SLAC-PUB--2837

DE82 005272

COMPARISON OF WEAK INTERACTION THEORY WITH EXPERIMENT*

Stanley G. Wojcicki
Physics Department and
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

TABLE OF CONTENTS

1. INTRODUCTION

It is the purpose of this review to see how well the existing experimental data agree with the standard weak interaction theory. A literal interpretation of this task would be clearly beyond the intended scope of this work; accordingly some decisions need to be made as to the material to be included. In making these choices, my guiding principle has been to discuss only those data which test the heart of the standard model without having to rely too much on various peripheral assumptions. In this spirit I tend to exclude, for example, the various predictions about the purely hadronic weak decays, since the expected accuracy of these predictions can be understood only in the framework of rather involved QCD calculations.[1] The agreement, or lack thereof, between the data and the predictions,

Invited talk presented at the Annual Meeting Of The Division Of The Particle And Fields of the APS, Santa Cruz, CA, September 9 - 11, 1981.

* Work supported by the Department of Energy, contract DE-AC03-76SF00515, and the National Science Foundation.

represent in this case more a test of the calculational techniques than of fundamental weak interaction theory. In the same spirit I tend to ignore various nuclear physics experiments whose interpretation is obscured by the uncertainties having to do with the nuclear matrix element calculations.

The main body of this review shall concentrate on what I consider the three cornerstones of today's standard model: charged current phenomenology as related to the V-A theory,[2] neutral current phenomenology in the framework of the Glashow-Weinberg-Salam model,[3] and the comparison of the charm picture with the Glashow-Iliopoulos-Maiani model.[4] In addition, I shall briefly discuss the extension of the old 4-quark picture to the Kobayashi-Maskawa 6 quark model[5] and summarize very briefly the present experimental and theoretical status of the CP violation. This program will clearly leave out some aspects of theoretical and experimental work that are at the forefront of testing and defining the standard model; neutrino masses and oscillations, and the axion hunts are two examples that come readily to mind. The main justification for this omission is their extensive coverage in parallel lectures. For the same reason, I shall not go beyond the standard model into the realm of SU(5), SO(10), and beyond.

To the extent possible, I would like to take a pedogogical and historical approach to this review. What I mean here, is that I will try to indicate as much as possible what specific aspect of the standard model is tested by a given experiment and where does this prediction come from. In addition, I will try to a certain extent to follow the historical development of the main ideas. The development of physics does not, however, always take a logical course - some of the recent work attacks similar questions that were originally confronted by experiments 20 years ago but in a different subfield. $\Delta\tau$ and μ decay comparison is one good example of such a situation. In these cases, I shall violate the history in the interest of a more rational logical structure.

To conclude these introductory remarks, I should acknowledge several recent excellent reviews, more limited in subject matter

covered then the present one, that have made my job considerably easier. I should mention especially the work of F. Scheck on muon physics,[6] J. J. Sakurai's on The Structure of Charged Currents[7] and the review of Weak Neutral Current by J. E. Kim, P. Langacker, M. Levine, and H. H. Williams.[8] As is apparent in what follows, I have drawn heavily on the material presented in those papers.

2. THE STATUS OF CHARGED CURRENTS

The charged current reactions played the same role in helping to formulate the weak interaction theory in the late 1950's that the neutral currents have enjoyed some 20 years later. After the "dark ages" of early and middle fifties characterized by confusion due to several contradictory experiments, came the Renaissance of the late fifties. It was characterized not only by brilliant theoretical insights as exemplified by prediction of parity non-conservation[9] and formulation of the V-A theory[2] but also by a variety of crucial and frequently ingenious experiments. Lack of space does not allow me to describe this fascinating chapter in the history of weak interaction physics; I shall limit myself to summarizing the main conclusions, showing what results they are based on, and discussing briefly how well these conclusions have withstood the twin tests of time and higher energies.

As will be seen in a moment some of the most precise experiments in this field have been performed over a decade ago. Since that time there have occurred great improvements in technology, and thus one can think today of improving the accuracy of some of these results by quite a good margin. Because of new theoretical interest there are current plans to redo some of these older classical experiments with a much improved precision; considerably higher accuracy can thus be expected in the near future.[10]

I would like to start this chapter on charged currents by summarizing some of the qualitative features of the standard picture that emerge from these experiments. These features are:

a) V-A nature of the interaction

b) short range of weak interactions (consistent with locality)

i.e. an intermediate vector boson that is heavy on the mass scale of the experiments in question.

c) 3 lepton families with similar structure

d) lepton conservation law

e) "universality" between μ weak interaction processes and nucleon β decays. The exact meaning of universality will be developed as we go on.

2.1 Leptonic Reactions

Next I would like to turn to specific experiments. The simplest, from the theoretical point of view, are pure leptonic reactions, as they do not involve any complications due to hadronic structure. Historically, muon decay was the sole laboratory for pure charged current study that fell into this category; today the list is expanded to 4 different processes, i.e.

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

(plus the charge conjugate reactions of the first 3 decays). It is still the muon decay, however, that provides the most precise experimental input and I shall start by reviewing the information available on this process.

The muon decay in the conventional picture is described by the Feynman diagram of Fig. 1. Because of the low values of 4-momentum transfer involved in comparison with the expected W mass, this picture is however indestinguishable experimentally from a simple V-A 4 point interaction. If we integrate over all directions, the electron spectrum is described by two parameters, conventionally called ρ and η. The ρ and η parameters, as well as ξ and δ discussed below, can be expressed in terms of scalar, pseudoscalar, vector, axial

Fig. 1. μ decay diagram

The other measureable set of parameters has to do with the polarization of the electron emitted in the muon decay. More specifically one can measure both the longitudinal polarization as well as the two components of the transverse polarization, one of which is forbidden by time reversal invariance. The values of these 3 polarization components as of the time of the 1979 Vancouver Conference are summarized in Table II.

Table II

Electron polarization: experiment vs. theory

Component	Exp. value	V-A Prediction	Reference
Longitudinal - P_ℓ	-1.00 ± 0.13	-1	World Avg. (1979)
	-0.94 ± 0.08		15
Transverse(T cons)P_{T_1}	β/A=-.004±.033	0	15
Transverse(T viol)P_{T_2}	β'/A=-.003±.033	0	15

Few words of explanation are needed regarding the transverse polarization components. The theoretical values of these components can be expressed in terms of α, α', β, β', A and ξ parameters (α, α', β, β' and A just like ξ, are functions of the different coupling constants) and are functions of both electron energy and angle of emission of electron with respect to muon spin direction. Thus it is more meaningful to fit these polarization data in terms of the above parameters rather than quote the absolute value of the polarization. The values quoted represent fits under the assumption of total cancellation of scalar and pseudoscalar coupling ($\alpha = \alpha' = 0$). The maximum possible value that β/A (and β'/A) can take is 0.25.

We can now write a phenomenological current responsible for the $\bar{e}\nu$ part of the charge retention Hamiltonian of μ decay as V-(1+ ϵ)A, and ask what are the experimental limits on ϵ. I would like to emphasize that since we are using the charge retention formalism, this question is not equivalent to the problem of possible existence of a heavy intermediate vector boson with right handed couplings. The limits set on ϵ by values[16] of η, ξP_μ, and P_T^ϕ are displayed in

vector, and tensor coupling coefficients that occur in muon decay Hamiltonian (see Ref. 4 for explicit formulas). Thus they measure directly the form of interaction responsible for the decay. The spectrum is quite sensitive to the value of ρ as can be seen from Fig. 2a; on the other hand the spectrum term involving η is multiplied by m_e/m_μ and thus the spectrum is affected very little as one varies η over its full allowed range from -1 to +1 (see Fig. 2b). Only at very low electron energies, is there any sensitivity to the value of η.

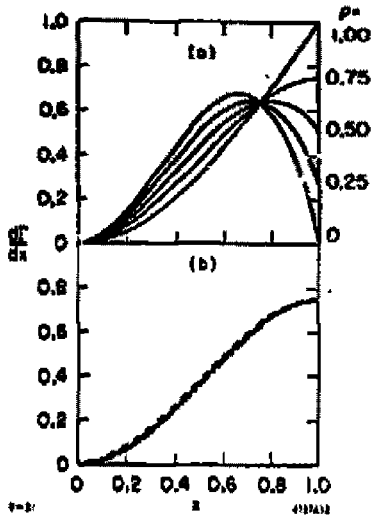

Fig. 2. Dependance of the electron spectrum on the value of ρ (a) and η (b). The solid curve in (b) corresponds to η=0; the outside 2 curves to η=1 and η=-1.

To take into account the correlation between muon spin direction and the electron momentum vector, 2 more parameters are required, ξ and δ. The former is related to the magnitude of the forward backward asymmetry; the latter parametrizes the difference in momentum spectrum of the electrons emitted at different angles. The most recent published values of these parameters are listed in Table I together with the V-A prediction. Since experimentally one always measures $\xi \times P_\mu$, I list the product of these 2 quantities in the Table.

Table I

Parameter	Exp. value	V-A Prediction	Reference
Shape - ρ	0.752 ± .003	0.750	11
Low energy shape - η	-0.12 ± 0.21	0	12
Shape difference - δ	0.755 ± .009	0.750	13
Asymmetry x P_μ - ξP_μ	0.972 ± .013	1	14

Fig. 3. One should emphasize that P_T^e and η measure intrinsically similar things (both can be expressed in terms of α and β), but P_T^e is free of the m_e/m_μ suppression factor discussed above.

The structure of the $\bar{\nu}_\mu \nu_e$ part of the same Hamiltonian can be tested[17] by measuring the cross section for the reaction

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

which depends both on the relative number of right handed and left handed neutrinos and the V, A interference term. The implications of the measurements by both the Gargamelle Collaboration[18] and more recently the CHARM experiment[19] are shown in Fig. 4.

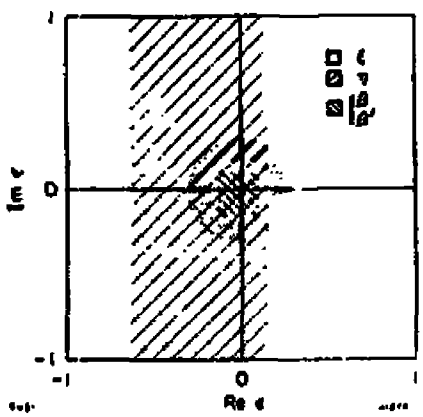

Fig. 3. Possible values of ξ allowed by different μ decay experiments.

