New Measurement of Deep-Inelastic e-p Asymmetries

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Spin-dependent asymmetries have been measured in inclusive deep-inelastic scattering of longitudinally polarized electrons by longitudinally polarized protons. Data were obtained at a scattering angle of 10° and for incident energies of 16.2 and 22.7 GeV, which cover the kinematic range $0.18 < x < 0.70$ and $3.5 < Q^2 < 10.0$ (GeV/c)^2. The present results provide a test of scaling and of the Bjorken and Ellis-Jaffe sum rules and are compared with various models of proton spin structure.

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The study of the structure of the proton and neutron through inclusive deep-inelastic scattering, initially with electrons but subsequently with muons and neutrinos as well, has played a central role in the establishment of the quark-parton theory of the composition of hadrons and later of quantum chromodynamics (QCD). Inclusive deep-inelastic electron-nucleon scattering is described by four independent structure functions. Two of these are spin dependent and determine the spin distribution of quark constituents inside the nucleon. Knowledge of these spin-dependent structure functions is important for tests of models of nucleon structure, of the Bjorken polarization sum rule, and of QCD, and is also essential for an understanding of spin effects in high-energy hadron-hadron scattering. Polarization-dependent proton-proton and proton-antiproton interactions of interest in high-energy colliders, for example, will depend for their interpretation upon knowledge of quark spin distributions.

The spin-dependent structure functions of the proton can be determined only from asymmetry measurements in the scattering of polarized leptons by polarized protons. In this Letter new polarized-electron–polarized-proton asymmetry measurements are reported, extending the data to higher Q^2 and higher x values than previously available. The new data have been obtained with a new, large-acceptance spectrometer designed to detect electrons scattered by $\theta = 10°$. Earlier data at lower values of Q^2 and x have been previously reported by us.[1-3] The method of the experiment was essentially the same as described previously. The experimental asymmetry $\Delta = P_e P_p f A$ was measured, in which P_e is the electron-beam polarization, P_p is the proton-target polarization, f is the fraction of detected electrons scattered from the free (polarizable) protons in the target, and

$$A = [d\sigma(\uparrow\downarrow) - d\sigma(\uparrow\uparrow)]/[d\sigma(\uparrow\downarrow) + d\sigma(\uparrow\uparrow)]$$

is the intrinsic electron-proton asymmetry. Here $d\sigma$ denotes the differential cross section $d^2\sigma(E, E', \theta)/d\Omega dE'$ for electrons of incident (scattered) energy E (E') scattered at a laboratory angle θ, and the arrows denote the antiparallel and parallel longitudinal spin configurations. From A the virtual-photon–proton asymmetry $A_1 = (\sigma_{1/2} - \sigma_{3/2})/(\sigma_{1/2} + \sigma_{3/2})$ is determined with use of the relation $A = D(A_1 + \eta A_2)$, where A_2 is an interference term bounded by $|A_2| \leq \sqrt{R}$ with R the ratio of the cross sections for absorption of longitudinal and transverse virtual photons, η and D are known kinematic expressions, and ηA_2 is assumed to be small compared to A_1.

The polarized-electron source[4] (PEGGY I), which is based on photoionization of electron-spin polarized ^{6}Li atoms, provided 5×10^8 e^-/pulse at 120 pps, and a beam polarization of 0.81 ± 0.03, as determined by a Møller double-arm coincidence measurement. The beam was steered upstream of the target by a closed-loop feedback position and energy steering system,[5] enabling systematic asymmetries related to beam steering to be maintained below the negligible value of 10^{-4}. The polarized target,[1,6] which is based on the method of dynamic nuclear polarization, consisted of $2.5\times 2.5\times 3.8$ cm^3 of butanol doped with porphyrexide. The beam was rastered over an area slightly greater than the 2.5×2.5-cm^2 target cross section, assuring uniform radiation damage and hence uniform polarization. The average target polarization, after the effects of radiation damage, was 0.58 ± 0.04, where most of the error arises from the systematic uncertainty in the size of the thermal equilibrium NMR signal. The value of f was obtained from known neutron/proton cross-section ratios[7] and from measured contributions from helium and other background material. Small corrections to f due to radiative processes and Fermi motion[8] were also included. The value of f averaged over our acceptance region was $\sim 0.150\pm 0.004$. The new spectrometer (Fig. 1), which was of the nonfocusing type, consisted of two dipole magnets, a 4-m-long N_2 gas threshold Čerenkov counter, a 3260-wire proportional wire chamber system, scintillator hodoscopes, and a segmented lead-glass shower counter 20 radiation lengths long. The spectrometer covered a very broad momentum band Δp of $\pm 0.5 p_0$ (p_0 being the central momentum setting) with an average solid angle $\Delta\Omega$ of 0.4 msr. The accuracy of the momentum determination was better than 1%.

