Measurements of the elastic electromagnetic form factor ratio $\mu_p G_{Ep}/G_{Mp}$ via polarization transfer

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We present measurements of the ratio of the proton elastic electromagnetic form factors, $\mu_p G_{Ep}/G_{Mp}$. The Jefferson Lab Hall A Focal Plane Polarimeter was used to determine the longitudinal and transverse components of the recoil proton polarization in ep elastic scattering; the ratio of these polarization components is proportional to the ratio of the two form factors. These data reproduce the observation of Jones *et al.* [Phys. Rev. Lett. **84**, 1398 (2000)], that the form factor ratio decreases significantly from unity above $Q^2 = 1\ \mathrm{GeV}^2$.

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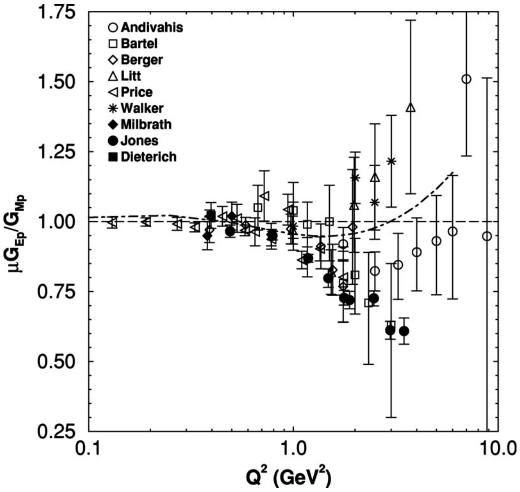

FIG. 1. World data for $r=\mu_p G_{Ep}/G_{Mp}$; open symbols indicate Rosenbluth separations [2–7] while solid symbols indicate polarization-transfer measurements [10–12]. The dot-dashed line is the parametrization from Ref. [13] to the cross section data, which indicates $r\approx 1$.

Measurements of the electric and magnetic elastic form factors G_{Ep} and G_{Mp} are important to our understanding of the internal structure of the proton, because they reflect the distributions of charge and magnetization. Most previous measurements of the form factors used the Rosenbluth separation method [1], which involves measuring cross sections at constant Q^2 and varying the beam energy and scattering angle to separate the electric and magnetic contributions. With increasing Q^2, the cross sections are increasingly dominated by the magnetic term G_{Mp}; at $Q^2\approx 3$ GeV^2, the electric term contributes only about 5% of the cross section. The various data sets [2–7] for G_{Ep} are not consistent for $Q^2>1$ GeV^2, despite uncertainties that exceed 20%—see Fig. 1. This may indicate that some of the experiments had underestimated the systematic errors.

An alternative technique is provided by the polarization-transfer method [8,9], which uses the transverse (P_t) and longitudinal (P_l) components of the recoil proton polarization after the scattering of a longitudinally polarized electron beam from a hydrogen target. With kinematic factors given in the laboratory frame, $\tau=Q^2/4M_p^2$, $r=\mu_p G_{Ep}/G_{Mp}$, and $I=r^2/\mu_p^2+\tau[1+2(1+\tau)\tan^2(\theta_e/2)]$, $P_t=-2\sqrt{\tau(1+\tau)}\tan(\theta_e/2)r/\mu_p I$, and $P_l=(E+E')\sqrt{\tau(1+\tau)}\times\tan^2(\theta_e/2)/M_p I$. The form factor ratio is then determined from

$$\frac{G_{Ep}}{G_{Mp}}=-\frac{P_t}{P_l}\frac{(E+E')}{2M_p}\tan\left(\frac{\theta_e}{2}\right). \tag{1}$$

Using the ratio of two polarization components measured at the same time greatly reduces systematic uncertainties. In particular, the polarimeter analyzing power and beam polarization do not affect the ratio of the form factors, but will affect the size of the uncertainties. The dominant systematic uncertainty is the knowledge of spin transport.

This method was first used by Milbrath *et al.* [10], to determine r at $Q^2=0.38$ and 0.50 GeV^2; good agreement with the Rosenbluth separation technique was obtained, as was subsequently the case for a $Q^2=0.4$ GeV^2 measurement from Mainz [11]. The first precise polarization transfer measurement at higher Q^2 [12], from 0.5 to 3.5 GeV^2, gave the surprising result shown in Fig. 1 that the form factor ratio decreases with increasing Q^2. The data of Ref. [12] are well represented as

$$r=1.0-0.14(Q^2-0.3), \tag{2}$$

for $0.3<Q^2<3.5$ GeV^2. Previously, it had been thought that $r\approx 1$ [13], although the decrease in r had been predicted in some models [14–16]. If this difference is due to a systematic problem with the Rosenbluth separation measurements, it would require for each Q^2 only a $\approx 2\%$ variation in the cross section as a function of energy to bring the data within 1σ of the polarization results. In a nonrelativistic interpretation, the observed decrease of r with Q^2 indicates that the charge distribution is more extended than is the magnetization distribution, although the two distributions apparently have the same rms radii.

