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DEEP INELASTIC SCATTERING OF POLARIZED ELECTRONS BY POLARIZED PROTONS*

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ABSTRACT

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 violation in the scattering of longitudinally polarized electrons by unpolarized nucleons.

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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 $d^2\sigma/d\Omega\, dE'$ over a wide range of the energy loss, ν, of the electron and the square of the four momentum transfer, q^2, to the proton. The two spin averaged proton structure functions $W_1(\nu, q^2)$ and $W_2(\nu, q^2)$ 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 correlation 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

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

with $d\sigma$ denoting the differential cross section $d^2\sigma(E, E', \theta)/d\Omega\, dE'$ for electrons of incident (scattered) energy E (E') and laboratory scattering angle θ, 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

$$\frac{d^2\sigma}{d\Omega dE'} = \left(\frac{d\sigma}{d\Omega}\right)_M \left(\frac{1}{\epsilon\,(1+\nu^2/Q^2)}\right) W_1 \left\{1+\epsilon R \pm \sqrt{1-\epsilon^2}\,\cos\psi\, A_1 \pm \sqrt{2\epsilon\,(1-\epsilon)}\,\sin\psi\, A_2\right\}, \tag{2}$$

in which $\left(\frac{d\sigma}{d\Omega}\right)_M$ is the Mott differential cross section, $\epsilon = \left[1+2(1+\nu^2/Q^2)\tan^2\frac{\theta}{2}\right]^{-1}$, $Q^2 = -q^2$, $R = \sigma_L/\sigma_T$ is the ratio of the cross sections for absorption of longitudinal and transverse virtual photons, and ψ 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

$$A_1 = (\sigma_{1/2} - \sigma_{3/2})/(\sigma_{1/2} + \sigma_{3/2}) \quad \text{and} \quad A_2 = 2\sigma_{TL}/(\sigma_{1/2} + \sigma_{3/2}) , \tag{3}$$

where $\sigma_{1/2}(\sigma_{3/2})$ 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 σ_{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 σ_T by $\sigma_{1/2} + \sigma_{3/2} = 2\sigma_T$.

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

$$A = D(A_1 + \eta A_2) , \tag{4}$$

where

$$D = (E-E'\epsilon)/E(1+\epsilon R) = \sqrt{1-\epsilon^2}\,\cos\psi/(1+\epsilon R) , \tag{5}$$

and

$$\eta = \epsilon\sqrt{Q^2}/(E-E'\epsilon) = \left[2\epsilon/(1+\epsilon)\right]^{1/2}\tan\psi \simeq \tan\psi . \tag{6}$$

The quantity D can be regarded as a kinematic depolarization factor of the virtual photon and is ~ 0.3 for our kinematic points. Positivity limits imposed on A_1 and A_2 are[7]

$$|A_1| \leq 1, \quad |A_2| \leq \sqrt{R} \tag{7}$$

In this experiment we determine the combination $A_1 + \eta A_2$ 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 η 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]

$$A_1(\nu, Q^2) \rightarrow A_1(\omega) \text{ as } \nu, Q^2 \rightarrow \infty \text{ with } \omega \text{ held constant} \tag{8}$$

($\omega = 2M\nu/Q^2$, 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 $A_1(\omega)$.[5,10]

The method of measuring the experimental asymmetry, Δ, 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 Δ 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 asymmetries 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 Δ by

$$\Delta = P_e P_p F A . \tag{9}$$

The electron polarization, P_e, was 0.51 ± 0.06, and the average target polarization, P_p, measured for each kinematic point, was $\simeq$ 0.40 with 10% uncertainty. 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 $\simeq$ 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 $R = 0.14$),[1] $A/D = A_1 + \eta A_2$, and upper limits for $|\eta A_2|$ (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 interference term A_2 will be considerably smaller than its positivity limit $\sqrt{R}$. It is therefore valid to compare our measured value of A/D to theoretical predictions for 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 nonconservation in the scattering of longitudinally polarized electrons from unpolarized nucleons, i.e., an interaction term of the form $\vec{\sigma}_e \cdot \vec{p}_e$ in which $\vec{\sigma}_e$ is the electron spin and $\vec{p}_e$ is the electron incident momentum. If we define Δ^+ (Δ^-) 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 asymmetry, Δ_{PNC}, associated with parity nonconservation by[15]

$$\Delta_{PNC} = (\Delta^+ - \Delta^-)/2 \equiv rP_e \ , \qquad (10)$$

in which $r = (d\sigma^- - d\sigma^+)/(d\sigma^- + d\sigma^+)$ is the asymmetry for electron polarization $P_e = 1$, 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 $(\mathrm{GeV}/c)^2$, 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 3×10^{-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 $r \simeq (10^{-5} \text{ to } 10^{-4})\, Q^2/M^2$.

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TABLE I

Results of Asymmetry Measurements

E(GeV)	θ (deg)	Q^2 (GeV/c)^2	W(GeV)$^{(a)}$	ω	Δ(%)	$A^{(b)}$	$D^{(c)}$	$A_1 + \eta A_2$$^{(b)}$	$\lvert\eta A_2\rvert$
9.711	9.000	1.680	2.059	3	0.44 ± 0.11	0.191 ± 0.057 (0.044)	0.284	0.67 ± 0.20 (0.16)	< 0.146
12.948	9.000	2.735	2.519	3	0.50 ± 0.17	0.215 ± 0.089 (0.080)	0.352	0.61 ± 0.25 (0.23)	< 0.109
9.711	9.000	1.418	2.560	5	0.28 ± 0.11	0.141 ± 0.058 (0.051)	0.412	0.34 ± 0.14 (0.12)	< 0.087

(a) W = missing mass of undetected hadron system.

