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# Topics In Weak Interaction Physics

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I

The struggle to discover sensible field theoretic models for the weak interactions seems to have been vigorously renewed just recently, by G. t'Hooft, S. Weinberg, B. Lee, and others. I have not myself participated in these activities and am only vaguely acquainted with the details. Nevertheless, for an opening topic, I would like to alert you to some of the developments, which have already gone far enough to have interesting experimental implications. First some background.

The well established features of weak interaction phenomenology are usually pictured as arising, effectively, from the self coupling of a charged current composed of leptonic and hadronic parts:

$$\mathcal{H}_{\text{weak}} = \frac{G}{\sqrt{2}} J_\lambda^\dagger J_\lambda, \qquad J_\lambda = j_\lambda + \ell_\lambda,$$

where

$$\ell_\lambda = \sum_{\ell = e, \mu} \bar{\psi}_{\nu_\ell} \gamma_\lambda (1+\gamma_5) \psi_\ell$$

is the lepton current and $j_\lambda$ is the hadron current. It is part of the picture that processes which can occur in first order are already well described in that leading order; and that process forbidden in first order are very very weak. Semileptonic interactions are well incorporated into the model, via the terms

$$\mathcal{H}_{\text{semileptonic}} = \frac{G}{\sqrt{2}} (j_\lambda \ell_\lambda^\dagger + \text{h.c.}).$$

The sole known example of a purely leptonic weak process, $\mu$ meson decay, is similarly built into the model via the terms

$$\mathcal{H}_{\text{leptonic}} = \frac{G}{\sqrt{2}} \ell_\lambda^\dagger \ell_\lambda .$$

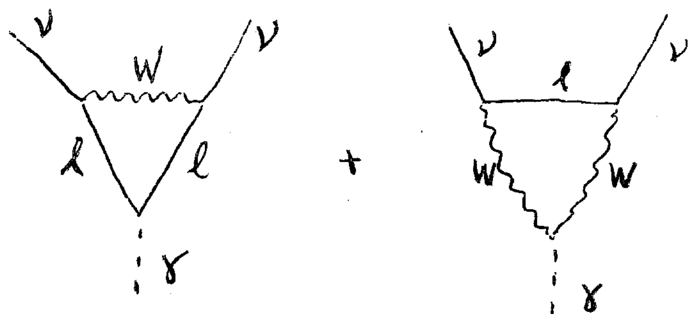
But here the current-current picture goes beyond present evidence in its prediction of "diagonal" terms, which would give rise to processes such as $\nu_\ell + \ell \rightarrow \nu_\ell + \ell$ with prescribed structure and strength. The current-current picture is least of all secure with respect to nonleptonic weak interactions, described in the model by the terms

$$\mathcal{H}_{\text{nonleptonic}} = \frac{G}{\sqrt{2}} j_\lambda^\dagger j_\lambda .$$

It is of course an attractive idea to build up the nonleptonic interactions out of the same hadron currents that figure in the semileptonic interactions. But the complexities of strong interaction effects still preclude any tests which would serve to affirm the picture in a convincing way. There <u>do</u> exist some partial, consistency tests, based on the application of current algebra and PCAC ideas to certain nonleptonic processes. What is involved here is the equal time commutator of an axial current with $\mathcal{H}_{\text{nonleptonic}}$ ; and in fact the model has come off reasonably well in these matters. Nevertheless, there are also troubles with this model of the nonleptonic interactions. With respect to isospin the strangeness changing terms contain pieces which transform like $\Delta I = 3/2$, in addition to the pieces with $\Delta I = 1/2$. Experimentally, on the other hand, the $\Delta I = 1/2$ rule seems to be well established. One has to invoke special dynamical effects in the strong interactions to suppress the unwanted $\Delta I = 3/2$ terms; but the various schemes that have been invented are none of them widely thought to be convincing.

The simple current-current model, to recapitulate, partly summarizes established phenomenology; partly goes beyond it, as with the prediction for $\nu_\ell + \ell$ scattering; and partly flies in the face of reasonably well established facts, as it does in connection with the $\Delta I = 1/2$ rule. The model has elegance and economy; and one can picture the current-current structure as arising from a more basic interaction which couples the currents to a single kind of charged, massive vector boson. However, even apart from the $\Delta I = 1/2$ rule troubles, the simple current-current scheme (with or without intermediate vector bosons) is well known to be unsatisfactory if taken literally as a proper field theoretic model. Higher order effects are generally divergent --the model is unrenormalizeable. In principle this needn't be regarded as decisive--the fault may lie in our perturbative methods. But until better and concrete methods can be found one cannot be sure that the model really preserves the conventional phenomenology embodied in the first order approximation. As a matter of fact, for nonleptonic processes even in first order the theory is probably divergent.

