New Results on the Electric Form Factor of the Proton

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The longitudinal, P_L , and transverse, P_T , polarizations of the recoil proton were measured for the elastic $\bar{e}p$ reaction in Hall A at JLab. The ratio of the electric, G_{Ep} , to the magnetic, G_{Mp} , form factors of the proton was obtained from the ratio P_T/P_L . Using this technique, an earlier experiment [1] in Hall A at JLab measured G_{Ep}/G_{Mp} for the four-momentum transferred, Q^2 , from 0.5 to 3.5 GeV^2 and found that above $Q^2 \approx 0.8 \text{ GeV}^2$ the ratio falls off linearly with Q^2 . New data presented here extend the measurement of G_{Ep}/G_{Mp} to $Q^2 = 5.6 \text{ GeV}^2$ and shows that it continues to fall linearly with Q^2 .

1. Introduction

The nucleon form factors describe the internal structure of the nucleon. At high Q^2 values, the nucleon can be treated as consisting of 3 free quarks, and perturbative QCD theory can be applied[2]. At $Q^2 < 1 \text{ GeV}^2$, the Vector Meson Dominance (VMD) model (see e.g. Ref. [3]) has been successful in modeling the nucleon form factors. Predicting nucleon form factors in the transition region between low Q^2 , where the meson picture is valid, to high Q^2 , where perturbative QCD is valid, is difficult.

The elastic ep cross section can be written in terms of the electric, G_{Ep} , and magnetic, G_{Mp} , form factors. In the limit $Q^2 \rightarrow 0$, $G_{Ep} = 1$ and $G_{Mp} = \mu_p$, the proton magnetic moment. The unpolarized elastic ep cross section is proportional to $G_{Ep}^2 + \epsilon G_{Mp}^2$, where ϵ is the virtual photon longitudinal polarization, $\epsilon = [1 + 2(1 + \tau) \tan^2(\frac{\theta_e}{2})]^{-1}$ and θ_e is the scattering angle of the electron and $\tau = Q^2/4M^2$ where M is proton's mass. By measuring the cross-section at a fixed Q^2 over a range of ϵ -values, the form factors G_{Ep} and G_{Mp} can be extracted from a linear fit to the data. At Q^2 below 1 GeV^2 , G_{Ep} and G_{Mp} have been determined with small error bars and $\mu_p G_{Ep}/G_{Mp}$ was found to be ≈ 1 as shown in Fig. 1. As Q^2 increases, the cross section is dominated by the G_{Mp} contribution, therefore extracting G_{Ep} becomes difficult. Conversely, G_{Mp} can be obtained from cross-section measurements with minimal error due to assumptions about G_{Ep} , so G_{Mp} is known to $Q^2 = 31 \text{ GeV}^2$ [4]. As seen in Fig. 1, the error bars on $\mu_p G_{Ep}/G_{Mp}$ grow with Q^2 , and above $Q^2 \approx 1 \text{ GeV}^2$, systematic differences between different experiments are evident. Therefore, a new experimental method for extracting G_{Ep} is needed.

2. Experiment

Precision measurements of polarization observables have become possible with the advent of polarized electron beams with $\approx 100\%$ duty factor, high current and high polariza-

tion. This experiment measured the longitudinal, P_L , and transverse, P_T , polarizations of the recoil proton for the elastic $e p$ reaction. Assuming one-photon exchange, the scattering of longitudinally polarized electrons results in a transfer of polarization to the recoil proton with only two non-zero components, P_L perpendicular to, and P_T parallel to the proton momentum in the scattering plane [5]. In terms of these polarization components, the ratio of the electric to magnetic form factors is:

$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_L(E_e + E_e')}{P_T} \tan\left(\frac{\theta_e}{2}\right). \quad (1)$$

in which E_e' is the scattered electron's energy and E_e is the incident beam energy. An experiment at Bates first used this method to determine G_{Ep}/G_{Mp} at $Q^2 = 0.38$ and 0.5 GeV^2 [6]. In 1998 at JLab, G_{Ep}/G_{Mp} was measured for Q^2 from 0.5 to 3.5 GeV^2 [1]. In that experiment, the protons and electrons were separately detected in high-resolution spectrometers (HRS). The polarization of the proton was measured in a focal plane polarimeter (FPP). In the FPP, two front straw chambers define the incident proton trajectory and two rear straw chambers defined the proton trajectory after scattering in the graphite analyzer. The number of protons which scattered from the analyzer can be expressed as a function of their azimuthal scattering angle, φ , as:

$$N_p^\pm(\varphi) = N_p^\pm \left[1 + (\pm A_y P_L^{fpp} + a_{inst}) \sin \varphi - (\pm A_y P_T^{fpp} + b_{inst}) \cos \varphi \right] \quad (2)$$

The $\pm$ represents the beam helicity aligned either parallel or anti-parallel to the beam momentum. The instrumental asymmetries are represented by a_{inst} and b_{inst} . P_L^{fpp} and P_T^{fpp} are the two perpendicular components of the proton polarization at the focal plane. A_y is the analyzing power of the graphite. The instrumental asymmetries can be eliminated by taking the difference $N_p^+(\varphi) - N_p^-(\varphi)$ from which P_L^{fpp} and P_T^{fpp} are obtained by Fourier analysis.

