II. NEUTRAL CURRENTS

II.1 Theoretical Considerations on Neutral Currents

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A. Introduction

I would like to address myself to the question of neutral currents in neutrino-induced reactions. The recent resurgence of theoretical interest in this subject is due to the possibility of constructing a renormalizable theory of weak (and electromagnetic) interactions based on gauge symmetry. It can be shown on very general grounds that such a model must contain either a neutral current interaction, or heavy leptons, or both.

A prototype of models which feature a neutral current interaction is the Weinberg model,[1] where the massive neutral vector boson Z couples to the neutral current

$$= ifZ_\alpha\left[\bar{\nu}_\mu\gamma^\alpha\left(\frac{1-\gamma_5}{2}\right)\nu_\mu - \bar{\mu}\gamma^\alpha\left(\frac{1}{2} - 2\sin^2\theta_w - \frac{1}{2}\gamma_5\right)\mu + (\mu \to e) + \left(J_3{}^\alpha - 2\sin^2\theta_w J_{em}^\alpha\right)\right], \tag{II.1}$$

where θ_w is a parameter of the model, $f \sin\theta_w \cos\theta_w = e$, and $J_3{}^\alpha$ is the third component of the isospin V-A current and J_{em}^α is the hadronic electromagnetic current. The mass of Z is given by the formula

$$\frac{G_F}{\sqrt{2}} = \frac{e^2}{8m_z{}^2\cos^2\theta_w\sin^2\theta_w}. \tag{II.2}$$

In the following we shall discuss the effects of the above neutral-current interactions on purely leptonic and semileptonic processes, and give bounds on the parameter $x = \sin^2\theta_w$ implied by the existing data, and present theoretical predictions on possible future experiments. I shall not quote experimental data to be presented at this Conference.

B. Leptonic Interactions

Consider, first, the process

$$\bar{\nu}_e + e \to \bar{\nu}_e + e. \tag{II.3}$$

There are two Feynman diagrams which contribute to this process.

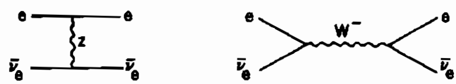


Fig. 2

The effective interaction for this process can be written as

$$\frac{G_F}{\sqrt{2}}\left[\bar{\nu}_e\gamma^\alpha(1-\gamma_5)\nu_e\right]\left[\bar{e}\gamma_\alpha(C_V - C_A\gamma_5)e\right], \tag{II.4}$$

where

$$C_V = \frac{1}{2} + 2\sin^2\theta_w, \text{ and } C_A = \frac{1}{2}. \tag{II.5}$$

The expected rate of events for this process is plotted against $x = \sin^2\theta_w$ in

Fig. 3 for the experimental setup (Savannah River Reactor) of Reines and collaborators:[3]

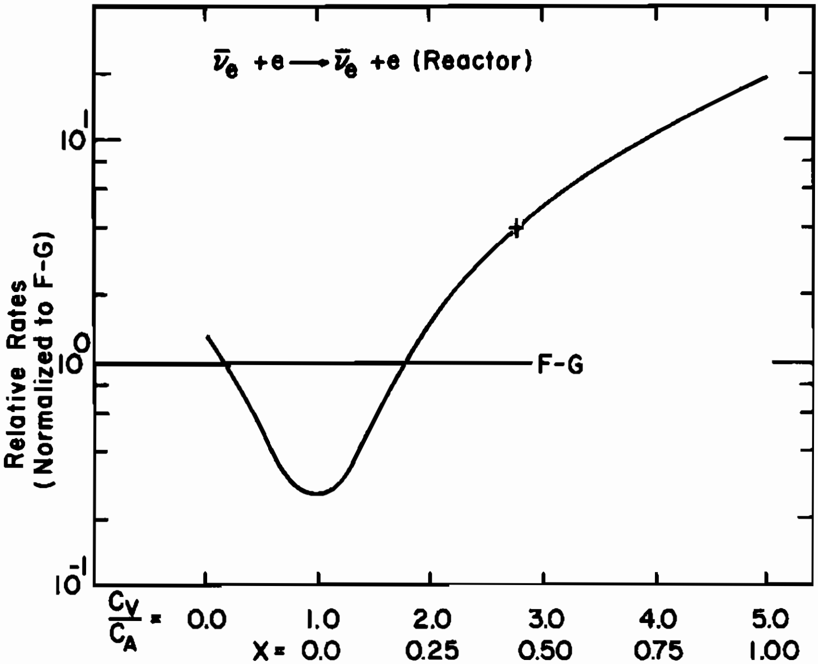


Fig. 3. The expected rates for $\bar{\nu}_e + e \to \bar{\nu}_e + e$, normalized to the Feynman-Gell-Mann theory prediction are given as a function of $x(= \sin^2\theta_w)$. The ratio C_V/C_A is related to x by $C_V/C_A = 1 + 4x$.

