Elastic Scattering of Polarized Electrons by Polarized Protons*

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We report on a new type of high-energy electron-proton scattering experiment in which longitudinally polarized electrons are scattered from longitudinally polarized protons. The asymmetry in elastic scattering at $Q^2 = 0.765$ (GeV/c)^2 was measured; our result agrees with the theoretical asymmetry and determines the sign of G_E/G_M to be positive.

In this Letter we describe a high-energy electron-proton scattering experiment in which polarized electrons are scattered from polarized protons, and present the first results for elastic scattering. Our first results for deep inelastic scattering are reported in the following Letter.[1]

The momentum and scattering angle of the scattered electrons were measured when longitudinally polarized electrons were scattered from longitudinally polarized protons. The basic quantity measured was the antiparallel-parallel asymmetry A in the differential cross sections given by

$$A = \frac{d\sigma(\uparrow\downarrow) - d\sigma(\uparrow\uparrow)}{d\sigma(\uparrow\downarrow) + d\sigma(\uparrow\uparrow)}, \qquad (1)$$

in which $d\sigma$ denotes the differential cross section $d\sigma(E, \theta)/d\Omega$ for incident electron energy E and laboratory scattering angle θ, and the arrows denote the antiparallel and parallel spin configurations.

If elastic scattering is described by the one-photon-exchange approximation, then the asymmetry can be expressed as[2]

$$A = \frac{\tau G_M}{G_E}\left\{\frac{2M}{E} + \frac{G_M}{G_E}\left[\frac{2\tau M}{E} + 2(1+\tau)\tan^2\frac{\theta}{2}\right]\right\} \times \left\{1 + \tau\left(\frac{G_M}{G_E}\right)^2\left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]\right\}^{-1}, \qquad (2)$$

in which $\tau = Q^2/4M^2$, $q^2 = -Q^2 = -4EE'\sin^2(\theta/2)$ is the square of the four-momentum of the virtual photon, M is the proton mass, E' is the scattered electron energy, and G_E and G_M are the electric and magnetic elastic form factors of the proton. The electron mass has been neglected. We chose to measure A for elastic scattering primarily to test the validity of our experimental method. Alternatively, we can regard our measurement as a test of Eq. (2) and as a determination of the sign of G_E/G_M.

The polarized electron source (PEGGY), which serves as an injector to the 20-GeV Stanford linear accelerator, is based on photoionization of a polarized Li^6 atomic beam by a pulsed uv light source.[3] Typical characteristics of the polarized electron beam are given in Table I. The electron polarization, P_e, was measured by Mott scattering at the output of PEGGY and by Møller scattering at high energy. The value given for P_e is based on the Møller scattering measurements.[4,5] The uncertainty, $\delta P_e/P_e = 12\%$, includes counting statistics (10%) and the uncertainty in the uv light intensity for photoionization. (The polarization depends upon light intensity through a depolarizing resonant two-photon ionization process.[6])

Protons were polarized by the method of dynamic nuclear orientation in a butanol target doped with 1.4% porphyrexide.[7] Typical operating conditions are given in Table II. The techniques of beam rastering and target annealing[8] were used to reduce the effects of radiation damage to an acceptable level. Targets were annealed about every two hours and replaced after about five exposures to the beam. The continuously

TABLE I. Characteristics of polarized electron beam.

Characteristic	Value
Pulse length	1.5 μsec
Repetition rate	120 pulses/sec
Electron intensity (at high energy)	$\sim 10^9 e^-$/pulse
Pulse-to-pulse intensity variation	< 5%
Electron polarization, P_e	0.51 ± 0.06
Polarization reversal time	3 sec
Time between reversals	2 min
Intensity difference upon reversal	< 5%
Lifetime of lithium oven load	70 hr
Time to reload system	36 hr

TABLE II. Operating characteristics of polarized proton target.

Characteristic	Value
Magnetic field (longitudinal field of superconducting magnet)	50 kG
Temperature	1.05°K
Target material	25 cm^3 of butanol-porphyrexide beads (~1.7 mm diam)
Initial polarization of free protons[a]	0.50 to 0.65
Depolarizing dose ($1/e$)	$\sim 3\times 10^{14} e^-/cm^2$
Polarizing time ($1/e$)	~4 min
Anneal or target change time (including polarizing)	~45 min

[a]Improvements in target operation gave the larger polarization values in the later parts of the experiment.

monitored NMR signal normalized to a thermal equilibrium (TE) signal was used to determine the average target polarization P_p. The uncertainty, $\delta P_p/P_p = 10\%$, includes the errors in the TE measurements (8%) and the uncertainty in the correction for nonuniform irradiation of the target (5%). (Only ~70% of the total 2.5-cm×2.5-cm target cross-sectional area was illuminated by the rastered electron beam.)

The electron beam from the accelerator was momentum-analyzed by a transport system whose absolute momentum calibration was ~0.1%. A momentum slit in the transport system limited the beam energy spread to ±0.375%. Spin precession in the 24.5° bend of the beam switchyard determined that only electrons whose energies were integral multiples of 3.237 GeV had full longitudinal polarization. The electron beam charge per pulse was monitored with two precision toroidal charge monitors. Just upstream of the target, a microwave beam position monitor measured the beam position for each beam pulse with a sensitivity of ~0.1 mm. Computer-controlled vernier steering magnets 99 m upstream of the target were used in conjunction with this position monitor to keep the raster pattern of the beam centered on the target.

