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# MEASUREMENTS OF THE NUCLEON FORM FACTORS AT LARGE MOMENTUM TRANSFERS*

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## ABSTRACT

New measurements of the electric $G_E(Q^2)$ and magnetic $G_M(Q^2)$ form factors of the nucleons are reported. The proton data cover the $Q^2$ range from 1.75 to 8.83 (GeV/c)$^2$ and the neutron data from 1.75 to 4.00 (GeV/c)$^2$, more than doubling the range of previous data. Scaled by the dipole fit, $G_D(Q^2)$, the results for $G_{Mp}(Q^2)/\mu_p G_D(Q^2)$ decrease smoothly from 1.05 to 0.92, while $G_{Ep}(Q^2)/G_D(Q^2)$ is consistent with unity. The preliminary results for $G_{Mn}(Q^2)/\mu_n G_D(Q^2)$ are consistent with unity, while $G^2_{En}$ is consistent with zero at all values of $Q^2$. Comparisons are made to QCD Sum Rule, di-quark, constituent quark, and VMD models, none of which agree with all of the new data.

## I. INTRODUCTION

Elastic electron-nucleon scattering, mediated by the exchange of a virtual photon is described in terms of the electric $G_E$ and magnetic $G_M$ form factors of the nucleons. They contain all the information about the deviation from pointlike behavior of the photon interaction with the charge and magnetization current distribution of the nucleons. Previously measured proton form factors [1] have been found to be approximated to the 5–10% level by a dipole fit:

$$G_D(Q^2) = \left(1 + \frac{Q^2}{0.71}\right)^{-2}$$

$$\approx \frac{G_{Mp}(Q^2)}{\mu_p} \approx G_{Ep}(Q^2)\,,$$

where $\mu_p$=2.79 nm is the proton magnetic moment and $Q^2 = q^2 - \nu^2$ with $\vec{q}$ and $\nu$ being the momentum and energy transfer to the nucleon. The neutron magnetic form factor was also fairly well described by the dipole fit:

$$\frac{G_{Mn}(Q^2)}{\mu_n} \approx G_D(Q^2)\,,$$

while the electric form factor $G_{En}(Q^2)$ was found to be positive, but close to zero [1].

The virtual photon interaction is thought to be composed of two pieces: a part mediated by the exchange of vector mesons at low $Q^2$ and a part involving direct interaction with the nucleon or its constituents at large $Q^2$. In the Vector Meson Dominace (VMD) picture, the form factors are expressed in terms of photon-meson coupling strengths and meson-nucleon vertex form factors. VMD parametrizations have given fair descriptions [2] of the existing low $Q^2$ data. For $Q^2 >> M_N^2$, where $M_N$ is the nucleon mass, quark counting scaling and the use of perturbative QCD predict that $G_{Mp} \sim 1/Q^4$, with the magnitute being sensitive to the valence quark distribution amplitudes [3]. Recently there have been calculations [4] trying to describe the intermediate $Q^2$ range. Gari and Krümpelmann (GK) have developed a phenomenological model using the VMD form at low $Q^2$ and the asymptotic QCD form at high $Q^2$ to fit the existing data. Other approaches include the relativistic constituent quark model, the use of QCD Sum Rules to make absolute predictions, and a diquark model which fits data for $Q^2 > 3$ (GeV/c)$^2$.

## 2. EXPERIMENT

The present experiment, SLAC NE11, improves the precision of previous experiments and extends the $Q^2$ range by more than a factor of two. The experiment was performed at the Stanford Linear Accelerator and used beams from the Nuclear Physics Injector with energies, $E$, from 1.5 to 9.8 GeV and average currents from 0.5 to 10 $\mu$A. Electrons scattered from 15 cm long liquid hydrogen and deuterium targets were simultaneously detected in two magnetic spectrometers, one on each side of the beam line. The SLAC 8 GeV/c spectrometer was set at central electron scattering angles, $\theta$, between 15° and 90° and central momenta, $E'$, between 0.5 and 7.5 GeV/c. The 1.6 GeV/c spectrometer, modified by adding a quadrupole doublet to quadruple its solid angle, detected electrons with momenta between 0.5 and 0.8 GeV/c and was fixed at 90°. Shower counters, Čerenkov counters and wire chambers were used in both spectrometers to measure particle trajectories and to distinguish electrons from pions and other backgrounds.

