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COMPLETE EXPERIMENTS TO DETERMINE
NEUTRAL CURRENT COUPLINGS *)

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A B S T R A C T

We propose experiments to determine completely the space-time and isospin (or quark quantum number) properties of the hadronic part of weak neutral currents. We also show how various models make very different predictions on the $(\bar{\nu})_n / (\bar{\nu})_p$ ratio as a function of x .

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One of the major tasks in weak interaction physics today is to determine the space-time and isospin (or quark quantum number) properties of the hadronic part of the weak neutral currents. In this note we show how measurements of the x distributions in inclusive processes

$$\begin{aligned}\bar{\nu}' + p &\longrightarrow \bar{\nu}' + \text{hadrons} \\ \bar{\nu}' + n &\longrightarrow \bar{\nu}' + \text{hadrons}\end{aligned}\quad (1)$$

on protons and neutrons separately, when supplemented by data on diffractive production of vector and axial vector mesons, completely determine the coupling constants - six altogether - of the neutral current interactions ^{*)}. We also illustrate how various theoretical models make very different predictions on the $(\bar{\nu})_n/(\bar{\nu})_p$ ratio as a function of x .

We write the effective Lagrangian for the neutral current interactions (assumed to be of vector, axial vector form) induced by left-handed (right-handed) neutrinos (antineutrinos) as follows :

$$\begin{aligned}\mathcal{L} = & - (G/\sqrt{2}) \bar{\nu} \gamma_\lambda (1 + \gamma_5) \nu \left\{ \frac{1}{2} [\bar{u} \gamma_\lambda (\alpha + \beta \gamma_5) u - \bar{d} \gamma_\lambda (\alpha + \beta \gamma_5) d] \right. \\ & + \frac{1}{2} [\bar{u} \gamma_\lambda (\gamma + \delta \gamma_5) u + \bar{d} \gamma_\lambda (\gamma + \delta \gamma_5) d] + \bar{s} \gamma_\lambda (\gamma' + \delta' \gamma_5) s \\ & \left. + \text{possible } \bar{c} c, \bar{t} t \text{ and } \bar{b} b \text{ terms} \right\}\end{aligned}\quad (2)$$

where the quark model notation has been used. The coupling constants α , β , γ , and δ , respectively, characterize the strength of isovector vector, isovector axial vector, isoscalar vector and isoscalar axial vector. The constants γ' and δ' measure the amount of isoscalar made up of strange quarks.

Various theoretical models proposed up to now make very definite predictions on the coupling constants $\alpha, \beta, \dots$. The one-parameter Salam-Weinberg model predicts ¹⁾

^{*)} Such measurements are expected to be feasible with the advent of hydrogen and deuterium-filled chambers with track sensitive targets.

$$\alpha = 1 - 2 \sin^2 \theta_w, \quad \beta = 1, \quad \gamma = -\frac{2}{3} \sin^2 \theta_w, \quad \delta = 0. \quad (3)$$

and, when supplemented by the GIM mechanism ²⁾,

$$\gamma' = -\frac{1}{2} + \frac{2}{3} \sin^2 \theta_w, \quad \delta' = -\frac{1}{2}. \quad (4)$$

More recently, a number of authors proposed "vectorlike models", a typical version of which predicts ³⁾

$$\alpha = \rho (1 - \sin^2 \theta_v), \quad \gamma = -\frac{1}{3} \rho \sin^2 \theta_v, \quad \gamma' = \rho \left(-\frac{1}{2} + \frac{1}{3} \sin^2 \theta_v\right), \\ \beta = \delta = \delta' = 0. \quad (5)$$

Note that with $\sin^2 \theta_v$ chosen to be $3/4$, isoscalar isovector interference becomes maximal and that the coupling becomes pure $\bar{d} \gamma_\lambda d$ as far as non-strange quarks are concerned. This has a definite experimental consequence, as we shall see later. If the neutral current that interacts with the neutrino current is postulated to be the electromagnetic current, we expect ⁴⁾

$$\alpha = \lambda, \quad \gamma = \frac{1}{3} \lambda, \quad \gamma' = -\frac{1}{3} \lambda, \quad \beta = \delta = \delta' = 0. \quad (6)$$

A variant of this model has been considered where the axial vector current also has the $SU(3)$ structure of the electromagnetic current ⁵⁾. Many other models could be considered, e.g., the Adler-Tuan V-A model predicts ⁶⁾

$$\alpha = \beta, \quad \gamma = \delta = \gamma' = \delta' = 0, \quad (7)$$

but the important point for us is that all models can be classified by specifying $\alpha, \beta, \dots$.

