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CHARGE SYMMETRY AND NEUTRAL CURRENT IN A UNIFIED MODEL
OF WEAK AND ELECTROMAGNETIC INTERACTIONS

Fayyazuddin *)

CERN - Geneva

and

Riazuddin

Pakistan Atomic Energy Commission, Islamabad

A B S T R A C T

It is pointed out that measurement of the ratio $\sigma^{\bar{\nu}N}/\sigma^{\nu N}$ and the V-A interference term for the high-energy inclusive processes $\nu(\bar{\nu}) + N \rightarrow \ell^{\mp} + \text{anything}$ (N is the proton-neutron average) can give an estimate of the violation of charge symmetry in these processes. We then give an expression for charge symmetry violation in terms of experimentally measured structure functions above charm threshold for the above processes for the Salam-Weinberg model. In addition, we give predictions for neutral current for the process $\nu(\bar{\nu}) + N \rightarrow \nu(\bar{\nu}) + \text{anything}$, below and above charm threshold for charged currents. It is pointed out that the predictions for the neutral current below charm threshold are the same as those due to a phenomenological neutral current with SU(3) structure

$$i \tilde{\psi} \gamma_{\mu} (1 + \gamma_5) \frac{1}{2} (\lambda_3 + \frac{1}{\sqrt{3}} \lambda_8 - \frac{1}{2} \sqrt{2/3} \lambda_0) \tilde{\psi}$$

where $\tilde{\psi} = \begin{bmatrix} P \\ N \\ \lambda \end{bmatrix}$. We use light cone algebra to obtain our results in the scaling region.

*) On leave of absence from the University of Islamabad, Pakistan.

1. INTRODUCTION

The scaling observed in the SLAC electron-scattering experiments has generated considerable interest in the light-cone analysis of structure functions for inelastic electron and neutrino scattering on nucleons. This is due to the fact that in the scaling limit, one is probing the structure of the current commutator near the light cone. The structure functions are related to the Fourier transform of the current commutator. It was pointed out by Fritzsch and Gell-Mann¹⁾ that all of the parton model and current algebra sum rules can be obtained, without making any detailed assumptions on the distribution of the partons in a hadron, by simply abstracting from the free quark model tensor and the $SU(3) \times SU(3)$ structure of the current commutators near the light cone. Once this assumption is made, we have definite predictions regarding the violation of charge symmetry for deep inelastic neutrino-nucleon scattering. We find that deviation from charge symmetry predictions is proportional to $\sin^2 \theta_c$, where θ_c is the Cabibbo angle. From the analysis of weak decays, we know that $\sin^2 \theta_c$ is very small and thus charge symmetry should hold to this accuracy. One way of testing $SU(3) \times SU(3)$ light-cone algebra is to verify that deviations from charge-symmetry predictions are small.

In recent years there has been much interest in unified models of weak and electromagnetic interactions. In the version studied by Salam and Weinberg²⁾ the weak and electromagnetic interactions are mediated by two massive charged vector bosons $W_\mu^\pm$, a neutral vector boson Z_μ and the massless photon A_μ . The model was extended by Weinberg³⁾ to include the hadron. The gauge group in this model is $S_L U(2) \times U(1)$ and the fundamental fermions on which the gauge symmetry acts are taken to be quark fields. In order to eliminate the strangeness-changing neutral current, a four-quark scheme of Glashow-Iliopoulos and Maiani⁴⁾ is used. The symmetries act on two $S_L U(2)$ multiplets

$$\frac{1+\gamma_5}{2} \begin{bmatrix} P \\ N_c \end{bmatrix}, \quad \frac{1+\gamma_5}{2} \begin{bmatrix} P' \\ N'_c \end{bmatrix},$$

with $N_c = N \cos \theta_c + \lambda \sin \theta_c$, $N'_c = -N \sin \theta_c + \lambda \cos \theta_c$ and on four right-handed singlets $\frac{1}{2}(1 - \gamma_5) (P', P, N, \lambda)$. Here P, N, λ and P' denote four quarks, the first three forming a $SU(3)$ triplet, while the fourth quark P' has the same charge as P but differs from the triplet by one unit of a new quantum number, the "Charm" C . The vector bosons A_μ, W_μ and Z_μ are coupled to the electromagnetic current J_μ^{em} , the weak hadronic charged current J_μ^W and weak hadronic neutral current J_μ^Z ; these currents being constructed from the four quark fields.

There are two characteristic features of this model, the introduction of the charm quantum number and the neutral currents. The consequences of light-cone algebra abstracted from the currents J_μ^{em} , J_μ^W and J_μ^Z may be relevant for the deep inelastic neutrino nucleon scattering. Some of these consequences have already been discussed in the literature⁵⁾. The purpose of this paper is to extend these consequences. In particular, we want to discuss the role of charge symmetry; in this model we do not know *a priori* whether the deviations from the predictions of charge symmetry are small or large.

First we point out that by measuring the ratio $R = \sigma^{\bar{\nu}N}/\sigma^{\nu N}$ and B for the reactions $\nu(\bar{\nu}) + N \rightarrow \ell^+ + \text{anything}$, we can determine the deviation from charge symmetry provided we assume scaling and the Callan-Gross⁶⁾ relation $F_L = 0$. Here N denotes the average of the proton-neutron target.

$$B \equiv - \int_0^1 \xi F_3(\xi) d\xi / \int_0^1 F_2(\xi) d\xi$$

is the $V - A$ interference term. This is discussed in Section 2.