The scattered electrons were detected and their momentum and scattering angle were measured with the Stanford Linear Accelerator Center (SLAC) 8-GeV spectrometer. Electron identification was achieved with a gas threshold Cherenkov counter, a 3.25-radiation-length-thick lead glass counter array which sampled the buildup of the electromagnetic shower, and a lead-Isolite[9] shower counter. Less than one pion in 10^3 was misidentified as an electron by this system. An online XDS 9300 computer monitored the experiment and wrote data on magnetic tape.

Data were taken in a series of runs, each of which lasted about two hours. Runs were terminated when radiation damage reduced the target polarization to about half its initial value. The proton polarization direction was constant during a run and was reversed between runs. Each run was divided into cylces, with each cycle in turn comprising eight miniruns of about one-minute duration each. The electron polarization direction remained constant during a minirun and was varied in the pattern $--++--++$, where $-$ ($+$) refers to the electron having negative (positive) helicity in the accelerator. This rapid modulation of the electron beam helicity was an important factor in avoiding systematic errors in the asymmetry measurement.

Each target raster pattern consisted of 313 points and was completed in 2.6 sec. An integral number of raster patterns was used for each minirun. The number of events taken in each minirun was normalized to the total charge measured by the toroids, and corrections were made for losses due to computer sampling, multiple hodoscope tracks, and dead time. The experimental asymmetry, Δ, is the quantity $\pm[(1256)-(3478)]/[(1256)+(3478)]$, where (1256) and (3478) refer to the sums of the corrected and normalized number of events in miniruns 1, 2, 5, 6 and 3, 4, 7, 8, respectively. The sign of Δ is chosen to give the antiparallel-minus-parallel asymmetry in accordance with Eq. (1). False asymmetries were measured with other combinations of miniruns.

Elastic scattering data were taken at the kinematic point for which $E = 6.473$ GeV, $E' = 6.066$ GeV, $\theta = 8.005°$, and $Q^2 = 0.765$ $(\mathrm{GeV}/c)^2$. A total of 2.1×10^6 electrons were detected with a typical

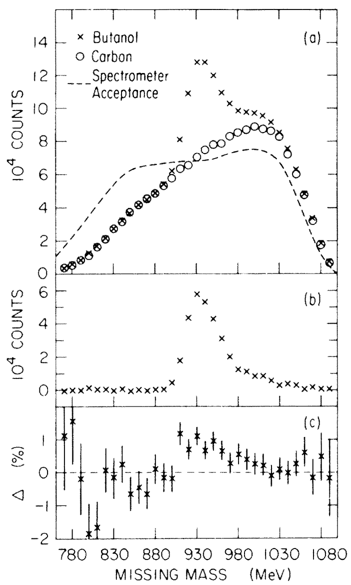

FIG. 1. Elastic scattering results for $E = 6.473$ GeV, $\theta = 8.005°$; (a) scattered electron counts versus missing mass with calculated spectrometer acceptance in arbitrary units; (b) scattered electron counts from free protons versus missing mass; (c) experimental asymmetry Δ versus missing mass.

counting rate of 0.25 scattered electrons per 1.5 μsec beam pulse. The combined missing mass (W) spectrum for electrons scattered from butanol for all runs independent of beam or target polarization is shown in Fig. 1(a), together with the background from electron-carbon scattering normalized to equal areas in the mass region $720 \leq W < 880$ MeV. Also shown in Fig. 1(a) is the spectrometer acceptance as determined from a Monte Carlo ray-tracing calculation. The free-proton spectrum (butanol minus background) versus missing mass is shown in Fig. 1(b). The experimental asymmetry, Δ, is shown plotted versus W in Fig.1(c). The positive asymmetry associated with elastic scattering from free protons is apparent. Values of Δ for three missing-mass regions are given in Table III. Several false asymmetries, calculated over the complete missing-mass region 720 MeV $\leq W \leq$ 1120 MeV, are shown in Table IV, together with the χ^2 values for the agreement with zero of the measured false asymmetries for the 21 individual runs. No statistically significant false asymmetry was found.

The differential-cross-section asymmetry A of Eq. (1) is related to Δ by

$$\Delta = P_e P_p F A. \qquad (3)$$

Here F is the fraction of scattered electrons

TABLE III. Experimental asymmetry, Δ.

