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Overview of nucleon form factor experiments with 12 GeV at Jefferson Lab

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Abstract. Since the R. Hofstadter pioneering experiments in the '50s, the measurements of the electromagnetic space-like nucleon form factors (FF's) have been a precious source of information for the understanding of the internal structure of the nucleons.

In the last 15 years, the polarization transfer experiments at the Thomas Jefferson National Accelerator Facility (JLab) have undermined our view of the mechanism of the electron scattering and renewed critical interest in the FF measurements.

In the coming years, JLab, with its upgraded 12 GeV polarized, high intensity, electron beam combined to new targets and readout equipments, will offer unprecedented opportunities to extend the current proton and neutron FF's measurements to higher momentum transfer Q^2 and to improve statistical and uncertainties at lower Q^2, where the nucleon size can be accurately investigated.

The measurements at high Q^2 will provide also new insights on the elusive quark orbital angular momenta, will contribute to constraint two of the nucleon Generalized Parton Distributions that are expected to describe more consistently the nucleon structure, and in general will test the validity of quite a few fundamental nucleon models in a region of transition between perturbative and non perturbative regimes.

A selection of the relevant properties of the FF's, and the main results of JLab are shortly reviewed; the new proposed and approved experiments on FF's at JLab are presented addressing some key details, the expected experimental achievements and the new equipment designed for them.

1. Introduction

The nucleon (proton or neutron) has an internal, spatially extended, structure [1, 2].

In the Breit frame of the elastic electron-nucleon scattering[1] the electromagnetic structure of the nucleon can be described by two functions, the Sachs FF's [3]:

$$G_{E(M)}(Q^2) = \int \rho_{E(M)}(\vec{r})\, e^{i\vec{q}\cdot\vec{r}} d^3\vec{r}$$

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[1] In the Breit frame the initial and the scattered nucleons have opposite 3-momenta (no energy transferred) which implies $Q^2 = \vec{q}^2$.

where $\rho_E(\vec{r})$ and $\rho_M(\vec{r})$ are the spatial charge and magnetization density distributions respectively, $\vec{q}$ is the 3-momentum transfer.

In this context, the nucleon electromagnetic current is described, in one photon exchange approximation, by the Dirac (F_1) and Pauli (F_2) scalar FF's which are linear combinations of the Sachs FF's. F_1 and F_2 are normalized at $Q^2 = 0$ to the nucleon charge and anomalous magnetic moment.

In the multipole expansion, the slopes of the Sachs FF's at $Q^2 = 0$ define the charge and magnetic radii of the nucleon by

$$\langle r^2 \rangle_{E,M} = -6 \left. \frac{dG_{E,M}(Q^2)}{dQ^2} \right|_{Q^2=0}$$

The individual contributions to the FF's of the nucleon constituents F_i^q are defined by [4]: $F_i = \sum_q e_q F_i^q$ here q is the constituent index, e_q its charge.

In the unified framework that consistently links the descriptions of the nucleon structure in the different scattering processes (elastic, deep inelastic, ...), the Dirac and Pauli FF's can be expressed as $F^q_{(1,2)}(Q^2) = \int_{-1}^{1} dx\ (H, E)^q(x, \xi, Q^2)$ where H^q and E^q are two of the four Generalized Parton Distributions [5], directly related to the quark orbital angular momentum J^q (in the Ji decomposition of the nucleon spin): $2J^q = \int_1^1 x dx\, [H^q(x, \xi, 0) - E^q(x, \xi, 0)]$

The above properties make evident the FF's key role in the investigation of the nucleon (hadrons) structure; any "fundamental" theory that aims to describe the nucleon structure must be able to calculate the FF's and likely predict them correctly.

From the experimental point of view the FF's are measured by elastic electron-scattering[2] by means of different methods, among them:

- Rosenbluth separation: the traditional method dominating the first 30 years of measurements; in one photon exchange approximation, the unpolarized e-p reduced elastic cross section is basically proportional to the Sachs FF's $d\sigma_r/d\Omega = \varepsilon\ G_E^2(Q^2) + \tau\ G_M^2(Q^2)$ with the kinematic variables $\varepsilon = 1/\left(1 + 2(1+\tau)\tan^2(\theta_e/2)\right)$ and $\tau = Q^2/(4M^2)$, being θ_e the electron scattering angle and M the mass of the nucleon. Measuring the cross sections for different scattering angles, the FF's can be extracted by a linear fit; in this way both G_E and G_M can be determined, with sensitivity depending on τ which suppress G_E at high Q^2 and G_M at low Q^2.
- Polarization transfer: as suggested by Akhiezer et al. [7], polarized electron-nucleon elastic scattering permits to measure the interference term $G_E G_M$ improving the accuracy of the measurements of the suppressed factor; unfortunately experiments with polarized particles (and adequate luminosity in lepton scattering) requires advanced technologies which has consolidated only in the recent years. In $\mathrm{H}(\vec{e}, e'\vec{p})$ and $^2\mathrm{H}(\vec{e}, e'\vec{n})\mathrm{H}$ the polarized electron transfers its polarization to the scattered nucleon, such that (in one photon exchange approximation):

