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#### Abstract

We report measurements of the asymmetry in deep inelastic scat－ tering 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 violation in the scattering of longitudinally polarized electrons by unpolarized nucleons．


（Submitted to Phys．Rev。Lett．）

[^0]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 accurate data have been obtained on the differential cross section $\mathrm{d}^{2} \sigma / \mathrm{d} \Omega \mathrm{dE}$ ' over a wide range of the energy loss, $\nu$, of the electron and the square of the four momentum transfer, $q^{2}$, to the proton. The two spin averaged proton structure functions $W_{1}\left(\nu, q^{2}\right)$ and $\mathrm{W}_{2}\left(\nu, \mathrm{q}^{2}\right)$ have been determined from these data。 Important, independent information is contained in two additional spin-dependent proton structure functions whose determination requires the measurement of spin corelation asymmetries. ${ }^{5}$

In this Letter we report the first results of an experiment done at the Stanford Linear Accelerator Center (SLAC) to measure the asymmetry, A, in the deep inelastic scattering of longitudinally polarized electrons by longitudinally polarized protons, where A is given by

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

with $d \sigma$ denoting the differential cross section $d^{2} \sigma\left(E, E^{\prime}, \theta\right) / d \Omega d E^{\prime}$ for electrons of incident (scattered) energy $E\left(E^{8}\right)$ and laboratory scattering angle $\theta$, and the arrows denoting the antiparallel and parallel spin configurations.

If the scattering is described by the one-photon exchange approximation, then for unpolarized electrons the virtual photons are linearly polarized, whereas for polarized electrons the photons are elliptically polarized。 The differential cross section for the scattering of longitudinally polarized electrons by longitudinally polarized protons is
$\frac{d^{2} \sigma}{d \Omega d E^{t}}=\left(\frac{d \sigma}{d \Omega}\right)_{M}\left(\frac{1}{\epsilon\left(1+\nu^{2} / Q^{2}\right)}\right) W_{1}\left\{1+\epsilon R \pm \sqrt{1-\epsilon^{2}} \cos \psi A_{1} \pm \sqrt{2 \epsilon(1-\epsilon)} \sin \psi A_{2}\right\}$,
in which $\left(\frac{\mathrm{d} \sigma}{\mathrm{d} \Omega}\right)_{\mathrm{M}}$ is the Mott differential cross section, $\epsilon=\left[1+2\left(1+\nu^{2} / \mathrm{Q}^{2}\right) \tan ^{2} \frac{\theta}{2}\right]^{-1}$, $\mathrm{Q}^{2}=-\mathrm{q}^{2}, \mathrm{R}=\sigma_{\mathrm{L}} / \sigma_{\mathrm{T}}$ is the ratio of the cross sections for absorption of longitudinal and transverse virtual photons, and $\psi$ is the angle between the directions of the virtual photon momentum and the proton spin。The $+(-)$ signs in Eq。(2) refer to the antiparallel (parallel) spin configurations.

The spin-dependent terms $A_{1}$ and $A_{2}$ are two new measurable quantities which can be expressed in terms of two spin-dependent structure functions. 5,6 Equivalently they can be expressed in terms of the total absorption cross sections of circularly polarized photons on polarized protons as

$$
\begin{equation*}
\mathrm{A}_{1}=\left(\sigma_{1 / 2}-\sigma_{3 / 2}\right) /\left(\sigma_{1 / 2}+\sigma_{3 / 2}\right) \quad \text { and } \quad \mathrm{A}_{2}=2 \sigma_{\mathrm{TL}} /\left(\sigma_{1 / 2}+\sigma_{3 / 2}\right) \tag{3}
\end{equation*}
$$

where $\sigma_{1 / 2}\left(\sigma_{3 / 2}\right)$ is the total absorption cross section when the z -component ( z is the direction of the virtual photon momentum) of angular momentum of the virtual photon plus proton is $1 / 2(3 / 2)$, and $\sigma_{\mathrm{TL}}$, which may be negative, is a term which arises from the interference between transverse and longitudinal photon-nucleon amplitudes. It should be noted that $\sigma_{1 / 2}$ and $\sigma_{3 / 2}$ are related to $\sigma_{\mathrm{T}}$ by $\sigma_{1 / 2}+\sigma_{3 / 2}=2 \sigma_{\mathrm{T}}$.

