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LETTER TO THE EDITOR

MEASUREMENT OF THE RATIO OF THE PROTON'S ELECTRIC TO MAGNETIC FORM FACTORS BY RECOIL POLARIZATION

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The longitudinal and transverse polarizations of the outgoing proton were measured for the reaction $^1\mathrm{H}(\vec{\mathrm{e}}, \mathrm{e}' \, \vec{\mathrm{p}})$ at four-momentum transfer squared of 0.5 to 3.5 GeV^2. The ratio of the electric to magnetic form factors of the proton is proportional to the ratio of the transverse to longitudinal polarizations.

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The understanding of the structure of the nucleons has been of fundamental importance for the past several decades in nuclear and particle physics; ultimately such an understanding is necessary to describe the strong force. Precise knowledge of charge and current distribution inside the nucleon is essential in any theory of strong interaction based on QCD. The electromagnetic interaction provides a unique tool to investigate the structure of the nucleons.

The electric, G_{Ep}, and magnetic, G_{Mp}, form factors of the proton are related to the transverse, P_t, and longitudinal, P_l, polarizations of the outgoing proton in the reaction $^1\mathrm{H}(\vec{\mathrm{e}}, \mathrm{e}' \, \vec{\mathrm{p}})$ [1,2]. In the one-photon exchange approximation, the relationship is:

$$P_t \propto G_{Ep} G_{Mp} \quad \text{and} \quad P_l \propto G_{Mp}^2 \,, \tag{1}$$

and the normal polarization of the outgoing proton is zero. Putting in the kinematical factors, the ratio G_{Ep}/G_{Mp} can be expressed as:

$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_l} \frac{(E_e + E_{e'})}{2M} \tan(\frac{\theta_e}{2}) \,, \tag{2}$$

where E_e is the beam energy, $E_{e'}$ is the scattered electron energy, M is the proton mass and θ_e is the angle of scattered electron.

The target transverse and longitudinal polarization components are mixed together as the magnetic moment of the proton precesses while traveling through the spectrometer. The focal plane polarization components are related to the target components by a nine element spin matrix:

$$\begin{pmatrix} P_n^{fp} \\ P_t^{fp} \\ P_l^{fp} \end{pmatrix} = \begin{pmatrix} S_{nn} & S_{nt} & S_{nl} \\ S_{tn} & S_{tt} & S_{tl} \\ S_{ln} & S_{lt} & S_{ll} \end{pmatrix} \begin{pmatrix} P_n \\ hP_t \\ hP_l \end{pmatrix}, \tag{3}$$

where h is the beam helicity and the fp superscript indicates a focal plane polarization. The matrix elements have to be calculated as a function of the target coordinates on an event by event basis.

The focal plane polarimeter (FPP) is used to determine the transverse, P_t^{fp}, and normal, P_n^{fp}, polarization at the focal plane by measuring the azimuthal angular distribution of the $\vec{p}+{}^{12}$C reaction. The FPP consists of two front straw-tube drift chambers which determine the trajectory of the proton incident onto the carbon analyzer, and two rear straw-tube drift chambers which reconstruct the track of the scattered proton. The azimuthal (ϕ) angular distribution in each bin of the polar scattering angle, θ, has the form:

$$N(\phi,\theta) = N_o(\theta)[1 - A(\theta)P_n^{fp}\cos(\phi) + A(\theta)P_t^{fp}\sin(\phi)]\,, \tag{4}$$

with $A(\theta)$ being the analyzing power of carbon. The helicity of the beam is flipped at a rate of 30 Hz, and this also flips the sign of P_n^{fp} and P_t^{fp}. The angular distributions, $N^+(\phi,\theta)$ and $N^-(\phi,\theta)$, are measured for the plus and minus helicity. Since the instrumental asymmetries are helicity independent, the difference, $N^+(\phi,\theta) - N^-(\phi,\theta)$, depends only on the physical quantities. Then a Fourier analysis of the difference of the angular distributions yields the quantities:

$$b(\theta) = -\frac{1}{\pi}\int_0^{2\pi} A_C(\theta)P_n^{fp}\cos^2\varphi\,\mathrm{d}\varphi \;;\; a(\theta) = \frac{1}{\pi}\int_0^{2\pi} A_C(\theta)P_t^{fp}\sin^2\varphi\,\mathrm{d}\varphi\,. \tag{5}$$

