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Analysis of the neutral-current interaction in the inclusive neutrino reactions

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Abstract. We attempt a general phenomenological analysis of the neutral weak current in the inclusive neutrino reactions using the parton model as a tool. From the recently reported data on these processes we determine the strength H of the neutral-current interaction as well as the amount of the VA interference. We find $(H/G)^2 = 0\cdot54 \pm 0\cdot06$ where G is the Fermi coupling constant and the VA interference contribution turns out to be $33 \pm 23\%$. We also discuss the comparison of the data with various models for the neutral hadronic current.

Keywords. Neutral current; weak interaction; inclusive neutrino reactions, phenomenological analysis; parton model; Weinberg's gauge model.

1. Introduction

Possible evidence for a neutral current in weak interactions has been reported by Hasert *et al* (1973) from experiments on neutrino reactions on nuclei. They have seen a large number of events which can be tentatively interpreted as

$$\nu_\mu (\bar{\nu}_\mu) + \mathcal{N} \rightarrow \nu_\mu (\bar{\nu}_\mu) + \text{Hadrons} \tag{1}$$

where $\mathcal{N}$ denotes the nucleon. Although other explanations are *not* yet ruled out, we shall assume that these are really the neutral-current events. According to Hasert *et al* (1973), the ratios of the neutral-current (N) to the charged-current (C) events are

$$\left(\frac{N}{C}\right)_\nu = 0\cdot21 \pm 0\cdot03 \tag{2}$$

$$\left(\frac{N}{C}\right)_{\bar{\nu}} = 0\cdot45 \pm 0\cdot09 \tag{3}$$

Our aim is to try to determine the nature of the neutral-current weak interaction from this type of data. It is rather unfortunate that the very first manifestation of the neutral current has been seen in the most complex reactions, namely, the inclusive processes in eq. (1). However, this is compensated by the circumstance that such complex reactions are known to exhibit a very simple structure for the nucleon, namely, the existence of point-like scattering centres (partons) inside the nucleon. This is what renders the analysis of these reactions possible at all.

Section 2 contains a brief discussion of the relevant leptonic neutral current. In section 3 and in the Appendix we analyse the hadronic neutral current using the parton model and in section 4 we discuss various models for the neutral current. Section 5 gives the conclusions of our analysis.

2. The leptonic neutral current

If the neutrino* is a two-component object satisfying

$$\gamma_5 \nu = \nu$$

then scalar, and tensor currents are not possible for the neutrino, for,

$$\bar{\nu}(1+\gamma_5)\,\nu = 0$$

$$\bar{\nu}\sigma_{\mu\nu}(1+\gamma_5)\,\nu = 0$$

Suppose, however, the neutral current does not respect the two-component neutrino theory. In other words, consider the possibility that the neutrino is really a four-component object although behaving like a two-component one in the usual charged-current weak currents. Then, we could write a scalar current

$$\bar{\nu}\,\{a_-(1-\gamma_5) + a_+(1+\gamma_5)\}\,\nu$$

where $a_\pm$ are arbitrary constants and a similar tensor current. But, if the neutrinos in the beam were produced in the decays of K, π or μ occurring through the well-known charged-current weak interaction, then they have negative helicity, so that

$$(1-\gamma_5)\,\nu = \bar{\nu}\,(1+\gamma_5) = 0$$

So, again the scalar and tensor neutral currents are *effectively* zero. Thus, although the neutral current may have scalar or tensor parts, we cannot detect them by using the neutrinos or antineutrinos produced in the conventional charged-current decay modes, as is the case with the present experimental situation.

Hence, the leptonic neutral current involved in the reactions in eq. (1) has to be $\bar{\nu}\gamma_\mu(1+\gamma_5)\,\nu$ and this is coupled to a hadronic neutral current N_μ so that the neutral current interaction is $\bar{\nu}\gamma_\mu(1+\gamma_5)\,\nu N_\mu$.