W (MeV)	Δ (%)
$720 \leq W < 890$	-0.36 ± 0.18
$890 \leq W < 1000$	$+0.63 \pm 0.10$
$1000 \leq W < 1120$[a]	$+0.15 \pm 0.13$

[a]Since a small fraction of the scattering events from free protons fall in this region, an asymmetry Δ of about +0.13% is expected.

within the elastic missing-mass region ($890 \leq W < 1000$ MeV) which originate from free protons. Using the normalized carbon spectrum to determine the bound-nucleon background, we obtained a value of $F = 0.27 \pm 0.02$. To obtain A, we could have used Eq. (3) with $P_e = 0.51$, the average value of $P_p \simeq 0.34$, and $\Delta = 0.0063 \pm 0.0010$ within the elastic region (Table III). Instead, we used a somewhat different method of calculation which took into account the gradual decrease of the target polarization during a run. Our final result is $A = 0.138 \pm 0.031$ (0.019), where the statistical counting error, shown in parentheses, is added in quadrature to the systematic errors in P_e, P_p, and F to determine the total uncertainty. The values obtained for Δ with the two different directions of proton polarization agree within statistical counting errors. This agreement provides an important test of the validity of our result. Systematic errors in Δ arising from a correlation of beam energy or angle with beam helicity are small compared to the statistical error, as is the error associated with the measurement of beam charge by the toroids. The effect of radiative corrections on A is expected to be small, and these corrections to the data have not yet been made.

The theoretical expression for A of Eq. (2) de-

TABLE IV. False asymmetries.

Combination of miniruns	Average asymmetry[a] (%)	$\chi^2(0)$ per degree of freedom
$\frac{(1234)-(5678)}{(1234)+(5678)}$	0.02 ± 0.07	13/21
$\frac{(1357)-(2468)}{(1357)+(2468)}$	0.01 ± 0.07	18/21
$\frac{(2367)-(1458)}{(2367)+(1458)}$	-0.08 ± 0.07	17/21

[a]Independent of sign of P_p.

pends on both the magnitude and sign of G_E/G_M. Unpolarized elastic scattering experiments determine G_E^2 and G_M^2, but not the sign of G_E/G_M. For $Q^2 = 0.765$ $(\mathrm{GeV}/c)^2$ these experiments[10] give $|\mu G_E/G_M| = 0.98 \pm 0.04$ in which $\mu = 2.79$. If G_E and G_M have the same sign, Eq. (2) yields $A = +0.112 \pm 0.001$, while if G_E and G_M have the opposite sign Eq. (2) gives $A = -0.017 \pm 0.002$. From our measured value of A we conclude that the theoretical and experimental values are in good agreement provided the signs of G_E and G_M are the same. The effect of proton structure on the hyperfine-structure interval in hydrogen involves an integral of the product of the proton structure functions and also gives the sign of G_E/G_M to be positive.[11]

The experimental method described in this Letter could in principle[2,12] be applied to determine G_E in the region $Q^2 \lesssim 2$ $(\mathrm{GeV}/c)^2$, where G_E is not well known, but its practical usefulness is limited by low counting rates.

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[1]M. J. Alguard *et al.*, following Letter [Phys. Rev. Lett. 37, 1261 (1976)].

[2]N. Dombey, Rev. Mod. Phys. 41, 236 (1969). The methodology of this paper was used to derive Eq. (2).

[3]V. W. Hughes *et al.*, Phys. Rev. A 5, 195 (1972); M. J. Alguard *et al.*, in *Proceedings of the Ninth International Conference on High Energy Accelerators, Stanford Linear Accelerator Center, Stanford, California, 1974*, CONF-740 522 (National Technical Information Service, Springfield, Va., 1974), p. 309.

[4]P. S. Cooper *et al.*, Phys. Rev. Lett. 34, 1589 (1975).

[5]We thank the members of SLAC Group A for their invaluable help in making the electron polarization measurement by Møller scattering in March 1976.

[6]M. J. Alguard *et al.*, Bull. Am. Phys. Soc. 21, 98 (1976).

[7]W. W. Ash, in Proceedings of the Brookhaven National Laboratory Workshop in Physics with Polarized Targets, June 1974, BNL Report No. 20415 (unpublished), p. 309; W. W. Ash *et al.*, to be published.

[8]M. Borghini *et al.*, Nucl. Instrum. Methods 84, 168 (1970).

[9]Isolite is the name for a plastic formed by adding a wavelength-shifter to Lucite.

[10]Ch. Berger *et al.*, Phys. Lett. 35B, 87 (1971); W. Bartel *et al.*, Nucl. Phys. B 58, 429 (1973).

[11]H. Grotch and D. R. Yennie, Rev. Mod. Phys. 41, 350 (1969); C. Zemach, Phys. Rev. 104, 1771 (1956).

[12]A. I. Akhiezer *et al.*, Zh. Eksp. Teor. Fiz. 33, 765 (1957) [Sov. Phys. JETP 6, 588 (1958)].

Deep Inelastic Scattering of Polarized Electrons by Polarized Protons*

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We report measurements of the asymmetry in deep inelastic scattering of longitudinally polarized electrons by longitudinally polarized protons. The antiparallel-parallel asymmetries are positive and large in agreement with predictions of quark-parton models of the proton. A limit is obtained on parity nonconservation in the scattering of longitudinally polarized electrons by unpolarized nucleons.

Experimental and theoretical studies of deep inelastic electron scattering from protons and neutrons have led in the past eight years to the important discovery of scaling and to the quark-parton model of nucleon structure.[1] Deep inelastic muon[2] and neutrino[3] scattering have confirmed these general ideas.[4]

For deep inelastic electron-proton scattering,