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ON THE STRUCTURE OF THE HADRONIC NEUTRAL CURRENT

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ABSTRACT

Using all available information from neutrino hadron interactions the coupling constants of the hadronic neutral current are determined independently of any gauge models. For inclusive and semi-inclusive scattering the quark parton model is assumed while for exclusive processes only general symmetry arguments are used. Essentially two solutions emerge from this analysis which are related by the VA ambiguity: either the isovector neutral current is predominantly vector and the isoscalar component predominantly axial-vector or vice versa. Both solutions are consistent with $SU(2) \times U(1)$ as the underlying gauge group, but with the standard weak isospin assignment for the electron only one of the solutions can account for the apparent absence of parity violation in bismuth.

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The determination of the coupling constants of the hadronic neutral current is now entering a crucial stage. On the one hand, the data on inclusive neutrino scattering have become very precise and all experiments are in agreement with each other. On the other hand, there is also an increasing amount of information on semi-inclusive and exclusive neutrino processes. The purpose of this letter is to use all available data on neutrino hadron scattering to determine the neutral current coupling constants independently of any gauge model. Since the methods to be employed have all been described in the literature, all details will be omitted here. For inclusive and semi-inclusive scattering use will be made of the quark parton model, while for exclusive processes only general symmetry arguments will be needed. Neglecting as usual strange and charmed quarks, the most general neutral current interaction for neutrino hadron scattering in the quark model is

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \bar{\nu} \gamma^\mu (1 + \gamma_5) \nu \int_\mu^{NC} \quad (1)$$

with

$$\int_\mu^{NC} = \bar{u} \gamma_\mu [u_L(1 + \gamma_5) + u_R(1 - \gamma_5)] u + \bar{d} \gamma_\mu [d_L(1 + \gamma_5) + d_R(1 - \gamma_5)] d \quad (2)$$

The neutral to charged current inclusive cross-section ratios $R, \bar{R}$ are obtained in terms of the coupling constants u_L, d_L, u_R, d_R and the ratio r of charged current antineutrino to neutrino cross-sections as

$$\begin{aligned} R &= u_L^2 + d_L^2 + r(u_R^2 + d_R^2) \\ \bar{R} &= u_L^2 + d_L^2 + r^{-1}(u_R^2 + d_R^2) \end{aligned} \quad (3)$$

The four published measurements ¹⁾⁻⁴⁾ of $R, \bar{R}$ are in good agreement with each other and may therefore be averaged to give

$$\begin{aligned} R &= 0.289 \pm 0.009 \\ \bar{R} &= 0.353 \pm 0.025 \end{aligned} \quad (4)$$

With ⁵⁾ $r=0.42$, one gets ^{*)}

*) The results are rather insensitive to reasonable variations in r .

$$\begin{aligned} u_L^2 + d_L^2 &= 0.275 \pm 0.012 \\ u_R^2 + d_R^2 &= 0.033 \pm 0.014 \end{aligned} \quad (5)$$

It has been argued first by Feynman ⁶⁾ that the parton model may also be used for semi-inclusive lepton hadron scattering in the so-called current fragmentation region ⁷⁾. This hypothesis has been tested rather successfully in electroproduction and charged current neutrino production of pions ⁸⁾⁻¹¹⁾. Various authors ¹¹⁾⁻¹⁷⁾ have therefore proposed to use this model to extract the neutral current coupling constants from semi-inclusive pion production.

It is a basic ingredient of the parton model that the chiral quarks scatter incoherently so that only the squares of u_L, d_L, u_R, d_R enter in observable quantities. Since inclusive scattering has already yielded two relations among the squares of the four coupling constants [Eq. (5)], two more measurements from semi-inclusive scattering are needed to obtain the maximal information within the parton model. This information has recently been given in terms of pion charge multiplicities in semi-inclusive pion production ¹⁸⁾. The theoretical analysis has been presented by Sehgal ¹⁹⁾ using a restricted sample to ensure the validity of the fragmentation hypothesis.

From the analysis of Ref. 19) and using the equations (5) from inclusive scattering one arrives at the one-standard-deviation domains for u_L^2, d_L^2 and u_R^2, d_R^2 shown in Fig. 1. These restrictions already exclude a large number of gauge models.

