DEEP INELASTIC SCATTERING: COMPARISONS WITH THE QUARK MODEL

Nobel Lecture, December 8, 1990

by

JEROME I. FRIEDMAN

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.

EARLY RESULTS

In the latter half of 1967 a group of physicists from the Stanford Linear Accelerator Center (SLAC) and the Massachusetts Institute of Technology (MIT) embarked on a program of inelastic electron proton scattering after completing an initial study[1] of elastic scattering with physicists from the California Institute of Technology. This work was done on the newly completed 20 GeV Stanford linear accelerator. The main purpose of the inelastic program was to study the electro-production of resonances as a function of momentum transfer. It was thought that higher mass resonances might become more prominent when excited with virtual photons, and it was our intent to search for these at the very highest masses that could be reached. For completeness we also wanted to look at the inelastic continuum since this was a new energy region which had not been previously explored. The proton resonances that we were able to measure[2] showed no unexpected kinematic behavior. Their transition form factors fell about as rapidly as the elastic proton form factor with increasing values of the four momentum transfer, q. However, we found two surprising features when we investigated the continuum region (now commonly called the deep inelastic region).

(1) Weak q^2 Dependence

The first unexpected feature of these early results[3] was that the deep inelastic cross-sections showed a weak fall off with increasing q^2. The scattering yields at the larger values of q^2 were between one and two orders of magnitude greater than expected.

The weak momentum transfer dependence of the inelastic cross-sections for excitations well beyond the resonance region is illustrated in Fig. 1. The differential cross section divided by the Mott cross section,[4] σ_{Mott}, is plotted as a function of the square of the four-momentum transfer, $q^2 = 2EE'(1-\cos\theta)$, for constant values of the invariant mass of the recoiling target system, W, where $W^2 = 2M(E-E') + M^2 - q^2$. The quantity E is the energy of the incident electron, E' is the energy of the final electron, and θ is the scattering angle, all defined in the laboratory system; M is the mass of the proton. The cross section is divided by the Mott cross section in order to remove the major part of the well-known four-momentum transfer depen-

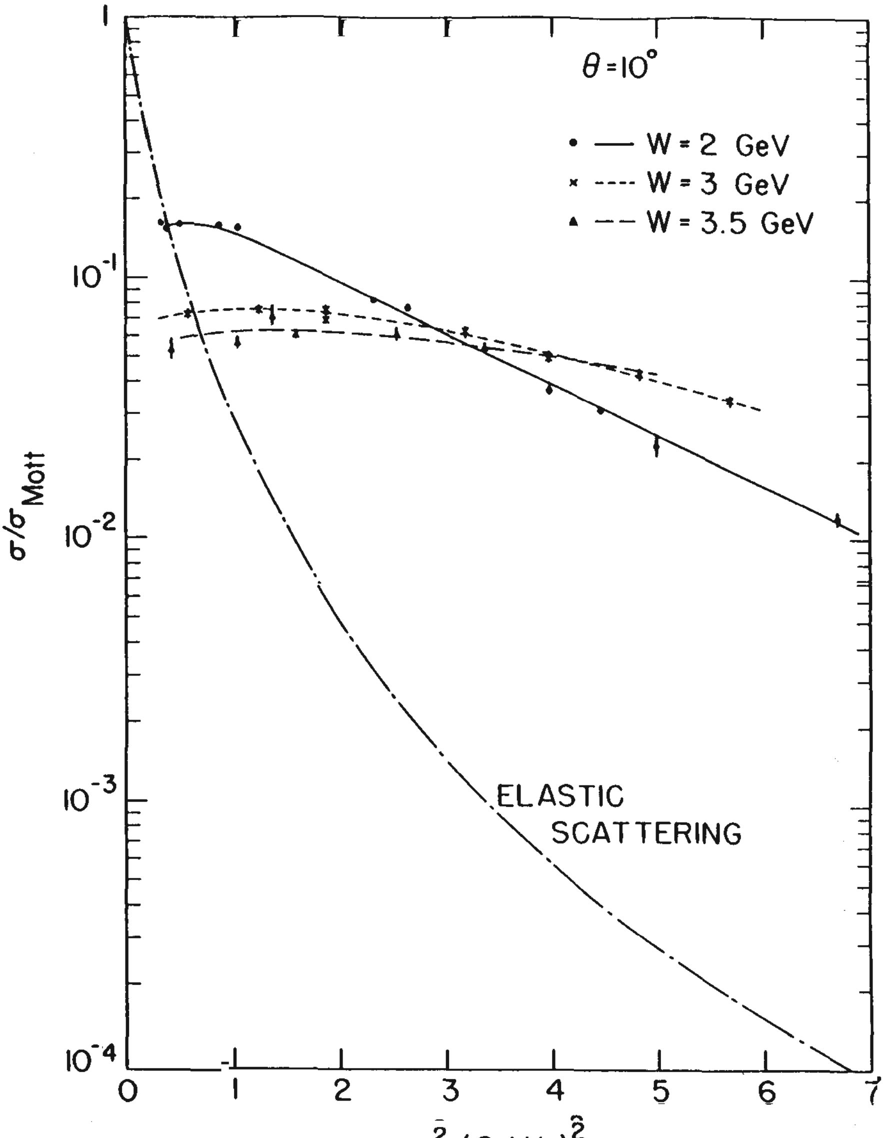

Fig. 1: $(d^2\sigma/d\Omega dE')/\sigma_{\mathrm{Mott}}$, in GeV^{-1}, vs. q^2 for W = 2, 3 and 3.5 GeV. The lines drawn through the data are meant to guide the eye. Also shown is the cross section for elastic e-p scattering divided by σ_{Mott}, $(d\sigma/d\Omega)/\sigma_{\mathrm{Mott}}$, calculated for θ = 10°, using the dipole form factor. The relatively slow variation with q^2 of the inelastic cross section compared with the elastic cross section is clearly shown.

dence arising from the photon propagator. The q^2 dependence that remains is related primarily to the properties of the target system. Results from 10° are shown in the figure for each value of W. As W increases, the q^2 dependence appears to decrease. The striking difference between the behavior of the deep inelastic and elastic cross sections is also illustrated in this figure, where the elastic cross section, divided by the Mott cross section for θ = 10°. is shown.

When the experiment was planned, there was no clear theoretical picture of what to expect. The observations of Hofstadter[5] in his pioneering studies of elastic electron scattering from the proton showed that the proton had a size of about 10^{-13} cm and a smooth charge distribution. This result, plus the theoretical framework that was most widely accepted at the time, suggested to our group when the experiment was planned that the deep inelastic electron proton cross-sections would fall rapidly with increasing q^2.

(2) Scaling

The second surprising feature in the data, scaling, was found by following a suggestion by Bjorken.[6] To describe the concept of scaling, one has to introduce the general expression for the differential cross section for unpolarized electrons scattering from unpolarized nucleons with only the scattered electrons detected.[7]

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{\text{Mott}}\left[W_2 + 2W_1 \tan^2\frac{\theta}{2}\right].$$

The functions W_1 and W_2 are called structure functions and depend on the properties of the target system. As there are two polarization states of the virtual photon, transverse and longitudinal, two such functions are required to describe this process. In general, W_1 and W_2 are each expected to be functions of both q^2 and ν, where ν is the energy loss of the scattered electron. However, on the basis of models that satisfy current algebra, Bjorken conjectured that in the limit of q^2 and ν approaching ∞, the two quantities νW_2 and W_1 become functions only of the ratio $\omega = 2M\nu/q^2$; that is

$$2MW_1\ (\nu, q^2) \longrightarrow F_1(\omega)$$
$$\nu W_2\ (\nu, q^2) \longrightarrow F_2(\omega).$$

The scaling behavior of the structure functions is shown in Fig. 2, where experimental values of νW_2 and $2MW_1$ are plotted as a function of ω for values of q^2 ranging from 2 to 20 GeV^2. The data demonstrated scaling within experimental errors for $q^2 > 2$ GeV^2 and $W > 2.6$ GeV.

