REVIEW OF EXPERIMENTAL MEASUREMENTS OF WEAK NEUTRAL-CURRENT INTERACTIONS

Klaus Winter
CERN, Geneva, Switzerland

Summary

Progress in experimental measurements and in analysis of the weak neutral-current interaction between leptons and between leptons and hadrons is reviewed. New results on neutrino-electron scattering, and on parity violation in atomic transitions and in electron-deuteron scattering, are discussed and combined. The ambiguity of V versus A coupling of the electron current is resolved. Progress in determining the quark current coupling is achieved by new data on its isospin dependence. The question of generation universality is discussed in the context of the GIM mechanism and confronted with experimental data. The nucleon structure has been probed in deep inelastic neutral-current scattering.

1. Introduction

New experimental measurements of neutral-current interactions, available at the time of this conference, allow study of the neutral current coupling of leptons and quarks in a less model-dependent way than could be done at the time of the 1978 Tokyo Conference[1]. The coupling constants can now be uniquely determined by the data. This progress is achieved in particular for the neutral electron current coupling owing to a new measurement of the y dependence of parity violation in the scattering of polarized electrons on deuterium. New measurements of neutrino and antineutrino scattering on electrons have been performed which will ultimately give the most reliable determination of the electro-weak mixing angle of the Weinberg-Salam model. They will allow a sensitive search for small deviations from that model, owing to the effects of additional Z^0 bosons, of triplet representations for Higgs bosons, or of mixing of the right-handed fermions into doublets.

Progress in determining the neutral quark current coupling is achieved in several ways by new data on its isospin dependence, for instance by a comparison of parity violation in atomic transitions and in polarized electron scattering, and by more precise measurements of the ratio of neutral-current and charged-current neutrino cross-sections on isoscalar targets and on hydrogen.

First results are now available on details of deep inelastic scattering in weak neutral-current interactions, and in particular on a comparison of the nucleon structure as seen by the neutral and by the charged current.

Within the context of the Weinberg-Salam model, incorporating the Glashow-Iliopoulos-Maiani (GIM) mechanism, the question of universality of the neutral-current coupling for the different generations of fermions may be studied experimentally by searching for small deviations from flavour conservation of the neutral current. Presently available data give stringent limits on this universality. However, deviations may also occur outside the context of that model, and the question of generation universality therefore remains open for direct experimental study.

2. Neutrino Scattering on Electrons

The first experimental observation of a weak neutral-current phenomenon was on the scattering of $\bar{\nu}_\mu$ on electrons[2]. Further observations, in particular on semileptonic neutral-current neutrino interactions[3] and on the scattering of polarized electrons on deuterium[4], have by now lent strong support to a unified gauge theory of the weak and the electromagnetic interaction as proposed by Weinberg and Salam. The main goal of pursuing the study of neutrino scattering on electrons is to determine the coupling constants of the leptonic weak neutral current, thus avoiding the ambiguities inherent in the use of hadronic targets. Until now, however, the extremely low cross-section has drastically limited the number of observed events, as illustrated in Tables 1 and 2.

Table 1

Summary of $\nu_\mu e^-$ scattering results

Experiment	CC sample	$\nu_\mu e$ cand.	Background	σ/E (10^{-42} cm^2/GeV)
GGM PS		1	0.3 ± 0.1	< 3 (90% c.l.)
Aachen-Padova		11	3	1.1 ± 0.6
GGM SPS	64,000	9	0.5 ± 0.2	$2.4^{+1.2}_{-0.9}$
Col.-BNL FNAL 15′	83,700	8	0.5 ± 0.5	1.8 ± 0.8
CHARM Calorim.	56,000	11	4.5 ± 1.4	2.6 ± 1.6
$\sin^2\theta = 0.22^{+0.08}_{-0.05}$			Mean	1.6 ± 0.4
L.Mo, VPI-Maryland-NSF-Oxford-Peking		46	12	1.4 ± 0.31 (Prelim.)

Table 2

Summary of $\bar{\nu}_\mu e^-$ scattering results

Experiment	CC sample	$\bar{\nu}_\mu e^-$ cand.	Background	σ/E (10^{-42} cm^2/GeV)
GGM PS		3	0.4 ± 0.1	$1.0^{+2.1}_{-0.9}$
Aachen-Padova		8	1.7	2.2 ± 1.0
GGM SPS	7400	0	< 0.2	< 2.7 (90% c.l.)
FMMS FNAL 15′	8400	0	0.2 ± 0.2	< 2.1 (90% c.l.)
BEBC TST, SPS	7500	1	0.5 ± 0.15	< 3.4 (90% c.l.)
All high energy	23300	1	< 1	
expected		6		
$\sin^2\theta = 0.23^{+0.09}_{-0.23}$			Mean	1.3 ± 0.6
CHARM	160,000	41 ± 10		∿ 1.8 ± 0.4 (Prelim.)

The axial-vector coupling constant g_A^e and the vector coupling constant g_V^e can be determined by a phenomenological, model-independent analysis. Assuming that leptons are point-like and that the outgoing neutrino is identical to the incoming neutrino, we obtain for the differential cross-section,

$$\frac{d\sigma}{dy}(\nu_\mu e) = \frac{\sigma_0}{2} E_\nu \left[(g_V^e + g_A^e)^2 + (g_V^e - g_A^e)^2 (1-y)^2 + \right. \qquad \text{(1a)}$$
$$\left. + \frac{m_e}{E_\nu} (g_V^{e^2} - g_A^{e^2}) \right]$$

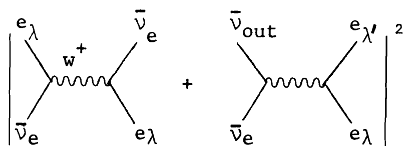
and

$$\frac{d\sigma}{dy}(\bar{\nu}_\mu e) = \frac{\sigma_0}{2} E_\nu \left[(g_V^e - g_A^e)^2 + (g_V^e + g_A^e)^2 (1-y)^2 - \right. \qquad \text{(1b)}$$
$$\left. - \frac{m_e}{E_\nu} (g_V^{e^2} - g_A^{e^2}) \right] ,$$

where $\sigma_0 = G^2 m_e / \pi = 8.6 \times 10^{-42}$ cm^2.

The cross-section of the scattering of antielectron-neutrinos on electrons has been measured by Reines et al.[5]; it gives important constraints on g_V^e and g_A^e, as well as a sensitive test of their generation universality, $g_V^e = g_V^\mu$. The interference term of neutral- and charged-current contributions to this reaction, averaged over the unobserved electron helicities λ and λ', is given by

$$\sigma = \frac{1}{2} \sum_{\lambda,\lambda'} \left| \text{(diagram)} \right|^2 , \qquad (2)$$



where the interference term is given, in the context of the Weinberg-Salam model, by

$$\left[T^3(e_L) + \sin^2 \theta \right] \cong -\frac{1}{2} + 0.23 , \qquad (3)$$

and should therefore be negative.

Observation of this interference term would therefore prove that the outgoing and incoming neutrinos are identical; that the neutral current couples to left-handed electrons, solving the ambiguity under exchange of g_V^e and g_A^e in Eq. (1); and that the neutral current is helicity-conserving in the same way as the charged current[6], and hence that its space-time structure is given by V and A contributions only. The experimental situation has recently been analysed by Kayser et al.[7]. The reactor experiment[5] provides some evidence for destructive interference; however, the precision is not sufficient to prove the existence of interference.

At this Conference new results on $\nu(\bar{\nu})_\mu e$ scattering have been presented, obtained using fine-grain electronic calorimeters. The apparatus used at Fermilab by a VPI-Maryland-NSF-Oxford-Peking Collaboration[8], led by L. Mo, is shown in Fig. 1. It consists of 49 modules with a fiducial target weight of 8.26 tons, each composed of an aluminium plate, one radiation length thick and 1×1 m^2 in cross-sectional area, a multiwire proportional chamber (MWPC) with anode and cathode read-out, and one layer of plastic scintillators.