3. The hadronic neutral current and the parton model

Our aim is to try to determine the properties of the hadronic neutral current N_μ from a knowledge of the inclusive neutrino cross-sections. We shall write N_μ in the form†

$$N_\mu = \frac{1}{\sqrt{2}}\,(H_V{}^3 V_\mu{}^3 + H_V{}^0 V_\mu{}^0 + H_A{}^3 A_\mu{}^3 + H_A{}^0 A_\mu{}^0) \qquad (4)$$

where $V_\mu{}^{3,0}$ and $A_\mu{}^{3,0}$ are vector and axial vector currents and the superscripts 3 and 0 denote the isovector and isoscalar parts respectively. The four coupling constants $H_V{}^{3,0}$ and $H_A{}^{3,0}$, which we shall take as real, are to be determined from experimental data.

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* Hereafter, the symbol ν will stand for ν_μ. Our choice for γ_5 is such that $(1+\gamma_5)/2$ is the projection operator for the *negative* helicity of the neutrino. So the charged current in the well-known weak interaction involves $\gamma_\mu(1+\gamma_5)$ which will be referred to as $V+A$.

† One may rule out a hadronic current in the form of the gradient of a scalar, for, in that case, the matrix element for the semileptonic process is zero for a massless two-component neutrino.

For the analysis of the neutral-current inclusive processes we shall use the simplest possible model which seems to be consistent with the existing data on the charged-current inclusive processes as well as the electromagnetic inclusive processes. Such a model is the so-called *quark-parton model*, according to which, the proton is made up of two isospin-" up " quarks (u) and one isospin-" down" quark (d).

The relevant part of the basic weak interaction in our model can be written as

$$\mathcal{L}_{\text{int}} = \frac{G}{\sqrt{2}} \{\bar{\mu}\gamma_\lambda (1 + \gamma_5)\, \nu \bar{u}\gamma_\lambda (1 + \gamma_5)\, d + h.\, c.\} + \frac{1}{\sqrt{2}} \bar{\nu}\gamma_\mu (1 + \gamma_5)\, \nu \{\bar{u}\gamma_\mu (H_V{}^u + H_A{}^u\gamma_5)\, u + \bar{d}\gamma_\mu (H_V{}^d + H_A{}^d\gamma_5)\, d\} \tag{5}$$

where G is the Fermi coupling constant and we have rewritten the neutral hadronic current N_μ in terms of the isodoublet u and d. The connection between the two sets of coupling constants is given by the formulae:

$$\left.\begin{aligned} H_{V,A}{}^3 &= H_{V,A}{}^u - H_{V,A}{}^d \\ H_{V,A}{}^0 &= H_{V,A}{}^u + H_{V,A}{}^d \end{aligned}\right\} \tag{6}$$

We have ignored the $\triangle S = 1$ part of the charged-current interaction.

The total cross-section for the inclusive processes can be simply obtained in the parton model by adding the cross-sections for the point-particles— in our case u and d. We shall write down all the formulae for the case when the nucleon contains three partons. The changes to be made in the more general case of arbitrary number of partons are indicated in the Appendix. Using ν^+ and ν^- to denote ν and $\bar{\nu}$ respectively, we have

$$\left.\begin{aligned} \sigma_{N,C}(\nu^\pm p) &= 2\sigma_{N,C}(\nu^\pm u) + \sigma_{N,C}(\nu^\pm d) \\ \sigma_{N,C}(\nu^\pm n) &= \sigma_{N,C}(\nu^\pm u) + 2\sigma_{N,C}(\nu^\pm d) \end{aligned}\right\} \tag{7}$$

where the subscripts N and C refer to the neutral and charged-current processes respectively. It is straightforward to calculate the total cross-sections for the point-particles u and d using the interaction in eq. (5). In the limit of very high neutrino energy E in the laboratory system, we get

$$\left.\begin{aligned} \sigma_N(\nu^\pm u) &= \tfrac{1}{3} CE\{(H_V{}^u)^2 + (H_A{}^u)^2 \pm H_V{}^u H_A{}^u\} \\ \sigma_N(\nu^\pm d) &= \tfrac{1}{3} CE\{(H_V{}^d)^2 + (H_A{}^d)^2 \pm H_V{}^d H_A{}^d\} \end{aligned}\right\} \tag{8}$$

$$\left.\begin{aligned} \sigma_C(\nu u) &= \sigma_C(\bar{\nu} d) = 0 \\ \sigma_C(\nu d) &= 3\sigma_C(\bar{\nu} u) = CEG^2 \end{aligned}\right\} \tag{9}$$