The most recent results of Gurr, Reines, and Sobel gives

$$\frac{\sigma_{exp}}{\sigma_{FG}} = 1.0 \pm 0.9,$$

where σ_{FG} is the prediction of the Feynman-Gell-Mann theory. From the figure above, we see that

$$\sin^2\theta_w \lesssim 0.4 \text{ (about 90\% confidence level).} \qquad \text{(II.6)}$$

Next, consider the process

$$\nu_\mu + e \to \nu_\mu + e. \qquad \text{(II.7)}$$

This process is of interest since, in the conventional Feynman-Gell-Mann theory, it proceeds only in higher orders. In the Weinberg model, the effective matrix element for this process is given by[2]

$$-\frac{G_F}{\sqrt{2}}\left[\bar{\nu}_\mu \gamma_\alpha (1 - \gamma_5)\nu_\mu\right]\left[\bar{e}\gamma^\alpha (C_V' - C_A'\gamma_5)e\right], \qquad \text{(II.8)}$$

where

$$C_A' = \frac{1}{2}, \text{ and } C_V' = \frac{1}{2} - 2\sin^2\theta_w. \qquad \text{(II.9)}$$

Figure 4 is a plot of the expected rate of events versus x, for a typical experimental condition at CERN. We await the latest result of CERN to be discussed at this session (see Section II.2).

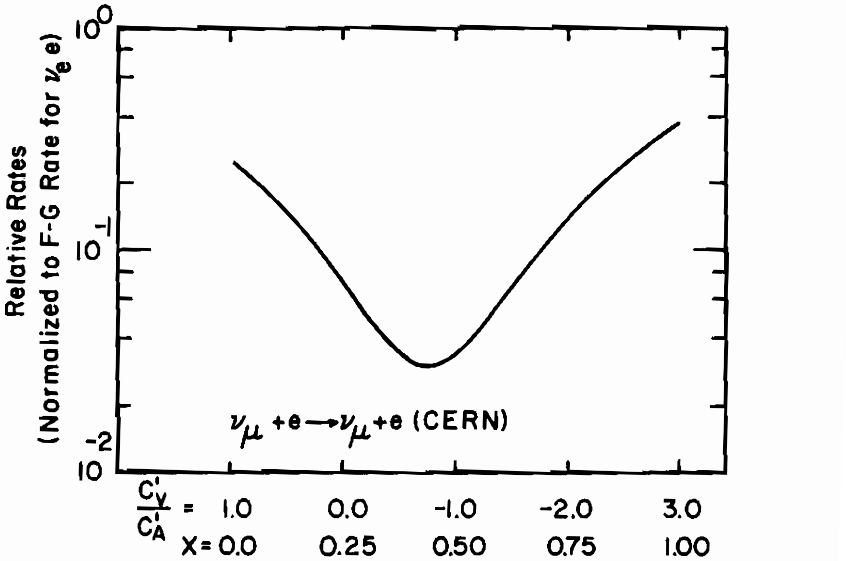


Fig. 4. The expected rates for $\nu_\mu + e \rightarrow \nu_\mu + e$, normalized to the Feynman-Gell-Mann theory prediction for $\nu_e + e \rightarrow \nu_e + e$, are given as a function of x (= $\sin^2 \theta_W$). The ratio C_V'/C_A' is related to x by $C_V'/C_A' = 1 - 4x$. The ν_μ spectrum of Holder et al., Nuovo Cimento 57A, 338 (1970) is used. Minimum energy of the recoil electron is taken to be 1 GeV, following Steiner, Phys. Rev. Letters 24, 1330 (1970).