In Section 3, we discuss the consequences of light-cone algebra abstracted from the free-quark model below charm threshold. In this case, the deviation from charge symmetry is of the order of $\sin^2 \theta_c$, namely ≈ 0 . The predictions of neutral currents are written down in such a way that they can be tested provided we know $\sin^2 \theta_W$. Conversely, these predictions can be used to determine $\sin^2 \theta_W$. If we assume that the present CERN data is for energies below charm threshold, we find that it is possible to find a solution for $\sin^2 \theta_W$ within the experimental value. It is pointed out that all these consequences are compatible with phenomenological neutral current which for fractionally-charged quarks has the $SU(3)$ structure

$$J_\mu^Z = i \bar{\Psi} \gamma_\mu (1 + \gamma_5) \frac{1}{2} \left(\lambda_3 + \frac{1}{\sqrt{3}} \lambda_8 - \frac{1}{2} \sqrt{\frac{2}{3}} \lambda_0 \right) \Psi \\ - 2 \sin^2 \theta_W J_\mu^{\text{em}},$$

where

$$J_\mu^{\text{em}} = i \bar{\Psi} \gamma_\mu \frac{1}{2} \left(\lambda_3 + \frac{1}{\sqrt{3}} \lambda_8 \right) \Psi \\ \Psi = \begin{bmatrix} P \\ N \\ \lambda \end{bmatrix}.$$

In Section 4, we discuss the predictions of the Salam-Weinberg model above charm threshold. These predictions provide a real test of this model. In particular, we point out that deviation from charge symmetry can be written in terms of experimentally measurable quantities for the inclusive reactions $\nu(\bar{\nu}) \rightarrow \ell^{\pm} +$ + anything above charm threshold. This will provide a test of the model when the data above charm threshold are available. It is pointed out that if the present trend in the data continues above charm threshold, the deviation from charge symmetry is compatible with zero for fractionally-charged quarks. In that case there will not be any marked change in passing from below to above charm threshold and it will be hard to test this model for inclusive processes.

2. SCALING AND CHARGE SYMMETRY

Assuming scale invariance, the high-energy neutrino scattering cross-section for the process $\nu(\bar{\nu}) + p \rightarrow \ell^{-(+)} +$ anything (we shall use the approximation $m_{\ell} = 0$ and take the target to be a nucleon) can be written⁷⁾:

$$\frac{d^2 \sigma^{\nu, \bar{\nu}}}{d\xi dy} = \frac{G^2 m E}{\pi} \left[\left(1 - y + \frac{1}{2} y^2\right) F_2^{\nu, \bar{\nu}}(\xi) - y^2 \xi F_L^{\nu, \bar{\nu}}(\xi) + y \left(1 - \frac{1}{2} y\right) \xi F_3^{\nu, \bar{\nu}}(\xi) \right], \quad (2.1a)$$

where

$$\xi = \frac{q^2}{2m\nu}, \quad y = \nu/E. \quad (2.1b)$$

Here E is the incident neutrino (anti-neutrino) energy, $\nu = E - E'$ is the energy transfer and $q^2 = 4EE' \sin^2 \theta/2$ is the momentum transfer. We note that

$$0 \leq \xi \leq 1; \quad 0 \leq y \leq \left(1 + \frac{m\xi}{2E}\right)^{-1} \quad (2.2a)$$

$$F_L(\xi) = \frac{1}{2\xi} F_2(\xi) - F_1(\xi). \quad (2.2b)$$

We write

$$F_i^{\bar{\nu} N} = \frac{1}{2} (F_i^{\bar{\nu} p} + F_i^{\bar{\nu} n}) \quad (2.3a)$$

$$F_i^{\sim N} = \frac{1}{2} (F_i^{\sim p} + F_i^{\sim n}), \quad i = 2, L, 3. \quad (2.3b)$$

We now define the following functions and parameters

$$F_i = \frac{1}{2} (F_i^{\sim N} + F_i^{\sim \bar{N}}) \quad (2.4a)$$

$$f_i = \frac{1}{2} (F_i^{\sim N} - F_i^{\sim \bar{N}}) \quad (2.4b)$$

$$R_L = \int_0^1 \xi F_L(\xi) d\xi / \int_0^1 F_2(\xi) d\xi \quad (2.5a)$$

$$B = - \int_0^1 \xi F_3(\xi) d\xi / \int_0^1 F_2(\xi) d\xi \quad (2.5b)$$

$$r_2 = \int_0^1 f_2(\xi) d\xi / \int_0^1 F_2(\xi) d\xi \quad (2.6a)$$

$$r_L = \int_0^1 \xi f_L(\xi) d\xi / \int_0^1 F_2(\xi) d\xi \quad (2.6b)$$

$$r_3 = - \int_0^1 \xi f_3(\xi) d\xi / \int_0^1 F_2(\xi) d\xi. \quad (2.6c)$$

It is clear that r_i ($i = 2, L, 3$) measure the deviation from charge symmetry. Further we note that positivity conditions for the structure functions F_i are given by⁷⁾

$$0 \leq \frac{|\xi F_3|}{F_2} \leq \frac{2 \xi F_1}{F_2} \leq 1. \quad (2.7)$$

From this we have

$$0 \leq R_L \leq \frac{1}{2} [1 - |B|] \quad (2.8a)$$

$$-1 \leq B \leq 1 - 2 R_L \quad . \quad (2.8b)$$

To proceed further we will make the reasonable assumption that

$$\frac{\int_0^1 \xi f_L(\xi) d\xi}{\int_0^1 \xi F_L(\xi) d\xi} = \frac{\int_0^1 \xi f_3(\xi) d\xi}{\int_0^1 \xi F_3(\xi) d\xi} = \frac{\int_0^1 f_2(\xi) d\xi}{\int_0^1 F_2(\xi) d\xi} = \alpha_2. \quad (2.9)$$

Thus we have

$$\alpha_L = \alpha_2 R_L \quad (2.10a)$$

$$\alpha_3 = \alpha_2 B. \quad (2.10b)$$

Defining

$$R = \frac{\sigma^{\nu N}}{\sigma^{\nu N}}, \quad (2.11)$$

we have from Eq. (2.1a)

$$(1+R) \sigma^{\nu N} = \frac{4}{3} \frac{G^2 m E}{\pi} \left[\int_0^1 F_2(\xi) d\xi \right] \times \left[1 - \frac{1}{2} R_L + \frac{1}{2} \alpha_2 B \right] \quad (2.12a)$$

$$(1-R) \sigma^{\nu N} = \frac{4}{3} \frac{G^2 m E}{\pi} \left[\int_0^1 F_2(\xi) d\xi \right] \times \left[\alpha_2 (1 - \frac{1}{2} R_L) + \frac{1}{2} B \right] \quad (2.12b)$$

