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NEUTRINO PHYSICS

C.H. Llewellyn Smith
CERN -- Geneva

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I. INTRODUCTION [1)]

It is now more than twelve years since Lee and Yang, Cabibbo and Gatto, Yamaguchi and others spelled out the theoretical reasons for studying neutrino reactions. In their Phys.Rev.Letter, Lee and Yang posed the nine questions which are listed in the Table. It is interesting to examine them and ask how many have been answered. It will be seen that only one question has been completely answered while neutrino experiments have so far yielded essentially no information about five of them.

Thus we are still ignorant about many fundamental questions concerning the weak interactions and the Table defines a large experimental programme even without adding the additional questions which have been raised in the last twelve years. In any case much recent work - particularly that concerning the deep inelastic region - presupposes answers to the original questions, which should really be tested first. I intend to begin by stressing how little evidence there is for many of the ideas which are commonly taken for granted and then turn to more interesting recent developments.

Apart from ν reactions, all our knowledge of weak interactions has been derived from studying the decays of only eight stable particles - μ, π, K, N, $\Lambda, \Sigma, \Xi, \Omega$ - and from μ capture. (This shows the fundamental reason for doing neutrino experiments - to study other processes and investigate the weak interactions at large energy/momentum transfer.) Most of these data can be satisfactorily described by a simple phenomenological theory involving only a few parameters. Thus we can distinguish a first goal of neutrino experiments :

1) to establish the domain of validity of the phenomenological theory and test the selection rules embodied in it.

It is well known, however, that the phenomenological theory cannot give a correct description at very high energies (we review the reasons for this in Section III). Thus a second goal is :

2) to provide clues for the construction of an alternative theory of weak interactions.

A third is :

3) given a theory, to use neutrinos to probe the structure of hadrons.

The rest of this talk is divided into three parts in which these goals are considered in more detail.

II. THE PHENOMENOLOGICAL THEORY

The phenomenological theory can (in part) be stated thus : apart from T violation, all known reactions involving neutrinos can be described by the effective interaction :

$$\mathcal{L}_{eff.} = \frac{G}{\sqrt{2}}\left[\left(j_\lambda^e + j_\lambda^\mu\right)^+ J^{h,\lambda} + j_\lambda^{e+} j^{\mu,\lambda} + h.c.\right] \qquad (1)$$

where

$$G = \frac{1.0 \times 10^{-5}}{M_p^2}$$

$$j_\lambda^\mu = \overline{\psi}_\mu \gamma_\lambda (1-\gamma_5)\psi_{\nu_\mu}$$

$$j_\lambda^e = \overline{\psi}_e \gamma_\lambda (1-\gamma_5)\psi_{\nu_e}$$

- J_λ^h is a current which depends on hadronic variables and behaves <u>as if</u> it were constructed from quark fields (p,n,λ), thus

$$J_\lambda^{h+} = \bar{p}\gamma_\lambda(1-\gamma_5)n\cos\theta_c + \bar{p}\gamma_\lambda(1-\gamma_5)\lambda\sin\theta_c$$

(where θ_C is the Cabibbo angle) -

and the notion of an effective interaction will be defined in the next section.

The point I wish to stress is that this is a minimal scheme. Interactions certainly exist with the quantum numbers of all the terms in $\mathcal{L}_{eff}$, which is probably the simplest form which can describe the existing data. However, the limits on other possible terms are actually very bad. Thus the data allow quite different forms of lepton conservation laws from that implied by Eq. (1), neutral currents (purely leptonic or with $\Delta S = 0$) with appreciable strength, etc.; the relevant data are reviewed in Ref. 1). Here we mention just three examples of badly tested "principles" embodied in $\mathcal{L}_{eff}$:

1) Semileptonic processes with $\Delta S > 1$ should not occur in lowest order. However, the best limit is :

$$\frac{|A(\Xi^{0} \to p e^{-} \bar{\nu}_e)|}{|A(\Xi^{-} \to \Lambda e^{-} \bar{\nu}_e)|} < 0.27.$$

The $\Delta S \leq 1$ hypothesis can, of course, be tested in neutrino reactions since it implies :

$$\bar{\nu} n \not\to \mu^{+} \Omega^{-}$$

$$\text{in } \bar{\nu} p \to \mu^{+} \Lambda^{0} (K^{0} + y \bar{K^{0}}), \quad y = 0$$

etc.

2) $\Delta S = 0$ semileptonic processes should obey a $\Delta I = 1$ rule. Examination of possible semileptonic decay processes shows that they put no constraints whatsoever on terms with $\Delta I \geq 2$ (in electromagnetic interactions a $\Delta I \leq 1$ rule is also usually assumed but there are no good limits on currents with $I \geq 2$ at present). Again, neutrino reactions can provide tests since this "rule" implies :

$$\frac{\sigma(\nu p \to \mu^{-} \Delta^{++})}{\sigma(\nu n \to \mu^{-} \Delta^{+})} = 3, \text{ etc.}$$

3) J^{h}_{λ} satisfies the "charge symmetry condition" :

$$J_{\lambda}^{h\,+} = - e^{-i\pi I_2} J_{\lambda}^{h} e^{i\pi I_2}$$

(this is equivalent to assuming that there are no second class currents in the approximation that T is conserved). This hypothesis predicts

$$\frac{\Gamma(\Sigma^{-} \to \Lambda e^{-} \bar{\nu}_e)}{\Gamma(\Sigma^{+} \to \Lambda e^{+} \nu_e)} = 1.64$$

with which the experimental ratio of 1.60±0.56 is obviously compatible. However, if we attribute significance to the data [compiled by Wilkinson et al. [2]] suggesting asymmetries in the ft values for β decays of mirror nuclei, then we would conclude that the charge symmetry condition is wrong. Luckily it can be tested by comparing ν with $\bar{\nu}$ interactions on d, Ne or any $I = 0$ target.

It is commonly supposed that the weak interactions are mediated by charged vector bosons ($W^{\pm}$) which interact thus :

$$\mathcal{L} = g_W \left(J_\lambda W^\lambda + h.c. \right) \tag{2}$$

where $J_\lambda = J_\lambda^h + j_\lambda^\mu + j_\lambda^e$, which reduces to

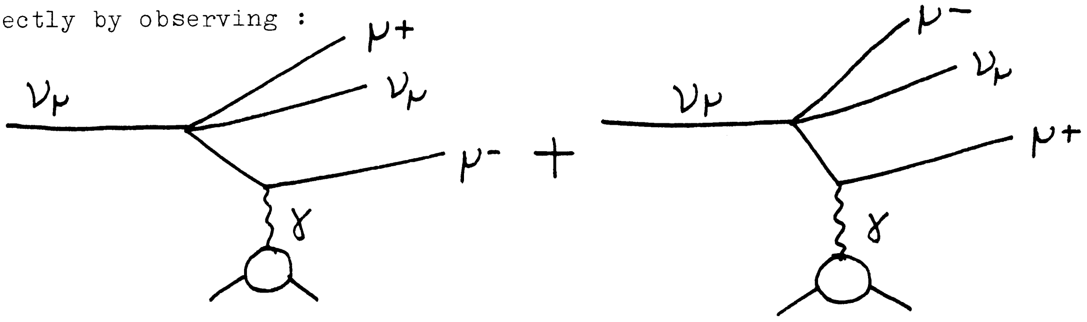
$$\mathcal{L}_{eff} = \frac{G}{\sqrt{2}} J_\lambda^+ J^\lambda , \left(\frac{G}{\sqrt{2}} = \frac{g_W^2}{M_W^2} \right), \tag{3}$$

at low momentum transfers. In addition to the properties already implied by Eq. (1), Eqs. (2) and (3) imply :