C. Semileptonic Processes

In the following we shall set the Cabibbo angle equal to zero. The effective interaction may be written as[4]

$$\frac{G_F}{\sqrt{2}}\left\{\bar{\mu}\gamma_\alpha(1 - \gamma_5)\nu_\mu\sqrt{2}\left(\frac{J_1{}^\alpha + iJ_2{}^\alpha}{\sqrt{2}}\right) + \bar{\nu}_\mu\gamma_\alpha(1 - \gamma_5)\nu_\mu\left[J_3{}^\alpha - 2\sin^2\theta_W J_{em}^\alpha\right]\right\}. \quad \text{(II.10)}$$

In making estimates of cross sections for pion production at currently available neutrino energies, it is customary to make the assumption of $\Delta(1236)$ dominance. Alternatively, we may assume the I = 3/2 and 1/2 amplitudes, X_3 and X_1, to be incoherent and assume[5]

$$|X_1|^2/\left[|X_3|^2 + |X_1|^2\right] \lesssim 0.3 \quad \text{(II.11)}$$

in the relevant energy range. In the following discussion we shall use the values of Argonne;[6]

$$\sigma(\nu + p \rightarrow \mu^- + p + \pi^+) = (0.78 \pm 0.16) \times 10^{-38}\ \text{cm}^2 \quad \text{(II.12)}$$

rather than the bigger value

$$(1.13 \pm 0.28) \times 10^{-38}\ \text{cm}^2 \tag{II.12a}$$

based on the 1967 CERN experiment.[7] The lower value [see Eq. (II.12)] results in less stringent lower bounds quoted below.

1. $\underline{\nu + p \to \nu + p}$

The magnitude of this cross section can be bounded on the basis of our knowledge of the electromagnetic form factors of the proton. Pais and Treiman[7] deduce the lower and upper bounds in this way, assuming $\sin^2 \theta_W \leq 0.35$:

$$0.15 \leq \frac{\sigma(\nu + p \to \nu + p)}{\sigma(\nu + n \to \mu^- + p)} \leq 0.25 \tag{II.13}$$

2. $\underline{\nu + p \to \nu + n + \pi^+}$

This process is an analogue of $\nu + p \to \mu^- + p + \pi^+$. Unfortunately, the Clebsch-Gordan coefficient is unfavorable for the neutral current process:

$$R_0 = \frac{\sigma(\nu + p \to \nu + n + \pi^+)}{\sigma(\nu + p \to \mu^- + p + \pi^+)} = \frac{1}{9} \tag{II.14}$$

in the Δ dominance approximation and in the limit $x = 0$ (Weinberg).[4] Without these approximations, but merely assuming Eqs. (II.6) and (II.11) and incoherence of X_1 and X_3, Albright et al. deduce[5]

$$R_0 \geq 0.03. \tag{II.15}$$

Let us recall the result of Cundy et al.,[8] $R_0 = 0.08 \pm 0.04$. The bound [Eq. (II.15)] applies also to the related ratio $\sigma(\nu + n \to \nu + p + \pi^-)/\sigma(\nu + p \to \mu^- + p + \pi^+)$.

3. $\underline{\nu + p \to \nu + p + \pi^0 \text{ and } \nu + n \to \nu + n + \pi^0}$

The ratio we shall consider is

$$R_1 = \frac{\sigma(\nu + p \to \nu + p + \pi^0) + \sigma(\nu + n \to \nu + n + \pi^0)}{2\sigma(\nu + n \to \mu^- + p + \pi^0)}. \tag{II.16}$$

The Clebsch-Gordan coefficient is favorable for this process:

$$R_1 = 1 \tag{II.17}$$

in the Δ-dominance approximation and in the limit $x = 0$. B. Lee[9] estimated this ratio in the static model of the Δ production, assuming $x < 0.35$:

$$R_1 \geq 0.4 \sim 0.6.$$

Assuming Δ dominance and $x < 0.35$, but otherwise making no dynamical assumption, Paschos and Wolfenstein[10] obtain

$$R_1 \geq 0.4.$$

[This number is based on the cross section (II.12a).] With the smaller value (II.12) and $x \leq 0.4$, one gets $R_1 \geq 0.3$.) If one considers the effect of X_1 with the bound given by Eq. (II.11), assuming X_1 and X_3 to be incoherent, and using Eq. (II.12) and $x \leq 0.4$, one gets

$$R_1 \geq 0.19. \tag{II.18}$$

The above result is to be compared with the experimental bound given by W. Lee[11]

$$R_1 \leq 0.14 \text{ (90\% confidence)}. \tag{II.19}$$

(Ed. Note: For relevant data presented to this Conference, see Section II.3.)

