PRECISION MEASUREMENT OF $R = \sigma_L/\sigma_T$ ON HYDROGEN, DEUTERIUM, AND BERYLLIUM TARGETS IN DEEP INELASTIC ELECTRON SCATTERING*

The E140X Collaboration

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We report new results on a precision measurement of the ratio $R = \sigma_L/\sigma_T$ from hydrogen, deuterium, and beryllium targets for deep inelastic electron scattering in the range $0.1 \leq x \leq 0.7$ and $0.5 \leq Q^2 \leq 7$ (GeV/c)^2. We find no measurable difference between R^p and R^d. Our results are consistent with, and more precise than, previous SLAC data. At high x, R is somewhat larger than order α_s^2 pQCD predictions, even when target mass effects are included.

The quantity R, the ratio of longitudinal (σ_L) to transverse (σ_T) cross sections in deep inelastic scattering, is a sensitive measure of the spin of the nucleon constituents. Within the naive parton model with spin-1/2 partons, R values are expected to be zero at large momentum transfer squared (Q^2), whereas with spin-0 partons, R values are expected to be large. Recent measurements [1,2] of the quantity R, made at the Stanford Linear Accelerator Center (SLAC), found R to be small (0.1-0.4) and to be decreasing with increasing Q^2. To compare with theoretical calculations, R can be expressed in terms of the longitudinal structure function F_L and the structure function F_2. In perturbative Quantum Chromodynamics (pQCD), $F_L \propto \alpha_s$ [3] and thus R is expected to decrease logarithmically with increasing Q^2. Very recent calculations of order α_s^2 terms [4] as well as greatly improved parton density models [5–7] have increased the precision of pQCD calculations, particularly at low Q^2. However, in the low Q^2 regime, target mass and nonperturbative effects give contributions to F_L and F_2 which are proportional to $1/Q^2$. Accurate data over a large range of Q^2 and Bjorken x can determine the size of the nonperturbative effects in the high x region and check the validity of the pQCD calculations in the low x region. Accurate values of R are also vital for the extraction of F_2 from unpolarized cross sections and the polarized structure functions g_1 and g_2 from asymmetry measurements.

The new data on R reported here expand the previous range of measured kinematics [1]. Included are measurements of $R^d - R^p$, the difference in R for deuterium and proton targets, and checks (with a single experiment) on the results for R from the SLAC global analysis [2], which was dependent on normalizing data from several different experiments.

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The differential cross section for scattering of an unpolarized charged lepton with an incident energy E, scattering angle θ and final energy E' can be written in terms of F_L and F_2 or σ_L and σ_T as:

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_M \left[\frac{F_2(x,Q^2)}{\nu\epsilon} - \frac{F_L(x,Q^2)}{Mx}\tan^2(\theta/2)\right] \tag{1}$$

$$= \Gamma\left[\sigma_T(x,Q^2) + \epsilon\,\sigma_L(x,Q^2)\right] , \tag{2}$$

where $\sigma_M = 4\alpha^2 E'^2 \cos^2(\theta/2)/Q^4$ is the Mott cross section, M is the proton mass, $\nu = E - E'$, $Q^2 = 4EE'\sin^2(\theta/2)$, $x = Q^2/2M\nu$ is a measure the longitudinal momentum carried by the quarks, $\Gamma = \alpha(1-x)E'/[4\pi^2 xME(1-\epsilon)]$, and $\epsilon = [1 + 2(1+\nu^2/Q^2)\tan^2(\theta/2)]^{-1}$ representing the virtual photon flux and relative longitudinal polarization respectively. R is defined as:

$$R(x,Q^2) = \sigma_L/\sigma_T = F_L/[(1+4M^2x^2/Q^2)F_2 - F_L], \tag{3}$$

The SLAC electron beams and the 8 GeV spectrometer facility were used to measure cross sections to better than 1% accuracy in the kinematic range $0.1 \le x \le 0.7$ and $0.5 \le Q^2 \le 7$ (GeV/c)^2. The electron beam was provided by the NPI injector in the normal accelerator mode (2 μsec spill) for energies less than 6.5 GeV and in the SLED mode (100 nsec spill) for energies up to 10 GeV. Individual settings of the 8 GeV spectrometer detected electrons scattered between angles of 11° and 50°, with momenta from 0.6 to 8 GeV/c. Electrons were identified from a background of pions and other particles using a gas Čerenkov counter and a lead glass electromagnetic calorimeter. Ten planes of wire chambers were used for tracking. Several additional planes of scintillation counter hodoscopes were installed for this experiment [8] to handle the high instantaneous rates.

