Precision Measurement of $R = \sigma_L/\sigma_T$ and F_2 in Deep-Inelastic Electron Scattering

S. Dasu,[1] P. de Barbaro,[1] A. Bodek,[1] H. Harada,[1] M. W. Krasny,[1] K. Lang,[1] E. M. Riordan,[1] R. Arnold,[2] D. Benton,[2] P. Bosted,[2] L. Clogher,[2] G. deChambrier,[2] A. Lung,[2] S. E. Rock,[2] Z. M. Szalata,[2] R. C. Walker,[3] B. W. Filippone,[3] J. Jourdan,[3] R. Milner,[3] R. McKeown,[3] D. Potterveld,[3] A. Para,[4] F. Dietrich,[5] K. Van Bibber,[5] J. Button-Shafer,[6] B. Debebe,[6] R. S. Hicks,[6] R. Gearhart,[7] L. W. Whitlow,[8] and J. Alster[9]

[1]*University of Rochester, Rochester, New York 14627*
[2]*The American University, Washington, D.C. 20016*
[3]*California Institute of Technology, Pasadena, California 91125*
[4]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[5]*Lawrence Livermore National Laboratory, Livermore, California 94550*
[6]*University of Massachusetts, Amherst, Massachusetts 01003*
[7]*Stanford Linear Accelerator Center, Stanford, California 94305*
[8]*Stanford University, Stanford, California 94305*
[9]*University of Tel-Aviv, Ramat Aviv, Tel-Aviv 69978, Israel*

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We report new results on a precision measurement of the ratio $R = \sigma_L/\sigma_T$ and the structure function F_2 for deep-inelastic electron-nucleon scattering in the kinematic range $0.2 \leq x \leq 0.5$ and $1 \leq Q^2 \leq 10$ $(\text{GeV}/c)^2$. Our results show, for the first time, a clear falloff of R with increasing Q^2. Our R and F_2 results are in good agreement with QCD predictions only when corrections for target-mass effects are included.

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The ratio $R = \sigma_L/\sigma_T$ of the longitudinal (σ_L) and transverse (σ_T) virtual-photon absorption cross sections measured in deep-inelastic lepton-nucleon scattering is a sensitive measure of the spin and the transverse momentum of the nucleon constituents. In the naive parton model with spin-$\frac{1}{2}$ partons, R is expected to be small, and to decrease rapidly with increasing momentum transfer, Q^2. With spin-0 partons, R should be large and increase with Q^2. Previous measurements[1-3] of R at the Stanford Linear Accelerator Center (SLAC) indicated that scattering from spin-$\frac{1}{2}$ constituents (e.g., quarks) dominates. However, the values of R were larger than expected, consistent with a constant value of 0.2. The measurement errors on those results left room for speculation about small admixtures of spin-0 constituents in nucleons[4] (e.g., tightly bound diquarks) and about unexpectedly large primordial transverse momentum for quarks.

Experiments[2] in the SLAC Q^2 range $[1 \leq Q^2 \leq 20$ $(\text{GeV}/c)^2]$ have also indicated deviations from the scaling of the structure functions F_1 and F_2. In quantum chromodynamics (QCD), logarithmic scaling violations[5] occur because of quark-gluon interactions. In addition, target-mass[6] and dynamical higher-twist[7] (nonperturbative effects due to binding of quarks in a nucleon) effects yield power-law violations of scaling. These effects lead to nonzero contributions to R which decrease with increasing Q^2.

Since the quality of the previous data was inadequate to test such predictions for R, we have made precision measurements of deep-inelastic electron-nucleon scattering cross sections from D, Fe, and Au targets, with particular emphasis on the extraction of the ratio R, and the structure functions F_1 and F_2. Studies of the difference $R^{\text{Fe}} - R^{\text{D}}$ and the ratio $F_2^{\text{Fe}}/F_2^{\text{D}}$ were presented earlier.[8] Here we report our results on the kinematic variation of R and F_2.

