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Neutral Currents in Semileptonic Reactions*

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ABSTRACT

The evidence for weak neutral currents is analysed in semileptonic reactions with special emphasis in their Lorentz and internal symmetry structure. It is found that present observations are consistent with the expectations of gauge theories, but other possibilities can not be ruled out. Of particular interest in this respect is the presence of a large isoscalar component. The excitation of the Δ -resonance by neutral currents is analysed, and pion-nucleon mass distributions are presented. Charge asymmetries sensitive to isoscalar-isovector interferences are discussed.

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INTRODUCTION

The revived interest in neutral currents arose with the possibility of constructing a renormalizable theory of weak interactions. This interest was further enhanced by their discovery and subsequent confirmation in numerous neutrino experiments. The present activity is partly motivated by the implications that this discovery has for other problems of high energy physics. It is believed that neutral currents play a crucial role in developing a finite and unified gauge theory of weak and electromagnetic interactions. It is also believed that they are intimately connected with the existence of new quantum numbers and consequently new hadronic states. The arguments leading to such conclusions have been discussed elsewhere and we review them very briefly.

In gauge theories the bad high energy behavior of tree graphs must be cancelled by other graphs. For example, to lowest order in perturbation theory the cross section for the production of zero helicity W's in processes like

$$\begin{aligned} \nu + \bar{\nu} &\rightarrow W^+ + W^- \\ e + \bar{e} &\rightarrow W^+ + W^- \end{aligned}$$

grows with the square of the c.m. energy and violates unitarity. Unitarity is restored by introducing other graphs whose role is to cancel the bad high energy behavior. The new graphs have either s-channel poles, which require neutral currents, or t-channel poles, which require heavy leptons.

The extension of these arguments to semileptonic reactions must satisfy additional constraints. It is observed that

$$\frac{K^+ \rightarrow \pi^+ e^+ e^-}{K^+ \rightarrow \mu^+ \nu} = (5 \pm 2) \times 10^{-6} \quad (1)$$

$$\frac{K_L \rightarrow \mu^+ \mu^-}{K^+ \rightarrow \mu^+ \nu} \leq 8 \cdot 10^{-9} \quad (2)$$

which imply that strangeness changing neutral currents are greatly suppressed (at least at low energies). To account for this suppression, but still

allow for $\Delta S = 0$ neutral currents, several schemes have been devised which invariably introduce new quantum numbers. They, in turn, require a new stratum of hadronic states carrying new quantum numbers. An elegant solution by Glashow, Iliopoulos and Maiani⁹ introduces a fourth quark carrying charm. In this scheme, there are two left handed multiplets

$$\psi_1 = \begin{pmatrix} p \\ n_c \end{pmatrix}, \quad \psi_2 = \begin{pmatrix} p' \\ \lambda_c \end{pmatrix} \quad (3)$$

where $n_c = n \cos \theta_c + \lambda \sin \theta_c$, $\lambda_c = -n \sin \theta_c + \lambda \cos \theta_c$, p, n, λ are the conventional quarks and p' is a new quark carrying charm. The neutral current operator is

$$J_\mu = \text{const. } \bar{\psi}_L \gamma_\mu (T_3 - Q \sin^2 \theta_W) \psi_L \quad (4)$$

with T_3 being the third component of the isospin operator, Q the charge operator and $\sin^2 \theta_W$ a mixing parameter. To lowest order the scheme gives only $\Delta S = 0$ neutral currents. In higher orders it suppresses induced $\Delta S = 1$ and 2 neutral current effects. The model also leads to a rich phenomenology which is now enjoying a good deal of attention since experiment is close to providing decisive tests.

Of basic importance to the above topics is the existence and nature of neutral currents. The first issue, concerning their existence, has been settled by the overwhelming evidence shown in Tables I and II. The next issue concerns their nature. To be precise, we would like to know

(α) The Lorentz structure of neutral currents. Are they vector and axial or scalar, pseudoscalar and/or tensor?

(β) The internal symmetry structure. Do they have components which can be classified within $SU(3)$ or are there also new components?