The edges of showers have been determined in two orthogonal projections using the MWPCs; their midpoint is assumed to be the centroid of the shower in that chamber. A straight-line fit to the centroids of the first five chambers of a shower gives an estimate of its direction. The results of tests in electron beams indicated an angular resolution of ±5 mrad at 4 GeV. Background due to semileptonic neutral-current interactions

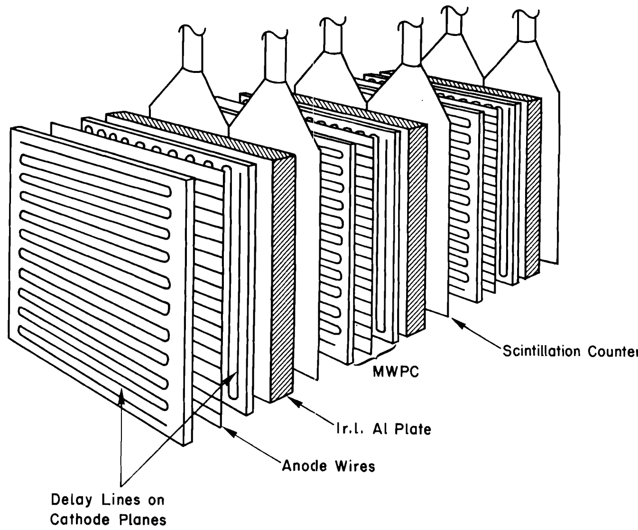


Fig. 1 Schematic view of the apparatus used by the VIP-Maryland-NSF-Oxford-Peking Collaboration to detect $\nu_\mu e$ scattering

is reduced by the requirement of a good straight-line fit, by rejecting events with visible backscattering, and by a dE/dx cut, requiring a fraction of the total energy > 12.5% to be deposited in the first three radiation lengths and > 25% in the first four.

Analysis of 249,000 triggers recorded for 0.95×10^{19} protons led to a final sample of 313 candidates. Figure 2 shows a distribution of events in $E\theta^2$.

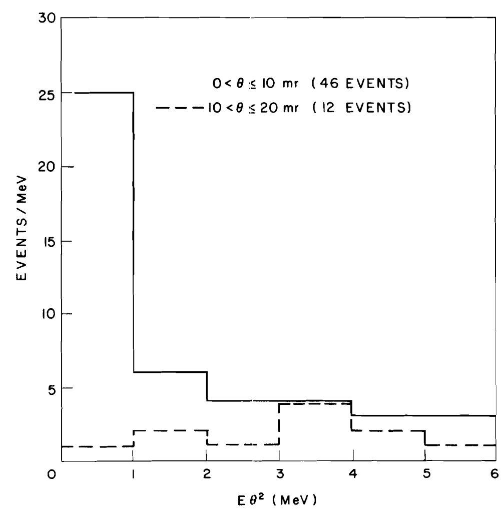


Fig. 2 Evidence for $\nu_\mu e$ scattering in the experiment of L. Mo et al. (Ref. 8)

This quantity is given by the kinematics of the reaction,

$$E\theta^2 = 2m_e(1 - y) , \qquad (4)$$

and has been used to select events with a small angle of the recoiling electron, characteristic of the electron mass. Events with angles smaller than 10 mrad are candidates for $\nu_\mu e$ scattering; events with larger angles, between 10 and 20 mrad, are assumed to represent the background, mainly due to the reaction $\nu_e n \to e^- p$, induced by the ν_e and $\bar{\nu}_e$ component of the neutrino beam. Subtracting these events gives 46 - 12 = 34 events for the process $\nu_\mu e^- \to \nu_\mu e^-$.

Evaluating the cross-section, corrections for the electron detection efficiency (54%), for the electron energy cut of 4 GeV, and for the trigger efficiency for the monitor reactions ($\nu_\mu N \to \mu^- X$ and $\nu_\mu N \to \nu_\mu X$) have been applied. Only statistical errors are quoted, giving a preliminary value of

$$\sigma/E = (1.40 \pm 0.31) \times 10^{-42}\ \mathrm{cm}^2/\mathrm{GeV}\ .$$

A partial view of the apparatus[9] used at the CERN Super Proton Synchrotron (SPS) by the CERN-Hamburg-Amsterdam-Rome-Moscow (CHARM) Collaboration is shown in Fig. 3. It consists of 78 subunits, each comprising a

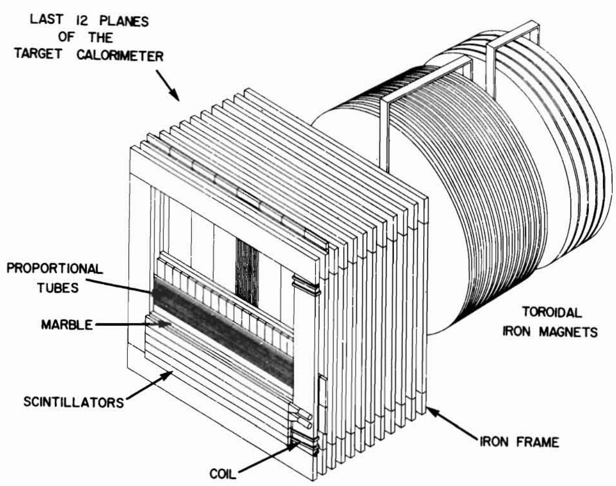


Fig. 3 Schematic view of the apparatus used by the CHARM Collaboration to detect $\nu_\mu e$ and $\bar{\nu}_\mu e$ scattering

marble plate of $3 \times 3\ \mathrm{m}^2$ surface area and 8 cm thickness, followed by a plane of 128 proportional drift tubes (each tube having dimensions of $3 \times 3 \times 400\ \mathrm{cm}^3$) and a plane of 20 plastic scintillators of dimensions $15 \times 300\ \mathrm{cm}^2$, 3 cm thick, oriented at 90° with respect to the tubes. A subunit is one radiation length thick. The 78 subunits of the target calorimeter are followed by four toroidal iron magnets to detect muons produced in charged-current events. The fiducial target weight is 99 tons. A typical $\nu_\mu e^-$ event is displayed in Fig. 4, showing the pulse height measured by the scintillation counters in units of equivalent minimum-ionizing particles. To select neutrino-electron scattering events it is required that they have showers occurring at a small angle with respect to the neutrino beam, and that the showers are recognized as being of an electromagnetic nature. The electron direction is determined by measuring the spatial distribution of the energy deposition of the electromagnetic shower in the calorimeter, with an angular resolution of 12.5 mrad at 15 GeV. The narrow angu-

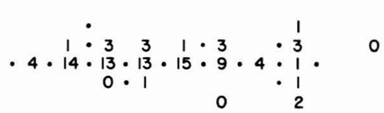


Fig. 4 Candidate of $\nu_\mu e$ scattering observed by the CHARM Collaboration. The numbers give the energy loss measured by scintillators in equivalent numbers of minimum ionizing particles. Dots represent hits in groups of five proportional tubes.

lar distribution of recoiling electrons is folded with this angular resolution, and the measured angles are expected to lie within an energy-dependent solid angle $\Delta\Omega = (\Delta\theta)^2$, centred around the neutrino direction. If the measured angle of a shower is expressed in units of this angular resolution, the distribution of the events as a function of $\theta/\Delta\theta$ becomes energy invariant.

Electromagnetic and hadronic showers are separated by the characteristic difference of their transverse energy profile. The results of measurements of the width of showers induced by electrons and by pions are shown in Fig. 5. Selecting events as indicated in the figure

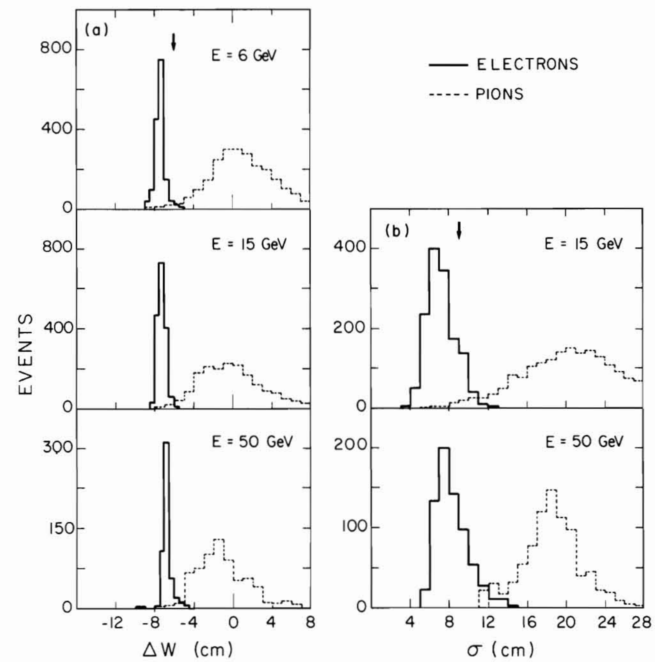


Fig. 5 Lateral shower width of electron- and pion-induced events as measured (a) by scintillators; (b) by proportional tubes (CHARM Collaboration, Ref. 9).

reduces the background due to semileptonic neutrino interactions by a factor of ∿ 100. Results obtained with a partially equipped detector (∿ 1/3) in the horn-focused wide-band neutrino beam of the CERN 400 GeV SPS, for a total flux of 3.1×10^{17} protons, are shown in Fig. 6.