For the case of protons polarized along the incident beam direction, the asymmetry A of Eq. (1) is

$$
\begin{equation*}
\mathrm{A}=\mathrm{D}\left(\Lambda_{1}+\eta \mathrm{A}_{2}\right), \tag{4}
\end{equation*}
$$

where

$$
\begin{equation*}
D=\left(E-E^{\prime} \epsilon\right) / E(1+\epsilon R)=\sqrt{1-\epsilon^{2}} \cos \psi /(1+\epsilon R), \tag{5}
\end{equation*}
$$

and

$$
\begin{equation*}
\eta=\epsilon \sqrt{\mathrm{Q}^{2}} /\left(\mathrm{E}-\mathrm{E}^{\prime} \epsilon\right)=[2 \epsilon /(1+\epsilon)]^{1 / 2} \tan \psi \approx \tan \psi . \tag{6}
\end{equation*}
$$

The quantity $D$ can be regarded as a kinematic depolarization factor of the virtual photon and is $\sim 0.3$ for our kinematic points. Positivity limits imposed on $A_{1}$ and $A_{2}$ are ${ }^{7}$

$$
\begin{equation*}
\left|A_{1}\right| \leq 1,\left|A_{2}\right| \leq \sqrt{R} \tag{7}
\end{equation*}
$$

In this experiment we determine the combination $\mathrm{A}_{1}+\eta \mathrm{A}_{2}$ by dividing the measured electron-proton asymmetry A by the depolarization factor D. Although we do not separately determine $A_{1}$ and $A_{2}$, our result is dominated by $A_{1}$ because the kinematic factor $\eta$ is small.

On the basis of a high energy sum rule derived with the algebra of currents for a quark model, it has been predicted ${ }^{8}$ that $A_{1}$ has a positive value greater than 0.2 over a large region of the deep inelastic continuum. Scaling relations are predicted for the spin-dependent proton structure functions, and hence also for $A_{1}: 9$

$$
\begin{equation*}
\mathrm{A}_{1}\left(\nu, \mathrm{Q}^{2}\right) \rightarrow \mathrm{A}_{1}(\omega) \text { as } \nu, \mathrm{Q}^{2} \rightarrow \infty \text { with } \omega \text { held constant } \tag{8}
\end{equation*}
$$

( $\omega=2 \mathrm{M} \nu / \mathrm{Q}^{2}, \mathrm{M}=$ proton mass). Specific models of proton structure make widely varying predictions for $A_{1}$. The simplest quark-parton model predicts $A_{1}=5 / 9$, and more elaborate models also predict large positive values for $\mathrm{A}_{1}(\omega)_{0}{ }^{5,10}$

The method of measuring the experimental asymmetry, $\Delta$, for deep inelastic electron-proton scattering was the same as that described for elastic scattering in the preceding Letter. ${ }^{11}$ For the inelastic case, the scattered electron counting rate was lower ( 0.02 to 0.06 electrons per pulse). Background due to misidentified pions was again negligible.