The differential cross section for scattering of an unpolarized charged lepton with an incident energy E, final energy E', and scattering angle θ can be written in terms of the structure functions F_1 and F_2 as

$$\sigma = \frac{d^2\sigma}{d\Omega\, dE'}(E,E',\theta) = \frac{4\alpha^2 E'^2}{Q^4}\cos^2(\theta/2)[F_2(x,Q^2)/\nu + 2\tan^2(\theta/2)F_1(x,Q^2)/M]$$
$$= \Gamma\sigma_T(x,Q^2)[1+\epsilon R(x,Q^2)], \qquad (1)$$

where α is the fine-structure constant, M is the nucleon mass, $\nu = E - E'$ is energy of the virtual photon which mediates the interaction, $Q^2 = 4EE'\sin^2(\theta/2)$ is the invariant four-momentum transfer squared, and $x = Q^2/2M\nu$ is a measure of the longitudinal momentum carried by the struck partons. In Eq. (1) the differential cross section is also related to $R(x,Q^2)$, with

$$\Gamma = \frac{\alpha}{4\pi^2}\frac{(2M\nu - Q^2)E'}{Q^2 ME}\frac{1}{1-\epsilon},$$

and

$$\epsilon=[1+2(1+\nu^2/Q^2)\tan^2(\theta/2)]^{-1}$$

representing the virtual-photon flux and polarization, respectively.

The SLAC electron beams and the 8-GeV spectrometer facility[2] were used to measure cross sections accurate to $\pm 1\%$ in the kinematic range $0.2 \leq x \leq 0.5$ and $1 \leq Q^2 \leq 10$ $(\text{GeV}/c)^2$ at up to five different values of ϵ (with a typical range of 0.35). Extensive efforts were made in this experiment to reduce systematic errors (summarized in Table I). Systematic effects that can vary with ϵ are especially relevant for the measurement of R. Effects due to beam flux, target density, and background contamination were described earlier.[8] The spectrometer acceptance in the range $|\Delta p/p| < 3.5\%$, $|\Delta\theta| < 6$ mrad, and $|\Delta\phi| < 28$ mrad, was studied as a function of angle and momentum setting. The change of acceptance with angle for the 20-cm D target was determined to be less than 0.4% with use of a Monte Carlo simulation of spectrometer optics. The momentum dependence of the acceptance ($< 0.3\%$), and the absolute value of the momentum setting ($\pm 0.05\%$) of the spectrometer were studied with a floating-wire technique. Detailed surveys of the spectrometer, targets, and beam line were done before and after the experiment. The absolute error in spectrometer angle was $\pm 0.003°$, with a $\pm 0.0015°$ uncertainty in the reproducibility. Measured elastic-peak positions[9] were used to determine the uncertainty in the incident energy to $\pm 0.1\%$.

Radiative corrections were calculated with use of the "exact" prescription of Akhundov, Bardin, and Shumeiko[10] (ABS) with additional "external" corrections (due to the straggling of electrons in the target material) calculated in the complete formalism of Mo and Tsai.[8,11] The "internal" corrections obtained with use of the ABS formalism agreed to better than 1% for each (x,Q^2,ϵ) point with an improved version of the "exact" formalism of Mo and Tsai.[12] In addition, the corrections calculated with different parametrizations of structure functions agreed to better than $\pm 0.2\%$. The ABS approach with fits to previous SLAC data[2] on F_2 was used for our final results, since it is based on a better theoretical formalism. This approach has also been used in recent neutrino[13] and muon[14] experiments.

The values of R, F_1, and F_2 were extracted from cross sections measured at various values of ϵ at fixed (x,Q^2) by our making linear fits, weighted by the statistical and point-to-point systematic uncertainty, to σ/Γ vs ϵ [see Eq. (1)]. The average χ^2/N_{DF} for these fits is 0.7, indicating that the estimate of systematic uncertainty is conservative. R values are insensitive to the absolute normalization of beam flux, target length, radiative corrections, and spectrometer acceptance.

The results for R obtained for all (x,Q^2) points and targets are shown in Table II. Since the differences $R^A - R^D$ are consistent with zero,[8] the results plotted in Fig. 1 represent averages over various targets at the same x and Q^2. Our results have small errors [see Fig. 1(a)] compared to previous SLAC experiments[2,3] (E49, E87, and E89) because (a) our cross sections were measured to better than $\pm 1\%$ statistical accuracy with large ϵ separation, (b) uncertainties in radiative corrections were reduced to the $\pm 1\%$ level, and (c) a single spectrometer with well determined acceptance was used.

TABLE I. Typical systematic errors on σ and R.