Much effort has gone into the search for more reasonable field theoretic models, although the criteria of reasonableness are by no means universally agreed upon in our present state of ignorance. The various models are often most definite in their implications for purely leptonic reactions and the question of neutral currents. It is useful to keep these issues especially in view. Notice that the simple model that we have been discussing involves charged currents only, so that in first order--and with neglect of electromagnetic effects--there is no provision for processes such as $\nu$ + hadrons $\rightarrow$ $\nu$ + hadrons; and similarly there is no provision for $\nu_\mu + e \rightarrow \nu_\mu + e$ or $\nu_e + \mu \rightarrow \nu_e + \mu$. However, already to first order in G neutrinos can couple to a virtual photon, according to



So these forbidden reactions,if no strangeness change is involved, are in fact formally allowed in order $Ge^2$. But it is a fact also that the loop diagrams are divergent.

I will return to these processes shortly, but let me now describe briefly a field theoretic model of the weak interactions which was introduced some time ago by Weinberg[1] and which is presently under active development.[2,3] The model is most definite for the leptonic interactions and is based on the criterion (the hope?) of renormalizability. Indeed, the scheme proposes to unify the weak and electromagnetic interactions of leptons. In general terms, according to Weinberg,[4] the strategy is as follows. First write a Lagrangian obeying some exact gauge symmetry, in which massless Yang-Mills fields interact with various particle fields and with a special multiplet of scalar fields. Next, choose a gauge in which all but a selected few (in the actual model, one) of the real scalar fields vanish. Then, break the gauge symmetry by giving to the surviving scalar fields non-vanishing vacuum expectation values, and redefine new shifted scalar fields with zero vacuum expectation values. In the resulting perturbation theory all the vector mesons acquire mass, except for those (e.g., the photon field) associated with unbroken symmetries.

In Weinberg's model for the leptons, the gauge group is $(SU_2)_L \times Y$ where, for the leptons, the symmetries act on a left handed $SU_2$ doublet

$$L = 1/2\ (1 + \gamma_5) \begin{pmatrix} \psi_{\nu_\ell} \\ \psi_\ell \end{pmatrix}$$

and a right handed singlet

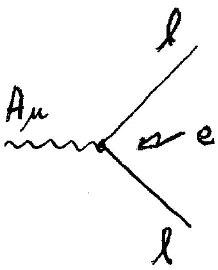
$$R = 1/2\ (1 - \gamma_5)\ \psi_\ell .$$

The hypercharge is

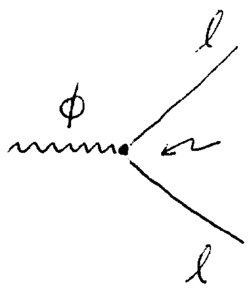
$$Y = N_R + 1/2\ N_L .$$

The resulting Lagrangian is very complicated and is not the kind of thing one would write down as a random guess. However, the starting theory, with massless Yang-Mills fields, is known to be renormalizable. The shifting procedure for the scalar fields amounts to a rearrangement of the perturbation series. Although it is not obvious that renormalizability is preserved in the shift, recent studies by 't Hooft[2] and B. Lee[3] suggest that in fact it might well be preserved.

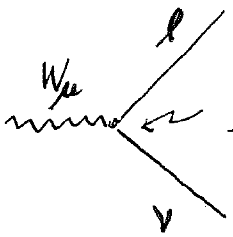
In its final shifted form the Weinberg model involves leptons, charged vector bosons ($W_\mu$), neutral vector bosons ($Z_\mu$), photons ($A_\mu$), and massive neutral scalar bosons ($\phi$). For our present purposes it will be enough to display only the terms which couple the leptons to the vector and scalar fields:



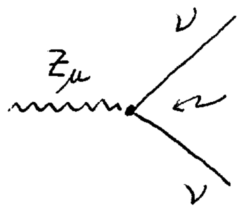

$$e\gamma_\mu$$



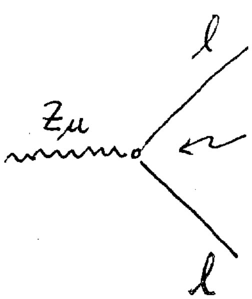

$$-m_\ell/\lambda$$




$$\frac{g}{\sqrt{2}}\,\gamma_\mu\left(\frac{1+\gamma_5}{2}\right)$$




$$\sqrt{g^2+g'^2}\,\gamma_\mu\left(\frac{1+\gamma_5}{2}\right)$$




$$\frac{1}{\sqrt{g^2+g'^2}}\,\gamma_\mu\left[g'^2\left(\frac{1-\gamma_5}{2}\right)+\frac{1}{2}\left(g'^2-g^2\right)\left(\frac{1+\gamma_5}{2}\right)\right]$$

Here

$$e = \frac{gg'}{\sqrt{g^2 + g'^2}} , \quad \frac{G}{\sqrt{2}} = \frac{1}{2\lambda^2}$$

and the vector boson masses (to zeroeth order in the fine structure constant) are

$$m_W = \frac{\lambda g}{2} , \quad m_Z = \lambda \frac{\sqrt{g^2 + g'^2}}{2} .$$

The mass of the scalar boson is unspecified. With

$$g = e/\sin\theta , \qquad g' = e/\cos\theta ,$$

we may write

$$\frac{G}{\sqrt{2}} = \frac{e^2}{8m_W^2 \sin^2\theta} = \frac{e^2}{8m_Z^2 \sin^2\theta \cos^2\theta} .$$