D. Inclusive Processes

The presently available data on the neutral current ($\Delta S = 0$) interaction is inconclusive as to its existence, even though the result (II.19) presents serious trouble for Weinberg-type models.

More decisive experimental tests are clearly called for. A promising approach may be to look at inclusive processes

$$\nu + N \to \nu + \text{anything} \tag{II.20}$$

Pais and Treiman,[7] and Paschos and Wolfenstein[10] have considered the bounds on process (II.20) at NAL energies.

Without any dynamical assumptions, Paschos and Wolfenstein[10] show that

$$R_{inc} = \frac{\sigma(\nu + p \to \nu + \text{anything}) + \sigma(\nu + n \to \nu + \text{anything})}{\sigma(\nu + p \to \mu^- + \text{anything}) + \sigma(\nu + n \to \mu^- + \text{anything})} \geq 0.18 \tag{II.21}$$

If one makes further assumptions that the neutrino-induced production scales as does the electroproduction, and that the main contribution to the total cross-section comes from the scaling region, the bound can be tightened:

$$R_{inc} \geq 0.23. \tag{II.22}$$

E. Concluding Remarks

It must be emphasized that the failure to detect a neutral current effect in any of the processes discussed above does not rule out the correctness of a unified gauge theory of weak and electromagnetic interactions. It may be that the nature makes use of a different scheme[12] than Weinberg's, which calls for the existence of heavy leptons but dispenses with neutral currents.

In such models, neutral current effects such as $\nu_\mu + e \to \nu_\mu + e$, $\nu_\mu + p \to \nu_\mu$ + anything will be induced in higher orders, and their magnitudes we expected to be of order of $G_F\alpha$.

References

[1] S. Weinberg, Phys. Rev. Letters 19, 264 (1967); Phys. Rev. Letters 27, 1688 (1971); A. Salam, Elementary Particle Theory, edited by N. Svartholm (Almqvist and Wiksell, Stockholm, 1968), p. 367.

[2] H. H. Chen and B. W. Lee, Phys. Rev. D5, 1874 (1972); G. 't Hooft, Phys. Letters 37B, 197 (1971).

[3] H. S. Gurr, F. Reines, and H. W. Sobel, Phys. Rev. Letters 28, 1406 (1972).

[4] S. Weinberg, Phys. Rev. D5, 1412 (1972).

[5] C. Albright, B. Lee, and E. Paschos, NAL-THY preprint 86 (1972).

[6] M. Derrick and P. Schreiner, private communication.

[7] A. Pais and S. B. Treiman, Rockefeller University preprint (1972).

[8] D. C. Cundy, G. Myatt, F. A. Nezrick, J. B. M. Pattison, D. H. Perkins, C. A. Ramm, W. Venus, and H. W. Wachsmuth, Phys. Letters 31B, 478 (1970).

[9] B. W. Lee, Phys. Letters 40B, 420 (1972).

[10] E. A. Paschos and L. Wolfenstein, NAL-THY preprint 69 (1972).

[11] W. Lee, Phys. Letters 40B, 423 (1972).

[12] See e.g., S. Glashow and H. Georgi, Phys. Rev. Letters 28, 1494 (1972).

Discussion

S. P. Rosen (Purdue Univ., Ind.): Does the result for $\bar{\nu}_e e$ scattering quoted by Dr. Lee, namely

$$\sigma_{exp}/\sigma_{FG} = 1.0 \pm 0.9$$

mean that Gurr, Reines, and Sobel believe that they have actually seen neutrino-electron scattering?

B. Lee: No.

II.2 Search for the Processes $(\nu_\mu + e^- \to \nu_\mu + e^-)$ and $(\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-)$ (#785)

Presented by V. Brisson
Ecole Polytechnique
Paris, France

The leptonic processes

$$\nu_\mu + e^- \to \nu_\mu + e^-$$

$$\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$$

are forbidden in a charged current-current weak interaction theory. Evidence for such reaction was searched in 167,000 muon pictures of Gargamelle exposed to the CERN ν beam and 223,000 pictures of the same chamber to the $\bar{\nu}$ beam. Events consisting of single electrons were searched for, where the electrons had a lab energy larger than 300 MeV and formed an angle smaller than 5° with the beam direction. These cuts ensured a good scanning efficiency, removed the background due to low-energy γ rays, without reducing the number of the genuine (νe) events if they existed.