The observed decrease of the form factor ratio has led to intense activity within various theoretical models, including the diquark model [17], the quark meson coupling model [18], relativistic constituent quark model [19], and possible SU(6) symmetry breaking [20]; there has even been some reconsideration of the perturbative quantum chromodynamics limits for the form factors [21]. Additional tests of the proton form factor ratio are planned at Jefferson Lab, using another polarimeter [22] and single-arm proton cross section measurements [23], as well as higher momentum-transfer measurements in both Hall A [24] and with a new polarimeter in Hall C [25].

Given this activity along with the lack of reproducibility of the Rosenbluth separation measurements at higher Q^2, it is important to demonstrate that the polarization-transfer technique is reproducible. We have again used this technique to determine r [26]. The measurements use the same facility as those of Ref. [12], and they demonstrate the reproducibility of the results, as measured in different experiments, with different kinematics. The change in kinematics is potentially significant. Although proton momentum is constant for constant Q^2, the change in beam energy and scattering angle leads to different event distributions in the spectrometer magnets and in the focal plane. Further, the variation of P_l and P_t with kinematics affects the sensitivity to the mixing of these components by the quadrupole focusing. Thus, changing kinematics tests the spin transport corrections. Reaction mechanism effects, such as two-photon exchange, depend on kinematics and, though difficult to calculate, are expected to be small [27].

In this Brief Report, we present two types of polarization measurements. First, we present 13 measurements of coincidence $ep\rightarrow ep$ polarizations, performed to calibrate the Jefferson Lab Hall A Focal Plane Polarimeter (FPP) for studies of the reactions $D(\vec{\gamma},p)n$ [28] and $H(\vec{\gamma},p)\pi^0$ [29]. Data for the two reactions were obtained with single-arm measurements of the outgoing proton; for the $^{1}H(\gamma,p)\pi^{0}$ reaction, the similar kinematics and count rates of protons from ep elastic scattering allowed single-arm measurements of the polarization transfer. Thus, second, we present single-arm proton polarization data from background measurements for this reaction, with the photon radiator removed. For most kinematic settings of the π^{0} photoproduction experiment, the elastic ep polarizations could be determined with uncertainties of 0.05–0.10. However, because r involves the ratio of polarizations, uncertainties on the ratio can be large; we present nine data points from the 39 singles measurements, with Q^2 up to 3.1 GeV^2.

The electron polarization during the experiment was between 60% and 80%, and was determined by a Møller polarimeter every few days with $\approx 3\%$ relative precision. The beam helicity state was flipped pseudorandomly at 30 Hz. Beam currents as high as 30 μA impinged on a 15-cm-long cryogenic hydrogen (LH2) target, but high data rates limited currents to a few μA at lower Q^2.

The scattered particles were detected in the essentially identical Hall A High Resolution Spectrometers. The scattering angle, momentum, and target interaction position of the event data are deduced from trajectories measured by the vertical drift chambers. For the coincidence (singles) data, elastic ep events were determined by cuts on the missing energy (reconstructed beam energy). The singles measurements include insignificant ($\approx 1\%$) single-arm backgrounds that are more suppressed in coincidence measurements— examples include misidentified π^{+} and protons from the $\gamma p \rightarrow p\gamma$ reaction.

For these calibrations, it was sufficient to have statistical uncertainties on r similar to the Rosenbluth separation data, rather than the very high precision of Jones *et al.* [12]. The recoil proton polarization was measured in the Focal Plane Polarimeter [30]. An analyzer block of graphite is divided into four sections, so that the analyzer thickness may be adjusted as a function of proton energy. Two straw chambers before (behind) the analyzer measure the proton trajectory before (after) the reaction, to determine the scattering angles.

The physical quantities of interest, P_t and P_l, were determined by means of the maximum likelihood technique, utilizing the azimuthal distribution of the protons scattered from the graphite analyzer, $I = I_0[1+\epsilon_y \cos(\varphi)+\epsilon_x \sin(\varphi)]$, for events with FPP polar scattering angles between 5° and 20°. The asymmetries ϵ_x and ϵ_y are proportional to the analyzing power and to the proton polarization perpendicular to its momentum as it enters the analyzer; they are linear functions of the proton's polarization components at the target. The relationship, given by a rotation which takes into account the change of coordinate system and the proton spin precession [31] in the spectrometer's magnetic fields, is calculated on an event by event basis.

Figure 2 shows angular distributions for the polarization-transfer components at two of the 11 energies of the experiments. These data are determined from the measured asymmetries, accounting for spin transport and Møller measurements of the beam helicity, and using analyzing powers interpolated from the coincidence ep measurements of Ref. [12]. The data are compared to calculations using Eq. (2) (solid line) and $r=1$ (dashed line). Since P_l is relatively insensitive to r, only the solid line is shown. The good agreement between the data and calculations for P_l confirms that the product of beam polarization and polarimeter analyzing power is well understood. Note that for some points the spin transport results in a rotation of P_l of about 180°, leading to large uncertainties.