One easily sees that

$$m_W \gtrsim 37 \text{ GeV}, \quad m_Z \gtrsim 75 \text{ GeV} !$$

For the leptonic reactions $\nu_e(\bar{\nu}_e) + e \rightarrow \nu_e(\bar{\nu}_e) + e$, the effective Lagrangian is

$$\text{Leff} = \frac{G}{\sqrt{2}} \left[\bar{\psi}_\nu \gamma_\mu (1+\gamma_5) \psi_\nu\right] \left[\bar{\psi}_e \gamma_\mu (C_V + C_A \gamma_5) \psi_e\right]$$

with

$$C_V = 1/2 + 2 \sin^2\theta$$
$$C_A = 1/2 \ ,$$

In the standard Feynman-Gell-Mann theory one has $C_V = C_A = 1$. H.H. Chen and B.W. Lee[5] have considered the Reines-Gurr[6] experiment on $\bar{\nu}_e + e$ scattering. When the latter is analyzed on the basis of the standard theory, one finds[6]

$$\frac{\sigma_{exp}}{\sigma_{F-G}} = 1.1 \pm 1.2 \ .$$

Analyzed in accordance with the structure implied by the Weinberg theory, the experiment provides a bound

$$\sin^2\theta \lesssim 0.325,$$

hence $m_W > 65$ GeV. The smallest possible cross section on the present model is one-fourth that of the Feynman-Gell-Mann theory. An order of magnitude reduction of the experimental bound would rule out the Weinberg theory--and long before that, the F-G theory.

In contrast to the F-G theory, Weinberg's model allows for the reaction $e + \nu_\mu(\bar{\nu}_\mu) \rightarrow e + \nu_\mu(\bar{\nu}_\mu)$ in lowest order. The effective Lagrangian here is

$$\text{Leff} = -\frac{G}{\sqrt{2}}\left[\bar{\psi}_{\nu_\mu}\gamma_\lambda(+\gamma_5)\psi_{\nu_\mu}\right]\left[\bar{\psi}_e\gamma_\lambda(C'_V + C'_A\gamma_5)\psi_e\right],$$

where

$$C'_V = 1/2 - 2\sin^2\theta$$

$$C'_A = 1/2 .$$

Recall that Steiner,[7] some time ago, had analyzed the CERN neutrino data in order to obtain an upper bound on the reaction $\nu_e + e \rightarrow \nu_e + e$, taking advantage of the fact that the beam contains some admixture of electron type neutrinos, in addition to the predominant muon type neutrinos. Albright[8] later observed that the same data can be used to set a bound on the $\nu_\mu + e \rightarrow \nu_\mu + e$ reaction, similarly not observed in the CERN experiment. He carried out the analysis on the basis of an effective $C'_V = C'_A$ structure and found

$$\sigma_{\exp}(\nu_\mu + e \rightarrow \nu_\mu + e) \lesssim 0.4 \quad \sigma_{F\text{-}G}(\nu_e + e \rightarrow \nu_e + e).$$

Chen and Lee[5] have recently updated the analysis. They find that, for any value of $\sin^2\theta$, the cross section expected on the Weinberg model is somewhat less than the experimental bound.

As it now stands, fairly modest improvements in the experiments on $\nu_e$-e and $\nu_\mu$-e scattering will serve to provide decisive tests of the Weinberg model. In the meantime theoretical tests of renormalizability, the original motivation for the model, are underway. For example, Weinberg[4] has studied the process $\nu + \bar{\nu} \rightarrow W^+ + W^-$. In conventional theories (to first order) the amplitude for production of zero helicity bosons is dominated by a pure J=1 term at large energy. The amplitude grows linearly with energy as $E \rightarrow \infty$ and it comes eventually into conflict with unitarity, so that higher order effects, or ad hoc "unitarity" cutoffs are required. On the present model the situation is saved by a contribution coming from exchange of the neutral vector boson, and for $E >> m_W$ the amplitude in fact falls like $E^{-1}$. A more severe, and more complicated test bearing on the performance of loop diagrams has to do with the reaction $\nu + \nu \rightarrow \nu + \nu$. In conventional theories, exchange of a pair of W bosons generates an uncompensated quadratic divergence, related to the unitarity failure for $\nu + \bar{\nu} \rightarrow W^+ + W^-$. In the present theory, there are many additional diagrams and it seems that the quadratic divergences all cancel out. What happens to the logrithmic divergences is not yet clear.

And so on! The outlook at present is hopeful, at least for the leptonic interactions. The situation is more problematic for the semileptonic and nonleptonic weak interactions. Whichever way the

the ideas develop, it is likely that one will be led to substantial neutral current effects. For the nonleptonic interactions, as already discussed, decisive tests will be hard to come by. Nevertheless, appropriate couplings between neutral hadron currents could be useful to provide a theoretical basis for the $\Delta I = 1/2$ rule. This, it seems to me, is a reasonable guide for model building. On the other hand, for the semileptonic reactions, interactions between neutral hadron and lepton currents <u>are</u> something one could directly recognize experimentally and these effects may well play a decisive role.