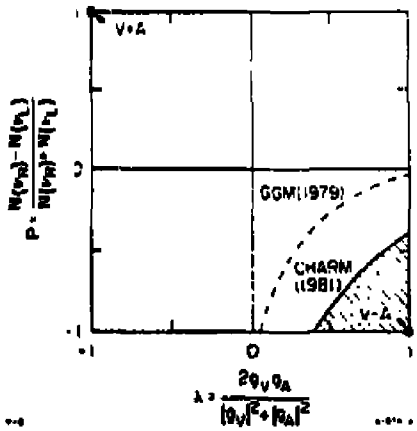

Fig. 4. Limits on P and λ set by the Gargamelle and CHARM experiments on inverse μ decay.

It is clear that the muon decay process, probing the weak interaction structure is consistent with the conventional V-A picture. A good test of possible admixtures of S and P interaction is provided by the measurement of μ polarization from the inclusive reaction

$$\nu_\mu + A \to \mu^+ + X$$

where A stands for a nuclear target. The first such measurement was performed several years ago by CHARM Collaboration[20] and their

result, i.e. P = 1.09 ± .22, imposed a 95% C.L. of 18% on possible admixture of S and P interaction. More recently the sensitivity of the experiment was increased[21] by studying the muon polarization as a function of y variable (inelasticity). As can be seen from Fig. 5a, any possible S, P admixture will be relatively more important at high y values. The μ decay asymmetry, however, shows no trace of y dependence and within statistical and systematic errors its magnitude is consistent with what one would expect on the basis of V-A prediction of maximum polarization.

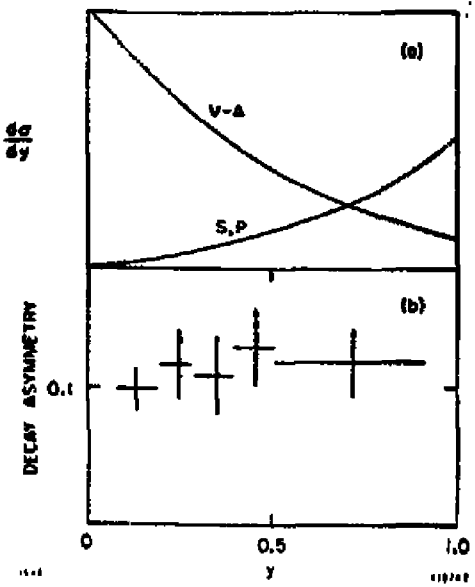

Fig. 5. a) Expected y distributions for V-A and S, P; b) decay asymmetry of the stopped μ's as a function of y.

I would like next to summarize very briefly some of the other features of weak interaction theory that have been deduced from μ decay. The first very important point, already noticed over 20 years ago, is the apparent universality of weak interaction coupling constant in a variety of different processes. More specifically very intriguing was the fact that the weak coupling constant as deduced from μ decay appears to agree within 2% with the vector coupling constant in β decay as deduced from the study of O^{14}. It was this question of why the vector part of the weak interaction does not get renormalized by strong interactions that was the motivation for the conserved-vector current (CVC) theory. The small discrepancy of 2% can be understood today in terms of the Cabibbo theory and its subsequent generalization to 6 quarks.

The muon decay also provides the most stringent tests of lepton conservation number, and more specifically of the separate

conservation law of both the electron and muon number. The limits on the muon "forbidden" decay modes, i.e. the ones that induce $\mu \to e$ transitions have been summarized[6] by Scheck and at this conference by Martin Cooper. They attain now values in the neighborhood of 10^{-9} of total decay rate and provide important constraints on any theory incorporating μ-e mixing.

Most of the observed leptonic processes cannot distinguish[22] between the so called additive lepton conservation law which implies

$$\Sigma L_\mu = \text{constant}$$

$$\Sigma L_e = \text{constant}$$

i.e. separate conservation of electron and muon number and the multiplicative law, which would demand only

$$\Sigma(L_e + L_\mu) = \text{constant}$$

$$(-1)^{\Sigma L_\mu} = \text{constant} \quad .$$

One can discriminate between these 2 alternatives by searching for a decay mode

$$\mu^+ \to e^+ + \bar{\nu}_e + \nu_\mu$$

which is forbidden by the first, more stringent hypothesis, but allowed by the second one. This decay has been recently searched for at LAMPF by looking for secondary interaction of the decay electron neutrino, i.e.

$$\bar{\nu}_e + A \to e^+ + \ldots$$

The decay process allowed by both schemes i.e.

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

will yield only ν_e, whose interactions to produce e^- serve as convenient normalization. The quoted limit[23] is

$$R = \frac{\mu^+ \to e^+ \bar{\nu}_e \nu_\mu}{\mu^+ \to e^+ \nu_e \bar{\nu}_\mu} < 6.5\% \quad (90\% \text{ of C.L.})$$

proving the dominance of the additive law.

Two other questions, related to the lepton conservation law, deserve to be mentioned here. The first one consists of the connected

problems of neutrino masses, oscillations and decay. This is a field of great theoretical and experimental interest at the present time and its various aspects have been discussed at this conference by both Adelberger (neutrino mass experiment) and Soni (neutrino oscillations). The space limitations do not permit any discussion of these complex and interesting questions; I would like to merely state here my personal opinion that as yet no convincing case has been made either for neutrino oscillations nor for non zero neutrino masses.[24]

The second topic deals with the double beta decay which could occur if lepton conservation law is violated (e.g. ν is a Majorana neutrino) and if the leptonic part of the weak interaction current does not obey exact γ_5 invariance. Thus if the latter invariance is broken at some level, either by non zero neutrino mass or explicit existence of both left and right handed currents (due for example to presence of both right handed and left handed coupled W bosons), then the limits on neutrinoless double β decay can limit the conceivable descriptions of the neutrino.

Traditionally,[25] limits on double β decay without neutrinos have come from the geochemical experiments on ^{82}Se, ^{128}Te, and ^{130}Te, which searched for corresponding noble gases trapped in the ore. The amount of the noble gas admixture could then be translated (if the age of ore is known) into a sum of both neutrinoless and 2 neutrino (i.e. allowed in standard picture) double beta decay rates. Much higher matrix element for 2 lepton emission makes this study an effective way of setting limits on neutrinoless process. The field has recently been thrown into a state of flux by a reported observation[26] in a cloud chamber of 2 neutrino $\beta\beta$ decay of ^{82}Se with a rate 28 times higher then the total $\beta\beta$ rate obtained by geochemical means. Furthermore, a recent theoretical calculation of this process[27] appears to agree with the latest laboratory result, lending additional credibility to this result. The interesting conclusion is that Russian m_{ν_e} measurement,[24] new limit on ^{82}Se neutrinoless double beta decay,[26] and the theoretical calculations[27] appear to be incompatible with a Majorana electron neutrino. Clearly all of

these results are rather preliminary at this stage but they lead us to believe that better laboratory experiments on double β decay can teach us something fundamental about weak interactions.

The τ decay phenomena provide us not only a means of testing the hypothesis that τ with its neutrino form a third leptonic doublet but also allow one to repeat many of the μ-decay studies at higher energies. The τ situation has recently been reviewed[28] comprehensively by Perl and most recent results have been summarized at this conference by Feldman. To avoid duplication, I shall only briefly enumerate the points most salient to the theme of this review.

In the conventional picture, the τ decay can be described by the generalized Feynman diagram of Fig. 6. In terms of this diagram, the most important conclusions can be summarized as follows:

a) The τ appears to couple to the same intermediate vector boson that is responsible for other weak interactions. This statement is based on the fact that all the measured branching ratios (i.e. behavior of vertex B) of the τ agree with the predictions based on standard W hypothesis.

b) At the vertex A, the coupling as determined by a measurement[29] of the Michel ρ parameter is consistent with V-A. The experimental value of $\rho = 0.72 \pm 0.10$ should be compared with the theoretical V-A prediction of 0.75.

c) The ν_τ appears to be distinct[30] from ν_e and ν_μ; its mass is consistent with zero,[29] albeit the precision is still quite poor ($m_{\nu_\tau} < 250$ MeV).

d) There is now a first measurement of τ lifetime which measures the coupling strength at vertex A. The Mark II group finds[31]

$$\tau_\tau = (4.6 \pm 1.8) \times 10^{-13} \text{ secs}$$

in good agreement with the prediction from e, μ, τ universality of 2.8×10^{-13} secs.

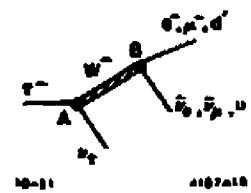

Fig. 6. τ decay diagram

2.2. Hadronic Processes

So far the discussion has been limited to the leptonic part of the weak current. Turning now to the hadronic sector, the early experiments indicated that V-A also seems to be operative there, but the complications due to strong interactions make a straightforward formalism more difficult. By applying, however, rather general principles or by resorting to a specific model, these difficulties can be overcome to a large extent and accurate predictions are possible. I would like next to turn to some of the confrontations of the charged current weak interaction theory with the experiment in the hadronic sector.

Historically the conserved vector current theory[32] and the related isotriplet current hypothesis have been the first truly successful link between the weak and electromagnetic interactions. By placing the vector weak interaction charged current in the same multiplet with the isovector part of the electromagnetic current, it provided an explanation of lack of renormalization effects and predicted the existence of some direct weak interactions between various particles. The latter hypothesis allowed one to calculate precisely (except for small electromagnetic corrections) the matrix elements for a variety of processes involving hadrons. One of the most celebrated of these predictions was the β decay of the pion, i.e.

$$\pi^+ \to \pi^0 e^+ \nu_e$$

which according to the CVC should occur with a miniscule branching ratio of 1.045×10^{-8}. A new experiment at LAMPF measuring this branching ratio[33] quotes a preliminary result of $(1.02 \pm .06)\times 10^{-8}$, representing already a significant improvement over the old world average.

Another recent, and quite different test of the CVC hypothesis, involves the measurement of the branching ratio $\tau^- \to \rho^- \nu$. The decay rate for this process can be related via CVC to the annihilation cross section $e^+e^- \to \rho^0$. The latest experimental number of[34]

$$BR\ (\tau^- \to \rho^- \nu) = (21.6 \pm 1.8(\text{stat}) \pm 3.6(\text{syst}))\%$$

agrees very well with the most up to date prediction[35] of $(21.5 \pm 1.5)\%$.

I would like to turn now to a brief discussion of the parton (or quark) model which has had some remarkable successes in predicting the behavior of hadrons in terms of structure composed of elementary constituents. As we shall see later on, the quark approach has been remarkably successful in linking the theory with experiment in the field of neutral current phenomena. Here I want to address myself specifically to the idea that quarks make up a V-A charged current of the same kind as the leptons, and thus the knowledge of hadron composition can lead to some very specific experimental predictions.

If the quark part of the current is pure V-A then we have explicit predictions:

ν - quark (or $\bar{\nu}$ - antiquark)scattering: $d\sigma/dy$ = constant

$\bar{\nu}$ - quark (or ν - antiquark)scattering: $d\sigma/dy = (1-y)^2$.

