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ABSTRACT

New data on the x-dependence of the ratio of down to up quarks in the proton are presented from neutrino and antineutrino experiments using the Fermilab 15-foot bubble chamber filled with hydrogen. The new data are in good agreement with existing data from electron scattering experiments performed at SLAC but are not accurate enough at large x to discriminate between the QCD prediction and a (1-x) behavior as $x \to 1$.

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The most accurate existing data on the ratio of isospin-down (d) to isospin-up (u) quarks in the proton comes from measurements [1, 2] of the ratio $R = \sigma^{en}/\sigma^{ep}$ in deep inelastic electron scattering experiments using hydrogen and deuterium targets. (σ^{en} and σ^{ep} are the cross sections for electron scattering from neutrons and protons respectively). Particular theoretical interest [3, 4, 5, 6, 7] centers on the behavior of R for $x \to 1$: ($x = Q^2/2m\nu$ where Q^2 is the square of the 4-momentum transfer and ν is the energy transfer measured in the rest frame of the target nucleon). One very interesting possibility [6] is that the ratio $d/u \to 1/5$ as $x \to 1$, which if verified experimentally would provide strong support for the validity of a theory like Quantum Chromodynamics (QCD) in which the quarks are bound by the exchange of vector gluons. [7] Another possibility is that $d/u \to 0 \sim (1-x)$ as $x \to 1$, as has been predicted by Feynman. [3].

Unfortunately the existing electron data are not accurate enough at large x to discriminate between the QCD prediction and a (1-x) behavior. Furthermore since the dominant source of error at large x is the inherent theoretical uncertainty as to the effect of nuclear binding in deuterium, we cannot expect the accuracy of the electron data to improve indefinitely with increasing statistics. Neutrino and antineutrino experiments using hydrogen targets make possible a direct determination of d and u under conditions where nuclear effects are absent. A measurement of the neutrino to antineutrino cross-section ratio for $x \to 1$ using a free proton target could provide a unique and decisive experimental test of the validity of QCD. In this paper we present data on the ratio d/u obtained from neutrino and anti-neutrino experiments using the Fermilab 15-foot bubble chamber filled with hydrogen. [8, 9]

In the quark model the quantity R measured in electron scattering experiments is given in terms of the quark distributions by the relation

$$R(x) = \frac{4(d(x) + \bar{d}(x)) + (u(x) + \bar{u}(x)) + (s(x) + \bar{s}(x))}{4(u(x) + \bar{u}(x)) + (d(x) + \bar{d}(x)) + (s(x) + \bar{s}(x))} \quad (1)$$

For large x ($\gtrsim 0.2$) the contribution of the antiquarks and the strange quarks can be neglected and we have

$$d/u = (4R - 1)/(4 - R) \qquad (x \gtrsim 0.2) \qquad (2)$$

In Fig. 1 the black data points represent the quantity (2) computed from the published data for R. (reference 1 for $x < 0.3$ and reference 2 for $x > 0.3$).⁺ The solid curve is a theoretical fit due to Field and Feynman [10] which includes an estimate for the effect of the antiquarks. The fit is chosen to fall to zero like (1-x) as $x \to 1$ in accord with Feynman's prediction. The shaded region represents the estimated systematic error in the electron data believed to be $\sim \pm 0.05$ for $x \gtrsim 0.7$. The contribution to the systematic error due to the uncertainty in

⁺Newer less precise data for R have been given by Atwood for larger values of Q^2. Within the errors the newer data are consistent with the data given in Ref. 1.

the momentum spectrum of the neutron in the deuteron increases rapidly with increasing x and dominates as $x \to 1$. [12] The magnitude of this uncertainty is itself difficult to estimate, and the systematic error may be considerably larger than indicated in Fig. 1. [13] While the data shown appear to agree very well with a (1-x) behavior, it is clear that the electron data are nonetheless not adequate to exclude the prediction of QCD.

The new data come from neutrino and antineutrino experiments performed using the Fermilab 15-foot bubble chamber filled with hydrogen in a wide-band horn focussed neutrino/antineutrino beam. The energy of the primary proton beam was 300 GeV for the neutrino running and 400 GeV for the bulk of the antineutrino running with the result that the energy spectrum of the neutrino and the antineutrino events is rather similar. For both the neutrino and the antineutrino sample the mean energy is approximately 30 GeV for events in the energy range 10-200 GeV. The methods used to obtain a sample of charged current events and to obtain an estimate for the neutrino energy in individual events are discussed in references 8 and 9. In order to minimize the effect of a possible scanning bias in the antineutrino data and to reduce the effect of various sources of background in both sets of data the requirements $0.1 < y < 0.8$ and E between 10 and 200 GeV ($y = \nu/E$ and E is the energy of the incoming neutrino) are applied to all events. The remaining data sample consists of approximately 340 neutrino events and 330 antineutrino events. Further details of the running conditions, analysis techniques, and background problems are discussed in references 8 and 9.