At the present time, evidence on neutral current effects is entirely negative. Thus, in high energy neutrino experiments at CERN[9] one has obtained the bounds implied by

$$\frac{\sigma(\nu_\mu + p \to \nu_\mu + p)}{\sigma(\nu_\mu + n \to \mu^- + p)} = 0.12 \pm .06 ,$$

$$\frac{\sigma(\nu_\mu + p \to \nu_\mu + \pi^+ + n)}{\sigma(\nu_\mu + p \to \mu^- + p + \pi^+)} = 0.08 \pm 0.04 .$$

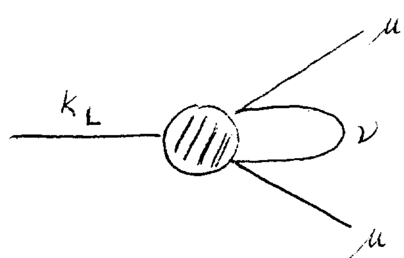
Even in the conventional F-G model, recall, one expects effects which simulate neutral current couplings in such $\Delta S = 0$ processes, arising from the first order weak coupling of neutrinos to virtual photons. The corresponding contributions to the above cross section ratios are formally of order $\alpha^2$, hence negligible--though in fact the integrals diverge. For strangeness changing decay processes, the bounds on neutral current effects are far more restrictive and will no doubt pose serious difficulties for Weinberg-type models. Thus one has the experimental bound[10]

$$\frac{\Gamma(K^+ \to \pi^+ + \nu + \nu)}{\Gamma(K^+)} \lesssim 1.2 \times 10^{-6} .$$

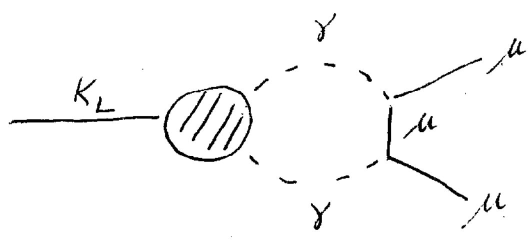
And then there's the famous $K_L \to \mu^+ + \mu^-$ puzzle.

II

This brings us to our next topic. The process $K_L \to \mu^+ + \mu^-$ is especially well suited experimentally to the search for neutral current effects, or other exotic phenomena, e.g., higher order weak effects:



Where charged lepton pairs are involved, as here, there is however always the limitation that contributions can also arise from more conventional and therefore less interesting electromagnetic mechanisms. In this case:




The reaction $K_L \to 2\gamma$ is first order weak and is part of conventional phenomenology; and the conversion of two (real or virtual) photons into a muon pair is part of standard quantum electrodynamics. Although the rate for $K_L \to 2\gamma$ decay is well enough known experimentally, the $K_L \to 2\mu$ rate cannot be calculated exactly on this mechanism, since this would require knowledge of the amplitude for $K_L$ going into a pair of virtual photons. But roughly speaking, we expect that

$$\frac{\Gamma(K_L \to 2\mu)}{\Gamma(K_L \to 2\gamma)} \approx \left(\frac{1}{137}\right)^2 ,$$

hence

$$\frac{\Gamma(K_L \to 2\mu)}{\Gamma(K_L)} \approx 2 \times 10^{-8} .$$

This is a very tiny branching ratio for the conventional mechanism and leaves ample scope, it seems, for contributions from the more exotic mechanisms of primary interest. However, as everyone knows, the experimentalists have looked earnestly for $K_L \to 2\mu$ events and have not found any; and the Berkeley group has established an upper bound given by[11]

$$\left.\frac{\Gamma(K_L \to 2\mu)}{\Gamma(K_L)}\right|_{\mathrm{exp}} \lesssim 1.8 \times 10^{-9}.$$

This is one order of magnitude below expectation and a great embarass-ment for the theorists. Of course the latter have often been wrong before in their crude estimates. More serious is the fact that they had a fairly convincing argument, based on unitarity considerations, for setting a <u>lower bound</u> on the $K_L \to 2\mu$ rate, a bound given by[12]

$$\left.\frac{\Gamma(K_L \to 2\mu)}{\Gamma(K_L)}\right|_{\substack{\text{naive}\\ \text{unitarity}}} \gtrsim 6 \times 10^{-9},$$