$$\frac{1}{\sigma^{\nu N}} \frac{d\sigma^{\nu N}}{dy} = \frac{3}{4} \frac{1+R}{\left[1 - \frac{1}{2} R_L + \frac{1}{2} r_2 B\right]} \times (1+r_2) \left[1 - (1-B)y \left(1 - \frac{1}{2} y\right) - R_L y^2\right] \quad (2.13a)$$

$$\frac{1}{\sigma^{\nu N}} \frac{d\sigma^{\bar{\nu} N}}{dy} = \frac{3}{4} \frac{1+R}{\left[1 - \frac{1}{2} R_L + \frac{1}{2} r_2 B\right]} \times (1-r_2) \left[1 - (1+B)y \left(1 - \frac{1}{2} y\right) - R_L y^2\right] \quad (2.13b)$$

$$\begin{aligned} \frac{1}{\sigma^{\nu N}} \left[\frac{d\sigma^{\nu N}}{dy} - \frac{d\sigma^{\bar{\nu} N}}{dy} \right] &= \frac{3}{4} \frac{1+R}{\left[1 - \frac{1}{2} R_L + \frac{1}{2} r_2 B\right]} \\ &\times \left[2r_2 + (2B - 2r_2)y \left(1 - \frac{1}{2} y\right) + 2r_2 B y^2 \right]. \end{aligned} \quad (2.13c)$$

If we have charge symmetry, then $r_2 = 0$, and it is clear from Eq. (2.13c), that any deviation from $y(1 - \frac{1}{2} y)$ distribution will indicate violation of charge symmetry.

We will now assume the Callan-Gross relation $2\xi F_1(\xi) = F_2(\xi)$, viz. $R_L = 0$. There is experimental support for this relation from the electroproduction data. In any case if B comes out to be experimentally nearly equal to 1, then from Eq. (2.8a) it follows that $R_L \approx 0$. It follows from Eqs. (2.12) and (2.13) that

$$\frac{1-R}{1+R} = (r_2 + \frac{1}{2} B) / (1 + \frac{1}{2} r_2 B) \quad (2.14)$$

$$\frac{1}{\sigma^{\nu N}} \frac{d\sigma^{\nu N}}{dy} = \frac{3}{4} \frac{1+R}{1+\frac{1}{2}r_2 B} (1+r_2) \times \left[1 - (1-B)y \left(1 - \frac{1}{2}y\right) \right] \quad (2.15a)$$

$$\frac{1}{\sigma^{\bar{\nu} N}} \frac{d\sigma^{\bar{\nu} N}}{dy} = \frac{3}{4} \frac{1+R}{1+\frac{1}{2}r_2 B} (1-r_2) \times \left[1 - (1+B)y \left(1 - \frac{1}{2}y\right) \right]. \quad (2.15b)$$

Equation (2.14) can also be written

$$\frac{1+r_2}{1-r_2} = \frac{1}{R} \frac{2-B}{2+B}. \quad (2.16)$$

From Eqs. (2.15), we have for $y = 1$

$$\frac{1}{\sigma^{\nu N}} \frac{d\sigma^{\nu N}}{dy} \bigg/ \frac{1}{\sigma^{\bar{\nu} N}} \frac{d\sigma^{\bar{\nu} N}}{dy} \bigg|_{y=1} = \frac{1}{R} \frac{2-B}{2+B} \frac{1+B}{1-B}. \quad (2.17)$$

It is clear from Eqs. (2.16) and (2.17), that by experimentally measuring R and the y distribution for neutrino and anti-neutrino scattering, we can determine both B and r_2 . The magnitude of r_2 will determine whether our assumption that the light-cone algebraic structure is responsible for scaling is correct or not. From the present experimental data, we know that⁸⁾ $R = 0.38$, but the value of B is not as yet known. At present we can give only bounds on r_2 . From Eqs. (2.8b) (with $R_L = 0$) and (2.14), we have

$$\frac{1-3R}{1+3R} \leq r_2 \leq \frac{3-R}{3+R}. \quad (2.18a)$$

Using $R = 0.38$, we get

$$-0.07 \leq r_2 \leq 0.79 \quad . \quad (2.18b)$$

If the experimental value of R remains near $1/3$ even at higher energy, it is clear that deviation from charge symmetry can be large only if the value of B comes out to be appreciably different from 1. On the other hand, if $B \approx 1$, then $r_2 \approx (1 - 3R)/(1 + 3R)$ and any strong deviation from charge symmetry is possible only if R is appreciably different from $1/3$. The measurement of B is crucial to determine r_2 if we believe that the present experimental value for R will not change appreciably. It is clear from Eq. (2.15a) that for $B \approx 1$, we have a flat distribution for $d\sigma^{\text{VN}}/dy$. But the flat distribution will support charge symmetry only if R comes out to be near $1/3$. We can get strong deviation from charge symmetry if either B changes appreciably from the value 1, but the present experimental value for R persists or B remains near 1, but R changes appreciably from $1/3$ or both B and R change appreciably from the value $B \approx 1$ and $R = 1/3$.

The present trend in the experimental data does not indicate that R will come out to be drastically different from 0.38; in that case strong deviation from charge symmetry is possible if B comes out to be very much different from 1. Finally, probably B is not negative or zero; in that case Eqs. (2.18) become

$$\frac{1-3R}{1+3R} \leq r_2 < \frac{1-R}{1+R} \quad (2.19a)$$

$$-0.07 \leq r_2 < 0.48 \quad . \quad (2.19b)$$

3. PREDICTION OF LIGHT-CONE ALGEBRA BELOW CHARM THRESHOLD

In this section, we shall discuss the predictions of light-cone algebra below the charm threshold for the Salam-Weinberg model. Below the charm threshold the charged hadronic weak current has the usual Cabbibo form and thus the predictions for this current are the same as one gets from the usual $SU(3) \times SU(3)$ light-cone algebra. The electromagnetic current in the Salam-Weinberg model has a component which involves charm particles and if we assume that this component can be ignored for the uncharmed targets, then again the electromagnetic current reduces as in usual $SU(3) \times SU(3)$ algebra.