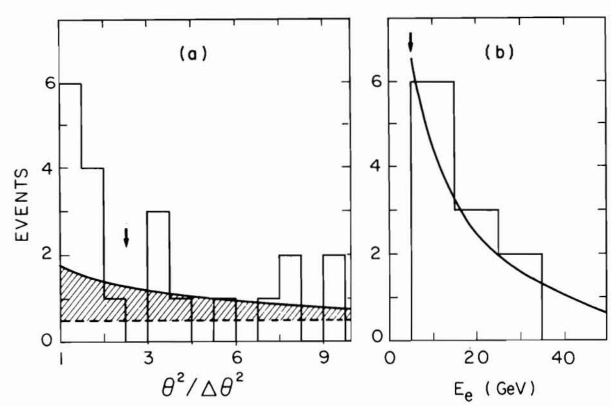


Fig. 6 Results of the CHARM Collaboration (Ref. 9) on $\nu_\mu e$ scattering. a) Angular distribution, the dashed line shows the background due to $\nu_\mu N \to \nu_\mu X$, the shaded area is the background due to $\bar{\nu}_e N \to e^- p$. b) Energy distribution of events with $\theta^2/\Delta\theta^2 \leq 2.25$; the line is the expectation for $\sin^2\theta = 0.23$.

After subtraction of the background, 6.5 ± 2.6 events of the reaction $\nu_\mu e \to \nu_\mu e$ are observed. By normalizing to the sum of observed charged- and neutral-current semileptonic events, a cross-section of

$$\frac{\sigma}{E} = \left\{ 2.6 \begin{matrix} \pm 1.4 \text{ (statistical error)} \\ \pm 0.8 \text{ (systematic error)} \end{matrix} \right\} \times 10^{-42} \text{ cm}^2/\text{GeV}$$

is found. Both results are consistent with earlier experiments and in good agreement with the Weinberg-Salam model.

The summary of results on $\bar{\nu}_\mu e$ scattering shows a certain anomaly in the absence of events at high energy. In total, 23,000 semileptonic charged-current events have been reported and only one candidate for the reaction $\bar{\nu}_\mu e$, while five to six events are expected on the basis of the model assuming $\sin^2\theta = 0.25$.

The CHARM Collaboration has reported at this Conference a preliminary result on $\bar{\nu}_\mu e$ scattering which shows that there is no anomaly. Data have been recorded in the horn-focused wide-band antineutrino beam at the CERN SPS. A total flux of 10^{18} protons of 400 GeV was incident on the target of the neutrino beam. Preliminary results, based on a sample of 160,000 semileptonic charged-current events, are shown in Fig. 7; the distribution in $(\theta/\Delta\theta)^2$ is peaked at low values, as expected for the reaction $\bar{\nu}_\mu e \to \bar{\nu}_\mu e$. After subtraction of

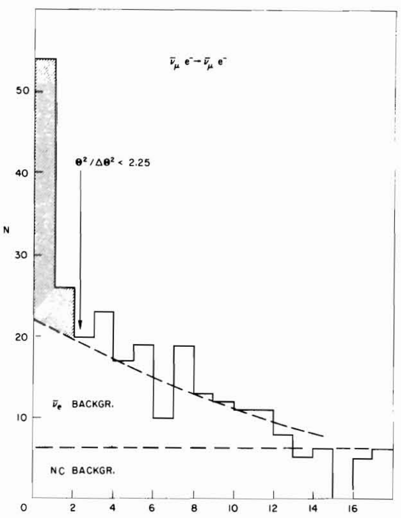


Fig. 7 Preliminary result of the CHARM Collaboration on $\bar{\nu}_\mu e$ scattering, showing 41 ± 10 events above the background.

the background, 41 ± 10 events of this reaction are found, and a preliminary value of the cross-section of

$$\sigma/E \sim (1.8 \pm 0.4) \times 10^{-42} \text{ cm}^2/\text{GeV} ;$$

only the statistical error is given at this stage of the analysis; systematic uncertainties have not yet been evaluated.

The results contributed to this conference have been reported as being preliminary and have therefore not been included in the mean values quoted in Tables 1 and 2. Definitive results will be available soon and will then be statistically very significant; for example, the ratio of the cross-sections for $\bar{\nu}_\mu e$ and $\nu_\mu e$ scattering, based on 50 events in each channel, will determine the value of the electro-weak mixing angle, $\sin^2\theta$ with an error of ~ 0.025, free of the ambiguities encountered in neutral-current interactions with hadronic targets.

An accurate determination of the cross-section has to include radiative corrections[10]. The renormalizability of the Weinberg-Salam theory allows for calculation of the Born term and of higher-order corrections. Sehgal[11] has calculated corrections to the ν_e-ν_μ universality in neutral-current interactions, and finds for $q^2 \cong 0$:

$$(\sin^2\theta)_{\nu_\mu} - (\sin^2\theta)_{\nu_e} = \frac{\alpha}{6\pi} \ln \frac{m_\mu^2}{m_e^2} = 0.004 . \quad (5)$$

The most significant conclusion to be drawn from the new results on neutrino-electron scattering is that at high energy a fully electronic fine-grain calorimeter can detect these rare processes and separate them reliably from the dominant semileptonic reactions.

3. Scattering of Polarized Electrons on Deuterium

Interference between weak and electromagnetic interaction of electrons has been demonstrated in the scattering of polarized electrons and in atomic transitions (see Section 4). The asymmetry of the scattering of left-handed (e^-_L) and right-handed (e^-_R) electrons has recently been measured at SLAC as a function of the inelasticity y[12]. The y dependence of the asymmetry can be parametrized in the form[13]

$$\frac{A}{Q^2} = \frac{3G_F}{5\sqrt{2}\pi\alpha} \left[\left(C_{1u} - \frac{1}{2}C_{1d}\right) + \left(C_{2u} - \frac{1}{2}C_{2d}\right) \frac{1-(1-y)^2}{1+(1-y)^2} \right] , \quad (6)$$

$$= a_1 + a_2 \, f(y) .$$

It has been argued that corrections due to scaling violations, to deviations from $R = \sigma_L/\sigma_T = 0$, and to antiquarks are very small. A fit of all data gives

$$a_1 = (-9.7 \pm 2.6) \times 10^{-5}$$
$$a_2 = (\ 4.9 \pm 8.1) \times 10^{-5} . \quad (7)$$

The constant term measures contributions from axial-vector coupling of the electron and the y-dependent term contributions from the vector coupling of the electron. Assuming that the weak neutral current is mediated by a *single* Z^0 boson and the strength of the $\nu\bar{\nu}Z^0$ coupling is *unity* ("factorization")[14], the coefficients of Eq. (6) can be expressed in terms of electron and quark coupling constants,

$$C_{1u} - \frac{1}{2}C_{1d} = g_A^e(2g_V^u - g_V^d)$$
$$C_{2u} - \frac{1}{2}C_{2d} = g_V^e(2g_A^u - g_A^d) . \quad (8)$$

This relation can be satisfied if we choose the axial-vector dominant solution in νe scattering, $g_A \simeq -1/2$, in agreement with the Weinberg-Salam model. A single parameter fit of the SLAC data may then be justified; it gives

$$\sin^2\theta = 0.224 \pm 0.020 \ (\pm 0.010 \text{ QPM uncertainties}) . \quad (9)$$

The possibility of a right-handed electron forming a doublet with a heavy neutral lepton E^0, in a symmetrical way with the usual left-handed doublet, would lead to $C_{1u} - 1/2\, C_{1d} \cong 0$ and is therefore excluded in a model-independent way by this new result.

4. Parity Violation in Atomic Transitions

The controversy due to conflicting results on optical rotation in bismuth vapour has now been resolved by two new results, one from the Novosibirsk group[15], giving a more accurate result and also reasons why the experiments of the Seattle and the Oxford Groups may be unreliable, the other from a Berkeley group[16], based on a measurement of the asymmetry of the absorption cross-section of photons of positive and negative helicity in thallium vapour, giving a positive result, however of less accuracy. The results of these new experiments and of the old ones are summarized in Table 3. They may be

Table 3

Summary of results on parity violation in atomic transitions

Experiment	Atom	Line (nm)	Result (Exp./W-S)
BARKOV (Ref. 15)	Bi	648	1.07 ± 0.14
COMMINS (Ref. 16)	Tl	293	$2.3^{+3.1}_{-1.4}$
SEATTLE	Bi	876	0.2 - 0.3
OXFORD	Bi	648	0.2 - 0.5

related to the parametrization of the asymmetry of polarized electron scattering given in Eq. (8), by defining a weak charge which is measured by the weak-electromagnetic interference in atomic transitions,

$$Q_W = -4g_A^e \left[g_V^u(2Z+N) + g_V^d(Z+2N) \right] , \qquad (10)$$

under the same assumptions[14] of "factorization".