For the V+A quark current the predictions are simply interchanged (y is the standard inelasticity parameter). Thus if nucleons were composed exclusively of quarks we could readily test the handedness of the quark current. Unfortunately, the presence of the $q\bar{q}$ sea in the nucleons makes the interpretation of the ν scattering data slightly more obscure.

The antiquark component, however, cannot participate in single charm production, i.e. for neutrino interactions we can only have processes

$$\nu_\mu + d \to \mu^- + c + \ldots$$

$$\nu_\mu + s \to \mu^- + c + \ldots$$

Thus $\mu^-\mu^+$ events, to the extent that they represent a pure sample of charm production followed by muonic decay of charm particles, constitute a convenient test of quark handedness in charged current weak interactions. More specifically, the general y distribution can be written as

$$\frac{d\sigma}{dy} = a + (1-a)(1-y)^2$$

where (1-a) represents the V+A admixture. The recent result[36] from

the CDHS collaboration gives $(1-\alpha) \leq 0.10$, consistent with pure left-handedness. This limit, however, is comparable to the magnitude of the $(1-y)^2$ component present in non-charm producing neutrino interactions and normally interpreted as due to antiquarks in the sea. Accordingly, the value of $(1-\alpha)$ quoted does not contribute very much towards restricting the nature of the current.

I would like to turn finally to another general principle that has provided us with a wealth of theoretical predictions that appear to be well satisfied by the experiment, namely the Cabibbo theory. In the original formulation,[37] the universality of weak interactions meant that the leptonic weak interaction current has the same strength as the total hadronic current, which has 2 components. One of these of strength proportional to $\cos^2\theta_c$, is relevant to the $\Delta S=0$ processes; the other, proportional to $\sin^2\theta_c$, governs the $\Delta S=\pm 1$ channels. In the quark language, we say that the mass eigenstates are not identical to weak interaction eigenstates, and that the lower member of the lightest quark weak interaction doublet is d' defined as

$$d' = d\cos\theta_c + s\sin\theta_c \ .$$

θ_c, the Cabibbo angle, is a free parameter to be determined by the experiment, and whose theoretical prediction represents an important challenge to all higher symmetry models.

The formalism has been since extended first to the second doublet, containing the charm quark and more recently to the six-quark world by the addition of 3 more parameters. However, even in the 6 quark picture, the original predictions involving u, d, and s quarks, as well as purely leptonic processes, differ from the 6 quark predictions only in second order of quantities that appear to be small experimentally. Thus for the purpose of present discussion we shall stick with a single parameter formalism.

The strength of $\Delta S=\pm 1$ transitions (i.e. $\sin^2\theta_c$) can be measured in 2 independent ways i.e.

a) The $K_{\ell 3}$ decays (both neutral and charged) represent pure vector transitions and hence the SU_3 breaking effects are supposed to be small as one extrapolates the Dalitz plot density to $q^2=0$.

(Ademollo-Gatto theorem).[38] Thus the decay rate coupled with the form factor determination can yield the value of $\sin\theta_c$.

b) The baryonic semileptonic decays are completely parametrized by the D/F ratio in the axial-vector matrix elements and the Cabibbo angle θ_c (provided that one uses CVC to obtain behavior of some of the form factors and assumes absence of second class currents). Thus a global fit to neutron and hyperon decay data will yield these 2 parameters.

Schrock and Wong have recently performed an analysis[39] of the above data to obtain

$$\sin\theta_c = 0.219 \pm 0.003 \quad \text{from } Ke_3 \text{ data}$$

$$\sin\theta_c = 0.220 \pm 0.003 \quad \text{from baryonic decay data}$$

To allow for possible theoretical errors having to do with SU_3 breaking effects, radiative corrections, etc., they prefer to quote an average value with a larger error, i.e.

$$\sin\theta_c = 0.219 \pm 0.01 \ .$$

More recently, the WA2 collaboration have presented new results on hyperon semileptonic decays from the CERN hyperon beam.[40] Their data are considerably more extensive than the previously available total world sample, and they have been analyzed within the framework of CVC and Cabibbo theory. Non branching ratio measurements (i.e. asymmetry coefficients, charged lepton-neutrino correlations, Dalitz density, etc.) can be analyzed to extract the ratio of form factors g_1/f_1 without any assumption as to the value of $\sin\theta_c$. g_1/f_1, in turn, can be expressed for each decay as a linear combination of D and F coupling constants i.e. a straight line in the D, F space. Self consistency of the picture exhibits itself in a common intersection point for all the data. The g_1/f_1 data are shown in Fig. 7b. The branching ratio measurements (translated into partial decay rates) do involve $\sin\theta_c$, and their results can be displayed in the D-F space only after a best fit to $\sin\theta_c$ has been made (Fig. 7a). The WA2 group has also performed a global fit to D, F, and θ_c parameters using all of their data as well as the g_1/f_1 measurement for neutron

decay, obtaining

$$\sin\theta_c = 0.228 \pm 0.012$$

in good agreement with the previously quoted value.

Clearly the self-consistency of the hyperon data and the agreement of the 2 methods of determination of $\sin\theta_c$ constitute an important test of the Cabibbo theory. The relative decay rates $\pi \to \mu\nu$ and $K \to \mu\nu$ are also consistent with that picture although the much larger SU_3 breaking effects have made the test less quantitative. Finally, one should mention that the first results on the τ decay processes[41]

$$\tau^- \to \rho^- + \nu_\tau$$
$$\tau^- \to K^{*-} + \nu_\tau$$
$$\tau^- \to \pi^- + \nu_\tau$$
$$\tau^- \to K^- + \nu_\tau$$

also agree with the theory within the very limited statistics of the present experiments.

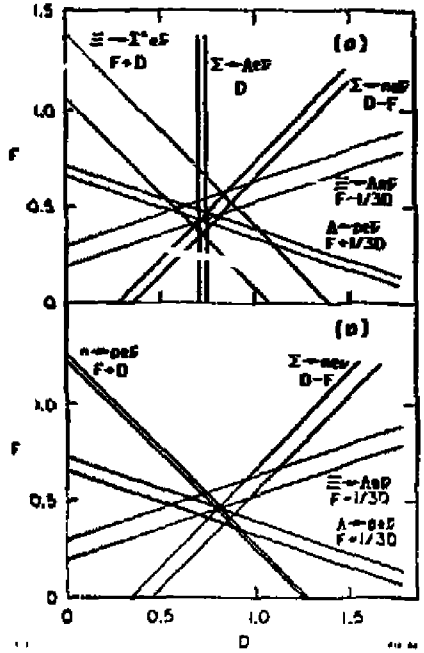

Fig. 7. The limits on D and F couplings imposed by the semileptonic hyperon branching ratio measurements (a) and the g_1/f_1 ratios (b).

2.3. Limits Imposed on Alternate Models

I have tried in the preceding discussion to show that the charged current processes are consistent within the experimental errors with the conventional picture of weak interactions. I would like to conclude this chapter with a very cursory look as to what limits are imposed by the current data on some of the alternate models that have a certain degree of popularity today. More

specifically I would like to look at the possibility of charged Higgs particles contributing as the intermediary to the weak interaction and at the postulate of the existence of right handed coupled intermediate vector boson, W_R. The former arises naturally in Glashow-Weinberg-Salam model with a complex Higgs structure; the latter's attractiveness has to do with restoring left-right symmetry and making the preferential lefthandedness a strictly low energy phenomenon. Since comprehensive reviews of these topics have been recently given by Strovink[10] and Sakurai,[7] I shall limit myself to only stating some general conclusions.

The charged Higgs models have been recently discussed by Haber, Kane and Sterling[42] and McWilliams and Li.[43] In the notation of ref. 43 the Lagrangian for the charged Higgs coupling is

$$L = 2^{3/4} \sqrt{G_F}\, M_H \{\bar{\psi}_f [a^L_{ff'} (\tfrac{1+\gamma_5}{2}) + a^R_{ff'} (\tfrac{1-\gamma_5}{2})] \psi_{f'}\} H + H.C.$$

and the experimental problem is to determine the limits (or values) of $a_{ff'}^L$ and $a_{ff'}^R$. In general the effects of charged Higgs particles will exhibit themselves as presence of effective scalar and pseudoscalar couplings and apparent violation of e, μ universality. The Fierz interference term in pure Fermi transitions imposes best limits on Higgs contributions to nuclear β decay,[43] i.e.

$$-0.025 < (a^R_{du} + a^L_{du}) a^L_{ev} < 0.035 \quad .$$

The limits from μ decay on products of leptonic couplings to Higgs are approximately an order or magnitude weaker.[10]

In the standard Higgs models, the couplings are proportional to fermion masses. Thus comparison of $\pi \to e\nu$ to $\pi \to \mu\nu$ decay rates does not provide any information about Higgs couplings (recall that in V-A theory the matrix element also goes as m_e/m_μ). However, there are models where couplings are independent of fermion masses; in those cases this measurement can provide quite stringent limits. The comparison of latest experimental number with theory translates into

$$|(a^R_{du} - a^L_{du})||a^L_{ev}| \lesssim 6.5 \times 10^{-4}$$

if the present 2 σ discrepancy is attributed entirely to Higgs.

The natural motivation for a heavy righthanded coupled boson is the restoration of left-right symmetry. Models incorporating a Lagrangian that is left-right symmetric[44] can be characterized by 2 parameters, i.e. the ratio of the masses of the two bosons and their mixing angle. The sensitivity of various experiments to possible existence of a heavy right handed boson has been recently summarized by several authors[44,45,10]. The ρ value from μ decay provides the most stringent constraint on the allowed value of the mixing angle; electron polarization from Gamow-Teller transitions give the most stringent limits on the mass ratio. The current status of these measurements has been recently summarized by Koks and van Klinken[46] who have measured the polarization for low energy electrons by looking at the decay products from ^{3}H decay. According to the V-A theory, the polarization of the electrons after correcting for Coulomb effects (i.e. P/A) should be just equal to the velocity of electrons in natural units. The summary of data is shown in Fig. 8 and the agreement appears good but the anomalous behavior of older measurements in the intermediate energy region is still not very well understood.

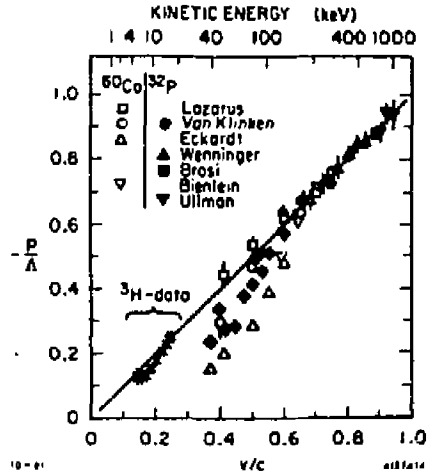

Fig. 8. Summary of data on electron polarization from nuclear β decay (from Koks and van Klinken)

The constraints on the Z-boson model imposed by the different experiments are best expressed in the plane defined by the mixing angle and the mass squared ratio. They are exhibited in Fig. 9 and come from the paper by Strovink.[10] The lower limit on the mass of the righthanded boson appears to be about 240 GeV (under the assumption that the corresponding neutrino is massless, or at least has very low mass). The anticipated

improvements in the ξP_μ value from the upcoming round of experiments should significantly improve the limits on both δ and ζ parameters.