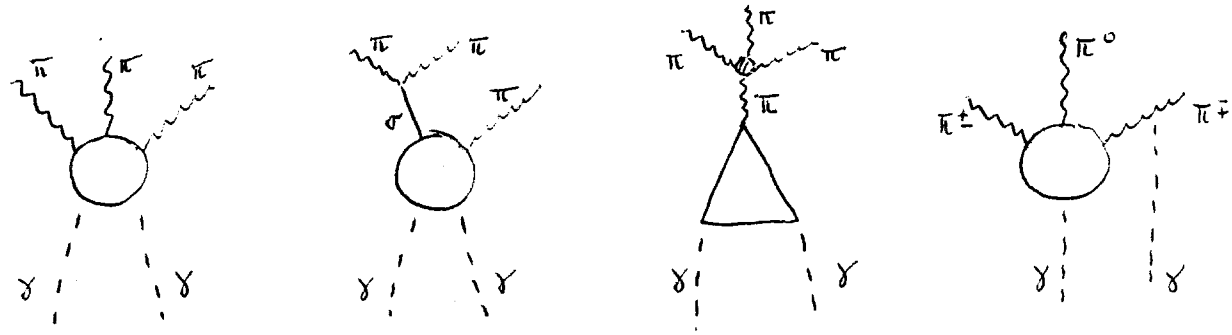
a result three times bigger than the experimental upper bound. The naive unitarity estimate is based on the seemingly reasonable assump-tion that CP violating effects can be ignored for neutral K meson phenomena (everywhere else we've met them these effects have certainly been small). In addition, in the unitarity equation for the absorptive $K_L \to 2\mu$ amplitude it is supposed that only the intermediate $2\gamma$ state contributions need be considered and moreover that the $K_L \to 2\gamma$ amplitude has no absorptive part. What one is ignoring are contributions to the absorptive $K_L \to 2\mu$ amplitude coming from the intermediate states

$2\pi\gamma$ and $3\pi$, and contributions to the absorptive $K_L \to 2\gamma$ amplitude coming from the $3\pi$ intermediate states. It can be reliably shown that neglect of the $2\pi\gamma$ state is well justified on the present scale of interest.[13]

On the other hand the 3 $\pi$ state contributions have been more problematic.[14] No experimental information is available on the needed amplitudes for $3\pi \to 2\mu$ and $3\pi \to 2\gamma$, and as for theory, the problem is a complicated one.

On the basis of rough phase space and essentially dimensional arguments most people who have contemplated the situation have come to the conclusion that the $3\pi$ contributions are indeed negligible, by as much as a couple of orders of magnitude. Recently, more detailed estimates have been made as a byproduct of investigations into the application of soft pion methods for the processes $3\pi \to 2\gamma$.[15] The issues that arise here--PCAC, current algebra, Ward identity anomalies--are quite interesting in their own right and could legitimately be taken up in a talk on the weak interactions. However, let me present the conclusions only in outline. Solely from standard PCAC and current algebra considerations, and in a way which is otherwise model independent, one claims to be able to compute the $3\pi \to 2\gamma$ amplitudes exactly to second order in pion momenta, for real or virtual photons.[16] The final expressions contain three parameters, of which two are well enough known numerically. These latter are the PCAC constant f that describes $\pi \to \mu\nu$ decay, and the parameter $F_\pi$ which describes $\pi^0 \to 2\gamma$ decay and which absorbs the Adler anomaly effects. A third parameter, call it $\chi$, measures the isotensor component of the "$\sigma$ term" in the current algebra analysis of $\pi$-$\pi$ scattering. This latter parameter is often taken to be equal to zero.

Although, as said, the final results are supposed to be model independent apart from the assumed validity of PCAC and of standard current algebra, it helps with visualization to adopt a specific soft pion model. In the $\sigma$ model the relevant diagrams are as follows:




The $\pi$-$\pi$ scattering amplitude enters in the third diagram; the Adler anomaly, absorbed in the parameter $F_\pi$, appears in the third and fourth diagrams.

There is no value in displaying here the lengthy expressions for the $3\pi \rightarrow 2\gamma$ amplitudes. It will be enough to say, on the basis of these soft pion results, that the $3\pi$ state contributions do nothing to resolve the $K_L \rightarrow 2\mu$ puzzle--the contributions are too small by a factor of $10^{-4}$!! Two qualifications ought to be noted. For one thing the pions that figure in the $K_L \rightarrow 2\mu$ puzzle are not, all three, so very soft. After all, $(q_1 + q_2 + q_3)^2$ = (kaon mass)$^2$, and the kaon mass is not really small on a hadronic scale. So the soft pion methods, even if right, are being pushed here. A second and more technical point is this. The soft pion expressions display no damping as the virtual photons go off mass shell. Correspondingly the $3\pi \rightarrow 2\mu$ amplitude, which involves a loop integration, is logarithmically divergent. In the numerical estimate cited above a "reasonable" cutoff was supplied. Despite these qualifications, however, it is hard to believe that the final estimates can be off by a factor of ten thousand.

So far we have ignored CP violating effects. There are two kinds of effects to be considered. For one thing, the state $K_L$ is known to have a small CP impurity, parameterized by the complex quantity $\epsilon$ in

$$K_L \simeq K_2 + \epsilon K_1$$

Here $K_2$ is CP odd, $K_1$ is CP even, and $|\epsilon| \sim 2 \times 10^{-3}$. In addition, allowance must now be made for the possibility that the states $K_2$ and $K_1$ can violate CP invariance in their decays, in particular in decay to the $2\mu$ and $2\gamma$ channels. Christ and Lee[17] have parameterized the general case, using CPT invariance and ignoring all but the $2\gamma$ intermediate states (of both CP parities, however) for the absorptive $K_L \rightarrow 2\mu$ amplitude. The $K_L \rightarrow 2\mu$ puzzle, it is then seen, can be resolved if for some reason or other the $K_1 \rightarrow 2\mu$ amplitude is very large, so large that even when multiplied by $\epsilon$ it is still big enough to compare with and partly cancel against the $K_2 \rightarrow 2\mu$ amplitude. Since