Comparing Eqs. (10) and (8) it is noted that they determine different linear combinations of the coupling constants, the heavy atom experiments are more sensitive to the isoscalar coupling of the quarks, and the SLAC experiment to their isovector coupling. Hence, a consistency check between them is possible only by using the neutrino-hadron data under the assumption of factorization. This is demonstrated in Fig. 8. We conclude

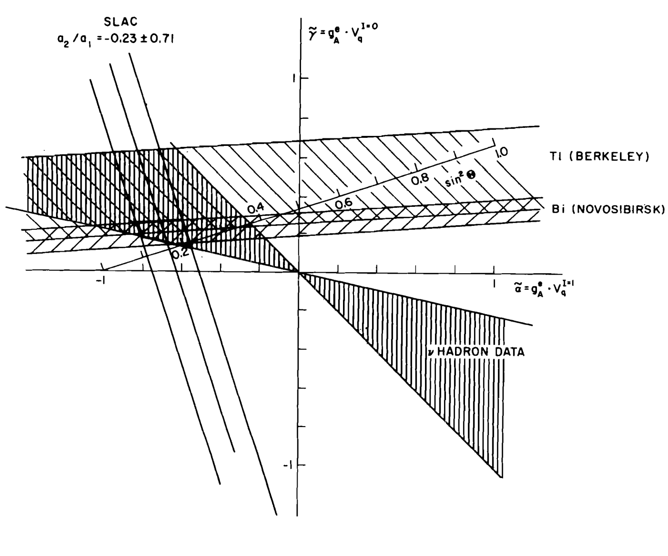


Fig. 8 Determination of the $g_A^e \cdot g_V^{quark}$ couplings from the experiments on parity violation in electron-deuteron scattering (Ref. 12) and in atomic transitions (Ref. 15). The factorization constraint from ν-hadron data is also shown (Ref. 28).

that the SLAC experiment, the Novosibirsk experiment, and the neutrino-hadron data agree, if we assume factorization, and that there is clear disagreement with the old atomic transition experiments. The dominance of isovector over isoscalar coupling of the quarks is also demonstrated by these experiments.

5. Coupling of the Weak Neutral Electron Current

The effective Lagrangian of neutrino-electron interactions and of electron-hadron interactions involves the weak neutral electron current,

$$J_\mu^e = \bar{e}\gamma_\mu(g_V^e + g_A^e\gamma_5)e \; . \qquad (11)$$

It is determined by two coupling constants. The study of neutrino-electron scattering at high energy leaves an ambiguity between g_V^e and g_A^e; for a comparison with the gauge models, it is essential to resolve it. This can now be achieved, for the first time, using the new SLAC data (described in Section 3) and the neutrino-hadron data (to be described in Section 8), assuming factorization[14]. The results shown in Fig. 9 clearly favour

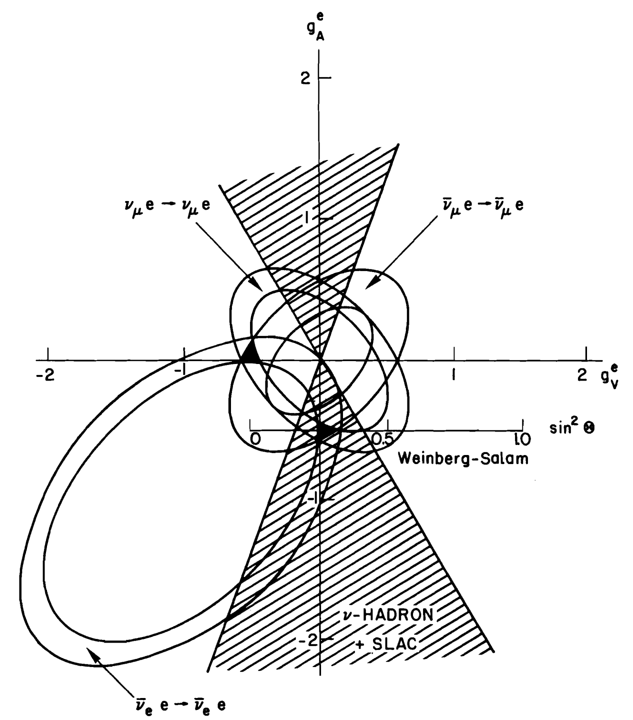


Fig. 9 Determination of the νe coupling constants. The factorization constraint from electron-deuteron and ν-hadron scattering solves the g_A-g_V ambiguity.

$g_A^e \simeq -1/2$, in agreement with the gauge models, with the values[16]

$$g_V^e = 0.043 \pm 0.066$$

$$g_A^e = -0.545 \pm 0.045 \qquad (12)$$

$$\rho = 1.010 \pm 0.098 \; .$$

Within the context of a generalized $SU(2)\otimes U(1)$ gauge model, the leptonic and hadronic weak neutral currents are described by five parameters, $\rho = m_W^2/m_Z^2 \cos^2\theta$, $\sin^2\theta$, $T_R^3(u)$, $T_R^3(d)$, and $T_R^3(e)$. A simultaneous fit of the data shown in Fig. 9 gives[16]

$$\rho = 1.010 \pm 0.057$$

$$\sin^2 \theta = 0.244 \pm 0.040 \tag{13}$$

$$T^3_R(e) = 0.044 \pm 0.058 \ .$$

The value of $T^3_R(e)$ is close to zero, as is expected in models without right-handed doublets. Using the relation $|T^3_R(e)| = 1/2 \sin^2 \alpha_e$, we obtain an upper limit[16] on mixing between right-handed singlets and doublets,

$$\sin^2 \alpha_e \leq 0.084 \ . \tag{14}$$

6. Inclusive Neutral-Current Neutrino Reactions on Isoscalar Targets

The effective Lagrangian of neutrino-hadron interaction contains the weak neutral current of quarks of charge +2/3 (u) and of charge -1/3 (d) (I shall assume generation universality):

$$J_\mu = \bar{u}\gamma_\mu(g^u_V+g^u_A\gamma_5)u + \bar{d}\gamma_\mu(g^d_V+g^d_A\gamma_5)d \ . \tag{15}$$

I shall use for the discussion the chiral coupling constants introduced by Sehgal, e.g.

$$u_L = g^u_V + g^u_A \ , \quad u_R = g^u_V - g^u_A \ . \tag{16}$$

Measurements of deep inelastic neutrino scattering from isoscalar targets determine the strength of the left-handed and right-handed couplings, $u^2_L + d^2_L$ and $u^2_R + d^2_R$, either by the ratio of cross-sections for neutral- and charged-current interactions,

$$R_\nu = \frac{\sigma(\nu N \to \nu X)}{\sigma(\nu N \to \mu^- X)}$$
$$R_{\bar{\nu}} = \frac{\sigma(\bar{\nu} N \to \bar{\nu} X)}{\sigma(\bar{\nu} N \to \mu^+ X)} \tag{17}$$

or by the differential cross-sections $(d\sigma/dy)(\nu N \to \nu X)$ and $(d\sigma/dy)(\bar{\nu}N \to \bar{\nu}X)$. The experimental results determine a ring-shaped region in a plot of u_L versus d_L or u_R versus d_R.

Before discussing these, I would like to make a remark concerning the space-time structure of the neutral quark current. Observation of maximal interference with the electromagnetic current, reported by the SLAC experiment[12], allows us to reach the conclusion that the weak neutral current is helicity conserving, as is the electromagnetic current, and hence that it can be composed of vector and axial-vector contributions only.

New, more precise results on cross-section ratios and differential cross-sections have been reported at this conference. First results on x distributions are available, allowing a comparison of the nucleon structure as probed by the neutral and by the charged current.

The experimental problems, encountered in separating neutrino interactions by the neutral and charged current, are of a different nature in the two experiments reporting new results at this conference. In the CHARM experiment[17], events are classified as neutral-current or charged-current interaction by computer decision, on an event-by-event basis. A charged-current event is defined as having a non-interacting track of 600 g/cm^2 minimum range in marble ($\sim$ 1.1 GeV/c muon momentum); all other events are classified as neutral-current events. The CHARM detector has a high efficiency for detecting low-energy showers (a cut $E_h > 2$ GeV has been applied in the analysis) and good energy resolution $[\Delta E_h/E_h = (1 + 43/\sqrt{E/\text{GeV}})\%]$.