3. NEUTRAL CURRENT REACTIONS - COMPARISON WITH THEORY

3.1. Introduction to the standard model.

I would like to commence this chapter with a brief introduction [47] to the standard model. We can start out by recalling the first three steps of Bjorken-Llewellyn Smith's recipe[48] on how to build a gauge theory i.e.

1. Choose a gauge group
2. Choose a fermion representation content
3. Choose Higgs scalar representation content

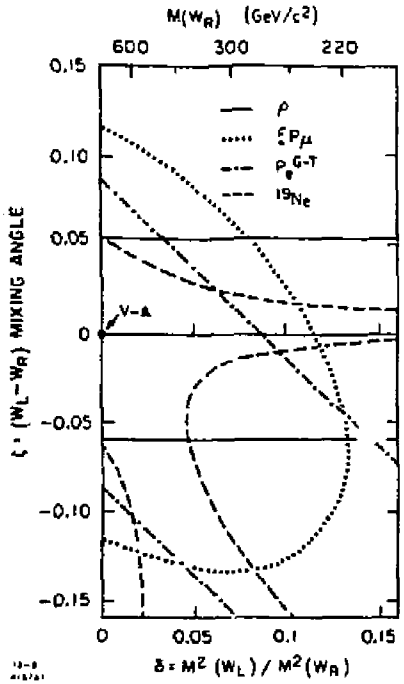

Fig. 9. Constraints on the 2-boson model imposed by different low energy experiments (from Strovink).

In a certain sense SU(2), called here weak isospin in analogy with strong interactions, is a natural component of a successful gauge group, since, as we have seen from the previous discussion, the lepton family appears to divide itself into various multiplets. Since in SU(2) we have 3 structure matrices (the familiar Pauli matrices) this will imply 3 vector gauge bosons. The 2 charged bosons can be identified naturally with the intermediate vector bosons responsible for the charged current weak interactions; the neutral vector boson, however, is not a good candidate for the photon because a coupling of gauge bosons with lepton multiplets will yield a coupling of the neutral boson to the neutrinos. Accordingly one has to enlarge the gauge group at least to SU(2) x U(1) which yields

one new neutral gauge boson and provides additional degrees of freedom that are necessary to obtain agreement with theory.

Regarding step 2, isospin doublets of the form

$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L , \qquad \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L , \qquad \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}_L$$

are the obvious candidates for fermion representation of left handed leptons because of the successes of the V-A theory. However in light of the fact that there appear to be no right-handed neutrinos and the photon does couple to right-handed charged leptons, the natural assignment for the right handed charged leptons is isospin singlets, i.e.

$$(e^-)_R \ , \ (\mu^-)_R \ , \ (\tau^-)_R \quad .$$

Parenthetically one should remark here that gauge theories without new neutral massive bosons can be constructed for example with a group structure O(3). They are characterized by the multiplet assignment such that $Q = T_3$ and thus require postulating new leptons.

The standard model makes similar multiplet assignment for the quarks, i.e.

$$\begin{pmatrix}u\\ d'\end{pmatrix}_L , \qquad \begin{pmatrix}c\\ s'\end{pmatrix}_L \text{ and perhaps } \begin{pmatrix}t\\ b'\end{pmatrix}_L$$

(where d', s', and b' are some appropriate linear combinations of mass eigenstates d, s, and b) and u_R, d_R, c_R, s_R, b_R and perhaps t_R.

The reasons here are less compelling than in the lepton sector. First of all, there is the esthetic quark-lepton symmetry agreement. This symmetry allows one to have the simplest possible Higgs structure, as discussed below. Experimentally there is only evidence that u, d, and s couple in a lefthanded way (and only at low energies, as discussed previously). In principle u_R and d_R could be in a higher multiplet with heavier quarks, but the absence of high y anomaly in ν interactions[49] would force the mass of that quark to be so high that it would not effect the ν phenomenology at energies studied to any appreciable degree. Furthermore, according to Glashow-Weinberg theorem,[50] one way to guarantee absence of flavor changing neutral

currents is to assign to all quarks of a given handedness and the same charge, the same weak isospin (T) and the same third component (T_3).

Turning now to the Higgs scalars, a single Higgs doublet is the minimum necessary requirement for SU(2) x U(1) with the above fermion representation. With that assignment, we shall have only one non-zero vacuum expectation value and thus only one real-life Higgs particle, the neutral member of the doublet. It turns out that adding additional Higgs doublets would not effect the phenomenology of weak interactions, but would generate additional visible Higgs scalars (both charged and neutral). A different Higgs multiplet structure, would, however, affect some of the predictions to be discussed below.

We have seen that so far we have tacitly introduced at least 3 parameters, which can be taken to be:

g - strength of coupling of SU(2) vectors

g' - strength of coupling of U(1) vector

v - vacuum expectation value of Higgs scalar

There are still other parameters, like the couplings of the U(1) vector boson to right and left handed quarks and leptons (a priori these are undetermined by the formalism). These additional parameters, however, are constrained by our requirement that we need to form 2 linear combinations out of the 2 neutral gauge bosons, one of which will be the photon (γ) and the other massive carrier of neutral current weak interactions (Z_0). The photon combination must satisfy certain requirements, i.e. be massless, and couple vectorially to the charge. It turns out that imposition of these requirements removes all additional degrees of freedom. Furthermore it specifies the strength of Z_0-quark and Z_0-leptor couplings in terms of the above 3 free parameters and third component of weak isospin.

It is convenient to re-express the three arbitrary parameters above in terms of constants more directly accessible to experiments, i.e.:

e - electronic unit of charge

G_F - weak coupling constant

$\sin^2\theta_w$ - where θ_w is defined by $\tan\theta_w \equiv g'/g$. As we shall see in a moment $\sin^2\theta_w$ is a parameter occurring in all of the neutral current phenomenology.

We can now enumerate some of the explicit predictions that fall out of the formalism discussed above:

a) all neutral current phenomenology is determined once fermion assignments are made and $\sin^2\theta_w$ is measured.

b) masses of gauge bosons can be determined from <u>low-energy</u> experiments:

$$M_w = \frac{2^{-5/4}\, G_F^{-1/2} e}{\sin\theta_w} \qquad M_Z = M_w/\cos\theta_w$$

These predictions are independent of the details of the fermion representation assigned; the second prediction depends on having only Higgs doublets.

c) The ratio M_w/M_Z can be measured in low energy reactions by comparing the strength of neutral current and charged reactions. It is customary to define

$$M_w/M_Z \cos\theta = \rho$$

and to have experiments test whether $\rho=1$ (as it should be for doublet Higgs structure).

d) The left handed and right handed couplings of quarks and leptons can be expressed as

$$\varepsilon_{L,R}(i) = T_3^{L,R}(i) - Q(i)\sin^2\theta_w \ ,$$

Note that the above expression follows from the general SU(2) x U(1) gauge group. The standard (G-W-S) model makes the expression specific by assigning multiplet structure (and hence T_3) to all the fermions.

I would like to end this general discussion by a brief discussion about factorization.[51] Consider the diagrams in Fig. 10 representing some of the different neutral current weak interaction processes. For simplicity, assume that the couplings indicated refer to the strength of coupling of lefthanded fermions indicated (q stands for one of the quarks) to the Z^0 (assume that there is only 1 of these, as in SU(2) x U(1)). The essential point to be made here is that

any one single process can only measure the product of the two relevant coupling constants, e.g. AB for neutrino electron scattering. Factorization means that the coupling constants thus extracted will satisfy the expression stated graphically in Fig. 10, i.e.

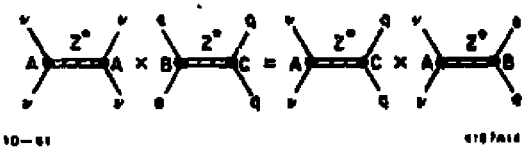

Fig. 10. Schematic representation of factorization.

$$A^2 \times BC = AB \times AC$$

This is clearly true under the assumptions stated above, but generally will not be true if there are more than 1 Z^0. In that case, the coupling constants to different Z^0's can be different and instead of a single numbers A, B, C, we shall have a vector A_μ, B_μ, C_μ of dimensionality equal to the number of Z^0's. Each reaction will then measure a dot product of the 2 appropriate vectors and it will no longer be necessarily true that

$$A \cdot A \times B \cdot C = A \cdot B \times B \cdot C$$

It is frequently customary to parametrize neutral current reactions by linear combinations of c's we have defined above i.e.

a) for neutrino quark reactions: α, β, γ, and δ representing vector isovector, axial isovector, vector isoscalar and axial isoscalar coupling constants.

b) for neutrino electron reactions: g_V and g_A, representing vector and axial coupling constants.

c) for electron-quark reactions: $\tilde{\alpha}$, $\tilde{\beta}$, $\tilde{\gamma}$, $\tilde{\delta}$ defined analogously as in (a).

d) for $ee \to \mu\mu$ reactions: h_{VV}, h_{AA}, h_{VA}, representing vector-vector (i.e. vector interaction at both vertices), axial-axial, and vector-axial coupling constants.

Note that in all these cases these parameters are defined to include the strength of coupling at both vertices.

For models characterized by a single Z-boson and under the assumption of e-μ universality, we have 7 independent parameters

corresponding to the couplings of ν_L, u_L, d_L, e_L (and μ_L), u_R, d_R and e_R (and μ_R). Thus 6 factorization relations must exist, whose validity tests the single Z^0 hypothesis. To test the standard model one can either analyze each reaction in terms of its own characteristic parameters and subsequently see if factorization relations are satisfied, or analyze all reactions right away in terms of the above 7 independent parameters and see if a self-consistent solution exists. I shall tend to use the second approach but occasionally will utilize a more general analysis.

3.2 Purely leptonic reactions - ν electron scattering

The purely leptonic reactions fall naturally into 2 classes; ν-electron scattering discussed in this section and $e^+e^- \to$ leptons, discussed subsequently. So far, 3 different ν electrons scattering channels have been investigated, i.e.

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

The effective Lagrangian density for these processes can be written as

$$L_{eff} = \frac{G_F}{\sqrt{2}} \bar{\nu} \gamma_\mu (1 + \gamma_5)\nu J^e_\mu$$

where J^e_μ is the electronic current given by

$$J^e_\mu = c_L(e)\bar{e} \gamma_\mu(1 + \gamma_5)e + c_R(e)\bar{e} \gamma_\mu(1 - \gamma_5)e$$

and $c_L(e)$ and $c_R(e)$ are the couplings of the left and righthanded electron that have been discussed previously.

