Deep-Inelastic *e-p* Asymmetry Measurements and Comparison with the Bjorken Sum Rule and Models of Proton Spin Structure

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(Received 26 April 1978)

We report new measurements of the asymmetry in the deep-inelastic scattering of longitudinally polarized electrons by longitudinally polarized protons in the kinematic range $2 \leq \omega \leq 10$, $1 \leq Q^2 \leq 4$ $(\text{GeV}/c)^2$, and $2 \leq W \leq 4$ GeV. We compare our results with the Bjorken sum rule and with several theoretical models of the internal spin structure of the proton.

We have previously reported[1-3] on an experiment in which longitudinally polarized electrons were scattered from longitudinally polarized protons and have presented the first data on the asymmetry in deep-inelastic e-p scattering. In this Letter we report new asymmetry data, make appropriate radiative corrections, and discuss the theoretical implications of the results.

The basic quantity determined is the asymmetry $A = [d\sigma(\uparrow\downarrow) - d\sigma(\uparrow\uparrow)]/[d\sigma(\uparrow\downarrow) + d\sigma(\uparrow\uparrow)]$, in which $d\sigma$ denotes 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 denote the antiparallel and parallel longitudinal spin configurations. The momentum and scattering angle of the scattered electrons are observed, and the experimental asymmetry $\Delta = P_e P_p F A$ is measured, in which P_e is the electron-beam polarization, P_p is the proton-target polarization, and F is the fraction of detected electrons scattered from the free (polarizable) protons in the complex target.

The experimental method was essentially the same as that reported previously, but some significant improvements in operating conditions were achieved. We increased P_e to 0.85 ± 0.08 by elimination of a multistep photoionization process.[4] Improvements in the target microwave system increased the average value of P_p to 0.50 with a smaller systematic uncertainty of ± 0.04. Reduction of extraneous material increased F to ~ 0.13. The electron beam was rastered over an area somewhat greater than that of the target, giving uniform radiation damage and hence uniform polarization over the target volume. However, only data for which the beam was within a fiducial region of the target were used for the results. As a test of the experimental method, the asymmetry in elastic scattering at $E = 6.47$ GeV, $\theta = 8.0°$, $Q^2 = 0.765$ $(\text{GeV}/c)^2$ was measured giving $A = 0.092 \pm 0.017$, in reasonable agreement with the theoretical value $A = 0.112 \pm 0.001$ and the previously measured value[1] of $A = 0.138 \pm 0.031$.

The results of our asymmetry measurements for seven deep-inelastic kinematic points are given in Table I. Additional kinematic information for each point is given in Table II. The variables used in Table I are defined in Ref. 2. The depolarizing factor D depends on the value of $R = \sigma_L/\sigma_T$. Here we use the current value[5] of $R = 0.25$ and change our earlier results accordingly. In addition to Δ and A, we give the radiatively corrected values for A and for the virtual-photon–proton asymmetry $A/D = A_1 + \eta A_2$. The quantity A_1 equals $(\sigma_{1/2} - \sigma_{3/2})/(\sigma_{1/2} + \sigma_{3/2})$, in which $\sigma_{1/2}$ $(\sigma_{3/2})$ 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 $\frac{1}{2}$ $(\frac{3}{2})$. The quantity ηA_2 is a small interference term whose calculated upper limits are shown in Table I. We shall approximate A_1 by A/D.

We have made radiative corrections to our measured asymmetries using the extensive data available on the spin-averaged cross sections,[6] our measured A values (Table I), and the calculated values of A for elastic scattering. In order to unfold the asymmetries we chose several trial functions for $A(\nu, Q^2)$ in the relevant kinematic region and used each of these together with the spin-averaged cross sections to generate $d^2\sigma(\uparrow\uparrow)/d\Omega\, dE'$ and $d^2\sigma(\uparrow\downarrow)/d\Omega\, dE'$. For each kinemat-

TABLE I: Results of asymmetry measurements.