The dynamical origin of scaling was not clear at that time, and a number of models were proposed to account for this behavior and the weak q^2 dependence of the inelastic cross section. While most of these models were firmly imbedded in S-matrix and Regge pole formalism, the experimental results caused some speculation regarding the existence of a possible point-like structure in the proton. In his plenary talk at the XIV International Conference on High Energy Physics held in Vienna in 1968, where preliminary results on the weak q^2 dependence and scaling were first presented, Panofsky[2] reported "... theoretical speculations are focused on the possibility that these data might give evidence on the behavior of point-like charged structures in the nucleon." However, this was not the prevailing point of view. Even if one had proposed a constituent model at that time it was not

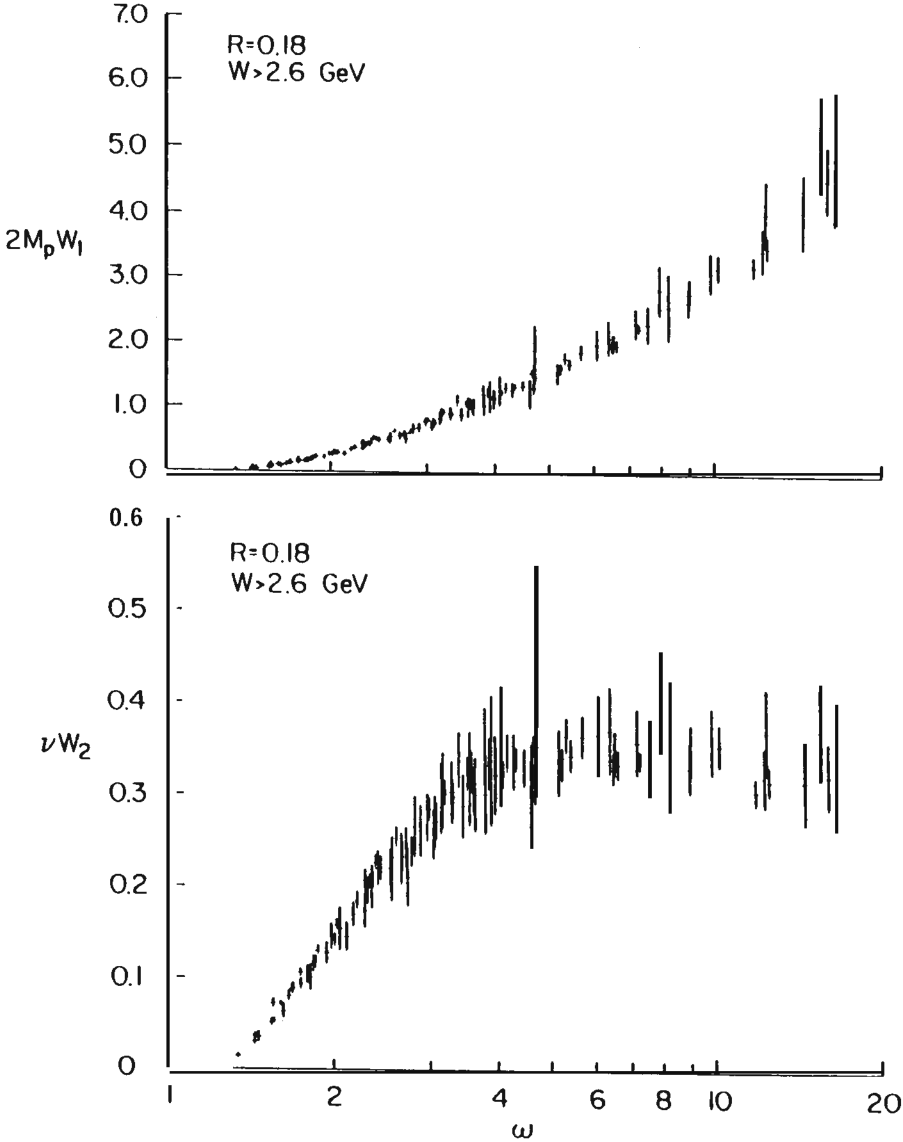

Fig. 2: $2MW_1$ and νW_2 for the proton as functions of ω for $W > 2.6$ GeV, $q^2 > 1(\mathrm{GeV}/c^2)$, and using R = 0.18. Data from Ref. [34]. The quantity R is discussed in the section of this paper entitled *Models*.

clear that there were reasonable candidates for the constituents. Quarks, which had been proposed independently by Gell-Mann[8] and Zweig[9] as the building blocks of unitary symmetry[10] in 1964, had been sought in numerous accelerator and cosmic ray investigations and in the terrestrial environment without success. Though the quark model provided the best available tool for understanding the properties of the many recently discovered hadronic resonances, it was thought by many to be merely a mathematical representation of some deeper dynamics, but one of heuristic value. Considerably more experimental and theoretical results had to be accumulated before a clear picture emerged. More detailed descriptions of the develop ment of the deep inelastic program and its early results are given in the written versions of the 1990 Physics Nobel Lectures of R. E. Taylor[11] and H. W. Kendall.[12]

NON-CONSTITUENT MODELS

The initial deep inelastic measurements stimulated a flurry of theoretical work, and a number of non-constituent models based on a variety of theoretical approaches were put forward to explain the surprising features of the data. One approach related the inelastic scattering to forward virtual Compton scattering, which was described in terms of Regge exchange[13-17] using the Pomeranchuk trajectory, or a combination of it and non-diffractive trajectories. Such models do not require a weak q^2 dependence, and scaling had to be explicitly inserted. Resonance models were also proposed to explain the data. Among these was a Veneziano-type model[18] in which the density of resonances increases at a sufficiently rapid rate to compensate for the decrease of the contribution of each resonance with increasing q^2. Another type of resonance model[19] built up the structure functions from an infinite series of N and Δ resonances. None of these models was totally consistent with the full range of data accumulated in the deep inelastic program.

One of the first attempts[20] to explain the deep inelastic scattering results employed the Vector Dominance Model, which had been used to describe photon-hadron interactions over a wide range of energies. This model, in which the photon is assumed to couple to a vector meson which then interacts with a hadron, was extended, using ρ meson dominance, to deep inelastic electron scattering. It reproduced the gross features of the data in that νW_2 approached a function of ω for ν much greater than M_ρ the mass of the ρ meson. The model also predicted that

$$R = \frac{\sigma_S}{\sigma_T} = \left(\frac{\varepsilon q^2}{M_\rho^2}\right)\left(1 - \frac{q^2}{2M\nu}\right),$$

where R is the ratio of σ_S and σ_T, the photo-absorption cross-sections of longitudinal and transverse virtual photons, respectively, and ε is the ratio of the vector meson-nucleon total cross sections for vector mesons with polarization vectors respectively parallel and perpendicular to their direction of motion. Since the parameter ε is expected to have a value of about 1 at high energies, this theory predicted very large values of R for values of $q^2 > M_\rho^2$. The ratio R can be related to the structure functions in the following way

$$R = \frac{W_2}{W_1}\left(1 + \frac{\nu^2}{q^2}\right) - 1.$$

The measurements of deep inelastic scattering over a range of angles and energies allowed W_1 and W_2 to be separated and R to be determined experimentally. Early results for R and the predictions of the vector dominance model are shown in Fig. 3. The results showed that R is small and does not increase with q^2. This eliminated the model as a possible description of deep inelastic scattering.

Various attempts[21] to save the vector meson dominance point of view were made with the extension of the vector meson spectral function to higher masses, including approaches which included a structureless continuum of higher mass states. These calculations of the Generalized Vector Dominance model failed in general to describe the data over the full kinematic range.

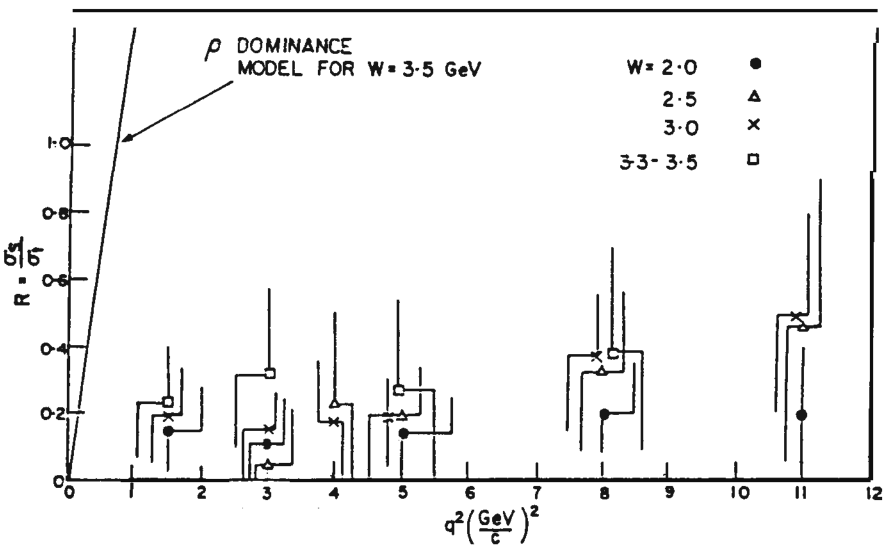

Fig. 3: Measured values of $R = \sigma_S/\sigma_T$ as a function of q^2 for various values of W. The p meson dominance prediction is also shown, calculated for $W = 3.5$ (see Ref. [20]).

CONSTITUENT MODELS

The first suggestion that deep inelastic electron scattering might provide evidence of elementary constituents was made by Bjorken in his 1967 Varenna lectures.[22] Studying the sum rule predictions derived from current algebra,[23] he stated, ". . . We find these relations so perspicuous that, by an appeal to history, an interpretation in terms of elementary constituents is suggested." In essence, Bjorken observed that a sum rule for neutrino scattering derived by Adler[24] from the commutator of two time components of the weak currents led to an inequality[25] for inelastic electron scattering,

$$\int_{q^2/2M}^{\infty} d\nu \left[W_2^p(\nu, q^2) + W_2^n(\nu, q^2)\right] \geq \frac{1}{2},$$

where W_2^p and W_2^n are structure functions for the proton and neutron, respectively.