For purposes of writing the expression for cross section, it is customary to define the vector and axial coupling constants:

$$g_V^e = c_L(e) + c_R(e)$$
$$g_A^e = c_L(e) - c_R(e)$$

The differential cross section section can be written as

$$\frac{d\sigma}{dy} = \frac{G^2 mE}{2\pi}\left|A + B(1-y)^2 + \frac{Cmv}{E}\right|$$

where y is the inelasticity, m the mass of electron and E the neutrino laboratory energy. For neutrino scattering (ν_μ, ν_e) we have

$$A = (g_V + g_A)^2$$

$$B = (g_V - g_A)^2$$

$$C = (g_V^2 - g_A^2)$$

and for antineutrino the coefficients A, B, C are obtained by substituting $g_A \to -g_A$. In general for accelerator experiments, the last term can be neglected because m << E. The expression for the total cross section then becomes (for neutrino electron scattering)

$$\frac{\sigma_{TOT}}{E} = \frac{G^2 m}{2\pi} \left| (g_V + g_A)^2 + 1/3\ (g_V - g_A)^2 \right|$$

Before looking at the data one needs to make 2 explanatory comments:

a) for the last reaction i.e.

$$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$$

in addition to Z^0 exchange diagram there is also a charged current, W exchange diagram. The latter is characterized by $g_V = 1$, $g_A = 1$ and thus since the 2 diagrams contribute coherently we must substitute

$$g_V \to 1 + g_V^{N.C.}$$

$$g_A \to 1 + g_A^{N.C.}$$

b) g_V and g_A can be thought of as products of couplings at the neutrino vertex and the electron vertex. Alternatively, in the standard model coupling at the neutrino vertex is unity, and they can be viewed as Z^0-s coupling constants.

We can right away write down the predictions for these coupling constants for the standard SU(2) x U(1) G-W-S model. They are listed in Table III below

Table III

Neutrino-electron scattering coupling constants (G-W-S model)

Reaction	c_L	c_R	g_V	g_A
$\bar{\nu}_\mu, \nu_\mu + e^-$	$-\frac{1}{2} + \sin^2\theta_W$	$\sin^2\theta_W$	$-\frac{1}{2} + 2\sin^2\theta_W$	$-\frac{1}{2}$
$\bar{\nu}_e + e^-$	$-\frac{1}{2} + \sin^2\theta_W$	$\sin^2\theta_W$	$\frac{1}{2} + 2\sin^2\theta_W$	$\frac{1}{2}$

The experimental cross section values together with their errors define elliptical bands in the g_V, g_A space. The $\bar{\nu}_e e$ ellipse is displaced from the origin because of the extra charged current term (the g_V, g_A space in our convention corresponds to neutral current g_V and g_A only). The latest compilation of data are displayed in Fig. 11 and they come from Barbiellini's talk at the 1981 Bonn Conference. The $\bar{\nu}_e e^-$ data comes from the reactor experiment of Reines et al.;[52] the $\bar{\nu}_\mu e^-$ ellipse is dominated by the new result from the CHARM Collaboration,[53] and the $\nu_\mu e^-$ result is influenced mostly by the Fermilab experiment of Heinterberg et al.[54]. The data yield 2 possible solutions for g_V and g_A, one of which is compatible with the G-W-S model and a value of $\sin^2\theta_W$ around 0.25. As we shall see later, the non G-W-S solution appears excluded by the e^+e^- work and neutrino hadron scattering coupled with factorization.

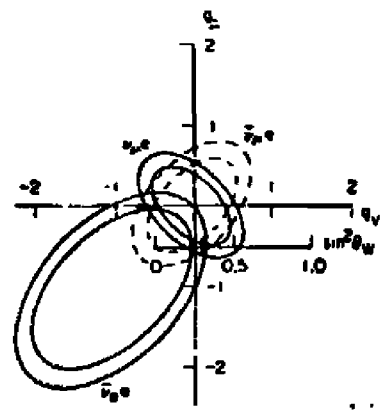

Fig. 11. Summary of $\nu_\mu e$, $\bar{\nu}_\mu e$, and $\bar{\nu}_e e$ scattering data.

3.3 e^+e^- → leptons

We consider here the experimental study of the reactions:

$$e^+ + e^- \to e^+ + e^-$$

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

$$e^+ + e^- \to \tau^+ + \tau^-$$

The interest in these reactions from the point of view of this review lies in the fact that they are sensitive to the interference effects between γ and Z^0 diagrams, as shown in Fig. 12. (The first reaction has additional 2 diagrams with γ and Z^0 in the t channel). In principle these reactions can yield information on 3 different coupling constants, commonly referred to as h_{VV}, h_{AA}, and h_{VA}, which in the standard model and assuming lepton universality reduce to:

$$h_{VV} = g_V^2 = \tfrac{1}{4}(1 - 4\sin^2\theta_W)^2$$

$$h_{AA} = g_A^2 = \tfrac{1}{4}$$

$$h_{VA} = g_V g_A = \tfrac{1}{4}(1 - 4\sin^2\theta_W)$$

The term multiplied by h_{VV} shows up[55] in the expression for total cross section as a percentage change away from the prediction of one photon exchange diagram and rises linearly with s. h_{VA} gives rise to parity violating effects like non zero helicity of outgoing leptons and cross section dependance on the helicity of the incident electron or positron. Finally h_{AA} will manifest itself as a forward backward asymmetry of the outgoing leptons of a given charge.

Besides the intrinsic difficulty, connected with the measurement of the first 2 effects they are expected to be very small in the standard model. This is due to the fact that they are predicted to vanish if $\sin^2\theta_W = 0.25$, which appears to lie very near the experimental value. Thus it is not surprising that none of these effects have been observed as yet. There appears now, however, evidence for presence of non zero h_{AA} terms. The most convincing evidence comes from the observed asymmetry in the reaction

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

The results on that reaction, as well as the related $\tau^+\tau^-$ channel, presented[56] at the Bonn

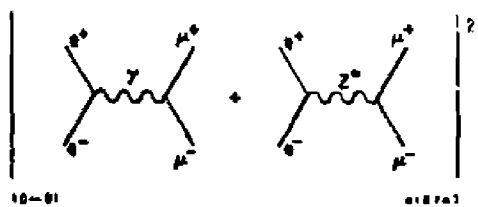

Fig. 12. The two interfering diagrams in $e^+e^- \to \mu^+\mu^-$.

Conference are summarized in Table IV.

Table IV

Charge Asymmetry Results for e^+e^- Annihilation

	MARK II	CELLO	JADE	MARKJ	PLUTO	TASSO	Last 4 combined
$A_{\mu\mu}$ (%)	-4±3.5	$-1.3\ ^{+9}_{-10}$	-11±4	-3±4	7±10	-11.3±5.0	-7.7±2.4
GWS Pred	-4	-5.8	-7.8	-7.1	-5.8	-8.7	-7.8
$A_{\tau\tau}$ (%)				-6±12		0±11	
GWS Pred				-5		-7	

Though still limited statistically, the agreement with the standard model is quite impressive.

The effect in angular distribution for

$$e^+ + e^- \rightarrow e^+ + e^-$$

is much less significant. The folded angular distribution from MARK J is shown[57] in Fig. 13 and shows preference for $h_{AA} = \frac{1}{2}$, $h_{VV} = 0$ solution over the $h_{VV} = \frac{1}{2}$, $h_{AA} = 0$ hypothesis. The full angular distributions from the other 4 PETRA detectors[57] (Fig. 14) do not appear to show very much discriminating power between the same 2 alternatives.

Alternatively one can combine all the available data on the 3 leptonic channels, i.e. total cross section as a function of s, angular distribution of Bhabha scattering and the forward-backward $\mu^+\mu^-$ and $\tau^+\tau^-$ asymmetry to extract both h_{VV} and h_{AA} simultaneously. This has been done by the 5 different groups at PETRA (not all the different pieces of input were utilized by all groups) and the results[56] are shown in Fig. 15. I have

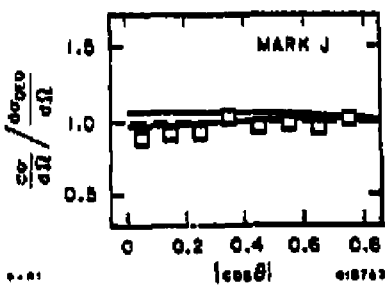

Fig. 13. Comparison of MARK J data on $e^+e^- \rightarrow e^+e^-$ with predictions based on 2 different sets of values for h_{AA} and h_{VV}. The lower curve corresponds to $h_{AA}=\frac{1}{2}$, $h_{VV}=0$; the upper one to $h_{AA}=0$, $h_{VV}=\frac{1}{2}$.

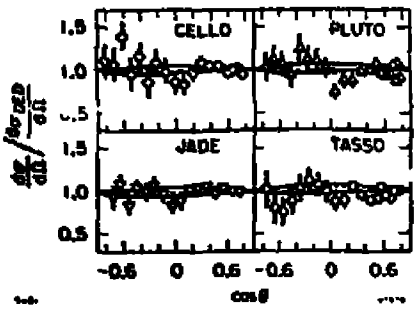

Fig. 14. Comparison of PETRA data on $e^+e^- \to e^+e^-$ with predictions based on 2 different sets of values for h_{AA} and h_{VV}. The lower curves correspond to $h_{AA}=\frac{1}{2}$, $h_{VV}=0$; the upper to $h_{AA}=0$, $h_{VV}=\frac{1}{2}$.

also indicated on the same figure the 2 possible solutions obtained from the νe scattering data, to illustrate that e^+e^- data clearly favors the one compatible with the GWS model.

In summary all of the pure leptonic reactions are consistent with the GWS model. The e^+e^- statistics are still quite limited but they appear to give first indication that μ-e universality also holds for neutral current couplings.

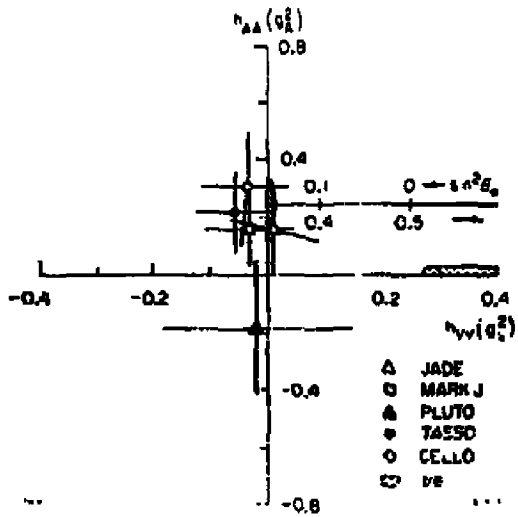

Fig. 15. Summary of PETRA data on h_{VV} and h_{AA}. Also indicated are the 2 solutions from the νe data (assuming factorization).