ω	Q^2 $(\mathrm{GeV}/c)^2$	ν (GeV)	W (GeV)	Δ (%)	A[b]	D	A[c]	A_1+A_2[c,d]	$\lvert\eta A_2\rvert$[e]
2.0	4.09	4.35	2.22	1.28 ± 0.26	$0.211\pm0.051(0.042)$	0.33	0.213 ± 0.057	0.67 ± 0.18	<0.18
3.0	1.68	2.69	2.06	0.51 ± 0.18	$0.009\pm0.037(0.034)$				
3.0[a]	1.68	2.69	2.06	0.44 ± 0.11	$0.191\pm0.057(0.044)$	0.26	0.131 ± 0.039	0.52 ± 0.15	<0.20
3.0	2.74	4.37	2.52	0.95 ± 0.35	$0.166\pm0.065(0.060)$	0.32	0.188 ± 0.066	0.60 ± 0.21	<0.15
3.0[a]	2.74	4.37	2.52	0.50 ± 0.17	$0.215\pm0.089(0.080)$				
4.9	1.02	2.65	2.20	0.29 ± 0.11	$0.058\pm0.023(0.022)$	0.25	0.062 ± 0.031	0.25 ± 0.13	<0.16
5.0[a]	1.42	3.78	2.56	0.28 ± 0.11	$0.141\pm0.058(0.051)$	0.38	0.148 ± 0.073	0.41 ± 0.20	<0.12
5.0	2.95	7.87	3.56	0.63 ± 0.33	$0.099\pm0.062(0.061)$	0.49	0.109 ± 0.081	0.23 ± 0.17	<0.07
10.0	1.70	9.12	4.04	0.42 ± 0.19	$0.100\pm0.038(0.035)$	0.58	0.117 ± 0.057	0.22 ± 0.11	<0.04

[a]Values previously reported in Ref. 2.
[b]Measured values without radiative corrections. The total errors are statistical counting errors added in quadrature to the systematic errors in P_e, P_p, and F; the numbers in parentheses are the 1-standard-deviation counting errors.
[c]Radiatively corrected values (see Table II).
[d]Calculated using weighted average of D.
[e]Calculated upper limits using $R=0.25$.

ic point these cross sections were radiated using the equivalent radiator method.[7] Then asymmetries were formed and compared with the measured asymmetries. Thus we were able to obtain a number of functions consistent with our data. These functions were compared with preliminary results[8] in the resonance region and were found to be consistent. Radiative contributions to a given kinematic point come from a kinematic region with lower ω and lower missing mass W. For each point we chose a cut in ω so as to exclude contributions from the resonance region and then used our functions for $A(\nu, Q^2)$ to correct our asymmetries. The corrected values for A were insensitive to the choice of function. The elastic tail contributes only a few percent to the cross section in our kinematic region. We note that corrected values of $A_1+\eta A_2$ in Table II are larger than the uncorrected value by no more than 0.05. The statistical errors are increased by factors from 1.2 to 1.7 because 14% to 34% of the events originated from regions below the ω cuts. Systematic errors associated with radiative corrections are small compared to statistical errors. The final asymmetry value corresponds to a range of ω values and can be associated with a weighted average value of ω.

Our radiatively corrected values of $A/D\simeq A_1$ from Tables I and II are plotted versus $x=1/\omega$ in Fig. 1. For a given ω, the $A/D\simeq A_1$ values for different Q^2 agree within their errors, which is consistent with the predicted[9] scaling relation $A_1(\nu, Q^2)\rightarrow A_1(\omega)$ as $\nu, Q^2\rightarrow\infty$ with ω held constant. Henceforth we shall assume scaling and at each

TABLE II. Kinematics and radiative corrections.