where C is a constant. Hence, we get the cross-sections for proton and neutron

$$\left.\begin{aligned} \sigma_N(\nu^\pm p) &= \tfrac{1}{3} CE\{2(H_V{}^u)^2(1 + \beta_u{}^2 \pm \beta_u) + (H_V{}^d)^2(1 + \beta_d{}^2 \pm \beta_d)\} \\ \sigma_N(\nu^\pm n) &= \tfrac{1}{3} CE\{(H_V{}^u)^2(1 + \beta_u{}^2 \pm \beta_u) + 2(H_V{}^d)^2(1 + \beta_d{}^2 \pm \beta_d)\} \end{aligned}\right\} \tag{10}$$

$$\left.\begin{aligned} \sigma_C(\nu p) &= CEG^2; & \sigma_C(\nu n) &= 2CEG^2 \\ \sigma_C(\bar{\nu} p) &= 2CEG^2/3; & \sigma_C(\bar{\nu} n) &= \tfrac{1}{3} CEG^2 \end{aligned}\right\} \tag{11}$$

where

$$\beta_u = \frac{H_A^u}{H_V^u}; \qquad \beta_d = \frac{H_A^d}{H_V^d} \tag{12}$$

The constant C is given by

$$C = 2m\hat{u}/\pi \tag{13 a}$$

m_u being the effective mass of u. If the distribution of the momenta of u and d is taken into account, then the formula for C becomes

$$C = \frac{2}{\pi} m_p \int_0^1 x f(x)\, dx \tag{13 b}$$

where m_p is now the mass of the proton and $f(x)$ is the normalised probability for finding a point-particle with a fraction x of the four-momentum of the nucleon (this probability being assumed to be the same for both u and d). However, the value of C is irrelevant for our analysis, since we shall be concerned with the ratios of cross-sections only.

We may consider the following ratios:

$$\frac{2\sigma_N(\bar{\nu}p) - \sigma_N(\bar{\nu}n)}{2\sigma_N(\nu p) - \sigma_N(\nu n)} = \frac{1 + \beta_u^2 - \beta_u}{1 + \beta_u^2 + \beta_u} \tag{14}$$

$$\frac{2\sigma_N(\bar{\nu}n) - \sigma_N(\bar{\nu}p)}{2\sigma_N(\nu n) - \sigma_N(\nu p)} = \frac{1 + \beta_d^2 - \beta_d}{1 + \beta_d^2 + \beta_d} \tag{15}$$

$$\frac{2\sigma_N(\nu p) - \sigma_N(\nu n)}{\sigma_C(\nu p)} = \frac{(H_V^u)^2}{G^2}(1 + \beta_u^2 + \beta_u) \tag{16}$$

$$\frac{2\sigma_N(\nu n) - \sigma_N(\nu p)}{\sigma_C(\nu p)} = \frac{(H_V^d)^2}{G^2}(1 + \beta_d^2 + \beta_d) \tag{17}$$

From these four equations, the four parameters β_u, β_d, H_V^u and H_V^d can be determined. But the solution is not unique because of the quadratic ambiguities which can be easily enumerated. It can be seen that if β_u is a solution of the first equation, then $1/\beta_u$ also is a solution; similar is the case with the second equation. Actually this function

$$\phi(\beta) \equiv \frac{1 + \beta^2 - \beta}{1 + \beta^2 + \beta}$$

(which is the ratio of $\bar{\nu}$ to ν cross-section on the point-particles u or d) plays an important role in the analysis and so it is plotted in figure 1. One may note that $\phi(\beta)$ lies between 1/3 and 3 for all values of β and becomes unity in the case of pure V or pure A interaction. The third and fourth equations above determine only the magnitude and not the sign of H_V^u and H_V^d. To sum up, the magnitudes of all the coupling constants and the relative signs between the V and A coupling constants are determinable, but there exist equivalent solutions with V and A coupling constants interchanged.