3.4 Semihadronic Neutral Current Reactions: ν-Hadron Interactions

These processes present additional complication that is not present in purely leptonic interactions, i.e. the fact that hadrons are complex structures. Thus we have to rely on the quark model and sometimes other theoretical assumptions to make the connection between theoretical predictions and experimental reality. Fortunately, the structure functions of the nucleons are known now quite well in the region of interest as is the fraction and composition of quark-antiquark sea. Serious theoretical and calculational difficulties still remain: questions regarding exclusive pion production channels and size of atomic physics effects are some of the examples illustrative of this point.

The reactions I shall discuss fall naturally into 2 different categories: ν-hadron scattering experiments and weak-electromagnetic interference experiments in hadronic reactions. I shall begin by discussing the neutrino reactions.

This topic has been comprehensively reviewed rather recently[8,58] and the new experimental data[59] since that literature review was completed appear consistant with the previous conclusions. Accordingly I shall rely heavily on the published review of Kim et al.[8].

Just as for the ν electron channels, we can write the effective Lagrangian density

$$\mathcal{L}_{eff} = \frac{G_F}{\sqrt{2}} \bar{\nu} \gamma_\mu (1+\gamma_5)\nu \, J^H_\mu$$

with the hadronic current J^H_μ given by

$$J^H_\mu = \sum_i \left[c_L(i)\bar{q}_i \gamma_\mu (1+\gamma_5) q_i \right] + \left[c_R(i)\bar{q}_i \gamma_\mu (1-\gamma_5) q_i \right]$$

where the sum extends over all the quark flavors, i.e. u, d, c, s, b, etc. An alternative notation, involves decomposition into isovector (isoscalar) vector and axial vector currents. Ignoring the heavier quarks

$$J^H_\mu = \tfrac{1}{2}\alpha(\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d) + \tfrac{1}{2}\beta(\bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d)$$

$$+ \tfrac{1}{2}\gamma(\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d) + \tfrac{1}{2}\delta(\bar{u}\gamma_\mu\gamma_5 u + \bar{d}\gamma_\mu\gamma_5 d)$$

The 2 sets of couplings are related linearly in an obvious manner. As far as the heavier quarks are concerned, it is generally customary in the fits to assume generation symmetry i.e. that s(c) quark couplings will be the same as the d(u) quark couplings as required in the GWS model. Heavier quarks are generally ignored. The results, however, are not too sensitive to these assumptions.

There is a variety of experimental input that determine the quark neutral current couplings. I enumerate them briefly below:

a) measurement of $R_\nu \equiv \sigma_\nu^{NC}/\sigma_\nu^{CC}$ and $R_{\bar\nu} \equiv \sigma_{\bar\nu}^{NC}/\sigma_{\bar\nu}^{CC}$ from an isoscalar target. These measurements are sensitive to $u_L^2 + d_L^2$ and $u_R^2 + d_R^2$ since no information about isospin structure of the neutral current can be obtained.

b) Deep inelastic scattering from neutron and proton targets. These are measurements equivalent to (a) except that the isoscalar target is replaced by a single nucleon. Thus the experiments differentiate between $u_L(u_R)$ and $d_L(d_R)$.

c) Inclusive pion production ($\nu A \to \nu\pi X$). The charge of the leading pion provides some information about the nature of the struck quark from the knowledge of the quark fragmentation function $D_q^\pi(z)$.

d) Elastic scattering: $\nu p \to \nu p$ and $\bar\nu p \to \bar\nu p$. These cross sections are written in terms of the vector and axial-vector form factors of the proton. The former can be related by CVC to the electromagnetic form factors; some additional assumptions are needed to parametrize the axial form factors.[60]

e) Exclusive pion production channels. The analysis of these channels is probably most complicated theoretically since it is obscured by the imperfect knowledge of the relevant hadronic matrix elements. Abbott and Barnett use the model developed by Adler[61] to perform the analysis.

f) The exclusive reaction

$$\bar\nu_e + d \to \bar\nu_e + n + p$$

can proceed only via axial current and the magnitude of its cross section is predicted by the GWS model.

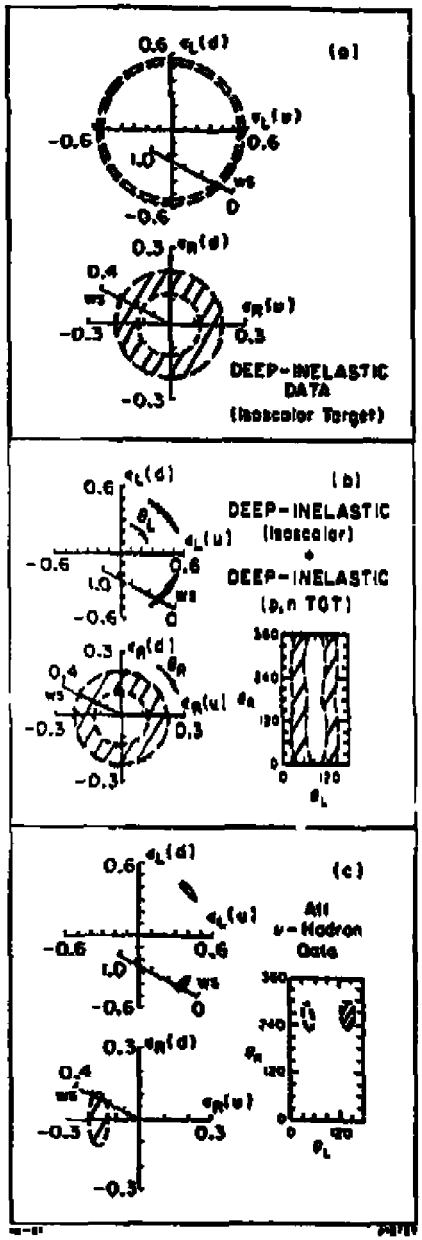

Fig. 16 illustrates the constraints imposed by the different sets of input data. The data are parametrized by $\epsilon_L(d)$, $\epsilon_L(u)$, $\epsilon_R(d)$ and $\epsilon_R(u)$ and it is convenient to display the constraints as allowed regions in both left-handed and right-handed coupling constant spaces. Again it should be recalled that in both these spaces the standard model limits the allowed region to a straight line segment, each point on which corresponds to a different value of $\sin^2\theta_W$.

Fig. 16a shows the restrictions imposed by R_ν, $R_{\bar\nu}$ measurements on an isoscalar target. As mentioned earlier only an annular region in each space can be defined by these data. Adding the data on neutron and proton targets, restricts the allowed regions to those shown in Fig. 16b. There is also a correlation between the allowed regions in the $\epsilon_L(u)$ - $\epsilon_L(d)$ space and the

Fig. 16. Constraints imposed on the neutral current couplings by the neutrino-hadron data: a) data on isoscalar targets only; b) data on isoscalar targets combined with data on neutron and proton targets; c) all ν-hadron data (from Kim et al.).

$\epsilon_R(u) - \epsilon_R(d)$ space which is displayed as a shaded region in the θ_L, θ_R plot. Finally, Fig. 16c illustrates the allowed regions if all the ν hadron data of the first 4 types (a-d) are included. Of the two allowed regions in the lefthanded space, the non GWS region (unshaded) is excluded both by the exclusive pion production data[58] and the experiment of Pasierb et al.,[62] on $\bar{\nu}_e d$ reaction.

In summary, we see thus that all of the neutrino hadron data define (within errors) a single set of coupling constants, both in lefthanded and righthanded space. Furthermore, both solutions are consistent with the constraint imposed by the standard model and both correspond to the same value of $\sin^2\theta_W$. Finally the value of $\sin^2\theta_W$ (0.2 - 0.25) is consistent with that obtained from the purely leptonic reactions. The GWS has obviously passed another stringent test.

3.5 Weak-electromagnetic interference in hadronic interactions

The relevant experiments here fall into following categories:

a) polarized electron deep inelastic scattering

b) parity violation in atomic experiments

c) $e^+e^- \rightarrow$ hadrons

It is the first two categories that have provided so far the most relevant information although the situation regarding the atomic parity experiments has been confused from the start, both in experimental results and theoretical calculations. In the famous SLAC parity violating electron scattering experiment[63] one studies the reaction

$$e^- + d \rightarrow e^- + X$$

with polarized electrons. Due to the interference between the γ and Z^0 exchange diagrams, the cross sections for electrons polarized parallel and antiparallel to the beam will be unequal. The size of this asymmetry as a function of x and y Feynman variables has been calculated by Cahn and Gilman[64] in the framework of the parton model. If one neglects antiquarks as well as heavy quarks, the expression for asymmetry A_D, defined by

$$A_D = \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-}$$

becomes

$$\frac{A_D}{Q^2} = -\frac{9G_F}{5\sqrt{2}\pi\alpha}\left\{\left[Q_u \cdot V_u + Q_d \cdot V_d\right]A_e + F(y)\left[Q_u \cdot A_u + Q_d \cdot A_d\right]V_e\right\}$$

$$= -\frac{6G_F}{5\sqrt{2}\pi\alpha}\left\{\left[V_u A_e - \tfrac{1}{2} V_d A_e\right] + F(y)\left[A_u V_e - \tfrac{1}{2} A_d V_e\right]\right\}$$

where V_u is the vector coupling of the u quark, A_u the axial coupling of the u quark, and similarly for V_d, A_d, V_e, A_e. Q_u and Q_d are charges of the up and down quarks, respectively. F(y) is defined by:

$$F(y) = \frac{1 - (1-y)^2}{1 + (1-y)^2}$$

The expression above is model independent. If factorization holds (and ν-2° coupling is unity) then

$$V_u = \varepsilon_L(u) + \varepsilon_R(u)$$

$$A_u = \varepsilon_L(u) - \varepsilon_R(u)$$

$$V_e = g_V^e \equiv \varepsilon_L(e) + \varepsilon_R(e)$$

and similarly for A_e, V_d, A_d.

