NEUTRINO INTERACTIONS

D. H. Perkins
Oxford University

INTRODUCTION

The main developments in the experimental study of neutrino reactions, which have taken place in the last year, have been:

i) First observations of the elastic $\Delta S = 1$ reactions $\bar{\nu}p \to \mu^+\Lambda$ and $\bar{\nu}p \to \mu^+\Sigma^0$.

ii) First measurements of the cross-sections for the $\Delta S = 0$ reactions $\nu n \to \mu^- p$ and $\nu p \to \mu^-\Delta^{++}$ in deuterium and hydrogen.

iii) New and more precise limits on purely leptonic neutral currents, from experiments to detect the elastic scattering of $\bar{\nu}_e$, ν_μ and $\overline{\nu_\mu}$ on electrons; and new limits on neutral hadronic weak currents leading to single pion production.

iv) First detailed measurements of the total cross-sections for both ν_μ and $\overline{\nu_\mu}$ on nucleons up to energies of 10 GeV; some preliminary analysis of the differential inelastic cross sections; and the first qualitative data on inelastic $\Delta S = +1$ neutrino and $\Delta S = -1$ antineutrino cross sections.

While the results under (i) and (ii) do not contain any surprises, and those under (iii) do not yet constitute a decisive test against the Salam-Ward-Weinberg theory of neutral currents, the preliminary data on cross-sections (iv) provide an astonishing verification of the Gell-Mann/Zweig quark model of hadrons. Furthermore, it has been possible, for the first time, to make a reliable comparison between the inelastic electro-production and neutrino production cross-sections, and these turn out to be in exact agreement with the principles of CVC and chiral symmetry.

This report is divided into three parts. In Part I, I discuss the new data on elastic and quasi-elastic neutrino scattering on nucleons; in Part II, the experimental situation relating to neutral currents; and in Part III, the results on inelastic neutrino-nucleon scattering.

Part I ELASTIC AND QUASI-ELASTIC NEUTRINO SCATTERING BY NUCLEONS

A) The Elastic Reaction $\nu_\mu + n \to \mu^- + p$

New data was presented on this reaction from the ANL experiment in the 12' D_2 chamber (Mann et al 1972). Before discussing this it is perhaps worthwhile to recapitulate briefly the conventional method of extracting the nucleon axial vector form factor from the data.

The matrix element for the hadronic weak current has the most general form, assuming vector particle exchange between lepton and hadron currents:-

$$\langle p|J_\alpha|n\rangle = \frac{G}{\sqrt{2}} \overline{u_p} \left[\gamma_\alpha(g_V + \gamma_5 g_A) + iP_\alpha(f_V + \gamma_5 f_A) - iq_\alpha(h_V + \gamma_5 h_A)\right] u_n \tag{1}$$

where $P = p_p + p_n$, $q = p_p - p_n$, and p_n, p_p are the 4 momenta of the initial and final nucleon. The three vector form-factors g_V, f_V, h_V and the three axial vector form-factors g_A, f_A, h_A are arbitrary. The standard assumptions which are made to simplify the problem are:-

i) T-invariance of the interaction, and first-class currents only. Then $f_A = h_V = 0$.

ii) The induced pseudoscalar term, involving the "axial magnetic" form factor h_A, is assumed to be dominated by pion exchange. On any reasonable assumptions, this term contributes at most 2 - 3% to the cross-section at GeV energies, and is therefore dropped.

iii) The remaining vector terms, continuing f_V and g_V, are fixed from the isotriplet current hypothesis ($\Delta I = 1$ rule) whereby J^+_{weak}, J^-_{weak} and $(J_3)_{e.m.\ isovector}$ are components of the same isospin 1 current. Thus g_V and f_V are determined in terms of the isovector electric and magnetic form-factors measured in e-p and e-n elastic scattering.

There then remains one axial form-factor g_A to determine, which, in analogy with the observed behaviour of the electromagnetic form-factors, is parametrized by means of the dipole formula

$$g_A(q^2) = \frac{g_A(o)}{(1 + q^2/M_A^2)^2} \tag{2}$$

where $g_A(o) = 1.25$ as determined from neutron decay. Thus, the experiment amounts to a determination of one number, M_A.

The ANL experiment observed the reaction in deuterium

$$\nu_\mu + d \rightarrow \mu^- + p + p_s \tag{3}$$

where p_s is the spectator proton. In 25% of events, the spectator produces a measurable track, so that, since the neutrino direction (but not energy) is known, a 3C kinematic fit is obtained. If the spectator is unmeasurable, one can set, as the constraint, an upper limit to the spectator momentum (1 mm in D_2 corresponds to a momentum 75 MeV/c). It was observed that the spectator spectrum from events fitting hypothesis (3) with $P(\chi^2)>1\%$ followed the usual Hulthen distribution, with an isotropic angular distribution as expected. Estimated background from neutron reactions and inelastic (π^o production) processes was small (<5%). From a preliminary sample of 95 events, the value of M_A was found by a maximum likelihood method applied to the q^2-distribution of all events and to the cross-section as a function of neutrino energy. These distributions are shown in figs 1 and 2. The best-fit value obtained was

$$M_A = 0.92 \pm 0.14 \text{ GeV/c}^2 \tag{4}$$

Table 1 shows the results of the ANL 12' D_2 experiment as well as those of previous experiments with spark chambers and heavy liquid bubble chambers. The spark chamber experiments suffer from severe problems with inelastic background and because of this, the possibility of large systematic errors in M_A cannot be excluded. The first three experiments did not incorporate monitoring of the neutrino flux, so that the value of M_A is based only on the shape of the q^2 distribution. In the CERN propane bubble chamber experiment, as well as the recent ANL experiment, the flux was determined to within $\pm 15\%$, so that both q^2-distributions and $\sigma(E)$ have been used for the fits to M_A.

In comparison with the previous experiments, the ANL D_2 chamber experiment has smaller background, and another significant advantage is that the computation of the expected cross-section in D_2, in terms of that for a free neutron target, only involves a knowledge of the deuteron wave function. Thus the experiment is cleaner and more reliable than those with complex nuclei, where analysis not only involves less certain nuclear models for the effects of Fermi motion and the exclusion principle, but uncertainties from secondary nuclear scattering effects.

Table 1

Determinations of the axial form-factor parameter M_A, for the process

$\nu + n \rightarrow \mu^- + p$

Experiment	Target	Inelastic Background Subtraction	Quoted Flux Error	M_A, GeV	# events selected
CERN SC(1)	Aluminium	45%	$\pm$ 30%	0.65 $\pm$ 0.42	74
ANL SC(2)	Iron	10 - 25%		1.05 $\pm$ 0.20	—
CERN BC(3)	CF_3Br	10%	$\pm$ 30%	0.75 $\pm$ 0.25	~60
CERN BC(4)	C_3H_8	10%	$\pm$ 15%	0.73 $\pm$ 0.20	40
ANL BC(5)	D_2	≤5%	$\pm$ 15%	0.92 $\pm$ 0.14	95

(1) Holder et al Nuov. Cim 57A, 338 (1968)
(2) Kustom et al PRL 22, 1014, (1969)
(3) Block et al Phys. Lett. 12, 281 (1964)
(4) Budagov et al Nuov. Cim. Lett 2, 689(1969)
(5) Mann et al this conference (#784)

If we combine the results of all experiments, - and they are statistically consistent - one finds $(M_A)_{av} = 0.87 \pm 0.09$. However, for the reasons stated above, it seems safer to combine only the propane and deuterium data, which give

$$M_A = 0.87 \pm 0.12 \text{ GeV} \tag{5}$$

Although this is consistent with (4) it does have the advantage of averaging over two independent sets of flux errors. This figure may be compared with the best-fit value to the electromagnetic dipole form factor

$$M_V = 0.84 \pm 0.03 \text{ GeV} \tag{6}$$

Note that the error on M_A is coming within striking distance of that on M_V, which will of course ultimately limit the accuracy attainable on M_A as determined by present methods. When the scheduled D_2 runs and analysis thereof in the ANL chamber are completed in a year or so, the number of events will be increased by almost one order of magnitude. It may also be remarked that the completed deuterium experiment, which will provide the most precise and clean determination of M_A for the simplest possible neutrino process of elastic scattering, $\nu n \to \mu^- p$, will have been carried out rather more than 10 years after the very first experiments to analyse this process at BNL and CERN. Thus, more ambitious neutrino experiments, aimed for example at verifying the Adler sum rule in inelastic processes on protons at high q^2, are unlikely to be realised for some time.

Finally, it is of interest to remark that rather indirect estimates of M_A, in the region of low q^2, have been attempted from analysis of the observed electropion production cross-section just above threshold, by application of PCAC and soft-pion theorems. The most reliable experiment to date appears to be that of a DNPL-PISA collaboration (Botterill et al 1972), which gives $M_A = 0.98 \pm 0.14$ GeV, using the theoretical analysis of Furlan, Paver and Verzegnassi (1969, 1970). An experiment by Amaldi et al (1972) yields similar results. These numbers may be compared with those from the earlier analysis of Nambu and Yoshimura (1970) yielding $M_A = 1.34 \pm 0.05$ GeV. In view of the many assumptions and approximations required to extract the axial form factor from the data, the apparent agreement of the latest electroproduction data with more direct measurements in neutrino experiments should not be taken too seriously.

) Elastic Hyperon production by Antineutrinos

The first observations of hyperon production by antineutrinos have been made recently at CERN using the large heavy-liquid bubble chamber Gargamelle. Since the data was recently published, (Eichten et al 1972), it is only necessary to describe it very briefly.

Among 220,000 pictures in heavy freon (CF_3Br) a total of 13 events attributed to

$$\overline{\nu_\mu} + p \rightarrow \mu^+ + \Lambda \qquad (5)$$

and 2 events due to

$$\overline{\nu_\mu} + p \rightarrow \mu^+ + \Sigma^o \qquad (6)$$

were observed. Possible examples of $\bar{\nu} + n \rightarrow \mu^+ + \Sigma^-$ were also found, but these were not considered because of difficulties of observing and identifying such events in heavy liquid.

After small corrections for neutron star background and loss of Λ's of very short lifetime, the Λ production cross-section, averaged over the CERN anti-neutrino spectrum, was found to be

$$\sigma_\Lambda \text{ (freon)} = 1.3 \begin{smallmatrix} + 0.6 \\ - 0.3 \end{smallmatrix}) \times 10^{-40} cm^2/\text{proton}$$

The free proton cross-section was deduced from Monte-Carlo calculations of the effects of Λ-absorption and Σ - Λ conversion in the parent nucleus. The resulting free proton cross-section was found to be

$$\sigma_\Lambda\text{(free proton)} = 1.3 \begin{smallmatrix} + 0.9 \\ - 0.7 \end{smallmatrix}) \times 10^{-40} cm^2/\text{proton} \qquad (7)$$

This value was compared with the theoretical predictions of the SU3 model of Cabibbo and Chilton (1965) using as input the standard values $\theta_{Cabibbo} = 0.24$ and axial coupling coefficients F = 0.45, D = 0.70. With both vector and axial form factors parametrized by the dipole formula $(1 + q^2/m^2)^{-2}$, with M = 0.84 GeV, one obtains

$$\sigma_\Lambda\text{(theory)} = 2.4 \times 10^{-40} \ cm^2/\text{proton} \qquad (8)$$

in satisfactory agreement with (7). Within the large statistical errors, the relative numbers of events attributable to Λ and to Σ^o in reactions (5) and (6) were also in agreement with the SU3 (Cabibbo) theory.

C) Single Pion Production by Neutrinos

New data on single pion production by neutrinos in the ANL 12' chamber with D_2 and H_2 fillings was presented at this conference (Campbell et al 1972). A total of 105 events fitting the reaction

$$\nu_\mu + p \rightarrow \mu^- + \pi^+ + p, \quad \text{(3C fit)} \tag{9}$$

were observed in 360,000 pictures in H_2. In 145,000 D_2 pictures, 48 events were observed to fit the reaction

$$\nu_\mu + d \rightarrow \mu^- + \pi^+ + p + (n_s) \tag{10}$$

which is also a 3C fit if constraints are placed on the momentum of the spectator neutron. Background from processes such as $\gamma \rightarrow \pi^+ \pi^- p$, $np \rightarrow pp\pi^-$ was estimated to be <2% in H_2 and ∿5% in D_2.

Fig 3 shows the observed cross-section for single pion production from reactions (9) and (10), as a function of energy. Errors include a $\pm$ 15% flux uncertainty. The plot also contains results from a smaller sample (40) of events in a previous CERN experiment in propane C_3H_8 (Budagov et al 1969 (a)). In the latter experiment, free proton events were extracted by kinematic fitting; the cross-section errors arising in the subtraction of background carbon events (which contributed 15% of the total) were of order 5%. In both experiments, neutrino flux errors were $\pm$ 15%.

Fig. 4 shows the π^+p invariant mass distribution in the ANL data, the curve corresponding to a velocity - dependent Breit-Wigner (Dalitz and Sutherland 1966) for the Δ^{++} resonance. Fig. 5 indicates the scatter plot of polar and azimuthal angles (θ and ϕ) of the $\Delta^{++} \rightarrow \pi^+ + p$ decay, referred to a coordinate system in the $\pi + p$ centre of mass which takes as the z-axis the momentum transfer direction $\underline{q}$, and as x-axis the normal to the ν - μ scattering plane.

The main conclusions to be drawn from these plots are as follows:-

i) The ANL and CERN cross-sections are consistent, although the ANL cross-sections above 2GeV energy are somewhat below the CERN values.

ii) The bulk of events in the $\pi + p$ invariant mass spectrum lie inside the Δ resonance, which appears to account for 95% of the cross-section.

iii) The decay angular distributions do not show any striking structure, in contrast to the earlier and statistically weaker CERN experiment, where a possible asymmetry at the 2 S.D. level in a related angular distribution was observed for certain classes of event.

The results (ii) and (iii) together very probably indicate that, at the beam energies ($\sim$1 GeV) employed, weak pion production is very largely dominated by the Δ resonance, and that there is no evidence for any appreciable coherent, non-resonant background. This is most important from the viewpoint of theoretical interpretation of the data.

Analysis of the experiment has been discussed by Schreiner and Von Hippel (1972). First we remark that, assuming T-invariance and first-class currents, and $J = \frac{3}{2}$ only for the final state, the hadron current contains 4 axial and 4 vector terms (i.e. just double the number in the elastic case). One vector term drops out from CVC, and the remainder may be evaluated from CVC and an analysis of electropion production data in the resonance region. This still leaves 4 unknown axial terms, so that the data can only be compared with the predictions of various phenomenological models. A discussion of these is given in the review by Llewellyn-Smith (1972).

Among the multitude of theoretical papers, Schreiner and von Hippel discuss the predictions of Adler, Salin, Zucker and Bijtebier. The cross-sections for these models are included in Fig. 3. For "reasonable" values of the q^2-dependence (form-factors), some models, for example that of Adler, predict cross-sections which are too low. Schreiner and Von Hippel point out that the gross behaviour of σ (E) or dN/dq^2 are not particularly illuminating for theoretical understanding, and it is better to compare the density matrix elements, ρ, of the Δ-decay (which have the additional advantage that the measured values are flux-independent).

Table 2 shows the observed ρ values from the ANL experiments, together with the model predictions. In each case, the value of M_A has been allowed to vary to agree with the observed total cross-sections, and the χ^2 probability for the fit to the angular distributions evaluated. Considering the complexity of the models, most of them give a reasonable fit to the decay angular distributions (at around the 1% level). It is fairly clear that a considerable increase in statistical weight of the experimental data will be needed in order to pin down the discrepancies with the different models and allow real headway to be made.

Table 2 (after Schreiner and Von Hippel)

Observed and predicted decay density matrix elements in weak pion production. The values of M_A are those required to fit $\sigma(E)$. P (χ^2) is the probability of the fit to the angular distribution.

Model	M_A (GeV)	ρ_{33}	ρ_{3-1}	ρ_{31}	$P(\chi^2)$
Salin	0.53	0.62	0.08	0.17	1%
Adler	1.13	0.69	-0.02	-0.11	10%
Bijtebier	0.71	0.66	-0.02	0.14	0.1%
Zucker	0.80	0.77	-0.02	-0.12	1%
Experiment		0.58 ± 0.09	-0.24 ± 0.11	-0.18 ± 0.11	

PART II. NEUTRAL WEAK CURRENTS

A comprehensive discussion of the "unified" gauge theories of weak and electromagnetic interactions, which have come to prominence over the last years, is given in the review by B.W. Lee in these proceedings. These theories require either neutral intermediate vector bosons (as well as charged) and therefore neutral weak currents, or heavy leptons (or both).