The antiparallel-parallel asymmetry $\Delta$ was measured for three deep inelastic kinematic points and the results are given in Table I. Several false
asymmetries were also measured and are listed in Table II，together with the chi－squared values for the agreement with zero of the measured false asym－ metries for the indicated degrees of freedom（number of individual runs）．No statistically significant false asymmetries were found。

The asymmetry A of Eq。（1）is related to $\Delta$ by

$$
\begin{equation*}
\Delta=P_{e} P_{p} F A \tag{9}
\end{equation*}
$$

The electron polarization，$P_{e}$ ，was $0.51 \pm 0.06$ ，and the average target polari－ zation，$P_{p}$ ，measured for each kinematic point，was $\propto 0.40$ with $10 \%$ un－ certainty．The quantity $F$ is the fraction of detected electrons scattered from free protons．This is taken as the ratio of the number of free protons to the total number of nucleons in the target，including measured contributions from helium and other background sources．A small correction for the difference in scattering cross sections of neutrons and protons was also included。 The value for $F$ ，determined for each point，was $\approx 0.11$ with a $10 \%$ uncertainty

The measured values of $A$ are listed in Table $I$ ．The uncertainties are dominated by counting statistics．No radiative corrections have yet been made． Also listed are the quantities D （evaluated using $\mathrm{R}=0.14$ ），${ }^{1} \mathrm{~A} / \mathrm{D}=\mathrm{A}_{1}+\eta \mathrm{A}_{2}$ ， and upper limits for $\left|\eta A_{2}\right|$（taking $A_{2}=\sqrt{R}$ ）．From Table I it is seen that $A / D$ is dominated by $A_{1}$ 。 Furthermore，parton theories predict ${ }^{12}$ that the inter－ ference term $A_{2}$ will be considerably smaller than its positivity limit $\sqrt{\text { R。 }}$ It is therefore valid to compare our measured value of $A / D$ to theoretical predic－ tions for $\mathrm{A}_{1}$ as shown in Fig。1。

With the explicit assumption that $A / D=A_{1}$ our values of $A_{1}$ are indeed positive and large in accord with early theoretical expectations from sum rules．${ }^{8}$ The two values for $\omega=3$ agree within their errors，which is consistent with the expectation that $A_{1}$ satisfies the scaling relation，given by Eq．（8）．

Our data are consistent with the predictions of the quark－parton models shown as curves（a）${ }^{5}$ and（b）${ }^{10}$ in Fig．1，but disagree strongly with the resonance model ${ }^{13}$（curve（c））and the bare nucleon－bare meson model ${ }^{14}$（curve（d））。 We note that the theoretical curves are all given for the scaling limit．

Data from this experiment can also be used to place a limit on parity non－ conservation in the scattering of longitudinally polarized electrons from un－ polarized nucleons，$i_{。} \mathrm{e}$ ，an interaction term of the form $\vec{\sigma}_{\mathrm{e}} \circ \overrightarrow{\mathrm{p}}_{\mathrm{e}}$ in which $\vec{\sigma}_{\mathrm{e}}$ is the electron spin and $\vec{p}_{e}$ is the electron incident momentum．If we define $\Delta^{+}\left(\Delta^{\top}\right)$ as the asymmetry for protons polarized along（against）the beam direction and if the magnitude of $P_{p}$ is the same for both cases，then we can define an asym－ metry，$\Delta_{\mathrm{PNC}}$ ，associated with parity nonconservation by ${ }^{15}$

$$
\begin{equation*}
\Delta_{\mathrm{PNC}}=\left(\Delta^{+}-\Delta^{-}\right) / 2 \equiv \mathrm{rP} \mathrm{e}_{\mathrm{e}} \tag{10}
\end{equation*}
$$

in which $\mathbf{r}=\left(\mathrm{d} \sigma^{-}-\mathrm{d} \sigma^{+}\right) /\left(\mathrm{d} \sigma^{-}+\mathrm{d} \sigma^{+}\right)$is the asymmetry for electron polariza－ tion $P_{e}=1$ ，and the superscripts－and＋refer to the electron beam helicity。 From the deep inelastic scattering data summarized in Table I for $Q^{2}$ between 1.4 and $2.7(\mathrm{GeV} / \mathrm{c})^{2}$ ，we find r is consistent with zero．For the combined data we have an upper limit of $r<5 \times 10^{-3}$ with a $95 \%$ confidence level．For the elastic scattering data reported in the preceding Letter，${ }^{11}$ again $r$ is consistent with zero and its upper limit is less than $3 \times 10^{-3}$ with a $95 \%$ confidence level。 The gauge theories of weak and electromagnetic interactions，which contain parity violation，predict ${ }^{16,17}$ considerably smaller values of $r \approx\left(10^{-5}\right.$ to $\left.10^{-4}\right) Q^{2} / M^{2}$.

