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Measurement of G_{Ep}/G_{Mp} via polarization transfer at Q^2 = 0.4 (GeV/c)^2

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Abstract. The polarization transfer from longitudinally polarized electrons to protons in the elastic scattering $p(\vec{e}, e' \vec{p})$ has been measured around Q^2 = 0.4 (GeV/c)^2 with the three-spectrometer facility at the Mainz microtron MAMI. From this polarization transfer the ratio $G_{Ep}/(G_{Mp}/\mu_p)$ has been determined. The ratio is found to be slightly less than unity in agreement with recent results from other laboratories and from the Rosenbluth separation of cross sections measured with unpolarized electrons.

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1 Introduction

The advent of high polarization electron beams has made the exploitation of polarization degrees of freedom in A(e,e'p) reactions possible [1–7]. For example, polarization transfer in elastic $p(\vec{e}, e' \vec{p}\,')$ can be used to determine the electric and magnetic magnetic form factors, G_{Ep} and G_{Mp}, of the proton. In the one-photon exchange approximation, the transverse P_x and longitudinal P_z transfer components are directly related to G_{Ep} and G_{Mp} by [8,9]

$$P_x = a\frac{G_{Ep}G_{Mp}}{G_{Ep}^2 + cG_{Mp}^2}P_e, \tag{1}$$

$$P_y = 0, \tag{2}$$

$$P_z = b\frac{G_{Mp}^2}{G_{Ep}^2 + cG_{Mp}^2}P_e. \tag{3}$$

The coordinates are chosen such that $\hat{\mathbf{z}}$ points in the direction of the momentum transfer $\mathbf{q}$, i. e. in the direction of the recoiling proton, $\hat{\mathbf{y}}$ is perpendicular to the scattering plane: $\hat{\mathbf{y}} = (\mathbf{k}_i \times \mathbf{k}_f)/|\mathbf{k}_i \times \mathbf{k}_f|$, and $\hat{\mathbf{x}} = \hat{\mathbf{y}} \times \hat{\mathbf{z}}$; these polarization components thus refer to a coordinate frame fixed to the scattering plane. P_e is the longitudinal polarization of the incident electron beam and a, b, and c are kinematical factors

$$a = -2\sqrt{\tau(1+\tau)}\tan(\Theta_e/2)\,, \tag{4}$$

$$b = 2\tau\sqrt{(1+\tau)}\sqrt{1+\tau\sin^2(\Theta_e/2)}\frac{\tan(\Theta_e/2)}{\cos(\Theta_e/2)}\,, \tag{5}$$

$$c = \tau\left(1 + 2(1+\tau)\tan^2(\Theta_e/2)\right)\,, \tag{6}$$

which depend on the electron scattering angle Θ_e and on $\tau = Q^2/(4m_p^2)$, where Q^2 is the negative of the four-momentum transfer squared and m_p the proton mass.

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Eqs. (1) and (3) yield the ratio of the electric and magnetic form factors, R, as

$$R = \frac{G_{Ep}}{G_{Mp}} = \frac{b}{a} \cdot \frac{P_x}{P_z}. \quad (7)$$

One thus gets R from a measurement of the longitudinal and transverse polarizations without knowing the polarization of the incident electron beam [2,7].

We also note that each of P_x and P_z is dependent only on R, not on the two form factors separately. Eqs. (1,3) thus lead to a consistency relation between P_x and P_z which we express in terms of the polarization transfer $\pi_i = P_i/P_e$ as

$$\frac{b}{a^2}\pi_x^2 = \left(1 - \frac{c}{b}\pi_z\right)\,\pi_z\,. \quad (8)$$

With P_y being zero, eq. (8) is equivalent to the consistency relation given in ref. [10] for the case of pseudoscalar meson electroproduction in parallel kinematics, which, expressed in terms of the polarization transfer defined above, reads

$$\frac{1}{2}\sqrt{\frac{1+\epsilon}{1-\epsilon}}\pi_x^2 + \frac{1}{2}\sqrt{\frac{1-\epsilon}{1+\epsilon}}\pi_y^2 = \pi_z\left(1 - \frac{1}{\sqrt{1-\epsilon^2}}\pi_z\right). \quad (9)$$

In this form, the consistency relation is written in terms of the transverse polarization $\epsilon = (1 + \frac{2|\mathbf{q}|^2}{Q^2}\tan^2(\Theta_e/2))^{-1}$. Thus, as a byproduct, comparison of eqs. 8 and 9 yields relations between the coefficients a, b, c and the polarization ϵ.

2 The elastic $p(\vec{e}, e'\,\vec{p})$ measurement

The elastic $p(\vec{e}, e'\,\vec{p})$ measurements have been performed at the 3-spectrometer setup of the A1-collaboration at the Mainz microtron MAMI [11,12], making use of the recently installed proton polarimeter [13]. At an energy E_0 = 854.4 MeV the electron beam had its maximum longitudinal polarization at the target, a 49.5 mm long Havar cell filled with LH_2. Beam currents of polarized electrons [14] of about 2 μA with polarizations between 68% and 78% for the three measurements were used.