The CDHS Collaboration[18] uses a statistical method of separating neutral-current and charged-current events, based on the total event length, and a cut on detected hadron energy, $E_h > 10$ GeV. This method is illustrated in Fig. 10, showing the observed event length distribution in the 200 GeV narrow-band antineutrino beam at the CERN SPS.

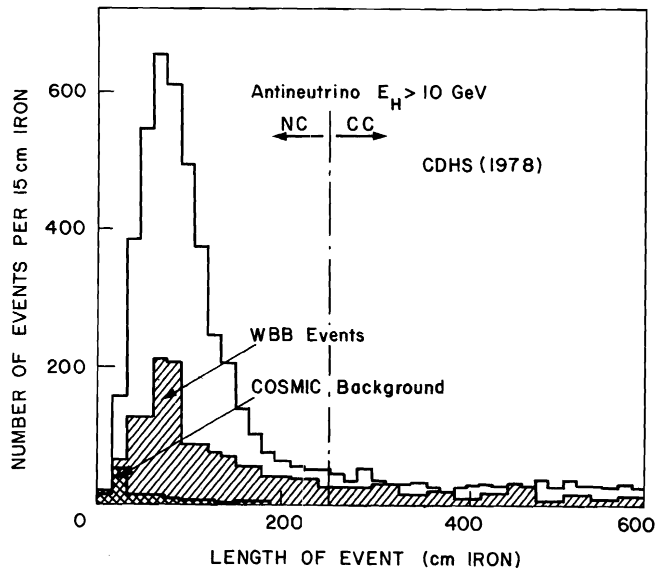


Fig. 10 Distribution of event length for antineutrinos measured (Ref. 18) in the CDHS calorimeter. The dominant background is shown.

Both sets of data have to be corrected for various effects mixing neutral-current and charged-current events, and for background due to decays before momentum analysis (wide-band beam background) and to the interaction of ν_e from K_{e3} decays. Owing to the different methods of event classification and event selection, the corrections are different for the two experiments, as shown in Table 4.

Table 4

Corrections for NC/CC event classification and background

		Neutrinos		Antineutrinos	
		CHARM	CDHS	CHARM	CDHS
Raw events		9200	21724	2700	4539
WBB backg.	(%)	-0.8	- 3.9	-4.4	-30.4
Hidden CC	(%)	-6.7	-17.8	-2.4	- 7.1
π/K decay	(%)	+1.6	< 0.5	+1.6	< 0.5
ν_e (K_{e3})	(%)	-7.0	-11.6	-2	- 5.7
Event length	(%)	-	+ 1.7	-	+ 1.6

The CHARM Collaboration has developed a statistical method based on the observed radial distance of the event vertex from the beam axis, for resolving the dichromatic energy ambiguity of the neutrino beam.

Figures 11 and 12 show the y distributions of neutral charged events with $E_h > 2$ GeV and, for comparison,

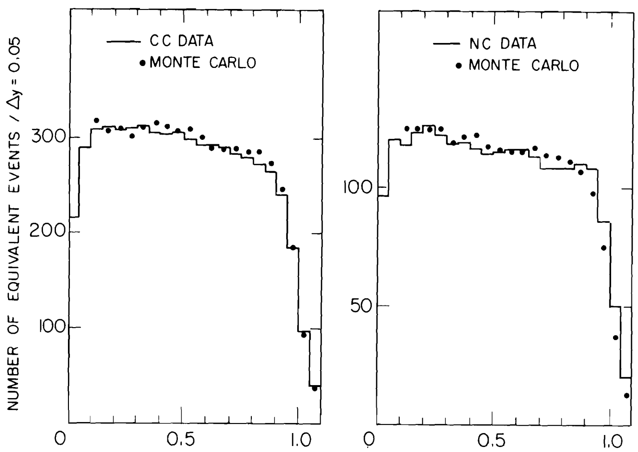


Fig. 11 Preliminary data of the CHARM Collaboration (Ref. 17) on y distribution of inclusive neutrino scattering

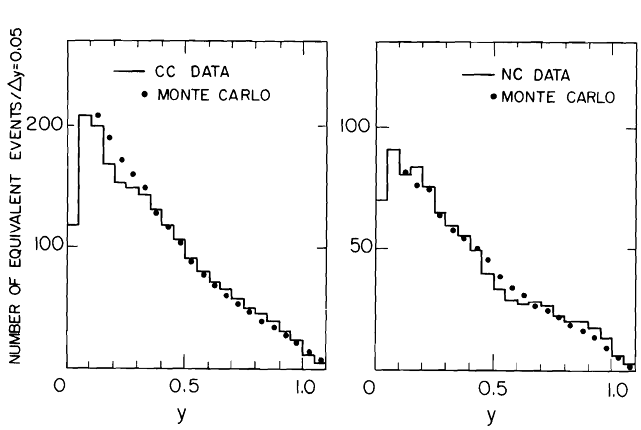


Fig. 12 As in Fig. 11, for antineutrino scattering

the result of a Monte Carlo simulation based on present knowledge of quark and antiquark distributions[19] of the nucleon and assuming the Weinberg-Salam model with an electro-weak mixing angle of $\sin^2\theta = 0.25$. The figures also show the distributions obtained by analysing charged-current events in the same way, using the hadron energy information only. The agreement of these preliminary data with the predictions is good.

Acceptance corrections, resolution effects, and other instrumental uncertainties are expected to cancel, to first order, by forming the ratios of the neutral current and charged current differential y distributions.

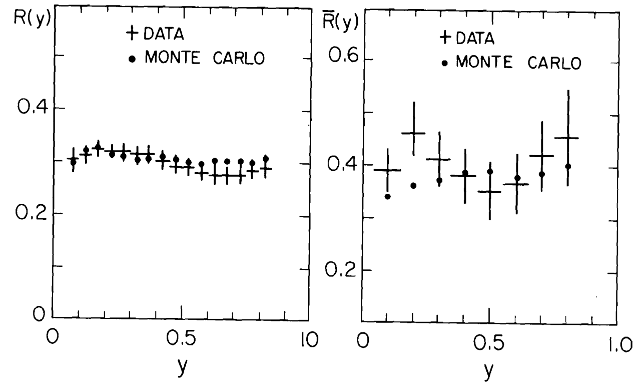


Fig. 13 y dependence of the ratio NC/CC for neutrinos and antineutrinos, CHARM Collaboration (Ref. 17). The simulation assumes $\sin^2\theta = 0.25$.

Figure 13 shows these ratios, R_ν and $R_{\bar\nu}$, as a function of y, and, for comparison, the results of a Monte Carlo simulation assuming $\sin^2\theta = 0.25$. The y dependence of $R_{\bar\nu}$ is sensitive to the contribution of right-handed quark coupling to the neutral-current interaction. The agreement of these preliminary data with the predictions is good.

Integrating the y distributions gives the ratios of cross-sections of neutral- and charged-current neutrino interactions, R_ν and $R_{\bar\nu}$. The results reported at this Conference are summarized in Table 5.

Table 5

New results on ratios of neutral- and charged-current cross-sections

Experiment	E_h	R_ν	$R_{\bar\nu}$
CDHS (Ref. 18)	> 10 GeV	0.307 ± 0.008	0.373 ± 0.025
CHARM (Ref. 17) (Prelim.)	> 2-10 GeV (depending on radius)	0.30 ± 0.020	0.39 ± 0.024

Relating these values to the electro-weak mixing angle, or, in a model-independent analysis, to the coupling constants u_L, d_L, u_R, and d_R, requires theoretical analysis of deep inelastic neutrino scattering, incorporating scaling violations predicted by QCD and sea-quark distributions. The effect of the uncertainties in this analysis and of the dominant experimental uncertainties on R, $\bar{R}$ and on $\sin^2\theta$ are summarized in Table 6, together with an estimate of the ultimate limitation of accuracy in $\sin^2\theta$, inherent in the measurement of R. Figure 14 shows a comparison of old and new measurements of R_ν and $R_{\bar\nu}$, and the results of predictions, one based on the simple quark model, the other on a calculation[16] incorporating the effects of QCD, assuming $\Lambda = 0.47$, $a_s \sim \bar{s}/\bar{u} = 0.5$, and $r = \sigma(\bar\nu N \to \mu^+X)/\sigma(\nu N \to \mu^-X) = 0.48$ and incorporating the $E_h > 10$ GeV cut of the CDHS experiment. The value of R_ν, and hence the best value for $\sin^2\theta$, is affected very little by varying these parameters; $R_{\bar\nu}$ serves as a check on the model consistency, and is indeed sensitive to the values of a_s and r, and to QCD effects.