Before writing the weak and electromagnetic currents in the Salam-Weinberg model, we define

$$\Psi = \begin{bmatrix} P' \\ P \\ N \\ \lambda \end{bmatrix}, \quad \tilde{\Psi} = \begin{bmatrix} P \\ N \\ \lambda \end{bmatrix} \quad (3.1a)$$

$$W = \begin{bmatrix} 0 & u \\ 0 & 0 \end{bmatrix}, \quad u = \begin{bmatrix} -\sin \theta_c & \cos \theta_c \\ \cos \theta_c & \sin \theta_c \end{bmatrix} \quad (3.1b)$$

$$W^0 = [W, W^\dagger]_-, \quad \tilde{W}^0 = \begin{bmatrix} 1 & & \\ & -1 & \\ & & -1 \end{bmatrix} \quad (3.1c)$$

$$Q = \begin{bmatrix} a & & & \\ & a & & \\ & & a^{-1} & \\ & & & a^{-1} \end{bmatrix}, \quad \tilde{Q} = \begin{bmatrix} a & & & \\ & a^{-1} & & \\ & & & \\ & & & a^{-1} \end{bmatrix} \quad (3.1d)$$

We can now write the currents J_μ^W , J_μ^{em} and J_μ^Z :

$$\begin{aligned} J_\mu^W &= i \bar{\Psi} \gamma_\mu (1 + \gamma_5) W \Psi \\ &= \cos \theta_c J_\mu^0 + \sin \theta_c J_\mu^1 + J_\mu^{\Delta C = \pm 1} \end{aligned} \quad (3.2a)$$

$$\begin{aligned} J_\mu^{\text{em}} &= i \bar{\Psi} \gamma_\mu Q \Psi \\ &= i \bar{\tilde{\Psi}} \gamma_\mu \tilde{Q} \tilde{\Psi} + a V_\mu^c \end{aligned} \quad (3.2b)$$

$$\begin{aligned}
 J_\mu^Z &= \frac{1}{2} [J_\mu^{W^0} - 4 \sin^2 \theta_W J_\mu^{em}] \\
 &= \frac{i}{2} \bar{\tilde{\Psi}} \gamma_\mu (1 + \gamma_5) \tilde{W}^0 \tilde{\Psi} \\
 &\quad + 2 J_\mu^C - 2 \sin^2 \theta_W J_\mu^{em}, \tag{3.2c}
 \end{aligned}$$

where

$$J_\mu^0 = i \bar{\tilde{\Psi}} \gamma_\mu (1 + \gamma_5) \frac{\lambda_1 + i \lambda_2}{2} \tilde{\Psi} \tag{3.3a}$$

$$J_\mu^1 = i \bar{\tilde{\Psi}} \gamma_\mu (1 + \gamma_5) \frac{\lambda_4 + i \lambda_5}{2} \tilde{\Psi} \tag{3.3b}$$

$$\begin{aligned}
 J_\mu^{\Delta C = \pm 1} &= \bar{P}' \gamma_\mu (1 + \gamma_5) \lambda \cos \theta_c \\
 &\quad - \bar{P}' \gamma_\mu (1 + \gamma_5) N \sin \theta_c \tag{3.3c}
 \end{aligned}$$

$$V_\mu^C = i \bar{P}' \gamma_\mu P' \tag{3.3d}$$

$$J_\mu^{W^0} = i \bar{\Psi} \gamma_\mu (1 + \gamma_5) W^0 \Psi \tag{3.3e}$$

$$J_\mu^C = i \bar{P}' \gamma_\mu (1 + \gamma_5) P'. \tag{3.3f}$$

Below charm threshold, we can put

$$J_\mu^W = \cos \theta_c J_\mu^0 + \sin \theta_c J_\mu^1. \tag{3.4}$$

Then using light-cone algebra^{1,5)}, we have

$$F_2(\xi) = 2\xi \left[2\sqrt{2/3} G_0^A(\xi) + (\cos^2 \theta_c - \frac{1}{2} \sin^2 \theta_c) \frac{2}{\sqrt{3}} G_8^A(\xi) \right] \tag{3.5a}$$

$$F_3(\xi) = -2 \left[2\sqrt{2/3} G_0^S(\xi) + (\cos^2 \theta_c - \frac{1}{2} \sin^2 \theta_c) \frac{2}{\sqrt{3}} G_8^S(\xi) \right] \quad (3.5b)$$

$$f_2(\xi) = -2\xi \left[-\frac{3}{2} \sin^2 \theta_c \frac{2}{\sqrt{3}} G_8^S(\xi) \right] \quad (3.5c)$$

$$f_3(\xi) = -2 \left[-\frac{3}{2} \sin^2 \theta_c \frac{2}{\sqrt{3}} G_8^A(\xi) \right] \quad (3.5d)$$

$$F_L(\xi) = 0 \quad (3.5e)$$

$$F_2^{eN}(\xi) = 2\xi \left[(a^2 - a + \frac{1}{2}) 3b(\xi) + (a - \frac{1}{2})(c(\xi) - b(\xi) + y(\xi)) \right] \quad (3.6a)$$

$$\frac{1}{2}(F_2^{ep}(\xi) - F_2^{en}(\xi)) = 2\xi \left[2(a - \frac{1}{2})d(\xi) \right] \quad (3.6b)$$

$$F_2^{ZN}(\xi) = \frac{2\xi}{4} \left[6b(\xi) + 16 \sin^4 \theta_w \left((a^2 - a + \frac{1}{2}) 3b(\xi) + (a - \frac{1}{2})(c(\xi) - b(\xi) + y(\xi)) \right) - 4 \sin^2 \theta_w \left(3b(\xi) + 2(a - \frac{1}{2})(c(\xi) - b(\xi) + y(\xi)) \right) \right] \quad (3.7a)$$

$$F_3^{ZN}(\xi) = -\frac{1}{4} 2 \left[6b'(\xi) - 4 \sin^2 \theta_w \left(3b'(\xi) + 2(a - \frac{1}{2})(c'(\xi) - b'(\xi) + y'(\xi)) \right) \right] \quad (3.7b)$$