In dealing with these issues we are fortunate because there are two separate kinematic regions where we know a good deal about the charged-weak and electromagnetic matrix elements. In the deep inelastic region we have a scaling law and an explicit parton model both of which have been success-

ful in interpreting experiments. This region provides information concerning the Lorentz structure. In the low energy region, on the other hand, there is the $\Delta(1236)$ resonance, whose excitation by conventional currents is well understood. Consequently, a detailed study of its excitation by neutral currents might provide relevant information concerning their isospin structure.

In the next few sections we study properties of the neutral currents with emphasis on their space-time and isospin structure.

SPACE-TIME STRUCTURE OF CURRENTS

The general local neutral current interaction between neutrinos and hadrons assuming T-invariance and left-handed incident neutrinos has the form

$$\mathcal{L} = \frac{G}{(2)^{\frac{1}{2}}} \left\{ \bar{\nu} \gamma_{\mu} (1-\gamma_5) \nu (V^{\mu} + A^{\mu}) + \bar{\nu} (1-\gamma_5) \nu S + i \bar{\nu} \gamma_5 (1-\gamma_5) \nu P \right. \\ \left. + \bar{\nu} \sigma_{\mu\lambda} (1-\gamma_5) \nu T^{\mu\lambda} \right\} \quad (5)$$

where $S, P, V^{\mu}, A^{\mu}, T^{\mu\lambda}$ are scalar, pseudoscalar, vector, axial-vector and tensor hadronic currents. They are hermitean and have a general internal symmetry structure which is not shown explicitly. G is the Fermi coupling constant. In calculating cross sections we observe that there are no interference terms between the (V, A) and (S, P, T) interactions because the former do not flip the neutrino helicities, while (S, P, T) couplings do so. We can thus discuss separately the contributions from the two classes and look for differences which can distinguish between them. One obviously can discuss specific channels, but the inclusive reactions on matter

$$\nu(\bar{\nu}) + N \rightarrow \nu(\bar{\nu}) + X \quad (6)$$

are the easiest to be measured and we concentrate on them. It is also convenient to extend the Bjorken scaling phenomenon to the (S, P, T) currents and obtain the double differential cross section in the scaling limit

$$\frac{d\sigma^{\nu, \bar{\nu}}}{dx dy} = \frac{G_{ME}^2}{\pi} \left\{ xy^2 [F_{ss} + F_{pp}] + 4xy(2-y) [F_{ST} + F_{PT}] \right. \\ \left. + 4[x(2-y)^2 F_{TT}^1 + 4(1-y) F_{TT}^2 - 2x^2 y^2 F_{TT}^3 + 2xy^2 F_{TT}^4] \right\} \quad (7)$$

Here $x = Q^2/2M\nu$, $y = \nu/E$ and $F_{ij}^\alpha = F_{ij}^\alpha(x)$ are the scaling limits of the structure functions bilinear in the currents i and j and the superscript α is used in order to distinguish the different contributions of the tensor terms. For comparison we give the corresponding cross section for the (V,A) combination

$$\frac{d\sigma^{\nu, \bar{\nu}}}{dx dy} = \frac{G_{ME}^2}{\pi} \left\{ (1-y) \bar{F}_2 + \frac{1}{2} y^2 [2x \bar{F}_1 + \bar{y} y (1 - \frac{1}{2} y) [x \bar{F}_3]] \right\} \quad (8)$$

where the superscript bar emphasizes that we allow for an arbitrary admixture of V and A currents.

Remarks: 1) In the absence of T-couplings and for any admixture of S- and 11,12

P-couplings

$$\frac{d\sigma^{\nu}}{dy} = \frac{d\sigma^{\bar{\nu}}}{dy} = \frac{G_{ME}^2}{\pi} y^2 \int_0^1 x [F_{SS}(x) + F_{PP}(x)] dx \quad (9)$$

The rise of the cross sections with y^2 is a unique signature of S and P interactions. The results presented by the CIT-FNAL group¹³ indicate that this possibility is already ruled out. The equality of the two cross sections is another testable property. Table I gives the world's compilation of data on inclusive neutral current reactions. The Gargamelle data¹⁴ give

$$\frac{\sigma_{NC}^{\nu}}{\sigma_{CC}^{\nu}} = 0.22 \pm 0.03 \quad \text{and} \quad \frac{\sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\bar{\nu}}} = 0.14 \pm 0.04 \quad (10)$$

which within two standard deviations are consistent to being equal. The ratios from the HPWF-collaboration are also consistent with equal ν and $\bar{\nu}$ neutral current cross sections. It is important to determine this number precisely, because it is also relevant to the presence of a V-A interference term.