This is equivalent to:

$$\lim_{E\to\infty}\left[\frac{d\sigma_{ep}}{dq^2}+\frac{d\sigma_{en}}{dq^2}\right]\geqslant\frac{2\pi\alpha^2}{q^4}.$$

The above inequality states that as the electron energy goes to infinity the sum of the electron-proton plus electron-neutron total cross sections (elastic plus inelastic) at fixed large q^2 is predicted to be greater than one-half the cross section for electrons scattering from a point-like particle. Bjorken also derived a similar result for backward electron scattering.[26] These results were derived well before our first inelastic results appeared. In hindsight, it is clear that these inequalities implied a point-like structure of the proton and large cross sections at high q^2, but Bjorken's result made little impression on us at the time. Perhaps it was because these results were based on current algebra, which we found highly esoteric, or perhaps it was that we were very much steeped in the physics of the time, which suggested that hadrons were extended objects with diffuse substructures.

The constituent model which opened the way for a simple dynamical interpretation of the deep inelastic results was the parton model of Feynman. He developed this model to describe hadron-hadron interactions,[27] in which the constituents of one hadron interact with those of the other. These constituents, called partons, were identified with the fundamental bare particles of an unspecified underlying field theory of the strong interactions. He applied this model to deep inelastic electron scattering after he had seen the early scaling results that were to be presented a short time later at the 14th International Conference on High Energy Physics, in Vienna, in the late-summer of 1968. Deep inelastic electron scattering was an ideal process for the application of this model. In electron-hadron scattering the electron's interaction and structure were both known, whereas in hadron-hadron scattering neither the structures nor the interactions were understood at the time.

In this application of the model the proton is conjectured to consist of point-like partons from which the electron scatters. The model is implemented in a frame approaching the infinite momentum frame, in which the relativistic time dilation slows down the motions of the constituents nearly to a standstill. The incoming electron thus "sees" and incoherently scatters from partons which are noninteracting with each other during the time the virtual photon is exchanged. In this frame the impulse approximation is assumed to hold, so that the scattering process is sensitive only to the properties and momenta of the partons. The recoil parton has a final state interaction in the nucleon, producing the secondaries emitted in inelastic scattering. A diagram of this model is shown in Fig. 4.

Consider a proton of momentum $\mathbf{P}$, made up of partons, in a frame approaching the infinite momentum frame. The transverse momenta of any parton is negligible and the i^{th} parton has the momentum $\mathbf{P}_i = x_i\mathbf{P}$, where x_i is a fraction of the proton's momentum. Assuming the electron scatters from a point-like parton of charge Q_i (in units of e), leaving it with the same mass and charge, the contribution to $W_2(\nu, q^2)$ from this scattering is

$$W_2^{(i)}(\nu, q^2) = Q_i^2\, \delta(\nu - q^2/2Mx_i) = \frac{Q_i^2 x_i}{\nu}\, \delta(x_i - q^2/2M\nu).$$

The expression for νW_2 for a distribution of partons is given by

$$\nu W_2(\nu, q^2) = \sum_N \mathrm{P}(N) \left(\sum_{i=1}^{N} Q_i^2 \right) x f_N(x) = F_2(\mathrm{x})$$

where

$$x = \frac{q^2}{2M\nu} = \frac{1}{\omega}$$

and where P(N) is the probability of N partons occurring. The sum

$$\left(\sum_{i=1}^{N} (\mathrm{Q}_i)^2 \right)$$

is the sum of the squares of the charges of the N partons, and $f_N(x)$ is the distribution of the longitudinal momenta of the charged partons.

It was clear that the parton model, with the assumption of point-like constituents, automatically gave scaling behavior. The Bjorken scaling variable ω was seen to be the inverse of the fractional momentum of the struck parton, X, and νW_2 was shown to be the fractional momentum distribution of the partons, weighted by the squares of their charges.

In proposing the parton model, Feynman was not specific as to what the partons were. There were two competing proposals for their identity.

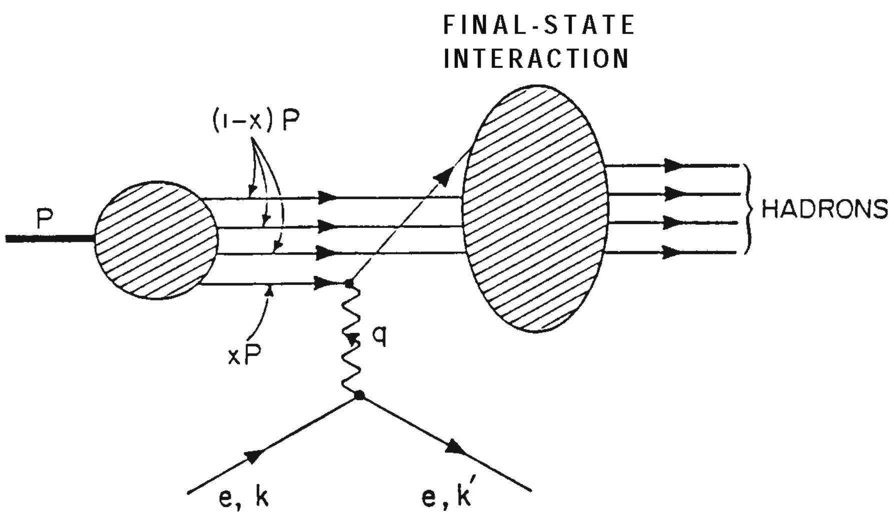

Fig. 4: A representation of inelastic electron nucleon scattering in the parton model. k and k' are the incident and final momenta of the electron. The other quantities are defined in the text.

Applications of the parton model identified partons with bare nucleons and pions,[28-30] and also with quarks[31-33]. However, parton models incorporating quarks had a glaring inconsistency. Quarks required strong final state interactions to account for the fact that these constituents had not been observed in the laboratory. Before the theory of Quantum Chromodynamics (QCD) was developed, there was a serious problem in making the "free" behavior of the constituents during photon absorption compatible with the required strong final state interaction. One of the ways to get out of this difficulty was to assign quarks very large masses but this was not considered totally satisfactory. This question was avoided in parton models employing bare nucleons and pions because the recoil constituents are allowed to decay into real particles when they are emitted from the nucleon.

Drell, Levy and Yan[28] derived a parton model, in which the partons are bare nucleons and pions, from a canonical field theory of pions and nucleons with the insertion of a cutoff in transverse momenta. The calculations showed that the free point-like constituents which interact with the electromagnetic current in each order of perturbation theory and to leading order in logarithms of $2M\nu/q^2$ are bare nucleons making up the proton and not the pions in the pion cloud.

A further development of the approach that identified bare nucleons and pions as partons was a calculation by Lee and Drell[30] that provided a fully relativistic generalization of the parton model that was no longer restricted to an infinite momentum frame. This theory obtained bound state solutions of the Bethe-Salpeter equation for a bare nucleon and bare mesons, and connected the observed scale invariance with the rapid decrease of the elastic electromagnetic form factors.

When the quark model was proposed in 1964 it contained three types of quarks, up (u), down (d), and strange (s), having charges 2/3, - 1/3, and - 1/3, respectively, and each of these a spin 1/2 particle. In this model the nucleon (and all other baryons) is made up of three quarks, and all mesons consist of a quark and an antiquark. As the proton and neutron both have zero strangeness, they are (u,u,d) and (d,d,u) systems respectively. Bjorken and Paschos[31] studied the parton model for a system of three quarks, commonly called valence quarks, in a background of quark-antiquark pairs, often called the sea, and suggested further tests for the model. A more detailed description of a quark-parton model was later given by Kuti and Weisskopf.[32] Their model of the nucleon contained, in addition to the three valence quarks, a sea of quark-antiquark pairs, and neutral gluons, which are quanta of the field responsible for the binding of the quarks. The momentum distribution of the quarks corresponding to large ω was given in terms of the requirements of Regge behavior. Decisive tests of these models were provided by extensive measurements with hydrogen and deuterium targets that followed the early results.

MEASUREMENTS OF PROTON AND NEUTRON STRUCTURE FUNCTIONS

The first deep inelastic electron scattering results[3] were obtained in the period 1967 - 1968 from a hydrogen target with the 20 GeV spectrometer set at scattering angles of 6° and 10°. By 1970 the proton data [34] had been extended to scattering angles of 18°, 26° and 34° with the use of the 8 GeV spectrometer. The measurements covered a range of q^2 from 1 GeV^2 to 20 GeV^2, and a range of W^2 up to 25 GeV^2. By 1970 data[35] had been also obtained at scattering angles of 6° and 10° with a deuterium target. Subsequently, a series of matched measurements[36-36] with better statistics and covering an extended range of q^2 and W^2 were done with hydrogen and deuterium targets, utilizing the 20 GeV, the 8 GeV, and the 1.6 GeV spectrometers. These data sets provided, in addition to more detailed information about the proton structure functions, a test of scaling for the neutron. In addition, the measured ratio of the neutron and proton structure functions provided a decisive tool in discriminating among the various models proposed to explain the early proton results.