We note that $G_{0,8}^{S,A}(\xi)$ are Fourier transforms of $\tilde{G}_{0,8}^{S,A}(p \cdot z)$ defined as

$$\begin{aligned}
 & \frac{1}{2} (2\pi)^3 \frac{p_0}{m} \langle p | J_{\epsilon}^{0,8} (S_A; z, 0) | p \rangle \\
 &= \frac{1}{2} (2\pi)^3 \frac{p_0}{m} \langle p | \left[\frac{1}{2} (i \bar{\Psi}(z) \gamma_{\epsilon} (1 + \gamma_5) \frac{\lambda_{0,8}}{2} \tilde{\Psi}(0) \right. \\
 & \quad \left. \pm \frac{1}{2} (z \leftrightarrow 0) \right] | p \rangle \\
 &= \tilde{G}_{0,8}^{S,A}(p \cdot z) \left(\frac{p_{\epsilon}}{m} \right) + \dots \\
 &= \frac{1}{2} (2\pi)^3 \frac{p_0}{m} \langle p | V_{\epsilon}^{0,8} (S_A; z, 0) | p \rangle, \quad (3.8)
 \end{aligned}$$

where z is light like, $z^2 \approx 0$. The omitted terms are proportional to z_{μ} and play no role in our discussion. $b'(\xi)$, $y'(\xi)$ and $c'(\xi)$, and $b(\xi)$, $y(\xi)$ and $c(\xi)$ are Fourier transforms of $\tilde{G}_R^{S,A}(p \cdot z)$ defined as

$$\begin{aligned}
 & \frac{1}{2} (2\pi)^3 \frac{p_0}{m} \langle p | J_{\epsilon}^R (S_A; z, 0) | p \rangle \\
 &= \frac{1}{2} (2\pi)^3 \frac{p_0}{m} \langle p | \left[\frac{1}{2} (i \bar{\Psi}(z) \gamma_{\epsilon} (1 + \gamma_5) \wedge_R \Psi(0) \right. \\
 & \quad \left. \pm \frac{1}{2} (z \leftrightarrow 0) \right] | p \rangle \\
 &= \tilde{G}_R^{S,A}(p \cdot z) \left(\frac{p_{\epsilon}}{m} \right) + \dots, \quad (3.9)
 \end{aligned}$$

where $R = B, Y, I_3$ and C and $\wedge_R$ are given by

$$\begin{aligned}
 \wedge_B &= \begin{bmatrix} 1/3 & & & \\ & 1/3 & & \\ & & 1/3 & \\ & & & 1/3 \end{bmatrix}, & \wedge_3 &= \begin{bmatrix} 0 & & & \\ & 1/2 & & \\ & & -1/2 & \\ & & & 0 \end{bmatrix} \\
 \wedge_Y &= \begin{bmatrix} 1/3 & & & \\ & 1/3 & & \\ & & 1/3 & \\ & & & -2/3 \end{bmatrix}, & \wedge_C &= \begin{bmatrix} 1 & & & \\ & 0 & & \\ & & 0 & \\ & & & 0 \end{bmatrix}. \quad (3.10)
 \end{aligned}$$

We shall now assume that J_μ^C or V_μ^C does not contribute significantly for uncharged targets such as the nucleon which we are considering. We are assuming that $\langle p | J_\mu^C | p \rangle \ll \langle p | J_\mu^{\tilde{W}^0} | p \rangle$. This is probably justified because the nucleon consists primarily of P and N quarks. Thus we can put $c(\xi) = 0 = c'(\xi)$, $b, b' = \sqrt{2/3} G_0^{A,S}$, $d, d' = G_3^{A,S}$ and $y, y' = 2/\sqrt{3} G_8^{A,S}$. We thus have from Eqs. (3.6) and (3.7)

$$F_2^{eN}(\xi) = 2\xi \left[(a^2 - a + \frac{1}{2}) 3\sqrt{2/3} G_0^A(\xi) - (a - \frac{1}{2}) \left(\sqrt{2/3} G_0^A(\xi) - \frac{2}{\sqrt{3}} G_8^A(\xi) \right) \right] \quad (3.11a)$$

$$\frac{1}{2}(F_2^{ep}(\xi) - F_2^{en}(\xi)) = 2\xi \left[2(a - \frac{1}{2}) G_3^A(\xi) \right] \quad (3.11b)$$

$$F_2^{ZN}(\xi) = \xi \left[1 - 4a(1-a)\sin^2\theta_w \right] 3\sqrt{2/3} G_0^A(\xi) - 2\sin^2\theta_w (1 - 2\sin^2\theta_w) F_2^{eN}(\xi) \quad (3.12a)$$

$$F_3^{ZN}(\xi) = -\frac{1}{2} \left[6\sqrt{2/3} G_0^S(\xi) - 4\sin^2\theta_w \left(3\sqrt{2/3} G_0^S(\xi) - 2(a - \frac{1}{2}) \left(\sqrt{2/3} G_0^S(\xi) - \frac{2}{\sqrt{3}} G_8^S(\xi) \right) \right) \right] \quad (3.12b)$$

We now discuss the consequences of Eqs. (3.5), (3.11) and (3.12). From Eqs. (3.5c) and (3.5d), we see that deviation from charge symmetry is proportional to $\sin^2\theta_c$, which is a small quantity. We will now take $\sin^2\theta_c \approx 0$ and $\cos^2\theta_c \approx 1$, so that $r_2 \approx 0$. Putting then $r_2 = 0$, in Eqs. (2.14) and (2.15), we get the well-known predictions of charge symmetry and scaling. In particular,

$$\sigma^{\nu N}(1+R) = \frac{4}{3} \frac{G^2 m E}{\pi} \int_0^1 F_2(\xi) d\xi. \quad (3.13)$$