Half a million events were collected at each of two spectrometer settings with E (E') = 22.66 (11.5) GeV and E (E') = 16.19 (10.0) GeV. Analysis of the data is complete and includes radiative corrections which were made following the procedure described earlier.[2,9] Detailed numerical tables of our results can be found elsewhere.[10] Figure 2 shows measured values of $A/D \simeq A_1$ plotted versus Q^2 in three intervals of x. The error bars include statistical (dominant) and systematic (small) errors. Not included are the uncertainties due to the interference term $\eta A_2 = A/D - A_1$; for the different kinematic points the upper bound for $|\eta A_2|$ varies between 0.2 and 0.9 of the one-standard-deviation error in A/D.[10] To test scaling of A_1 the measured values of A/D were divided by $\sqrt{x}$ (which describes well the x dependence) and least-squares straight lines were fitted in the region $Q^2 > 2$ (GeV/c)^2. The assumption of scaling (zero slope) gave χ^2/DOF (degree of freedom) of 0.43/5, 2.4/5, and 5/3 and confidence levels of 99%, 80%, and 18%, for the top, middle, and bottom boxes, respectively. We conclude that the predicted scaling[11] of A_1 holds within our errors.

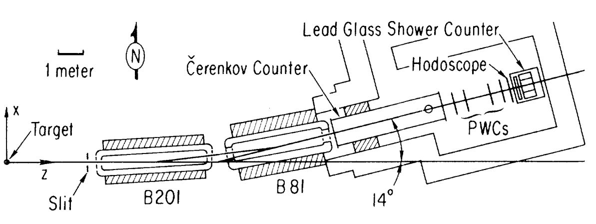

FIG. 1. New spectrometer. The field of the two bending magnets is perpendicular to the z-x plane shown. The spectrometer z axis was set up for a fixed vertical scattering angle of 10° above the beam line.

The values of A/D, combined for different Q^2, are plotted as a function of x in Fig. 3. These data are well described by the relation $A/D = (0.94\pm 0.08)\sqrt{x}$ (with χ^2/DOF = 9.5/11). Also shown are the predictions of various models of nucleon structure. Our data are consistent only with the Carlitz/Kaur and the Schwinger models of A_1 (both with confidence levels of 70%). The Carlitz/Kaur model is characterized by a single u quark carrying the entire spin of the proton in the limit $x \to 1$ so that $A_1 \to 1$ as $x \to 1$. The theo-

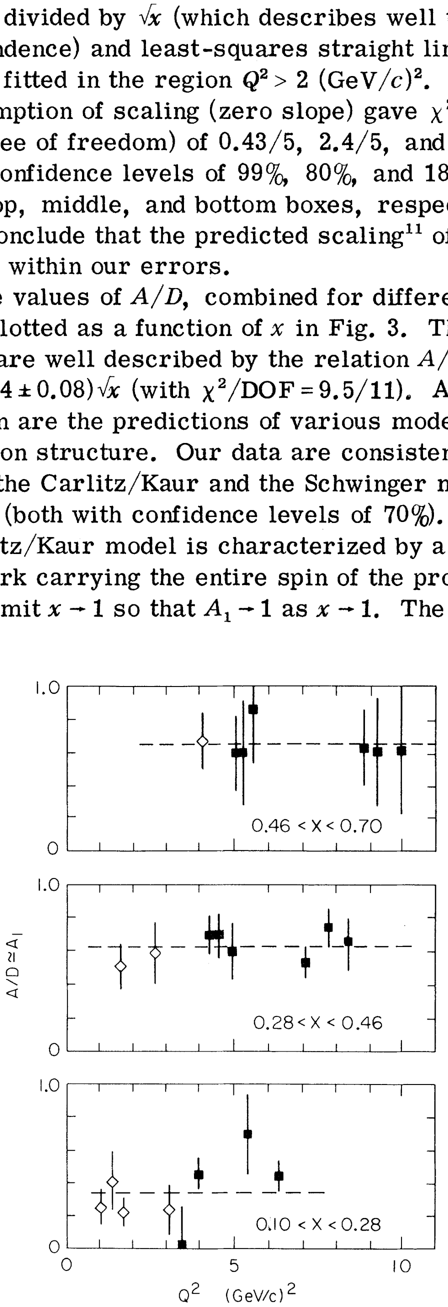

FIG. 2. Radiatively corrected values of $A/D \simeq A_1$ obtained in our previous experiment (open diamonds), and in this experiment (closed squares). A_1 is the virtual-photon–proton asymmetry defined as $(\sigma_{1/2} - \sigma_{3/2})/(\sigma_{1/2} + \sigma_{3/2})$.

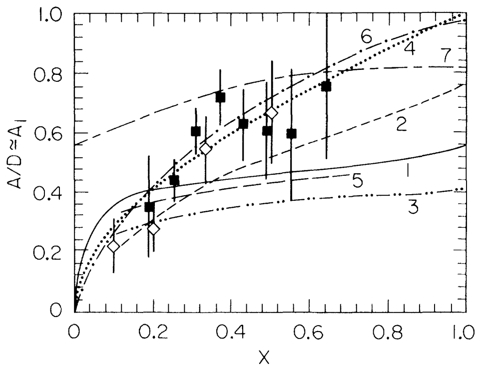

FIG. 3. Experimental values of $A/D \simeq A_1$ compared with theories for A_1: curve 1, symmetrical valence quark model (Ref. 12); curve 2, current quarks (Ref. 13); curve 3, orbital angular momentum (Ref. 14); curve 4, unsymmetrical model (Ref. 15); curve 5, MIT bag model (Ref. 16); curve 6, source theory (Ref. 17); curve 7, quark-geometrodynamics (Ref. 18).