Neutron cross sections were extracted from measured deuteron cross sections using the impulse approximation along with a procedure to remove the effects of Fermi motion. The method used was that of Atwood and West,[39] with small modifications[40] representing off-mass-shell corrections. In this method the measured proton structure functions, W_1, and W_2, were kinematically smeared over the Fermi momentum distribution of the deuteron and combined to yield the smeared proton cross section σ_{ps}. Subtracting the smeared proton cross section from the measured deuteron cross section yielded the smeared neutron cross section $\sigma_{ns} = \sigma_d - \sigma_{ps}$. With the use of a deconvolution procedure[37] on σ_{ns}, the unsmeared neutron cross section σ_n was obtained. From this and the measured value of the proton cross section σ_p the ratio σ_n/σ_p, which is free of kinematic smearing, was determined. The results were insensitive to the choice of the deuteron wave function used to calculate the momentum distribution of the bound nucleons, as long as the wave functions were consistent with the known properties of the deuteron and the n-p interaction.

The conclusions that were derived from the analysis of these extensive data sets were the following:

(1) The deuterium and neutron structure functions showed the same approximate scaling behavior as the proton. This is shown in Fig. 5 which presents νW_2 for the proton, neutron, and deuteron as a function of x for data ranging in q^2 from 2 GeV^2 to 20 GeV^2.

(2) The values of R_p, R_n, and R_d were equal within experimental errors. This is shown in Fig. 6, where the difference of R_d and R_p is plotted.

(3) The ratio of the neutron and proton inelastic cross sections falls continuously as the scaling variable x approaches 1. From a value of about 1 near x = 0, the experimental ratio falls to about 0.3, in the neighbor-

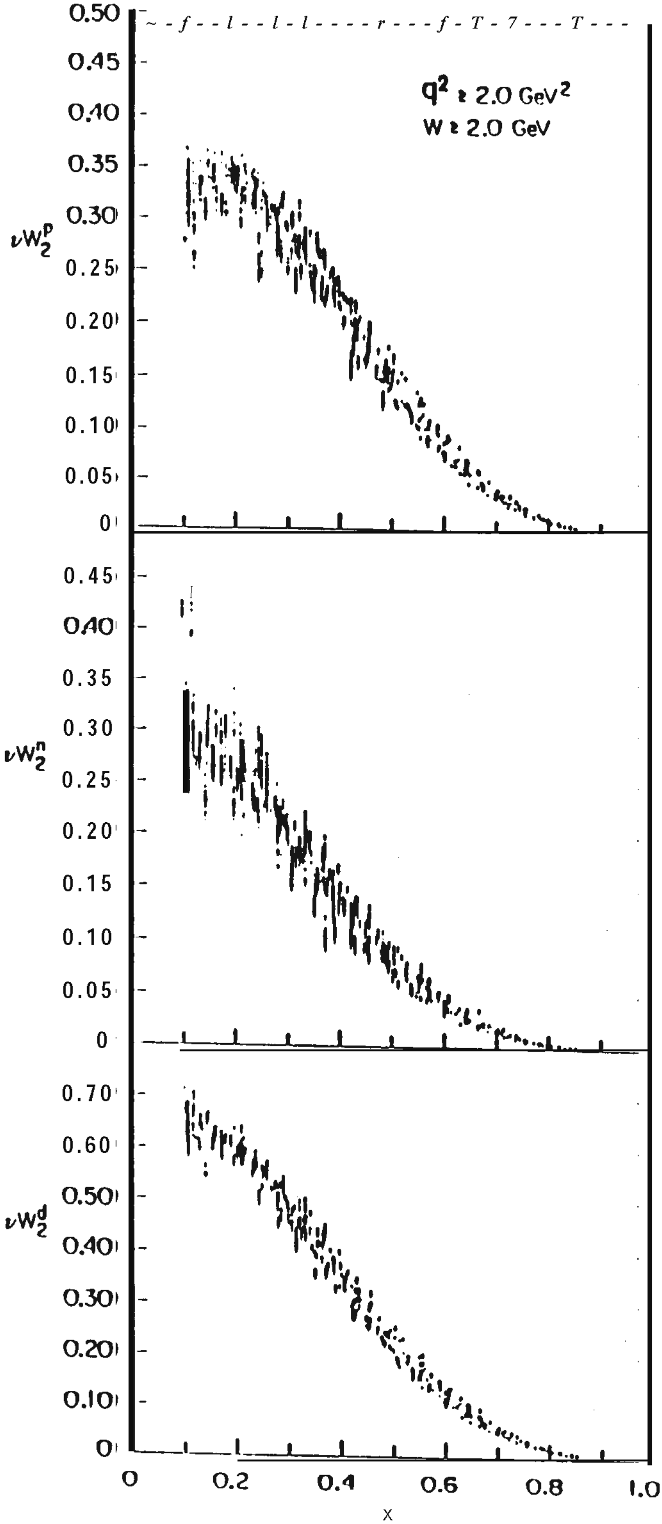

Fig. **5: Values of νW_2^p, νW_2^n and νW_2^d plotted against x. Data from Ref. [36]**

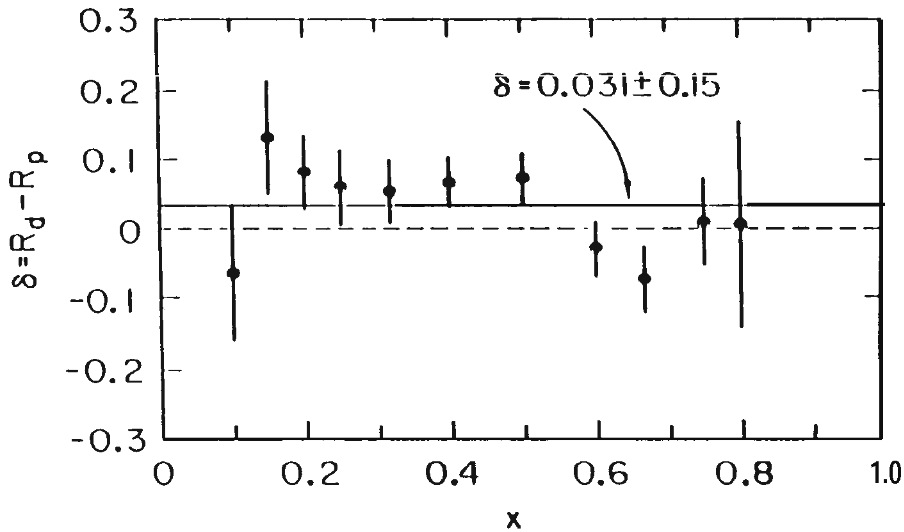

Fig. 6: Average values of the quantity δ = R_d-R_p for each of the 11 values of x studied. Errors shown are purely random. The systematic error in δ is 0.036. Data from Refs. [36] and [37].

hood of x = 0.85. This is shown in Fig. 7 in which σ_n/σ_p is plotted as a function of x. These results put strong constraints on various models of nucleon structure, as discussed later.

SUM RULE RESULTS

A sum rule generally relates an integral of a cross section (or of a quantity derived from it) and the properties of the interaction hypothesized to produce that reaction. Experimental evaluations of such relations thus provide a valuable tool in testing theoretical models. Sum rule evaluations within the framework of the parton model provided an important element in identifying the constituents of the nucleon. The early evaluations of weighted integrals of $\nu W_2(\omega)$ with respect to ω were based on the assumption that the nucleon's momentum is, on the average, equally distributed among the partons. Two important sum rules, which were evaluated for neutrons and protons, were:

$$I_1 = \int_1^\infty \nu W_2(\omega) \frac{d\omega}{\omega^2} = \sum_N P(N) \frac{\left(\sum_{i=1}^N Q_i^2\right)}{N}$$

$$I_2 = \int_1^\infty \nu W_2(\omega) \frac{d\omega}{\omega} = \sum_N P(N) \sum_{i=1}^N Q_i^2 ,$$

where I_2 is the weighted sum of the squares of the parton charges and I_1 [31,41] is the mean square charge per parton. The sum I_2 is equivalent to a sum rule derived by Gottfried[42] who showed that for a proton which consists of three nonrelativistic point-like quarks I_2^p equals 1 at a high q^2. The experimental