A theory of the first type was proposed by Salam and Ward (1964) and Weinberg (1967). Since this theory makes very definite predictions about the amplitudes of the neutral currents, it is very susceptible to experimental test.

In the Salam-Ward-Weinberg theory, the massless Yang-Mills gauge fields consist of an isospin triplet of vector bosons W^+, W^-, W^o, a singlet vector boson B^o, and two isodoublets of scalar mesons ϕ^-, ϕ^o and ϕ^+, $\bar{\phi}^o$ (in addition to the leptons). The coupling of the bosons $W^{\pm,o}$ to the lepton current is denoted by g, and that of the scalar boson to the lepton current by g'. As a result of spontaneous symmetry breaking, the bosons acquire mass. $W^\pm$ and $\phi^\pm$ combine to form the conventional massive intermediate vector bosons W^+ and W^-. W^o and B^o mix to form the massless photon and a massive neutral vector boson Z^o:-

$$\begin{aligned} Z^\circ &= W^\circ \cos\theta + B^\circ \sin\theta \\ \gamma &= B^\circ \cos\theta - W^\circ \sin\theta \end{aligned} \tag{11}$$

where θ is an arbitrary mixing angle (frequently called the Weinberg angle). W^+ and W^- mediate the charge-changing part of the weak interactions, and Z° and γ mediate the neutral current weak and electromagnetic interactions respectively. Because the theory is unified, one obtains the following relations between the couplings:-

$$e = gg'/\sqrt{g^2 + g'^2}$$

$$\sin\theta = g'/\sqrt{g^2 + g'^2}$$

$$\cos\theta = g/\sqrt{g^2 + g'^2}$$

or $$\boxed{\sin^2\theta = e^2/g^2} \qquad (o<e^2/g^2<1) \tag{12}$$

while for the boson masses

$$M^2_{W\pm} = \frac{\sqrt{2}\, g^2}{8G} = \frac{\sqrt{2}\, e^2}{8G \sin^2\theta}$$

$$M^2_{Z^\circ} = \frac{\sqrt{2}(g^2 + g'^2)}{8G} = M^2_{W\pm} \sec^2 \theta$$

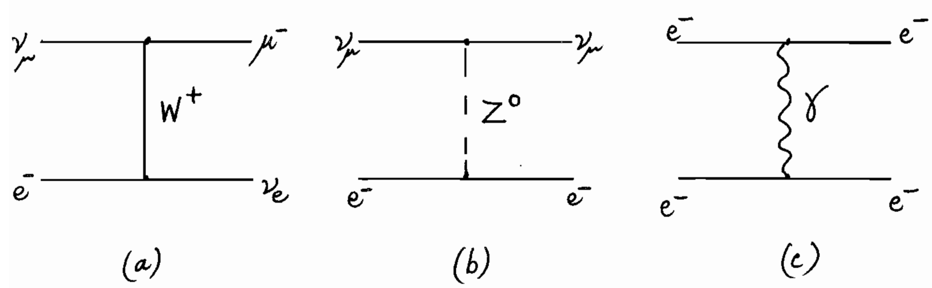
where G is the Fermi constant. In numbers,

$$\begin{aligned} M_{W\pm} &= 37/\sin\theta \text{ GeV} \\ M_{Z^\circ} &= M_{W\pm} \sec\theta > 52 \text{ GeV} \end{aligned} \tag{13}$$

Thus θ, or equivalently e^2/g^2, is the only free parameter of the theory.

A) Leptonic Neutral Currents; Neutrino-Electron Scattering

The purely leptonic electromagnetic and weak interactions are now described by the diagrams



where in addition to the conventional graphs (a) and (c), there is introduced the neutral weak current (b). From the viewpoint of neutrino interactions, this has the effect of modifying the couplings g_V and g_A describing elastic scattering from electrons as follows (t'Hooft 1971) :-

TABLE III

Leptonic Couplings in the Weinberg Theory

Reaction	Weinberg g_V	Weinberg g_A	V-A Theory g_V	V-A Theory g_A
$\nu_e + e^- \rightarrow e^- + \nu_e$	$\frac{1}{2} + \frac{2e^2}{g^2}$	$+\frac{1}{2}$	1	1
$\bar{\nu}_e + e^- \rightarrow e^- + \bar{\nu}_e$	$\frac{1}{2} + \frac{2e^2}{g^2}$	$-\frac{1}{2}$	1	-1
$\nu_\mu + e^- \rightarrow e^- + \nu_\mu$	$-\frac{1}{2} + \frac{2e^2}{g^2}$	$-\frac{1}{2}$	0	0
$\bar{\nu}_\mu + e^- \rightarrow e^- + \bar{\nu}_\mu$	$-\frac{1}{2} + \frac{2e^2}{g^2}$	$+\frac{1}{2}$	0	0

The coefficients g_V and g_A enter into the differential spectrum of recoil electrons from elastic neutrino-electron scattering, which has the form

$$\frac{d\sigma}{dE} = \frac{G^2 m}{\pi} \left[(g_V + g_A)^2 + (g_V - g_A)^2 \left(1 - \frac{E}{E_\nu}\right)^2 + \frac{mE}{E_\nu^2} \left(g_A^2 - g_V^2\right) \right] \tag{14}$$

where E and E_ν are the lab energies of recoil electron and incident neutrino, m is the electron mass. The cross-sections for the reactions in Table III are shown in Fig. 6.

i) Observations on the process $\bar{\nu}_e + e^- \to e^- + \bar{\nu}_e$

As indicated in (14) and in Fig. 6, the cross-section for this reaction in the Weinberg and V-A theories is

$$\text{V-A} \qquad \sigma(\bar{\nu}_e\, e^- \to e^-\, \bar{\nu}_e) = \frac{4}{3}\frac{G^2 m}{\pi} E_\nu = 0.54 \times 10^{-41}\, E_\nu \text{ cm}^2/\text{electron}$$

$$\text{Weinberg} \quad \sigma(\bar{\nu}_e\, e^- \to e^-\, \bar{\nu}_e) = (0.136 \to 2.86) \times 10^{-41}\, E_\nu \text{ cm}^2/\text{electron} \qquad (15)$$

The form of the electron spectrum, in the approximation $E_\nu >> m$, is indicated in Fig. 7. The important point is that the shape of the recoil spectrum depends on e^2/g^2; in particular, if e^2/g^2 is in the region of its maximum value (unity) the proportion of recoil electrons near the end-point $E \sim E_\nu$ is much greater than for the V-A case, or for $e^2/g^2 \sim 0$.

An experiment to detect the scattering of antineutrinos $\bar{\nu}_e$ by electrons has been carried out by Gurr, Reines and Sobel (1972) using the Savannah River reactor. Events were recorded in 7.8 kg segmented plastic scintillator, surrounded by 330 kg NaI and 2200ℓ liquid scintillator in anticoincidence. Neutron and γ-shielding was provided by means of a 20 cm thick Pb blanket as well as water tanks. The expected signal was sought for by measuring the (reactor on - reactor off) difference, Δ, averaged over a period of 150 days. In order to reduce background effects as much as possible, only relatively high energy recoil electrons ($3.6 < E < 5$ MeV) were recorded. Since at these energies, the reactor spectrum (Fig. 8) is falling off very rapidly, and because of the form of the recoil spectrum (Fig. 7), the rate depends very critically on the cut-off energy. Table IV shows typical results on count rates from the experiment, as well as the expected value of the reactor-associated

TABLE IV

Counting rates, per day, from the reactor experiment of Gurr et al, averaged over 150 days. The rates are for recoil electrons within the energy range $E_{min} < E < 5$ MeV.

E_{min} (MeV)	R_{on}	R_{off}	Δ(expt)	Δ(V-A)
3.0	6.43 ± 0.26	6.49 ± 0.35	-0.06 ± 0.44	0.40
3.4	1.82 ± 0.18	1.81 ± 0.18	+0.01 ± 0.22	0.21
3.8	0.68 ± 0.08	0.54 ± 0.10	+0.14 ± 0.13	0.12

signal, if it is entirely due to $\bar{\nu}_e\, e^- \to e^-\, \bar{\nu}_e$ scattering according to the V-A theory. However, the observed difference (if it is real) is also consistent with the expected effects from various background processes, the chief of which is $\bar{\nu} + p \to n + e^+$. The conclusion of the authors is that the upper limit to the rate, at the one standard deviation level, is $\lesssim 0.2$ events/day, corresponding to a partial cross-section $\sigma < 6.10^{-47}$ cm^2/ electron for producing recoil electrons inside the range $3.6 < E < 5$ MeV. This is probably the lowest cross-section limit that has ever been measured. The stated limit corresponds to $\sigma \lesssim 1.9\ \sigma_{V-A}$ (1 s.d.) or at 90% C.L:-

$$\sigma \lesssim 3\ \sigma_{V-A} \tag{16}$$

It must be emphasized that the experiment is an extremely difficult one. The result (16) is arrived at by assuming errors on counting rate differences are purely statistical, and that possible absolute errors in the computed $\bar{\nu}_e$ spectrum (stated to be of accuracy ±10%), calibration of detectors, counter efficiencies etc have negligible effect. It should also be borne in mind that direct checks of the antineutrino spectrum, for example from the cross-section for the reaction $\bar{\nu}_e + p \to n + e^+$, could not in themselves exclude 50% uncertainties in the flux in the high energy tail (i.e.at $\sim$5 MeV).

Setting aside these reservations, the experiment leads to limits on e^2/g^2 for the Weinberg theory. In Fig. 9, the falling curve indicates the 90% C.L. limit on cross-section in terms of e^2/g^2. As explained previously (Fig. 7), the acceptance improves as e^2/g^2 increases and the recoil spectrum becomes flatter, so that the cross-section limit falls. The Weinberg cross-section (14) is indicated by the rising curve. The calculations were made independently by C. Baltay (1972) and B.W. Lee (1972), and lead to a similar result, which is

$$\boxed{e^2/g^2 < 0.35} \qquad 90\%\ \text{C.L.} \tag{17}$$

ii) Observations on the process $\nu_\mu + e^- \to e^- + \nu_\mu$; $\bar{\nu}_\mu + e^- \to e^- + \bar{\nu}_\mu$

New data was presented at the conference on these reactions from the CERN Gargamelle collaboration (Brisson, paper no. 785), which includes Aachen, Brussels, CERN, Milan, Orsay, Ecole Polytechnique, and UCL. In 160,000 ν and 223,000 $\bar{\nu}$ pictures analysed to date, a scan was made for candidates for the above reactions fulfilling the criteria

$$E_{recoil} > 0.3\ \text{GeV}$$

$$\theta_{recoil} < 5°$$

In the heavy liquid (CF_3Br) employed, single energetic electrons are readily observed, through the characteristic showers they produce. In the elastic scattering process, the recoil travels in the forward direction ($\theta_{recoil} \sim \sqrt{\frac{2m}{E_\nu}} \sim 1°$ for typical energies in the CERN beam), so that the signature of a genuine event is very clear-cut.

The result of the experiment to date was that no candidates were observed, and that any possible background contributions (for example, any γ background, or events of the type $\nu_e + n \rightarrow e^- + p$, with the proton absorbed in the nucleus) are quite negligible. Using the measured scanning efficiencies for γ-rays, the 90% C.L. limits on the cross-sections are

$$\left.\begin{array}{l} \sigma(\nu_\mu\, e^- \rightarrow e^-\, \nu_\mu) < 0.7 \times 10^{-41}\, E_\nu \text{ cm}^2\text{/electron} \\ \sigma(\bar{\nu}_\mu\, e^- \rightarrow e^-\, \bar{\nu}_\mu) < 1.0 \times 10^{-41}\, E_\nu \text{ cm}^2\text{/electron} \end{array}\right\} \quad (E_\nu \text{ in GeV})^* \qquad (18)$$

These numbers were obtained by comparing the upper limit on the number of electron events with the total number of events in the film, using the relations σ^ν (tot) = $0.7 \times 10^{-38}\, E_\nu$ and $\sigma^{\bar{\nu}}$(tot) = $0.27 \times 10^{-38}\, E_\nu$ (cm²/nucleon) given in Part III of this report.

Fig. 10 shows the expected number of events, according to the Weinberg theory, for the antineutrino and neutrino runs separately, and the sum of the two. The integration over the CERN spectrum, taking into account the acceptance criterion $E_{recoil} > 0.3$ GeV, was performed by C. Baltay (1972). [Note that dividing the running time equally between neutrinos and antineutrinos gives a better coverage of all values of the Weinberg angle than neutrinos alone, despite the three-fold lower antineutrino flux. This was just a piece of good luck, rather than judgement at the time the exposures were planned]. The limit set by these results for the Weinberg theory is

$$\boxed{e^2/g^2 < 0.6} \qquad (19)$$

B) Experiments on Hadronic Neutral Weak Currents

i) The Process $\nu_\mu\, p \rightarrow \nu_\mu p$

Limits on this neutral current process have been given in an old CERN propane chamber experiment (Cundy *et al* 1970). Since one observes only a recoil proton,

---

* According to the V-A theory, the corresponding cross-section for $\nu_e\, e^- \rightarrow e^-\, \nu_e$ is $1.6 \times 10^{-41}\, E_\nu$ cm²/electron.

and it was necessary to limit the neutron background ($np \to np$), cuts were made on the momentum transfer ($0.3 < q^2 < 1$ GeV^2) and on the fitted neutrino energy ($1 < E_\nu < 4$ GeV) using the elastic kinematics on free protons in the propane. Comparison was made with the charge-changing reaction $\nu n \to \mu^- p$ for the same events on energy and momentum transfer to the hadron, with the result

$$R = \frac{\sigma(\nu p \to \nu p)}{\sigma(\nu n \to \mu^- p)} = 0.12 \pm .06 \tag{20}$$

The observed "$\nu p \to \nu p$" candidates were in fact ascribed to neutron background. The expected value of R, for neutral currents, has been given by Weinberg (1971), but only for the case where $q^2 \simeq 0$. For the range $0.3 < q^2 < 1$ GeV^2 employed in the experiment, integration of the Weinberg formulae gives the curve shown in Fig. 11 due to Myatt (1972). From (20) the 90% C.L.upper limit is

$$R < 0.22$$

or from Fig. (11)

$$\boxed{e^2/g^2 < 0.85} \tag{21}$$

This limit is inferior to that from the leptonic neutral current processes, (19) and (17.

ii) Single Pion Production; $\nu n \to \nu n \pi^o$, $\nu p \to \nu p \pi^o$, $\nu p \to \nu n \pi^+$

There have been, to date, 4 experiments to look for possible evidence of single pion production via weak neutral currents; the results of 2 of these were presented in the parallel sessions.

a) CERN 1.2m Propane Chamber Experiment (Cundy *et al* 1970)

This experiment found for the ratio

$$\frac{\sigma(\nu p \to \nu n\ \pi^+)}{\sigma(\nu p \to \mu^- p \pi^+)} \leq 0.08 \pm 0.04$$

If we assume pion production dominated by the (3,3) resonance, this gives

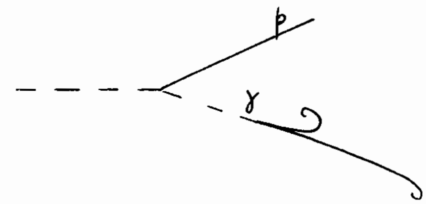
$$R_1 = \frac{\sigma(\nu p \to \nu \Delta^+)}{\sigma(\nu p \to \mu^- \Delta^{++})} = \frac{3\sigma(\nu p \to \nu n \pi^+)}{\sigma(\nu p \to \mu^- p \pi^+)} < 0.46 \quad (90\%\ \text{C.L.}) \tag{22}$$

b) ANL 12' H_2,D_2 Chamber Experiment (Cho *et al* 1972)