$$\frac{P_t}{P_l} \tan\left(\frac{\theta}{2}\right) \propto -\frac{G_E}{G_M}$$

  where P_t and P_l are the transverse and longitudinal polarization components (in the scattering plane) of the recoil nucleon.
- Double polarization: similarly to the polarization transfer, in elastic polarized scattering $\overrightarrow{\mathrm{H}}(\vec{e}, e'p)$ or $^3\overrightarrow{\mathrm{He}}(\vec{e}, e'n)$ the beam-target asymmetry A, at first approximation, is proportional to G_E/G_M.

[2] The present discussion is limited to the space-like FF's which are accessible at JLab. For a recent review on time-like FF's refer to [6].

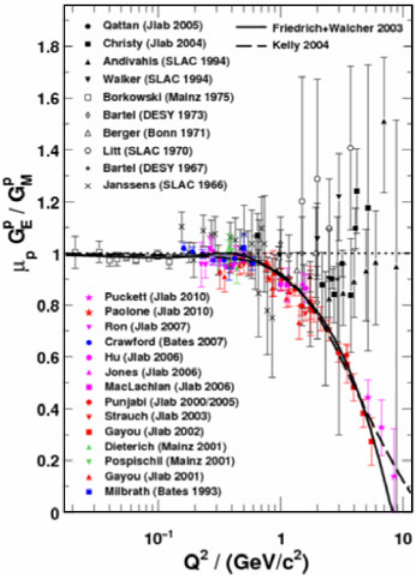


Figure 1. Current experimental status on the Sachs FF's ratio in the proton (black curves are phenomenological fits, the dotted line at $R_p = 1$ represents the dipole model), plot is from [8]; the fit of the measurements by means of the polarization transfer method (referred by the bottom half of the labels in the plot) provides $R_p(Q^2) \approx 1 - 0.13\left(Q^2 - 0.29\right)$ in evident disagreement with the Rosenbluth data (referred by the upper half of the labels in the plot). The discrepancy has triggered a renewed theoretical and experimental activity: currently the most favorite candidate that could explain it is the two photon exchange (TPE) [9] in the elementary process; in fact the Rosenbluth method is more sensitive to the TPE, while in the experiments that involve the interference term, the effects mainly cancel out. Three experiments (Novosibirsk/VEPP-3, JLab/CLAS and DESY/OLYMPUS) are currently trying to measure the TPE effect by e^-/e^+ asymmetry; the preliminary results from VEPP-3[10] seem to confirm the somehow unexpected relevance of the TPE in elastic scattering and in the Rosenbluth separation in particular.

2. Quick glance on experimental status of FF's

All measurements since the pioneering experiments at SLAC in the '50 [2] till the end of the last century have been performed using the Rosenbluth separation[3]. Those measurements support the dipole description of the FF's $G_D(Q^2) = \left[1 + Q^2/0.71\right]^{-2}$ corresponding to a nucleon spatial distribution of the form $\rho(r) \sim \rho(0)/\left(1 + e^{(r-c)/a}\right)$. In addition, the proton $R_p(Q^2) \equiv \mu_p G_E^p / G_M^p \approx 1$ (μ_p is the magnetic moment) seems to be fairly constant with Q^2, despite the large fluctuations and errors at larger Q^2.

This apparent consolidated situation has been mined by a new class of measurements of R_p performed at JLab in the past decade[12] by means of the polarization transfer method at relatively high $1 < Q^2 < 8$ GeV/c^2 as shown in Fig. 1 and detailed in the relative caption.

A new framework has emerged where polarized experiments, thanks to the latest development in polarizing beam, target and instrumentation, are considered the most reliable source of FF's data; many theoretical models are trying to explain the $R_p(Q^2)$ behavior and most of them reproduce reasonably well the available data ($Q^2 < 8.0$ GeV^2) but diverge at larger Q^2, in the unexplored region.