From Eqs. (3.12), using Eqs. (3.5) (with $\theta_c = 0$) and Eq. (3.11a), we have

$$\begin{aligned} \int_0^1 F_2^{ZN}(\xi) d\xi &= \frac{[1 - 4a(1-a)\sin^2\theta_w]}{2(a-1)^2} \\ &\times \left[\int_0^1 F_2^{eN}(\xi) d\xi - (a - \frac{1}{2}) \int_0^1 F_2(\xi) d\xi \right] \\ &\quad - 2\sin^2\theta_w (1 - 2\sin^2\theta_w) \int_0^1 F_2^{eN}(\xi) d\xi \end{aligned} \quad (3.14a)$$

$$\begin{aligned} - \int_0^1 \xi F_3^{ZN}(\xi) d\xi &= - \frac{1 - 2\sin^2\theta_w}{2} \int_0^1 \xi F_3(\xi) d\xi \\ &\quad + (1 - 4(1-a)\sin^2\theta_w) \int_0^1 \xi \dot{V}(\xi) d\xi \end{aligned} \quad (3.14b)$$

where

$$\dot{V}(\xi) = \sqrt{2/3} G_0^S(\xi) - \frac{2}{\sqrt{3}} G_8^S(\xi) > 0 \quad (3.15)$$

The experimental data indicate that quarks are probably fractionally-charged particles, so that $a = 2/3$. In what follows in this section, we shall take $a = 2/3$. In particular, Eqs. (3.14) become

$$\begin{aligned} \int_0^1 F_2^{ZN}(\xi) d\xi &= \frac{1}{2} \left[\int_0^1 F_2^{eN}(\xi) d\xi \right] \\ &\times \left[\left(1 - \frac{8}{9}\sin^2\theta_w\right) \left(9 - \frac{3}{2}\gamma\right) - 2\sin^2\theta_w(1 - 2\sin^2\theta_w) \right] \quad (3.16a) \\ - \int_0^1 \xi F_3^{ZN}(\xi) d\xi &= - \frac{1 - 2\sin^2\theta_w}{2} \int_0^1 \xi F_3(\xi) d\xi \\ &\quad + \left(1 - \frac{4}{3}\sin^2\theta_w\right) \int_0^1 \xi \dot{V}(\xi) d\xi, \end{aligned} \quad (3.16b)$$

where

$$\eta \equiv \int_0^1 F_2(\xi) d\xi / \int_0^1 F_2^{eN}(\xi) d\xi \quad (3.16c)$$

We are now in a position to discuss the predictions of neutral currents for the inclusive process

$$\nu(\bar{\nu}) + N \longrightarrow \nu(\bar{\nu}) + \text{anything} \quad (3.17)$$

below charm threshold for the corresponding inclusive process $(\nu) \bar{\nu} + N \rightarrow \ell^{\mp} + \text{anything}$. For reaction (3.17), we have on using Eqs. (3.16a,b):

$$\begin{aligned} \frac{\sigma^{\nu\nu N} + \sigma^{\bar{\nu}\bar{\nu} N}}{\sigma^{\nu N}} &= (1+R) \frac{\int_0^1 F_2^{ZN}(\xi) d\xi}{\int_0^1 F_2(\xi) d\xi} \\ &= \frac{1+R}{2\eta} \left[\left(1 - \frac{8}{9} \sin^2 \theta_W\right) \left(9 - \frac{3}{2} \eta\right) \right. \\ &\quad \left. - 2 \sin^2 \theta_W (1 - 2 \sin^2 \theta_W) \right] \quad (3.18a) \end{aligned}$$

$$\begin{aligned} \frac{\sigma^{\nu\nu N} - \sigma^{\bar{\nu}\bar{\nu} N}}{\sigma^{\nu N}} &= - \frac{1+R}{2} \frac{\int_0^1 \xi F_3^{ZN}(\xi) d\xi}{\int_0^1 F_2(\xi) d\xi} \\ &= \frac{1+R}{2} \left[\frac{1 - 2 \sin^2 \theta_W}{2} B \right. \\ &\quad \left. + \left(1 - \frac{4}{3} \sin^2 \theta_W\right) \frac{\int_0^1 \xi \hat{V}(\xi) d\xi}{\int_0^1 F_2(\xi) d\xi} \right] \quad (3.18b) \end{aligned}$$

Equations (3.18a,b) are our main predictions. In Eq. (3.18a), everything, in principle, is experimentally known from the electroproduction and from the inclusive neutrino nucleon scattering data for charged weak currents except $\sin^2 \theta_W$. Knowing $\sin^2 \theta_W$ from leptonic or semi-leptonic elastic scattering data, we can test this prediction. On the other hand, this equation can be used to determine

$\sin^2 \theta_W$ as everything else is experimentally known. From Eq. (3.18b), we get the inequality

$$\frac{\sigma^{\nu\nu N} - \sigma^{\bar{\nu}\bar{\nu} N}}{\sigma^{\nu N}} > \frac{1+R}{2} (1 - 2\sin^2 \theta_W) B \quad (3.19)$$

provided

$$\sin^2 \theta_W \leq 3/4 \quad (3.20)$$

We get the result of Paschos and Wolfenstein⁹⁾ if $B = 1$ and $\int_0^1 \xi v'(\xi) d\xi = 0$.

The present experimental data^{8,10)} give $R = 0.38$, $\eta = 3.4 \pm 0.7$,

$$\frac{\sigma^{\nu\nu N}}{\sigma^{\nu N}} \approx 0.21 \pm 0.03, \quad \frac{\sigma^{\bar{\nu}\bar{\nu} N}}{\sigma^{\bar{\nu} N}} = 0.45 \pm 0.09.$$

We find

$$\frac{\sigma^{\nu\nu N} + \sigma^{\bar{\nu}\bar{\nu} N}}{\sigma^{\nu N}} = 0.38 \pm 0.06.$$

Taking this value to be 0.38, we find from Eq. (3.18a) that no solution for $\sin^2 \theta_W$ exists for $\eta \leq 3.4$. Just to illustrate, we find $\sin^2 \theta_W = 0.21$ for $\eta = 4$, whereas $\sin^2 \theta_W = 0.5$ for $\eta = 3.6$. (We have taken the smaller solution for the two values of η given above.)