$$K_S \simeq K_1 + \epsilon K_2$$

this implies a large rate for $K_S \to 2\mu$. In short, the puzzle of the anomalously small $K_L \to 2\mu$ rate is to be resolved by an anomalously large $K_S \to 2\mu$ rate. The detailed analysis predicts that

$$\frac{\Gamma(K_S \to 2\mu)}{\Gamma(K_S)} > 5 \times 10^{-7},$$

a ratio which is larger than what one would have expected by a factor of $10^2 - 10^3$. It is important to observe that if the puzzle is resolved along these lines one could conclude that CP violation must occur in the decays of one or both of the states $K_2$ and $K_1$; i.e., among other interesting conclusions, one could rule out the super weak theory of CP violation. The Christ-Lee analysis doesn't in itself suggest <u>why</u> the $K_1 \to 2\mu$ amplitude should be so large. One possibility, suggested by Wolfenstein,[18] is a direct, CP violating coupling of a neutral, axial vector lepton current and a neutral, strangeness changing hadronic current. This produces a coupling of $K_1$ to a lepton pair in the $^1S_0$ state but does not contribute to $K_2 \to 2\mu$ decay. In any case, the important thing for the moment is to look for the process $K_S \to 2\mu$. Several experiments are now under way. It would also be interesting to look for anomalies in other processes, such as $K_L \to \ell^+ + \ell^- + \gamma$ decay, where the normal mechanism is as described by Dalitz,

$K_L \rightarrow \gamma + \gamma \rightarrow \gamma + \ell^+ + \ell^-$.

III

The subject of deep inelastic lepton-hadron scattering will no doubt form part of Bjorken's talk this afternoon; and I hope also that it will be debated by our distinguished panel. By now the subject has been reviewed so many times that speakers and audiences alike have surely had their fill of the general experimental and theoretical lore. Nevertheless, Bjorken and I agreed that, in order to expedite the later discussions, maybe another brief outline of the issues might be in order here.[19] After all, one component of the subject has to do with the weak interaction processes

$$\nu(\bar{\nu}) + N \rightarrow \mu^{-} (\mu^{+}) + \text{hadrons},$$

which are the weak analog of the electromagnetic processes

$$e + N \rightarrow e + \text{hadrons}.$$

On the conventional picture, the neutrino processes probe hadronic physics via weak, vector and axial vector currents, in the same way that the electron processes probe hadron structure via the electromagnetic current. But it must be remembered for the neutrino processes that purely weak interaction issues are also at stake. Do the leptons $\nu$ and $\mu$ effectively couple locally to the hadrons, as our formulas usually assume, or through intermediate bosons, or are there non-local components in the lepton coupling--such as might arise from higher order weak effects? Do new kinds of leptons get produced at high energies? For example, a heavy neutral lepton $\nu^*$ which, decaying into a $\mu$ meson and one or more hadrons, fools us as to the origin of the observed muon.

On the direct current-current picture, and with neglect of the muon mass, the differential cross section has a structure given by

$$\frac{\partial\sigma^{(\nu,\overline{\nu})}}{\partial q^2 \partial\nu} = \frac{G^2}{2\pi} \cdot \frac{1}{4\epsilon^2}$$

$$\times \left\{ 2 W_1^{(\nu,\overline{\nu})} q^2 + W_2^{(\nu,\overline{\nu})} \left[4\epsilon^2 - 4\epsilon\nu - q^2\right] \mp W_3^{(\nu,\overline{\nu})} q^2 \left(\frac{2\epsilon - \nu}{M}\right)\right\}$$

where the $W_i$ depend only on the two variables $q^2 = (q_\nu - q_\mu)^2$ and $\nu = -q\cdot p/m$. Here

$$W_{\nu\mu} = \frac{1}{2\pi}\int dx\, e^{-iq\cdot x} <p \mid \left[j_\nu^\dagger(x), j_\mu(0)\right] \mid p> = W_1\left(\delta_{\nu\mu} - \frac{q_\nu q_\mu}{q^2}\right)$$

$$+ \frac{W_2}{m^2}\left(p_\nu - \frac{q\cdot p}{q^2} q_\nu\right)\left(p_\mu - \frac{q\cdot p}{q^2} q_\mu\right) + 1/2 \frac{W_3}{m^2} \epsilon_{\nu\mu\alpha\beta} p_\alpha q_\beta$$

+ terms proportional to $q_\nu$ or $q_\mu$.

If the current-current interaction is mediated by vector bosons of mass M, the formula should be modified by a factor

$$\left(\frac{M^2}{M^2+q^2}\right)^2 .$$

Whether or not this factor intervenes, the assumed locality of the lepton couplings implies that $\epsilon^2\ \partial\sigma/\partial q^2\ \partial\nu$ is a second order polynomial in neutrino energy $\epsilon$ for fixed $q^2$ and $\nu$. In itself this already constitutes an important (but difficult) test of our ideas. A departure from this behavior could arise from various sources. One possibility is direct production of a new kind of lepton, which decays into the observed muon plus hadrons.