The kinematics of the measurement are summarized in table 1. The x and z polarization components of the recoiling proton calculated with eqs. (1,3) using the form factor parameterization [16] are given in table 2; polarization-transfer components between 0.39 and 0.48 are expected. Also shown in table 2 is the analyzing power of the inclusive proton-carbon scattering, A_C, according to [17], which is of the order 0.5. Starting from this analyzing power known below 20°, we extended its measurement with high statistical accuracy up to 45° in the course of the present experiment [13]. The results agree with older low statistics measurements [15].

While only the two polarization components transverse to the proton's momentum in the focal plane are measurable, due to the precession of the proton's spin on its way through the spectrometer all three components relative to the scattering plane, P_x, P_y, and P_z, are accessible. In the case of elastic scattering only P_x and P_z are different from zero, and P_x^{fp} and P_y^{fp} are linear combinations of them. Knowing the spin rotation in the spectrometer from a stepwise numerical solution of the Thomas-equation [18] in the known fields of the spectrometer, P_x and P_z can be determined. This is achieved via a χ^2-minimizing procedure, which is described in detail in [13].

	kinematics			
	Θ'_e	$\lvert\mathbf{p}_{e'}\rvert$ (MeV/c)	Θ'_p	$\lvert\mathbf{p}_{p'}\rvert$ (MeV/c)
1	–48.2°	655	49.5°	643
2	–50.6°	641	47.9°	668
3	–54.4°	619	45.5°	705

Table 1. The kinematics of the three measurements performed at an incident electron energy of 854.4 MeV.

	calculated polarization transfer			FPP	
	P_x/P_e	P_z/P_e	$\lvert\mathbf{P}\rvert/P_e$	T_C^{7cm} (MeV)	A_C^{McN}
1	–0.390	0.399	0.558	162	0.47
2	–0.403	0.432	0.591	178	0.51
3	–0.419	0.483	0.640	203	0.53

Table 2. The polarization transfer expected for the kinematics given in Table 1. T_C^{7cm} is the kinetic energy in the center of the 7 cm thick carbon analyzer, and A_C^{McN} is the analyzing power averaged over Θ_s between 7° and 20° as given by McNaughton et al. and Aprile-Gibone et al. [17].

A detailed discussion of the systematic uncertainties can be found in ref. [13]. In the ratio P_x/P_z both A_C and P_e cancel out, and the systematic error in the form factor ratio is dominated by the back tracing of the polarization through the spectrometer, which depends on the target vertex. It is the uncertainty in the determination of the latter which dominates the systematic error. False asymmetries, which originate from position and angular dependent efficiencies of the tracking detectors, do not affect the extraction of the beam-helicity dependent polarization components P_x and P_z. For the beam-helicity independent P_y they can be corrected for [13]. As a result, we measured P_y consistent with zero within 1 to 2 standard deviations (less than 0.017) in the three kinematics of the present experiment, as it is expected for this reaction.

3 Results

The form factor ratios $G_{Ep}/(G_{Mp}/\mu_p)$ measured at three values of Q^2 are listed in table 3 (μ_p is the magnetic moment of the proton measured in units of the nuclear magneton). They are compared in fig. 1 with values measured in the same momentum transfer region at MIT Bates [2] and at Jefferson Laboratory [7].

The data from the different laboratories are in very good agreement. The weighted average of the data shown in fig. 1 is 0.979 ± 0.013 (here only the statistical errors are taken into

kinematics	Q^2 (GeV^2/c^2)	$G_{E}p/(G_{Mp}/\mu_p)$
1	0.373	$0.999 \pm 0.028_{stat} \pm 0.046_{sys}$
2	0.401	$1.011 \pm 0.029_{stat} \pm 0.044_{sys}$
3	0.441	$0.936 \pm 0.033_{stat} \pm 0.039_{sys}$

Table 3. Results for $R = G_{Ep}/(G_{Mp}/\mu_p)$ with statistical and systematic errors.

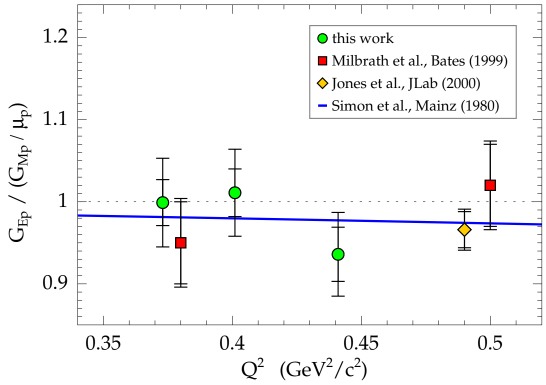

Fig. 1. Ratio $R = G_{Ep}/(G_{Mp}/\mu_p)$ from the elastic $p(\vec{e}, e' \ \vec{p}')$ measurements (circles) in comparison with other double-polarization results from MIT Bates [2] (squares) and with the lowest Q^2-value from the Jefferson Laboratory [7] (rhomb). The dotted line just represents the expectation $R = 1$ from form factor scaling while the solid line is a fit to Rosenbluth-separated data [16].

account since the systematic errors have been dealt with on different footings). This value is in excellent agreement with R = 0.978 calculated from the fit to a Rosenbluth separation of elastic scattering cross sections which yielded G_{Ep} and G_{Mp} separately [16].

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