# ELASTIC SCATTERING OF POLARIZED ELECTRONS BY POLARIZED PROTONS＊ 

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#### Abstract

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 $Q^{2}=0.765(\mathrm{GeV} / \mathrm{c})^{2}$ was measured；our result agrees with the theoretical asymmetry and determines the $\operatorname{sign}$ of $G_{E} / G_{M}$ to be positive．


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[^0]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 electron were measured when longitudinally polarized electrons were scattered from longitudinally polarized protons. The basic quantity measured was the antiparallelparallel asymmetry $A$ in the differential cross sections given by

$$
\begin{equation*}
A=\frac{d \sigma(\uparrow \downarrow)-d \sigma(\uparrow \uparrow)}{d \sigma(\uparrow \downarrow)+\mathrm{d} \sigma(\uparrow \uparrow)} \tag{1}
\end{equation*}
$$

in which $d \sigma$ denotes the differential cross section $d \sigma(E, \theta) / d \Omega$ for incident electron energy $E$ and laboratory scattering angle $\theta$, 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 ${ }^{2}$

$$
\begin{equation*}
A=-\frac{\tau G_{M}}{G_{E}}\left\{\frac{2 M}{E}+\frac{G_{M}}{G_{E}}\left[\frac{2 \tau M}{E}+2(1+\tau) \tan ^{2} \frac{\theta}{2}\right]\right\}\left\{1+\tau\left(\frac{\mathrm{G}_{\mathrm{M}}}{\mathrm{G}_{\mathrm{E}}}\right)^{2}\left[1+2(1+\tau) \tan ^{2} \frac{\theta}{2}\right]\right\}^{-1} \tag{2}
\end{equation*}
$$

in which $\tau=Q^{2} / 4 M^{2}, q^{2}=-Q^{2}=-4 E E^{?} \sin ^{2}(\theta / 2)$ is the square of the $4-$ momentum of the virtual photon, $M$ is the proton mass, $E^{\mathbf{~}}$ 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 (SLAC), is based on photoionization of a
polarized $L i^{6}$ atomic beam by a pulsed uv light source。 ${ }^{3}$ Typical character－ istics of the polarized electron beam are given in Table I．The electron polar－ ization，$P_{e}$ ，was measured by Mott scattering at the output of PEGGY and by Moller scattering at high energy．The value given for $P_{c}$ is based on the Mфller scattering measurements ${ }^{4,5}$ The uncertainty，$\delta \mathrm{P}_{\mathrm{e}} / \mathrm{P}_{\mathrm{e}}=12 \%$ ，includes counting statistics（ $10 \%$ ）and the uncertainty in the uv light intensity for photo－ ionization．（The polarization depends upon light intensity through a depolar－ izing 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 $I_{\text {I }}$ ．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 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 measure－ ments $(8 \%)$ and the uncertainty in the correction for nonuniform irradiation of the target $(5 \%$ ）。（Only $\sim 70 \%$ of the total $2.5 \mathrm{~cm} \times 2.5 \mathrm{~cm}$ 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 $\sim 0$ 。1\％。A mo－ mentum slit in the transport system limited the beam energy spread to $\pm 0.375 \%$ ． Spin precession in the $24.5^{\circ}$ bend of the beam switchyard determined that only electrons whose energies were integral multiples of 3.237 GeV had full longi－ tudinal 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 $\sim 0.1 \mathrm{~mm}$. 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 SLAC 8 GeV spectrometer. Electron identification was achieved with a gas threshold Cerenkov 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 cycles, 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，$\Delta$ ，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 mini－ runs $1,2,5,6$ and $3,4,7,8$ ，respectively．The sign of $\Delta$ 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 $\mathrm{E}=6.473 \mathrm{GeV}, \mathrm{E}^{\prime}=6.066 \mathrm{GeV}, \theta=8.005^{\circ}$ ，and $\mathrm{Q}^{2}=0.765(\mathrm{GeV} / \mathrm{c})^{2}$ 。A total of $2.1 \times 10^{6}$ electrons were detected with a typical counting rate of 0.25 scat－ tered electrons per $1.5 \mu \mathrm{sec}$ 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。1a，together with the background from electron－carbon scattering normalized to equal areas in the mass region $720 \leq \mathrm{W}<880 \mathrm{MeV}$ 。Also shown in Fig。1a is the spectrometer acceptance as determined from a Monte Carlo ray tracing calculation．The free proton spec－ trum（butanol minus background）versus missing mass is shown in Fig．1b． The experimental asymmetry，$\Delta$ ，is shown plotted versus $W$ in Fig。1c。 The positive asymmetry associated with elastic scattering from free protons is ap－ parent．Values of $\Delta$ for three missing mass regions are given in Table III。 Several false asymmetries，calculated over the complete missing mass region $720 \mathrm{MeV} \leq \mathrm{W} \leq 1120 \mathrm{MeV}$ ，are shown in Table IV，together with the chi－squared 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 $\Delta$ by