## 3. PROTON FORM FACTORS

The proton form factors were determined by first converting the experimental elastic $e$-$p$ cross sections, $\sigma(E,\theta)$, corrected for radiative effects, to reduced cross sections $\sigma_R$:

$$\sigma_R(Q^2,\epsilon) = \epsilon\left(1+\frac{1}{\tau}\right)\frac{E}{E'}\frac{\sigma(E,\theta)}{\sigma_{\rm Mott}}$$
$$= G^2_{M_p}(Q^2) + \frac{\epsilon}{\tau}G^2_{E_p}(Q^2)\,,$$

where

$$\tau = \frac{Q^2}{4M_p^2}\,,\qquad \epsilon = \left[1+2(1+\tau)\tan^2\left(\frac{\theta}{2}\right)\right]^{-1}\,,$$

and $\sigma_{\rm Mott}$ is the Mott cross section. Linear fits to the reduced cross sections at each value of $Q^2$ were performed to obtain $G_{E_p}$ from the slope and $G_{M_p}$ from the intercept (Rosenbluth separation method). The extracted [5] proton form factors, scaled by the dipole fit, are shown in Fig. 1. The results at $Q^2$=8.83 (GeV/c)$^2$ were obtained by combining our backward angle data with previous forward angle data [1] normalized to the present experiment at $Q^2$=5 (GeV/c)$^2$. The new data for both $G_{E_p}$ and $G_{M_p}$ are in reasonable agreement with previous lower $Q^2$ data [1].

The new data for $G_{M_p}$ are in fairly good agreement with three commonly-used VMD fits to previous data: Höhler *et al.* [2] (long dashed curves), Iachello, Jackson, and Lande [2] (IJL, dotted curves), and the GK fit [4] (solid curves). The data for $G_{E_p}$ lie above all these fits for $Q^2 > 3$ (GeV/c)$^2$, and are in especially poor agreement with the IJL fit. The simple dipole form actually shows the best agreement with the $G_{E_p}$ data. For $Q^2 \geq 4$ (GeV/c)$^2$, both $G_{M_p}$ and $G_{E_p}$ are in fair agreement with the prediction of Radyushkin [4], (dash-dotted curves), which used QCD Sum Rules to fix the parameters of the soft quark wave functions and incorporates local quark-hadron duality to calculate the form factors. One of the diquark model fits of Kroll *et al.* [4] (short dashed curves) is in better agreement with the $G_{M_p}$ data than the $G_{E_p}$ data. This model views the proton as built up from quarks and diquarks, the latter being treated as quasi-elementary particles. The relativistic constituent-quark calculations of Chung *et al.* [4] are sensitive to parameters such as the effective quark mass, quark wavefunction, and confinement scale. The predictions using a representative choice of parameters

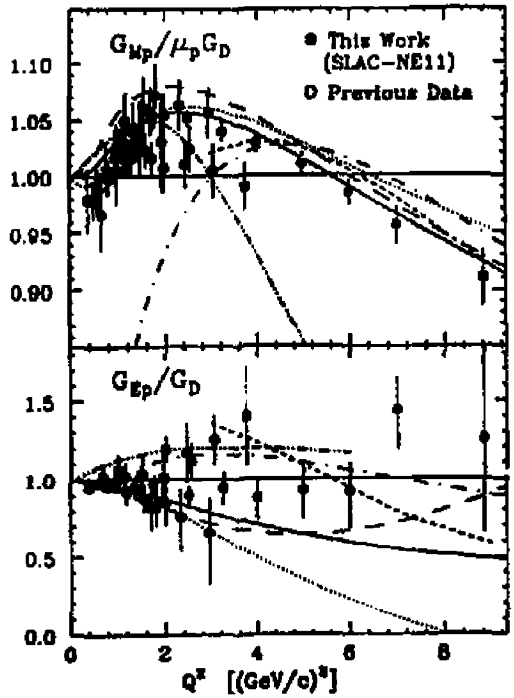


Figure 1. Proton form factors, scaled by the dipole fit, along with previous data and theoretical calculations (see text). Error bars include statistical and point-to-point systematic errors.

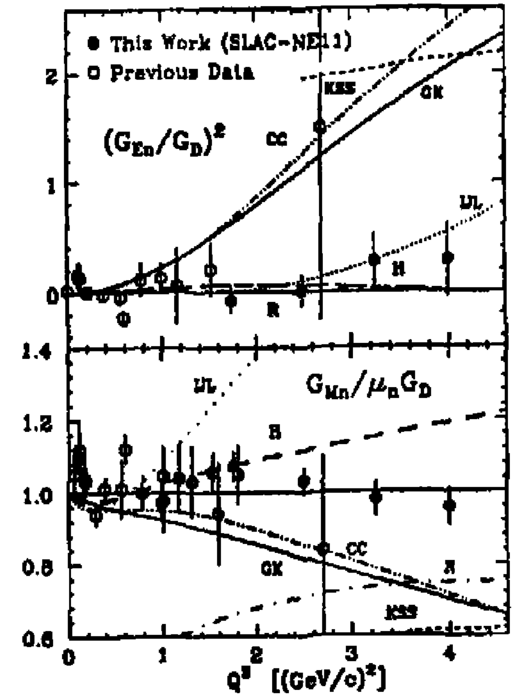


Figure 2. Preliminary neutron form factors, scaled by the dipole fit, along with previous data and theoretical calculations (see text). Error bars include statistical and point-to-point systematic errors.