1) Additional "diagonal" leptonic processes :

$$\nu_e + e \rightarrow \nu_e + e$$
$$\nu_\mu + \mu \rightarrow \nu_\mu + \mu$$
$$\text{etc.}$$

with definite cross-sections. Sixteen years have passed since this was first predicted, but these cross-sections have not yet been measured. These processes are, of course, extremely hard to observe directly [note that $\sigma(\nu_e e) \sim$ $\sim G^2 s = 2G^2 m_e E_\nu^{lab} = 5 \times 10^{-43} E_\nu^{lab}(\text{GeV})\ \text{cm}^2$] but they could perhaps be seen indirectly by observing :



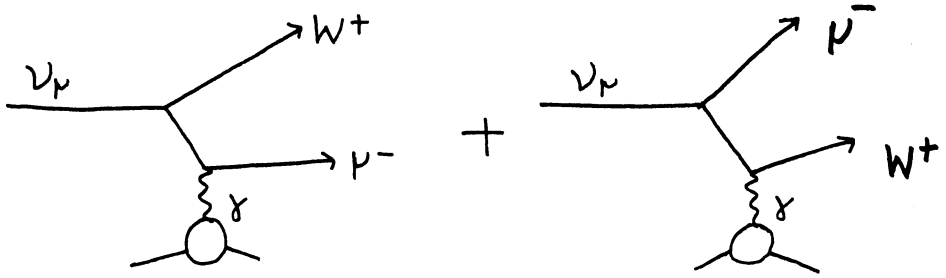
If there are neutral leptonic currents (as required by various theories discussed below) the predictions for these "diagonal" processes would change. In any case it is extremely important to try to observe them.

2) Non-leptonic processes. These are really outside the scope of this talk, but we observe that : a) $\Delta S = 0$ processes with the order of magnitude required by the current-current theory are known to exist; b) the well-known $\Delta S = 1$ processes present some problems. Their gross features can be described by $I = \frac{1}{2}$ amplitudes; small $I = \frac{3}{2}$ amplitudes are needed but in no case are then required to be $> 5\%$ *). This is not really understood, in my

*) Since this was written I have discovered that substantially larger $I = \frac{3}{2}$ amplitudes are now needed in $K \rightarrow 3\pi$. See the discussion of the papers submitted by Pirone et al., and Hitlin et al., at the Batavia conference in the article by Zakharov in the parallel session led by M.K. Gaillard (to be published in the Proceedings).

opinion, and is a problem for the current-current model. Furthermore, the model naïvely predicts amplitudes about a factor of five too small for these processes.

3) The existence of W's. One of the primary aims of neutrino experiments is to observe the process :



In this way, W's of up to 15 GeV could perhaps be seen at NAL and the CERN-SPS. The clearest way to observe W's is in $e^+e^- \to W^+W^-$, but there are no machines approved which could reach $M_W \gtrsim 4.5$ GeV. If theoretical calculations based on the parton model are not badly wrong, W's of up to about 40 GeV could perhaps be observed in the process $pp \to W+ \ldots$ at the new accelerators and the ISR. The existence of W's of even higher mass might be inferred from characteristic deviations from scaling in deep inelastic neutrino reactions.

To <u>summarize this section</u> : there is a phenomenological theory which describes most decay processes satisfactorily in terms of a few parameters. Nevertheless many fundamental questions first posed many years ago are still open. In particular, we would like further information concerning :

1) the validity of selection rules, neutral currents, form of lepton conservation law, isospin properties, etc. [Note that ideally we would like tests at high as well as low energy; currents with (e.g.) $\Delta S = 4$ or $\Delta I = 10$ could not show up below the 4K and the 9π thresholds, respectively.]

2) "Diagonal" cross-sections.

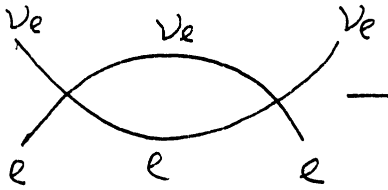
3) W's.

III. POSSIBLE THEORIES OF WEAK INTERACTIONS

III.A Problems with the Conventional Theory

If we take the current-current form and try to calculate second order effects, we immediately encounter divergent integrals :

$$J_\lambda J^\lambda \xrightarrow[e.g.]{}$$



$$\longrightarrow \int \frac{d^4k}{k^2} = \infty \; !$$

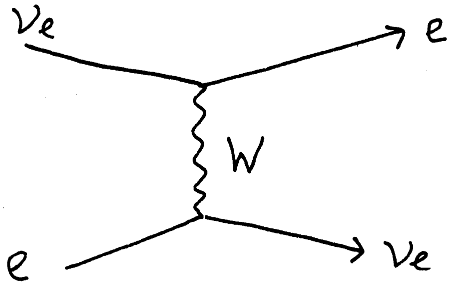
Divergent integrals also occur in quantum electrodynamics but in that case they can be absorbed by renormalization. Here, however, we are dealing with a "non-renormalizable" theory and it turns out that an increasing number of arbitrary constants must be introduced in each successive order to render all matrix elements finite. An alternative way to look at the problem of the divergent second order amplitude above is to consider calculating it by writing a dispersion integral over the imaginary part, which is proportional to the lowest order cross-section for $\nu_e + e \to \nu_e + e$. It is a safe approximation to neglect the electron mass at high energy in this case and therefore (on dimensional grounds)

$$\sigma(\nu_e + e \to \nu_e + e) \underset{(s \gg m_e^2)}{\sim} G^2 s. \tag{4}$$

Consequently the dispersion relation requires two subtractions [3], the subtraction constants being the first of the arbitrary constants alluded to above.

Faced with this proliferation of arbitrary constants an "effective Lagrangian philosophy" is usually adopted according to which higher order terms are simply discarded and the matrix elements of $\mathcal{L}_{eff}$ are supposed to describe the data completely. However, as is well known, this "philosophy" must fail at high energies. In the current-current model the interaction $\nu_e + e \to \nu_e + e$ occurs at a point (zero impact parameter). It is purely s wave and is bounded by unitarity to be $\leq$ const/s. The predicted cross-section [Eq. (4)] overtakes this bound at the so-called "unitarity limit". The most stringent bound is actually obtained in the inelastic process $\nu_\mu + e \to \mu + \nu_e$ where the limit is reached at $E^\nu_{c.m.} \sim 320$ GeV (corresponding to $E^\nu_{lab} \sim 10^5$ GeV).

In these processes, the situation can be improved by introducing a W which "spreads out" the cross-section over many partial waves :



The lepton masses can again be neglected at high energies and, since the coupling g_W [Eq. (2)] is dimensionless,

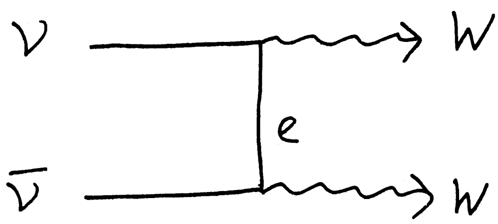
$$\frac{d\sigma}{dQ^2} \sim \frac{g_W^4}{(Q^2+M_W^2)^2} \quad , \quad \sigma \sim \frac{g_W^4}{M_W^2}$$

for $s \gg M_W^2$. The dispersion relation now converges [3] and we can calculate the second order amplitude. [The s wave cross-section, which behaves as

$$\sigma_{S\,Wave} \sim \frac{g_W^2}{s} \log\left(s/M_W^2\right) ,$$

still violates unitarity at some astronomical energy, but this is only a problem if we adopt an "effective philosophy" and reject higher orders; even renormalizable theories eventually violate exact unitarity if we work in a fixed order.]