Table I - Neutral Current Measurements for Total Cross-Sections

Ratio	Experiment	Energy Range	Group
$\frac{\sigma(\bar{\nu}N \rightarrow \nu \pi^+)}{\sigma(\bar{\nu}N \rightarrow \mu^+ \pi^+)}$	0.217 ± 0.026	1-10 GeV	Gargamelle ²
	0.11 ± 0.05	5-150 GeV	HPW-FNAL ³
	$0.22 \pm$	$E_\pi \approx 38$ GeV	CIT-FNAL ⁵
		$E_K \approx 108$ GeV	
	0.20 ± 0.06	1-10 GeV	BNL ⁷
$\frac{\sigma(\bar{\nu}N \rightarrow \nu \pi^-)}{\sigma(\bar{\nu}N \rightarrow \mu^- \pi^-)}$	0.43 ± 0.12	1-10 GeV	Gargamelle ²
	0.32 ± 0.09	5-150 GeV	HPW-FNAL ³
	$0.33 \pm$	$E_\pi \approx 38$ GeV	CIT-FNAL ⁵
		$E_K \approx 108$ GeV	

$$2) \quad \frac{1}{E} \left(\frac{d\sigma^{\nu}}{dy} - \frac{d\sigma^{\bar{\nu}}}{dy} \right) \propto y(1-y) \quad (11)$$

the y dependence is identical for the two classes of couplings.

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3) Theorem: For any admixture of V and A there is a corresponding admixture of S, P and/or T which yields the same y -distributions for reactions (6).

The proof follows by looking at Eqs. (7) and (8), because (V,A) gives at most a quadratic distribution in y . From (7) we see that we obtain again at most quadratic terms with enough arbitrary coefficients to imitate the (V,A) y -distribution (remark (2) is also relevant). The theorem implies that it is difficult to distinguish (S,P,T) and (V,A). Extensive studies of this issue indicate that in order to separate the interactions one needs precise and difficult experiments of exclusive channels or the observation of neutral currents in electron-positron experiments.

I have gone into some detail in discussing the presence of S,P,T couplings for neutrinos because their existence will have some important consequences. Their existence means that there are two new states: a

right-handed neutrino and a left-handed antineutrino; that the multiplet structure is more complicated and that gauge Yang-Mills theories do not provide a complete picture. Keeping all this in mind, it is still useful to proceed and analyze the data in terms of the (V,A) possibility¹⁴ looking for deviations which can reveal new components or confirm the theoretical expectations and thus provide additional support for the gauge theories.

ISOVECTOR COMPONENTS

In analogy with the effective current-current interaction for charged currents, we write an effective neutral current interaction

$$\mathcal{L} = \frac{G}{(2)^{\frac{1}{2}}} J_{\lambda}^{\lambda} J_{\lambda}^{\lambda} \quad (12)$$

where J_{λ} is a hermitean neutral current of the form

$$J_{\lambda} = \bar{\nu}_e \gamma_{\lambda} (1 - \gamma_5) \nu_e + \bar{e} \gamma_{\lambda} (\nu_e + a_e \gamma_5) e + \begin{pmatrix} e & \mu \\ \nu_e & -\nu_{\mu} \end{pmatrix} \\ + v_3 v_{\lambda}^3 + a_3 A_{\lambda}^3 + v_0 v_{\lambda}^0 + a_0 A_{\lambda}^0 + \sin \theta_c [v_6 v_{\lambda}^6 + a_6 A_{\lambda}^6 + v_7 v_{\lambda}^7 + a_7 A_{\lambda}^7] \quad (13)$$

The underlying assumption is that the hadronic neutral current components transform like an octet representation of SU(3) plus an SU(3) singlet. The superscripts indicate the particular SU(3) assignments. In general, the couplings v_{λ}^7 and A_{λ}^7 to other currents lead to CP violation⁸ and will be omitted. The suppression of K decays in Eq. (1) and (2) suggest that v_6 and a_6 are very small so we set them equal to zero. The remaining currents are representative of a large number of the possibilities discussed in the literature. We mention three distinct examples. (1) In the Weinberg-Salam¹⁵ model $a_3 = 1$, $v_3 = 1 - 2 \sin^2 \theta_w$. Both $v_0 \neq 0$ and $a_0 \neq 0$ in the extension of the model that incorporates strange particles.