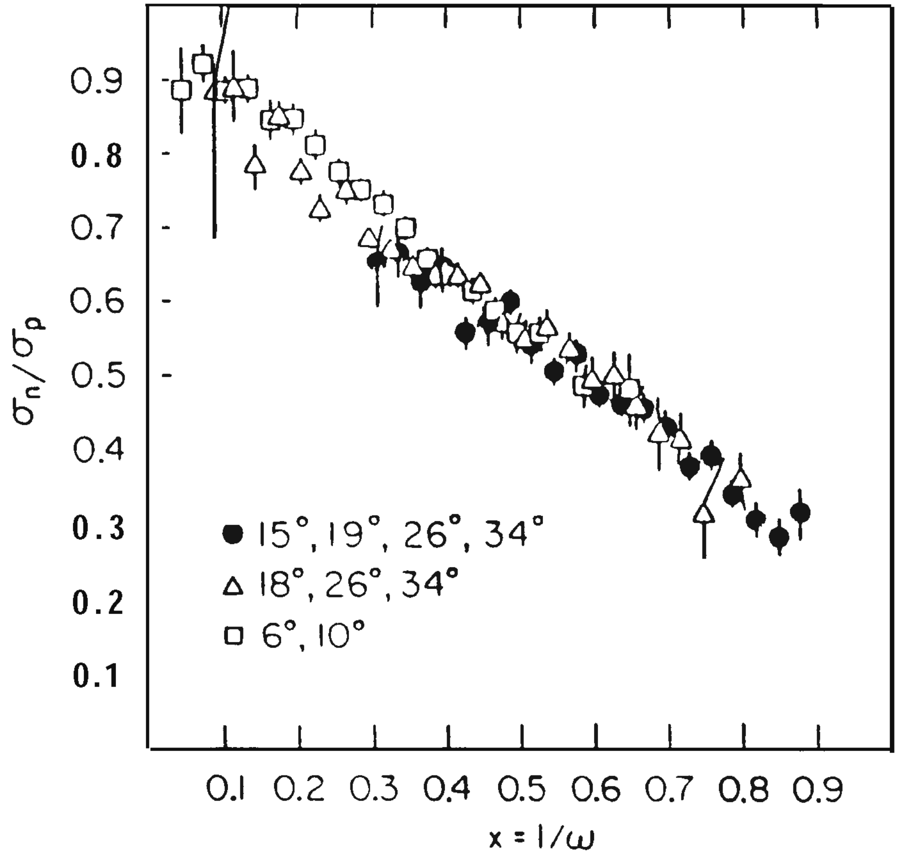

Fig. 7: Values of σ_n/σ_p as a function of x determined from the results presented in Refs. [36] and [37].

value of this integral when integrated over the range of the MIT-SLAC data gave:

$$I_2^P = \int_1^{20} \frac{d\omega}{\omega} \nu W_2^p = 0.78 \pm 0.04$$

where the integral was cut off for $\omega > 20$ because of insufficient information about R_p. Since the experimental values of νW_2 at large ω did not exclude a constant value (see Fig. 2), there was some suspicion that this sum might diverge. This would imply that in the quark model scattering occurs from a infinite sea of quark-antiquark pairs as ν approaches ∞. Table 1 gives a summary of the early comparisons of the experimental values of the sum rules with the predictions of various models. Unlike I_2, the experimental value of I_1 was not very sensitive to the behavior of νW_2, for $\omega > 20$. The experimental value was about one-half the value predicted on the basis of the simple three-quark model of the proton, and it was also too small for a proton having three valence quarks in a sea of quark-antiquark pairs. The Kuti-Weisskopf model[32] which included neutral gluons, in addition to the

TABLE 1: Early Sum Rule Results[a] — Theory[b] and Measurements[c]					
	Expected Value[e]		Measurement	ω_m[f]	$q^2(\mathrm{GeV}/c)^2$
	3 Quark	3 Quark + "Sea"			
I_1^p	$\frac{1}{3}$	$\frac{2}{9}+\frac{1}{3\langle N\rangle}$	0.159 ± 0.005	20	1.0
			0.165 ± 0.005	20	1.5
			0.172 ± 0.009[d]	20[d]	1.5[d]
			0.154 ± 0.005	12	2.0
I_1^n	$\frac{2}{9}$	$\frac{2}{9}$	0.120 ± 0.008	20	1.0
			0.115 ± 0.008	20	1.5
			0.107 ± 0.009	12	2.0
I_2^p	1	$\frac{1}{3}+\frac{2\langle N\rangle}{9}$	0.739 ± 0.029	20	1.0
			0.761 ± 0.027	20	1.5
			0.780 ± 0.04[d]	20[d]	1.5[d]
			0.607 ± 0.021	12	2.0
I_2^n	$\frac{2}{3}$	$\frac{2\langle N\rangle}{9}$	0.592 ± 0.051	20	1.0
			0.584 ± 0.050	20	1.5
			0.429 ± 0.036	12	2.0
$I_2^p - I_2^n$	$\frac{1}{3}$		0.147 ± 0.059	20	1.0
			0.177 ± 0.057	20	1.5
			0.178 ± 0.042	12	2.0

[a] From J. I. Friedman and H. W. Kendall, Ann. *Rev. Nucl.* **Sci.** 22, 203 (1972). Excerpts from this publication are used in the present paper.
[b] Reference [31].
[c] Calculated from preliminary results, later published as Refs. [35,36], except where noted.
[d] Data from Ref. [3].
[e] (N) expectation value of number of quarks.
[f] w_m is upper limit of integral.

valence quarks and the sea of quark-antiquark pairs, predicted a value of I_1^P that was compatible with this experimental result.

The difference $I_2^p - I_2^n$ was of great interest because it is presumed to be sensitive only to the valence quarks in the proton and the neutron. On the assumption that the quark-antiquark sea is an isotopic scalar, the effects of the sea cancel out in the above difference, giving $I_2^p - I_2^n = 1/3$. Unfortunately, it was difficult to extract a meaningful value from the data because of the importance of the behavior of νW_2, at large ω. Extrapolating $\nu W_2^p - \nu W_2^n$

toward $\omega \to \infty$ for $\omega > 12$, with the asymptotic dependence $(1/\omega)^{\frac{1}{2}}$ expected on the basis of Regge theory, we obtained a rough estimate of $I_2^p - I_2^n = 0.22 \pm 0.07$. This was compatible with the expected value, given the error and the uncertainties in extrapolation. The difference $\nu W_2^p(x) - \nu W_2^n(x)$, plotted in Fig. 8 shows a peak, which would be expected in theoretical models[31,32] involving quasi-free constituents.

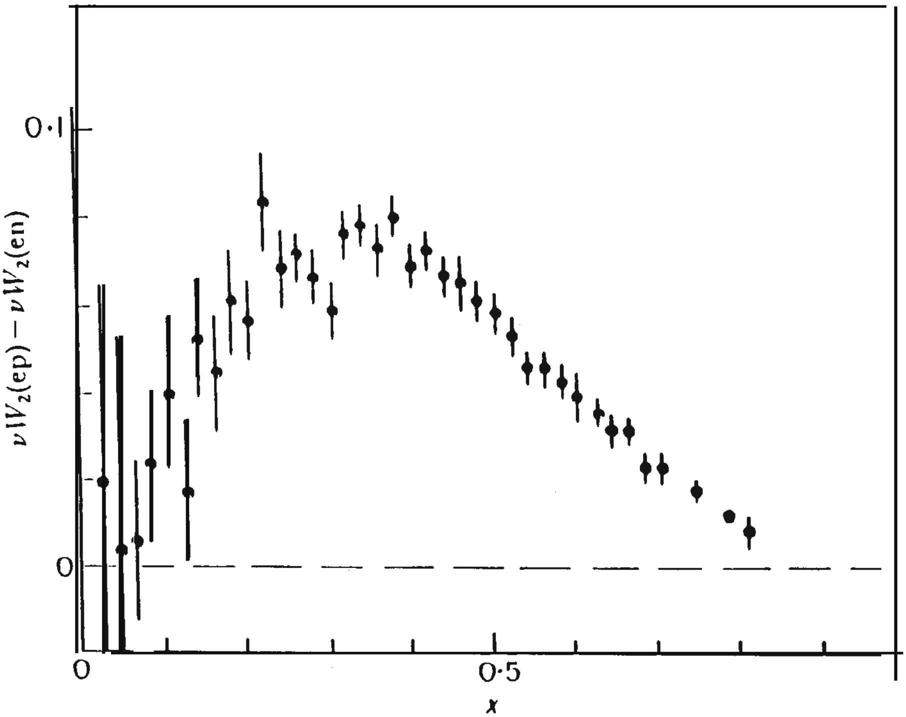

Fig. 8: Values of $\nu W_2^p - \nu W_2^n$ as a function of x.

The Bjorken inequality previously discussed, namely,

$$\int_{q^2/2M}^{\infty} d\nu \left[W_2^p(\nu, q^2) + W_2^n(\nu, q^2)\right] \geq \frac{1}{2}$$

was also evaluated. This inequality was found to be satisfied at $\omega \approx 5$.

Extensions of the quark-parton model allowed the weighted sum

$$\int \frac{d\omega}{\omega^2} \nu W_2$$

to be theoretically evaluated without making the assumption that the momentum of the nucleon is equally distributed among different types of partons. If $u_p(x)$ and $d_p(x)$ are defined as the momentum distributions of up and down quarks in the proton then $F_2^p(x)$ is given by

$$F_2^p(x) = \nu W_2^p(x) = x\left[(Q_u^2(u_p(x) + \bar{u}_p(x)) + Q_d^2(d_p(x) + \bar{d}_p(x)))\right]$$

where $\bar{u}_p(x)$ and $\bar{d}_p(x)$ are the distributions for anti-up and anti-down quarks, and Q_u^2 and Q_d^2 are the squares of the charges of the up and down quarks, respectively. The strange quark sea has been neglected.