Source	Uncertainty	Error (±) in σ	Error (±) in R
Beam steering	0.003°	0.1%	0.005
Incident energy	0.1%	0.3%	0.014
Charge measurement	0.3%	0.3%	0.014
Target density	0.2%	0.2%	0.009
Acceptance vs θ	0.1%	0.1%	0.005
Acceptance vs p	0.1%	0.1%	0.005
e^+/e^- background	0.1%	0.1%	0.005
Scattered energy	0.05%	0.1%	0.005
Spectrometer angle	0.002°	0.1%	0.005
Detector efficiency	0.1%	0.1%	0.005
Total point to point		0.5%	0.025
Radiative corrections	1.0%	1.0%	0.030

TABLE II. Values of R for each (x,Q^2) point and target are tabulated separately with statistical and systematic errors. D and Fe(2) targets are of 2.6% radiation lengths (r.l.) each, whereas Au and Fe(6) are of 6% r.l. Values of χ^2 per degree of freedom for the two-parameter fits are also shown.

Target	x	Q^2 $[(\text{GeV}/c)^2]$	$\Delta\epsilon$	$R=\sigma_L/\sigma_T$ Value	Stat	Syst	χ^2/N_{DF}
D	0.20	1.0	0.36	0.348	0.039	0.040	1.8/3
D	0.20	1.5	0.32	0.275	0.041	0.041	5.1/3
D	0.20	2.5	0.37	0.100	0.047	0.039	0.1/1
D	0.20	5.0	0.25	0.198	0.054	0.047	0.8/2
D	0.35	1.5	0.30	0.296	0.050	0.046	0.6/3
D	0.35	2.5	0.36	0.154	0.033	0.038	1.8/3
D	0.35	5.0	0.33	0.126	0.037	0.039	1.0/2
D	0.50	2.5	0.51	0.199	0.025	0.034	2.1/3
D	0.50	5.0	0.46	0.104	0.028	0.036	1.4/2
D	0.50	7.5	0.37	0.155	0.061	0.039	⋯/0
D	0.50	10.0	0.35	0.047	0.038	0.038	0.0/1
Fe(2)	0.20	1.0	0.36	0.323	0.042	0.040	0.6/3
Fe(2)	0.50	2.5	0.51	0.221	0.051	0.035	⋯/0
Fe(6)	0.20	1.0	0.36	0.270	0.041	0.038	5.1/3
Fe(6)	0.20	1.5	0.32	0.147	0.037	0.038	1.5/3
Fe(6)	0.20	2.5	0.37	0.247	0.058	0.040	1.3/1
Fe(6)	0.35	1.5	0.30	0.344	0.062	0.046	3.3/3
Fe(6)	0.35	2.5	0.36	0.255	0.044	0.038	3.3/3
Fe(6)	0.35	5.0	0.33	0.150	0.045	0.040	0.2/2
Fe(6)	0.50	2.5	0.51	0.220	0.028	0.034	2.1/3
Fe(6)	0.50	5.0	0.46	0.080	0.041	0.035	0.2/2
Au	0.20	1.0	0.36	0.322	0.043	0.041	0.9/3

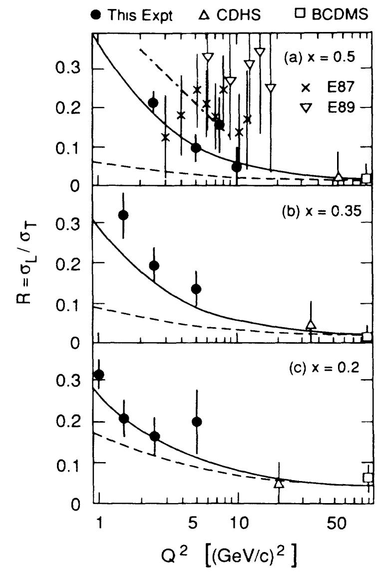

FIG. 1. The values of R at (a) $x=0.5$, (b) $x=0.35$, and (c) $x=0.2$ are plotted vs Q^2, with statistical and systematic errors added in quadrature. Predictions from perturbative QCD (quark-gluon interaction effects, the dashed curve), QCD with target-mass effects (solid curve), Ekelin and Fredriksson diquark model (dot-dashed curve), and earlier data from experiments E87 and E89 at SLAC, and CDHS (ν-Fe), and BCDMS (μ-C/H) at CERN are also plotted.

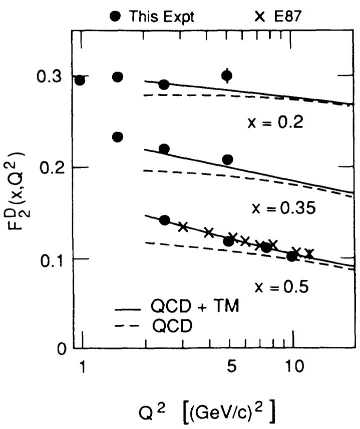

FIG. 2. The values of F_2^D extracted from our data at $x=0.2$, 0.35, and 0.5 are plotted vs Q^2. Only statistical and point-to-point systematic errors are shown. There is an additional normalization error of $\pm 3\%$. The QCD structure function (dashed curve), and the prediction for F_2 including the target-mass effects (solid curve) are also plotted. Data from SLAC experiment E87 are also plotted at $x=0.5$ for comparison.