If the valence quark model is valid, certain combinations of the four coupling constants α , β , γ and δ can be determined by comparing the inclusive reactions (1) with their charged current analogues :

$$\begin{aligned} \bar{\nu} + p &\longrightarrow \mu^{-(*)} + \text{hadrons} , \\ \bar{\nu} + n &\longrightarrow \mu^{-(*)} + \text{hadrons} . \end{aligned} \quad (8)$$

Using the standard quark-parton techniques, we readily derive

$$\frac{(d\sigma_{NC}^{\nu p} + d\sigma_{NC}^{\nu n}) + (d\sigma_{NC}^{\bar{\nu} p} + d\sigma_{NC}^{\bar{\nu} n})}{(d\sigma_{CC}^{\nu p} + d\sigma_{CC}^{\nu n}) + (d\sigma_{CC}^{\bar{\nu} p} + d\sigma_{CC}^{\bar{\nu} n})} = \frac{1}{4} (\alpha^2 + \beta^2 + \gamma^2 + \delta^2) , \quad (9a)$$

$$\frac{(d\sigma_{NC}^{\nu p} + d\sigma_{NC}^{\nu n}) - (d\sigma_{NC}^{\bar{\nu} p} + d\sigma_{NC}^{\bar{\nu} n})}{(d\sigma_{CC}^{\nu p} + d\sigma_{CC}^{\nu n}) - (d\sigma_{CC}^{\bar{\nu} p} + d\sigma_{CC}^{\bar{\nu} n})} = \frac{1}{2} (\alpha\beta + \gamma\delta) , \quad (9b)$$

$$\frac{(d\sigma_{NC}^{\nu p} + d\sigma_{NC}^{\bar{\nu} p}) - (d\sigma_{NC}^{\nu n} + d\sigma_{NC}^{\bar{\nu} n})}{(d\sigma_{CC}^{\nu p} + d\sigma_{CC}^{\bar{\nu} p}) - (d\sigma_{CC}^{\nu n} + d\sigma_{CC}^{\bar{\nu} n})} = -\frac{1}{2} (\alpha\gamma + \beta\delta) , \quad (9c)$$

$$\frac{(d\sigma_{NC}^{\nu p} - d\sigma_{NC}^{\bar{\nu} p}) - (d\sigma_{NC}^{\nu n} - d\sigma_{NC}^{\bar{\nu} n})}{(d\sigma_{CC}^{\nu p} - d\sigma_{CC}^{\bar{\nu} p}) - (d\sigma_{CC}^{\nu n} - d\sigma_{CC}^{\bar{\nu} n})} = -\frac{1}{2} (\alpha\delta + \beta\gamma) . \quad (9d)$$

where $d\sigma$ may stand for $d\sigma/dx dy$ or $d\sigma/dx$ (y integrated out). In writing the charged current cross-sections $\cos^2 \theta_{\text{Cabibbo}}$ has been set to unity. Equations (9a), (9b), (9c) and (9d), respectively, determine the over-all strength, VA (but not isoscalar isovector) interference, isoscalar isovector (but not VA interference), and VA and isoscalar isovector interference. Note that the distributions are insensitive to the coupling constants γ' and δ' because the valence quark model ignores s and $\bar{s}$ within the nucleon.

The valence quark model ⁷⁾ is known to be reliable for $x \gtrsim 0.2$ where the contributions due to the sea of quark-antiquark pairs become negligible^{*)}; later we consider corrections due to the sea. In addition, at high energies ($E \gtrsim 40$ GeV) the naïve valence quark model breaks down in the low x -high y region because of the now well established "anomalies" in the charged current data ⁸⁾.

Experiments performed with isoscalar targets (targets containing equal numbers of protons and neutrons) yield information on only the first two [(9a) and (9b)] of the four relations; this means that the coupling constants are undetermined when only isoscalar targets are available. With separate data on proton and neutron targets we have four equations and four unknowns. However, let us note that there are two ambiguities.

- i) vector axial vector ambiguity:

the right-hand sides of (9a)-(9d) are invariant under

$$\alpha \leftrightarrow \beta, \quad \gamma \leftrightarrow \delta$$

- ii) isoscalar-isovector ambiguity:

$$\alpha \leftrightarrow \gamma, \quad \beta \leftrightarrow \delta.$$

These ambiguities tell us, for example, that we cannot discriminate a vector dominant solution from an axial vector dominant solution (or an isovector dominant solution from an isoscalar dominant solution) on the basis of inclusive data alone.