Using charge symmetry it can be shown that

$$\frac{1}{2}\int_0^1 \left[F_2^p(x) + F_2^n(x)\right] dx = \left[\frac{Q_u^2 + Q_d^2}{2}\right] \int_0^1 x\left[u_p(x) + \bar{u}_p(x) + d_p(x) + \bar{d}_p(x)\right] dx\,.$$

The integral on the right-hand side of the equation is the total fractional momentum carried by the quarks and antiquarks, which would equal 1.0 if they carried the nucleon's total momentum. On this assumption the expected sum should equal

$$\frac{Q_u^2 + Q_d^2}{2} = \frac{1}{2}\left[\frac{4}{9} + \frac{1}{9}\right] = \frac{5}{18} = 0.28\ .$$

The evaluations of the experimental sum from proton and neutron results over the entire kinematic range studied yielded

$$\frac{1}{2}\int \left[F_2^p(x) + F_2^n(x)\right] dx = 0.14 \pm 0.005\ .$$

This again suggested that half of the nucleon's momentum is carried by neutral constituents, gluons, which do not interact with the electron.

IDENTIFICATION OF THE CONSTITUENTS OF THE NUCLEON AS QUARKS

The confirmation of a constituent model of the nucleon and the identification of the constituents as quarks took a number of years and was the result of continuing interplay between experiment and theory. By the time of the XVth International Conference on High Energy Physics held in Kiev in 1970 there was an acceptance in some parts of the high energy community of the view that the proton is composed of point-like constituents. At that time we were reasonably convinced that we were seeing constituent structure in our experimental results, and afterwards our group directed its efforts to trying to identify these constituents and making comparisons with the last remaining competing models.

The electron scattering results which played a crucial role in identifying the constituents of protons and neutrons or which ruled out competing models were the following:

(1) Measurement of R

At the Fourth International Symposium on Electron and Photon Interactions at High Energies held in Liverpool in 1969, MIT-SLAC results were presented which showed that R was small and was consistent with being independent of q^2. The subsequent measurements,[36,37] which decreased the errors, were consistent with this behavior.

The experimental result that R was small for the proton and neutron at large values of q^2 and ν required that the constituents responsible for the scattering have spin 1/2, as was pointed out by Callan and Gross.[43] These results ruled out pions as constituents but were consistent with the constituents being quarks or bare protons.

(2) The σ_n/σ_p Ratio

As was discussed in a previous section σ_n/σ_p decreased from 1 at about x = 0 to 0.3 in the neighborhood of x = 0.85. The ratio σ_n/σ_p is equivalent to W_2^n/W_2^p for $R_p = R_n$, and in the quark model a lower bound of 0.25 is imposed on W_2^n/W_2^p. While the experimental values approached and were consistent with this lower bound, Regge and resonance models had difficulty at large x, as they predicted values for the ratio of about 0.6 and 0.7, respectively, near x = I, and pure diffractive models predicted 1.0. The relativistic parton model in which the partons were associated with bare nucleons and mesons predicted a result for W_2^n/W_2^p which fell to zero at x = 1 and was about 0.1 at x = 0.85, clearly in disagreement with our results.

A quark model in which up and down quarks have identical momentum distributions would give a value of W_2^n/W_2^p = 2/3. Thus, the small value observed experimentally requires a difference in these distributions and quark-quark correlations at low x. To get a ratio of 0.25, the lower limit of the quark model, only a down quark from the neutron and an up quark from the proton can contribute to the scattering at the value of x at which the limit occurs.

(3) Sum Rules

As previously discussed, several sum rule predictions suggested point-like structure in the nucleon. The experimental evaluations of the sum rule related to the mean square charge of the constituents were consistent with the fractional charge assignments of the quark model provided that half the nucleon's momentum is carried by gluons.

EARLY NEUTRINO RESULTS

Neutrino deep inelastic scattering produced complementary information that provided stringent tests of the above interpretation. Since charged-current neutrino interactions with quarks were expected to be independent of quark charges but were hypothesized to depend on the quark momentum distributions in a manner similar to electrons, the ratio of the electron and neutrino deep inelastic scattering was predicted to depend on the quark charges, with the momentum distributions cancelling out.

That is

$$\frac{\frac{1}{2}\int\left[F_2^{ep}(x)+F_2^{en}(x)\right]dx}{\frac{1}{2}\int\left[F_2^{\nu p}(x)+F_2^{\nu n}(x)\right]dx}=\frac{Q_u^2+Q_d^2}{2}$$

where $1/2\ (F_2^{\nu p}(x)+F_2^{\nu n}(x)$ is the F_2 structure function obtained from neutrino-nucleon scattering from a target having an equal number of neutrons and protons. The integral of this neutrino structure function over x is equal to the total fraction of the nucleon's momentum carried by the constituents of the nucleon that interact with the neutrino. This directly measures the fractional momentum carried by the quarks and antiquarks because gluons are not expected to interact with neutrinos.

The first neutrino and anti-neutrino total cross-sections were presented in 1972 at the XVI International Conference on High Energy Physics held at Fermilab and the University of Chicago. The measurements were made at the CERN 24 GeV Synchrotron with the use of the large heavy-liquid bubble chamber "Gargamelle." At this meeting Perkins,[44] who reported these results, stated that, ". . . the preliminary data on the cross-sections provide an astonishing verification for the Gell-Mann/Zweig quark model of hadrons."

These total cross section results, presented in Fig. 9, demonstrate a linear dependence on neutrino energy for both neutrinos and anti-neutrinos that is a consequence of Bjorken scaling of the structure functions in the deep inelastic region. By combining the neutrino and anti-neutrino cross-sections

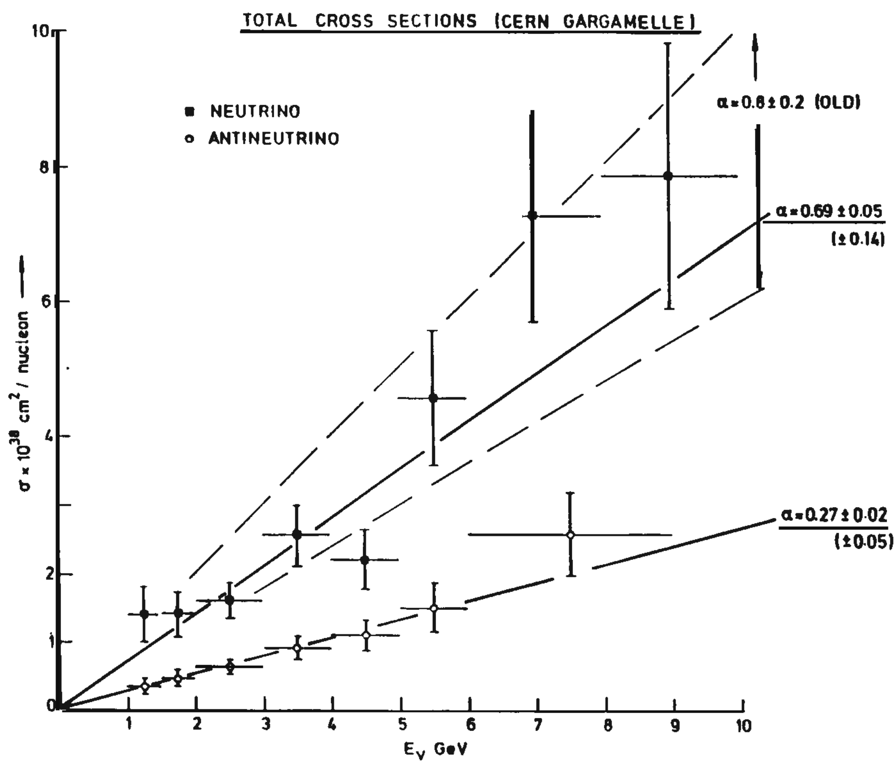

Fig. 9: Early Gargamelle measurements of neutrino nucleon and anti-neutrino nucleon cross sections as a function of energy. These results were presented at the XVI International Conference on High Energy Physics, NAL-Chicago, 1972, Ref. [44].

the Gargamelle group was able to show that

$$\frac{1}{2}\int\left(F_2^{\nu p}(x) + F_2^{\nu n}(x)\right)\,dx = \int x\left[u_p(x) + \bar{u}_p(x) + d_p(x) + \bar{d}_p(x)\right]dx = 0.49 \pm 0.07$$

which confirmed the interpretation of the electron scattering results that suggested that the quarks and antiquarks carry only about half of the nucleon's momentum. When this result was compared with

$$\frac{1}{2}\int\left[F_2^{ep}(x) + F_2^{en}(x)\right]dx$$

they found that the ratio of neutrino and electron integrals was 3.4 ± 0.7 as compared to the value predicted for the quark model, 18/5 = 3.6. This was a striking success for the quark model.