Table 6

Theoretical and experimental uncertainties in analysing NC neutrino scattering

Source	ΔR_ν	$\Delta R_{\bar\nu}$	$\Delta \sin^2 \theta$
Quark model with sea + QCD	+0.0003	+0.0085	+0.0078
Uncertainty in strange sea	±0.0003	±0.01	±0.0092
WBB background (CDHS)	0.002	0.018	0.018
ν_e background (K/π ratio)	0.005	0.0015	0.008
Ultimate accuracy			±0.005

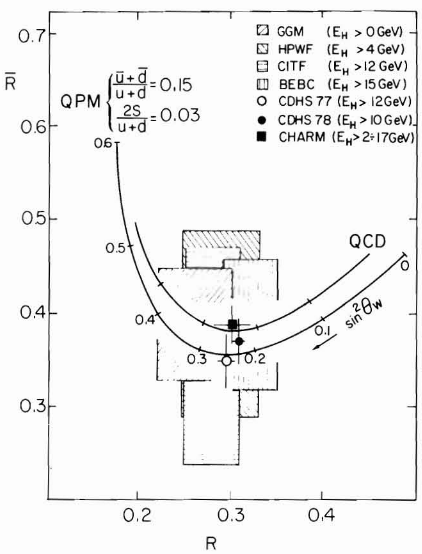


Fig. 14 Comparison of measurements of R and $\bar{R}$ with calculations based on the quark-parton model (QPM) and on QCD corrections (Ref. 16). Both calculations assume E_h > 10 GeV.

A way to avoid this model dependence of extracting the coupling constants by using the following expressions has been proposed by Paschos and Wolfenstein[20]:

$$\frac{\sigma^\nu(NC) - \sigma^{\bar\nu}(NC)}{\sigma^\nu(CC) - \sigma^{\bar\nu}(CC)} \simeq \frac{1}{2}(1 - 2 \sin^2 \theta) . \qquad (18)$$

It implies neglecting the product $\gamma\delta$ as compared to $\alpha\beta$ in Sakurai's notation[4], representing the isoscalar axial-vector interaction, amounting to a correction of $\sim$ (6 ± 4)%. The CDHS Collaboration obtains a value of

$$\sin^2 \theta = 0.228 \pm 0.018 \qquad (19)$$

uncorrected for this effect. The left-handed and right-handed chiral coupling constants are determined in the same way, giving

$$u_L^2 + d_L^2 = 0.298 \pm 0.008$$
$$u_R^2 + d_R^2 = 0.029 \pm 0.006 . \qquad (20)$$

6.1 Neutral current x distributions

Two groups have reported first results on x distributions determined from neutral-current neutrino interactions with isoscalar targets. A Columbia-Rutgers-Stevens Collaboration[21] working at the Brookhaven AGS has obtained data from an exposure of the 7′ BNL bubble chamber (filled with neon) to a narrow-band beam of (10 ± 1) GeV/c parent momentum. The data reported consist of 50 candidates of neutral-current events, of which 16 are due to background, and 68 charged-current events. The kinematics of neutral-current neutrino interactions is shown schematically in Fig. 15. The

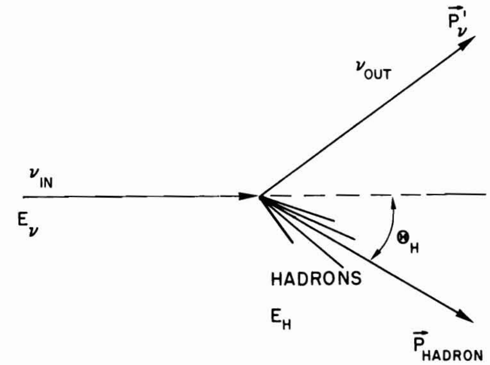


Fig. 15 Kinematics of neutral-current neutrino scattering; E_h and θ_h are measured, E_ν is inferred from the beam.

incident neutrino energy is inferred from the narrow-band beam, neglecting its component from K decay; E_h and $\vec{p}_h$ are measured. The value of x is calculated using for the momentum of the undetected outgoing neutrino the value

$$\vec{p}'_\nu = \vec{p}_{\nu inc} - \vec{p}_h .$$

The observed x distribution, uncorrected for 30% background, is shown in Fig. 16, together with the expected distribution for charged-current events.

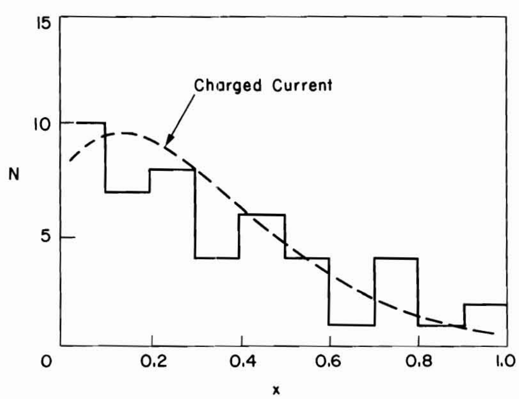


Fig. 16 x distribution of neutral-current events obtained by the CRS Collaboration (Ref. 21) using the 7′ BNL bubble chamber filled with neon.

The CHARM Collaboration has reported[17] first results based on 9200 neutrino events and 2700 antineutrino events, obtained using their new detector and the CERN 200 GeV/c narrow-band neutrino beam. The angle θ_h of the hadronic shower with respect to the neutrino beam direction (see Fig. 15) was determined by the line connecting the vertex of the shower and the barycentre of the deposited energy. Using the measured values of E_h

and θ_h and the statistical method of determining E_ν, ideograms of x distributions were obtained. This method has been checked by calculating the x variable of charged-current events using the measured muon momentum and the hadron energy E_h. Figure 17 shows the distribution of the difference between the value of x_μ, determined from the muon measurement, and the variable x,

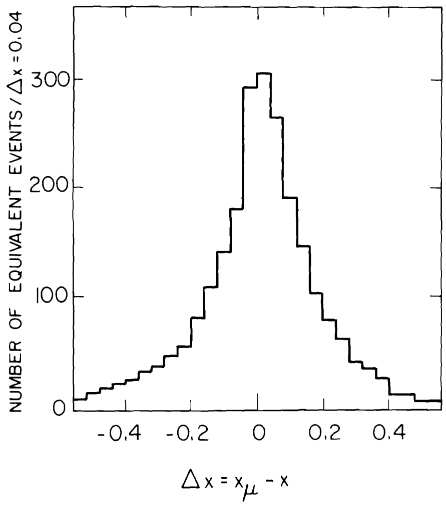


Fig. 17 Preliminary distribution of the difference of x_μ and x, determined in charged-current events using muon measurements and using hadron shower measurements.

obtained from the shower measurement and the statistical method, on an event-by-event basis. The width at half maximum ($\Delta x = \pm 0.12$) is satisfactory; the tails are reflecting strong correlations of the errors. The statistical method has been applied to neutral-current and to charged-current events, and the ratios of the cross-sections, R(x) and $\bar{R}(x)$ have been determined as a function of x, cancelling in this way, to first order, acceptance corrections, resolution effects, and other uncertainties. The results are shown in Fig. 18; the

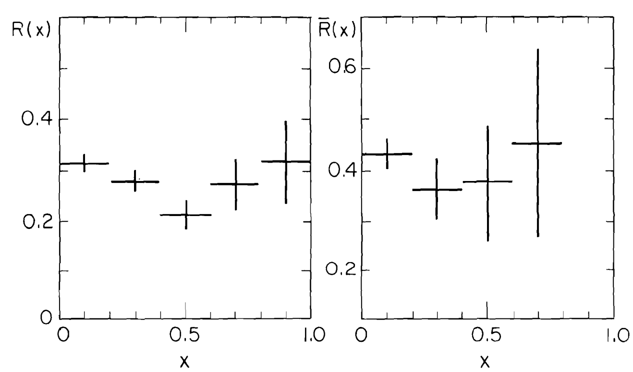


Fig. 18 First x distributions of the ratio NC/CC for neutrinos (R) and antineutrinos ($\bar{R}$) obtained by the CHARM Collaboration (Ref. 17)

x distributions probed by the neutral and by the charged current are observed to be proportional to each other, as expected in the quark model and as already confirmed for the electromagnetic and the charged current. With improved statistics differences are expected to be observed, owing to the coupling of the neutral current to the sea of strange quarks.

7. Isospin Structure of the Neutral Quark Current

Measurements of inclusive neutral-current neutrino scattering on isoscalar targets determine two combinations of the chiral coupling constants of the u and the d quarks, $u_L^2 + d_L^2$ and $u_R^2 + d_R^2$. Measurements of inclusive neutrino scattering on neutrons and protons can be used to determine the coupling of the u and the d quark separately.