The experiment sought to determine a limit on the ratio

$$\frac{\sigma(\nu p \to \nu p \pi^o)}{\sigma(\nu p \to \mu^- p \pi^+)}$$

by looking for events consisting of a single proton, with a converted γ-ray pointing at one end of the proton track (see sketch). Background events due to $np \to np\pi^o$ were subtracted by measuring the cross-section for $np \to pp\pi^-$ (2C fit) and assuming Δ dominance. The final result of the experiment was to give



$$R_1 = \frac{\sigma(\nu p \to \nu\Delta^+)}{\sigma(\nu p \to \mu^-\Delta^{++})} < 0.31 \qquad (90\%\ \text{C.L.}) \qquad (23)$$

The results (22) and (23) are compared with the theoretical estimate of R_1 by Paschos and Wolfenstein (1972) from the Weinberg theory, in Fig. 12. Evidently neither experiment sets any useful limit on the parameter e^2/g^2.

c) Columbia Spark-Chamber Experiment (W. Lee 1972)

The events were recorded in the early Columbia/BNL neutrino experiment, in ¼" thick aluminium plate spark-chambers. Events were observed which were attributable to $\nu n \to \nu n\pi^o$ or $\nu p \to \nu p\pi^o$, and to $\nu n \to \mu^- p\pi^o$ (shower events with or without a penetrating charged particle (muon)). The observed ratio of event numbers was

$$R_2' = \frac{\sigma(\nu n \to \nu n\pi^o) + \sigma(\nu p \to \nu p\pi^o)}{2\sigma(\nu n \to \mu^- p\pi^o)} \leq \frac{5}{2 \times 12}$$

without any cuts. A problem in this experiment is that isolated γ showers can be confused with electron showers from the background process $\nu_e n \to e^- p$. If the π^o's come from decay of a low-lying resonance, they will generally be of low energy, whilst the electron events will be generally of 1 GeV or more. So the cut $E_{\pi^o} < 0.4$ GeV (based on a spark count) was made. This left no neutral current candidates, and the corrected ratio

$$R_2 = \frac{\sigma(\nu n \to \nu n\pi^o) + \sigma(\nu p \to \nu p\pi^o)}{2\sigma(\nu n \to \mu^- p\pi^o)} = \frac{0}{2 \times 9} \qquad (24)$$

or

$$R_2 < 0.14, \quad 90\%\ \text{C.L.} \qquad \text{(but read on !)}$$

In fact, although these reactions have been written as if they occurred on single nucleons, they of course took place in nuclei (aluminium). In complex nuclei, charge-exchange effects are important. This is illustrated by the early CERN

CF_3Br bubble chamber experiments. They measured the ratio of single π^o to single π^+ production i.e. in terms of elementary cross-sections

$$Q = \frac{\sigma(\nu n \to \mu^- p\pi^o)}{\sigma(\nu p \to \mu^- p\pi^+) + \sigma(\nu n \to \mu^- n\pi^+)}$$

If the pion-nucleon state is pure $\Delta(\frac{3}{2}, \frac{3}{2})$, we expect $Q = 2/(9 + 1) = 0.2$. Experimentally, one observed $Q = 0.5$! Although a ratio $\frac{1}{2}$ is expected for pure $I = \frac{1}{2}$, rather than $\frac{3}{2}$, the result probably means that although $I = \frac{3}{2}$ is dominant, charge-exchange effects inside the nucleus are very important (a conclusion reinforced by the observation of a few events with π^-). If we take this viewpoint, we are forced to conclude that the $\mu^-\pi^o$ events are at least double the number from $\nu n \to \mu^- p\pi^o$ direct. The effect may be smaller in aluminium, but clearly the denominator in (24) needs to be divided by a factor of up to 2 (the numerator is already zero, so we cannot reduce it). So the true upper limit to R_2 may be as high as 0.25.

d) CERN-Gargamelle CF_3Br Experiment (1972)

New preliminary results on the ratio R_2 were presented by Cho in a parallel session. On a small sample of the neutrino film, the ratio

$$\frac{N(\text{single } \pi^o + (0 \text{ or } 1 \text{ proton}))}{2N(\text{single } \pi^o + \mu^- + (0 \text{ or } 1 \text{ proton}))} = \frac{8}{128}$$

This includes a fiducial volume cut to eliminate, as far as possible, neutron-induced events, predominantly around the walls of the chamber, but there was no π^o energy cut, as $\nu_e \to e^-$ events are easily distinguished. Thus, neglecting charge-exchange effects, the above figures give

$$R_2 = \frac{\sigma(\nu n \to \nu n\pi^o) + \sigma(\nu p \to \nu p\pi^o)}{2\sigma(\nu n \to \mu^- p\pi^o)} \leq 0.11 \quad (90\%\ \text{C.L}) \qquad (25)$$

which is consistent with (24).

In freon (CF_3Br) we know that charge exchange is important. If we assume $I = \frac{3}{2}$ dominance, then in the numerator of (25), extra π^o events can be fed in via charged pion production, where $\sigma(\nu p \to \nu\pi^+ n + \nu n \to \nu\pi^- p) \simeq \frac{1}{2}\sigma(\nu n \to \nu n\pi^o + \nu p \to \nu p\pi^o)$. In the denominator, however, the effects of the Clebsch-Gordan coefficients are much more severe, since $\sigma(\nu p \to \mu^- p\pi^+ + \nu n \to \mu^- n\pi^+) = 5\sigma(\nu n \to \mu^- p\pi^0)$. Thus again, the quoted ratio (25) must be multiplied by a factor of order 2.5 to get a more reliable number.

Finally we come to the theoretical predictions of R_2 from the Weinberg model. Fig. 13 shows some of the results. The curve due to Paschos and Wolfenstein (1972) assumes $\Delta(I = \frac{3}{2})$ dominance. Of course, this is observed to be the case for the process $\nu p \to \mu^- \pi^+ p$ described earlier, where $I = \frac{3}{2}$ necessarily; but there are no strong reasons for supposing it to dominate in $\nu p \to \nu p\pi^0$, for example. Thus, Paschos and Lee (1972) and Albright, Lee and Paschos (1972) have assumed 30% $I = \frac{1}{2}$ incoherent admixture, with the result that R_2 falls by a factor of around 2 in the region of interest.*

The results (24) and (25) in themselves suggest therefore that e^2/g^2 is large. If however one assumes the Reines limit $e^2/g^2 < 0.35$, the lower limit to the expected values of R_2 are $R_2 > 0.5$ ($I = \frac{3}{2}$ only) or $R_2 > 0.27$ with 30% $I = \frac{1}{2}$ admixture. This is hardly a decisive discrepancy with the data, equations (24) and (25), if one bears in mind the reservations on the data made above. Any possible discrepancy is of course removed if we ignore the reactor experiment and take only the CERN limit (19) on leptonic neutral currents.

iii) Inclusive Neutrino Reactions

Many of the experimental and theoretical difficulties which bedevil the discussion of neutral weak hadronic currents in specific reaction channels, as in the example of single pion production described above, are avoided if one considers the deep inelastic inclusive processes. Thus one compares the ratio

$$R_{incl} = \frac{\sigma(\nu + N \to \nu \;\; + \text{anything})}{\sigma(\nu + N \to \mu^- + \text{anything})} \tag{26}$$

for the same range of energy/momentum transfer to the nucleon. A detailed study of this problem is under way in the CERN Gargamelle experiments. Among the backgrounds which give events simulating $\nu N \to \nu \;$ + anything, are of course (i) high energy neutrons, (ii) high energy K^0's in equilibrium with the neutrino beam as it traverses the muon shield, (iii) genuine ($\nu + N \to \mu^-$ + anything) events where the μ^- is of very short range and undergoes nuclear capture rather than decay and can be classified as a proton, and so forth. The full analysis will therefore take some time.

---

*The small differences in the curves marked "Paschos and Lee" and "Albright, Lee and Paschos" in Fig. 13 arise from the fact that the asymptotic cross section for $\nu p \to \mu^- \Delta^{++}$, which enters the calculation, was based in the first case on the CERN value $(1.13 \pm 0.28)\, 10^{-38}\ \text{cm}^2$ and in the second, on the ANL value $(0.78 \pm 0.16) \times 10^{-38}\ \text{cm}^2$.

In the old CERN HLBC experiment, an analysis by the author gave $R_{incl} < 0.17$. Theoretical predictions of (26) according to the Weinberg model have been given by several authors. For example, Pais and Treiman (1972) invoke Bjorken scaling in inclusive reactions and the quark-parton relation $W_{1,2}(V) = W_{1,2}(A)$, and obtain:-"

$$R_{incl} = \tfrac{1}{2}\left(1 - \frac{2e^2}{g^2}\right) + \frac{8G^2ME\int_0^1 F_2^{em}\,dx}{3\pi\,\sigma(\nu + N \to \mu^- + \text{anything})}\left(\frac{e^4}{g^4}\right) \tag{27}$$

$$= \tfrac{1}{2} - \frac{e^2}{g^2} + 0.83\,\frac{e^4}{g^4}$$

using the results on inclusive electromagnetic and weak cross-sections discussed in Part III of this report. Thus, using no information whatever from the previous limits on e^2/g^2, one finds

$$0.5 > R_{incl} > 0.2 \tag{28}$$

In this sense, the inclusive processes apparently offer the best possibility of proving or disproving the Weinberg theory as applied to hadronic weak neutral currents; such data as is available now suggest that the experimental value of R_{incl} is somewhat below the limit (28). However, one can criticize any results from existing neutrino experiments on the grounds that the events are not in the true scaling region.

C) Conclusions about Neutral Currents

As far as the Weinberg theory is concerned, the most definitive and unambiguous evidence for or against, must come from the purely leptonic reactions considered in (A), since the hadronic processes involve details of strong interactions which might contain unknown suppression effects. The question therefore arises as to possible improvements in the accuracy of the neutrino-electron scattering experiments in the future.

As I have tried to indicate, the reactor experiment is beset with severe background problems. Even if in future improved experiments, a clear signal is detected, it is necessary, in order to finally demolish the Weinberg theory, to prove that the observed signal rate is consistent with the V-A predictions within close limits. It is difficult to believe that this could be achieved to a precision of better than 20%.

On the other hand, a continued search for the reactions $\nu_\mu + e^- \to \nu_\mu + e^-$ and $\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$ is much more promising, since a signal is a certain indication of neutral currents. In the CERN Gargamelle experiment to date, the expected number of events was between 1 and 9, and none was observed. The scheduled continuation of the experiment, if the CERN Booster were operated at 5.10^{12} ppp, would give a total expected event number between 5 and 50. If none were observed, this would be fairly conclusive evidence against the Weinberg theory.

In this section, I have discussed neutral currents only from the standpoint of the Salam-Ward- Weinberg theory. The possibility of detecting possible neutral currents at a much lower level appears remote. For example, the ultimate lower limit on the cross-section for $\bar{\nu}_\mu + e^- \rightarrow e^- + \bar{\nu}_\mu$ in high energy neutrino experiments is set by the $\bar{\nu}_e$ background from $K^- \rightarrow e^- \bar{\nu}_e \pi^0$ decay. The $\bar{\nu}_e$ flux is around 0.5% of the $\bar{\nu}_\mu$ flux, so that it would be difficult to reach a limit on $\sigma(\bar{\nu}_\mu + e^- \rightarrow e^- + \bar{\nu}_\mu)$ much below 1% of the V-A cross-section for $\bar{\nu}_e + e^- \rightarrow e^- + \bar{\nu}_e$.

The summarized results on neutral current cross sections are given in Table 5.

TABLE 5

Limits on Neutral Current Couplings

Cross Section	Authors	90% C.L. Upper Limit
$\sigma(\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-)$	Gurr, Reines, Sobel PRL 28 1406 (1972)	$< 3.0\ \sigma_{V\text{-}A}(\bar{\nu}_e + e^- \to e^- + \bar{\nu}_e)$
$\sigma(\nu_\mu + e^- \to \nu_\mu + e^-)$	CERN Gargamelle (#785)	$< 0.44\ \sigma_{V\text{-}A}(\nu_e + e^- \to e^- + \nu_e)$
$\sigma(\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-)$	CERN Gargamelle (#785)	$< 0.62\ \sigma_{V\text{-}A}(\nu_e + e^- \to e^- + \nu_e)$
$\dfrac{\sigma(\nu_\mu n \to \nu_\mu n\pi^0 + \nu_\mu p \to \nu_\mu p\pi^0)}{2\sigma(\nu_\mu n \to \mu^- p\pi^0)}$	W.Y. Lee (#239)	< 0.14 See comments in text
$\dfrac{\sigma(\nu_\mu n \to \nu_\mu n\pi^0 + \nu_\mu p \to \nu_\mu p\pi^0)}{2\sigma(\nu_\mu n \to \mu^- p\pi^0)}$	CERN Gargamelle (#785)	< 0.11
$\dfrac{\sigma(\nu_\mu p \to \nu_\mu \Delta^+)}{\sigma(\nu_\mu p \to \mu^- \Delta^{++})}$	Cundy et al PL 31B, 478 (1970) Cho et al (#473)	< 0.46 < 0.31
$\dfrac{\sigma(\nu_\mu p \to \nu_\mu p)}{\sigma(\nu_\mu n \to \mu^- p)}$	Cundy et al ibid)	< 0.22
$\dfrac{\sigma(\nu_\mu N \to \nu_\mu + \text{anything})}{\sigma(\nu_\mu N \to \mu^- + \text{anything})}$	CERN 1.2m HLBC (unpublished)	$\lesssim 0.2$

CROSS-SECTIONS

A. Scaling Behaviour of Total Cross-Sections

As reported by Heusse in a parallel session (paper #783), preliminary data has been obtained from the analysis of about 1000 antineutrino and 1000 neutrino interactions of E > 1 GeV in the CERN Gargamelle chamber.

Cross-sections have been measured for the inclusive reactions

$$\nu_\mu + N \to \mu^- + \text{anything}$$

$$\bar{\nu}_\mu + N \to \mu^+ + \text{anything}$$

Since a wideband beam is employed, the incident energy in each event is found by equating it to the visible energy of secondaries in the chamber. Since the chamber dimensions are 4.5m x 1.5m, and the radiation length and nuclear interaction length in the liquid(CF_3Br)are 0.11m and 0.70m respectively, γ-rays, neutrons etc. are detected with high efficiency and only minor corrections for energy loss need be applied. In freon (CF_3Br), the neutron proton ratio is 1.19; therefore, to good approximation, the cross-section measured represents* the isospin-averaged cross-section, $(\sigma_n + \sigma_p)/2$.

The total ν and $\bar{\nu}$ cross-sections as a function of energy are shown in Fig. 14. In this as in the previous experiment in the CERN 1.2m chamber (Budagov et al 1970), the data can be fitted by a linear relation

$$\sigma = \alpha E \tag{29}$$

where the values of the coefficient α are given in Table 6.

---

* For the effects of $n/p \neq 1$ on the analysis, see para. B7 (ii) below.

TABLE 6

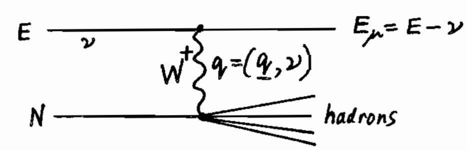
Total Cross-Sections

Experiment	Target	$\alpha = \sigma/E$ (units 10^{-38} cm^2/nucleon GeV)	Energy Range	# Events (E > 1 GeV)
CERN 1.2m HLBC	C_3H_8	$\alpha_\nu = 0.80 \pm 0.20$	1-10 GeV	900
Gargamelle	CF_3Br	$\alpha_\nu = 0.69 \pm 0.14$	1-10 GeV	1000
Gargamelle	CF_3Br	$\alpha_{\bar{\nu}} = 0.27 \pm 0.05$	1- 9 GeV	1000
$R = \sigma^{\bar{\nu}}/\sigma^{\nu} = 0.38 \pm 0.02$			2- 9 GeV	---
$\frac{dR}{dE} = -0.01 \pm 0.016\ GeV^{-1}$			2- 9 GeV	

Errors for the Gargamelle data include a ±15% error on absolute flux calibration and a ±5% error on relative ($\bar{\nu}/\nu$) flux calibration. The cross-section ratios are given in Fig. 15.