Although in processes such as $\nu_e + e \to \nu_e + e$ the high energy behaviour is greatly improved by the introduction of a W, we are now faced with disaster in other diagrams such as



The problem occurs when the W is longitudinally polarized. In its rest frame the W's polarization is described by three vectors :

$$\begin{array}{c} t \\ x \\ y \\ z \end{array} \quad \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} , \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix} , \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} .$$

Under a Lorentz transformation along the z axis the transverse (T), x and y, components are unchanged, dimensional analysis still governs at high energies and

$$\sigma(\nu\bar{\nu}\to W_T W_T) \underset{(s \gg M_W^2)}{\sim} \frac{g_W^2}{s} .$$

However, the longitudinal (L) polarization vector becomes

$$\epsilon_\mu^L = \frac{1}{M_W}\left(|\vec{k}|, 0, 0, k_0\right) = \frac{k_\mu}{M_W} + O\left(\frac{M_W}{k_0}\right)$$

so that

$$\sigma(\nu\bar{\nu}\to W_L W_L) \underset{(s \gg M_W^2)}{\sim} \frac{g_W^2}{M_W^4}\, s$$

rendering the contribution of the WW state to the fourth order (in g_W) amplitude for $\nu\bar{\nu}\to\nu\bar{\nu}$ uncalculable except in terms of arbitrary constants.

Another way to exhibit this problem is to note that the spin projection operator (obtained by summing over the polarization vectors above and writing the result covariantly) is

$$\sum \epsilon_\mu \epsilon_\nu = -g_{\mu\nu} + \frac{k_\mu k_\nu}{M_W^2} .$$

The $k_\mu k_\nu$ term (due to the longitudinal component) prevents the propagator

$$\frac{-g_{\mu\nu} + \frac{k_\mu k_\nu}{M_W^2}}{k^2 - M_W^2}$$

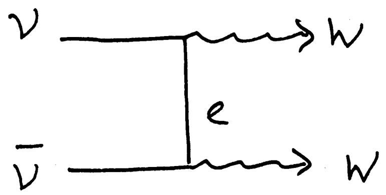
from falling off as $k_\mu \to \infty$ thus making higher order terms unrenormalizably infinite.

Before discussing possible ways out of this apparent dilemma we consider <u>attempts to estimate the cut off energy/momentum Λ beyond which the conventional weak interaction theory is expected to fail</u> (the strong interactions do not provide a cut-off according to current algebra - light cone - parton ideas). Estimates of the most divergent contributions (due to Ioffe et al.) to

$K_L^o \to \mu^+ \mu^-$ yield $\Lambda \lesssim 23$ GeV, while (yet more model dependent) calculations of the K_L^o-K_S^o mass difference give $\Lambda \approx 4$ GeV. This suggests that the conventional theory may fail at quite modest momentum transfers and is therefore very encouraging for experimentalists. However, it has to be said that the details of the calculation would make no sense in finite theories, although they are probably valuable as order of magnitude estimates. [We shall see below that these results are embarrassing for theories which unify weak and electromagnetic interactions in which $\Lambda \sim M_W \sim e/\sqrt{G}$ is expected.]

III.B Some Possible Theories

We have discussed the fact that with the simple current-current form or the traditional picture with W's [Eqs. (2) and (3)] we cannot calculate to all orders without introducing an infinite number of arbitrary constants. In the latter case trouble first occurs in diagrams such as



We now consider some possible ways out of this problem.:

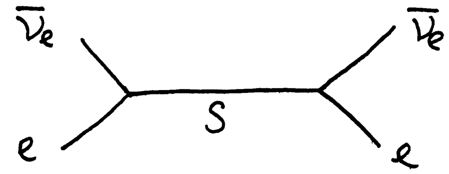
1) It can be asserted that "perturbation theory is irrelevant". If this were so, it is not clear that $\mathcal{L}_{eff}$ would be connected in any way with the "true" Lagrangian. In any case, such an assertion on its own is scarcely scientific, being without predictive powers.

2) Salam et al., have considered "non-polynomial Lagrangians" which are closely related to Eq. (2) [4]. Techniques have been developed for handling such Lagrangians (at least in simple cases); the method amounts essentially to giving a "minimal" prescription for assigning values to the arbitrary constants encountered in the usual approach. It would be nice if advocates of this approach could commit themselves to definite predictions for higher order weak interactions and high energy behaviour.

3) As observed by Gell-Mann, Goldberger, Kroll and Low, the propagator $\Delta_{\mu\nu}^{ij}$ which connects currents j_μ^i and j_ν^j can be made to behave as $1/k^2$ as $k \to \infty$ provided $i \neq j$, by introducing additional scalar bosons with a derivative coupling to j_μ thus :

$$\Delta^{ij}_{\mu\nu} = \frac{-g_{\mu\nu} + \frac{k_\mu k_\nu}{M_W^2}}{k^2 - M_W^2} + \frac{g_i^* g_j \; k_\mu k_\nu}{k^2 - M_S^2}$$

(This led these authors to stress the importance of measuring the diagonal – $i = j$ – matrix elements which, they suggested, might be described by something quite different from the conventional theory.) The non-renormalizable divergences of higher order diagrams could all be removed if the second term entered with a minus sign. This means abandoning the notion of positive metric and seems to lead to violations of unitarity, e.g., the amplitude corresponding to the diagram

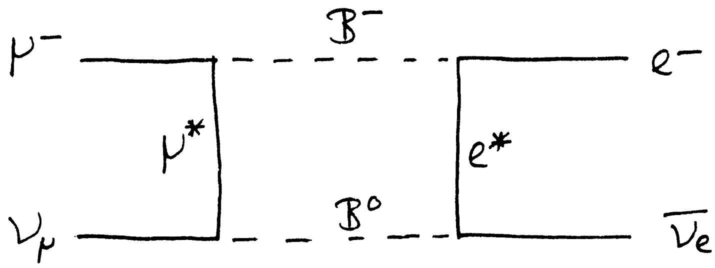


has the opposite sign than in usual theories; the imaginary part of this amplitude gives the probability for producing the particle S which is now negative! Lee and Wick observed [5] that this does not matter if all negative metric particles (such as S) are unstable and therefore cannot really be produced. With four new bosons in place of each one in the conventional theory, all amplitudes can be made not only renormalizable but actually finite; similarly a negative metric "heavy photon" can be introduced to make electromagnetic amplitudes finite. The most important experimental implications of this model are the existence of scalar bosons, which should be produced by neutrinos [note, however, that if $M_W > M_S$ we expect

$$W \to S + \gamma$$
$$\hookrightarrow \text{hadrons}$$

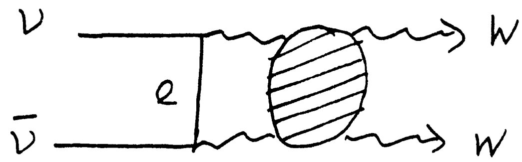
to be the dominant decay mode], and a "heavy photon" which should be seen (e.g.) in $e^+e^- \to \mu^+\mu^-$ and $pp \to \mu^+\mu^- + \ldots$.

4) "Conspiracy". Models can be devised [6] in which the weak interactions are mediated by scalar bosons (so that the theory is renormalizable) whose couplings are arranged so as to simulate the usual V-A interaction at low energies. For example, in the theory of Kummer and Segrè, μ decay is a fourth order process, described by the diagram :



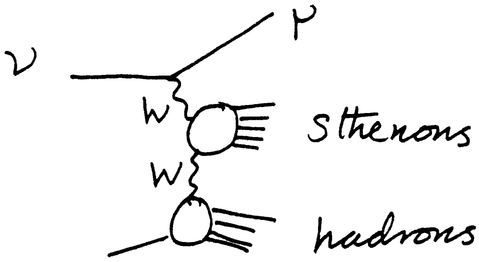
where $B^{\bar{o}}$ are heavy scalar bosons and $\mu^*(e^*)$ is a heavy muon (electron). A large ménagerie of new particles must be introduced, whose couplings must conspire to satisfy many relations, in order to reproduce the successful aspects of the usual theory, such as (e.g.) CVC (which in this model appears to be an accidental small momentum transfer effect). The existence of these models is of considerable interest but, in view of their inelegant features, I personally would only advocate them as a last resort.