In order to get information also on the relative signs of u_L, d_L, u_R, d_R we must turn to exclusive processes. Since the parton model is not applicable in this case, it is convenient to introduce another set of coupling constants g_V, g_A, z, s [also called ²⁰⁾ $\alpha, \beta, 3\gamma, 3\delta$] by

$$\begin{aligned} g_V &= u_L + u_R - d_L - d_R \\ g_A &= u_L - u_R - d_L + d_R \\ z &= 3(u_L + u_R + d_L + d_R) \\ s &= 3(u_L - u_R + d_L - d_R) \end{aligned} \quad (6)$$

Three of these constants can be defined completely independently of the quark model by writing the hadronic neutral current in the form

$$J_{\mu}^{NC} = g_V V_{\mu}^3 + g_A A_{\mu}^3 + z V_{\mu}^0 + A_{\mu}^0 \quad (7)$$

where V_{μ}^3 (A_{μ}^3) is the third component of the isotriplet containing the charged vector (axial-vector) currents, V_{μ}^0 is the isoscalar electromagnetic current and A_{μ}^0 is the isoscalar axial current. As A_{μ}^0 cannot be related to other known currents outside the quark model frame its matrix elements are not known in general for exclusive processes. If the results are to be really model independent we therefore have to analyze the data without making any assumptions about A_{μ}^0 .

Our aim is to determine the coupling constants g_V, g_A, z, s or, equivalently u_L, d_L, u_R, d_R . There is one over-all sign which could only be determined in interference experiments; this sign is fixed by requiring $g_V + g_A$ to be positive which is equivalent to taking d_L negative with the values given in Fig. 1. In principle, there is then a threefold ambiguity left related to the signs of u_L, u_R, d_R . Two of these ambiguities have been discussed in the literature²⁰⁾ as VA ambiguity ($g_V \rightleftharpoons g_A, z \rightleftharpoons s$) and isovector-isoscalar ambiguity ($g_V \rightleftharpoons z/3, g_A \rightleftharpoons s/3$).

There is a third ambiguity which may be characterized by the sign of d_R . However, Fig. 1 shows that d_R is actually compatible with zero so that this ambiguity will not have much impact on g_V, g_A, z, s . With present data on exclusive scattering there is certainly no hope to resolve this ambiguity.

We are thus left with essentially four different solutions which are shown in the $g_V - g_A$ plane as domains a, b, c, d in Fig. 2. Comparing with the general bounds from inclusive scattering also shown in the same figure we see that a, b are the dominantly isovector solutions, while for c, d the isoscalar part prevails. The VA ambiguity is obvious.

As a first attempt to resolve these ambiguities let us turn to single pion production off nucleons. The preliminary neutrino data from Gargamelle²¹⁾ are in agreement with earlier Argonne results²²⁾, but with much larger statistics. The bounds on g_V, g_A for an arbitrary isoscalar component of the neutral current have been derived before²³⁾. Using all available Gargamelle data supplemented by Argonne results for processes not yet analyzed in the CERN experiment one obtains the bounds displayed in Fig. 2. Although

a complete error analysis is not yet possible it is worth noting that the area of the excluded central region in Fig. 2 is directly proportional to $2\sigma(\pi^0)-\sigma(\pi^+)-\sigma(\pi^-)$, summed over proton and neutron. This quantity is more than four standard deviations away from zero according to the Gargamelle experiment ²¹⁾.

The four solutions are also shown in the g_V - z plane in Fig. 3. Bounds for $g_{V,z}$ were derived ²⁵⁾ earlier without any assumption about the axial neutral current using data from the only experiment ²⁴⁾ that has measured both νp and $\bar{\nu} p$ elastic scattering. Those bounds are also shown in Fig. 3. Taking the evidence from both exclusive processes together we conclude that both "isoscalar" solutions c,d are excluded at least at the 1.5 standard deviation level. At this level of significance only the dominantly isovector solutions survive, or, in other words, u_L and d_L must have opposite signs. The remaining VA ambiguity which cannot be resolved at present is related to the unknown sign of u_R .

Taking into account the allowed values for the isoscalar coupling constants z,s shown in Fig. 4, the qualitative structure of the hadronic neutral current can be summarized as follows :

- 1) the hadronic neutral current is predominantly isovector;
- 2) if the isovector part is dominantly vector, the isoscalar component is dominantly axial-vector and vice versa.

How can we expect to distinguish between the two possible neutral current structures ? Without any assumption about the underlying gauge group the answer can only come from neutrino hadron interactions. The most important test in the immediate future will come from the combined results of neutrino and antineutrino pion production, both exclusive and semi-inclusive (but not restricted to the current fragmentation region). Those experiments will provide an independent determination of g_V, g_A and they will in principle allow to test for the magnitude of the isoscalar axial coupling ^{23),26)}. However, in order to extract this information it is absolutely necessary that the same experimental criteria are used for the analysis of ν and $\bar{\nu}$ data.