(2) In the model of Beg and Zee¹⁶ the neutral current is proportional to the electromagnetic current ($a_3 = a_0 = 0$).

(3) In Sakurai's model $a_3 = v_3 = 0$. The current is an SU(3) singlet with the vector part identified as the baryonic current and it may also have a chiral (axial) partner ($v_0 \neq 0$, maybe $a_0 \neq 0$). There are numerous other models but their enumeration is beyond the scope of these lectures.

Concerning the isovector components the problem is now reduced to the determination of the parameters v_3 and a_3 . There are two general theorems which are helpful in this respect.

Theorem II. Consider the cross sections

$$\begin{aligned}\Sigma^0 &= \sigma(\nu p \rightarrow \nu x_1) + \sigma(\bar{\nu} n \rightarrow \bar{\nu} x_2) \\ \Sigma^+ &= \sigma(\nu p \rightarrow \mu^+ x_3) + \sigma(\bar{\nu} n \rightarrow \mu^+ x_4)\end{aligned}\quad (14)$$

with the corresponding cross sections for antineutrinos denoted by $\bar{\Sigma}^0$ and $\bar{\Sigma}^-$. Let x_i refer to the sum of all final states or a subset of states, subject only to the requirement that a sum over all possible charge configurations has been performed,

$$\text{THEN} \quad R_I = \frac{\Sigma^0 + \bar{\Sigma}^0}{\Sigma^+ + \bar{\Sigma}^-} \geq \frac{1}{2} \frac{v_3^2 v + a_3^2 A}{v + A} \quad (15)$$

where $V(A)$ is the contribution of v_λ^3 (A_λ^3) alone to the cross section.

In applying the results to the total cross sections we can appeal to the experimental observation that

$$v \approx A$$

and obtain

$$R_I \geq \frac{1}{4}(v_3^2 + a_3^2) \quad (16)$$

R_I can be evaluated from Table 1 giving

$$0.27 \pm 0.09 \geq R_I \text{ to 90\% confidence level.} \quad (17)$$

The main conclusion is that the v_λ^3 on A_λ^3 couplings cannot be maximal ($|v_3| = |a_3| = 1$). This is shown graphically in Fig. 1 where the interior of the large circle is the allowed physical region.

Theorem III : Under the same assumptions of theorem II

$$R_{II} = \frac{\Sigma^0 - \bar{\Sigma}^0}{\Sigma^+ - \bar{\Sigma}^-} = \frac{1}{2} v_3 a_3 + \frac{1}{2} v_0 a_0 \frac{\sigma_I^0}{\sigma_I^+} \quad (18)$$

where σ_I^0 (σ_I^+) is the contribution to the cross section arising from the V-A interference term of the isoscalar (charged) current.

We could calculate R_{II} from Table 1, but the errors are so large that Eq. (18) is not very restrictive. To demonstrate the restrictions implied by the theorem we consider the central values given by the experiments. Neglecting the isoscalar term, the Gargamelle results give the hyperbola H shown in Fig. 1. For the HPWF experiment the hyperbola degenerates into the two axes and implies that neutral currents are only vector or only axial.

Further restrictions are obtained by appealing to Schwartz's inequalities for the isovector and isoscalar currents. For the Gargamelle data the physical region is constrained to lie within the octagon ABCD, which looks very much like a rectangle. The HPWF experiment gives a different region but it too premature to take two standard deviations very seriously, because the experimental values require further refinements.

To sum up, for any arbitrary isoscalar current v_3 and a_3 cannot be maximal. For a multi-parameter theory the latitude of physical possibilities is shown in Fig. 1. This is a natural extension of the model independent bounds often discussed in the literature and could be realized within the gauge theories.