From the spin transfer matrix, $P_n^{fp} = S_{nt}\cdot hP_t + S_{nl}\cdot hP_l$ and $P_t^{fp} = S_{tt}\cdot hP_t + S_{tl}\cdot hP_l$. With this substitution, we can approximate the integrations by sums over all $N = N_0^+ + N_0^-$ events:

$$
\begin{aligned}
b(\theta) &\simeq -\frac{2}{N}\left[|h|A_C(\theta)P_t^{tgt}\cdot\sum_{i=1}^{N}S_{nt}^{i}\cos^2\varphi_i + |h|A_C(\theta)P_l^{tgt}\cdot\sum_{i=1}^{N}S_{nl}^{i}\cos^2\varphi_i\right] \\
a(\theta) &\simeq \frac{2}{N}\left[|h|A_C(\theta)P_t^{tgt}\cdot\sum_{i=1}^{N}S_{tt}^{i}\sin^2\varphi_i + |h|A_C(\theta)P_l^{tgt}\cdot\sum_{i=1}^{N}S_{tl}^{i}\sin^2\varphi_i\right]
\end{aligned}
\qquad (6)
$$

After solving these two equations for the 2 unknowns ($|h|A_C(\theta)P_t$) and ($|h|A_C(\theta)P_l$), the ratio P_t/P_l is extracted and using Eq. 2, the ratio G_{Ep}/G_{Mp} is calculated.

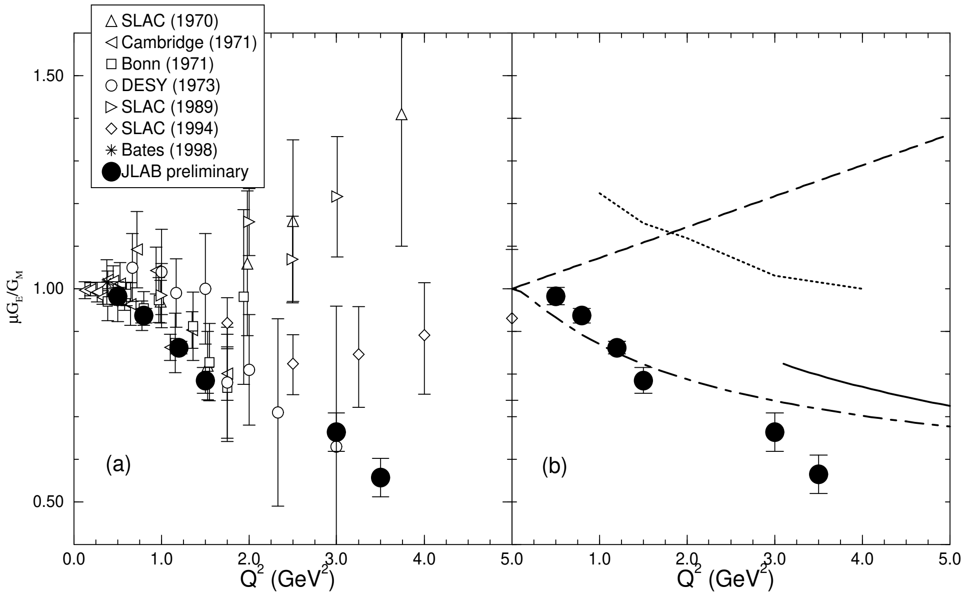

Fig. 1. New $\mu G_{Ep}/G_{Mp}$ preliminary measurement at Jlab in (a) compared to previous world data (Refs. 3 to 9) and in (b) compared to model predictions of Ref. 10 (dash-dotted), Ref. 12 (dashed), Ref. 13 (dotted) and Ref. 14 (solid).