(b) The total errors are the statistical counting errors added in quadrature to the systematic errors in P_e, P_p, and F; the numbers in parentheses are the one standard deviation counting errors.

(c) D is obtained from Eq. (5) using R = 0.14.

TABLE II

False Asymmetries(a)

Data Point	Quantity	$\frac{(1234)-(5678)}{(1234)+(5678)}$	$\frac{(1357)-(2468)}{(1357)+(2468)}$	$\frac{(2367)-(1458)}{(2367)+(1458)}$
$\omega = 3$	Average value (irrespective of sign of target polarization)	+0.04 ± 0.11%	-0.04 ± 0.11%	+0.14 ± 0.11%
Q^2=1.680	$\chi^2(0)$/deg. freedom	18/34	38/34	27/34
$\omega = 3$	Average value	-0.30 ± 0.17%	-0.03 ± 0.17%	+0.24 ± 0.17%
Q^2=2.735	$\chi^2(0)$/deg. freedom	33/30	26/30	40/30
$\omega = 5$	Average value	-0.12 ± 0.11%	-0.10 ± 0.11%	-0.03 ± 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]

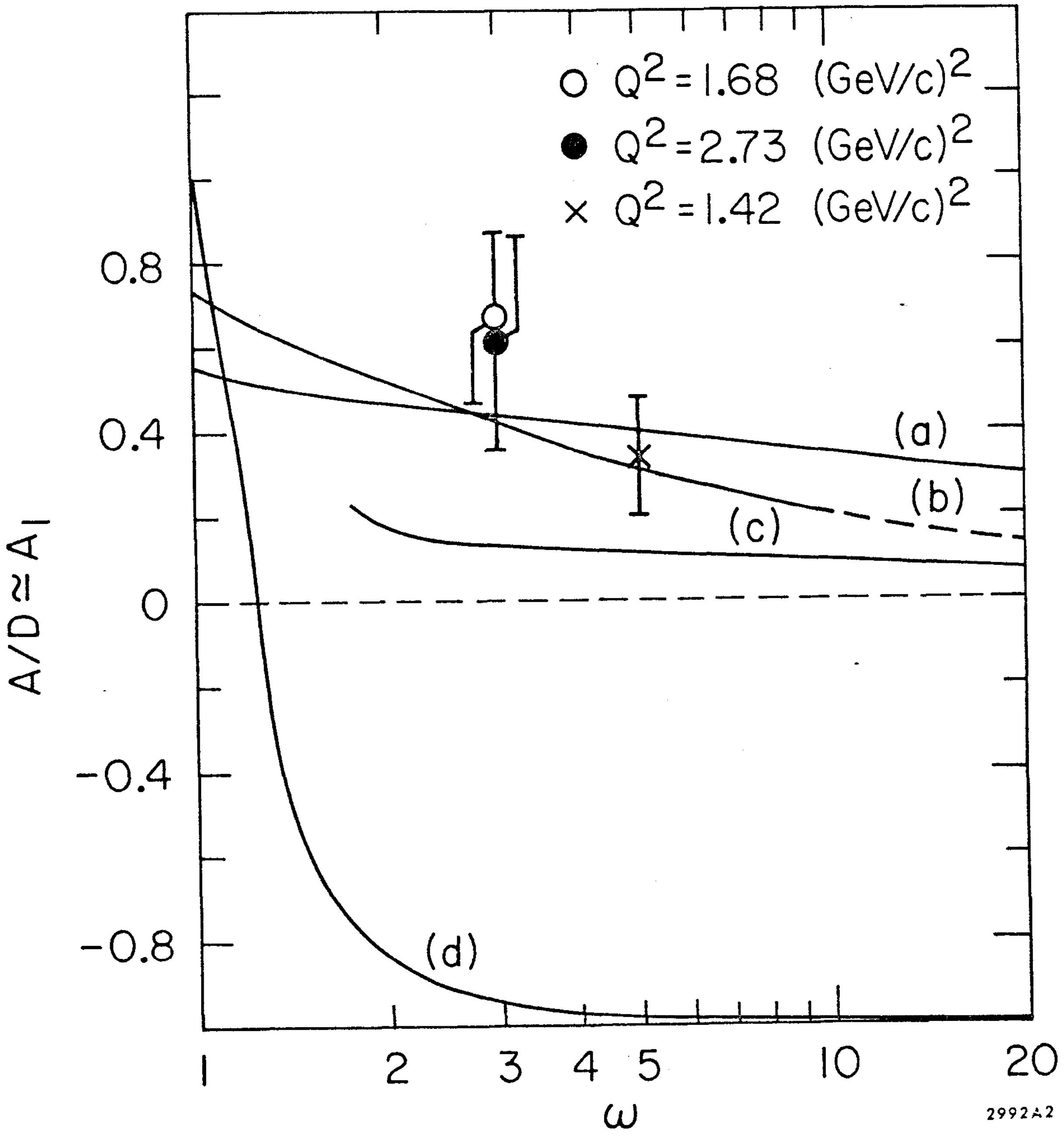

Fig. 1

Experimental values of $A/D \approx A_1$ and theoretical predictions of the virtual photon-proton asymmetry A_1 versus ω. 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 μ^2/m_p^2 in the theory is taken equal to 0.12.