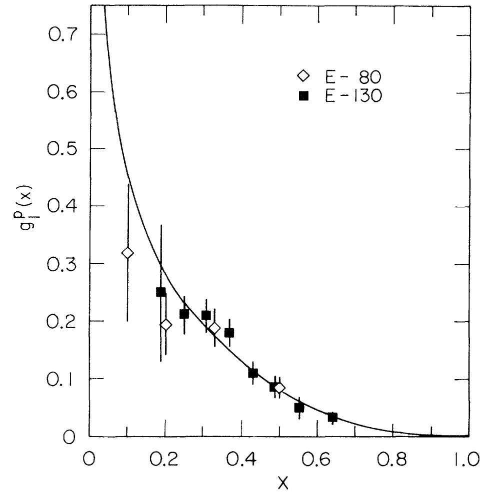

FIG. 4. Experimental values of the spin-dependent structure function $g_1^p(x) = A_1^p(x)F_2^p(x)/2x(1+R^p)$. F_2^p and R^p are from unpolarized data. The smooth curve is obtained with $A_1^p(x) = 0.94\sqrt{x}$.

retical determination of the quark spin distributions inside the nucleon is a difficult nonperturbative calculation not amenable at present to a rigorous QCD approach. However, that the leading quark has the same helicity as the nucleon has been shown[19] on the basis of perturbative QCD calculations.

Our data also permit a test of the Ellis-Jaffe sum rule[20] for the proton,

$$S_{\mathrm{EJ}}^p = \int_0^1 g_1^p\,dx = \int_0^1 \frac{dx}{2x}\,\frac{A_1^pF_2^p}{1+R^p} = \frac{(0.89)}{6}\left|\frac{g_A}{g_V}\right| = 0.186 \pm 0.001, \qquad (1)$$

as well as the Bjorken polarization sum rule,[21]

$$S_{\mathrm{Bj}} = \int_0^1 (g_1^p - g_1^n)\,dx = \int_0^1 \frac{dx}{2x}\left(\frac{A_1^pF_2^p}{1+R^p} - \frac{A_1^nF_2^n}{1+R^n}\right) = \frac{1}{6}\left|\frac{g_A}{g_V}\right| = 0.209 \pm 0.001, \qquad (2)$$

on the assumption that A_1^n is approximated by zero as suggested by simple quark-parton models. In the above equations g_1 is the polarized-nucleon structure function,[22] F_2 is the spin-averaged structure function of the nucleon, $R = \sigma_L/\sigma_T$, p and n refer to proton and neutron, and g_A (g_V) is the axial (vector) weak coupling constant of neutron β decay. The Bjorken sum rule [Eq. (2)], derived originally from current algebra, is also a consequence of QCD up to correction terms of order α_S. On the other hand, the Ellis-Jaffe sum rule [Eq. (1)] requires the additional model-dependent assumption that the net spin polarization of strange sea quarks is zero. The integrand $g_1^p(x)$ is plotted in Fig. 4 using $A/D \simeq A_1^p(x)$ from our data, $F_2^p(x, Q^2)$ from available lepton data parametrizations,[23] and the value $R^p = 0.25 \pm 0.10$ from the SLAC ep data.[24] The smooth curve is obtained from our fit $A_1 = 0.94\sqrt{x}$ and F_2^p evaluated at $Q^2 = 4$ (GeV/c)^2 (which is the mean Q^2 value of our data). The integral of $g_1^p(x)$ in the data region $0.1 < x < 0.64$ is 0.095 ± 0.008, which saturates 45% of the Bjorken sum rule. The integral over the full x range using the Regge-theory prediction[25] $A_1 \propto x^{1.14}$ for small x and our fit $A_1 = 0.94\sqrt{x}$ for large x gives[26]

$$\int_0^1 g_1^p(x)dx = 0.17 \pm 0.05. \qquad (3)$$

In conclusion, our result is consistent with the Ellis-Jaffe sum rule for the proton. This implies that our results are also consistent with the Bjorken sum rule provided that the neutron contribution is as small as suggested by the Ellis-Jaffe sum rule for the neutron.[20]

An experiment to measure the asymmetry in polarized muon-proton scattering with Q^2 values as high as 100 (GeV/c)^2 will be carried out in the near future. Together with our results, these data will serve as a test of QCD predictions of scaling violation. The usefulness of polarization experiments at future e-p colliders, with both electrons (positrons) and protons being polarized, has recently been examined.[27] A proposal has been made to SLAC to measure the electron-neutron asymmetry using a polarized deuteron target.

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