Thus, apart from these quadratic ambiguities, *all the four fundamental coupling constants $H_V^{3,0}$ and $H_A^{3,0}$ of the neutral current can be phenomenologically determined from a knowledge of $\sigma_N(\nu \pm p)/\sigma_C(\nu p)$ and $\sigma_N(\nu \pm n)/\sigma_C(\nu p)$.*

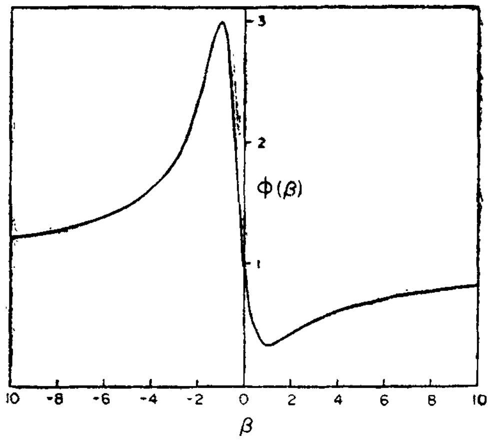

Figure 1. Plot of the function $\phi(\beta) = (1+\beta^2-\beta)/(1+\beta^2+\beta)$. This function represents both $\sigma_N(\bar{\nu}u)/\sigma_N(\nu u)$ and $\sigma_N(\bar{\nu}d)/\sigma_N(\nu d)$ in terms of the A/V ratio β.

However, at the present stage, the only information available [given in eqs (2) and (3)] is for a target of heavy nucleus. So, it is more appropriate to consider the cross-sections on the isospin-averaged nucleon target

$$\sigma_{N,C}(\nu^{\pm}\mathcal{N}) \equiv \tfrac{1}{2}\{\sigma_{N,C}(\nu^{\pm}p) + \sigma_{N,C}(\nu^{\pm}n)\} \tag{18}$$

From eqs (10), (11) and (18), we get

$$\sigma_N(\nu^{\pm}\mathcal{N}) = \tfrac{1}{2}CE\{(H_V{}^u)^2(1+\beta_u{}^2 \pm \beta_u) + (H_V{}^d)^2(1+\beta_d{}^2 \pm \beta_d)\} \tag{19}$$

$$\sigma_C(\bar{\nu}\mathcal{N}) \quad = \tfrac{1}{3}\sigma_C(\nu\mathcal{N}) = \tfrac{1}{2}CEG^2 \tag{20}$$

The ratio $\frac{1}{3}$ occurring in eq. (20) is not far from the experimental value of $\sigma_C(\bar{\nu}\mathcal{N})/\sigma_C(\nu\mathcal{N})$ which is $0\cdot38 \pm 0\cdot02$ (Perkins 1972) and this in fact is one of the important supports for the simple model used here. But our interest is in the following ratios of the neutral- to charged-current total cross-sections:

$$r \equiv \frac{\sigma_N(\nu\mathcal{N})}{\sigma_C(\nu\mathcal{N})} = \frac{1}{3}\left\{\left(\frac{H_V{}^u}{G}\right)^2(1+\beta_u{}^2+\beta_u) + \left(\frac{H_V{}^d}{G}\right)^2(1+\beta_d{}^2+\beta_d)\right\} \tag{21}$$

$$\bar{r} \equiv \frac{\sigma_N(\bar{\nu}\mathcal{N})}{\sigma_C(\bar{\nu}\mathcal{N})} = \left\{\left(\frac{H_V{}^u}{G}\right)^2(1+\beta_u{}^2-\beta_u) + \left(\frac{H_V{}^d}{G}\right)^2(1+\beta_d{}^2-\beta_d)\right\} \tag{22}$$

It is worthwhile to point out that these formulae on which we base all our subsequent analysis are in fact valid even if we allow the nucleon to contain an arbitrary (but fixed) number of the isodoublets u and d. For details the reader is referred to the Appendix.