The conditions become more restrictive, if one assumes that the isoscalar contribution is much smaller than the isovector. This is a reasonable assumption, because in parton model calculations they couple to strange and charm-quark distributions which make them small. For zero isoscalar current contributions the allowed physical region from Eq. (15) is a circular ring indicated in Fig. 1. Its overlap with the region within the octagon is indicated by the shaded areas. The fact that one of them contains the point $a_3 = 1$ and $v_3 = 0.28$ is consistent with the

Weinberg-Salam theory. It is evident that estimates of the isoscalar components are very important and we analyze them in the next section.

ISOSCALAR COMPONENTS

Most of the studies concerning the internal symmetry structure of neutral currents deal with low energy reactions where the number of final state particles is limited. In this case both the initial and final states have precise quantum numbers and it is possible to infer the internal symmetry structure of the current. A clear example is provided by single pion production, where one expects to see evidence for the excitation of the Δ -resonance. The absence of the Δ will imply the absence of an $I=1$ component, belonging to the same multiplet with the charged currents. The analysis of such reactions is greatly facilitated by earlier calculations²³ in isobar models which account for electromagnetic and weak pion production. A relativistic generalization of the static model, developed by²⁴ Adler, has been applied extensively to charged current reactions and seems to be successful. Theoretical interpretations are easiest in experiments with hydrogen and deuterium targets. Experimental considerations, however, necessitate the use of complex nuclear targets and in the latter part of this section we address the question of nuclear corrections involved in the interpretation of the experiments.

Reactions in hydrogen and deuterium

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The following charged current reactions have been observed

$$\nu p \rightarrow \mu^- p \pi^+ \quad (19)$$

$$\nu n \rightarrow \mu^- p \pi^0 \quad (20)$$

$$\nu n \rightarrow \mu^- n \pi^+ \quad (21)$$

The rates and pion-nucleon mass distributions are within the expectations of the model. Figure 2 shows the data for reaction (19) together with the²⁵ theoretical calculation. The theoretical curve is normalized to the integrated experimental cross section. In the same Fig. 1 plotted the pre-

diction of the model for the reaction

$$\bar{\nu}_n \rightarrow \mu^+ n \pi^- \quad (22)$$

We note that the ratio of $\bar{\nu}/\nu$ is in the vicinity of 0.38 over an extensive range of pion-nucleon masses. Measurement of this reaction provides a specific test for the $I = 3/2$ amplitude of the model. The striking feature in reactions (19) and (22) is the dominant Δ -resonance. A smaller enhancement in the Δ -region has also been observed²⁵ for reactions (20) and (21), but the statistics are more limited. The data are again consistent with the model calculations.

In discussing neutral currents one encounters the matrix elements of new operators and it is desirable to discuss them independent of specific dynamic models. Results of this general nature are available in the form²⁶ of lower bounds. For the Weinberg-Salam theory they are listed in Table II together with the experimental observations. The bounds are consistent with the experimental values, but they still allow substantial isoscalar contributions. It is therefore desirable to go beyond the bounds and attempt detailed comparisons between theory and experiment. Estimates of the pion-nucleon mass distributions are along these lines.

I describe here one general approach.

- 1) Reaction (19) determines the $I = 3/2$ amplitude. The relative vector and axial contributions can be inferred from reactions (19) and (21), provided that the two terms are relatively real.
- 2) The magnitude of the $I = 1/2$ amplitude can be obtained from the sum

$$\sigma(\nu_n \rightarrow \mu^- n \pi^+) + \sigma(\nu_n \rightarrow \mu^- p \pi^0) \quad (23)$$

where the interference term between the two isospin amplitudes is absent. The relative contributions of vector and axial matrix elements is also determined by comparing them with corresponding electroproduction data.