In the quark model the ratio of the neutrino and antineutrino cross sections on protons is given by

$$\left(\frac{d^2\sigma}{dxdy}\right)^{\nu p} \Big/ \left(\frac{d^2\sigma}{dxdy}\right)^{\bar{\nu} p} = \frac{d(x)\cos^2\theta + s(x)\sin^2\theta + (1-y)^2 \ \bar{u}(x)}{(1-y)^2 \ u(x) + \bar{d}(x)\cos^2\theta + \bar{s}(x) \ \sin^2\theta} \quad (3)$$

where θ is the Cabibbo angle ($\sin^2\theta \sim 0.06$). Unfortunately the relative flux in the the two experiments is unknown and it is not possible to determine the magnitude of the cross section ratio from experiment. The best that can be done at the present time is to normalize the two sets of data using model-dependent estimates for the integrals of the quark momentum distributions leaving the shape of the x-dependence to be determined by experiment. For this purpose we use the estimates of Field and Feynman, based on electron scattering data. Integrating the differential cross sections over the region $0.1 < y < 0.8$ we have:

$$d/u = 0.44 \left(\frac{1}{N} \frac{dN}{dx}\right)^{\nu p} \Big/ \left(\frac{1}{N} \frac{dN}{dx}\right)^{\bar{\nu} p} \quad (x \gtrsim 0.2) \qquad (4)$$

The ratio (4) has been computed from the x-distributions in the two experiments after applying corrections to account for resoluton smearing and backgrounds. The results are shown in Fig. 1 (open circles) for comparison with the electron data. The broken curve is the prediction from Field and Feynman. For $x \lesssim 0.2$ the neutrino data falls below the electron data as would be expected if antiquarks play an important role. For $x \gtrsim 0.2$ the neutrino data is in substantial agreement with the electron data. The data point plotted at $x = 0.7$ represents the ratio of all of the data in the range $0.6 < x < 1.0$. The neutrino data are compatable with the QCD prediction for $x \to 1$ but do not differentiate between the QCD prediction and a $(1-x)$ behavior.

In the experimental determination of the ratio d/u as a function of x from Eq. 4 one of the most important experimental problems which has to be considered is the effect of smearing in x due to errors in the estimate of the hadron energy. The effect of the smearing is to produce an overestimate of the cross section at large x which does not completely cancel in the ratio because the x-distributions for neutrinos and antineutrinos are different. In the present experiments the resolution in hadron energy $\delta\nu/\nu$ is typically ±20% and the correction factor applied to the ratio for $x > 0.6$ is 0.82. The effect of smearing increases very rapidly as $x \to 1$, so that a determination of the ratio in an x-range closer to $x = 1$ is essentially impossible in the present experiments even with very high statistics.

It is apparent from Fig. 1 that in order to discriminate clearly between the QCD prediction and a $(1-x)$ behavior it will be necessary to measure the ratio for $x \gtrsim 0.7$. The resolution, $\delta x/x$ will have to be ~ ±5% or better in order to exploit the advantages of the free nucleon target. We estimate that the required statistical precision could be obtained with 10,000 neutrino and 10,000 antineutrino events. We believe that the theoretical importance of the measurement justifies the considerable experimental investment which is required.