$$
\begin{equation*}
\Delta=P_{e} P_{p} F A \tag{3}
\end{equation*}
$$

Here $F$ is the fraction of scattered electrons within the elastic missing mass region（ $890 \leq \mathrm{W}<1000 \mathrm{MeV}$ ）which originate from free protons．Using the
normalized carbon spectrum to determine the bound nucleon background，we ob－ tained 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 $P_{p} \approx 0.34$ ，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 polariza－ tion during a run．Our final result is $A=0.138 \pm 0.031(0.019)$ ，where the sta－ tistical 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 $\Delta$ 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 $\Delta$ arising from a cor－ relation 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）depends on both the magnitude and sign of $\mathrm{G}_{\mathrm{E}} / \mathrm{G}_{\mathrm{M}}$ ．Unpolarized elastic scattering experiments determine $\mathrm{G}_{\mathrm{E}}{ }^{2}$ and $\mathrm{G}_{\mathrm{M}}{ }^{2}$ ，but not the sign of $\mathrm{G}_{\mathrm{E}} / \mathrm{G}_{\mathrm{M}}$ ．For $\mathrm{Q}^{2}=0.765(\mathrm{GeV} / \mathrm{c})^{2}$ these ex－ periments ${ }^{10}$ give $\left|\mu \mathrm{G}_{\mathrm{E}} / \mathrm{G}_{\mathrm{M}}\right|=0.98 \pm 0.04$ in which $\mu=2$ 。79。 If $\mathrm{G}_{\mathrm{E}}$ and $\mathrm{G}_{\mathrm{M}}$ 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 $Q^{2} \gtrsim 2(\mathrm{GeV} / \mathrm{c})^{2}$ where $G_{E}$ is not well known， but its practical usefulness is limited by low counting rates．

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TABLE I
Characteristics of Polarized Electron Beam

| Charactcristic | Value |
| :--- | :--- |
| Pulse length | $1.5 \mu \mathrm{sec}$ |
| Repetition rate | 120 pps |
| Electron intensity (at high energy) | $\sim 10^{9} \mathrm{e}^{-} / \mathrm{pulse}$ |
| Pulse to pulse intensity variation | $<5 \%$ |
| Electron polarization, $\mathrm{P}_{\mathrm{e}}$ | $0.51 \pm 0.06$ |
| Polarization reversal time | 3 sec |
| Time between reversals | 2 min |
| Intensity difference upon reversal | $<5 \%$ |
| Lifetime of lithium oven load | 70 hrs |
| Time to reload system | 36 hrs |

TABLE II
Operating Characteristics of Polarized Proton Target

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

${ }^{(a)}$ Improvements in target operation gave the larger polarization values in the later parts of the experiment.

TABLE III
Experimental Asymmetry, $\Delta$

| $\mathrm{W}(\mathrm{MeV})$ | $\Delta(\%)$ |
| :---: | :---: |
| $720 \leq \mathrm{W}<890$ | $-0.36 \pm 0.18$ |
| $890 \leq \mathrm{W}<1000$ | $+0.63 \pm 0.10$ |
| $1000 \leq \mathrm{W}<1120^{\text {(a) }}$ | $+0.15 \pm 0.13$ |

${ }^{(a)}$ Since a small fraction of the scattering events from free protons fall in this region, an asymmetry $\Delta$ of about $+0.13 \%$ is expected.

TABLE IV
False Asymmetries

| Asymmetry | $\frac{1234-5678}{1234+5678}$ | $\frac{1357-2468}{1357+2468}$ | $\frac{2367-1458}{2367+1458}$ |
| :---: | :---: | :---: | :---: |
| Average (independent <br> of sign of $\left.P_{p}\right)$ | $(+0.02 \pm 0.07) \%$ | $(+0.01 \pm 0.07) \%$ | $(-0.08 \pm 0.07) \%$ |
| $\chi^{2}(0) /$ deg. freedom | $13 / 21$ | $18 / 21$ | $17 / 21$ |



Fig. 1
Elastic scattering results for $E=6.473 \mathrm{GeV}, \theta=8.005^{\circ}$ : (a) scattered electron counts versus missing mass; calculated spectrometer acceptance in arbitrary units; (b) scattered electron counts from free protons versus missing mass; (c) experimental asymmetry $\Delta$ versus missing mass.


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