Table 11. Neutral Current Measurements for Single Pion Production

Reaction	Experiment	Theory	Ref	Target
$R_0 = \frac{\sigma(\nu p \rightarrow \nu p \pi^0)}{\sigma(\nu p \rightarrow \mu^- p \pi^+)}$	$= 0.40 \pm 0.22$	≥ 0.10	4, 24	H ₂
$R_+ = \frac{\sigma(\nu p \rightarrow \nu n \pi^+)}{\sigma(\nu p \rightarrow \mu^- p \pi^+)}$	$= 0.13 \pm 0.06$	≥ 0.08	4, 24	H ₂
$R_- = \frac{\sigma(\nu n \rightarrow \nu p \pi^-)}{\sigma(\nu p \rightarrow \mu^- p \pi^+)}$	$= 0.07 \pm 0.03$		4	D ₂
$R_{0+} = R_0 + R_+$	$= 0.53 \pm 0.23$	≥ 0.10	4, 26	H ₂ , D ₂
$R = \frac{\sigma(\bar{\nu} N \rightarrow \bar{\nu} N' \pi^0)}{\sigma(\bar{\nu} N \rightarrow \mu^- N' \pi^0)}$	$= 0.17 \pm 0.06$	≥ 0.03	6, 26	75% Al 25% C
	≤ 0.21		27	Freon

3) The phase of the $I = 3/2$ amplitude relative to the $I = 1/2$ amplitude is assumed to be given by the phase of the Breit-Wigner denominator. In general this is the phase of a resonance relative to a non-resonant background.

The calculation indicates that the $I = 1/2$ amplitude is important and it is most important away from the peak of the resonance. The phases of the amplitudes are also important. Figure 3 shows the pion-nucleon mass distribution for the reaction

$$\nu p \rightarrow \nu p \pi^0 \quad (24)$$

at an incident neutrino energy of 1 GeV. Curve (a) shows the expectation of models with destructive interference below the resonance and constructive above the resonance. Curve (b) corresponds to constructive interference below the resonance. Curve (c) shows the incoherent sum of the two amplitudes. Figure 4 shows the results of a similar calculation but for

the sum of the cross sections

$$d\sigma(\nu p \rightarrow \nu p \pi^0) + d\sigma(\nu p \rightarrow \nu n \pi^+) \quad (25)$$

In this case the interference term between the two isospin amplitudes cancels out. A prominent feature of Figs. 3 and 4 is their similarity to
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corresponding mass distributions in electroproduction.

Nuclear Targets

The cross sections on heavy nuclear targets are considerably different because of multiple scattering and charge exchange corrections within the nuclei. There are two types of calculations available at this time.
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In the first approach, one considers the scattering from an isospin zero nucleus and describes the final states in terms of the isospin of the resulting nucleus and a pion. The lower bounds derived are also included in
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Table II and are again consistent with experiment. In the second approach, one calculates the cross sections on free protons and neutrons and then folds in the nuclear corrections. The main aspects of the nuclear-corrections-model could be tested in electromagnetic and charged current experiments but this has not been done as yet. To indicate the importance
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of the $I = 1/2$ amplitude and of the nuclear corrections we discuss the ratio

$$R = \frac{\sigma(\nu'' p'' \rightarrow \nu p \pi^0) + \sigma(\nu'' n'' \rightarrow \nu n \pi^0)}{2\sigma(\nu'' n'' \rightarrow \mu^- p \pi^0)} \quad (26)$$

which has been measured in ${}_{13}\text{Al}$ ²⁷. Table III shows the different contributions to R in the Weinberg-Salam theory. The model also indicates that

$\sin^2 \theta_W$	Δ -only	$\Delta_1 + (I = 1/2)$	$\Delta + (I = 1/2) +$ charge exchange correction
0.3	0.56	0.40	0.23
0.4	0.46	0.33	0.18

Table III

the charge exchange correction for the reactions in the numerator is ~10% while the corresponding correction for the denominator is ~50%. The origin of this disparity lies in the presence of a large correction from reaction (19).

Other calculations on single pion reactions by the Princeton group³⁰ were reported at this meeting by Colglazier.³¹ The low energy theorem⁴ derived for $\nu_n \rightarrow \nu p \pi^-$ is still untested, because the new Argonne data are not sensitive to such small cross sections.

The main conclusion from all the studies so far is the following: There is no statistically significant evidence which indicates a discrepancy between the expectations of gauge theories and experiment. However, as was already mentioned, the comparisons made so far are not very sensitive to isoscalar contributions. Detailed pion-nucleon mass distributions are sensitive to large isoscalar terms, but because one encounters many corrections their sensitivity is also limited. Additional tests are needed.