To resolve the ambiguities we must resort to exclusive processes. The importance of studying nuclear transitions such as ⁹⁾

$$\bar{\nu}_e + {}^7\text{Li}(\frac{3}{2}^-) \longrightarrow \bar{\nu}_e + {}^7\text{Li}^*(\frac{1}{2}^-), \quad (10)$$

$$\bar{\nu}_e + \text{D} \longrightarrow \bar{\nu}_e + n + p \quad (11)$$

*) Even though we use the parton model language, some of our results can also be obtained without using quark partons. For example, the isovector parts of (9a) and (9b) can be determined using only isospin invariance, Bjorken scaling, chiral symmetry and maximal V-A interference.

whose cross-sections at low energies are proportional to β^2 alone has already been emphasized in this connection. We may also consider diffractive reactions

to resolve the ambiguities. As is well known, in photoproduction and in low q^2 electroproduction the reactions

proceed with characteristic features we expect from diffractive production. Likewise we expect the reactions (12) to proceed via diffractive mechanism as long as the current has a component with the same quantum number as the vector (or axial vector) meson in question. Calculations have been performed to estimate the cross-sections for (12) using vector or axial vector meson dominance¹⁰⁾. Such calculations are highly model-dependent and can, at best, be qualitative. However, if we compare (12) with their charged current analogues, the model uncertainties cancel out, and the relevant coupling constants may be extracted. Specifically we obtain

$$\frac{\frac{d\sigma}{dq^2}(\nu + N \longrightarrow \nu + \rho^0 + N)}{\frac{d\sigma}{dq^2}(\nu + N \longrightarrow \mu^- + \rho^+ + N)} \Big|_{\text{diffractive}} = \frac{1}{2} \alpha^2, \quad (14)$$

$$\frac{\frac{d\sigma}{dq^2}(\nu + N \longrightarrow \nu + A_1^0 + N)}{\frac{d\sigma}{dq^2}(\nu + N \longrightarrow \mu^- + A_1^+ + N)} \Big|_{\text{diffractive}} = \frac{1}{2} \beta^2. \quad (15)$$

Note that to resolve the ambiguities in inclusive data, only crude knowledge of diffractive processes is sufficient, e.g., whether $|\alpha| > |\beta|$ or $|\alpha| < |\beta|$, or whether $\alpha^2 + \beta^2$ is sizeable or much smaller than $\alpha^2 + \beta^2 + \gamma^2 + \delta^2$. We may also mention in passing that the elusive coupling constant γ' , which measures the strength of the vector part of $\bar{s}s$ (ϕ like piece), can be estimated by comparing the ϕ -to- ω ratio in the neutral current reactions to the corresponding ratio in the electroproduction reactions¹¹⁾

$$\frac{\left. \frac{d\sigma}{dq^2} (\nu + N \rightarrow \nu + \varphi + N) \right|_{\text{diffactive}}}{\left. \frac{d\sigma}{dq^2} (\nu + N \rightarrow \nu + \omega + N) \right|_{\text{diffactive}}} = \frac{\gamma^{1/2}}{\gamma^2} \frac{\left. \frac{d\sigma}{dq^2} (e + N \rightarrow e + \varphi + N) \right|_{\text{diffactive}}}{\left. \frac{d\sigma}{dq^2} (e + N \rightarrow e + \omega + N) \right|_{\text{diffactive}}} \quad (16)$$

at the same values of q^2 *).

Let us now return to the inclusive reactions (1). From the experiments already performed ¹²⁾, we roughly know the over-all strength :

$$\alpha^2 + \beta^2 + \gamma^2 + \delta^2 \approx 1.0 - 1.3 \quad , \quad (17)$$

and data relevant to the question of vector axial vector interference on isoscalar targets ($\alpha\beta + \delta\gamma$) are now beginning to come out ¹³⁾. However, virtually nothing is known about isoscalar-isovector interference ^{**)} ($\alpha\gamma, \beta\delta, \alpha\delta$ and $\beta\gamma$), which can be isolated only by examining how the cross-section on proton targets differs from that on neutron targets ^{***)}. Various theoretical models predict very different results on this interference term. To show this we first relate the proton-neutron difference in the neutral current reactions (1) to the proton-neutron difference in the electroproduction reactions ; this is possible in the valence quark model because the differences in both cases are proportional to the difference in the quark distribution functions of the u type and of the d type, $U(x)-D(x)$. We obtain

*) It is very important to make comparison at the same values of q^2 because the four processes are expected to have different q^2 dependence.

**) We do know, however, from single pion production that models with pure isoscalar ($\alpha = \beta = 0$) are unlikely ¹⁴⁾.

***) It has been noted ¹⁵⁾ that the charge ratios in pion semi-inclusive distributions are sensitive to isoscalar isovector interference. However, to extract the coupling constants in a quantitative manner, we must rely on the details of parton fragmentation models.