ω	Q^2 $(\mathrm{GeV}/c)^2$	E (GeV)	θ (deg)	Range of ω	Weighted average of ω	Fraction of events inside cuts	Radiative correction[a]	$A_1+\eta A_2$ corrected
2.0	4.09	12.95	11.0	1.7–2.0	1.95	0.86	+0.02	0.67 ± 0.18
3.0	1.68	9.71	9.0	2.5–3.0	2.93	0.75	+0.02	0.52 ± 0.15
3.0	2.74	12.95	9.0	2.5–3.0	2.92	0.77	+0.03	0.60 ± 0.21
4.9	1.02	9.71	7.0	3.5–4.9	4.63	0.73	+0.03	0.25 ± 0.13
5.0	1.42	9.71	9.0	3.5–5.0	4.73	0.75	+0.04	0.41 ± 0.20
5.0	2.95	16.18	8.5	3.5–5.0	4.72	0.77	+0.03	0.23 ± 0.17
10.0	1.70	16.18	7.0	6.0–10.0	9.21	0.66	+0.05	0.22 ± 0.11

[a]$(A_1+\eta A_2)_{\text{corrected}}-(A_1+\eta A_2)_{\text{uncorrected}}$.

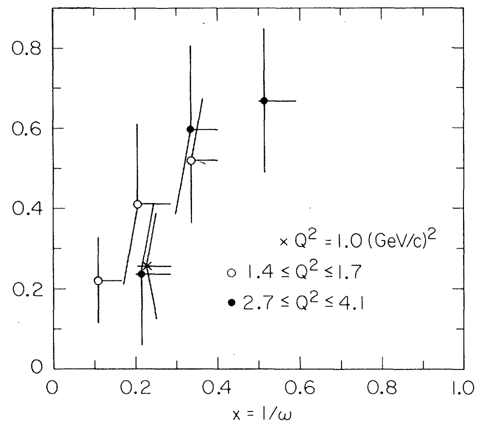

FIG. 1. Experimental values of $A/D \simeq A_1$ vs x. The horizontal bars give the range in x associated with the radiative corrections.

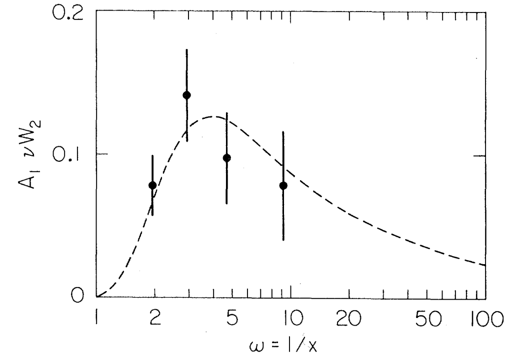

FIG. 2. Experimental values of $A_1\nu W_2$ vs ω. The dashed curve uses $A_1 = 0.78\omega^{-1/2}$.

ω point take the weighted average of the $A_1(\nu, Q^2)$ values to give $A_1(\omega)$.

The Bjorken sum rule for polarized electroproduction is an important general consequence of quark current algebra.[10] It applies in the scaling limit and reads

$$\int_{\omega=1}^{\infty} d\omega\,\omega^{-1}(A_1^{\,p}\nu W_2^{\,p} - A_1^{\,n}\nu W_2^{\,n}) = \tfrac{1}{3}|g_A/g_V| = 0.417 \pm 0.003, \qquad (1)$$

where W_2 is the nucleon structure function, p and n refer to proton and neutron, and g_A (g_V) is the axial (vector) weak coupling constant of β decay. The experimental value[11] for $|g_A/g_V|$ is used in Eq. (1). In the absence of experimental information on $A_1^{\,n}$ we approximate $A_1^{\,n} = 0$, since quark-parton models of the neutron predict that $A_1^{\,n}$ is small. Values of $\nu W_2^{\,p}$ were obtained from cross-section measurements.[12] Figure 2 shows $A_1\nu W_2 \equiv A_1^{\,p}\nu W_2^{\,p}$ plotted versus ω. The value of the integral from $\omega = 1.95$ to $\omega = 9.21$ obtained from our data is 0.16 ± 0.03, saturating 40% of the sum rule. Evaluation of the complete integral requires extrapolation to large and small values of ω, the more significant uncertainty coming from the large-ω contribution. We fit our asymmetry data to the form $A_1 = c\omega^{-1/2}$, obtaining a value $c = 0.78 \pm 0.13$. This form, suggested by Regge theory[13] for large ω, represents a satisfactory fit to our data over the entire measured range. The dashed curve in Fig. 2 shows the resulting values of $A_1\nu W_2$ for this parametrization and gives a value for the full integral of 0.34 ± 0.05 which is consistent with the sum rule. An alternative approach is to assume the validity of the Bjorken sum rule to place limits on the large-ω behavior of the asymmetry. If the asymmetry A_1 at large ω is assumed to be proportional to ω^{-k}, then our data require $0 < k \lesssim 1$.