In the future the diffractive production of vector and axial-vector mesons ²⁰⁾ and the neutrino excitation of certain nuclear transitions ²⁷⁾ should provide other methods to resolve the VA ambiguity.

After this model independent analysis let us now turn to a very specific model, i.e., $SU(2) \times U(1)$. Bernabéu and Jarlskog²⁸⁾ have given two consistency relations to test the $SU(2) \times U(1)$ group structure assuming the standard weak isospin assignments for all left-handed fields. At present, only the relation

$$g_V + g_A + z + s = -2(v_e + a_e) \quad (8)$$

can be tested where v_e, a_e are the electronic neutral current coupling constants defined by

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \bar{\nu}_\mu \gamma^\lambda (1 + \gamma_5) \nu_\mu \bar{e} \gamma_\lambda (v_e + a_e \gamma_5) e \quad (9)$$

Both solutions a and b give

$$-0.59 \leq v_e + a_e \leq -0.29 \quad (10)$$

in agreement with all existing ν_e data²⁹⁾. Quite independently of the arguments given before, the solutions c and d are also incompatible with $SU(2) \times U(1)$ and the ν_e data.

With the standard weak isospin assignments for the left-handed quarks we have

$$\begin{aligned} u_L &= x \left(\frac{1}{2} - \frac{2}{3} \sin^2 \theta \right) \\ d_L &= x \left(-\frac{1}{2} + \frac{1}{3} \sin^2 \theta \right) \\ u_R &= x \left(I_{3R}^u - \frac{2}{3} \sin^2 \theta \right) \\ d_R &= x \left(I_{3R}^d + \frac{1}{3} \sin^2 \theta \right) \end{aligned} \quad (11)$$

for the most general $SU(2) \times U(1)$ model. $I_{3R}^{u,d}$ are the third isospin components of the right-handed quark fields, θ is the Weinberg angle and x depends on the spontaneous symmetry breaking mechanism [$x=1$ in the Salam-Weinberg model³⁰⁾]. From the values for u_L, d_L shown in Fig. 1, we find $x \simeq 1$, $\sin^2 \theta \simeq 0.3$ independently of I_{3R}^u and I_{3R}^d . The two models consistent with all existing neutrino experiments can then be characterized as follows :

$$\begin{aligned} \text{Model a) : } & I_{3R}^u > 0, I_{3R}^d \approx 0 \\ \text{Model b) : } & I_{3R}^u \approx I_{3R}^d \approx 0 \end{aligned}$$

Model a) is identified as one version of the bottom-quark model ³¹⁾ while model b) is practically ^{*)} the original Salam-Weinberg theory ³⁰⁾.

A final remark concerns the recent measurements ³²⁾ of parity violation in bismuth. Within $SU(2) \times U(1)$ and the standard isospin assignment for the electron only model a) is consistent with the data as shown in Fig. 3. As is well known, model b) can be easily reconciled with the apparent absence of parity violation by putting the right-handed electron into a doublet. This is just a reflection of the general statement that results for the hadronic neutral current with and without neutrinos cannot be combined in a model independent way.

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*) Given the uncertainties inherent in the parton model analysis of semi-inclusive pion production the slight discrepancy between the Salam-Weinberg model and the right-handed couplings u_R, d_R should not be taken seriously; the model is well within 1.5 standard deviations.

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FIGURE CAPTIONS

Figure 1 : One-standard-deviation domains for u_L^2, d_L^2 and u_R^2, d_R^2 from inclusive and semi-inclusive neutrino hadron scattering ¹⁹⁾. Broken lines are the bounds from inclusive scattering alone. Also shown are the predictions of the Salam-Weinberg model ³⁰⁾ for various values of $\sin^2\theta$.

Figure 2 : Domains a,b,c,d for the isovector couplings g_V, g_A . Bounds from inclusive scattering : allowed values inside full lines. Bounds from exclusive pion production ²³⁾ are given by broken lines : + for allowed regions , - for forbidden regions.

Figure 3 : Domains a,b,c,d in the g_V -z plane. Bounds from elastic scattering ²⁵⁾ : allowed values inside full lines (inside broken lines at 1 standard deviation). 90% confidence limits from Bi experiments ³²⁾ at Oxford (dash-dotted lines) and Seattle (dotted lines) within $SU(2) \times U(1)$ and standard electron assignment.

Figure 4 : Allowed domains a,b for the isoscalar coupling constants z,s.

FIG.1

FIG.2

FIG. 3

FIG. 4