As is well known, a linear dependence of σ on E is expected from Bjorken scaling in the deep inelastic region. For later use we write down the relevant formulae here. We denote the space-time components of the 4-momentum transfer from lepton to nucleon by $q = (\underline{q},\nu)$ where $\nu = E - E_\mu$ is the energy transfer in the nucleon rest-frame. In the scaling region, the cross-section is a function of the ratio of the two Lorentz scalars q^2 and ν, in terms of the scaling variables

$$x = q^2/2M\nu \qquad (1 > x,\ y > 0) \qquad (30)$$
$$y = \nu/E$$



The differential cross-section has the form:-

$$\mathrm{Lt}\left\{\begin{matrix} E \to \infty \\ q^2 \to \infty \\ \nu \to \infty \\ x,y \text{ finite}\end{matrix}\right\} \frac{d^2\sigma^{\nu,\bar{\nu}}}{dx\,dy} = \frac{G^2ME}{\pi}\left[\{1 - y(1 + \cancel{\frac{Mx}{2E}})\}\,F_2(x) + \frac{y^2}{2}\,\{2xF_1(x)\} \mp y(1 - \frac{y}{2})\,\{xF_3(x)\}\right] \tag{31}$$

where the third term in the coefficient of F_2 drops out as $E \to \infty$. Integration of (31) gives $\sigma \propto E$. The three structure functions F_1, F_2 and F_3 depend only on the dimen$ionless variable x. The final term (F_3) is the V-A interference term, which changes sign under neutrino/antineutrino interchange. Eqn. (31) can also be written in terms of the hypothetical absorption cross-sections for the mediating vector bosons $W^{\pm}$:-

$$\frac{d^2\sigma^{\nu,\bar{\nu}}}{dx\,dy} = \frac{G^2ME}{\pi}\,F_2(x)\,\left[(1 - y) + \frac{y^2}{2}\,(R + L) \mp y(1 - \frac{y}{2})\,(L - R)\right] \tag{32}$$

with

$$\begin{aligned} R &= \sigma_R/(\sigma_R + \sigma_L + 2\sigma_S) \\ L &= \sigma_L/(\sigma_R + \sigma_L + 2\sigma_S) \end{aligned} \tag{33}$$

where σ_L, σ_R and σ_S are the absorption cross-sections for left-handed, right-handed and scalar currents (bosons). The sign change in going from neutrino to antineutrino ($L \leftrightarrow R$) is then obvious. Since σ_L,σ_R and σ_S must be positive definite, the positivity conditions on the F_i are

$$|xF_3| \leq 2x\,F_1 \leq F_2 \tag{34}$$

The remarkable feature about the data in Fig. 14 is that the scaling relation $\sigma \propto E$ is observed, although the data refer to the shallow, rather than deep, inelastic region. "True" scaling is observed in the SLAC e-p and e-n experiments only for ν/M and $q^2/M^2 > 2$-3. In the neutrino experiments, we have at E = 5 GeV, $\overline{q^2} \sim 1$ GeV and $\bar{\nu} \sim 2$ GeV; while at 2 GeV, $\overline{q^2} = 0.4$ and $\bar{\nu} = 1$ only. The ultra-precocious scaling in this case may have an explanation in dual models (Bloom and Gilman 1970).

B. Comparison of Neutrino-Nucleon and Electron-Nucleon Inclusive Cross-Sections

An important question is to what extent the coefficients α in Table 6 measured in low-energy (< 10 GeV) neutrino experiments, really represent the behaviour of weak cross-sections in the "true" (high energy) scaling region. It is instructive to compare the coefficients with the SLAC/MIT data in the scaling region (Bloom et al 1970). As explained previously, this comparison has, for the present, to be limited to the neutron-proton average cross-sections.

The steps in the comparison are as follows:-

1) Assume $2xF_1 = F_2$ (the Callan-Gross relation). This follows if the longitudinal cross-section in (33) can be neglected in comparison with the transverse i.e. $\sigma_S \ll \sigma_L, \sigma_R$. This seems to be the case in the SLAC/MIT data. The equation $2xF_1 = F_2$ corresponds to spin $\frac{1}{2}$ partons in the constituent models. (It is simply the relation between magnetic and electric scattering for Dirac point particles of g = 2 and mass xM). Further, the closeness of the ratio $\sigma_{\bar{\nu}}/\sigma_\nu$ to $\frac{1}{3}$, as discussed below, positively requires dominance of spin $\frac{1}{2}$ constituents; any other spin $0,1,\frac{3}{2}$ ... etc. would give $\frac{1}{3} < \sigma_{\bar{\nu}}/\sigma_\nu < 3$.

2) Assume the Cabibbo angle $\theta_C = 0$, for simplicity, so that one neglects $\Delta S = 1$ transitions. (The small correction required for $\Delta S = 1$ processes is discussed later).

Then from isospin symmetry (i.e. $\Delta I = 1$ only if $\Delta S = 0$ only) we get

$$F_i^{\bar{\nu}p} = F_i^{\nu n}, \quad F_i^{\bar{\nu}n} = F_i^{\nu p} \qquad i = 1,2,3.$$

Thus writing N as a neutron-proton average

$$\underline{F_i^{\bar{\nu}N}} = \frac{1}{2}(F_i^{\bar{\nu}n} + F_i^{\bar{\nu}p}) = \underline{F_i^{\nu N}} \tag{35}$$

3) Integrating (31) we then have

$$\frac{d\sigma^{\nu N,\bar{\nu}N}}{dy} = \frac{G^2ME}{\pi}\left[\int_0^1 F_2^{\nu N}\,dx\right]\left[1 - (1 \mp B)\left(y - \frac{y^2}{2}\right)\right] \tag{36}$$

where the quantity B contains the V-A interference term F_3:-

$$B = -\int_0^1 x\,F_3^{\nu N}\,dx \Big/ \int_0^1 F_2^{\nu N}\,dx \tag{37}$$

If we now add ν and $\bar{\nu}$ cross-sections, the B-term will drop out. Integrating over y then gives

$$\sigma^{\nu N} + \sigma^{\bar{\nu}N} = \frac{G^2ME}{\pi} \cdot \frac{4}{3} \cdot \int_0^1 F_2^{\nu N}\, dx$$

From the coefficients in Table 6 we get

$$\boxed{\begin{aligned}\int F_2^{\nu N}\, dx &= \frac{3\pi}{4G^2M} (\alpha^{\nu} + \alpha^{\bar{\nu}}) \\ &= 0.47 \pm 0.07\end{aligned}} \tag{38}$$

(This equation has a simple meaning in the constituent models. Thus, write D(x) and U(x) for the number of partons in the neutron with 4-momentum x, with isospin "down" and "up" respectively, with $\bar{D}(x)$ and $\bar{U}(x)$ for antipartons. Assuming isospin ½ partons, then $F_2^{\nu n}(x) = 2x\{D(n) + \bar{D}(x)\}$ while $F_2^{\nu p}(x) = 2x\,\{U(x) + \bar{U}(x)\}$. So

$$\int F_2^{\nu N} dx = \int x\, [D(x) + \bar{D}(x) + U(x) + \bar{U}(x)]\, dx \tag{39}$$

is simply the fractional 4-momentum of the nucleon carried by all isovector constituents. The remaining 4-momentum (53%) therefore has to be ascribed to gluons, $\Lambda\bar{\Lambda}$ pairs or other isoscalar objects).

4) Next we consider the SLAC/MIT electron scattering data which give

$$\int_0^1 F_2^{\gamma n}\, dx = 0.12 \pm 0.02, \quad \int_0^1 F_2^{\gamma p} dx = 0.16 \pm 0.02$$

or

$$\int F_2^{\gamma N} dx = 0.14 \pm 0.02 \tag{40}$$

where the errors are to cover the extrapolation of the integrals from the actual lower limit of the data (x = 0.08) to x = 0. The electromagnetic cross-sections contain both isovector and isoscalar contributions. In high energy photoproduction, the ratio (isoscalar)/(isovector) = 0.1 and assuming a similar result for virtual photons we can estimate

$$\left[\int F_2^{\gamma N} dx\right]_{\text{isovector}} = 0.13 \pm 0.02 \tag{41}$$

5) The extended CVC hypothesis, namely that the e.m. isovector and weak vector (V) currents ($\Delta S = 0$) are the I_3 and $I_{\pm}$ components of the same isospin current, predicts

$$[\int F_2^{\gamma N}\,dx]_V = 2[\int F_2^{\gamma N}\,dx]_{\text{isovector}}$$

6) Finally chiral symmetry, or $|V| = |A|$ coupling for the weak hadronic current - as indicated by the success of the Adler-Weisberger relation - gives

$$[\int F_2^{\nu N}\,dx]_{V,A} = 4[\int F_2^{\gamma N}\,dx]_{\text{isovector}}$$

or from (41):

$$\boxed{\int F_2^{\nu N}\,dx = 0.52 \pm 0.08} \tag{42}$$

This is the prediction from the electron data and the minimum number of assumptions of general principle, and is to be compared with the observed value (38).

7) Two minor corrections can be introduced to the neutrino data:-

(i) First we should subtract off the observed $\Delta S = 1$ part of the cross-section, and replace G^2 in (38) by $G^2 \cos^2\theta_{\text{Cabibbo}}$. This is strictly necessary in the comparison with the electron data, which can apply only to the $\Delta S = 0$ cross-section. As indicated below, roughly 4% of the $\bar{\nu}$ cross-section and 1% of the ν cross-section come from $\Delta S = -1$ and $\Delta S = +1$ processes. With $\sec^2\theta_{\text{Cabibbo}} = 1.065$, $\int F_2^{\nu N}dx$ in (38) is increased by 5 %.

(ii) If $\sigma^{\nu n} > \sigma^{\nu p}$, the n/p averaged cross-section will be less than the cross-section per nucleon in freon, which has $n/p = 1.19$. An approximate estimate is found by assuming $\sigma^{\nu n}/\sigma^{\nu p} = \sigma^{\bar{\nu} p}/\sigma^{\bar{\nu} n} = 2$, as suggested by the quark model. Then $\alpha^{\nu N} = 0.97\,\alpha^{\nu}$ (freon), and $\alpha^{\bar{\nu} N} = 1.03\,\alpha^{\bar{\nu}}$(freon). This has the effect of reducing $\int F_2^{\nu N}\,dx$ by 1.5%.

Thus, the effect of corrections (i) and (ii) is to give a slightly revised value

$$\boxed{[\int F_2^{\nu N}\,dx]_{\Delta S = 0} = 0.49 \pm 0.07} \tag{43}$$

The agreement between (43) and the prediction (42) lends strong support to the view that the coefficients α in Table 6, determined in the low energy region $1 < E < 10$ GeV, in fact closely represent the values in the scaling region at high energy. The results are summarized in Table 7. Considering the quite different techniques in the two sets of experiments, the measure of agreement is somewhat miraculous.

TABLE 7

Observed and Predicted Values of $\int F_2^{\nu N}\,dx = \frac{1}{2}\int(F_2^{\nu n} + F_2^{\nu p})dx$

Neutrino Data		From electron data, using CVC, $\lvert V\rvert = \lvert A\rvert$ & 10% isoscalar
0.47 ± 0.07	0.49 ± 0.07	0.52 ± 0.08
assuming $\theta_c = 0$	corrected for $\Delta S = 1$,	
n/p = 1	n/p = 1.19 in freon	

C. Comparison with Parton Models

The values of $\int F_2^{\nu N}/ F_2^{\gamma N}$ predicted by the different parton models have been given in numerous papers (for example Llewellyn-Smith (1972), Nachtmann (1972), Gourdin (1971)),, and are summarized in Table 8. As emphasized by Feynmann in the parallel session, the Gell-Mann/Zweig quark model with fractional charges, either in the original form or in the red, white and blue version of Gell-Mann, is in close agreement with both the observed ratio $\int F_2^{\nu N}/\int F_2^{\gamma N}$ and the value of $\sigma^{\bar{\nu}}/\sigma^{\nu}$. It is also unique in predicting correctly the limit $F_2^{\gamma n}(x)/F_2^{\gamma p}(x) \sim 0.25$ as $x \to 1$.

The new neutrino data does not exclude the Han-Nambu model, which however is in trouble with the e-n/e-p scattering ratio.

D. Gluon Contributions

In the framework of the Gell-Mann/Zweig quark model, the new neutrino data, together with the electron data, give enough information to determine the gluon contribution (rather than set limits on it). In the nomenclature above, and with S-$\bar{S}$ to represent strange quarks and anti-quarks, we have

TABLE 8

Quark Model Predictions (all spin $\frac{1}{2}$)

Model	Nucleon Built From :-	$\frac{\int F_2^{\nu N} dx}{\int F_2^{\gamma N} dx}$	$\sigma^{\bar{\nu}}/\sigma^{\nu}$	$F_2^{\gamma n}(x)/F_2^{\gamma p}(x)$ $x=1 \rightarrow 0$
Gell-Mann/Zweig	3 fractional charge quarks	3.6 $(=\frac{18}{5})$	$\frac{1}{3}$	$\frac{1}{4} \rightarrow 1$
	3 valence quarks + many $Q\bar{Q}$ pairs	~ 3.0	~ 1.0	~ 1
Han-Nambu	3 integral charge triplets	$\lesssim 3.3$	$\frac{1}{3}$	$\frac{1}{2} \rightarrow 1$
Integral charge (eg Sakata, GIM)	Integral charge triplet or quartet	$\lesssim 2.0$	$\frac{1}{3}$	$0 \rightarrow \infty$
Experiment		3.4 ± 0.7	0.38	$\sim 0.25 \rightarrow 1$

$$(\int F_2^{\nu N} dx)_{\Delta S = 0} = \int (U + D + \bar{U} + \bar{D})\ x dx$$

$$\int F_2^{\gamma N} dx = \frac{1}{9} \int (5[U + D + \bar{U} + \bar{D}] + 2[S + \bar{S}])\ x dx$$

$$1 - \varepsilon = \int (U + D + \bar{U} + \bar{D} + S + \bar{S})\ x dx$$

where ε is the fractional 4-momentum of the nucleon carried by gluons. From these three equations we get the energy-momentum sum rule

$$1 - \varepsilon = 9[\int F_2^{\gamma N}\ dx - \frac{1}{6} \int F_2^{\nu N}\ dx]$$

or inserting the numerical values

$$\varepsilon = 0.46 \pm 0.21 \qquad (44)$$

A more precise value can be obtained if we assume any $Q\bar{Q}$ sea is SU3 symmetric, so that $S = \bar{S} = \bar{D} = \bar{U}$. Then we may use the value of $B = (D + U - \bar{D} - \bar{U})/(D + U + \bar{D} + \bar{U})$ deduced from the cross-section ratio $\sigma^{\bar{\nu}}/\sigma^{\nu}$, which gives

$B = 0.9 \pm 0.1$, as indicated below. Thus the relation

$$(1 - \varepsilon) = [1 + (\frac{1 - B}{2}) \int F_2^{\nu N} dx$$

gives

$$\varepsilon = 0.49 \pm 0.08 \tag{45}$$

Since B is near unity, this result is not significantly different from (44), i.e. the contribution from isoscalar ($\Lambda\bar{\Lambda}$) partons is small.

In some models (Budny 1972), the $Q\bar{Q}$-sea is not SU3- symmetric and contains predominantly $\Lambda\bar{\Lambda}$ quarks, and the Cabibbo angle is taken as a free variable at high q^2 (as discussed below, there is evidence from the inelastic $\bar{\nu}$ data against this). It appears then just possible to account for the neutrino cross-sections without invoking any gluon contribution (however, two hypotheses are required instead of one). Such models seem to be excluded by the fact that they predict a large proportion of $\Delta S = +1$ neutrino reactions, contrary to observation.

E. The Ratio $\sigma^{\bar{\nu}}/\sigma^{\nu}$ and the V-A Interference Term, F_3

Perhaps the single most significant result of the CERN experiment lies in the value of the interference term F_3, or B. In the V-A theory, spin $\frac{1}{2}$ parton constituents are coupled to the lepton current via $(1 - \gamma_5)$, with F_3 negative, while antipartons have coupling $(1 + \gamma_5)$ with F_3 positive. Thus the magnitude of F_3 provides a measure of the average helicity,* or equivalently the baryon number of the nucleon constituents. In this sense the neutrino experiments give information not attainable in electron scattering, which measures only the (charge)^2 and gyromagnetic ratio of the partons.

There are, in principle, 4 independent methods of determining the F_3 term:-

(i) the overall cross-section ratio $R = \sigma^{\bar{\nu}}/\sigma^{\nu}$

(ii) The y-distribution in antineutrino events

(iii) the y-distribution in neutrino events

(iv) the cross-section ratio $\sigma_{\Delta S = 1}/\sigma_{\Delta S = 0}$ in neutrino events.