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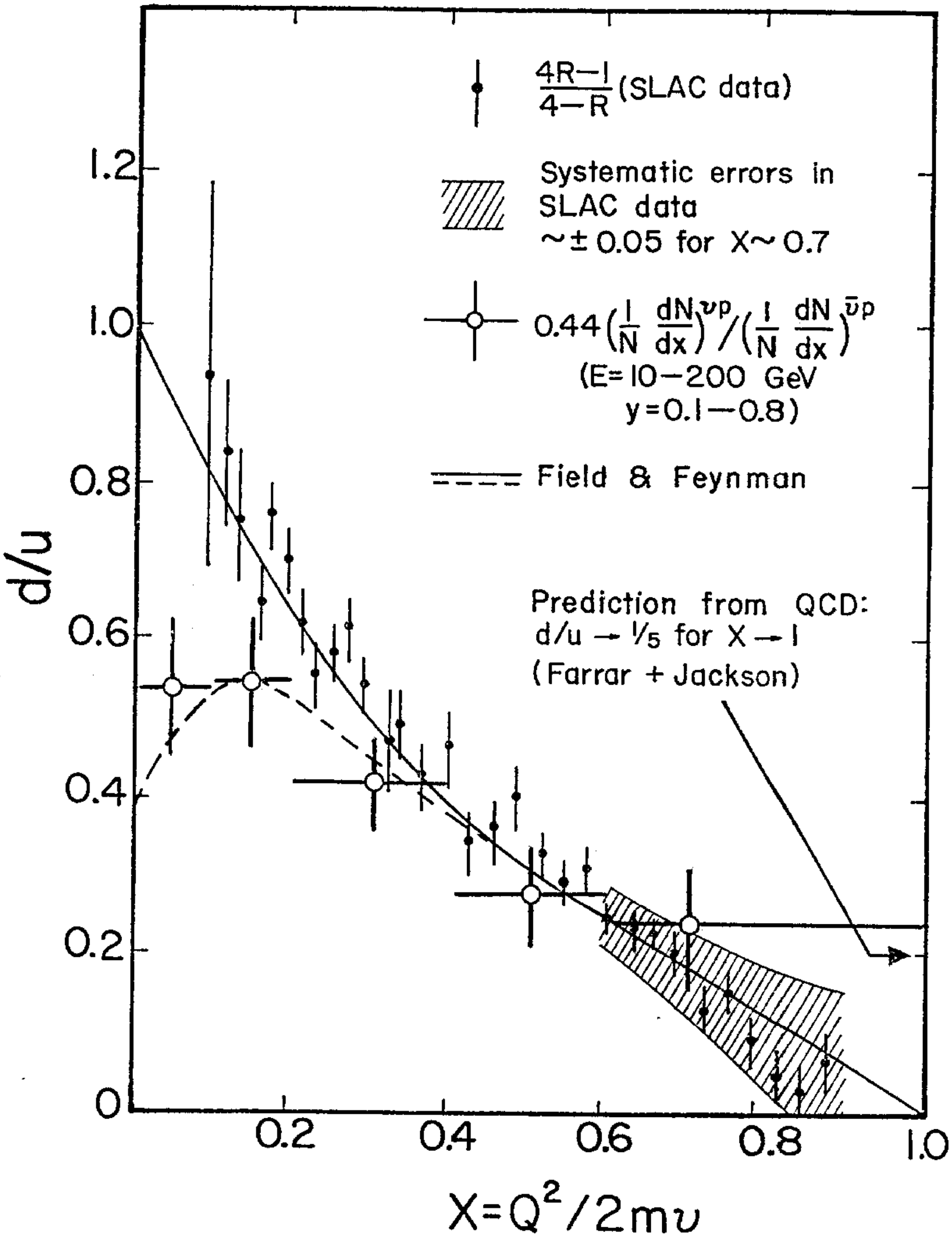
FIGURE CAPTION

Figure 1: Experimental data on the ratio d/u from neutrino and antineutrino experiments on hydrogen (open circles). The quantity plotted is $0.44 \left(\frac{1}{N}\frac{dN}{dx}\right)^{\bar{\nu}p} \Big/ \left(\frac{1}{N}\frac{dN}{dx}\right)^{\nu p}$ which measures the ratio d/u in the region where antiquarks and strange quarks can be neglected ($x \gtrsim 0.2$). Data from electron scattering experiments on hydrogen and deuterium is shown for comparison (black dots). The quantity plotted is (4R-1)/(4-R) where $R = \sigma^{en}/\sigma^{ep}$. The shaded region represents an estimate for the systematic errors in the electron data at large x. The broken curve and the solid curve are predictions for the neutrino/antineutrino data and for the electron data respectively, based on theoretical fits (reference 10) to the electron data.



$\frac{4R-1}{4-R}$ (SLAC data)
Systematic errors in SLAC data ~± 0.05 for X~ 0.7
$0.44\left(\frac{1}{N}\frac{dN}{dx}\right)^{\nu p}/\left(\frac{1}{N}\frac{dN}{dx}\right)^{\bar{\nu} p}$
(E=10-200 GeV
y=0.1-0.8)
Field & Feynman
Prediction from QCD:
d/u → 1/5 for X → 1
(Farrar + Jackson)
d/u
1.2
1.0
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1.0
$X=Q^2/2m\upsilon$

Fig. 1