The predictions for A_1 in the scaling limit from several quark-parton models as well as that from source theory are shown as a function of x in Fig. 3, together with our measured values of $A/D \simeq A_1$. These predictions are in qualitative agreement with the experimental data. Clearly, more accurate data, particularly for lower ω, are required to distinguish among these models.

As discussed in Ref. 2 our data place a limit on parity nonconservation in the scattering of

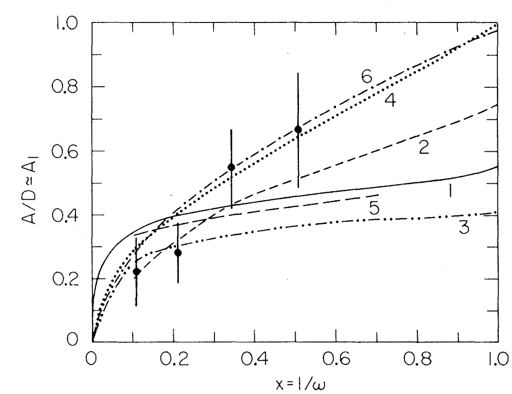

FIG. 3. Experimental values of $A/D \simeq A_1$ compared to theoretical predictions for A_1. The models are as follows: (1) a relativistic symmetric valence-quark model of the proton (Ref. 14); (2) a model incorporating the Melosh transformation which distiguishes between constituents and current quarks (Ref. 15); (3) a model introducing nonvanishing quark orbital angular momentum (Ref. 16); (4) an unsymmetrical model in which the entire spin of the nucleon is carried by a single quark in the limit of $x = 1$ (Ref. 17); (5) the MIT bag model of quark confinement (Ref. 18); (6) source theory (Ref. 19).

longitudinally polarized electrons from unpolarized nucleons by measuring the asymmetry $r = (d\sigma^- - d\sigma^+)/(d\sigma^- + d\sigma^+)$ in which the superscripts refer to the electron helicity for a fully polarized electron beam. From the data in Table I for Q^2 between 1 and 4 $(\mathrm{GeV}/c)^2$, we have $|r| < 3\times10^{-3}$ at a 95% confidence level.

We are indebted to L. Boyer, M. Browne, S. Dhawan, S. Dyer, R. Eisele, R. Fong-Tom, W. Kapica, H. Martin, J. Sodja, and L. Trudell for their exceptional efforts in the prepration and running of this experiment. This research was supported in part by the U. S. Department of Energy under Contracts No. EY-76-C-02-3075 and No. EY-76-C-03-0515, the German Federal Ministry of Research and Technology, and the Japan Society for the Promotion of Science.

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Charmed-*D*-Meson Production by Neutrinos

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(Received 4 May 1978)

We have observed the production of the D^0 meson by neutrinos followed by the decay $D^0 \to K_S{}^0 + \pi^+ + \pi^-$. Correcting for detection efficiencies and K^0 decay branching ratios, we find that the production of the D^0 followed by decay into $K^0\pi^+\pi^-$ corresponds to (0.7 $\pm$ 0.2)% of all charged-current neutrino interactions.

The hadronic quantum number charm was postulated[1,2] to explain, among other things, the absence of strangeness-changing weak neutral currents. The recently discovered $J/\psi(3100)$, and the associated ψ' and χ states,[3] possess the attributes of hidden charm. The first direct observation of a charmed meson, the $D(1865)$, was in e^+e^- collisions at SPEAR.[4] In this paper, we report the only other direct observation of the D meson, produced in this case in neutrino-hadron interactions. The decay mode observed is $D^0 \to K_s{}^0\pi^+\pi^-$ with $K_s{}^0 \to \pi^+\pi^-$.

The experiment was carried out at the Fermi National Accelerator Laboratory using the two-