We now identify r and $\bar{r}$ with the experimental ratios given in eqs (2) and (3) so that

$$r = 0\cdot21 \pm 0\cdot03 \tag{2$'$}$$

$$\bar{r} = 0\cdot45 \pm 0\cdot09 \tag{3$'$}$$

This is only of approximate validity since the experimental ratios of Hasert *et al* pertain to only those events for which the energy-transfer to the hadrons is greater than 1 GeV. As the energy E of the incident neutrino becomes higher, this identification would be better valid, in view of the expected Bjorken scaling. However, this may not be the case at the present neutrino energy which is 1–10 GeV. Hence our numerical results should be regarded as tentative and they can be improved when higher energy data become available.*

Although a complete determination of all the four parameters is not possible from the two eqs (21) and (22), certain important combinations of the parameters can nevertheless be determined. For this purpose we consider the sum and difference of $3r$ and $\bar{r}$ and thus get

$$\tfrac{1}{2}(3r + \bar{r}) = H^2/G^2 \tag{23}$$

$$2\left(\frac{3r - \bar{r}}{3r + \bar{r}}\right) = 2\,\frac{(H_V{}^u H_A{}^u + H_V{}^d H_A{}^d)}{H^2} \tag{24}$$

where we have defined

$$H^2 = (H_V{}^u)^2 + (H_A{}^u)^2 + (H_V{}^d)^2 + (H_A{}^d)^2 \tag{25}$$

Hence, from the already known experimental values of r and $\bar{r}$ given in eqs (2′) and (3′), we are able to determine the "total strength" of the neutral current H and the value of the VA interference term:

$$(H/G)^2 = 0\cdot 54 \pm 0\cdot 06 \tag{26}$$

$$\frac{2\,(H_V{}^u H_A{}^u + H_V{}^d H_A{}^d)}{H^2} = 0\cdot 33 \pm 0\cdot 23 \tag{27}$$

Hence one may draw two conclusions: (*a*) The strength of the neutral-current interaction is comparable to that of the charged-current interaction as one would have expected from the values of r and $\bar{r}$; (*b*) The VA interference term seems to be small, in contrast to the case of the charged-current where it is unity. So, *a pure $V + A$ or a pure $V - A$ theory for the complete neutral current is not favoured by the data.* The tentative nature of this conclusion should be emphasized both in view of the large error in eq. (27) and because of the cut in the energy-transfer already discussed.

For the sake of completeness, we may also record here the ratio of the antineutrino to neutrino cross-section for the neutral current. In our model it is given by

$$\frac{\sigma_N(\bar{\nu}\mathscr{N})}{\sigma_N(\nu\mathscr{N})} = \frac{\bar{r}}{3r} = 0\cdot 71 \pm 0\cdot 18 \tag{28}$$

where we have used the numerical values of r and $\bar{r}$ from eqs (2′) and (3′). If we replace the factor 1/3 in the middle of this equation by the experimental value of $\sigma_C(\bar{\nu}\mathscr{N})/\sigma_C(\nu\mathscr{N}) = 0\cdot 38 \pm 0\cdot 02$ (Perkins 1972), we get instead the purely empirical value $\sigma_N(\bar{\nu}\mathscr{N})/\sigma_N(\nu\mathscr{N}) = 0\cdot 81 \pm 0\cdot 20$.

The procedure we have adopted thus far assumes only the point-constituent nature of the nucleon, but is otherwise quite general. From the two experimental ratios we have deduced two combinations of the neutral-current parameters. This

* One can correct for this cut in the energy-transfer by using the formulae from the parton model (*see* Sehgal 1973). However, since this is a correction of order 1/E as compared to the leading term, one should then also consider the non-scaling terms which are also of order $1/E$. Needless to say such detailed estimates of the non-leading terms would depend sensitively on the various assumed details of the parton models.

is as far as we can go within the general framework at the present stage. In the next section, we shall discuss the range of values of the four parameters H_V^u, H_V^d, β_u and β_d allowed by the present data. We shall do this by considering a variety of possible models for the hadronic neutral current.

4. Models for the neutral current

4.1. *Model with same* A/V *ratio for* u *and* d

This model is perhaps the simplest and is defined by the equality

$$\beta_u = \beta_d = \beta$$

With this model, β can be determined from the equation:

$$\frac{\bar{r}}{3r} = \frac{1 + \beta^2 - \beta}{1 + \beta^2 + \beta}$$

and then, $\{(H_V^u)^2 + (H_V^d)^2\}/G^2$ can be determined using

$$r = \frac{1}{3} \frac{(H_V^u)^2 + (H_V^d)^2}{G^2} (1 + \beta^2 + \beta)$$

Remembering the quadratic ambiguity already discussed, the results can be written in the form:

$$\frac{H_A^u}{H_V^u} = \frac{H_A^d}{H_V^d} = 0{\cdot}17 \pm 0{\cdot}13; \quad \frac{(H_V^u)^2 + (H_V^d)^2}{G^2} = 0{\cdot}52 \pm 0{\cdot}07$$

or

$$\frac{H_V^u}{H_A^u} = \frac{H_V^d}{H_A^d} = 0{\cdot}17 \pm 0{\cdot}13; \quad \frac{(H_A^u)^2 + (H_A^d)^2}{G^2} = 0{\cdot}52 \pm 0{\cdot}07$$