5) "Evasion". It has been suggested that W's may interact strongly with each other [7] (some models have been proposed in which they also interact strongly - in pairs - with hadrons). These strong interactions could damp out the bad high energy behaviour encountered in the usual theory, e.g., by a final state interaction in the example considered previously :



This suggestion is evasive in the sense that it shifts the problem into the intractable realm of the strong interactions. Presumably strongly interacting W's should exhibit typical strong interaction phenomena - bound states, resonances, Regge recurrences, etc. Thus there may be large families of new particles dubbed "sthenons" by Appelquist and Bjorken [8] at the insistence of the editor of Phys.Rev. (in place of the earlier name "nguvons" which replaced the original term "Garryons" - in honour of Garry Feinberg who was one of the first to consider strongly interacting W's).

Experimentally these models imply that for $s \gg M_W^2$ the diagrams



become important and

$$\frac{\sigma(\nu A \to \mu^- + \text{sthenons} + \text{hadrons})}{\sigma(\nu A \to \mu^- + \text{hadrons})} \sim 1$$

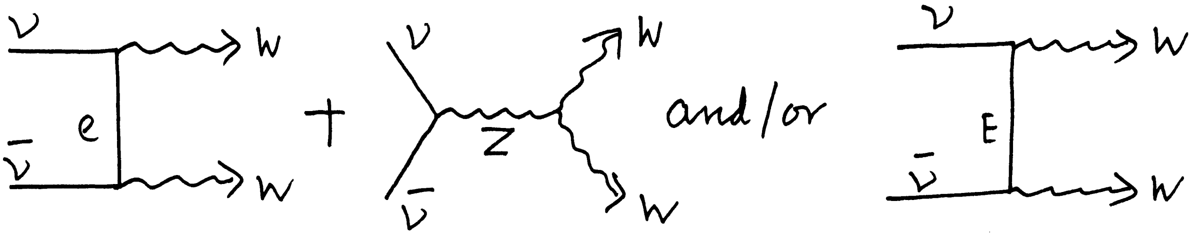
(the linearly rising total cross-section having flattened out at $s \sim M_W^2$, as in all models with W's). Further implications are considered by Appelquist and Bjorken [8].

6) "Cancellation". The last possibility which we shall consider is to introduce new contributions which cancel the bad high energy behaviour encountered previously. Systematic attempts to do this lead more or less inexorably to spontaneously broken gauge theories of the Higgs type. In view of the recent interest in these theories we shall now discuss them at some length.

III.C Spontaneously Broken Gauge Theories [9]

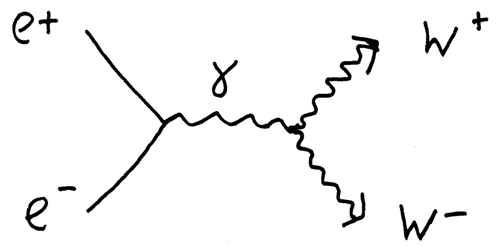
Motivation [10]

In order to cancel the bad high energy behaviour encountered in $\nu\bar{\nu} \to WW$ with other contributions in the same order, we must introduce new exchanges in the s channel or the t (or u) channel (whose couplings can be adjusted to cancel the offending terms) :

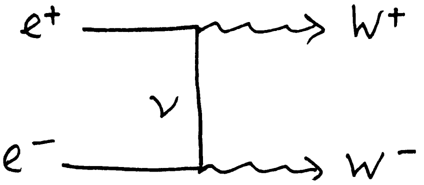


Thus cancellation requires the existence of either neutral currents or heavy leptons (with $Q = \pm 1$) or both.

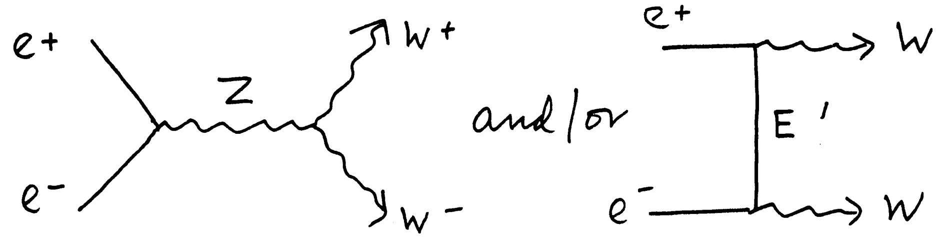
Next consider the reaction $e^+e^- \to W_L^+ W_L^-$ in which the diagram



leads to disaster. In this case there exists another contribution with which it might be thought that cancellation could be arranged :



However, because of the V-A vertex structure, this is impossible since we can always polarize the electrons so that this contribution vanishes. Once again cancellation requires the introduction of new exchanges :



(where $|Q_{E'}| = 0$ or 2). If, in the interest of economy, we wish to use the same Z (and/or related particles E and E') to effect the cancellation in the case of $e^+e^- \to W^+W^-$ and $\nu\bar{\nu} \to W^+W^-$ then there must be a relation between the strengths of the weak and electromagnetic interactions.

If we actually pursue this cancellation idea systematically in processes of the type $L\bar{L} \to W\bar{W}$, then we are led to relations between the couplings which are characteristic of Yang-Mills theories [10] (i.e., the "conspiracy relations" needed to give the desired cancellation look rather natural since they have a Clebsch-Gordan like character). It is well known that the electrodynamics of charged vector bosons is best behaved at high energies when the gyromagnetic ratio has the Yang-Mills value $\lambda = 2$ [e.g., in lowest order $\sigma(\gamma\gamma \to WW) \sim s$, for $\lambda \neq 2$, $\sim \ln s$ for $\lambda = 2$].

It turns out that renormalizable theories involve one more new type of particle - scalar mesons (ϕ) coupled to W's and to fermions. The necessity of the ϕ can be motivated by considering $\bar{\nu}_e e \to 3W$; with the couplings introduced so far, this process makes a divergent contribution to $\bar{\nu}_e e \to \bar{\nu}_e e$. The introduction of ϕ's is the simplest way to achieve convergence [a more detailed discussion of this argument, which is due to H. Quinn, is given in the Appendix to B.W. Lee's article [9]].

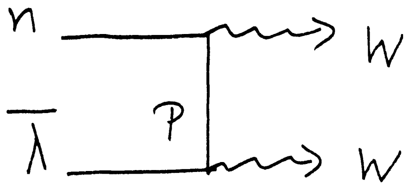
To sum up : the demand that all Born terms are well behaved at high energy in a theory with W's requires the existence of neutral currents and/or heavy leptons with couplings of the Yang-Mills type; in higher orders new scalar mesons are needed. [Further : it is most economical to unite the weak and electromagnetic interactions. This leads to a relation of the form $M_W \sim \alpha/\sqrt{G} \sim 100$ MeV. Thus in Weinberg's model $M_W = 37$ GeV/$\sin\theta \geq 37$ GeV while in the Georgi-Glashow model $M_W = 53$ GeV$\times\sin\beta \leq 53$ GeV when θ and β are parameters in these theories.] These, then, appear to be necessary conditions for the construction of a renormalizable theory of this type. It is now believed that they are also sufficient conditions and that spontaneously broken gauge theories with these ingredients are renormalizable [these developments are associated with the names of Higgs, Kibble, 't Hooft, B.W. Lee, Weinberg, Salam and others [9)]].