Within the next few years additional neutrino results solidified these conclusions. The results presented[45] at the XVII International Conference on High Energy Physics held in London in 1974 demonstrated that the ratio 18/5 was valid both as a function of x and neutrino energy. Figure 10, taken

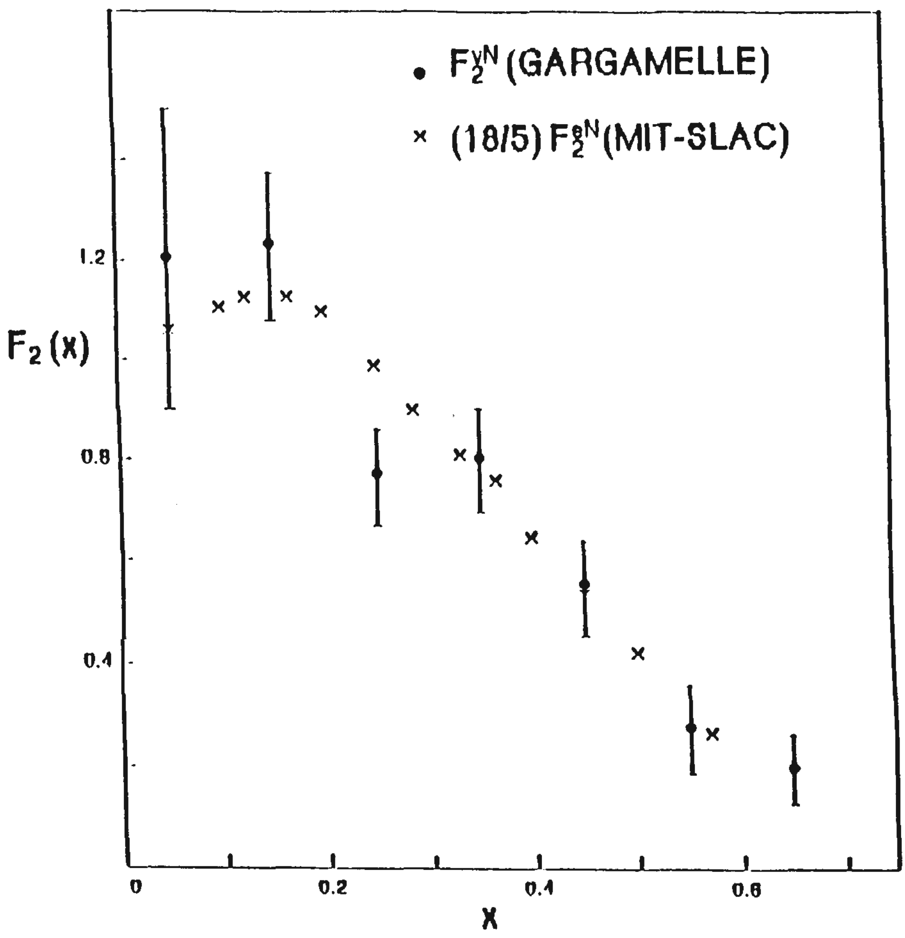

Fig. 10: Early Gargamelle measurements of $F_2^{\nu N}$ compared with $(18/5)F_2^{eN}$ calculated from the MIT-SLAC results.

from Gargamelle data, shows a comparison of $F^{\nu N}(x)$ and 18/5 F_2^{eN}, where $F_2^{\nu N}$ and F_2^{eN} each represents an average of proton and neutron structure functions, and Fig. 11 shows the ratio of the integrals of the two structure

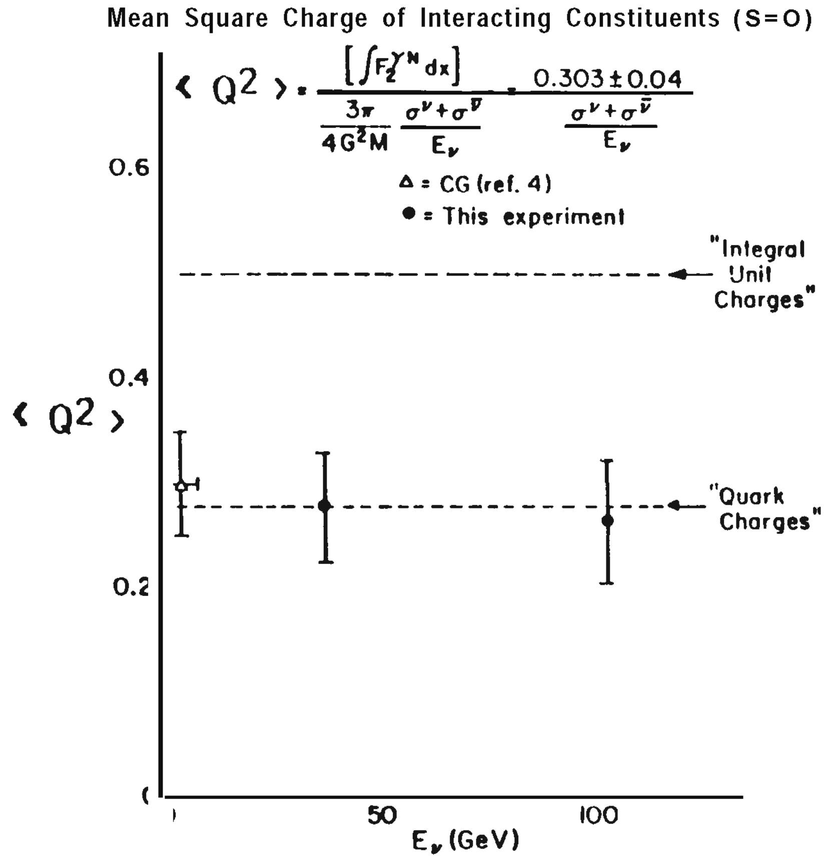

Fig. 11: Comparison of the ratio of integrated electron-nucleon and neutrino-nucleon structure functions to the value 5/ 18 expected from quark charges. The open triangle data point is from Gargamelle and the tilled-in circles are from the CIT-NAL Group. From Ref. [45]. The quantity Q²) is the mean square charge of the quarks in a target consisting of an equal number of protons and neutrons.

functions as a function of neutrino energy calculated from Gargamelle and CIT-NAL data. In addition, the Gargamelle group evaluated the Gross-Llewellyn Smith sum rule[46] for the F^3 structure function, which uniquely occurs in the general expressions for the inelastic neutrino and antineutrino nucleon cross sections as a consequence of parity non-conservation in the weak interaction. This sum rule states that

$$\int F_3^{\nu N}(x)\, dx = (\text{number of quarks}) - (\text{number of antiquarks})$$

which equals 3 for a nucleon in the quark model. Obtaining values of $F_3^{\nu N}(x)$ from the differences of the neutrino and anti-neutrino cross sections, the

Gargamelle group found the sum to be 3.2 ± 0.6, another significant success for the quark model.

GENERAL ACCEPTANCE OF QUARKS AS CONSTITUENTS

After the London Conference in 1974, with its strong confirmation of the constituent quark model, a general change of view developed with regard to the structure of hadrons. The bootstrap approach and the concept of nuclear democracy were in decline, and by the end of the 1970's, the quark structure of hadrons became the dominant view for developing theory and planning experiments. A crucial element in this change was the general acceptance of QCD,[47],[48] which eliminated the last paradox, namely, why are there no free quarks? The infra-red slavery mechanism of QCD provided a reason to accept quarks as physical constituents without demanding the existence of free quarks. The asymptotic freedom property of QCD also readily provided an explanation of scaling, but logarithmic deviations from scaling were inescapable in this theory. These deviations were later confirmed in higher energy muon and neutrino scattering experiments at FNAL and CERN. There were a number of other important experimental results reported in 1974 and the latter half of the decade which provided further strong confirmations of the quark model. Among these were the discovery of Charmonium[49,50] and its excited states,[51] investigations of the total cross section for $e^+e^- \rightarrow$ hadrons,[52] and the discoveries of quark jets[53] and gluon jets.[54] The constituent quark model, with quark interactions described by QCD, became the accepted view of the structure of hadrons. This picture which is one of the foundations of the Standard Model has not been contradicted by any experimental evidence in the intervening years.

ACKNOWLEDGMENTS

There were many individuals who made essential contributions to this work. An extensive set of acknowledgments is given in Ref. [55].

REFERENCES

1. D. H. Coward et al., Phys. *Rev. Lett. 20, 292* (1968).
2. W. K. H. Panofsky, in *Proceedings of 14th International* Conference *on High Energy Physics* Vienna (1968) 23. The experimental report, presented by the author, is not published in the Conference Proceedings. It was, however, produced as a SLAC preprint.
3. E. D. Bloom *et* al. *Phys. Rev. Lett.* 23, 930 (1969); M. Breidenbach *et al. Phys. Rev. Lett. 23, 935* (1969).
4. The Mott cross-section $\sigma_{\text{Mott}} = \dfrac{e^4}{4E^2}\dfrac{\cos^2\theta/2}{\sin^4\theta/2}$
5. R. W. McAllister and R. Hofstadter, *Phys. Rev.* 102, 851 (1956).
6. J. D. Bjorken, *Phys. Rev.* 179, 1547 (1969); In a private communication, Bjorken told the MIT-SLAC group about scaling in 1968.
7. S. D. Drell and J. D. Walecka, *Ann. Phys. (NY) 28,* 18 (1964).