No "candidate" both for ν or $\bar{\nu}$ neutral interactions, was observed. To estimate upper limits for the cross sections contributions have been made for

- scanning efficiency (found to be 80%).
- detection efficiency due to the geometric and kinematical cuts (found to be $\sim$87%).

Limits on the cross-sections were derived from the value $\sigma_{total} = 0.8 \pm 0.2\ E_\nu 10^{-38}\ cm^2$ for charged current events, using as a normalization the effective number of events with a μ^- (μ^+ for $\bar{\nu}$) observed in the experiment.

With 90% confidence, the limits are:

$$\sigma(\nu_\mu + e^- \to \nu_\mu + e^-) \leq 0.7 \times 10^{-41}\ E_\nu\ cm^2$$

$$\sigma(\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-) \leq 1.0 \times 10^{-41}\ E_{\bar{\nu}}\ cm^2$$

A comparison with the Weinberg model is given in Fig. 5. It can be seen that the result does not rule out the model, but restricts the value of θ, the "Weinberg angle" to $\sin^2\theta \leq \sim 0.6$ or $\theta \leq \sim 50°$. The forthcoming experiment with Gargamelle will probably increase the available statistics by a factor of 3. Then (see Fig. 5) it should be possible to reach a more definite conclusion on this question.

II.3 Searches for Neutral Currents in ν + Nucleon $\to$ ν + Nucleon + π (#239, 473, 785)

Presented by Y. Cho
Argonne National Laboratory
Argonne, Illinois

The results of a Columbia optical spark-chamber experiment (#239) yielded

$$R_1 = \frac{\sigma\left(\nu_\mu n \to \nu_\mu n\pi^0\right) + \sigma\left(\nu_\mu p \to \nu_\mu p\pi^0\right)}{2\sigma\left(\nu_\mu n \to \mu^- p\pi^0\right)} < 0.14 \quad (90\%\ CL)$$