Furthermore in the GWS model the y independent coefficient becomes $-3/8 + 5/6 \sin^2\theta_w$ and the y dependent coefficient $\frac{3}{2}(\sin^2\theta_w - \frac{1}{4})$. The experimental results of Prescott et al.[63] give:

$$\frac{A_D}{Q^2} = \left[(-9.7 \pm 2.6) + (4.9 \pm 8.1)\, F(y)\right] \times 10^{-5}$$

which translates into the following constraints on the coupling constants:

$$V_u A_e - \tfrac{1}{2} V_d A_e = -0.23 \pm 0.06$$

$$A_u V_e - \tfrac{1}{2} A_d V_e = 0.11 \pm 0.19$$

The experiments looking at parity violation in atomic transitions can measure a linear combination of $V_u A_e$ and $V_d A_e$ that is almost orthogonal to that investigated at SLAC. Thus in principle these 2 sets of experiments can determine coupling constants quite well. In practice,

however, the status of atomic parity experiments has had a rather confusing history and some of the discrepancies between the older and newer experiments are still not completely understood. In addition the situation is also clouded by the difficulties of theoretical interpretation; the value of the magnitude of the parity violation expected in the GWS model has been reduced by a factor of 2 as more sophisticated calculations were performed.[65]

In light of this checkered past history and the fact that a detailed discussion of these experiments is given in Adelberger's review at this Conference, I shall limit myself to merely summarizing all the results in the Table below. Different experiments prefer to quote their results in terms of different quantities, i.e. weak charge (Q_W), ratio of E_1 to M_1 matrix elements (R), and amount of rotation due to parity violation ($\Delta\phi_{PNC}$ - related to R through number of absorption lengths in the vapor). I prefer to keep in the Table their original choices when presenting their results.

Table V

Summary of atomic parity violation experiments

Group	Element	λ	Quantity quoted	Experimental value	Theoretical* prediction	Ref.
Berkeley	Tl	2927	Q_W	-155±63	-116.5	66
Washington	Bi	8757	R	$(-0.7\pm2.1)\times10^{-8}$ $(-10.4\pm1.7)\times10^{-8}$	$-(8-12)\times10^{-8}$	67 68
Novosibirsk	Bi	6476	R	$(-20.2\pm2.7)\times10^{-8}$	$-(10-16)\times10^{-8}$	69
Oxford	Bi	6476	R	$(2.7\pm4.7)\times10^{-8}$ $(-10.7\pm1.5)\times10^{-8}$	$-(10-16)\times10^{-8}$	70 1
Moscow	Bi	6476	$\Delta\phi_{PNC}$	$(-0.22\pm1.0)\times10^{-8}$	10^{-7}	72

*Range of theoretical values for R represents my relatively uninformed estimate based on the spread of values obtained from various calculations.

The atomic parity experiments can best be compared with SLAC ed experiment if one uses the concept of weak charge,[73] defined by

$$Q_W(N,Z) = -4\,V_u A_e\,(2Z+N) + V_d A_e\,(Z+2N)$$

and thus for Thallium we have

$$Q_W\ (123,81) = -\ 1140\ V_u A_e - 1308\ V_d A_e$$

The Berkeley result can thus be expressed as

$$-1140\ V_u A_e - 1308\ V_d A_e = -\ 115 \pm 63$$

$$V_u A_e + 1.15\ V_d A_e = \ \ .14 \pm .06$$

I have also converted the results of the most recent Washington experiment and the Novosibirsk experiment into weak charge by utilising the central value of theoretical predictions indicated in Table V. The results of these 3 experiments are displayed together with the SLAC experiment in Fig. 17. Clearly the result is consistent with the GWS model and a value of $\sin^2\theta_w = 0.23$.

I end this section with a very brief comment on the channels

$$e^+ + e^- \rightarrow \text{hadrons}$$

which can also exhibit effects of γ-Z^0 interference. The normalised cross section for the production of quark pair $f\bar{f}$ can be written as (before QCD corrections)

$$R_f = Q_f^2 - 8sQ_f g_V^e g_V^f\ g\ P(s) + 16s^2 g^2 (g_V^{e\,2} + g_A^{e\,2})(g_V^{f\,2} + g_A^{f\,2}) P'(s)$$

where the 3 terms represent the photon term, γ-Z^0 interference term, and Z^0 term respectively, P(s) is the propagator term for the γ-Z^0 interference and P'(s) for the pure Z^0 exchange, and $g = 4.47 \times 10^{-5}$ GeV^{-2}.

In the framework of the GWS model g_V^e and g_V^f are functions of $\sin^2\theta_w$ and thus the total cross section will have a mild dependance on that parameter (θ_w also comes in the propagator terms through m_Z^0). Thus if QCD corrections are believed to be known exactly one can write the total normalized cross section as a function of $\sin^2\theta_w$. This kind of analysis has been performed by the MARK J group[74] and their results for R as a function of $\sqrt{s}$ are shown in Fig. 18. The 95% C.L. limits yield

$$\sin^2\theta_w = 0.27^{+0.34}_{-0.08}\ .$$

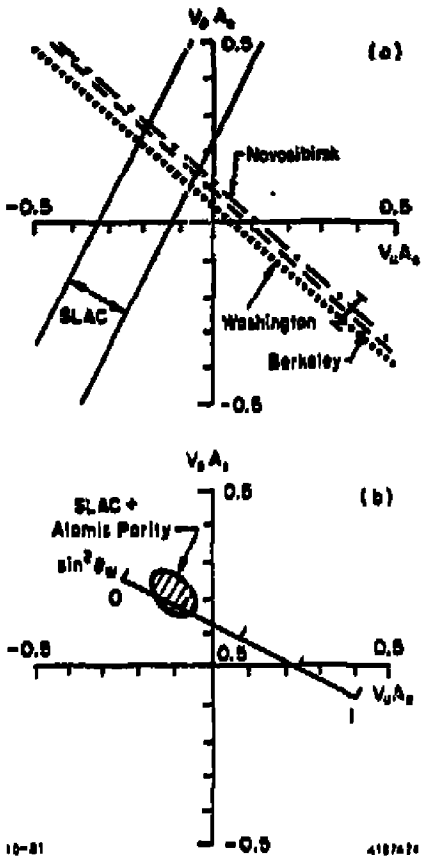

Fig. 17. a) Constraints imposed in the V_eA_e, V_uA_e space by the SLAC polarized ed experiment and some of the recent atomic parity violation experiments. For clarity the error range (both experimental and theoretical) is shown only for the Berkeley experiment. b) Comparison of these experiments with the GWS prediction.

One should add here, parenthetically, that the contribution of the heavy quarks to the value of R is just as important as of the u and d quarks. Thus the situation here is different from the experiments on stationary targets.

3.6 Summary of neutral current processes

It should be clear from the above that the GWS model appears to satisfy all the data. 3 separate kinds of reactions (purely leptonic, ν hadron, and electron hadron) give self-consistent solutions with a value of $\sin^2\theta_W \approx 0.23$. One would like to be a little more quantitative about how good the

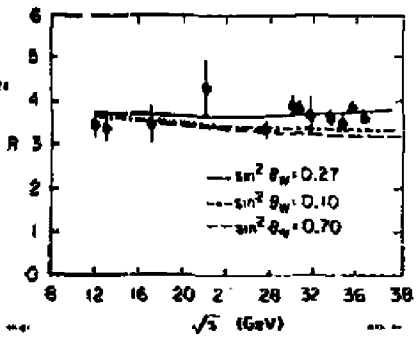

Fig. 18. Mark J results on R as a function of $\sqrt{s}$ compared to theoretical predictions with different values of $\sin^2\theta_W$.

agreement really is. For this purpose, I shall quote here some of results obtained by Kim et al.[8] from global fits to all the data they considered. The data included there were significantly scarcer than available today and discussed in this report. At the time of their fits none of the e^+e^- data were available and atomic parity experimental situation was much more obscure than it is today. Thus none of these data were included in their fits. Furthermore the recent high statistics experiments on $\nu_\mu e$ and $\bar{\nu}_\mu e$ scattering were unavailable at that time, as well as some of the recent ν hadron data. Nevertheless, all of these new experiments support the results obtained by Kim et al., and thus would not change the values resulting from their fits significantly.

I would like next to discuss some of the results of their fits and their implications.

a) factorization. As already mentioned, the different subsets of the data can be fitted in a totally model independent way.[75] Subsequently, the different coefficients can be compared to see if they satisfy the factorization relations (true if there is only one Z^0 present). We have seen, however, that the different pieces of data are all consistent with the GWS model, a single Z^0 hypothesis. Hence they must satisfy the factorization relations.

As an example, however, of how these tests work in practice, I illustrate in Fig. 19 the 2 regions in g_V^e , g_A^e space allowed by the νe scattering experiment. We have a general factorization relation[51]

$$g_V^e/g_A^e = \left[(\alpha + \gamma/3)(\hat{\beta} + \hat{\delta}/3)\right] / \left[(\hat{\alpha} + \hat{\gamma}/3)(\beta + \delta/3)\right]$$

whose right hand side can be evaluated from neutrino hadron and SLAC ed experiment. Without errors, this relation would give a straight line in g_V^e , g_A^e space; the errors broaden it out to two triangular sectors. Clearly, the factorization admits the predominately axial solution and is incompatible with the vector one.

b) 5 parameter fit. If one assumes SU(2) x U(1) with conventional T_{3L} assignments we can fit the data to 5 parameters, i.e.

$$\rho^2 \ , \ \sin^2\theta_W, \ T_{3R}^u \ , \ T_{3R}^d \ , \ T_{3R}^e$$

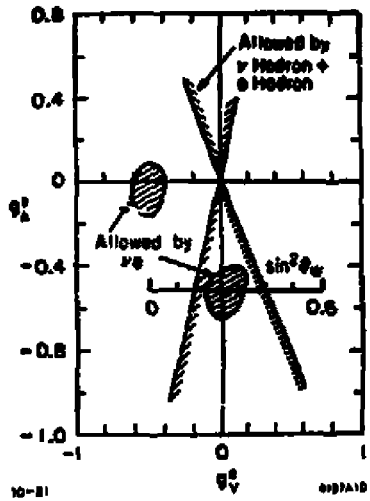

Fig. 19. A graphical representation of one of the factorization relations (from Kim et al.).

where we have ignored the μ and τ leptons as well as heavy quarks. Kim et al. obtain for this fit:

$$\rho^2 = 1.018 \pm 0.045$$

$$\sin^2\theta_W = 0.249 \pm 0.031$$

$$T_{3R}^u = -0.010 \pm 0.040$$

$$T_{3R}^d = -0.101 \pm 0.058$$

$$T_{3R}^e = -0.039 \pm 0.047$$

The feature of the fit that I want to emphasize here is that all right-handed fermions are compatible with the singlet assignment, i.e. GWS model. More specifically, doublet structure of the type $(E^0\ e^-)_R$ is ruled out, where E^0 is a heavy righthanded electron neutrino.