---

* The helicities of partons and antipartons are ∓ 1 only in the relativistic limit. If we take $\bar{x} = 0.2$ and neutrino energy E = 4 GeV as typical, the helicity is $|\frac{v}{c}| = \frac{E/M}{E/M + \bar{x}} \approx 0.95$ only, where v = parton velocity in neutrino-parton centre of mass.

At the present time, there is preliminary information on (i) and (ii), the analysis of (iii) has not yet been started, and there is only crude qualitative information on (iv).

i) The Overall Cross-section Ratio $R = \sigma^{\bar{\nu}}/\sigma^{\nu}$

From integration of (36) we get the following expression for $B = -\int x F_3\, dx / \int F_2\, dx$:-

$$R = \frac{\sigma(\bar{\nu})}{\sigma(\nu)} = \frac{2 - B}{2 + B} \tag{46}$$

The average of R in the interval $2 < E < 9$ GeV (Table 6 and Fig. 15) gives

$$B = 0.90 \pm 0.04 \tag{47}$$

In the case of the ratio R, the correction factor due to the n/p ratio in freon, to arrive at a true value $(\sigma^{\bar{\nu}n} + \sigma^{\bar{\nu}p})/(\sigma^{\nu n} + \sigma^{\nu p})$ is $1.03/0.97 = 1.06$ (see B(ii) above). Thus*

$$\begin{aligned} R_{\text{corrected}} &= \frac{\sigma^{\bar{\nu}N}}{\sigma^{\nu N}} = 0.40 \\ B_{\text{corrected}} &= 0.86 \pm 0.04 \end{aligned} \tag{48}$$

A value $R = \frac{1}{3}$, $B = 1$ would imply

a) Scattering from spin $\frac{1}{2}$ constituents only. For $J \neq \frac{1}{2}$, R falls inside the limits $\frac{1}{3} < R < 3$.

b) Pure V-A coupling (principle of maximum parity violation).

c) L.H. (particle) constituents, only, with no R.H. (antiparticle) constituents (i.e. no $Q\bar{Q}$ pairs).

The observed value of B appears to be close to, but significantly less than, unity. This certainly implies that spin $\frac{1}{2}$ partons predominate, and, since parity violation is near maximal, that antipartons play only a minor role.

Again the question arises whether this interpretation, in the language of the deep inelastic "Bjorken scaling" region, is really valid in the shallow inelastic domain ($E < 10$ GeV) of the experiments. One can attempt to extrapolate the data into the "true" scaling region. The fitted dependence of R on E, given in Table 6, is, remarkably, very weak.

*For the $\Delta S = 0$ cross sections only, the corrected values are essentially the same, namely $R = 0.39$ and $B = 0.87$.

Fig. 16 shows the one standard deviation errors on the E dependence of R. Since scaling at SLAC is observed at around 20 GeV, we can provisionally conclude that the results (48) typify the scaling region rather closely. In any case, the filling-in of Fig. 16 over the range 10-50 GeV at NAL and the CERN SPS will clearly be of vital importance.

Assuming provisionally that the existing data on the gross cross-section ratio really represent scaling, the relative antiparticle/particle populations are given by

$$\frac{\text{4-momentum of isovector antipartons}}{\text{4-momentum of isovector partons + antipartons}} = \frac{\int(\bar{D} + \bar{U})x\,dx}{\int(D + U + \bar{D} + \bar{U})x\,dx}$$

$$= \frac{1 - B}{2} \simeq 0.07 \qquad (49)$$

If we assume an SU3 symmetric $Q\bar{Q}$ sea, we get

$$\frac{\text{4-momentum of antipartons}}{\text{4-momentum of partons + antipartons}} = \frac{3}{2}\ \frac{(1 - B)}{(3 - B)} \simeq 0.10 \qquad (50)$$

The fact that the F_3 term is so large implies that diffractive terms (Pomeron exchange in the corresponding elastic scattering amplitude) must be, on average, quite small*. From the electron scattering data, diffractive contributions had been expected to dominate the region of small x (< 0.1) as exemplified by the near equality of $F_2^{\gamma p}$ and $F_2^{\gamma n}$ in that region. The point is that, in the neutrino cross-sections, most of the contribution comes from $x < 0.3$ and indeed $F_2(x)$ peaks at $x \sim 0.1$ (Myatt and Perkins 1971). Because of the positivity condition

$$|x\,F_3(x)| < F_2(x)$$

and the result

$$\int x\,F_3(x)\,dx \sim 0.9 \int F_2(x)\,dx$$

it follows that diffractive terms must be limited to the region of extremely small x (<<0.1). This point awaits further analysis of the CERN data (I understand that the preliminary x-distributions for ν and $\bar{\nu}$ are essentially indentical, so that it may be that xF_3/F_2 may not vanish for any x). In any case, the above estimates for the magnitude of diffractive

---

* The F_3 term necessarily corresponds to exchange of a particle of odd G-parity, and is therefore forbidden for Pomeron exchange.

contributions appear to be in reasonable agreement with the Kuti Weisskopf and Landshoff-Polkinghorne estimates from electron data.

The result (50) obviously has ramifications on other leptonic processes. For example, the reaction

$$p + p \rightarrow \ell^{+}\ell^{-} + \text{anything}$$

is interpreted, in the parton model, in terms of annihilation of a parton from one nucleon with an antiparton from the other, to form a lepton pair. Detailed measurements of the ratio $xF_3(x)/F_2(x)$ as a function of x, which should be forthcoming shortly, will therefore be of great interest.

ii) The y-distribution in Antineutrino Events

The first results on the inelasticity distributions in $\bar{\nu}$ events are given in Fig. 17, for E > 3 GeV (the form of the distribution does not depend on the energy).

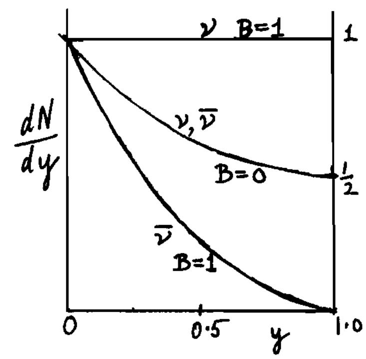
In the scaling region the expected distribution would have the form, from (36)

$$\begin{aligned} \frac{dN(\bar{\nu})}{dy} &= 1 - (1 + B)\left(y - \frac{y^2}{2}\right) \\ &= \frac{1}{2}(1 - B) \text{ as } y \rightarrow 1 \end{aligned} \tag{51}$$

Thus the intensity near $y \sim 1$ is a direct measure of the difference of B from unity. There are two main conclusions to be drawn from Fig. 17. First, the entire distribution $y = 0 \rightarrow 1$ cannot be fitted by the form (51), for any B value, because of an excess of events of $y < 0.1$, contributed entirely by the elastic process $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$. Presumably as $E \rightarrow \infty$, and the total cross-section grows, this elastic peak would disappear. For $y > 0.1$ however, the data can be well fitted by (51), as the examples B = 1 and B = 0.85 indicate.

Secondly, the intensity near y = 1 appears to be finite, so B < 1. Fig. 18 shows the expected proportion f (>0.8) of events with $1 > y > 0.8$, as a function of G. The observed f value, $0.043 \pm .011$, is seen to be in good agreement with that expected from the B value (48) deduced from the gross cross-section ratio. This is an important result; the ratio R is averaged over all x and y values, including those in the low q^2, ν region, while the fraction of events with $y > 0.8$ corresponds to those of $\nu > 3$ GeV only.

As indicated in the sketch, for $B \sim 1$ the expected distribution dN/dy for <u>neutrinos</u> should be quite flat. The new data from Gargamelle is therefore eagerly awaited. However the result depends much more critically on correct treatment of ambiguous events than for $\bar{\nu}$, since the difference in fall-off of dN/dy as y varies from $0 \to 1$, for different B values, is smaller.



iii) The $\Delta S = 1/\Delta S = 0$ Cross-Section Ratio in ν, $\bar{\nu}$ Events

According to the $\Delta S/\Delta Q = +1$ rule, neutrino reactions ($\Delta Q = +1$) can give rise to $\Delta S = +1$ hadron states:-

$$\nu_\mu + N \to \mu^- + N + \left\{ \begin{matrix} K^0 \\ K^+ \end{matrix} \right. + \ldots\ldots \tag{52}$$

In the framework of the quark model, such reactions can only proceed by scattering off the $Q\bar{Q}$ sea i.e.

$$\begin{aligned} \nu\bar{p}_Q &\to \mu^- \bar{\Lambda}_Q \\ \nu\Lambda_Q &\to \mu^- p_Q \end{aligned} \tag{53}$$

Thus observations on single K^+ and K^0 production by neutrinos provides an independent method of measuring the B term. Since the $\Delta S = 1$ rate is suppressed by $\tan^2 \theta_{Cabibbo} \simeq 0.06$, the present experiments are unable to give detailed information on $\Delta S = 1$ structure factors, and we just consider gross cross-sections.

The process (52) is just one of three types of strange particle production by ν and $\bar{\nu}$. It is necessary to consider all of these to find the backgrounds and corrections to the process of interest. The relevant raw data on strange-particle production is summarized in Table 9:-

a) The second column gives the number of associated production events (containing $K\bar{K}$, or hyperon + K^+ or K^0) in various experiments, divided by the total number of events above the effective A.P threshold (approximately $E > 2$ GeV). All results seem to be consistent within the large statistical errors. The corrected average

TABLE 9

Strange Particle Production by Neutrinos and Antineutrinos

Experiment	Associated Production ($\Delta S = 0$) $\left[\frac{\#(K\bar{K} + YK)}{\#(\text{all} > 2\ \text{GeV})}\right]$	$\Delta S = -1$ Production by $\bar{\nu}$	$\Delta S = +1$ Productinn by ν $\#(K + n\pi)/\#(\text{all} > 2\ \text{GeV})$
CERN 1.2m ν	12/420	---	3/420
CERN GGM ν (sample)	6/380	---	8/380
CERN GGM $\bar{\nu}$	8/470	$\frac{\#\Lambda,\Sigma}{\#\ \text{Elastic}} = \frac{15}{370} \sim .04$ $\frac{\#\ Y + n\pi}{\#\ \text{all} > 2\ \text{GeV}} = \frac{8}{470} \sim .02$	---
ANL D_2 ν	$\sim$1/50	---	$\sim$1/50 (3C fit event)
Raw Average Corrected ratio	0.02 ↓ $\sim$0.06	0.02 ↓ $\sim$ 0.04	0.014 ↓ corrected for A.P. background 0.005 ↓ corrected for single K detection $\sim$ 0.01

ratio allows roughly for the detection probability for both K-particle and hyperon.

b) The third column in Table 9 gives data on elastic hyperon and inelastic hyperon production by antineutrinos. The two processes appear to constitute about the same fraction of the appropriate elastic or inelastic $\Delta S = 0$ cross-section (It may be noted that for the elastic Λ,Σ production, $\overline{q^2} \sim 0.2$ GeV , whilst for inelastic (Y^*) production, $\overline{q^2} \sim 1$ GeV ; there is therefore no evidence here that the Cabibbo angle can depend dramatically on q^2).

c) The final column gives the numbers of candidates for $\Delta S = +1$ neutrino processes. In the heavy liquid experiments, the events are not kinematically fitted and a correction is required for background from associated production processes where the $\overline{K}$ or Y escapes detection. After this subtraction, an upward correction for K^+ or K^o detection efficiency is required. The final figure

$$\left[\frac{\sigma^{\nu}(\Delta S = +1)}{\sigma^{\nu}(\Delta S = 0)}\right]_{E \text{ large}} = 0.01 \tag{54}$$

is unlikely to be correct to better than a factor 2.

If we use the value of B from (48), then we expect from (50) and a quark model with an SU3 symmetric $Q\overline{Q}$ sea:-

$$\begin{aligned}\frac{\sigma^{\nu}(\Delta S + +1)}{\sigma^{\nu}(\Delta S = 0)} &\simeq (1 - B) \tan^2 \theta_c \\ &\simeq 0.01\end{aligned} \tag{55}$$

The agreement between (54) and (55) to within a factor 2 or so, provides an independent demonstration that antipartons make only a small contribution to the nucleon 4-momentum.

In the future, further operation of Gargamelle at CERN with the booster plus the coming into operation of large chambers at NAL and the CERN SPS, will allow a full statistical analysis and produce quantitative measurements of the $\Delta S = +1$ cross-sections, as well as some detail on the appropriate structure factors.

F. Conclusions

In summary, the new data on total ν, $\bar{\nu}$ cross-sections from the CERN Gargamelle collaboration leads to the following results:-

i) Both ν and $\bar{\nu}$ total cross-sections in the range 2-10 GeV are linear with energy, in accord with Bjorken scaling.

ii) Averaged over neutrons and protons, the weak $\Delta S = 0$ cross-sections observed are in beautiful agreement with the predictions from the electromagnetic deep inelastic cross-sections, and the twin postulates of CVC and chiral symmetry.

iii) The ratio $\sigma(\bar{\nu})/\sigma(\nu)$ indicates a vector-axial vector interference term equal to 86 ± 5% of the maximum possible value for the V,A theory. This indicates that diffractive contributions in the corresponding elastic scattering amplitude are small.

iv) In terms of constituent models, the fractionally charged (Gell-Mann/Zweig) quark model is the <u>only</u> one which fits both the neutrino and electron data.

v) The fractional nucleon 4-momentum carried by gluons is 50%.

vi) The fractional 4-momentum carried by antiquark constituents is only $\sim$10% of that carried by quarks and antiquarks together.

Finally, since the new data described above comes from the experiments in the Gargamelle bubble chamber, funded by the French Government, it seems not inappropriate to quote a few lines from Voltaire. This clearly warns us not to accept too literally simple pictures, like the quark model, based on heuristic arguments, to describe the internal structure of the nucleon:-

> "Les Philosophes qui font des systèmes sur la secrète construction de l'univers, sont comme nos voyageurs qui vont à Constantinople, et qui parlent du Sérail: Ils n'en ont vu que les dehors, et ils prétendent savoir ce que fait le Sultan avec ses Favorites".

Voltaire: "Pensées Philosophiques" (1766)

<u>Acknowledgements</u>

I am grateful to Professor F. Scheck of SIN, Zurich, for drawing my attention to the above passage; to Dr. C. Baltay for several discussions on neutral currents, and from whose review article I have taken much of the material in Part II of this report; and to members of the CERN Gargamelle collaboration for discussions of the data.