Technical aside : what is a spontaneously broken gauge theory ? Recall that the invariance of Lagrangians under phase transformations $\psi \rightarrow e^{ie\chi}\psi$ leads to charge conservation. If we allow χ to become an arbitrary function of space time $\chi(x)$ and still demand invariance then we must introduce a new massless field A_μ which transforms as $A_\mu \rightarrow A_\mu + \partial_\mu \chi$ and (as a minimal requirement) make the replacement $\partial_\mu \psi \rightarrow (\partial_\mu - ieA_\mu)\psi$ in the Lagrangian. This gauge invariance leads to the well-known result that in an amplitude involving a photon with momentum k we can make the replacement $\epsilon_\mu(k) \rightarrow \epsilon_\mu(k) + \beta k_\mu$ without changing any physical results. Recall that the origin of the problem with W's was that

$$\epsilon_\mu^L(k) = \frac{k_\mu}{M_W} + O\left(\frac{M_W}{k_0}\right).$$

If there was some sort of gauge invariance for the charged W's, so that we could change ϵ_μ by terms proportional to k_μ with impunity, then the k_μ term in ϵ_μ^L would have to be totally ineffective and our problems would be solved. Yang and Mills showed that the required gauge invariance can be obtained by generalizing invariance under such transformations as, e.g., isospin $(\psi \rightarrow e^{i\vec{\tau}\cdot\vec{\lambda}}\psi)$ to space time dependent transformations $(\psi \rightarrow e^{i\vec{\tau}\cdot\vec{\lambda}(x)}\psi)$; this requires the introduction of isospin multiplets of vector mesons (W's). The problem is that the invariance requires that $M_W = 0$. This is avoided by producing a "spontaneous breakdown" of the symmetry so that the solution (in which $M_W \neq 0$) does not have the full symmetry of the Lagrangian (in which $M_W = 0$) [11)]; traces of the symmetry remain in the relations between the couplings which give rise to systematic cancellations in divergent amplitudes (in the way discussed above). The spontaneous breakdown in implemented by introducing scalar mesons ϕ coupled to the W's (as already encountered above); the ϕ's have a self-interaction such that at the classical potential minimum $\phi = \lambda \neq 0$. Thus in the ground state the coupling $(\sim \phi^2 W^2)$ becomes a mass term $(\sim \lambda^2 W^2)$.

Problems : the introduction of neutral currents and/or heavy leptons and ϕ's seems a small price to pay for a renormalizable model which unites weak and electromagnetic interactions. Why then has no model emerged which has gained general acceptance ? The problem is that in all models considered so far the baryon structure is a mess. It turns out that models with three quarks are essentially impossible [12]. Since we do not want a $\Delta S = 1$ neutral current, the badly behaved quark amplitude



cannot be cancelled with an s channel exchange. New t (or u) channel exchanges require that the number of "quarks" is increased to at least four; thus schemes with 5, 8, 11, etc., "quarks" have been considered. These schemes go beyond SU(3); a new quantum number, conserved by strong interactions, called "charm" (a sort of new strangeness) is introduced and SU(3) is supposed to hold as a low energy remnant of some higher symmetry. The non-appearance of "charmed particles" is explained by attributing large masses to them. (We consider the phenomenological implications of charm very briefly below.)

Another problem is that those second order effects which are quadratically divergent in the phenomenological theory are of order $G(GM_W^2) \sim G\alpha$ in these theories. The fact that $K_L^0 \to \mu^+\mu^-$ does not occur above the $G\alpha^2$ level can generally be arranged at a price [e.g., in the O(3) model of Georgi and Glashow this can be done by increasing the original choice of 5 quarks to 8 [13]]. However, the fact that

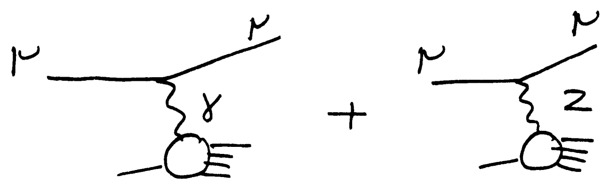
$$m_{K_L^0} - m_{K_S^0} \approx \frac{1}{2}\Gamma_{K_S^0} \sim G^2$$

is harder to explain; again it is easy to suppress the natural magnitude $(\sim G\alpha)$ but the fact that it is suppressed to exactly the conventional second order level has to be put in by hand.

Phenomenology

Regardless of the validity of the theories considered above, they have already played an important role in stimulating experimentalists to improve the limits on neutral currents. It is to be hoped that they will also stimulate searches for heavy leptons and charmed particles. We now examine some relevant phenomenology.

1) Neutral currents. The failure to observe neutral currents in neutrino reactions has cast considerable doubt on the only known model [the SU(2)×U(1) model of Weinberg] which has no heavy leptons [14]. However, there are plenty of models with neutral currents as well as heavy leptons [*]. In some of these the neutral current is not coupled to the neutrino, so its only observable effects might be in e^+e^-, eN and μ N collisions. Unfortunately the effects are probably small; the interference term in



is of order $GQ^2/4\pi\alpha$ relative to the purely electromagnetic contribution [but the apparent violation of scale invariance produced by the Z might be detectable at very high energies [15]], e.g., a simple guess for the parity violating difference of cross-sections for left and right-handed μ's (e's) gives

$$\frac{|d\sigma^L - d\sigma^R|}{d\sigma^L + d\sigma^R} \sim 10^{-4}\left(\frac{4\omega}{3+\sqrt{\omega}}\right)\frac{Q^2}{M_P^2}\ \frac{Q^2}{2M_P E_\mu^{lab}}$$

(where $\omega = 2\nu/Q^2$). More serious estimates are given in Ref. 15).

2) Heavy leptons [16]. We only consider here heavy leptons of the type encountered in gauge theories, which have the same lepton numbers as muons or electrons; a review of some ideas and evidence about these and other species of heavy leptons has recently been given by Perl [17]. When we considered cancelling part of the electron exchange contribution to $\nu\bar{\nu}\to W\bar{W}$ we were led to contemplate the introduction of a heavy lepton in either the t or the u channel. In simple models, it turns out that in this case the appropriate choice is such that there is an M^+ with the same lepton numbers as ν_μ and μ^-. Cancellation in $\mu^+\mu^-\to W^+W^-$ is likewise achieved with an M^0.

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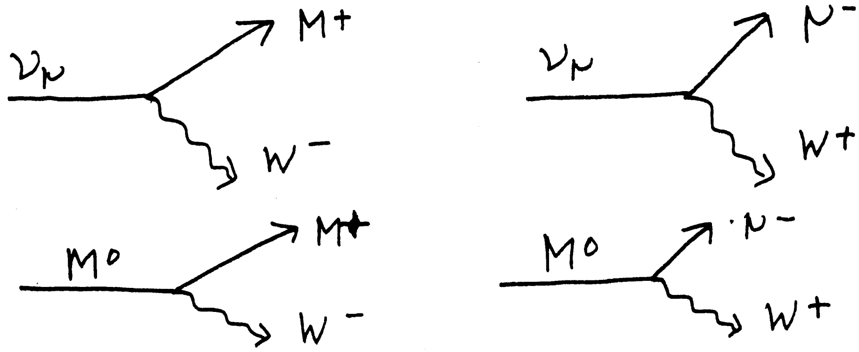
*) A survey of several models has been given by J.D. Bjorken [to be published in Proceedings 1972 International Conference on High Energy Physics (Batavia)]. See also the Appendices in Ref. 16).

Thus the fundamental vertices are :



[more technically, when we augment the simplest "iso-doublet" structure (ν_μ, μ^-) we are led, e.g., to consider "iso-triplets" (M^+, ν_μ, μ^-), and M^0's mixed with ν_μ]. The fact that M^+ and μ^- have the same lepton number will be seen to lead to very good signatures for $M^\pm$ production.

The decays are simple to investigate. The main results are :

a. according to currently popular ideas :

$$\frac{\Gamma(M^{\pm}_{0} \to \text{leptons})}{\Gamma(M^{\pm}_{0} \to \text{lepton} + \text{hadrons})} \sim 1$$

thus making it easy to identify M's from their leptonic decays. [If $M_{\text{heavy lepton}} > M_W$ then the dominant decay mode is $M \to W + \text{lepton}$.]

b. for masses $\gtrsim$ 800 MeV [18], the lifetime of this particular species of heavy lepton is such that they would not leave visible tracks.

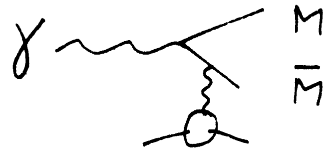
Several <u>production processes</u> might be contemplated :

1. $$e^+ e^- \to M^+ M^-$$

$$M^- \to \begin{cases} \bar{\nu}_\mu \, \mu^- \, \bar{\nu}_\mu \\ \bar{\nu}_\mu \, e^- \, \bar{\nu}_e \\ \bar{\nu}_\mu + \text{hadrons} \end{cases} \qquad M^+ \to \begin{cases} \nu_\mu \, \mu^+ \, \nu_\mu \\ \nu_\mu \, e^+ \, \nu_e \\ \nu_\mu + \text{hadrons} \end{cases}$$

In this process M's with mass almost up to the beam energy should be seen with the design luminosity of machines under construction (giving limits of ~4.5 GeV in a few years).