Finally all our predictions in this section are valid for a phenomenological neutral current which for fractionally-charged quarks has the SU(3) structure

$$J_\mu^Z = i \bar{\Psi} \gamma_\mu (1 + \gamma_5) \frac{1}{2} \left(\lambda_3 + \frac{1}{\sqrt{3}} \lambda_8 - \frac{1}{2} \sqrt{2/3} \lambda_9 \right) \tilde{\Psi} - 2\sin^2 \theta_W J_\mu^{em} \quad (3.21a)$$

where

$$J_\mu^{em} = i \bar{\Psi} \gamma_\mu \frac{1}{2} \left(\lambda_3 + \frac{1}{\sqrt{3}} \lambda_8 \right) \tilde{\Psi}. \quad (3.21b)$$

4. PREDICTIONS OF LIGHT-CONE ALGEBRA
ABOVE CHARM THRESHOLD

In the Salam-Weinberg model, we must use the expression J_μ^W as given in Eq. (3.2a) above charm threshold. Then using light-cone algebra the structure functions F_2 and F_3 are given by⁵⁾

$$F_2(\xi) = 6\xi l(\xi) \quad (4.1a)$$

$$F_3(\xi) = -6 l'(\xi) \quad (4.1b)$$

$$f_2(\xi) = 2\xi [-c(\xi) + l'(\xi) - y(\xi)] \quad (4.2a)$$

$$f_3(\xi) = -2 [-c(\xi) + l(\xi) - y(\xi)] \quad (4.2b)$$

The expressions for F_2^{eN} , F_2^{ZN} and F_3^{ZN} are as given in Eqs. (3.6a), (3.7a) and (3.7b). From the above equations and Eqs. (3.6a) and (3.7a,b), we have

$$F_2^{ZN}(\xi) = \left[\frac{1}{4} - a(1-a)\sin^2\theta_w \right] 2F_2(\xi) - 2\sin^2\theta_w (1-2\sin^2\theta_w) F_2^{eN}(\xi) \quad (4.3a)$$

$$\xi F_3^{ZN}(\xi) = \frac{1-2\sin^2\theta_w}{4} 2\xi F_3(\xi) - 2(a-\frac{1}{2})\sin^2\theta_w f_2(\xi) \quad (4.3b)$$

$$\xi f_3(\xi) = \frac{1}{a-\frac{1}{2}} \left[F_2^{eN}(\xi) - (a^2-a+\frac{1}{2})F_2(\xi) \right] \quad (4.4)$$

From Eq. (4.4), we have

$$z_3 = \frac{1}{a-\frac{1}{2}} \left[(a^2-a+\frac{1}{2}) - \frac{1}{\eta} \right] \quad (4.5a)$$

Now if we use our assumption that $r_3 = r_2 B$, we have

$$r_2 = \frac{1}{(a - 1/2)B} \left[(a^2 - a + \frac{1}{2}) - \frac{1}{\eta} \right], \quad (4.5b)$$

Now from Eq. (2.12a) (with $R_L = 0$) and using Eq. (4.5a), we have

$$\begin{aligned} & (a^2 + a - 1/2) \int_0^1 F_2(\xi) d\xi \\ &= \frac{3\pi}{4G^2 m} \left(\alpha^\nu + \alpha^{\bar{\nu}} \right) 2(a - 1/2) \\ & \quad + \int_0^1 F_2^{eN}(\xi) d\xi. \end{aligned} \quad (4.6)$$

In writing Eq. (4.6), we have assumed that $\sigma^{\nu N} = \alpha^\nu E$, $\sigma^{\bar{\nu} N} = \alpha^{\bar{\nu}} E$. Assuming $a = 2/3$, we can determine $\int_0^1 F_2(\xi) d\xi$ from the experimental data using Eq. (4.6).

Now we discuss the predictions of the neutral weak current for the reaction (3.17) above charm threshold for the charged weak current. Using Eqs. (4.3a,b), (4.5a,b) and (2.12a), we have

$$\begin{aligned} \frac{\sigma^{\nu\nu N} + \sigma^{\bar{\nu}\bar{\nu} N}}{\sigma^{\nu N}} &= (1+R) 2(a - 1/2) \\ & \times \frac{2 \left[\frac{1}{4} - a(1-a) \sin^2 \theta_W \right] \eta - 2 \sin^2 \theta_W (1 - 2 \sin^2 \theta_W)}{\left[(a^2 + a - 1/2) \eta - 1 \right]} \end{aligned} \quad (4.7a)$$

$$\begin{aligned} \frac{\sigma^{\nu\nu N} - \sigma^{\bar{\nu}\bar{\nu} N}}{\sigma^{\nu N}} &= \frac{1+R}{1 + \frac{1}{2} r_3} \\ & \times \left[\frac{1 - 2 \sin^2 \theta_W}{4} B - r_2 (a - 1/2) \sin^2 \theta_W \right] \end{aligned} \quad (4.7b)$$

$$\begin{aligned}
 & \frac{1}{\sigma^{\nu N}} \left[\frac{d\sigma^{\nu\nu N}}{dy} + \frac{d\sigma^{\bar{\nu}\bar{\nu} N}}{dy} \right] \\
 &= \frac{3}{2} \frac{1+R}{1+\frac{1}{2}r_3} \left(1-y+\frac{1}{2}y^2 \right) \\
 & \quad \times \left[2 \left(\frac{1}{4} - a(1-a)\sin^2\theta_w \right) - 2\sin^2\theta_w \left(1-2\sin^2\theta_w \frac{1}{\eta} \right) \right]
 \end{aligned}
 \tag{4.7c}$$

$$\begin{aligned}
 & \frac{1}{\sigma^{\nu N}} \left[\frac{d\sigma^{\nu\nu N}}{dy} - \frac{d\sigma^{\bar{\nu}\bar{\nu} N}}{dy} \right] \\
 &= \frac{3}{2} \frac{1+R}{1+\frac{1}{2}r_3} y \left(1-\frac{1}{2}y \right) \\
 & \quad \times \left[\frac{1-2\sin^2\theta_w}{2} B + 2r_2 \left(a-\frac{1}{2} \right) \sin^2\theta_w \right].
 \end{aligned}
 \tag{4.7d}$$

In Eqs. (4.7b,c,d), r_3 and r_2 are as given in Eqs. (4.5a,b). We see from Eq. (4.7a) that with $a = 2/3$, everything is, in principle, known from the experimental data and therefore from this equation we can determine $\sin^2\theta_w$.