Hence, in the framework of this model, the present data are not inconsistent with either a pure vector or a pure axial vector for the hadronic neutral current.

4.2. *Model with equal and opposite* A/V *Ratio for* u *and* d

This model is defined by

$$\beta_u = -\beta_d = \beta$$

If we further take $(H_V^u)^2 = (H_V^d)^2$, the interference term drops out from the isospin-averaged cross-sections and we get

$$\frac{\sigma_N(\bar{\nu}\mathcal{N})}{\sigma_N(\nu\mathcal{N})} = \frac{\bar{r}}{3r} = 1.$$

This should be compared with the experimental value given in eq. (28). To the extent that the discrepancy is only about 1.5 standard deviations this case cannot probably be ruled out.† Then, from r one gets

$$\frac{(H_V^u)^2 + (H_A^u)^2}{G^2} = 0{\cdot}32 \pm 0{\cdot}05$$

† If there is a real discrepancy, one may take $(H_V^u)^2$ to be unequal to $(H_V^d)^2$, which is a variant of this class of models.

Note that β is left undetermined so that it can be as high as unity. So, a pure $V-A$ interaction for u and a pure $V+A$ interaction for d, or *vice versa*, is not ruled out by the present data.

Thus, models (4.1) and (4.2) illustrate two rather distinct ways of achieving the small VA interference term in eq. (27).

4.3. *Weinberg-type model*

Consider the neutral-current interaction

$$\mathcal{L}_{\text{int}}^{N} = \frac{1}{\sqrt{2}} \bar{\nu}\gamma_{\mu}(1+\gamma_5)\,\nu\,[H_{VA}{}^{3}\{\bar{u}\gamma_{\mu}(1+\gamma_5)\,u - \bar{d}\gamma_{\mu}(1+\gamma_5)\,d\} + H_V{}^{e} j_{\mu}{}^{e}]$$

where $j_{\mu}{}^{e}$ is the hadronic electromagnetic current. Unfortunately, a specification of the charges of u and d is now necessary and consequently there are several possibilities. If we take the partons to be the Gell-Mann-Zweig quarks, then,

$$j_{\mu}{}^{e} = \tfrac{2}{3}\bar{u}\gamma_{\mu}u - \tfrac{1}{3}\bar{d}\gamma_{\mu}d \ldots$$

We can now determine $H_{VA}{}^{3}$ and $H_V{}^{e}$ from the values of r and $\bar{r}$. We find

$$\frac{H_V{}^{e}}{H_{VA}{}^{3}} = \tfrac{1}{2}\{\lambda \pm \sqrt{\lambda^2 + 8\lambda}\}; \qquad \lambda = \frac{27}{5}\left(\frac{\bar{r}-r}{3r-\bar{r}}\right)$$

$$\left(\frac{H_{VA}{}^{3}}{G}\right)^2 = \frac{1}{2}(3r-\bar{r})\left(2 + \frac{H_V{}^{e}}{H_{VA}{}^{3}}\right)^{-1}$$

Using r and $\bar{r}$ from eqs (2′) and (3′) we get the two solutions:

Solution 1:

$$\frac{H_V{}^{e}}{H_{VA}{}^{3}} = -1\cdot 64 \pm 0\cdot 25; \quad \left(\frac{H_{VA}{}^{3}}{G}\right)^2 = 0\cdot 23 \pm 0\cdot 03 \tag{29}$$

Solution 2:

$$\frac{H_{VA}{}^{3}}{H_V{}^{e}} = 0\cdot 11 \pm 0\cdot 10; \quad \left(\frac{H_V{}^{e}}{G}\right)^2 = 0\cdot 64 \pm 0\cdot 25 \tag{30}$$

Note that the second solution is consistent with a pure "electromagnetic" neutral current, *i.e.* $H_{VA}{}^{3} = 0$.