2. $\gamma A \rightarrow M^+M^- + \ldots$ by the mechanism



The cross-section can be calculated exactly [19]. It seems unlikely that mass limits of $\gtrsim$ 3 GeV can be set from this process with machines under construction.

3. $$\nu_\mu A \rightarrow M^+ + \ldots\ldots$$
$$M^+ \rightarrow \begin{cases} \nu_\mu\, e^+\, \nu_e \\ \nu_\mu\, \mu^+\, \nu_\mu \\ \nu_\mu + \text{hadrons} \end{cases}$$

The results of a (model dependent) calculation of the cross-section are shown in the Figure. From this figure we may probably conclude that $M_{M+} > 1$ GeV. In the CERN 1967 HLBC experiment over 100 events with $E_\nu > 4$ GeV were observed. Were M^+ to exist with mass $\sim$ 1 GeV, there would have been $\gtrsim$ 25 M^+ production events as well. Were M^+ to have a mass $\sim$ 1.5 GeV this number would drop to $\sim$5, probably consistent with the data. On the basis of this figure we conclude that neutrino experiments at NAL and the CERN-SPS could eventually set mass limits in the 5-10 GeV range.

4. $\mu^+ N \rightarrow M^0 + \ldots$. In models examined by us :

$$4\times 10^{-37}\,\text{cm}^2 \lesssim \sigma \lesssim 2.5\times 10^{-35}\,\text{cm}^2$$

for a fully polarized μ^+ beam (the best case) of 100 GeV, and $M_{M^0} \leq 4$ GeV. This experiment looks possible but very difficult.

5. $e^+e^- \rightarrow M^0 \overline{\nu}_\mu$. The cross-section is very model dependent, e.g., for E/beam = 4 GeV and $M_{M^0} \leq 2$ GeV it is nominally $\sim 2\times 10^{-37}$ cm^2, but it turns out to be actually $\sim 10^{-35}$ cm^2 in one model.

6. $pp \rightarrow M^+M^- + \ldots$. The cross-section is given by :

$$\frac{\sigma(pp \rightarrow M^+M^- + \ldots)}{\sigma(pp \rightarrow \mu^+\mu^- + \ldots)} = \left(1 - \frac{4M_M^2}{Q^2}\right)^{1/2}\left(1 + \frac{2M_M^2}{Q^2}\right)$$

The feasibility of finding M's (or heavy electrons) this way depends on how large $\sigma(pp \to \mu^+\mu^- + \ldots)$ turns out to be.

3) Charm. As discussed above, fashionable theories suggest the existence of a new "charm" quantum number. The properties of "charmed" particles are quite analogous to those of "strange" particles except that the lightest charmed particle is probably heavier than 1 GeV. A guess would be that hadronic $(C \to \text{hadrons})$ and leptonic $(C \to \mu\nu + \text{hadrons})$ decays are roughly equally probable (within a factor of ten ?). In strong interactions there must be "associated production"

$$pp \to C\bar{C}' + \ldots .$$

$$p\bar{p} \to C\bar{C}' + \ldots .$$

They could be copiously produced in the reaction

$$e^+e^- \to C^+C^-.$$

Single C's could be produced by neutrinos :

$$\nu A \to \mu C + \text{hadrons}$$

which may make neutrino experiments the best place to search for them if they are heavy.

Conclusions

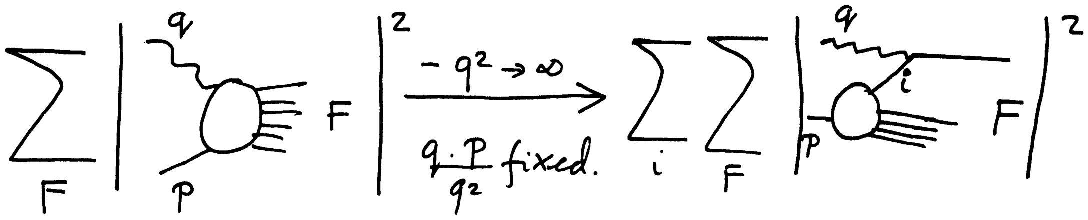
Many experiments can look for heavy leptons and charmed particles and it is, of course, important to try to do this independent of present theory. [Unfortunately, in most gauge models there is no upper limit on the heavy lepton mass [20] so theorists can - and will - retreat by increasing the mass if they are not found.]

IV. NEUTRINOS AS PROBES OF HADRON STRUCTURE

If the usual description of the $\nu_\mu - \mu$ current is correct, then we can use neutrinos to probe the structure of the hadronic current with which it interacts (via a W or not). For example, we can measure form factors, test the Cabibbo theory, test PCAC using Adler's theorem $(\sigma^{\nu+A \to \mu+F}(\theta_{\mu\nu}=0) \propto \sigma^{\pi^+ + A \to F})$, test current algebra sum rules, etc. We will return to the question of the fundamental Adler sum rule later; first we consider the scaling property discovered in the SLAC-MIT inelastic electron scattering experiments, which suggests that it might be possible to obtain fundamental information about the structure of hadrons by studying deep inelastic neutrino reactions. We will consider just one illustrative example of the sort of results that have been obtained.

All our discussion will be based on the supposition that scaling continues to hold at much larger Q^2 and also that it holds in weak as well as in electromagnetic interactions. It is, of course, very important to test scaling; it is broken by factors $\log(Q^2/M^2)$ in perturbation theory and we have no soluble models to test the assertion that the same might not be true in exact solutions of field theories and/or in the real world. [The absence of the photon propagator means that relative to electron scattering a much larger fraction of the neutrino events are at large Q^2 so that quite good tests of scaling may be obtained : note that a W propagator would break scaling in a trivial way - by a factor $1/(1+Q^2/M_W^2)^2$ - which may provide a sensitive test for W's [21].] If the (expected ?) $\log Q^2$ factors do not show up then we can reject arguments based on perturbation theory and perhaps even have a little confidence in formal calculations of the light cone commutator of currents or (equivalently for the predictions discussed below) the parton model, which give a simple picture of the SLAC-MIT results but are invalid in perturbation theory.

If the current-current picture is correct then we can measure the total current (W?) - nucleon cross-section in inelastic neutrino scattering. According to the parton model, the "deep inelastic" cross-section is given by adding incoherently the contributions from all the constituents :



Consider models in which the constituents with which the current interacts have spin $\frac{1}{2}$ (as suggested by the small value of σ_S/σ_T observed in the SLAC-MIT experiments), isospin $\leq \frac{1}{2}$ and a weak current of the form $\bar{\psi}\gamma_\lambda \times (1-\gamma_5)\tau^+\psi$. At high energies, the $(1-\gamma_5)$ structure implies that the left-handed (right-handed) current interacts only with particles (antiparticles). Thus the parity violating quantity $\sigma_{\text{left}} - \sigma_{\text{right}}$ (which is proportional to the structure function W_3 whose scaling limit is called F_3) is proportional to the difference of the distributions of particles and anti-particles in the nucleon. Integration over these distributions leads in these models to the sum rule :

$$-\frac{1}{2}\int \left(F_3^{\nu p}(x)+F_3^{\nu n}(x)\right)dx$$

$$= (\text{No. of } I=\tfrac{1}{2} \text{ spin } \tfrac{1}{2} \text{ particles} - \text{No. of } I=\tfrac{1}{2} \text{ spin } \tfrac{1}{2} \text{ antiparticles}) \text{ in the nucleon}$$

$$= 3 \quad (\text{Quark model})$$

$$= 1 \quad (\text{"Sensible"-?-models}),$$

where $x = Q^2/2q\cdot p$ and we have made the (presumably good) approximation $\theta_{\mathrm{Cabibbo}} = 0$. This is an example of just one of several relations which can be derived in such "free field" models (and also of course from the light commutators abstracted from them) which can test very directly the properties of any underlying field theory (theoretically it would be very interesting to have measurements of the other two structure functions which can only be separated by measuring the outgoing lepton's polarization to order $m_L^2/E_\nu M_p$ - here we need heavy leptons !).