8. M. Gell-Mann, Phys. Lett. 8, 214 (1964).
9. G. Zweig, CERN preprint 8182/TH 401 (1964); CERN preprint 8419/TH 412.
10. M. Gell-Mann, Caltech Synchrotron Laboratory Report CTSL-20 (1961); Y. Neeman, Nucl. Phys. 26, 222 (1961).
11. R. E. Taylor, Deep Inelastic Scattering: The Early Years. Les Prix *Nobel 1990.*
12. H. W. Kendall, Deep Inelastic Scattering: Experiments on the Proton and the Observation of Scaling. *Les Prix Nobel 1990.*
13. H. D. Abarbanel, M. L. Goldberger and S. B. Treiman, *Phys. Rev. Lett. 22, 500* (1969).
14. H. Harari, *Phys. Rev. Lett. 22,* 1078 (1969); *Phys. Rev. Lett. 24, 286* (1970).
15. T. Akiba, *Lett. Nuovo Cimento 4,* 1281 (1970).
16. H. Pagels, *Phys. Rev.* D3, 1217 (1971).
17. J. W. Moffat and V. G. Snell, *Phys. Rev.* D30, 2848 (1971).
18. P. V. Landshoff and J. C. Polkinghorne, DAMPT 70/36 (1970).
19. G. Domokos, S. Kovesi-Domokos and E. Shonberg, *Phys. Rev.* D3, 1184 (1971); *Phys. Rev.* D3, 1191 (1971).
20. J. J. Sakurai, *Phys. Rev. Lett.* **31B, 22 (1970)**; J. Chou and J. J. Sakurai, *Phys. Lett.* **31B, 22 (1970).**
21. For a review of the Vector Dominance and Generalized Vector Dominance Models, see T. H. Bauer, R. E. Spital, D. R. Yennie and F. M. Pipkin, *Rev. Mod. Phys. 50,* 261 (1978).
22. J. D. Bjorken, *Proceedings of the International School of Physics "Enrico Fermi", Course XLI: Selected Topics in Particle Physics,* J. Steinberger, ed. (Academic Press, New York, 1968).
23. M. Cell-Mann, *Phys. Rev.* 125, 1062 (1962); For a review of current algebra see: J. D. Bjorken and M. Nauenberg, *Ann. Rev. Nucl. Sci.* **18, 229** (1968).
24. S. L. Adler, *Phys. Rev.* **143, 1144** (1966).
25. J. D. Bjorken, *Phys. Rev. Lett.* **16, 408** (1966).
26. J. D. Bjorken, *Phys. Rev.* **163, 1767 (1967).**
27. R. P. Feynman, *Phys. Rev. Lett. 23,* 1415 (1969); *Proceedings of the III International Conference on High Energy Collisions,* organized by C. N. Yang *et al.* (Gordon and Breach, New York, 1969).
28. S. Drell, D. J. Levy and T. M. Yan, *Phys. Rev.* **187, 2159 (1969)**; *Phys. Rev.* **Dl,** 1035, 1617 (1970).
29. N. Cabbibo, G. Parisi, M. Testa and A. Verganelakis, *Lett. Nuovo Cimento 4, 569 (1970).*
30. T. D. Lee and S. D. Drell, *Phys. Rev.* **D5,** 1738 (1972).
31. J. D. Bjorken and E. A. Paschos, *Phys. Rev.* **185, 1975 (1969).**
32. J. Kuti and V. F. Weisskopf, *Phys. Rev.* **D4, 3418** (1971).
33. P. V. Landshoff and J. C. Polkinghorne, Nucl. *Phys.* B28, 240 (1971).
34. G. Miller *et al., Phys. Rev.* D5, 528 (1972).
35. J. S. Poucher *et al., Phys. Rev. Lett. 32,* 118 (1974).
36. A. Bodek et *al., Phys. Rev. Lett. 30,* 1087 (1973); *Phys. Lett.* **51B, 417 (1974)**; *Phys. Rev.* D20, 1471 (1979).
37. E. M. Riordan *et al., Phys. Rev. Lett. 33,* 561 (1974); *Phys. Lett.* 52B, 249 (1974).
38. W. B. Atwood *et al., Phys. Lett.* **64B, 479** (1976).
39. W. B. Atwood and C. B. West, *Phys. Rev.* **D7, 773 (1973).**
40. A Bodek, *Phys. Rev.* D8, 2331 (1973).
4 1. C. G. Callan and D. J. Cross, *Phys. Rev. Lett.* **21, 311 (I 968).**
42. K. Gottfried, *Phys. Rev. Lett.* **18, 1174** (1967).
43. C. G. Callan and D. J. Cross, *Phys. Rev. Lett. 22, 156* (1969).
44. D. H. Perkins, in *Proceedings of the XVI International Conference on High Energy Physics,* Chicago and NAL, Vol. 4, 189 (1972).
45. Proceedings of the XVII International Conference on High Energy Physics, London, (1974). M. Haguenauer, p. IV-95; F. Sciulli, p.IV-105; D. C. Cundy, p. IV-131.

DEEP INELASTIC SCATTERING

ACKNOWLEDGEMENTS

JEROME I. FRIEDMAN

HENRY W. KENDALL

RICHARD E. TAYLOR

The physics experiments (Reference 1) cited in 1990 by the Royal Swedish Academy of Sciences were a study of the deep inelastic scattering of electrons from the nucleon. The program, carried out by personnel from MIT and SLAC, was a group effort and we are grateful to our collaborators, all of whom played essential roles in the program. D. Coward and H. DeStaebler were with the experiments from the beginning and made indispensable contributions throughout their course. Other collaborators, whose efforts made the program possible, were: W. B. Atwood, E. Bloom , A. Bodek, M. Breidenbach, G. Buschhorn, R. Cottrell, R. Ditzler, J. Drees, J. Elias, G. Hartmann, C. Jordan, M. Mestayer, G. Miller, L. Mo, H. Piel, J. Poucher, C. Prescott, M. Riordan, L. Rochester, D. Sherden, M. Sogard, S. Stein, D. Trines and R. Verdier. Valuable help with computing was provided by D. Dubin, R. Early, A. Gromme, and E. Miller.

The inelastic experiments were part of a larger program of electron scattering carried out at the linear accelerator. Many of our colleagues in the other experiments made contributions of direct relevance to the development of the inelastic experiments. B. Barish, K. Brown, P. Kirk, J. Litt, S. Loken, J. Mar, A. Minten, C. Peck, and J. Pine made contributions at the outset of the program, while C. Sinclair provided assistance in the later experiments. We are grateful for help from A. Boyarski, F. Bulos, R. Diebold, E. Garwin, R. S. Larsen, R. Miller, B. Richter, and D. Ritson.

This work could not have been done without the SLAC laboratory director, W. K. H. Panofsky, who established and led an outstanding laboratory that provided us with a superb accelerator and the opportunity to do these experiments. R. Neal and the SLAC Technical Division played a critical role in the building, implementation, and operation of the accelerator. We owe him and his division a deep debt of gratitude. We also thank J. Ballam and the SLAC Research Division, along with F. Pindar and Administrative Services for many helpful contributions to the program. J. I. Friedman and H. W. Kendall wish also to acknowledge aid and support provided by their many MIT colleagues, including W. Buechner (now deceased), P. Demos, M. Deutsch, F. Eppling, H. Feshbach, A. Hill, and V. F. Weisskopf.

We benefitted greatly from the willingness of J. D. Bjorken to help us understand both his own crucial works on inelastic scattering and those of other theorists. Our understanding of a number of physics issues associated with this program was also advanced by discussions with S. Drell, M. Gell-Mann, F. Gilman, K. Gottfried, R. Jaffe, K. Johnson, J. Kuti, F. Low, P. Tsai, V. Weisskopf, and G. West.

The spectrometer hardware was designed and constructed by a large team of engineers and technicians under the direction of E. Taylor. Among others, the group included M. Berndt, L. Brown, M. Brown, J. Cook, W. Davies-White, S. Dyer, R. Eisele, A. Gallagher, N. Heinen, E.K.Johnson, T. Lawrence, J. Mark, R. (Lou) Paul, and R. Pederson.

We gratefully acknowledge the suppport of this work provided by the US Department of Energy and its predecessor agencies.

REFERENCES

1. R. E. Taylor, Deep Inelastic Scattering: The Early Years. H. W. Kendall, Deep Inelastic Scattering: Experiments on the Proton and the Observation of Scaling, and J. I. Friedman, Deep Inelastic Scattering: Comparisons with the Quark Model. *Les Prix Nobel 1990.*