Measurements were made on 4 cm and 15 cm targets of liquid D_2 and H_2 and a 2.1cm Be target at up to four different values of ϵ for each value of (x, Q^2), with a typical ϵ-range of 0.4. To compensate for the small cross sections at $x \ge 0.5$, we used a new large acceptance optical tune of the 8 GeV spectrometer and the Be target to give a counting rate an order of magnitude greater than using the normal tune and liquid targets. Since R is a ratio measurement, the absolute spectrometer acceptance cancels. Other normalization errors such as absolute beam intensity, absolute target density, and absolute detector efficiency also cancel. The results for the difference $R^d - R^p$ have smaller systematic errors than those for the absolute value of R because many systematic uncertainties which depend on the spectrometer angle and momentum, and the beam energy and intensity cancel. In addition, the targets were changed frequently to avoid systematic errors due to changing efficiencies or beam conditions.

The systematic errors, summarized in Table I, are similar to those in a previous experiment [1] except for the large acceptance mode of the spectrometer. For that configuration, the momentum-dependence of the acceptance was compared with that of the normal mode at $x = 0.5$, and found to be constant within the statistical errors of 1.0%. The value of R measured with normal and large acceptances agreed to within the statistical error of 0.026.

Radiative corrections were calculated using the complete prescription of Mo and Tsai [9] for the "external" part, and that of Bardin et al. [10] for the "internal" part in a manner which has been implemented and tested in previous experiments [1]. Internal corrections were checked using an improved version [1] of the "exact" formalism of Tsai [9] and these agree with Bardin et al. calculations to better than 1.0% at each (x, Q^2, ϵ) point. In addition, the corrections calculated with different parameterizations of structure functions in both the resonance region [11,12] and the deep inelastic region [12,13] agree to better than 0.8% in cross section, and show a consistent behavior as a function of ϵ. The radiative elastic tail from hydrogen and the quasi-elastic tail from deuterium are independent of input model [14] to within ±0.2%. The radiative elastic tail from deuterium is also independent of input model [10,15] to within ±0.2%. A test of the external corrections was performed during this experiment by inserting an additional 4% radiator upstream of the 1.5% r.l. hydrogen target at the kinematics $Q^2 = 3.6$, $x = 0.5$. The measurements with and without additional radiator agreed to 1.5% ± 1.0% (stat) ± 0.3% (syst) We assign an ϵ-correlated error due to radiative corrections equivalent to 0.5% in cross section or 0.012 in R.

The difference $R^d - R^p$ was determined by making linear fits, weighted by the statistical and point-to-point (ϵ-uncorrelated) systematic errors, to the ratio of cross sections,

$$\sigma^d/\sigma^p = \sigma_T^d/\sigma_T^p(1 + \epsilon'(R^p - R^d)) , \tag{4}$$

versus $\epsilon' = \epsilon/(1 + \epsilon\bar{R}^d)$. The average χ^2 per degree of freedom for the goodness of fit was 0.4, indicating that the estimate of systematic point-to-point uncertainty is conservative. The results are plotted versus x for various Q^2 values in Fig. 1, together with results from the SLAC global analysis [2] and previous data from the NMC experiment [16]. Both the old and new values are consistent with zero within the errors. The average $R^d - R^p$ from this experiment is -0.013 ± 0.023 (stat) ± 0.006 (syst). Combining all the SLAC data shown gives an average of -0.005 ± 0.011, while combining all the data shown gives an average of 0.005 ± 0.010. We conclude that $R^d - R^p$ is consistent with zero, and also with the pQCD calculations, including target mass corrections, shown in Fig. 1 as the solid curve. There is no evidence for higher twist effects contributing to R differently for the proton and deuterium. The results are inconsistent with the diquark model prediction [17]. Also shown in Fig. 1 is the single measurement of $R_{Be} - R_p$ at $x = 0.5$ which, in agreement with experiments with other nuclear targets [1], is also consistent with 0.