REFERENCES

Adler S, Ann. Phys. 50, 189 (1968)

Albright C, B.W. Lea and E.A. Paschos; NAL-THY-86 (1972)

Amaldi E, M. Beneventano, B. Borgia, F. de Notaristefani, A. Fonderoli, P. Pistilli, I Sestili and M. Severi; Phys. Lett. 41B, 216 (1972)

Avignone F.T; PR D2, 2609 (1970)

Baltay C; CERN TCL/Int 72-10; Proc. Balaton Conf. (June 1972)

Bijtebier J; Nucl. Phys. B21, 158 (1970)

Bloom E and F.Gilman PRL 25, 1140 (1970)

Bloom et al SLAC PUB-815, 907 (1970, also G. Miller et al PR D5, 519 (1972)

Botterill D.R., D.W. Braben, P.R. Norton, A. del Guerra, A. Giazotto, M. Giorgi and A. Stefanini; DNPL preprint (1972)

Brisson V; Paper # 785 (CERN-GGM Collaboration)

Budagov I., D.C. Cundy, C. Franzinetti, W. Fretter, H. Hopkins, C. Manfredotti, G. Myatt, F. Nezrick, M. Nikolic, T. Novey, R. Palmer, J. Pattison, D. Perkins, C. Ramm, B. Roe, F. Stump, W. Venus and H. Wachsmuth; Phys. Lett. 29B 524 (1969a)

Budagov I, D.C. Cundy, C. Franzinetti, W.B. Fretter, H.W. Hopkins, C. Manfredotti, G. Myatt, F. Nezrick, M. Nikolic, T.B. Novey, R. Palmer, J.B. Pattison, D.H.Perkins, C.A. Ramm, B. Roe, R. Stump W. Venus, H. Wachsmuth & H. Yoshiki Phys. Lett. 30B, 364 (1969b)

Budagov I et al Nuov. Cim. Lett. 2, 689 (1969c)

Budny R., Oxford preprint (1972)

Cabibbo N. & F. Chilton, PR 137B, 1628 (1965)

Campbell J., G. Charlton, Y. Cho, M. Derrick, R. Engelmann, F. Fetkovich, L. Hyman, K. Jaeger, D. Jankowski, A. Mann, U. Mehtani, B. Musgrave, P. Schreiner, T. Wangler, J. Whitmore and H. Yuta (Paper # 821)

Cho Y, M. Derrick, R. Engelmann, L. Hyman, K. Jaeger, A. Mann, U. Mehtani, P. Schreiner and H. Yuta; (Paper # 473)

Cundy D.C., G. Myatt, F.A. Nezrick, J.B. Pattison, D.H. Perkins, C.A. Ramm, W. Venus and H. Wachsmuth; Phys. Lett. 31B 479 (1970)

Dalitz R.H. & D. Sutherland PR 146, 1180 (1966)

Eichten et al (Gargamelle collaboration) Paper # 782, Phys. Lett. 40B 593 (1972)

Furlan G.,N. Paver and C. Verzegnassi; Il. Nuov. Cim. 70A, 247 (1970)

Gourdin M, Nucl. Phys B29, 601 (1971)

Gurr H.S., F. Reines and H.W. Sobel PRL 28, 1406 (1972)

Heusse Ph. Paper # 783

t'Hooft G; Phys. Lett. 37B, 195 (1971)

Lee B.W: Phys. Lett. 40B 420 (1972)

Lee W.Y; Phys. Lett. 40B, 423 (1972)

Llewellyn-Smith C.H: Phys. Reports 3C, 261 (1972)

Mann A, V. Mehtani, B. Musgrave, Y. Oren, P. Schreiner, H. Yuta, R. Ammar, Y. Cho, M. Derrick, R. Engelmann and L. Hyman Paper # 784

Myatt G. (Unpublished, 1972)

Myatt G. & D.H. Perkins; Phys. Lett. 34B, 542 (1971)

Nachtmann O; Nucl. Phys. B38, 397 (1972)

Nambu Y and M. Yoshimura; PRL 24, 25 (1970)

Pais A. & S. Treiman COO-3505-25 1972

Paschos E.A. & B.W. Lee; NAL-THY-78 (Paper # 786)

Paschos E.A. & L. Wolfenstein; NAL-THY-69 (1972)

Salam A. & J.C. Ward; Phys. Lett. 13, 168 (1964)

Salin P, Il. Nuov. Cim. 48A, 506 (1967)

Schreiner P & F. von Hippel; Paper # 805 (1972)

Weinberg S. PRL 19, 1264 (1967)

Weinberg S. PR D5, 1412 (1972)

Zucker P. PR 40, 3350 (1971)

Fig.1

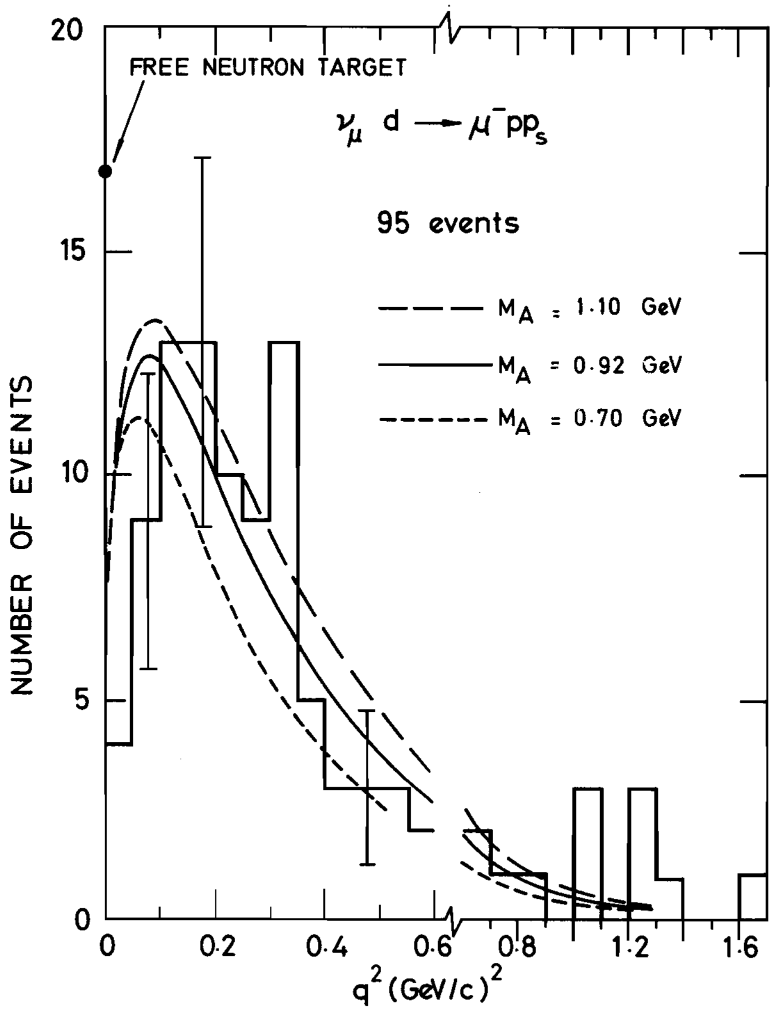

FREE NEUTRON TARGET
$\nu_\mu\ d \longrightarrow \mu^- p p_s$
95 events
M_A = 1·10 GeV
M_A = 0·92 GeV
M_A = 0·70 GeV
NUMBER OF EVENTS
$q^2\ (GeV/c)^2$
20
15
10
5
0
0
0·2
0·4
0·6
0·8
1·2
1·6

FIG. 2

ELASTIC NEUTRINO CROSS-SECTIONS $\nu_\mu + n \rightarrow \mu^- + p$

(ANL DEUTERIUM EXPERIMENT)

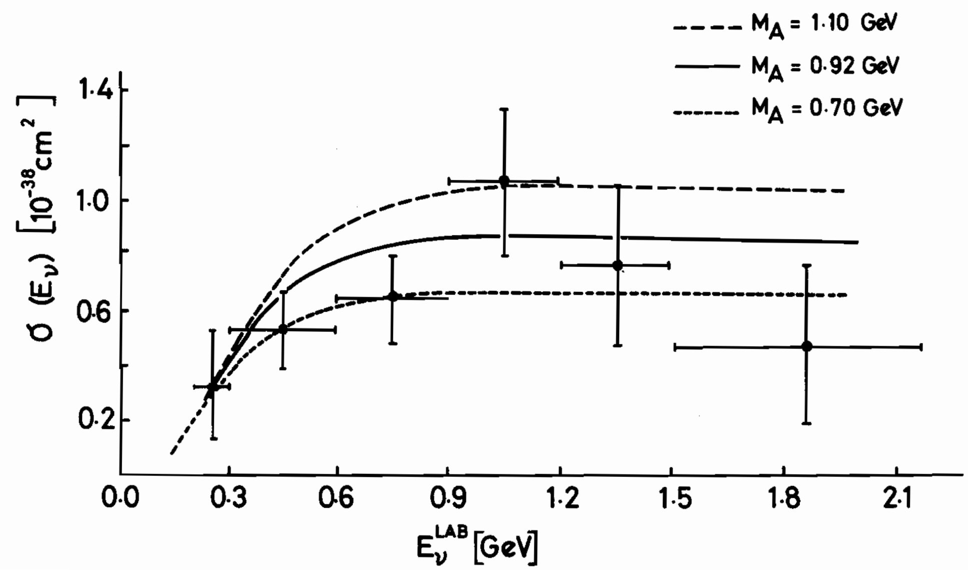
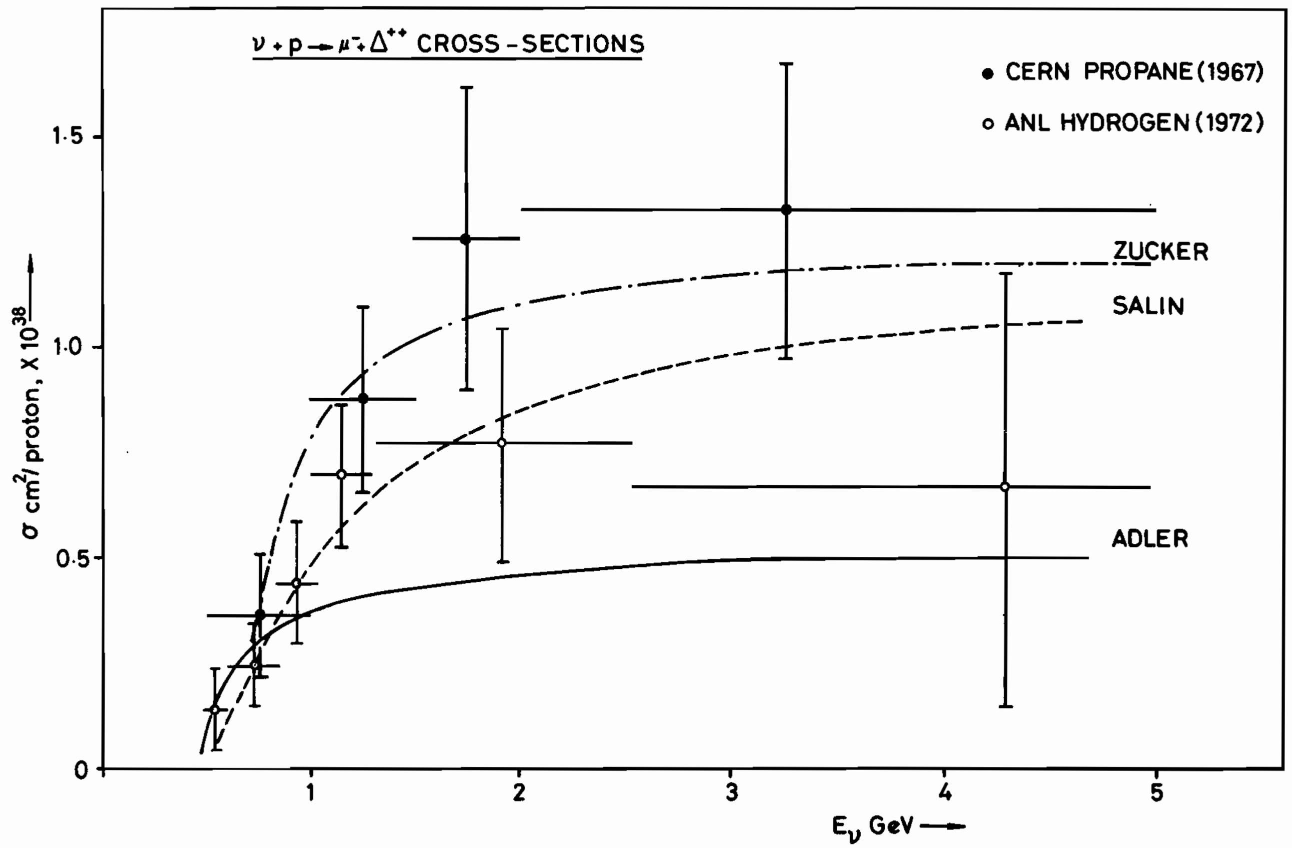


FIG. 3



$\nu + p \to \mu^- + \Delta^{++}$ CROSS-SECTIONS
● CERN PROPANE (1967)
○ ANL HYDROGEN (1972)
ZUCKER
SALIN
ADLER
σ cm^2/ proton, X 10^{38}
1·5
1·0
0·5
0
1
2
3
4
5
E_ν GeV

FIG. 4

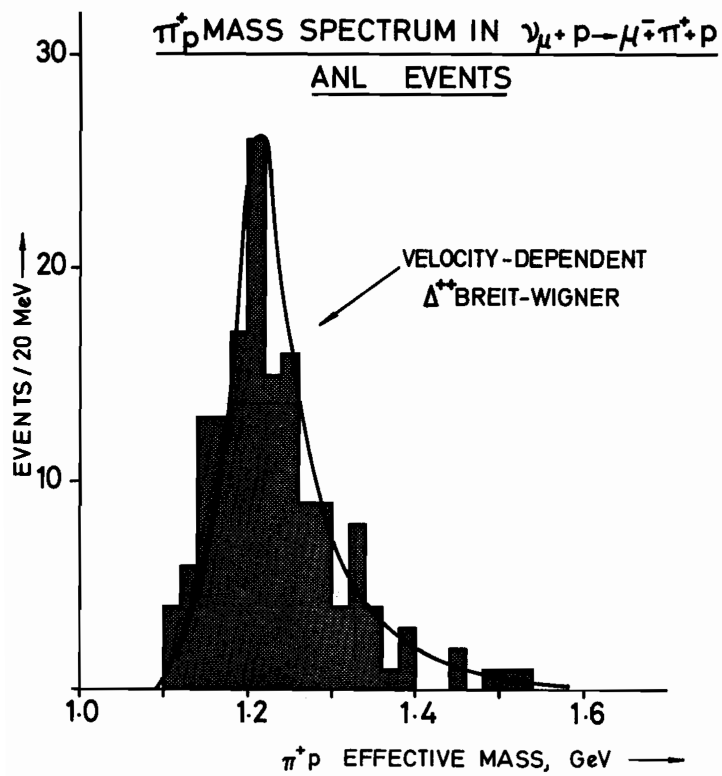

π^+p MASS SPECTRUM IN $\nu_\mu + p \to \mu^- + \pi^+ + p$
ANL EVENTS
VELOCITY - DEPENDENT
Δ^{++} BREIT-WIGNER
EVENTS / 20 MeV
30
20
10
1·0
1·2
1·4
1·6
π^+p EFFECTIVE MASS, GeV