There are measurements which are sensitive to the presence of an isoscalar-isovector interference term. For isoscalar targets the interference term shows up in the charge asymmetry of inclusive pion production²⁶

$$A_{\pi}(v) = \sigma(\nu N \rightarrow \nu \pi^+ X) - \sigma(\nu N \rightarrow \nu \pi^- X) \quad (27)$$

$$A_{\pi}(\bar{\nu}) = \sigma(\bar{\nu} N \rightarrow \bar{\nu} \pi^+ X) - \sigma(\bar{\nu} N \rightarrow \bar{\nu} \pi^- X) \quad (28)$$

Similarly for experiments on protons and neutron targets there are interference terms in the expressions⁸

$$A(v) = \sigma(\nu p \rightarrow \nu Y^+) - \sigma(\nu n \rightarrow \nu Y^0) \quad (29)$$

$$A(\bar{\nu}) = \sigma(\bar{\nu} p \rightarrow \bar{\nu} Y^+) - \sigma(\bar{\nu} n \rightarrow \bar{\nu} Y^0) \quad (30)$$

where the Y's stand for any final states summed over all possible charges.⁷ For bubble chamber experiments the study of the difference

$$A_{2\pi}(\nu) = \sigma(\nu + p \rightarrow \nu + p + \pi^+ + \pi^-) - \sigma(\nu + n \rightarrow \nu + n + \pi^+ + \pi^-) \quad (31)$$

is relatively simple and does not depend critically on the neutron background. In all these cases $[A(\nu) + A(\bar{\nu})]$ is sensitive to $v_0 v_3$ and $a_0 a_3$ while $[A(\nu) - A(\bar{\nu})]$ is sensitive to $v_0 a_3$ and $a_0 v_3$. $A_{2\pi}$ is proportional to the isoscalar-isovector interference and a large non-zero value will be evidence for substantial isoscalar components.

The study of η^0 meson production by charged and neutral currents is more demanding experimentally, but it is worth the effort, since it has a simple isospin structure. The general methods developed for single pion production are applicable and give additional constraints.

CONCLUSIONS AND OUTLOOK

The existence of muonless events in neutrino induced reactions is well established and their interpretation in terms of neutral currents seems natural.³² The general picture so far is consistent with the existence of vector and axial currents, which have both isovector and isoscalar components. However, one can not rule out other possibilities, nor can one determine yet the importance and magnitude of the different components. In this respect, there are several issues, whose resolution is relevant to future theoretical and experimental developments.

The absence of $\Delta S = 1$ neutral currents is inferred from low energy experiments. The absence of such components has never been tested at higher energies. In almost all theoretical models the absence of $\Delta S = 1$ components is taken for granted.

A dominant isoscalar component is not expected in gauge theories. This issue can be settled by studies on the excitation of the Δ -resonance, by determination of the charge asymmetries in Eqs. (27)-(31) and by the production of η^0 mesons. The existence of such a component is of importance not only to the internal structure of the models but it also has far-reaching applications providing a candidate for the explanation

supernovae explosions in massive stars.

Data with antineutrino beams are very limited. In fact data on reactions with specific final states are practically non-existent. Antineutrino reactions will clarify the space-time structure of the interactions and can provide more confidence for many of the calculations.

The theory for elastic scattering has been studied³⁴ in detail and it is known that the magnitude and Q^2 -dependence of the cross section can³⁵ distinguish among several models. An experiment sensitive to ν -p elastic scattering is now in progress.

Studies on the couplings of neutral currents³⁶ to $e\bar{e}$ and $\mu\bar{\mu}$ pairs are still in their infancy.

Looking back at the problems which were studied a few years ago, we can not fail to notice that considerable progress has been made. Most of the issues on the existence of neutral currents have been settled. The two new issues which have emerged, in the meanwhile, are concerned with the operator structure of the currents and their basic role within the framework of weak and electromagnetic interactions.

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Fig. 1 Physical ranges for the isovector coupling constants.

Fig. 2 Pion-nucleon mass distribution. Data are from Ref. 24. Solid curve corresponds to reaction (19); dashed curve to reaction (22).

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Fig. 3 Pion-nucleon mass distributions for reaction (24).

Fig. 4 Pion-nucleon mass distribution for the sum of reactions (25).

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