In terms of Dirac and Pauli FF's, the pQCD[4] predicts an asymptotic value of $F_2/F_1 \sim 1/Q^2$ while the new measurements seems to indicate the presence of a logaritmic function of Q^2 which modified pQCD models associate to the quark orbital angular momentum and gluon polarization effects.

Also at low Q^2 the situation has been recently broken up by a precise measurement of the proton radius by μp Lamb shift [14] which is 7.9 sigmas off the average measurements by *ep* scattering and hydrogen spectroscopy. The inconsistency could be related to the same effect that explain the high Q^2 behavior of the Rosenbluth measurements [9].

In the neutron case, R_n has measured up to $Q^2 < 4$ GeV^2. In this case the most reliable measurements have been done with the double polarization method, since the Rosenbluth separation is affected by large nuclear structure correlations (no free neutron target). Again different models

[3] There is a remarkable exception [11] that for the first time used the polarization transfer method, but at $Q^2 < 1$.

[4] Taking into account quark helicity conservation, the counting rules for gluon ($1/Q^2$), helicity flip ($1/Q^2$) and the mechanism of strong interaction via two gluon exchange, $F_1 \sim 1/Q^4$ while $F_2 \sim 1/Q^6$. Two gluon exchange mechanism seems to be suppressed according to recent measurement of Real Compton Scattering [13].

Table 1. Approved experiments on Form Factors at JLab with 12 GeV maximum energy beam. Proposals are available at [15].

Hall	Experiment	Title	Q^2 (GeV^2)
A	E12-07-108	Precision Measurement of the Proton Elastic Cross Section at High Q^2	up to 18
A	E12-07-109	Large Acceptance Proton Form Factor Ratio Measurements at 13 and 15 (GeV/c)^2 using Recoil Polarization Method	up to 12
A	E12-09-019	Precision Measurement of the Neutron Magnetic Form Factor up to $Q^2 = 18.0$ (GeV/c)^2 by the Ratio Method	up to 14
A	E12-09-016	Measurement of the Neutron Electromagnetic Form Factor Ratio G_E^n/G_M^n at High Q^2	up to 10
B	E12-07-104	Measurement of the Neutron Magnetic Form Factor at High Q^2 Using the Ratio Method on Deuterium	up to 14
C	E12-11-009	The Neutron Electric Form Factor at Q^2 up to 7 (GeV/c)2 from the Reaction $^2H(e,e'n)^1H$ via Recoil Polarimetry	up to 7
B	E12-11-106	High precision measurement of the proton charge radius [16]	$10^{-4} - 10^{-2}$

reproduce the data, but at large Q^2 their predictions tend to diverge very significantly. Constituent quark model overestimate the data, as does pQCD log scaling.

The new accumulated data, both on neutron and proton have recently permitted the extraction, with excellent accuracy, the up and down flavor components of the FF's[17]. Two rather surprising effects have emerged: Q^2 scaling of up and down $F_{1,2}$'s are different: d quark tends to saturate much earlier at around 2 GeV^2, and the ratios of F_2/F_1 for the two flavors seem to be constant after $Q^2 > 2$ GeV^2. A possible interpretation of these features is a diquark model of the nucleon [18]. In this decomposition the strange contribution to the FF's of the nucleon has been assumed to be 0, according to the available data, mostly taken ad JLab before the upgrade [19].

3. Near future JLab experiments on FF's

In summary the current theoretical and experimental status on FF's (and nucleon structure in general) clearly and strongly demand to refine our understanding at larger value of Q^2 (where fundamental models differ significantly, apparent scaling behaviour of the form factor components needs to be confirmed, FF's are a constrain for the GPD's, relevance of the pQCD should emerge) as well as at small Q^2 (importance of pion cloud effects, needs of a precise nucleon size estimation).

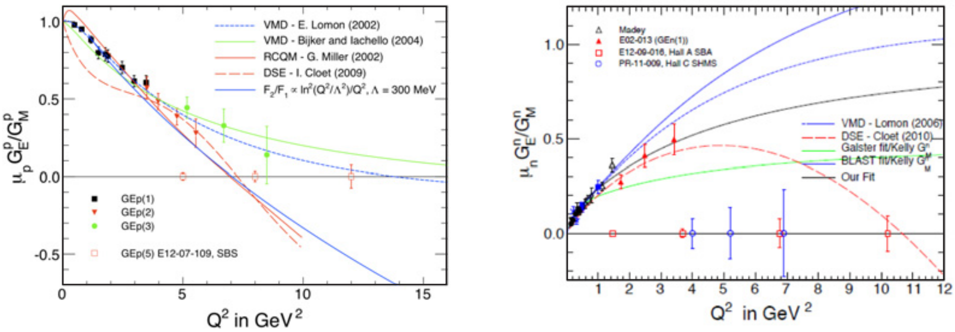
In both of these directions, Jeffersonal Lab, has played and/or is going to play a leading role thanks to the almost completed upgrade of the CEBAF polarized electron beam (doubled maximum energy) [20] combined with high beam intensity and new experimental equipments able to either operate in high luminosity or to cover large kinematical phases.