The F_3 sum rule is the only sum rule for $\nu p + \nu n$ (rather than $\nu p - \nu n$) data and hence can be tested in experiments on heavy nuclei. However, if the quark value is correct then the sum rule must converge very slowly (i.e., large Q^2 data are needed at very small x - large ω)[22]. There are also reasons to fear that the much more fundamental Adler sum rule (which is true in any "reputable" model) may converge very slowly or even be wrong.

In view of its fundamental importance, we will review the arguments advanced by Bjorken, Tuan, Sakurai and Thacker, which cast doubt on the validity of the Adler sum rule[23]. Separate sum rules can be written for the vector and axial vector contributions to the structure function F_2. Consider the vector sum rule which may be written

$$\int_1^\infty \left(F_2^{\nu n}(\omega)_{VV} - F_2^{\nu p}(\omega)_{VV}\right)\frac{d\omega}{\omega} = \int_0^1 \left(F_2^{\nu n}(x)_{VV} - F_2^{\nu p}(x)_{VV}\right)\frac{dx}{x}$$

$$= 1,$$

in the deep inelastic region. CVC gives the inequality

$$\left(F_2^{\nu n}+F_2^{\nu p}\right)_{VV} \ll 2\left(F_2^{ep}+F_2^{en}\right).$$

Hence, according to the SLAC data, the average of $F_2^{\nu p}+F_2^{\nu n}$ never exceeds ~ 0.6 – but the difference weighted by ω^{-1} must integrate to unity. There are two extreme ways to achieve this :

1) The sum rule may converge very slowly. This happens in many simple models (fitted to the SLAC data) in which the sum rule holds [24) – e.g., in the Kuti-Weisskopf model we must integrate up to $\omega = 476.51$ to get 0.9 on the right-hand side. This is certainly rather unexpected and according to some people's intuition, it is unreasonable [if we accept Rittenberg and Rubinstein's claim that $Q^2=0$ data can be translated to all Q^2 with a "modified scaling" variable then the convergence of the $(Q^2=0)$ Adler-Weisberger relation implies that we should get 0.9 by integrating only up to $\omega \approx 34$].

2) The so-(emotively)-called "bizzare behaviour" $F_2^{\nu n} \gg F_2^{\nu p}$ holds for $\omega \lesssim 5$, which probably implies the (already excluded ?) result

$$\frac{\sigma^{\nu n}}{\sigma^{\nu p}} \gtrsim 2.5.$$

The second option has also been considered unreasonable (I personally would not find an intermediate result – quite slow convergence and "rather bizzare" behaviour – at all repugnant; first – I do not know what is a reasonable rate of convergence and second – the fact that F_2^{en}/F_2^{ep} seems to be small for $\omega \sim 1$ suggests models in which $F_2^{\nu n} \gg F_2^{\nu p}$ for $\omega \sim 1$) [25). In any case these results invite us to entertain further alternatives :

3) Perhaps at large missing mass a new threshold is reached (quarks ?) which gives rise to a dramatic rise in the scaling functions which is needed to satisfy the sum rule in the scaling limit (but not to satisfy the Adler-Weisberger relation at $Q^2=0$!).

4) Perhaps the sum rule is wrong because either :

   a. the attractive (but very badly tested) current algebra hypothesis is wrong, or perhaps the weak current has pieces with $I \geq 1$, etc., (in these cases we would wonder why the Adler-Weisberger relation works), or

b. something is technically wrong with the derivation of the Adler sum rule; this sounds boring but it would mean that the light cone algebra, parton model, etc., are all quite irrelevant.

In any case, it is clear that accurate high energy neutrino experiments on hydrogen and deuterium are of crucial importance to test current algebra sum rules.

V. SUMMARY AND CONCLUSIONS

It is very likely that high energy neutrino experiments will reveal surprises which are quite unanticipated. At the very least, they will be of crucial importance for "traditional" weak interaction theory. They may also unveil fundamental information about hadron structure. I wish to end by stressing that in addition to heavy liquid bubble chamber and counter experiments (which are best suited for some things, such as search experiments -W's, heavy leptons, etc. - and measuring the "diagonal" cross-sections), neutrino (and antineutrino) experiments on hydrogen and deuterium with track sensitive targets (or perhaps mono-energetic beams or other devices) will be of crucial importance in testing the Adler (and other) sum rules, testing selection rules and eventually in unravelling detailed information about the behaviour of weak interactions at high energy.

ACKNOWLEDGEMENTS

I am grateful to J.S. Bell, D.G. Sutherland and K. Winter for comments on the manuscript, and to J. Prentki for discussions.

Questions raised by Lee and Yang [Phys.Rev.Letters 4, 307 (1970)]	Experimental answers from ν experiments
1) $\nu_\mu = \nu_e$?	$\nu_\mu \neq \nu_e$
2) Lepton conservation $\nu \to L^+$ and $\to L^-$?	$\sqrt{\frac{\sigma(\nu_\mu \to \mu^+)}{\sigma(\nu_\mu \to \mu^-)}} \leq 0.068$ but several different forms of conservation law still allowed
3) Neutral currents ?	$\sqrt{\frac{\sigma(\nu N \to \nu N \pi^0) + \sigma(\nu p \to \nu p \pi^0)}{2\sigma(\nu N \to \mu^- p \pi^0)}} \leq 0.37$
4) "Locality" (vector nature of weak interactions)	- - -
5) Universality between ν_μ and ν_e, μ and e ?	- - -
6) Charge symmetry ?	- - -
7) CVC; isotriplet current ?	- - -
8) W ?	$M_W > 1.8$ GeV
9) What happens at high energy ($E_\nu \to$ "unitarity limit") ?	- - -

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1) Detailed references and bibliographies may be found in, e.g. :

R.E. Marshak, Riazzuddin and C.P. Ryan, "Theory of Weak Interactions", Academic Press (1969);

A. Pais, Ann.Phys. 63, 361 (1971);

C.H. Llewellyn Smith, Phys.Reports 3C, No.5 (1972).

No attempt has been made to give systematic references assigning correct priorities, etc., in the present paper; most of the ideas cited without reference are "well known".

2) The evidence is not so compelling as it was a year ago; see

D.H. Wilkinson, to be published in Proceedings of the Few Nucleon Problem Conference, Los Angeles (1972), for a recent discussion. References may be traced from this paper, or from

B. Eman et al., Phys.Rev. 6C, 1 (1972).

3) The relevant integral is

$$\int_0^{\infty} ds' \left(\frac{\sigma^{\nu e}(s')}{s'-s} - \frac{\sigma^{\bar{\nu} e}(s')}{s'+s} \right)$$

In the $j_\lambda j^\lambda$ theory $\lim_{s \to \infty} \left(\frac{\sigma^{\nu e}}{\sigma^{\bar{\nu} e}} \right) \neq 1$

so with $\sigma \sim s$ two subtractions are needed. With W's the behaviour of σ changes by one power ($\sigma \to$ const) but nevertheless no subtractions are needed since

$$\lim_{s \to \infty} \left(\frac{\sigma^{\nu e}}{\sigma^{\bar{\nu} e}} \right) = 1$$

in this case.

4) For a review see,

A. Salam, Proceedings of the Rochester Meeting of the APS, Eds., A.C. Melissinos and P.F. Slattery, American Institute of Physics, New York (1971).