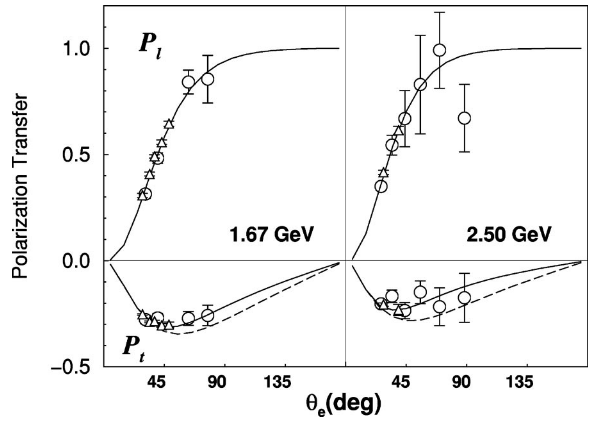

FIG. 2. Sample angular distributions for polarization transfer in elastic ep scattering at the two labeled beam energies. Circles indicate singles data, while triangles indicate coincidence data. The curves are described in the text.

The magnitude of P_t also depends on beam polarization and polarimeter analyzing power, in addition to a nearly linear dependence on r; the tendency of the dashed and solid curves in Fig. 2 to have increasing relative differences at higher energy and at larger scattering angles can be seen. Although most of the points do not clearly distinguish between the two curves, the better agreement of the data for P_t with the solid line is again indicative of the falloff of r at larger momentum transfers.

The coincidence results are shown in Table I. Because the spin transport varies across the focal plane, the quality of the spin transport description can be checked by binning the data in the reconstructed target quantities to search for variations.

TABLE I. Coincidence data for r from this work.

Q^2 (GeV^2)	E_e (GeV)	p_p (GeV/c)	r	Δr_{stat}	Δr_{sys}
0.32	1.00	0.594	0.930	0.067	0.007
0.35	1.00	0.615	0.910	0.061	0.004
0.39	1.15	0.658	0.961	0.033	0.005
0.46	1.00	0.721	0.952	0.034	0.006
0.57	1.67	0.809	0.959	0.039	0.007
0.76	1.67	0.954	0.966	0.033	0.012
0.86	1.67	1.030	0.865	0.029	0.015
0.88	3.24	1.048	0.923	0.086	0.013
1.02	1.67	1.134	0.900	0.038	0.022
1.12	2.50	1.208	0.825	0.027	0.020
1.18	1.67	1.242	0.851	0.050	0.023
1.42	4.11	1.450	0.733	0.058	0.029
1.76	2.50	1.615	0.816	0.115	0.069

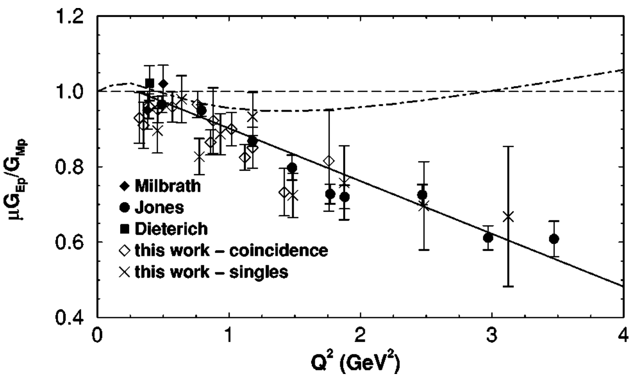

FIG. 3. Our results compared to earlier polarization-transfer measurements of Jones *et al.* [12], Milbrath *et al.* [10], and Dieterich *et al.* [11]. The dot-dashed line is the parametrization from Ref. [13], while the solid line is Eq. (2).

At the level of the uncertainties of these data, no significant variations were seen. The systematic uncertainties in r were evaluated by adding offsets equal to the systematic uncertainties in the target reconstructions to the corresponding target quantities to determine the variation of the extracted polarizations; varying the spectrometer model within COSY [31] has a smaller effect.

Figure 3 shows r obtained in this work compared with previous polarimeter measurements. The main conclusion is that we find a clear decrease in the form factor ratio above 1 GeV^2, in agreement with Ref. [12]. Equation (2) represents our coincidence data with a $\chi^2_{tot}=18$ for the 13 data points, in contrast with $\chi^2_{tot}=113$ for $r=1$. The nine form factor ratios determined from the proton singles measurements are also shown in Fig. 3. For these data, Eq. (2) gives $\chi^2_{tot}=11$, while $r=1$ gives $\chi^2_{tot}=60$. Again, the data exhibit the decrease of r with Q^2.

In conclusion, we have demonstrated that the polarimeter performance is understood by reproducing the calculated magnitudes of the polarization components and that the polarization-transfer technique with the Jefferson Lab Hall A focal plane polarimeter yields reproducible data. We confirm the decrease of the form factor ratio $r=\mu_p G_{Ep}/G_{Mp}$ observed in Ref. [12]. The results of other experiments with different experimental equipment [22,23,25] are eagerly awaited.

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