A list of already approved experiments to be performed in the experimental Halls of JLab is presented in Table 1. Basically all nucleon form factors will be measured in currently unexplored regions of Q^2, basically exploiting all possible methods. The most extended program will be carried on in Hall A, the largest experimental Hall, that can host different (and large) equipment.

Of all these experiments, the measurement of the proton form factor ratio at high Q^2 (E12-07-109 or GEp5) is likely the most demanding; in fact the Figure of Merit (FOM) of the experiment can be expressed by:

$$\mathrm{FOM_{GEp5}} \propto \frac{\epsilon^{pp} \cdot P_e^2 \cdot \Omega \cdot L}{Q^{16}} \cdot \frac{E^2 \tan^{-2}\frac{\theta}{2}}{(E+E')^2}$$

where ϵ^{pp} is the proton polarimeter efficiency, P_e the beam polarization, Ω the angular phase space, L the luminosity, and the other kinematical factors account for the elastic cross section and polarimeter



Top-left: E-12-07-109 (GEp5) by polarization transfer.
Top-right: E-12-09-016/E12-11-009 by polarization transfer and double polarization.
Bottom-right: E-12-09-019/E12-07-104 by cross section ratio.

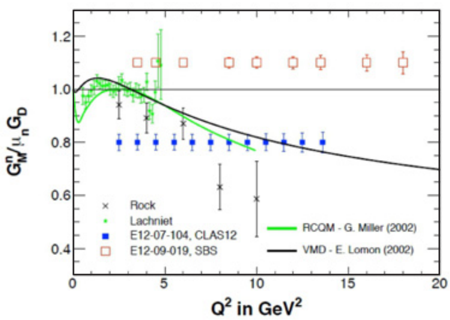


Figure 2. Expected accuracy in the new FF's experiments at JLab.

analyzing power. The large drop of Q^{-16} (mainly due to the elastic cross section) is compensated by the highest achievable luminosity (up to $10^{39}/\text{cm}^2/\text{s}$), beam polarization (as high as 85%), large acceptance ($\Omega \sim 50$ msr) and efficient detectors (including the proton polarimeter) specifically designed for the new Super BigBite Spectrometer (SBS)[21].

GEp5 is the latest of a series of successful JLab experiments that have measured, for the first time, the almost linear decrease of the electromagnetic proton form factor ratio G_E^p/G_M^p with Q^2. GEp5 will extend the previous measurements to higher Q^2 where a possible deviations from linearity is likely expected.

SBS will be used, in different configurations, in two other FF's experiments of the HallA: the measure of the neutron G_E^n/G_M^n (by double polarization) and the measurement of the neutron magnetic FF (by deuteron cross sections ratio). In particular in the double polarization experiment with polarized ^{3}He and FOM $\sim E^2/Q^{12}$ (being E the beam energy), the SBS magnet will be used to deflect the scattered charged particles to improve the neutron identification by a dedicated segmented calorimeter; in this experiment a new ^{3}He target based on spin-exchange by optical pumping, convection gas flow into the target cell, is expected to provide polarization larger than 50%.

A different experimental approach will be used in the measurement of G_E^n/G_M^n by polarization transfer in Hall C; here a segmented neutron polarimeter based on scintillators will be used and the proton struck by the analyzed (rather than the scattered neutron) will be detected. The total error will be dominated by the statistics error and therefore the highest luminosity ($10^{39}/\text{cm}^2/\text{s}$) will be used with a liquid deuteron target.

4. Conclusion

The plots in Fig. 2 summarize the expected results from all JLab approved experimental proposals on FF's at high Q^2; the new data will undoubtedly shed light on unexplored regions likely transition between non perturbative and perturbative regime; accuracy of the data will clearly permit the confutation or confirmation of rather fundamental models on nucleon structure; moreover they will provide hints on the role of quark orbital angular momentum and permit to extend the FF's flavor decomposition in a very interesting and discriminating Q^2 region.

The FF's experimental program at JLab will likely start taking data in the coming few years; it includes many experimental and theoretical aspects; some of them has been shortly addressed in this work.

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