, which challenged 50 years of cross section measurements. A recent measurement of  $G_{Ep}/G_{Mp}$  has reached

the maximum  $Q^2$  value of  $8.5 \text{ GeV}^2$ , and indicates that the quasi-linear decrease of this ratio most likely comes to an end in this range of  $Q^2$ -values.

The high- $Q^2$  surprise in  $G_{Ep}/G_{Mp}$ , have led to a several fundamental changes in the picture of the internal structure of the proton, and a revival of interest for elastic form factor data among nuclear theorists.

The recent results from double polarization experiments for the proton, together with the anticipated results following the 12 GeV upgrade of the JLab accelerator, will provide answers to a number of open questions crucial to the understanding of fundamental properties of the proton, and the nature of QCD in the confinement regime.

## 6 Acknowledgments

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