For the time being a dominant interest for the neutrino reactions is the question of Bjorken scaling; namely, the conjecture that

$$F_1 = mW_1,\ F_2 = \nu W_2,\ F_3 = \nu W_3$$

all approach nontrivial limits as $q^2$ and $\nu \to \infty$, for fixed $\omega = q^2/2m\nu$. For electroproduction scaling seems to be well supported by the data, moreover with

$$2\omega\ F_1^{em}(\omega) \simeq F_2^{em}(\omega),$$

i.e., $\sigma_{scalar} \simeq 0$. For neutrino processes the situation is much less clear experimentally. But among other things, scaling implies that the total cross section should grow linearly with energy at large energies.

The propane data, for the energy range 2-14 GeV, seem indeed to support this, with

$$\sigma/\text{nucleon} = (0.52 \pm 0.13)\ \frac{G^2 m\epsilon}{\pi}$$

It should be mentioned that this linear growth requires the assumption of direct current-current coupling, without intermediate vector boson exchange. In principle one could turn this around to set limits on the vector boson mass, but the neutrino energies in existing accelerator experiments are not yet high enough to accomplish anything interesting in this direction.

The main experimental question is whether we are already seeing true asymptotic scaling or whether the effect seen is an accidental approximation to it that will go away at higher momentum transfers. Theoretically it's hard enough to understand scaling as a mathematical statement for the limit $q^2 \to \infty$ ($\omega$ fixed). It's more puzzling still why asymptotia should set in so early (beyond a few $(\text{GeV})^2$).

A number of different approaches have been pursued, of which the least promising is renormalizable field theory treated perturbatively. It simply doesn't scale. Among other approaches certain ones involve ad hoc assumptions which take a simple form only in the so-called infinite momentum frame (with $\vec{q}$ along the Z-axis, $p_Z \to \infty$); so the assumptions cannot easily be formulated in an invariant way. The field theoretic model of Drell, Levy, and Yan,[20] with its ad hoc transverse momentum cutoff is of this character. So too is the physically intuitive and appealing (but maybe false) parton model of Feynman.[21] A new and very different kind of approach has been discussed recently by Drell and Lee.[22] The central idea here is to regard physical hadrons as bound states. I very much hope that Professor Lee will enlarge on this idea in our later discussions.

There is yet another approach, by way of the light cone, which is generally accepted as correct up to a certain point but which again develops an ad hoc character when one tries to go beyond that point. The acceptable part is this. Consider the formula which relates $W_{\nu\mu}$ to a Fourier transform of the matrix element of a current commutator. In the target rest frame, where $q_0 = \nu$, let $\vec{q}$ point along the 3-axis. Observe that in the scaling limit, $q_0 \to \infty$, $\omega$ fixed, we have

$$q_3 \to q_0 + m\omega .$$

The exponential factor damps all contributions to the integral except from those in the region

$$|x_0 + x_3| \lesssim \frac{1}{m\omega}, \quad |x_0 - x_3| \lesssim \frac{1}{2q_0} .$$

Since the commutator vanishes outside the light cone, the main contributions therefore come from the region

$$x^2 \simeq \frac{1}{q^2} \to 0,$$

i.e., the structure of $W_{\nu\mu}$ for $q^2 \to \infty$, $\omega$ fixed, is determined by the leading singularities of the current commutator on the light cone $x^2 = 0$. Leaving aside why scaling sets in so early (in $q^2$) --if it does-- in the scaling limit one is probing the light cone structure of current commutators. And the fact of scaling--if it's a fact--suggests that this structure is simple and therefore a worthy object of attention. Whatever the underlying reason for it, scaling implies that the leading light cone singularities are the same as those in a free field theory--another way of stating the point-like character of partons.

For a beginning, Fritzch and Gell-Mann had the idea to conjecture precisely the free field results for the light cone commutator, in order to fix not only the singularity structure but also the tensor and $SU_3$ structure.[23] Concerning the latter two issues, one has to specify in detail how the currents are constructed out of canonical fields; and for this they naturally adopted the quark model. For the rest one then recovers all the standard results of the "partons are quarks" parton model, as well as the more deeply rooted results, such as the Adler sum rule, that already follow from the equal time current algebra (taken together with a certain "no-subtraction" dispersion assumption). Let me list some of the results, always neglecting, for simplicity, $\Delta S \neq 0$ transitions.