Equation (4.5a) gives the deviation from the charge symmetry result above charm threshold. The induced strangeness-changing neutral current puts a strong restriction on charm threshold so that it is not very high. The present data give⁸⁾

$$\frac{3\pi}{4G^2m} (\alpha^\nu + \alpha^{\bar{\nu}}) = 0.47 \pm 0.07. \tag{4.8}$$

There is no indication, as yet, that this value is drastically changed from the value given in Eq. (4.8) at high energies. (We might have already reached charm threshold in the energy range at which data is now available.) Assuming the data are not drastically changed from the present value, we have (for $a = 2/3$) from Eq. (4.6),

$$\int_0^1 F_2(\xi) d\xi = 0.49 \pm 0.07 \tag{4.9a}$$

$$\eta = 3.5 \pm 0.7 \quad (4.9b)$$

where we have used $\int_0^1 F_2^{\text{eN}}(\xi) d\xi = 0.14 \pm 0.02$. From Eq. (4.5a), we see that

$$r_3 = \frac{5}{3} - \frac{6}{3.5 \pm 0.7} \approx 0. \quad (4.10)$$

Thus if $a = 2/3$ and the present data are not drastically changed at high enough energy (viz. above charm threshold), we will not have any strong deviation from charge symmetry results. However, if quarks are not fractionally charged we may expect strong deviation from the charge symmetry result even if the present data is not changed drastically above charm threshold. But the sum rules derived from $SU(3) \times SU(3)$ algebra which are certainly valid below charm threshold favour fractionally-charged quarks.

If we know $\sin^2 \theta_W$ from purely leptonic processes or semi-leptonic elastic process, then Eqs. (4.7) are predictions of the Salam-Weinberg model above charm threshold which can be directly tested. The possible deviation from charge symmetry as given in Eqs. (4.5) is independent of $\sin^2 \theta_W$. For fractionally-charged quarks, we see that any deviation from the sum rule

$$\frac{18}{5} = \int_0^1 F_2(\xi) d\xi / \int_0^1 F_2^{\text{eN}}(\xi) d\xi \quad (4.11a)$$

is a measure of the deviation from the charge symmetry result. In any case from Eq. (2.14), we see that

$$r_2 = \frac{(2-B) - R(2+B)}{(2-B) + R(2+B)}$$

so that from Eq. (4.5b), we have

$$\begin{aligned} & \frac{(2-B) - R(2+B)}{(2-B) + R(2+B)} B \\ &= \frac{1}{a - 1/2} \left[(a^2 - a + \frac{1}{2}) - \frac{1}{\eta} \right]. \end{aligned} \quad (4.11b)$$

This involves quantities which can be measured for inclusive neutrino and anti-neutrino scattering on nucleon targets involving only charged weak hadronic current and electromagnetic current, provided data is at high enough energy to be above charm threshold. In the Salam-Weinberg model above charm threshold any deviation from the sum rule (4.11a) is directly related to deviation from charge symmetry; no such correlation exists below charm threshold or in $SU(3) \times SU(3)$ light-cone algebra, where the charge symmetry holds to an accuracy of $\sin^2 \theta_c (\approx 0)$.

In the end we write down the other predictions⁵⁾ of $SU(4) \times SU(4)$ light-cone algebra which can also be tested.

$$\begin{aligned} & \frac{1}{2} \left[\langle \sigma^{\nu\nu p} + \sigma^{\bar{\nu}\bar{\nu} p} \rangle - \langle \sigma^{\nu\nu n} + \sigma^{\bar{\nu}\bar{\nu} n} \rangle \right] \\ &= \frac{G^2 m E}{\pi} \frac{2}{3} \left[-2 \sin^2 \theta_w (1 - 2 \sin^2 \theta_w) \int_0^1 (F_2^{ep}(\xi) - F_2^{en}(\xi)) d\xi \right] \end{aligned} \quad (4.12a)$$

$$\begin{aligned} & \frac{1}{2} \left[\langle \sigma^{\nu\nu p} - \sigma^{\bar{\nu}\bar{\nu} p} \rangle - \langle \sigma^{\nu\nu n} - \sigma^{\bar{\nu}\bar{\nu} n} \rangle \right] \\ &= - \frac{G^2 m E}{\pi} \frac{1}{3} \left[-2(a - \frac{1}{2}) \sin^2 \theta_w \int_0^1 (F_2^{\nu p}(\xi) - F_2^{\nu n}(\xi)) d\xi \right] \end{aligned} \quad (4.12b)$$

$$\begin{aligned} & \frac{1}{2} \left[\left(\frac{d\sigma^{\nu\nu p}}{dy} + \frac{d\sigma^{\bar{\nu}\bar{\nu} p}}{dy} \right) - \left(\frac{d\sigma^{\nu\nu n}}{dy} + \frac{d\sigma^{\bar{\nu}\bar{\nu} n}}{dy} \right) \right] \\ &= \frac{G^2 m E}{\pi} (1 - y + \frac{1}{2} y^2) \left[-2 \sin^2 \theta_w (1 - 2 \sin^2 \theta_w) \int_0^1 (F_2^{ep}(\xi) - F_2^{en}(\xi)) d\xi \right] \end{aligned} \quad (4.12c)$$

$$\begin{aligned} & \frac{1}{2} \left[\left(\frac{d\sigma^{\nu\nu p}}{dy} - \frac{d\sigma^{\bar{\nu}\bar{\nu} p}}{dy} \right) - \left(\frac{d\sigma^{\nu\nu n}}{dy} - \frac{d\sigma^{\bar{\nu}\bar{\nu} n}}{dy} \right) \right] \\ &= - \frac{G^2 m E}{\pi} y (1 - \frac{1}{2} y) \left[-2(a - \frac{1}{2}) \sin^2 \theta_w \int_0^1 (F_2^{\nu p}(\xi) - F_2^{\nu n}(\xi)) d\xi \right]. \end{aligned} \quad (4.12d)$$

We conclude that measurement of R and B will give us the estimate of the violation of charge symmetry for inclusive neutrino-nucleon scattering. This is especially important for high enough energy so as to be above charm threshold. Apart from the predictions for neutral current below and above charm threshold, we give a definite expression for charge symmetry violation in terms of experimentally-measured quantities for the Salam-Weinberg model.

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