Our results at $x=0.2$, 0.35, and 0.5 show a clear falloff of R with increasing Q^2. The agreement with a constant value of $R=0.2$ is poor ($\chi^2/N_{\mathrm{DF}}=34/10$). The high-$Q^2$ results from the CERN-Dortmund-Heidelberg-Saclay[13] (CDHS) and Bologna-CERN-Dubna-Munich-Saclay[14] (BCDMS) collaborations for ν-Fe and μ-C/H scattering, respectively, are also plotted. These results reinforce the conclusion that R decreases with increasing Q^2. Our results at all Q^2 show only a weak x dependence in the range $0.2 \leq x \leq 0.5$.

The values of F_2^D obtained from the fits to σ/Γ vs ϵ are plotted against Q^2 at various x in Fig. 2. These results are preliminary because studies of the absolute normalization (presently known to $\pm 3\%$) are not complete. A weak Q^2 dependence is evident. Earlier SLAC data[2] are shown for comparison. Note that these early data were radiatively corrected with use of the peaking approximation calculations. Detailed studies of F_2 from all SLAC experiments with our improved radiative corrections and parametrization of R will be reported in a future communication.

In perturbative QCD (to the order α_s) hard gluon bremsstrahlung from quarks and photon-gluon interaction effects yield contributions to the lepton-nucleon scattering cross section.[5] The leading Q^2 dependence of the structure functions is in α_s, and is therefore logarithmic in Q^2. The new R data (see Fig. 1) are not in agreement with these calculations[15] ($\chi^2/N_{\mathrm{DF}}=98/10$). The scaling violations in F_2 (see Fig. 2) are also not described very well by these QCD interaction effects alone. QCD calculations are not too sensitive to the value of Λ used ($\Lambda=200$ MeV). Target-mass effects[6] introduce terms proportional to M^2/Q^2 and give large contributions to R and F_2 at small Q^2 and large x. Our data for R and F_2 are in good agreement ($\chi^2/N_{\mathrm{DF}}=10/10$) with theory when target-mass effects by Georgi and Politzer[6] (GP) are added to perturbative QCD. The variation of R with x in the range $0.2 \leq x \leq 0.5$ is weak, in agreement with these predictions. However, the controversy about possible inconsistencies[7,16] in the original GP target-mass-effect calculations[6] is yet to be resolved unambiguously.[17] The QCD interactions and target-mass and higher-twist effects can be thought of as giving transverse momentum (k_T) to the quarks. In the naive parton model $R=4\langle k_T^2\rangle/Q^2$, and the data indicate a $\langle k_T^2\rangle$ value of 0.10 (GeV/c)^2 ($\chi^2/N_{\mathrm{DF}}=18/10$).

Several authors have speculated[4] that two of the valence quarks in a nucleon may form a tightly bound spin-0 diquark. The spin-0 diquarks are predicted to give large contributions to R at large x and low Q^2. Our highest x ($=0.5$) results for R do not favor this possibility. QCD with target-mass effects appears to account for all the Q^2 dependence of R, and therefore speculations[7] that dynamical higher-twist contributions to R (for $x \leq 0.5$) are large are not supported by our data.

An empirical parametrization of the perturbative QCD calculations of R, with an additional $1/Q^2$ term fitted to our data, is given by

$$R(x,Q^2)=\left[\frac{\alpha(1-x)^\beta}{\ln(Q^2/\Lambda^2)}+\frac{\gamma(1-x)^\delta}{Q^2}\right],$$

where $\alpha = 1.11$, $\beta = 3.34$, $\gamma = 0.11$, $\delta = -1.94$, and $\Lambda = 0.2$ GeV/c.

In conclusion, these results show for the first time a clear falloff of R with increasing Q^2 in the range $1 \le Q^2 \le 10$ (GeV/c)^2 for $x = 0.2$, 0.35, and 0.5. R and F_2 are in good agreement with QCD predictions only when corrections for GP target-mass effects are included. The new data do not favor large contributions from diquarks, nonperturbative, and higher-twist effects in our x range.

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