At this Conference a new result on the ratio of neutral- and charged-current cross-sections on protons has been reported by the Aachen-Bonn-CERN-Munich-Oxford Collaboration[22],

$$R_p = 0.51 \pm 0.04 \; . \tag{21}$$

This ratio determines $\sim (2u_L^2 + d_L^2)$, with small corrections due to right-handed coupling; the error is reduced by a factor of 4 over the earlier result of Harris et al.[23], allowing a statistically significant result to be extracted. The experiment was carried out at CERN using the Big European Bubble Chamber (BEBC) filled with hydrogen in the horn-focused wide-band neutrino beam of the SPS. Their sample of neutral-current candidates is contaminated by background due to i) the interaction of neutrons produced by neutrinos in front of the chamber, and ii) unidentified charged-current events, caused by the reduced efficiency at low muon momentum of the External Muon Identifier. Both sources of background can be strongly reduced by a cut in the total transverse momentum of the reaction products. Figure 19 shows the

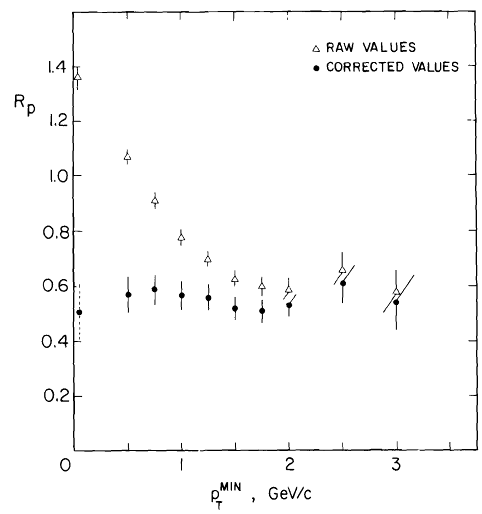


Fig. 19 Raw values of the ratio NC/CC on protons as a function of the total transverse momentum, obtained by the ABCMO Collaboration (Ref. 22).

variation of the raw ratio R_p as a function of the detected transverse momentum and the result of corrections for the background effects. A cut at 1.5 GeV/c is chosen in an attempt to equalize the statistical error, which increases with increasing p_T, and the systematic uncertainty of the corrections, which is decreasing. Combining values of R measured in neon and in hydrogen, as shown in Fig. 20, a region of allowed values of the left-handed chiral coupling constants is obtained, giving

$$u_L^2 = 0.15 \pm 0.05$$
$$d_L^2 = 0.17 \pm 0.07 \; . \tag{22}$$

New results have been reported at this Conference on the ratio of neutral-current cross-sections of neutrons and protons. Combining these data to evaluate the

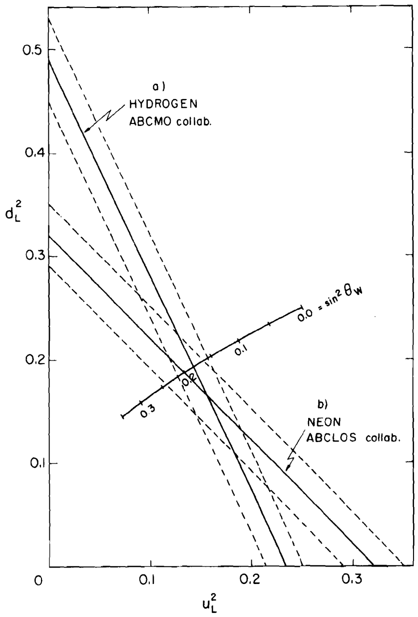


Fig. 20 Region of allowed values of left-handed chiral coupling parameters determined by measurements of R on neon and on hydrogen targets (Ref. 22).

following expressions gives direct information on the interference of isovector with isoscalar contributions,

$$\frac{\sigma(\nu p) - \sigma(\nu n)}{\sigma(\nu p) + \sigma(\nu n)} = u_L^2 - d_L^2 + \frac{1}{3}(u_R^2 - d_R^2) \qquad (23)$$

$$\frac{1}{1.9}\,\frac{\sigma(\bar{\nu}p) - \sigma(\bar{\nu}n)}{\sigma(\bar{\nu}p) + \sigma(\bar{\nu}n)} = u_R^2 - d_R^2 + \frac{1}{3}(u_L^2 - d_L^2) \ . \qquad (24)$$

For $\sin^2\theta = 0.23$ Eq. (24) is expected to be zero, equivalent to $\bar{R} = \sigma(\bar{\nu}n/\sigma(\bar{\nu}p) = 1.0$, and from Eq. (23) one derives the prediction $R = \sigma(\nu n)/\sigma(\nu p) = 1.1$. The results reported at this Conference are summarized in Table 7;

Table 7

Experimental results on neutral-current neutrino scattering on neutrons and protons. $R = \sigma(\nu n)/\sigma(\nu p)$, $\bar{R} = \sigma(\bar{\nu}n)/\sigma(\bar{\nu}p)$.

Experiment	Measured	Corrected	Predicted ($\sin^2\theta = 0.23$)
Gargamelle (Ref. 24)	$R = 0.76^{+0.15}_{-0.13}$	$0.84^{+0.15}_{-0.13}$	1.1
Mich-FNAL-IHEP-ITEP (Ref. 25) (15′ BCH)	$\bar{R} = 1.06 \pm 0.20$	-	1.0

the value of R reported by the Gargamelle group has been corrected by 10% to include elastic events in the cross-sections. They are in agreement with the predictions; however, their statistical errors are too large to allow the determination of $u_L^2 - d_L^2$ and $u_R^2 - d_R^2$. As in the case of R_p, neutrino data give a stronger constraint than antineutrino data; a 10% measurement of $R = \sigma(\nu n)/$ $/\sigma(\nu p)$ is equivalent to a 5% measurement of R_p. There is good reason to expect that this accuracy can be reached at high energy, where the correction for the unobserved elastic channel in $\sigma(\nu n)$ is reduced to $\sim 1\%$.

It is apparent from Fig. 21 that the data on inclusive neutrino scattering on isoscalar targets and on

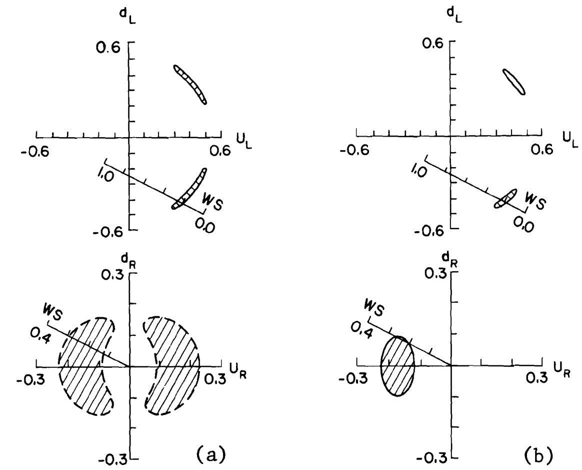


Fig. 21 Regions of allowed values of left-handed and right-handed coupling parameters of u-quarks and of d-quarks: a) determined from inclusive ν scattering on isoscalar and proton and neutron targets; b) determined by all ν-hadron data. The open region, corresponding to dominant isoscalar coupling, is excluded by data on $\nu N \to \nu\pi N$ and on $\bar{\nu}_e d \to \bar{\nu}_e np$ (Ref. 26).

proton and neutron targets allow two separate regions of the coupling constants u_L and d_L, and u_R and d_R; one is dominantly isovector (called solution A by Sakurai[3]) and the other is dominantly isoscalar. Previously, this latter solution has been excluded by the observation, in data on single-pion production, of a strong delta enhancement. An independent argument can now be derived from recent results on the reaction

$$\bar{\nu}_e d \to \bar{\nu}_e np \ , \qquad (25)$$

which has been studied by the Irvine group[26] using the intense flux of electron antineutrinos ($\sim 2.5 \times 10^{13}$ $cm^{-2}\ s^{-1}$) from the Savannah River fission reactor. Near threshold the final (np) system is in a ^1S state. The transition from the ^3S state of the deuteron to the ^1S (np) state can only occur via the isovector axial-vector part of the Lagrangian[27]. A cross-section of $(3.8 \pm 0.9) \times 10^{-45}$ cm^2 is measured, consistent with the dominant isovector solution of neutral-current coupling $[\sigma_{exp}/\sigma_{th}(A) = 0.8 \pm 0.2]$ and excluding the dominant isoscalar solution at the level of 2.8 standard deviations. The experiment directly determines the isovector axial-vector coupling constant[28] to be $\beta = \pm(0.9 \pm 0.1)$.