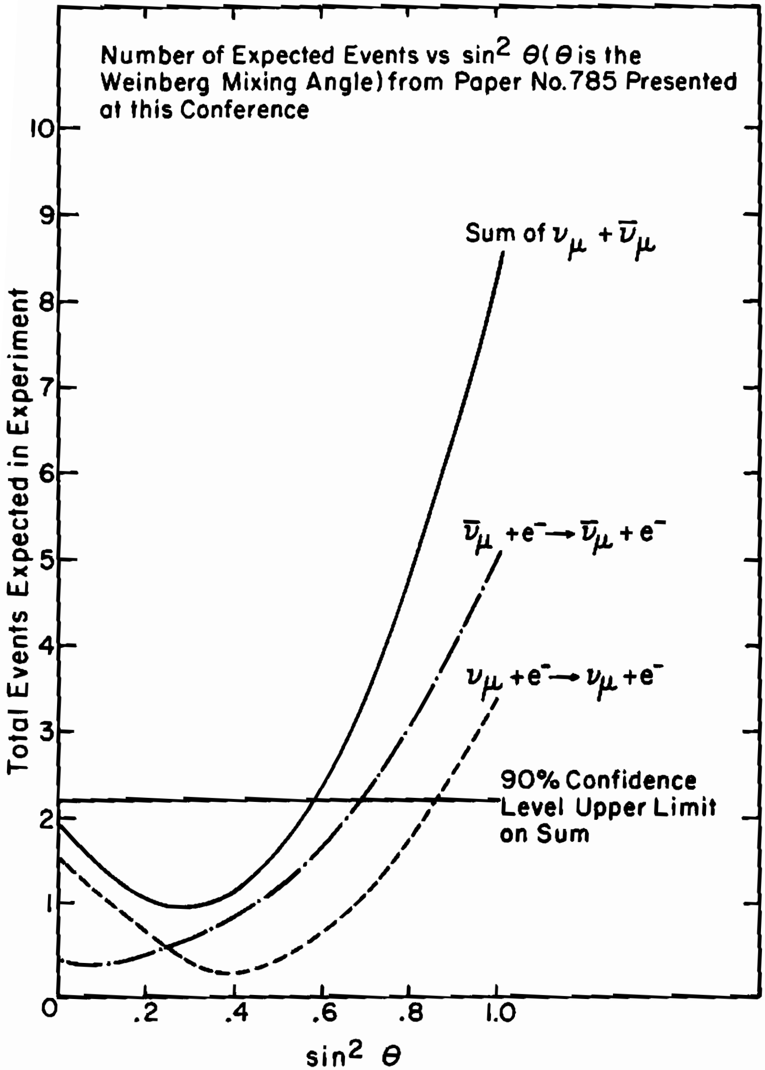

Number of Expected Events vs $\sin^2\theta$ (θ is the Weinberg Mixing Angle) from Paper No. 785 Presented at this Conference
Sum of $\nu_\mu + \bar{\nu}_\mu$
$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$
$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$
90% Confidence Level Upper Limit on Sum
Total Events Expected in Experiment
$\sin^2\theta$
0
.2
.4
.6
.8
1.0
1
2
3
4
5
6
7
8
9
10

Fig. 5

This experiment saw no events which were candidates for the numerator reaction and had 12 candidates for the denominator reaction. Of these 12 events, 3 were estimated to be background.

The 12-foot bubble-chamber group at Argonne reported on the basis of 361,000 pictures in H_2 and 145,000 pictures in D_2. They find

$$R_2 = \frac{\sigma\left(\nu_\mu p \to \nu_\mu p\pi^0\right) + \sigma\left(\nu_\mu p \to \nu_\mu n\pi^+\right)}{\sigma\left(\nu_\mu p \to \mu^- p\pi^+\right)} < 0.31 \text{ (90\% CL)},$$

where there are "about 121" candidates for the denominator reaction.

These experimental limits are compared with the theoretical predictions of the Weinberg model in Fig. 6.

In addition, the Gargamelle collaboration presented a very preliminary result based on an analysis of 90,000 pictures, $R_1 \leq 0.11$ (90% CL) where R_1 is defined above. This result was presented with the note of caution that the same data yields

$$R_4 \equiv \frac{\sigma\left(\nu_\mu n \to \mu^- p\pi^0\right)}{\sigma\left(\nu_\mu n \to \mu^- n\pi^+\right) + \sigma\left(\nu_\mu p \to \mu^- p\pi^+\right)} = 0.5$$

whereas $R_4 = 0.2$ is predicted by Δ dominance. Either the reactions do not proceed via the Δ or reinteractions inside the nucleus are so important that all channels are finally mixed. Before doing any comparison these reinteractions have to be known and corrected for.

Table II summarizes the present experimental limits.

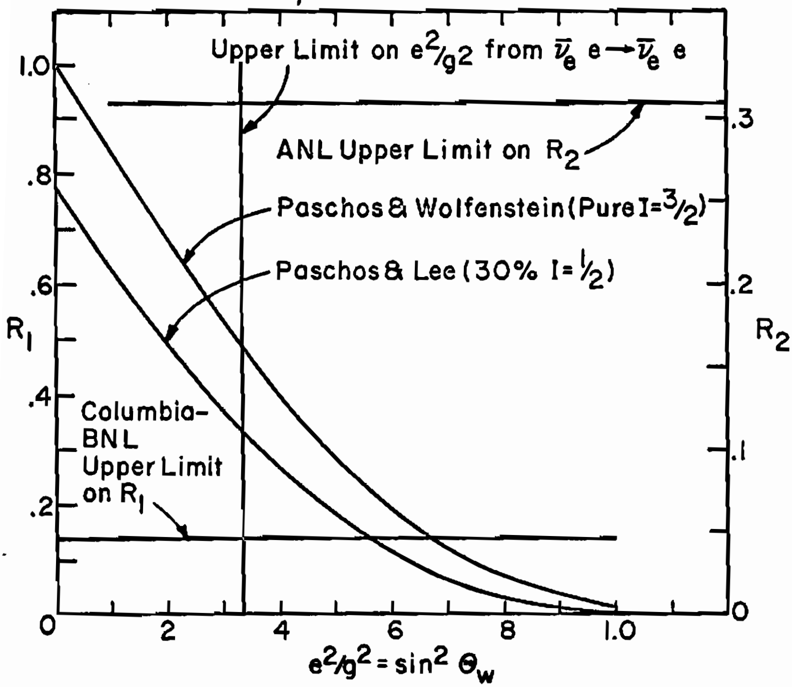
Discussion

Comments by C. Baltay (Columbia): Because of the uncertainties about the extent of $I = 3/2$ dominance and the serious reabsorption problems in heavy nuclei, I think that it is dangerous to draw any conclusions about the validity of the Weinberg model from the present experimental limits on the neutral current single π^0 production. The π^+ to π^0 ratio, which is around 2 in freon, and is expected to be around 5 if $I = 3/2$ dominance were complete, indicates that either $I = 3/2$ dominance is not complete or reabsorption effects are very important (or both).