Weinberg's model (Weinberg 1971) is a one-parameter model with

$$H_{VA}{}^{3} = G/2 \tag{31}$$

$$\frac{H_V{}^{e}}{H_{VA}{}^{3}} = -4\sin^2\theta_W \tag{32}$$

where θ_W is Weinberg's mixing angle. The prediction of Weinberg's model $(H_{VA}{}^{3}/G)^2 = 0\cdot 25$ is in remarkable agreement with solution 1 above, obtained with Gell-Mann-Zweig quarks. And we get the value of $\sin^2\theta_W$ from eqs (29) and (32)

$$\sin^2\theta_W = 0\cdot 41 \pm 0\cdot 06$$

These results on Weinberg's model have been previously obtained by Palmer (1973) and Sehgal (1973).

4·4. *Sakurai-type model*

As a last example, consider the model

$$\mathcal{L}_{\text{int}}{}^{N} = \frac{1}{\sqrt{2}} \bar{\nu}\gamma_{\mu}(1+\gamma_5)\,\nu\,[H_{VA}{}^{3}\{\bar{u}\gamma_{\mu}(1+\gamma_5)\,u - \bar{d}\gamma_{\mu}(1+\gamma_5)\,d\} + H_V{}^{b} j_{\mu}{}^{b}]$$

where $j_{\mu}{}^{b}$ is the baryonic current

$$j_{\mu}{}^{b} = \bar{u}\gamma_{\mu}u + \bar{d}\gamma_{\mu}\,d + \ldots$$

absorbing the baryonic number of u and d in $H_V{}^{b}$. We get

$$\left(\frac{H_{VA}{}^{3}}{H_V{}^{b}}\right)^2 = \frac{3r - \bar{r}}{3(\bar{r} - r)} = 0{\cdot}25 \pm 0{\cdot}27 \tag{33}$$

$$\left(\frac{H_V{}^{b}}{G}\right)^2 = \tfrac{3}{4}(\bar{r} - r) = 0{\cdot}18 \pm 0{\cdot}07 \tag{34}$$

We see that eq. (33) is consistent with a pure "baryonic" neutral current, *i.e.* $H_{VA}{}^{3} = 0$, recently advocated by Sakurai (1973).

5. Conclusions and discussion

When new phenomena (such as the possible existence of the neutral weak current) are experimentally discovered, it is essential to analyse the experimental results within a sufficiently general theoretical framework rather than interpret the data using a particular model of the new phenomenon. This is the point of view pursued in our analysis.

Such a general theoretical framework involves at least four parameters for the hadronic neutral current and they can all be determined from the formulae discussed in section 3 and in the Appendix, provided data for proton and neutron targets are separately available.

Since the averages $\frac{1}{2}\{\sigma_N(\nu^{\pm}p) + \sigma_N(\nu^{\pm}n)\}$ are essentially what are measured in the experiments of Hasert *et al.* performed with the Gargamelle bubble chamber, we need in addition $\sigma_N(\nu^{\pm}p)$ which can perhaps be obtained from experiments with a hydrogen bubble chamber suitably modified to increase the amount of matter. We should stress the importance of these latter experiments from the point of view of a general analysis of the hadronic neutral current.

From the available data on the isospin-averaged target we have determined the strength of the neutral current and the value of the VA interference term [given in eqs (26) and (27)]. The VA interference term appears to be rather small as compared to unity.

We have also compared the data with various models of the neutral current. However, until $\sigma_N(\nu^{\pm}p)$ and $\sigma_N(\nu^{\pm}n)$ are separately measured, a definitive statement on the models cannot be made. One can in fact construct a large class of models all consistent with the data on the isospin-averaged target. The only model which is not favoured by the present data is the one with a pure $V - A$ or a pure $V + A$ current.

We should now enumerate the assumptions and approximations made in our analysis.

(*a*) As already explained, we have ignored the effect of the exclusion of events with energy-transfer to the hadrons < 1 GeV. Strictly speaking, this is justified only for neutrino energy $E \gg 1$ GeV.