8. Coupling Parameters of the Neutral Current

Several authors have attempted to combine the results of the experiments discussed in this review in order to determine the coupling parameters of the neutral current. We distinguish three approaches:

i) a model-independent approach, assuming a single Z^0 boson, to determine seven parameters: u_L, d_L, u_R, d_R, g_V^e, g_A^e, and ρ;

ii) assuming a general SU(2)⊗U(1) model with left-handed doublets of fermions $[T_{3L}(\text{up}) = 1/2, T_{3L}(\text{down}) = -1/2]$, to determine five parameters, $\rho = m_W^2/m_Z^2 \cos^2\theta$, $\sin^2\theta$, $T_{3R}(u)$, $T_{3R}(d)$, and $T_{3R}(e)$;

iii) in the Weinberg-Salam gauge theory $\rho = 1$ and $T_{3R} = 0$, only one parameter, $\sin^2\theta$, is left.

The results of the analysis of Langacker[16] et al., Roos[16] et al., and Sakurai[28] are summarized in Table 8.

Table 8

Determination of the coupling parameters of the neutral current (Ref. 16)

Parameter	Factorization assumed	$\rho = 1$ assumed	$\sin^2\theta = 0.232$
u_L	0.351 ± 0.037	0.350 ± 0.030	0.345
d_L	-0.415 ± 0.055	-0.416 ± 0.026	-0.423
u_R	-0.179 ± 0.032	-0.180 ± 0.020	-0.155
d_R	-0.010 ± 0.046	-0.009 ± 0.043	+0.077
g_V^e	0.043 ± 0.066	0.044 ± 0.056	-0.036
g_A^e	-0.545 ± 0.045	-0.544 ± 0.043	-0.50
ρ	1.010 ± 0.098		

The factorization hypothesis and the assumption of a physical Z^0 boson[28] (coupling parameter of $\bar{\nu}\nu Z^0$ $c_\nu^2 > 0$) removes the sign ambiguity of the neutrino-quark coupling constants.

The value of ρ is close to one and therefore excludes, in the context of SU(2)⊗U(1), triplets of Higgs mesons. Assuming the validity of the Weinberg-Salam model, which is strongly suggested by the results of the model-independent analysis, the data determine a value of the electro-weak mixing angle of

$$\sin^2\theta = 0.230 \pm 0.009 \; . \qquad (26)$$

Is the prediction of the SU(5) grand unification scheme[29], $\sin^2\theta = 0.20$, at variance with this result? The values of ρ and of $\sin^2\theta$ are mainly determined by the experiments on inclusive neutrino scattering and the asymmetry in electron-deuterium scattering; Table 9 shows their relative sensitivity. If the error on $\sin^2\theta$ can be reduced to the theoretical uncertainty of 0.005, a significant comparison with the SU(5) prediction could be made.

Table 9

Sensitivity of the main experiments (Ref. 16). The correlation between ρ and $\sin^2\theta$ is 0.86.

Experiments	ρ	$\sin^2\theta$
Inclusive νN	0.981 ± 0.037	0.213 ± 0.038
ed asymmetry	1.74 ± 0.36	$0.293^{+0.033}_{-0.10}$

9. Limits on Charm-Changing Currents

The GIM mechanism provides the basis for the generation universality of the Weinberg-Salam model. It is therefore important to review its validity.

The search for "wrong" sign muons in inclusive neutrino reactions has given stringent limits[30] on the cross-section of the charm-changing reaction $\nu_\mu N \to \nu_\mu c$ (see Table 10). At this Conference a new result[31] has been reported by the ITEP-FNAL-IHEP-Michigan Collaboration on charmed particle production in antineutrino-nucleon neutral-current interactions. Events with a single positron have been searched for as a signature for charmed particle decay. All events found can be attributed to known sources. A 90% confidence upper limit is reported (see Table 10).

Previously, charm-changing neutral currents have also been searched for in the decay of charmed particles. Baltay et al.[32] have reported an upper limit on the ratio of the neutral-current and charged-current decay of charmed particles produced in charged-current neutrino reactions,

$$\frac{\Gamma(c \to e^+e^-X)}{\Gamma(c \to e^+\nu X)} < 0.02 \; . \qquad (27)$$

A search for $D^0 - \bar{D}^0$ mixing due to their neutral-current decay has been performed at SPEAR[33]. Mixing would lead to final states of D^0D^0 or $\bar{D}^0\bar{D}^0$ and hence to events with two electrons of equal charge from their semileptonic decays. In the energy range $3.72 < E < 4.14$ GeV an upper limited of

$$A = \frac{N(e^+e^+) + N(e^-e^-)}{N(e^\pm e^\mp)} < 0.05$$

has been determined.

Buccella and Oliver[34] have constructed a model Lagrangian for a $|\Delta c| = 1$ left-handed and right-handed ($\bar{c}u$) current:

$$J_\mu^{|\Delta c|=1} = g_L \bar{c}\gamma_\mu\left(\frac{1+\gamma_5}{2}\right)u + g_R \bar{c}\gamma_\mu\left(\frac{1-\gamma_5}{2}\right)u \; . \qquad (28)$$

It is conveniently used to correlate the results from the four types of experiments discussed so far. The upper limits on g_L and g_R, derived under the assumption of $\sin^2\theta = 0.25$, are summarized in Table 10. It can be

Table 10

Upper limits on charm-changing neutral-current coupling

Experiment	Quantity measured	Limit ($\sin^2\theta = \frac{1}{4}$)
CDHS (Ref. 30)	$R = \dfrac{\nu_\mu u \to \nu_\mu c}{\nu_\mu N \to \nu_\mu X} < 0.026$	$g_L^2 + \frac{1}{3} g_R^2 < 0.025$
IFIM (Ref. 31)	$\bar{R} = \dfrac{\bar{\nu}_\mu u \to \bar{\nu}_\mu c}{\bar{\nu}_\mu N \to \bar{\nu}_\mu c} < 0.04$	$g_L^2 + 3 g_R^2 < 0.06$
Col.-BNL (Ref. 32)	$R' = \dfrac{\Gamma(c \to e^+e^-X)}{\Gamma(c \to e^+\nu_e X)} < 0.02$	$g_L^2 + g_R^2 < 0.16$
SPEAR (Ref. 33)	A ($D^0 - \bar{D}^0$ mixing) < 0.05 If only left-handed currents ($\bar{c}$,u) i.e. $g_R = 0$	$\lvert g_L \rvert < 0.6 \times 10^{-3}$

noted that the search for D^0-$\bar{D}^0$ mixing gives the most stringent limit on g_L under the assumption of $g_R = 0$. The corresponding limits on charmed particle production by neutral-current interaction, $R,\bar{R} < 4 \times 10^{-7}$, are completely inaccessible to experiment. If, however, right-handed $|\Delta c| = 1$ neutral currents would exist, the search performed in antineutrino reactions would be a factor of 9 more sensitive than in neutrino reactions.

The limits quoted in Table 10 imply stringent constraints on the generation universality of the neutral-current parameters discussed in Section 8.

10. Concluding Remarks

With the recent advances in experiments showing parity violation in polarized electron scattering and in atomic transitions, our understanding of the weak neutral current has progressed. We now understand the electron current, and relate electron scattering successfully with neutrino scattering, demonstrating the factorization property based on the assumption of a single Z^0 boson.

Neutrino-electron scattering is a field that is expected to progress rapidly, following the demonstration that experiments at high energy, using electronic detectors, can detect these rare events and separate them reliably from the dominant semileptonic reactions.

Work in the field of inclusive neutrino-hadron scattering is still progressing. There is now definite hope of being able to determine directly the isovector-isoscalar interference by measurements of the ratio of the cross-sections of neutrino scattering on neutrons and on protons.

The model-independent analysis of the coupling parameters gives more precise values which are in close agreement with the ones derived from the gauge models. The theoretical uncertainties have been analysed and are found to be smaller than currently quoted experimental errors. Without imposing the gauge model constraint of $\rho = 1$, these results are completely dominated by data on inclusive neutrino scattering. More precise, independent results, e.g. from electron scattering, are therefore welcome.

The value obtained for the electro-weak mixing angle

$$\sin^2 \theta = 0.230 \pm 0.009$$

is not in agreement with the SU(5) prediction, although the statistical significance of this disagreement is not yet compelling.

One of the remaining open questions in neutral-current interactions is the generation universality. Do all quarks of charge $-\frac{1}{3}$ and all quarks of charge $\frac{2}{3}$ couple in the same way to the Z^0 boson? Within the context of the GIM mechanism the experimental situation is compelling. However, this universality remains to be established in a model-independent way, presumably at the large e^+e^- storage rings.

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NOTE: The discussion session associated with this paper has not been included as it was concerned exclusively with material not included in the written version of Dr. Winter's talk - Editor.