Results of Searches for Neutral Currents in $\nu_\mu N \rightarrow \nu_\mu N \pi$

$$R_1 = \frac{\sigma(\nu_\mu + p \rightarrow \nu_\mu + p + \pi^\circ) + \sigma(\nu_\mu + n \rightarrow \nu_\mu + n + \pi^\circ)}{2\sigma(\nu_\mu + n \rightarrow \mu^- + p + \pi^\circ)}$$

$$R_2 = \frac{\sigma(\nu_\mu + p \rightarrow \nu_\mu + p + \pi^\circ) + \sigma(\nu_\mu + p \rightarrow \nu_\mu + n + \pi^+)}{\sigma(\nu_\mu + p \rightarrow \mu^- + p + \pi^+)}$$



References to Papers Presented to this Conference:

$\bar{\nu}_e e \rightarrow \bar{\nu}_e e$: Reference given in Section 2.1.

ANL: Paper #473

Columbia-BNL: Paper #239

Paschos and Wolfenstein: Paper #540

Paschos and Lee: Paper #786

Fig. 6

TABLE II. Summary of Neutral Current Searches in Neutrino Interactions[1]

(Prepared by S. Aronson and E. I. Rosenberg)

Cross-Section Ratio	Approximate Upper Limit	Reference
$\dfrac{\sigma\left(\nu_\mu + e \to \nu_\mu + e^-\right)}{\text{V-A theory for } \sigma\left(\nu_e + e^- \to \nu_e + e^-\right)}$	0.44 (90% CL)	Paper #785 this Conference
$\dfrac{\sigma\left(\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-\right)}{\text{V-A theory for } \sigma\left(\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-\right)}$	2.1 (90% CL)	Paper #785 this Conference (CERN-Gargamelle Coll.)
$\dfrac{\sigma\left(\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-\right)}{\text{V-A theory for } \sigma\left(\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-\right)}$	3.0 (90% CL)	Phys. Rev. Letters 28, 1406 (1972) (Gurr, Reines, and Sobal)
$R_1 = \dfrac{\sigma\left(\nu_\mu + n \to \nu_\mu + n + \pi^0\right) + \sigma\left(\nu_\mu + p \to \nu_\mu + p + \pi^0\right)}{2\sigma\left(\nu_\mu + n \to \mu^- + p + \pi^0\right)}$	0.14 (90% CL)[3]	Paper #239 this Conference (W. Lee)
$R_2 = \dfrac{\sigma\left(\nu_\mu + p \to \nu_\mu + n + \pi^+\right) + \sigma\left(\nu_\mu + p \to \nu_\mu + p + \pi^0\right)}{\sigma\left(\nu_\mu + p \to \mu^- + p + \pi^+\right)}$ [2]	0.31 (90% CL)	Paper #473 this Conference (M. Derrick et al.)
$R_0 = \dfrac{\sigma\left(\nu_\mu + p \to \nu_\mu + n + \pi^+\right)}{\sigma\left(\nu_\mu + p \to \mu^- + p + \pi^+\right)}$	0.16 (90% CL)	Phys. Letters 31B, 478 (1970) (D. C. Cundy et al.)
$\dfrac{\sigma\left(\nu_\mu + p \to \nu_\mu + p\right)}{\sigma\left(\nu_\mu + n \to \mu^- + p\right)}$	0.24 (90% CL)	Phys. Letters 31B, 478 (1970) (D. C. Cundy et al.)

[1]Nonconference Data from C. Baltay--Review talk at 1972 Neutrino Conference, Balaton.

[2]Note that (1236) dominance yields $R_0 = 1/3 \quad R_2 = 1/9\ R_1$.

[3]Very preliminary results were also presented by the CERN-Gargamelle collaboration (see Section II.3).