(*b*) In fact, use of the parton model itself is justified only for much higher values of E than the present values (1–10 GeV). However, the fact that experimental data on the charged-current inclusive processes exhibit a behavior (such as the linear rise of σ_C with E) expected from scaling, already for E in the range 1–10 GeV (Perkins 1972) indicates that the gross features of the parton-model are perhaps valid even at such low energies.

(*c*) We have ignored contributions from the "sea" of quark-antiquark pairs. The deviation of $\sigma_C(\bar{\nu}\mathscr{N})/\sigma_C(\nu\mathscr{N})$ from 1/3, if it persists for still higher values of E, can be parametrized in terms of this contribution which can then be used to correct our formulae.

(*d*) We have also ignored the contributions from the "gluon". This can be justified if the gluon has some quantum number (such as "colour") which forbids its contribution to the neutral current.

Two other minor sources of error in our work are

(*e*) neglect of the small difference between the number of protons and that of neutrons in the target used (CF_3Br); and

(*f*) neglect of the strange hadrons.

Finally, one should keep in mind the possibility that the events seen by Hasert *et al* which we have so far attributed to the reaction in eq. (1) may be really due to the production of some heavy lepton mainly decaying into hadron channels. However, Llewellyn Smith (1973) has given some arguments indicating this possibility to be unlikely. We may remark that if this heavy lepton L is neutral and not too heavy and if the lepton current is assumed to be of the $V + A$ form $\bar{L}\gamma_\mu(1+\gamma_5)\,\nu$, then our analysis, especially that in section 3, remains valid even for this case.

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APPENDIX

Here we shall briefly discuss the model with an arbitrary (but fixed) number of the isodoublet partons inside the nucleon. If the number of d-partons in the proton is k, then by isospin invariance, the number of u-partons is $k+1$. The number of u and d partons in the neutron also is determined by isospin invarianec. It is straightforward to write the formulae for $\sigma_{N,C}(\nu^{\pm}p)$ and $\sigma_{N,C}(\nu^{\pm}n)$ by analogy to eqs (7), (10) and (11). The equations corresponding to eqs (14)–(17) will now involve k in the left-hand-side. However k can be eliminated in favour of $\sigma_C(\nu p)/\sigma_C(\nu n)$ so that we get

$$\frac{\sigma_N(\bar{\nu}p)\,\sigma_C(\nu n) - \sigma_N(\bar{\nu}n)\,\sigma_C(\nu p)}{\sigma_N(\nu p)\,\sigma_C(\nu n) - \sigma_N(\nu n)\,\sigma_C(\nu p)} = \frac{1 + \beta_u^2 - \beta_u}{1 + \beta_u^2 + \beta_u} \tag{A.1}$$

$$\frac{\sigma_N(\bar{\nu}n)\,\sigma_C(\nu n) - \sigma_N(\bar{\nu}p)\,\sigma_C(\nu p)}{\sigma_N(\nu n)\,\sigma_C(\nu n) - \sigma_N(\nu p)\,\sigma_C(\nu p)} = \frac{1 + \beta_d^2 - \beta_d}{1 + \beta_d^2 + \beta_d} \tag{A.2}$$

$$\frac{\sigma_N(\nu p)\,\sigma_C(\nu n) - \sigma_N(\nu n)\,\sigma_C(\nu p)}{\sigma_C^2(\nu n) - \sigma_C^2(\nu p)} = \frac{1}{3}\left(\frac{H_V^u}{G}\right)^2 (1 + \beta_u^2 + \beta_u) \tag{A.3}$$

$$\frac{\sigma_N(\nu n)\,\sigma_C(\nu n) - \sigma_N(\nu p)\,\sigma_C(\nu p)}{\sigma_C^2(\nu n) - \sigma_C^2(\nu p)} = \frac{1}{3}\left(\frac{H_V^d}{G}\right)^2 (1 + \beta_d^2 + \beta_d) \tag{A.4}$$

These equations replace eqs (14)–(17). So the four parameters of the neutral current can still be determined from a knowledge of the total cross-sections on proton and neutron targets.

As far as the isospin-averaged target is concerned, the cross-sections for the neutral-current processes as well as the charged-current processes get multiplied by the same factor $(2k + 1)/3$ and hence eqs (21) and (22) are left unaffected.

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