(1) The Adler sum rule, valid for any $q^2$:

$$\int d\nu \left\{ W_2^{(\bar{\nu}p)}(\nu, q^2) - W_2^{(\nu p)}(\nu, q^2) \right\} = 2 .$$

In the scaling limit:

(ii) $$2\omega\, F_1 = F_2$$

(iii) $$-\int d\omega \left\{ F_3^{(\nu p)} + F_3^{(\nu n)} \right\} = 6$$

(iv) $$12 \left( F_1^{(\gamma p)} - F_1^{(\gamma n)} \right) = F_3^{(\nu p)} - F_3^{(\nu n)}$$

and the inequalities, among others,

$$F_1^{(\gamma p)} + F_1^{(\gamma n)} \geq 5/18 \left( F_1^{(\nu p)} + F_1^{(\nu n)} \right)$$

and, notably,

$$1/4 \leq F_1^{(\gamma n)} / F_1^{(\gamma p)} \lesssim 4.$$

It must be emphasized that (ii) follows from the assumed spin 1/2 character of the partons (in the free field light cone language, from the spin 1/2 character of the elementary fields that go into the makeup of the currents). Other results depend additionally on the charges and other quantum numbers of the partons. If experiment were to require it, one could probably accommodate to troubles here by abandoning the quark model. I mention this because a possible trouble may be brewing for the ratio $F_1^{(\gamma n)}/F_1^{(\gamma p)}$. For $\omega \rightarrow 0$ the ratio seems to approach unity, as expected from a diffraction picture; but for $\omega \rightarrow 1$ the ratio seems experimentally headed for values that might well fall below one-fourth.[24] Some people are anyhow uncomfortable about the idea of identifying partons with quarks, on the intuitive ground that scaling oughtn't to set in at energies below the threshold for production of real physical quarks (they are presumably not being produced at SLAC). I leave this thorny question to others and return to the light cone.

It's no great triumph to recover scaling and other features of the parton model with a light cone approach based on a free field theory. When it somes to switching on strong interactions, as in the quark-gluon model, those ad hoc elements again reappear. Thus, it has been shown that the free field structure does survive, but only if one operates formally with the canonical equal time commutators and equations of motion.[25] Without the artificial and unitarity-destroying introduction of cutoffs, these formal manipulations cannot be justified. The virtue of the parton approach, and its free field light cone counterpart, is that one is led to nice conjectures to be worked with--let the justifications come later, preferably from experiment!

In this connection let me conclude by briefly reporting some recent results on inclusive electron-pair annihilation obtained by Callan and Gross on the basis of light cone arguments.[26] Consider the inclusive process

$$e^+ + e^- \rightarrow h + X,$$

where h is the detected hadron, of momentum p. Let q be the virtual photon momentum, so that $s = -q^2$; let $\nu = -q\cdot p/m$, and let $\theta$ be the angle between the hadron momentum and the collision axis, in the center of mass frame. In computing the inclusive cross section one encounters the tensor

$$W_{\nu\mu} = (2\pi)^3 \sum_X \langle 0 | j_\nu^{em} | X, h \rangle \langle X, h | j_\mu^{em} | 0 \rangle \, \delta\left(q - p - p_X\right)$$

$$= \overline{W}_1 \left(\delta_{\nu\mu} - \frac{q_\nu q_\mu}{q^2}\right) + \frac{\overline{W}_2}{m^2} \left(p_\nu - \frac{q\cdot p}{q^2}\, q_\nu\right)\left(p_\mu - \frac{q\cdot p}{q^2}\, q_\mu\right),$$

where $\overline{W}_{1,2}$ depend on $q^2$ and $\nu$. Better yet, define

$$\overline{F}_1 = m\, \overline{W}_1,$$

$$\overline{F}_L = \overline{F}_1 - \frac{1}{2\omega}\, \nu\, \overline{W}_2$$

and regard the structure functions as functions of $q^2$ and

$$\omega = -q^2/2m\nu.$$

For $s = -q^2$ large, $\omega$ fixed $(1 < \omega < \sqrt{s}/2m)$ the differential cross section is

$$\frac{\partial\sigma}{\partial\omega\,\partial\Omega} = \frac{\alpha^2}{2s}\,\frac{1}{\omega^3}\left\{\bar{F}_1(\omega, q^2)(1+\cos^2\theta) + \bar{F}_L(\omega, q^2)\sin^2\theta\right\}.$$

Adopting the free field quark model for current commutators, Callan and Gross first of all demonstrate scaling and transversality

$$q^2 \to \infty,\ \omega \text{ fixed:}\quad \begin{array}{l} \bar{F}_1(\omega, q^2) \to \bar{F}_1(\omega) \\ \bar{F}_L \to 0 \end{array}$$

Next they consider mean multiplicity n (s) as a function of s for large s. Accepting that the total cross section falls like $s^{-1}$, one has

$$n(s) \underset{s\to\infty}{=} \text{constant} \times \int_1^{\sqrt{s}/2m} \frac{d\omega}{\omega^3}\left[2\bar{F}_1(\omega, q^2) + \bar{F}_L(\omega, q^2)\right]$$

$$\sim \int_1^{\sqrt{s}/2m} \frac{d\omega}{\omega^3}\,\bar{F}_1(\omega)$$

The light cone argument suggests (if it is to be consistent) that $\bar{F}_1(\omega) \to 0$, $\omega \to \infty$, hence that n(s) approaches a constant for large s, contrary to the logarithmic growth with energy that one expects from "experience" with strong interaction phenomena.

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