The values of R were extracted from cross sections measured at various values of ϵ at fixed (x, Q^2) by making linear fits, weighted by the statistical and point-to-point systematic uncertainty, to σ/Γ versus ϵ (see Eq. 2). The average χ^2/d.f. for these fits is 0.5. The results are shown in Table 2. Since the differences $R^d - R^p$ are consistent with zero, the results shown in Figs. 2 and 3 and Table 3 are an average over all targets. For the $x \geq 0.6$ measurements, we make the reasonable assumption that $R^d = R^{Be}$. This is supported by the data at lower x on heavier nuclei, the small size of the EMC effect for Be, [18], and pQCD calculations. The new results shown as solid circles are consistent with the previous results and also with the previous SLAC empirical parameterization R_{world} [2] shown as the solid curve. The present data join smoothly to the higher energy muon data of BCDMS [19] and EMC [20], and to the neutrino data of CDHSW [21], CDHS [22], and CHARM [23]. The pQCD calculations [4], to order α_s, called $R^{(1)}$, and α_s^2, called $R^{(2)}$, based on the work of Van Neerven et al., are shown as dotted and dot-dash curves respectively. We used the MRS(A) [5] NLL parton distributions evolved down to $Q^2 = 0.625$ (GeV/c)^2. For lower Q^2, the MRS(A) distributions were matched to the GRV [6] distributions that are valid down to $Q^2 = 0.3$(GeV/c)^2. Other parton distributions [6,7] yield similar results over the range of Q^2 for which these distributions are valid. We use $\alpha_s(M_Z) = 0.117 \pm 0.005$ [24], the average result from LEP and deep inelastic data. We have used three light flavors in the calculation, and the effect of massive charm production by gluons was included [25] according to Laenen et al. [4]. The effects of including the mass of the charm quark was significant only at the lowest value of x. At higher x, these results were the same as the calculation, assuming three light flavors. The values of $R^{(2)}$ are significantly larger than $R^{(1)}$ in the kinematic range where the pQCD calculations are significant. Comparing the experimental data to the $R^{(2)}$ calculation, we find that: (1) At $x = 0.1$, $Q^2 > 1$(GeV/c)^2 the α_s^2 calculation is close to the data (and global fit to data). (2) At $x = 0.1$, $Q^2 < 1$ (GeV/c)^2 (see Fig. 2) the measured value of R is far below the steeply rising $R^{(2)}$, indicating that we may be outside the range of pQCD validity. A value of $\alpha_s(M_Z) = 0.123$ (LEP average) gives values of $R^{(2)}$ which are much higher. (3) For larger values of x, e.g., $x \geq 0.25$, $Q^2 \sim 3$(GeV/c)^2 (see Fig. 3) $R^{(2)}$ is less than half the measured value.

The addition of target mass effects [26], which go as x^3M^2/Q^2, are shown by the dashed curve in the figures ($R^{(2TM)}$). This effect becomes visible at higher values of x, but even for $x \geq 0.3$, $Q^2 \leq 3$(GeV/c)^2, $R^{(2TM)}$ is still significantly lower then the data and the global fit. The addition of an empirical higher twist term of the form $0.37(Q^2 - 1.34)/(Q^4 + 0.12)$ (not shown) gives an excellent fit over the entire data set, with χ^2/d.f.=1.1.

In conclusion, the new data are consistent with previous determinations of R and confirm the global analysis extraction over a wide range of x and Q^2. Calculations using second order pQCD combined with target mass corrections can match the data at low x for $Q^2 \geq 1$, but higher twist contributions are necessary for the higher x region.

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TABLE I. Summary of typical point-to-point systematic errors. An overall normalization error of 2% on the cross section does not affect the R measurement.

Source	Error (%)	$\Delta\sigma$(%)	ΔR
Beam energy	0.1	0.3	0.015
Beam charge	0.2	0.2	0.010
Spectrometer angle	0.1 mr	0.2	0.008
Scattered momentum	0.1	0.2	0.010
Dead time	0.2	0.2	0.010
Efficiency	0.1	0.1	0.005
End Cap subtraction	0.2	0.2	0.002
e^+/e^- background	0.2	0.2	0.010
Target density (liquid)	0.3	0.3	0.015
Target density (Be)	0.1	0.1	0.005
Acceptance (normal)	0.1	0.1	0.005
Acceptance (large)	0.5	0.5	0.022
Total (Be)		0.8	0.035
Total (H2,D2)		0.7	0.031

TABLE II. R for different targets. There is an additional systematic error of 0.012 due to radiative corrections.

x	Q^2	Target	Acceptance	R	ΔR^{stat}	ΔR^{sys}
0.10	0.5	4cm-H2	N	0.329	0.038	0.035
0.10	0.5	4cm-D2	N	0.259	0.031	0.033
0.10	1.0	4cm-H2	N	0.451	0.067	0.060
0.10	1.0	4cm-D2	N	0.349	0.059	0.054
0.35	3.0	15cm-H2	N	0.189	0.030	0.022
0.35	3.0	15cm-D2	N	0.233	0.032	0.026
0.50	3.6	15cm-H2	N	0.199	0.027	0.028
0.50	3.6	15cm-D2	N	0.194	0.028	0.028
0.50	3.6	4cm-D2	L	0.255	0.028	0.036
0.50	3.6	Be	L	0.182	0.026	0.032
0.60	5.0	Be	L	0.074	0.024	0.033
0.70	7.0	Be	L	0.099	0.035	0.038