FIG.5

SCATTER PLOT OF Δ^{++} DECAY ANGLES IN

ANL $\nu_\mu + p \to \mu^- p \pi^+$ EVENTS

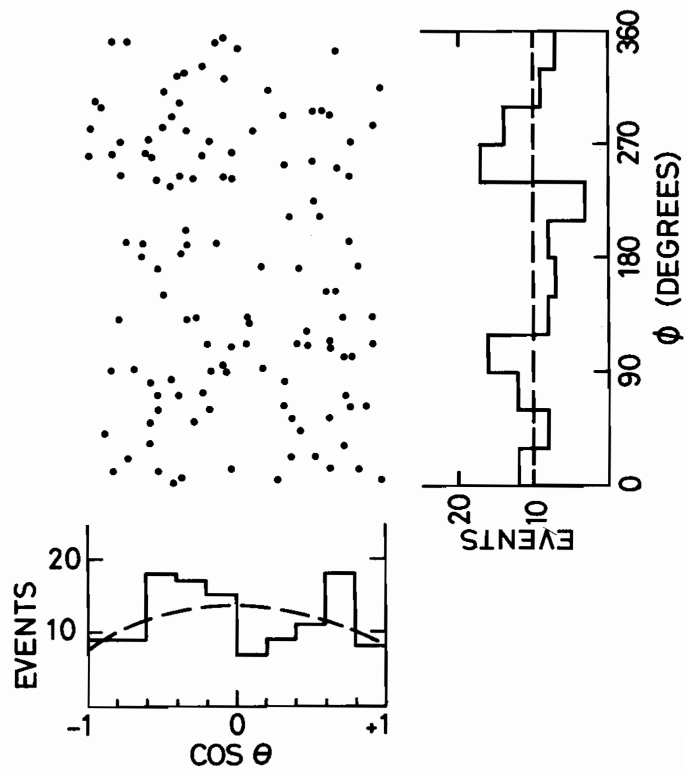


FIG.6

NEUTRINO-ELECTRON SCATTERING CROSS-SECTIONS IN WEINBERG MODEL

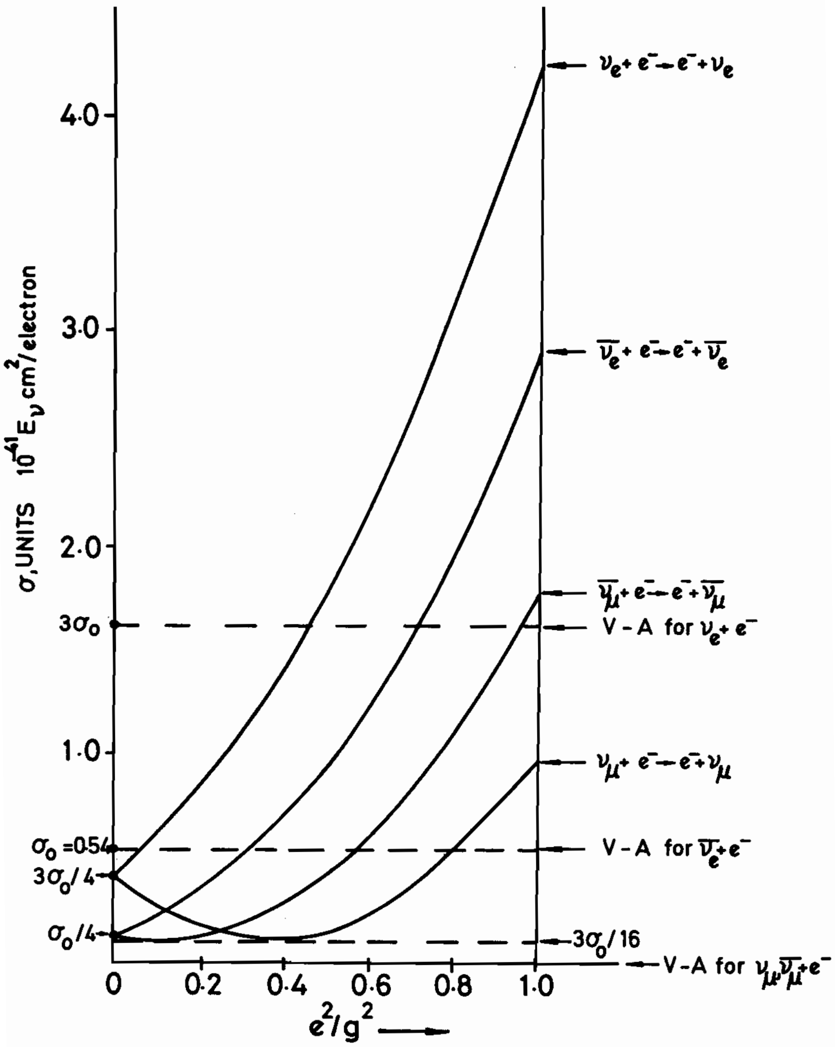


FIG. 7

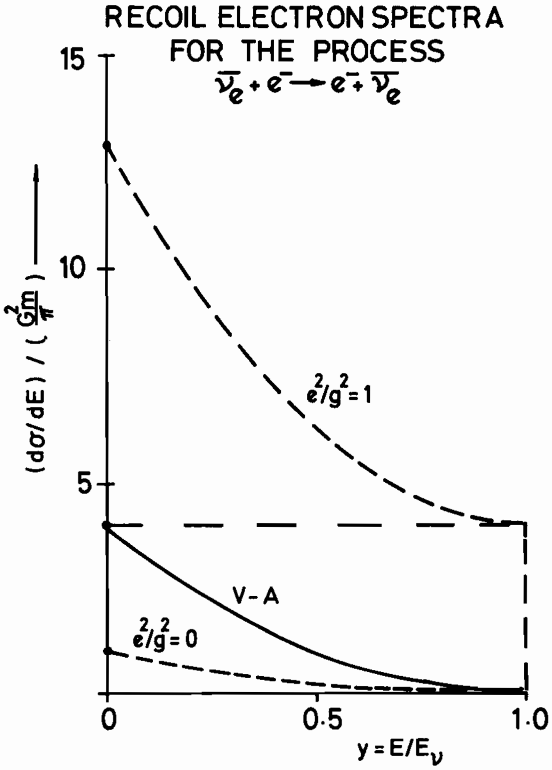

RECOIL ELECTRON SPECTRA
FOR THE PROCESS
$\bar{\nu}_e + e^- \rightarrow e^- + \bar{\nu}_e$
15
10
5
0
0.5
1.0
$(d\sigma/dE) / (\frac{G^2 m}{\pi})$
$e^2/g^2 = 1$
V-A
$e^2/g^2 = 0$
$y = E/E_\nu$

FIG. 8

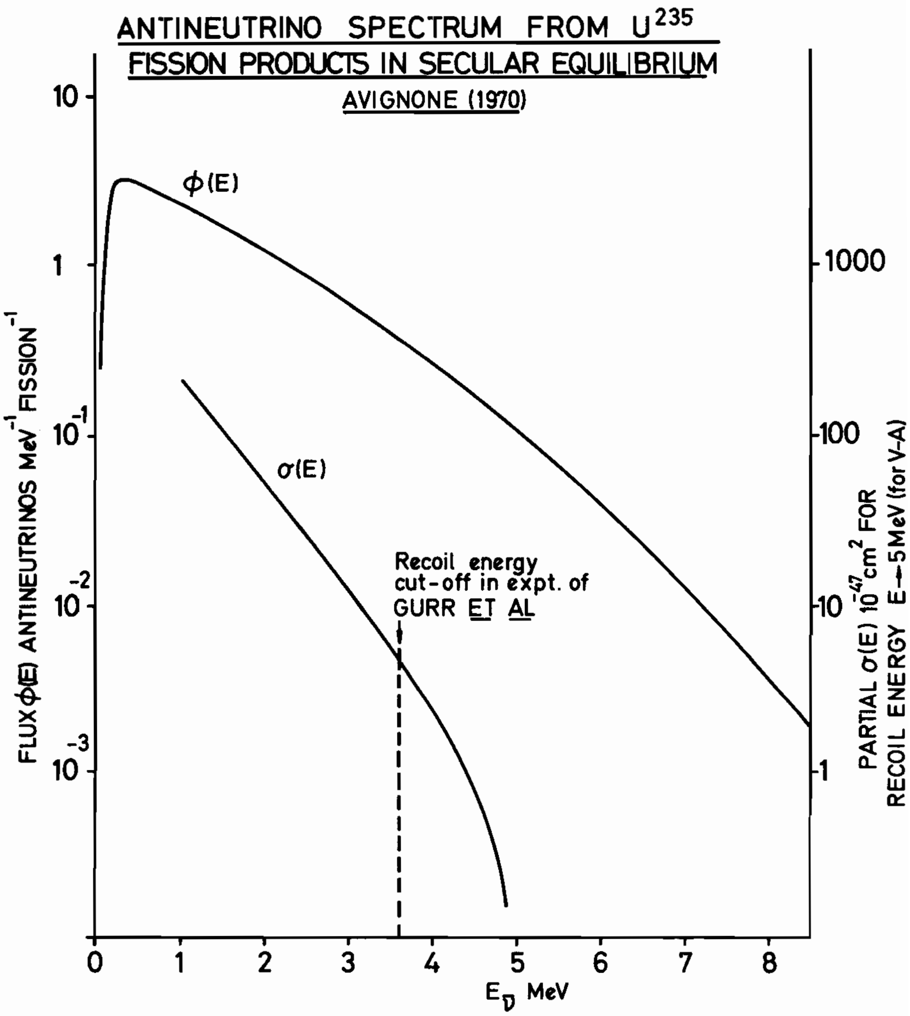

ANTINEUTRINO SPECTRUM FROM U235
FISSION PRODUCTS IN SECULAR EQUILIBRIUM
AVIGNONE (1970)
φ(E)
σ(E)
Recoil energy
cut-off in expt. of
GURR ET AL
FLUX φ(E) ANTINEUTRINOS MeV-1 FISSION-1
PARTIAL σ(E) 10-47 cm2 FOR
RECOIL ENERGY E→5 MeV (for V-A)
Eν̄ MeV
10
1
10-1
10-2
10-3
1000
100
10
1
0
1
2
3
4
5
6
7
8

FIG. 9

ANTINEUTRINO ELECTRON SCATTERING

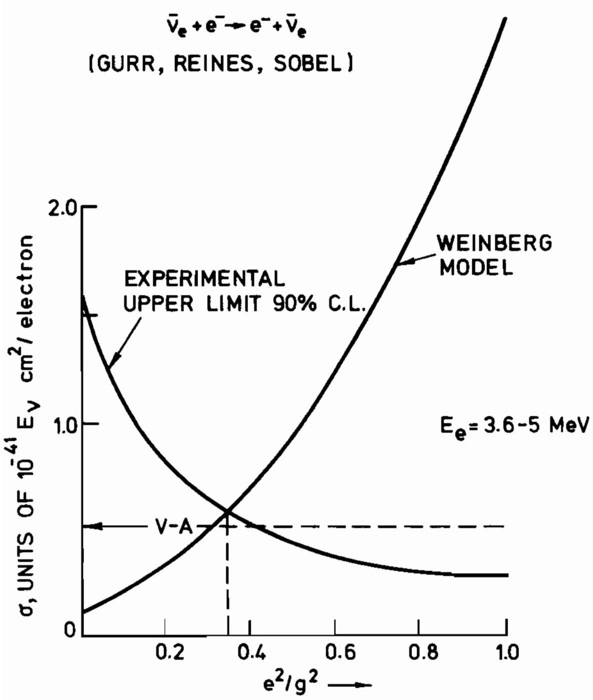


FIG. 10

NEUTRINO-ELECTRON SCATTERING IN WEINBERG MODEL

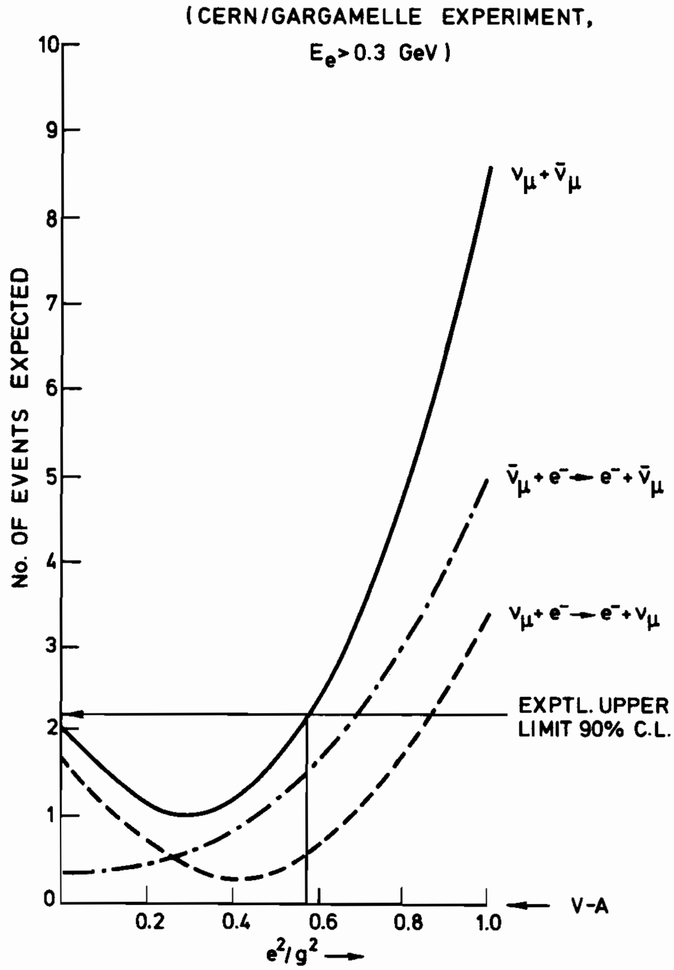
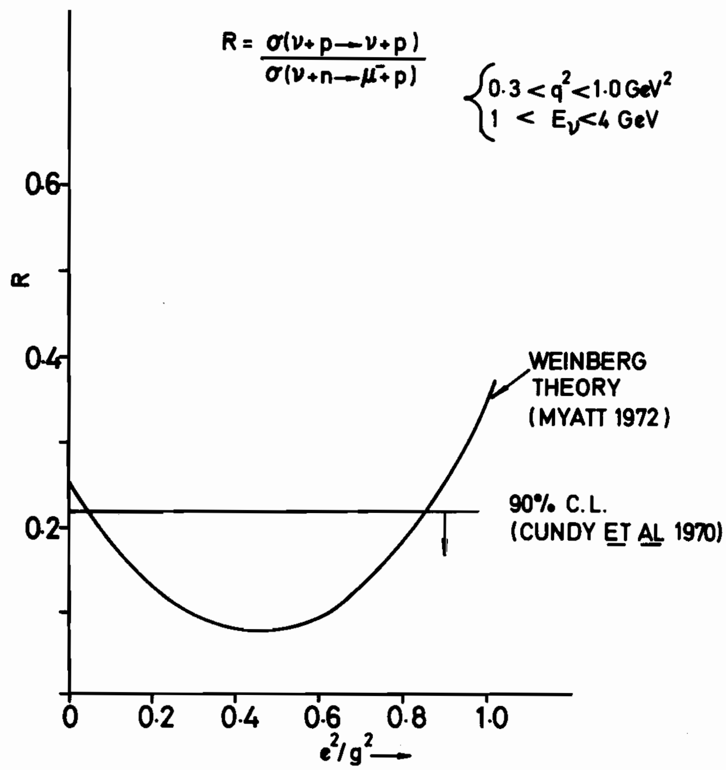
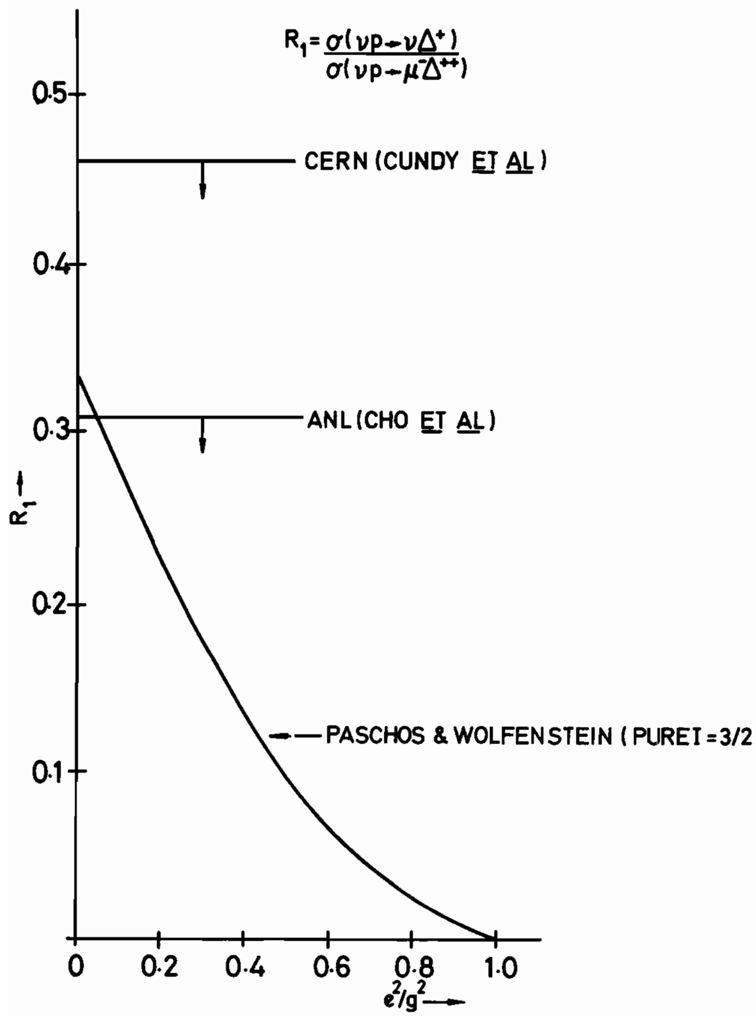


FIG.11



$R = \frac{\sigma(\nu + p \to \nu + p)}{\sigma(\nu + n \to \mu^- + p)}$
$\begin{cases} 0.3 < q^2 < 1.0\ GeV^2 \\ 1 < E_\nu < 4\ GeV \end{cases}$
0.6
R
0.4
0.2
WEINBERG THEORY (MYATT 1972)
90% C.L. (CUNDY ET AL 1970)
0
0.2
0.4
0.6
0.8
1.0
$e^2/g^2 \to$

FIG.12



$R_1 = \frac{\sigma(\nu p \to \nu \Delta^+)}{\sigma(\nu p \to \mu^- \Delta^{++})}$
0.5
0.4
0.3
0.2
0.1
R_1
CERN (CUNDY ET AL)
ANL (CHO ET AL)
PASCHOS & WOLFENSTEIN (PURE I = 3/2)
0
0.2
0.4
0.6
0.8
1.0
e^2/g^2