Previous measurements of the proton form factors used the Rosenbluth separation technique which measures the ep cross sections at the same Q^2 but at different virtual photon polarizations. The recoil polarization technique was used first at Bates to measure G_{Ep}/G_{Mp} at $Q^2 = 0.38$ and 0.5 GeV^2 [3]. The absolute error bars on the new Jefferson Lab data range from 0.017 at Q^2= 0.5 GeV^2 to 0.046 at Q^2= 3.5 GeV^2 and are a distinct improvement on the previous measurements that used the Rosenbluth separation technique (especially for $Q^2 > 1.5$ GeV^2). The data are plotted in Fig. 1a and one can clearly see a downward trend in the $\mu G_{Ep}/G_{Mp}$ ratio above Q^2= 1 GeV^2, where earlier there was a conflicting set of measurements. The striking feature of the new data is the fall-off of the $\mu G_{Ep}/G_{Mp}$ ratio from 1 starting at Q^2= 0.5 GeV^2 to a value of 0.55 at Q^2= 3.5 GeV^2. This indicates that the shapes of G_{Ep} and G_{Mp} are different. The improved quality of the data will have a clear impact on theoretical models.

The Q^2 region between 1 and 10 GeV^2 has been anticipated as the region where the transition from mesonic to quark-gluon degrees of freedom occurs. This transition region is a difficult area for theoretical models, and has led to numerous approaches to predicting the nucleon form factors. Also, the models tend to have parameters which have to be constrained by the data. In Fig. 1b, various model predictions are compared to the preliminary data from this experiment. The vector meson dominance model of Ref. 10 is an improvement on the original work of Ref. 11. It includes a new data set and a super-convergence condition to constrain the behavior of the form factors to the perturbative QCD predicted fall-off at large Q^2. In this model, above $Q^2 = 2.0$ GeV^2, the parameter which indicates the boundary between mesonic and quark degrees of freedom is sensitive to $\mu G_{Ep}/G_{Mp}$ and should be tightly constrained by the new data. The constituent quark model (CQM) has been extended in a relativistic way up to $Q^2 = 6.0$ by a number of theorists. Chung and Coester [12] investigated the dependence of the form factors on the constituent quark mass (m_q), the range parameter defining the confinement scale ($1/\alpha$) in a relativistic CQM. In Fig. 1b their prediction is plotted as a dashed line with $m_q = 0.24$ GeV and $\alpha = 0.635$ GeV. It significantly disagrees with the new data. Since the CQM predictions are sensitive to the values of m_q and α, the new data will constrain their values. The QCD sum-rule predictions of Radyushkin [13] are plotted as a dotted line and also disagree with the new data. In Ref. 14 the nucleon form factors were calculated in the diquark model, and the predicted $\mu G_{Ep}/G_{Mp}$ is plotted as a solid line. In the limit of $Q^2 \to \infty$, the di-quark framework becomes the hard scattering formalism of perturbative QCD.

It is important to compare the theoretical predictions to both the proton and neutron form factors. G_{Mp} has been measured to <5% accuracy up to $Q^2 = 15$ GeV^2. This experiment has reduced the error on G_{Ep}/G_{Mp} to a level comparable to G_{Mp}. With the new data, tighter constraints will be placed on theory to fit both form factors of the proton. In addition, at Jefferson Lab, experiments are planned to measure G_{Mn} and G_{En} which will further constrain theory.

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MJERENJE OMJERA ELEKTRIČNOG I MAGNETSKOG FAKTORA OBLIKA PROTONA ODBOJNOM POLARIZACIJOM

Mjerila se uzdužna i poprečna polarizacija izlaznih protona u reakciji $^1\mathrm{H}(\vec{\mathrm{e}},\mathrm{e}'\,\vec{\mathrm{p}})$ za kvadrate prijenosa četiri-impulsa od 0.5 do 3.5 GeV^2. Omjer električnog i magnetskog faktora oblika protona je razmjeran omjeru poprečne i uzdužne polarizacije.