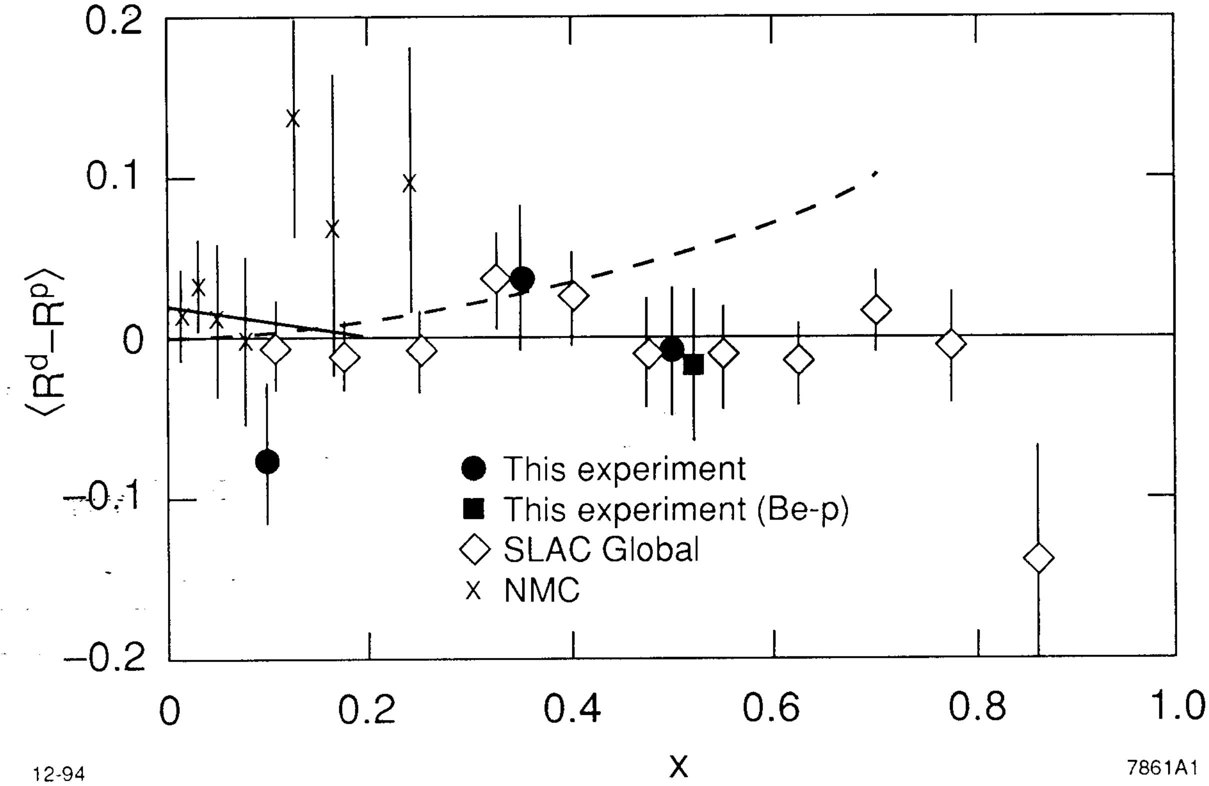
TABLE III. R averaged over targets. There is an additional systematic error of 0.012 due to radiative corrections.

x	Q^2	R	ΔR^{stat}	ΔR^{sys}
0.10	0.5	.287	0.024	0.029
0.10	1.0	.394	0.044	0.049
0.35	3.0	.210	0.022	0.021
0.50	3.6	.207	0.013	0.024
0.60	5.0	.074	0.024	0.033
0.70	7.0	.099	0.035	0.038

FIG. 1. The results for $R^d - R^p$ as a function of x for this experiment (solid) and from the SLAC global analysis [2]. Statistical and systematic errors are added in quadrature. The results from NMC [16] are also shown. The solid curve is the prediction from pQCD including target mass corrections. The dashed line is the prediction from a diquark model [17].