(dash double-dotted curves) lie above the $G_{Ep}$ data, and underestimate $G_{Mp}$ above $Q^2 = 2$ (GeV/c)$^2$.

## 4. NEUTRON FORM FACTORS

Quasi-elastic *e-d* cross sections, sensitive to the incoherent sum of scattering from a proton and a neutron, were extracted from the radiatively corrected measured inclusive spectra, after subtracting the inelastic contributions. These contributions were calculated using a Fermi-smearing model to convolute measured proton resonance region data with the deuteron wavefunction $\psi(k)$ and were fit to the deuterium data in the same region.

A reduced cross section per nucleon for quasi-elastic scattering was defined as:

$$\sigma_R(Q^2,\nu,\epsilon) = \epsilon(1+\tau')\,\frac{\sigma(E,E',\theta)}{\sigma_{\rm Mott}}$$

$$= R_T + \epsilon R_L\ ,$$

where $\tau' = \nu^2/Q^2$. The neutron form factors were extracted by a Rosenbluth separation of the nuclear response functions $R_T$, $R_L$ using our proton form factor measurements and a simplified form of McGee's [6] nonrelativistic Plane Wave Impulse Approximation quasi-elastic model:

$$R_{T,L} = \frac{M_N^2}{2q}\,G_{T,L}\int_{k_{\rm min}}^{k_{\rm max}} \frac{\psi^2(k)}{\sqrt{k^2+M_N^2}}\,k\,dk\ ,$$

where

$$G_T = \tau'(G_{Mp}^2 + G_{Mn}^2)\ , \qquad G_L = G_{Ep}^2 + G_{En}^2\ ,$$

and $k_{\rm min}, k_{\rm max}$ are the extreme values of the Fermi momentum of the struck nucleon. The results, shown in Fig. 2, were fairly insensitive to the choice of different $\psi(k)$'s used in the quasi-elastic model (Paris, Bonn and Reid Soft Core). A greater sensitivity was observed in the shape of the inelastic model, though the results were still within the error bars of Fig. 2.

It can be seen in Fig. 2 that the new neutron form factor data show much larger discrepancies with models that do the proton form factors. Among the VMD models, the IJL model [2] (dotted curves) is very poor at high $Q^2$ for $G_{Mn}$, while the Höhler fit[1] (H, dashed curves) is considerably better for both form factors. The GK fit [4] (solid curves) is completely ruled out by the $G_{En}$ data. The diquark model [4] (KSS, short-dash curves) which did reasonably well for the proton does extremely poorly for both $G_{En}$ and $G_{Mn}$. Like the GK fit, the relativistic constituent quark model [4] (CC, dash-double dotted curves) predicts $G_{En} = -\tau G_{Mn}$, and is also in poor agreement with the data for $G_{En}$. Finally, the Radyushkin QCD Sum Rule predictions [4] (R, dash-dotted curves) are in reasonable agreement with $G_{En}$, and approach the $G_{Mn}$ data at higher $Q^2$, where the calculations are expected to be valid. The best description of the data, however, is simply given by the dipole fit for $G_{Mn}$ and $G_{En}^2 = 0$. It can be seen from a careful comparison of Figs. 1 and 2 that the present data for $G_{Mn}, G_{Ep}$, and $G_{Mp}$ are all consistent with form factor scaling, perhaps implying that the spatial charge and magnetization distribution of the proton are similar even at small distance scales, and that the magnetization distribution of the proton and neutron are also very similar.

## 5. CONCLUSIONS

This experiment has extended the range over which the nucleon form factors have been separated by a factor of two and considerably reduced the error bars in the region of overlap. The results for $G_{Mp}/\mu_p G_D$ decrease smoothly with increasing $Q^2$, while the values for $G_{Ep}/G_D$ and $G_{Mn}/\mu_n G_D$ are consistent both with unity and with form factor scaling. The results for $G_{En}^2/G_D^2$ are consistent with zero. None of the existing models is in good agreement with all form factor results at all values of $Q^2$, although it is likely for several of the models that this could be remedied by adjusting free parameters.

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