We are happy to acknowledge helpful and stimulating discussions with J．D． Bjorken，F．Gilman，and J．Kuti。

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| $480{ }^{\circ} 0$ |  | でも ${ }^{\circ} 0$ | （IS0＊0） | $890^{\circ} 0 \mp$ 㑆 ${ }^{\circ} 0$ | II 0 于 $86^{\circ} 0$ | 9 | $099^{*} \%$ | 815＊${ }^{\circ}$ | $000 * 6$ | 1L2＊6 |
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| $1^{6} v^{4} \mid$ | $\text { (q) }{ }^{Z} v^{u}+{ }^{\mathrm{T}} \mathrm{~V}$ | （ $)^{\text {d }}$ |  | （q）${ }^{\mathrm{V}}$ | （\％）$\nabla$ | $\cdots$ |  | $z^{(0 / \Lambda \text { ə })^{\prime}}{ }^{\text {O}}$ | （ธวข）$\theta$ | （ $\Lambda$ วロ）曲 |


I

TABLE II
False Asymmetries ${ }^{\text {（a）}}$

| Data <br> Point | Quantity | $\frac{(1234)-(5678)}{(1234)+(5678)}$ | $\frac{(1357)-(2468)}{(1357)+(2468)} \frac{(2367)-(1458)}{(2367)+(1458)}$ |  |
| :--- | :---: | :---: | :---: | :---: |
| $\omega=3$ | Average value（irre－ <br> spective of sign of <br> target polarization $)$ | $+0.04 \pm 0.11 \%$ | $-0.04 \pm 0.11 \%$ | $+0.14 \pm 0.11 \%$ |
| $Q^{2}=1.680$ | $\chi^{2}(0) /$ deg。freedom | $18 / 34$ | $38 / 34$ | $27 / 34$ |
| $\omega=3$ | Average value | $-0.30 \pm 0.17 \%$ | $-0.03 \pm 0.17 \%$ | $+0.24 \pm 0.17 \%$ |
| $Q^{2}=2.735$ | $\chi^{2}(0) /$ deg。freedom | $33 / 30$ | $26 / 30$ | $40 / 30$ |
| $\omega=5$ | Average value | $-0.12 \pm 0.11 \%$ | $-0.10 \pm 0.11 \%$ | $-0.03 \pm 0.11 \%$ |
| $Q^{2}=1.418$ | $\chi^{2}(0) /$ deg。freedom | $34 / 35$ | $34 / 35$ | $30 / 35$ |

${ }^{(a)}$ See preceding Letter for definitions of false asymmetries．${ }^{11}$


Fig． 1

Experimental values of $A / D \approx A_{1}$ and theoretical predictions of the virtual photon－proton asymmetry $A_{1}$ versus $\omega_{0}$ Theoretical curves（a），（b），（c）， and（d）are obtained from Refs．5，10，13，and 14，respectively．For curve （c）the quark model with symmetry breaking is used：the model does not give values for $A_{1}$ in the range $1<\omega<2$ ，but rather gives $A_{1}(1)=1$ 。 For curve（d）the quantity $\mu^{2} / \mathrm{m}_{\mathrm{p}}^{2}$ in the theory is taken equal to 0 。 12 。


[^0]:    ＊Research supported in part by the Energy Research and Development Admin－ istration under Contract No。E（11－1）－3075（Yale）and Contract No。E（04－3）－ 515 （SLAC），the German Federal Ministry of Research and Technology and the University of Bielefeld，and the Japan Society for the Promotion of Science．