FIG.13

WEAK PION PRODUCTION VIA NEUTRAL CURRENT

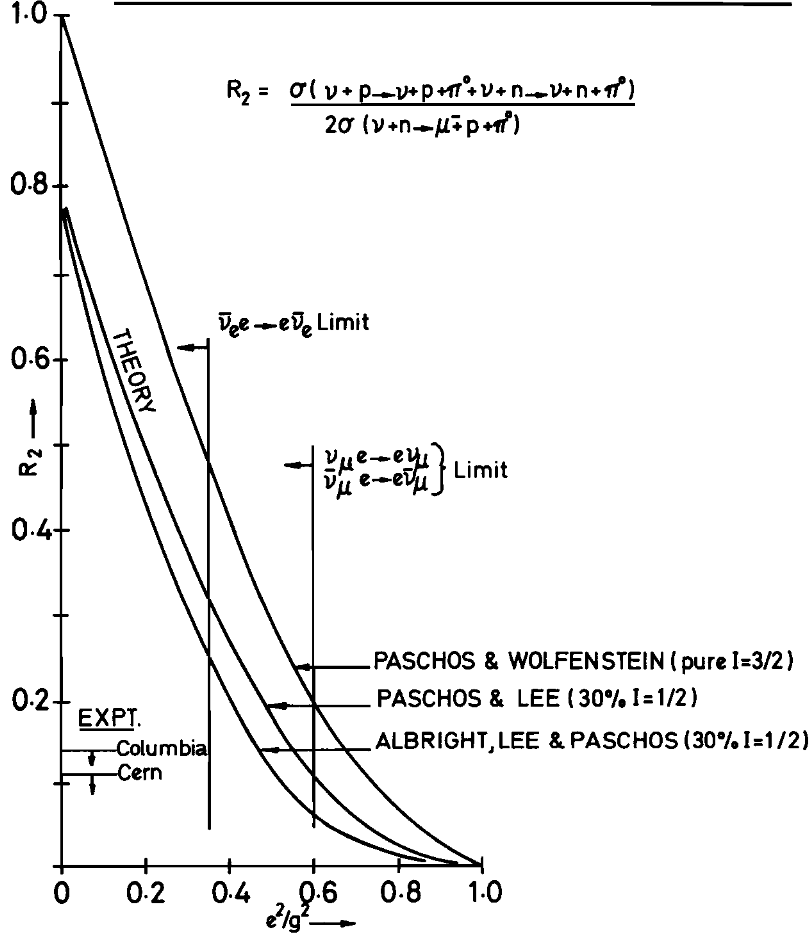


FIG. 14

TOTAL CROSS SECTIONS (CERN GARGAMELLE)

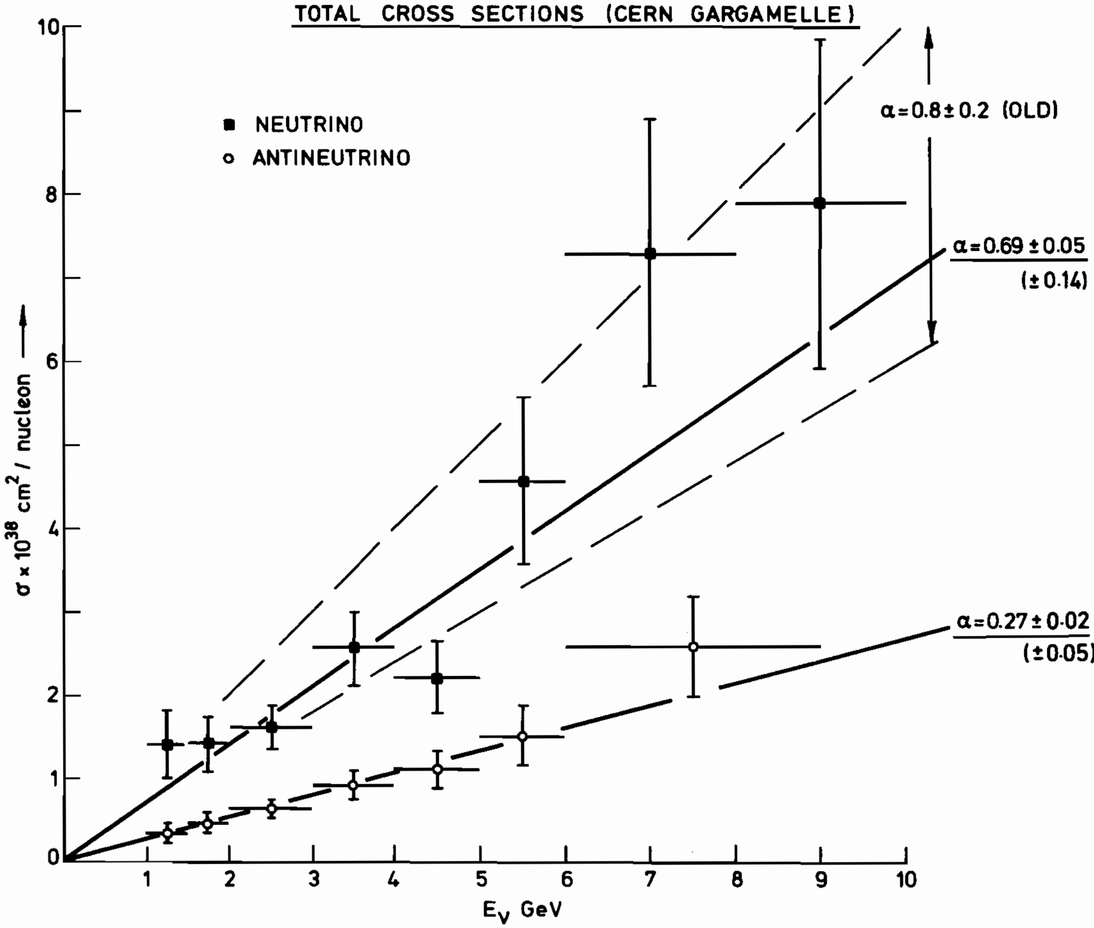


FIG.15

ANTINEUTRINO/NEUTRINO CROSS-SECTION RATIO (CERN GARGAMELLE)

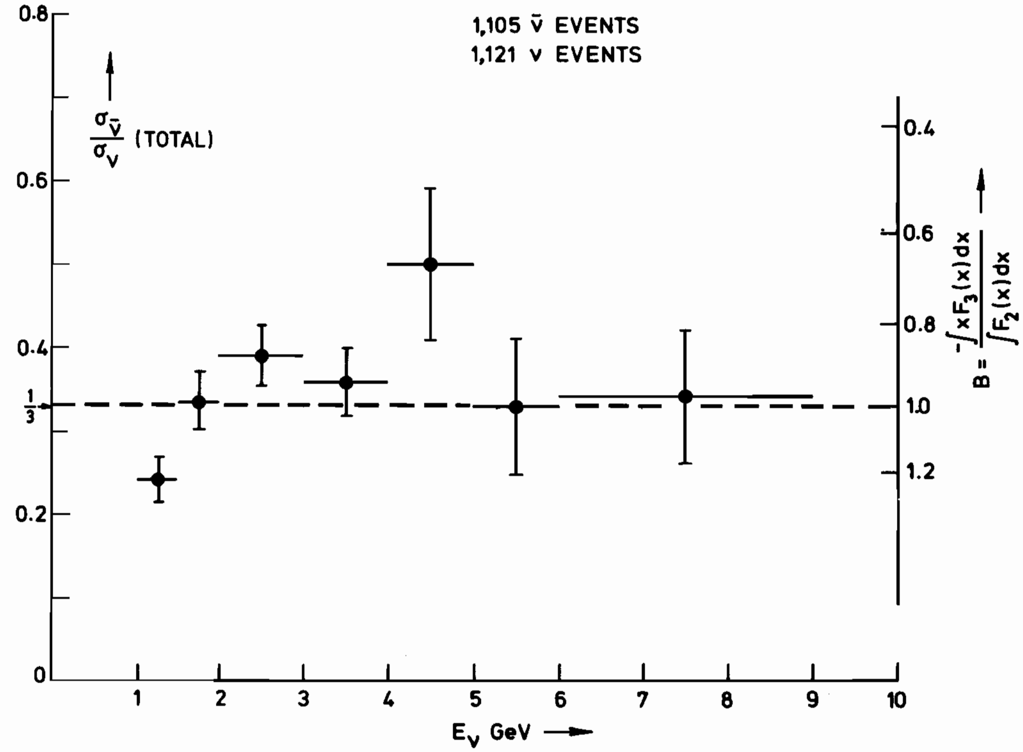


FIG. 16

$\bar{\nu}/\nu$ CROSS SECTION RATIO AS FUNCTION OF ENERGY

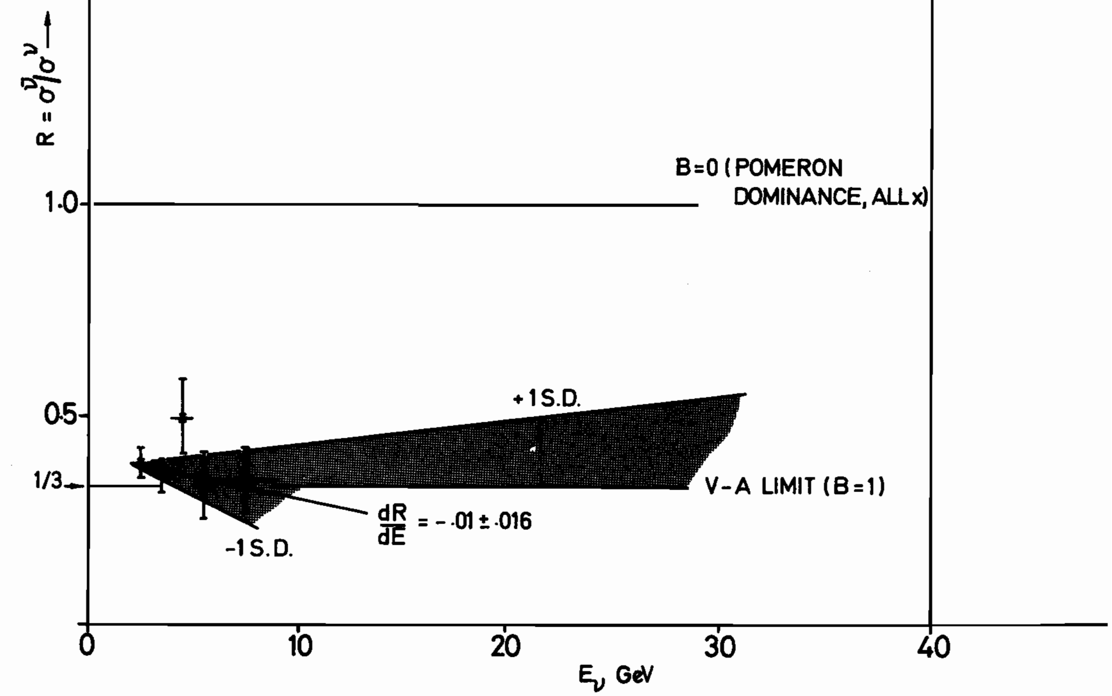
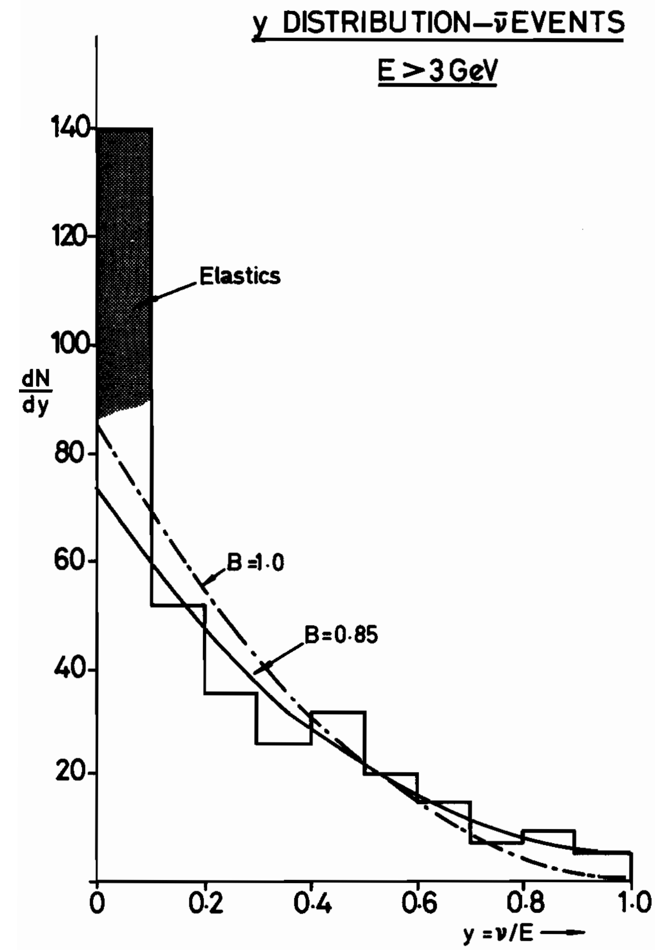


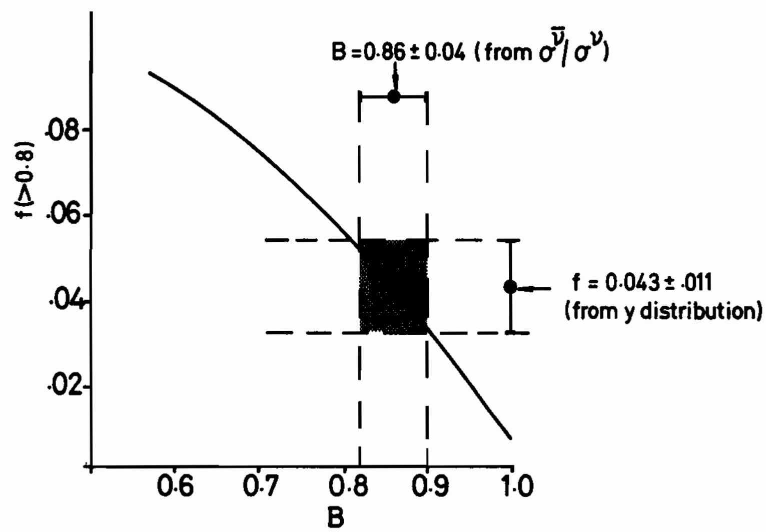
FIG. 17



y DISTRIBUTION–$\bar{\nu}$ EVENTS
E > 3 GeV
140
120
100
80
60
40
20
dN/dy
Elastics
B = 1.0
B = 0.85
0
0.2
0.4
0.6
0.8
1.0
y = ν/E

FIG. 18

FRACTION OF $\bar{\nu}$ EVENTS WITH $y>0.8$, $E>3$ GeV AS A FUNCTION OF B



DISCUSSION

A. Zichichi (Bologna): The value of m_A reported is obtained assuming a quadratic pole form for the axial nucleon form-factor, F_A. Can you distinguish between quadratic and linear pole formulae, and if so how much is m_A in the linear case?

D. H. Perkins: The answer is no, you cannot distinguish. Possibly when the Argonne data are complete, when there are more like a 1000 events, rather than 100, it might be possible to distinguish between the dipole and the monopole form. But if you prefer the monopole form then the value of m_A would be of the order of 0.6 GeV, rather than 0.9 GeV.

S. Nakamura (Tokyo): In the one pion production process, you once reported the Yoshiki bump or $\mu\pi$ resonance bump. What is the present situation about these two bumps?

D. H. Perkins: The $\mu\pi$ invariant mass distribution did appear in one of the slides. I did not comment on it. If there had been a great peak, I would have drawn your attention to it, of course. But there is no evidence for any $\mu\pi$ bump and this effect, which should be much more apparent in the hydrogen chamber than in the old CERN heavy liquid experiment, is completely absent. So there is no evidence whatever in these neutrino experiments for $\mu\pi$ resonances.

R. M. Weiner (Indiana): In the strange particle production experiment what is the admixture of antineutrinos from π's and K's in the beam?

D. H. Perkins: Above 5 GeV there are only antineutrinos from K-decays, below 4 GeV, only from π-decays, and between 4 and 5 GeV, a roughly equal mixture.