If the HRS was a simple dipole magnet, then the relation between the polarizations at the focal plane and those at the target would be $P_L^{fpp} = P_L$ and $P_T^{fpp} = P_T \cdot \sin \chi$ where χ is the spin precession angle. The HRS consists of two quadrupoles, a dipole, and an exit quadrupole, so the spin precession through the HRS has to be modeled. A method[13] was developed to use the spin precession matrix to extract the target polarizations from focal plane polarizations and therefore G_{Ep}/G_{Mp} .

The experiment E99-007 made new measurements of G_{Ep}/G_{Mp} at $Q^2 = 4.0, 4.8$ and 5.6 GeV^2 with overlap points at $Q^2 = 3.0$ and 3.5 GeV^2 , in the fall of 2000. To extend the measurement to higher Q^2 , two changes were made to the setup of the experiment. To increase the figure-of-merit of the FPP, CH_2 , instead of graphite, was used for the analyzer, and the thickness was increased to 100 cm (60 cm for $Q^2 = 3.5 \text{ GeV}^2$). Only for $Q^2 = 3.5 \text{ GeV}^2$ was a spectrometer used to detect the coincident electron. For the higher Q^2 points, a calorimeter of lead-glass detectors was built to detect the coincident electron. The placement of the calorimeter was made so that the solid angles of the two arms matched. The segmentation of the calorimeter was sufficient to distinguish elastic ep events by their two-body angular correlation.

The preliminary results for $\mu_p G_{Ep}/G_{Mp}$ are plotted in Fig. 1. These new measurements have the same slope as the previous JLab data. If the Q^2 dependence of $\mu_p G_{Ep}/G_{Mp}$ continues with the same slope, then G_{Ep} will cross zero at $Q^2 \approx 7.5 \text{ GeV}^2$. Many theories

Figure 1. World data for $\mu_p G_{Ep}/G_{Mp}$ versus Q^2 .

Figure 2. Comparison between $\mu_p G_{Ep}/G_{Mp}$ measured at JLab and several theoretical models

naturally predict that G_{Ep} falls off faster with Q^2 than G_{Mp} . In Fig. 2, the calculations of $\mu_p G_{Ep}/G_{Mp}$ from a vector meson dominance (VMD) model [3], a constituent quark (CQ) model [14], a soliton model [15], a di-quark model [16] and a cloudy bag model [17] are plotted as a dash-dotted, dotted, solid, short dashed, and long dashed lines, respectively. The parameters of the VMD model [3] were fitted to previous nucleon form factor data, and the fall-off of $\mu_p G_{Ep}/G_{Mp}$ with Q^2 is not as fast as the JLab data. An early calculation in a relativistic CQ model of Ref. [14], shows that $\mu_p G_{Ep}/G_{Mp}$ falls off rapidly with Q^2 . Recent calculations with different versions of the CQ model have been done[18]-[20], and all agree on the importance of a relativistic approach. The non-relativistic soliton model had difficulty describing the nucleon form factors, but Holzwarth [15] has done relativistic soliton calculations which gives remarkable agreement with the data. The di-quark model predicts a relatively flat Q^2 dependence to $\mu_p G_{Ep}/G_{Mp}$. If data at higher Q^2 are obtained, then whether one finds a flattening at higher Q^2 will be interesting. The cloudy bag model of Ref. [17] is an improved version which includes center-of-mass motion correction and relativistic effects which extend the range of the model to higher Q^2 .

3. Conclusion

The new data on $\mu_p G_{Ep}/G_{Mp}$ presented here show that the ratio continues to drop off linearly with increasing Q^2 and indicate that G_{Ep} might cross zero at $Q^2 \approx 7.5 \text{ GeV}^2$. While comparison to $\mu_p G_{Ep}/G_{Mp}$ is a stringent test of models of the nucleon, comparison to the individual proton and neutron electric and magnetic form factors is important. It has been proposed to extend the measurement of $\mu_p G_{Ep}/G_{Mp}$ to a Q^2 of 9 GeV^2 at JLab[21]. When combined with the cross-section measurements, this will allow a determination of the proton's G_{Ep} and G_{Mp} . In addition, over the past decade efforts have been made to improve the accuracy and range of Q^2 over which the neutron electric

and magnetic form factors are measured. The combination of all four of the nucleon electro-magnetic form factor will enable a greater understanding of the structure of the nucleon.

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