5) For an introductory account, see

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6) See, e.g.,

Y. Tanikawa and S. Watanabe, Phys.Rev. 113, 1344 (1959);

Y. Tanikawa and S. Nakamura, Prog.Theor.Phys.Suppl. 37 and 38, 306 (1966);

E.P. Shabalin, Yadernaya Fizika 8, 74 (1968); .../

W. Kummer and G. Segrè, Nuclear Phys. 64, 585 (1965);
N. Christ, Phys.Rev. 176, 2086 (1968);
E.P. Shabalin, Yadernaya Fizika 13, 411 (1971);
further references may be found in Ref. 1).

7) For a recent discussion see
R.E. Marshak, City College New York preprint, to be published in Proceedings of the "Neutrino '72" Conference, Lake Balaton, Hungary, June 1972.

8) T. Appelquist and J.D. Bjorken, Phys.Rev. D4, 3726 (1971).

9) For references to the original literature on this subject, see the talks by B.W. Lee and others in the Proceedings of the 1972 International Conference on High Energy Physics, Batavia - to be published.

10) The approach outlined here is known to many people (it was first impressed on me by J.D. Bjorken who has pursued it fairly systematically). More detailed work on these lines can apparently be found in a paper by Khriplovitch and Vainstein (submitted to Nuovo Cimento Letters), in Leningrad Winter School Lectures by Vainstein and Khriplovitch (I was informed of these Russian works by Bjorken) and in Copenhagen Summer School Lectures by J.S. Bell.

11) In theories formulated in a manifestly covariant way, spontaneous symmetry breaking requires the existence of zero mass "Goldstone" bosons. In this case, however, we can say that these bosons are absorbed by the W to give it the extra degree of freedom it needs when it acquires a mass.

12) Exceptions with unacceptable properties (such as $\theta_{\mathrm{Cabibbo}} = 45^{\circ}$) can be contrived.

13) B.W. Lee, J.R. Primack and S.B. Treiman, NAL preprint NAL-THY-74 (1972).

14) Wongyong Lee, Phys.Letters 40B, 423 (1972);
Report of Gargamelle group, presented at the 1972 International Conference on High Energy Physics, Batavia.
Theoretical estimates of neutral current cross-sections in these models have been made by :
B.W. Lee, Phys.Letters 40B, 420 (1972);
E.A. Paschos and L. Wolfenstein, NAL preprint NAL-THY-69 (1972).

15) A. Love, D.V. Nanopoulos and G.G. Ross, Rutherford preprint RPR/T/26 (1972).

16) The discussion here is based on

J.D. Bjorken and C.H. Llewellyn Smith, SLAC-PUB 1107 (1972). This paper compiles relevant phenomenology much of which is already known to many people (see, e.g., the references to work by Tsai and Gerstein and Folomeshkin).

17) M. Perl, SLAC-PUB-1062 (1972).

18) A limit of 900 MeV has been given by Zichichi et al., from e^+e^- colliding beam experiments at Frascati. (Contribution to the 1972 High Energy Conference, Batavia).

19) See, e.g., K.J. Kim and Y.S. Tsai, Phys.Letters 40B, 665 (1972).

20) An exception is the Georgi-Glashow model. See :

H. Quinn and J.R. Primack, to be published in Phys.Rev.

21) A W would cause the famous linearly rising ν cross-section to begin to flatten out at $s \sim M_W^2$. If the Pomeron contributes, the linear rise is replaced by $\ln(s/M_W^2)$; if it does not contribute, $\sigma \to$ const. In either case

$$\frac{\sigma^{\nu p}}{\sigma^{\bar{\nu} n}} \xrightarrow{s \gg M_W^2} 1, \quad \frac{\sigma^{\bar{\nu} p}}{\sigma^{\nu n}} \xrightarrow{s \gg M_W^2} 1$$

is expected.

22) In the quark model

$$|F_3^{\nu p + \nu n}| \lesssim \frac{18}{5} \omega F_2^{ep+en}$$

Hence (using the SLAC data)

$$\int_1^{12} |F_3^{\nu p + \nu n}| \frac{d\omega}{\omega^2} \lessapprox 3.6.$$

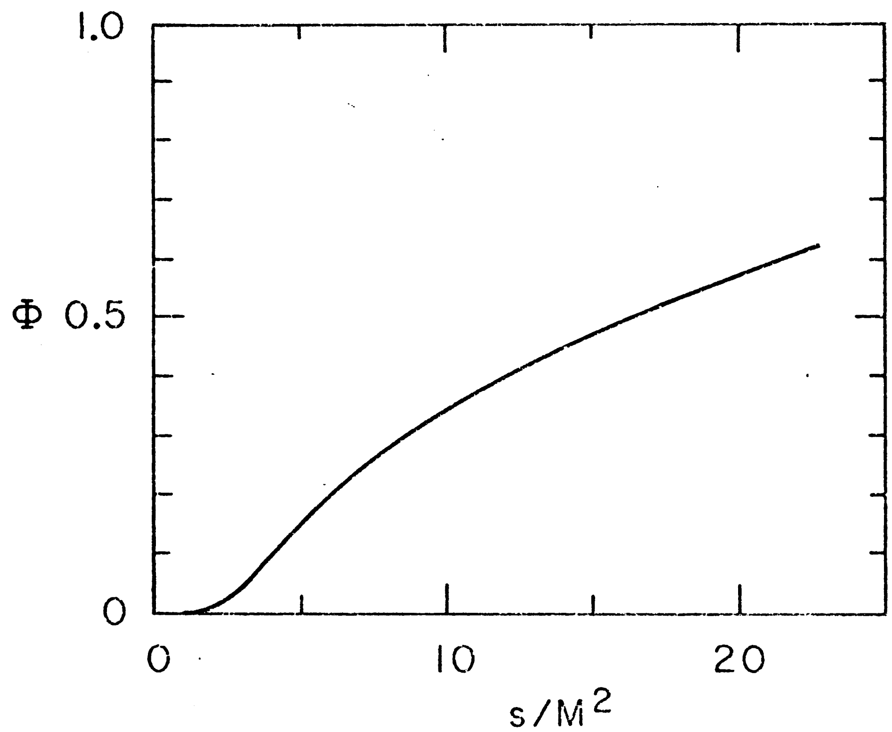
To reach the required value, we must clearly go to $\omega \gg 12$. This does not mean that the sum rule is wrong. With data limited to $\omega \lessapprox 20$ we could devise different extrapolations which give the desired value or fail by large amounts (note that if Regge behaviour holds $F_3 \sim \sqrt{\omega}$ as $\omega \to \infty$). Models exist (e.g., the Landshoff-Polkinghorne or Kuti-Weisskopf models) which fit existing data and satisfy the quark sum rule (but the convergence is, of course, extremely slow).

23) J.D. Bjorken and S.F. Tuan, SLAC-PUB-1049 (1972) - submitted to Comments on Nuclear and Particle Physics;

J.J. Sakurai, H.B. Thacker and S.F. Tuan, UCLA preprint, UCLA/72/TEP/58 (1972) - submitted to Nuclear Phys.

24) H. Pagels, Phys.Rev. D3, 1217 (1971) was the first to point out that Regge fits to the SLAC data implied that the Adler sum rule would have to converge very slowly.

25) In, e.g., the quark parton model if $F_2^{en}/F_2^{ep} \to \approx 1/4$ as $\omega \to 1$, this probably means that the virtual photon "sees" the neutron as an n quark and the proton as a p quark in this limit, which would imply $d\sigma^{\nu p}/d\sigma^{\nu n} \xrightarrow{\omega \to 1} 0$. Similar conclusions hold in many other parton models. Note also that the arguments of Bloom and Gilman (taken literally, in a way which is actually incompatible with parton-like models) also imply $d\sigma^{\nu p}/d\sigma^{\nu n} \xrightarrow{\omega \to 1} 0$.



Model dependent calculation of

$$\phi = \frac{\sigma(\nu A \to M^+ + \cdots)}{\sigma(\nu A \to \mu^- + \cdots)}$$

as a function of s/M_M^2 [taken from Ref. 16].