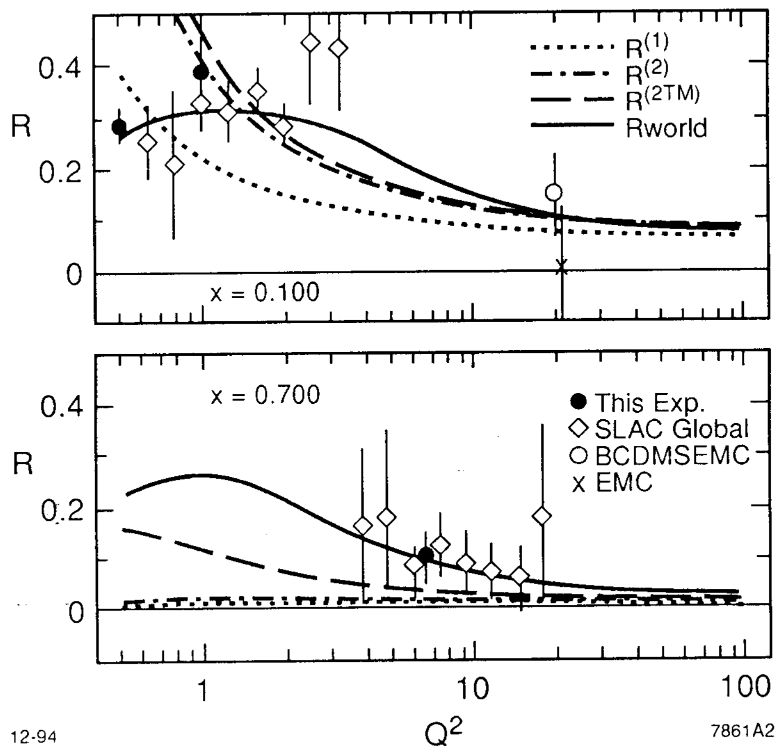
FIG. 2. The values of R as a function of Q^2 at two values of x. The solid symbols are results from this experiment, with statistical and systematic errors added in quadrature. The open diamonds are from the global analysis [2]. The open circles are from BCDMS [19] and the crosses are from EMC [18]. The perturbative QCD calculations [25] $R^{(1)}$ (dotted) and $R^{(2)}$ (dot-dash) have been calculated to order α_s and α_s^2, respectively, including the effects of the mass of the charm quark [4]. The $R^{(2TM)}$ curve (dashed) also includes target mass effects in the order α_s^2 pQCD calculation. The solid curve is an empirical parameterization of previous data [2].

FIG. 3. The values of R as a function of x at $Q^2 \sim 3(\mathrm{Gev/c}^2$. Also shown is the measured elastic value of R at x=1 ($\approx 0.328/Q^2$ for an isoscalar target, assuming elastic form factor scaling). The notation is the same as in Fig. 2, except the crosses are CDHSW [21].



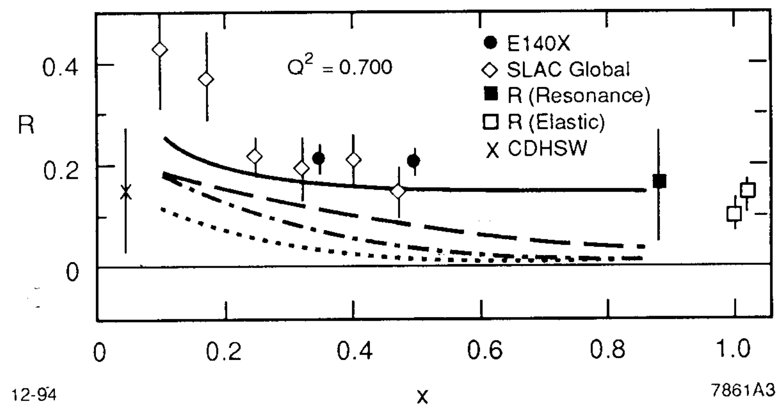
0.2
0.1
0
−0.1
−0.2
⟨Rd–Rp⟩
0
0.2
0.4
0.6
0.8
1.0
x
This experiment
This experiment (Be-p)
SLAC Global
NMC
12-94
7861A1

Fig. 1



R
0.4
0.2
0
R(1)
R(2)
R(2TM)
Rworld
x = 0.100
x = 0.700
This Exp.
SLAC Global
BCDMSEMC
x EMC
1
10
100
Q2
12-94
7861A2

Fig. 2



0.4
R
0.2
0
Q^2 = 0.700
E140X
SLAC Global
R (Resonance)
R (Elastic)
X CDHSW
0
0.2
0.4
0.6
0.8
1.0
12-94
x
7861A3

Fig. 3