$$\frac{\frac{d\sigma^{vp}}{dx}_{NC} - \frac{d\sigma^{vn}}{dx}_{NC}}{\frac{d\sigma^{vp}}{dx}_{NC} + \frac{d\sigma^{vn}}{dx}_{NC}} = \frac{5}{3} \frac{(2\alpha\gamma + 2\beta\delta + \alpha\delta + \beta\gamma)}{(\alpha^2 + \beta^2 + \gamma^2 + \delta^2 + \alpha\beta + \gamma\delta)} \frac{F_2^{ep}(x) - F_2^{en}(x)}{F_2^{ep}(x) + F_2^{en}(x)},$$

$$\frac{\frac{d\sigma^{\bar{v}p}}{dx}_{NC} - \frac{d\sigma^{\bar{v}n}}{dx}_{NC}}{\frac{d\sigma^{\bar{v}p}}{dx}_{NC} + \frac{d\sigma^{\bar{v}n}}{dx}_{NC}} = \frac{5}{3} \frac{(2\alpha\gamma + 2\beta\delta - \alpha\delta - \beta\gamma)}{(\alpha^2 + \beta^2 + \gamma^2 + \delta^2 - \alpha\beta - \gamma\delta)} \frac{F_2^{ep}(x) - F_2^{en}(x)}{F_2^{ep}(x) + F_2^{en}(x)}. \quad (18)$$

Using these we can solve for the neutron-to-proton ratios for the inclusive reactions (1), which we shall discuss later.

So far we have relied on the validity of the valence quark model which ignores the contributions from the sea of quark-antiquark pairs. We can work out corrections to the formulae (9a)-(9d) assuming that the sea transforms like an SU(3) singlet. It turns out that (9b) (9c) and (9d) are unchanged as long as the sea is SU(2) symmetric - we do not even need SU(3) here - while the right-hand side of (9a) should be replaced as follows :

$$\alpha^2 + \beta^2 + \gamma^2 + \delta^2 \longrightarrow \alpha^2 + \beta^2 + \gamma^2 + \delta^2 + (\gamma'^2 + \delta'^2) Q_{sea}(x) / [Q(x) + Q_{sea}(x)] \quad (19)$$

where

$$Q(x) \equiv \frac{1}{2} [U(x) + D(x)],$$

$$Q_{sea}(x) \equiv \frac{1}{2} [\bar{U}(x) + \bar{D}(x)] = S(x) = \bar{S}(x). \quad (20)$$

When the sea contributions are added, Eq. (18) is modified in a more involved way ; the corrections needed are too lengthy to be reproduced here.

In the Figure we have made plots of the neutron-to-proton ratios for the reactions (1) as functions of x using currently popular theoretical models. The neutron-to-proton ratio for electroproduction used as input was obtained from the data of the SLAC-MIT collaboration, as found in Atwood's Ph.D. Thesis ¹⁶⁾. In our plots we have taken into account the contributions due to the sea assuming that the sea is unitary singlet and the quark and antiquark distributions are given by a single universal function ¹⁷⁾

$$Q_{\text{sea}}(x) = 0.16 (1-x)^7 / x \quad (21)$$

which is consistent with the Gargamelle charged current data.

The neutron-to-proton ratio is unity, independent of x , for all models with a pure isovector (or pure isoscalar) current. In the electromagnetic current model the ratio in the neutral current reactions is, of course, equal to the ratio in electroproduction. In the Salam-Weinberg model with $\sin^2 \theta_W = 0.35$, isovector isoscalar interference mainly arises from the dominant isovector axial vector amplitude interfering with the small isoscalar vector amplitude, hence the effect changes sign as we go from ν to $\bar{\nu}$; in any case the whole effect is not very large. Experimentally the neutron-to-proton ratio in electroproduction approaches $1/4$ for x close to unity; in the quark model language this implies that the distribution function for the d type quark within the proton vanishes. In a model in which the current is of pure $\bar{d}d$ form, as in vectorlike models with $\sin^2 \theta_V = 0.75$, the neutron-to-proton ratio for the neutral current reactions then goes to infinity for x close to unity. This feature is apparent in the Figure.

When we consider the total cross-section ratios, the differences among the various models are less spectacular. This is shown in the Table.

To summarize, measurements of the x distributions of the inclusive reactions (1) on proton and neutron targets, when supplemented by information obtainable from diffractive production (12), completely determine the coupling constants of the weak neutral current interactions. In addition, we have shown that various theoretical models predict very different behaviour for the neutron-to-proton ratio as a function of x .

	$\sigma_{NC}^{\nu n} / \sigma_{NC}^{\nu p}$	$\sigma_{NC}^{\bar{\nu} n} / \sigma_{NC}^{\bar{\nu} p}$
Pure isovector (pure isoscalar)	1	1
Salam-Weinberg ($\sin^2 \theta_W = 0.35$) (SW)	1.13	0.955
Vectorlike ($\sin^2 \theta_V = 0.5$)	1.30	1.30
Vectorlike ($\sin^2 \theta_V = 0.75$)	1.56	1.56
Electromagnetic current (EM)	0.75	0.75

TABLE : The neutron-proton ratio for the total cross-sections in the inclusive reactions (1).

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FIGURE CAPTION

The neutron-proton ratio in the inclusive reactions (1)
as a function of x .

FIG. 1