Note that these data cannot say anything about heavy neutral muon neutrino, since none of the μ data were included in the fit. However, there is now independent evidence against $(N^0\ \mu^-)_R$ doublet from the work of A. R. Clark et al.[76] who rule out an N^0 decaying via

$$N^0 \to \mu^+ \mu^- \bar{\nu}_\mu$$

in the range $1 \leq m_{N^0} \leq 9$ GeV.

c) 2 parameter fit. Accepting the singlet assignment for the right handed fermions, the data can be fitted to 2 parameters only: ρ^2 and $\sin^2\theta_W$. The results of Kim et al. are,

$$\rho^2 = 1.002 \pm 0.015$$

$$\sin^2\theta_W = 0.234 \pm 0.013$$

The value of ρ^2 consistent with unity indicates that the data are consistent with Higgs doublet structure, i.e. absence of any other multiplets for Higgs scalars. In addition, this result has

implications on possible existence of heavy fermions. Because of renormalization effects involving loop diagrams, the presence of such fermions would be expected to displace the value of ρ away from unity. Specifically, the quoted 90% confidence level upper limit on ρ implies[77] an upper limit on any heavy fermion of 500 GeV, assuming that its partner is massless.

d) single parameter fit. Finally one can constrain $\rho^2 = 1$ and fit to $\sin^2\theta_w$ only. The result is

$$\sin^2\theta_w = 0.233 \pm 0.009$$
$$\chi^2 = 33.1 \text{ for } 45 \text{ d.o.f.}$$

This is an impressive result, and a great success for GWS model considering the variety of experimental results that have gone into this fit, and the fact that some of the input data are determined reasonably accurately by now. I should also emphasize that the new data obtained since Kim et al. fit will make this conclusion even stronger, since all of it is consistent with the above quoted value of $\sin^2\theta_w$.

4. GLASHOW-ILIOPOULOS-MAIANI (GIM) MODEL

The GIM model[4] was invoked to explain the absence of neutral currents in strangeness changing interactions deduced from searches for the decays

$$K_L^0 \to \mu^+\mu^-$$

and

$$K^+ \to \pi^+ \nu\bar{\nu} \ .$$

The authors picked up on an earlier suggestion by Bjorken and Glashow[78] to postulate a fourth quark, charm, which symmetrized the overall situation in the quark sector by hypothesizing that the left-handed quark doublets that participate in weak interactions are

$$\left(d \cos\theta_c + s \sin\theta_c\right)_L^u \qquad \text{and} \qquad \left(-d \sin\theta_c + s \cos\theta_c\right)_L^c$$

where θ_c is the previously discussed Cabibbo angle.

This postulate had far reaching consequences both in the field of spectroscopy of new particles and in the field of their

interactions (i.e. currents). The space is too short here to describe the many successes in spectroscopy; the basic idea was that the postulate of a new quark, with a new quantum number conserved by both strong and electromagnetic interactions, would imply that there should exist a whole spectrum of new particles,[79] both of the type $(\bar{c}c)$ and of the $(c\bar{q})$, (cqq), etc., where q stands for a light quark. Furthermore, the lowest lying charm states should be long lived ($\tau \gtrsim 10^{-13}$ sec) and decay only by weak interactions.

It is now well known that the observed charm spectroscopy agrees well with what one might expect from the GIM model and its many succeeding elaborations. One has seen the expected bound states (ψ/J , ψ' , η_c , χ) as well as the open charm states (D, F, Λ_c) and their masses agree remarkably well with the predictions of the model. Since these subjects have been reviewed extensively in the literature,[80] I will not discuss them any further, but turn instead to the question of predicted currents.

I shall start out by enumerating in Table VI the currents that are possible within the 4 quark model.

Table VI

Weak interaction currents in the 4 quark model

Current	ΔQ	ΔS	ΔC	GIM-Cabibbo Strength	K-M Strength	Typical Relevant Experiments
1) $\bar{u}d$	-1	0	0	$\cos\theta_c$	c_1	β decay, ν interactions
2) $\bar{u}s$	-1	-1	0	$\sin\theta_c$	s_1c_3	Ke_3, hyperon decay
3) $\bar{d}c$	1	0	1	$\sin\theta_c$	$-s_1c_2$	ν-charm, forbidden D decays
4) $\bar{s}c$	1	1	1	$\cos\theta_c$	$c_1c_2c_3-s_1s_3e^{i\delta}$	allowed D decays
5) $\bar{u}u$	0	0	0	depends on $\sin\theta_w$	-	N.C. ν interactions electron hadron interactions
6) $\bar{d}d$	0	0	0		-	
7) $\bar{s}s$	0	0	0	same as dd	-	ν interactions
8) $\bar{c}c$	0	0	0	same as uu	-	ν interactions, $\psi \to \nu\nu$
9) $\bar{d}s$	0	1	0	absent	-	$K_L^0 \to \mu^+\mu^-$, $K^+ \to \pi^+\nu\bar{\nu}$
10) $\bar{u}c$	0	0	1	absent	-	ν-charm-ν, charm decays

The first 2 charged currents and the first 2 neutral currents are "old" currents that have already been discussed. Furthermore the $\bar{d}s$ current is also an "old" current whose absence was the raison d'être for the GIM mechanism. Accordingly I shall limit my discussion to the other 5 currents, emphasizing mainly the comparison of the experimental data with the GIM predictions. One should note that the extension to the 6 quark mode (K-M scheme) will not change predictions within the experimental errors, since the K-M and GIM predictions are different only in the 2nd order of what appear experimentally to be small quantities (I use standard notation where $c_1 \equiv \cos\theta_1$, $s_3 \equiv \sin\theta_3$, etc.).

$\bar{d}c$ coupling. In principle one can extract this information in 2 different ways: by studying either charm production in ν interactions or the Cabibbo forbidden D decays. It turns out that the only reliable quantitative information one can obtain is from the lst process, so I shall discuss it first following the treatment of Sakurai[7] and Pakvasa, Tuan, and Sakurai.[81]

Charm can be produced in ν interactions in one of two ways: either off the d quarks

$$\nu + d \to \mu^- + c$$

or off the s quarks in the sea

$$\nu + s \to \mu^- + c \ .$$

It is the first process that is relevant to the coupling of interest; it can be separated out by studying the x distribution with the conclusion that 50-63% of charm production (more rigorously: oppositely charged dileptons, since that is signature used for charm identification) comes off the d quark. Using the total measured dilepton rate ($\sim 10^{-2} \pm 30\%$), allowing for threshold effects, and taking (9±1)% as the average semi-muonic branching ratio, one obtains

$$0.19 < |s_1 c_2| < 0.34 \ .$$

This should be compared with $\sin\theta_c = 0.229$ quoted earlier.

The Cabibbo suppressed branching ratio

$$D \to \pi + e + \nu_e$$

coupled with the lifetime measurement could in principle determine the same parameter, just as Ke_3 determines the value of $\sin\theta_c$. However, no data on these decay modes are available as yet. The non-leptonic branching ratios of the D^0 measured[82] to be

$$\Gamma(\pi^+\pi^-)/\Gamma(K^-\pi^+) = (3.3 \pm 1.5)\% \quad \Gamma(K^-K^+)/\Gamma(K^-\pi^+) = (11.3 \pm 3.0)\%$$

are difficult to interpret theoretically because of strong interaction effects. It can only be said that they support the qualitative conclusion that $\bar{d}c$ coupling is of order $\sin\theta_c$.

$\bar{s}c$ coupling. The cleanest channel to study here is

$$D^+ \to \bar{K}^0 + e^+ + \nu_e$$

because symmetry breaking effects are minimized in this channel for the same reason as in Ke_3 decay. The experimental input consists of D^+ lifetime and $D^+ \to \bar{K}^0 e^+ \nu_e$ exclusive branching ratio.[83] Together they yield:

$$\Gamma(D^+ \to K^0 e^+ \nu_e) = (1 \pm 0.5)\times 10^{11}\ \text{sec}^{-1}$$

This value, coupled with the assumption that the form factor in the decay is dominated by the F^* yields[7]

$$|c_1 c_2 c_3 - s_1 s_3 e^{-i\delta}| = 0.8 \pm 0.2$$

$\bar{s}s$ coupling. This neutral current coupling can be obtained from the $d\sigma/dy$ distribution in neutrino hadron neutral current interactions. The contents of the s, $\bar{s}$ sea has to be first obtained from charged current interactions. Jonker et al. obtain[84]

$$|g_s|^2/|g_d|^2 = 1.39 \pm 0.43$$

$\bar{c}c$ coupling. The strength of this coupling can be measured by observing ψ/J production in neutrino interactions, that presumably proceeds through the diagram illustrated in Fig. 20. The CDHS collaboration quotes[85]

$$|g_c|^2/|g_u|^2 = 1.7 \pm 0.5$$

In principle, at least, this coupling could also be measured by observing the decay mode $\psi/J \to \nu\bar{\nu}$, if one would know the exact number of neutrino flavors.

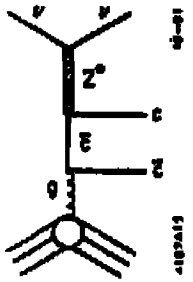

Fig. 20. Diagram for ψ/J production by neutrinos.

I should add here parenthetically that the fact that $e^+e^- \to$ hadrons agrees with the theory at high energies[74] says that N.C. coupling of heavy quarks (including $\bar{b}b$) cannot be anomalously large.

$\bar{u}c$ coupling. This current should vanish in the GIM model. It can be looked for in the reactions like

$$\nu_\mu + A \to \nu_\mu + c + \ldots$$
$$\qquad\qquad\quad \downarrow \to e^+ + \nu_\mu + \text{hadrons}$$

i.e. charm production by neutrino beams without any final state muon. From their work in neon filled bubble chamber, Baltay quotes[86]

$$\frac{\sigma \text{ (charm changing N.C.)}}{\sigma \text{ (total N.C.)}} \leq 3\%$$

based on no significant signal found. I believe that a comparable or better limit can be extracted from the emulsion work[87] in the ν beam at Fermilab, designed to measure charmed particle lifetime.

Alternatively, one can search for neutral current charm decays, for example by looking in neutrino interactions for signatures of the type

$$\nu_\mu + A \to \mu^- + c + \ldots$$
$$\qquad\qquad\quad \downarrow \to e^+ + e^- + \text{hadrons}$$

Based on no events of this type found, Baltay quotes[86]

$$\frac{\Gamma \text{ (charm changing neutral currents)}}{\Gamma \text{ (charm changing charged currents)}} \leq 2\%$$

In summary, the spectroscopy and interactions of the charm particles are in good agreement with the GIM model. In several sectors, however, there exists great deal of room for experimental improvement.

5. EXTENSION TO 6 QUARKS

In a remarkable paper, written before the discovery of the c quark, Kobayashi and Maskawa[5] argued that within the simplest SU(2) x U(1) model (i.e. only one Higgs doublet) with only 4 quarks, there

is no natural way to generate CP violation. They showed that one of the possible ways to have CP violation within this model, was to enlarge the quark population to 6. Within this framework the charged current would be written as:

$$J_+ = (\bar{u}\ \bar{c}\ \bar{t})\ U \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

where U is a unitary matrix that defines the mixing of the mass eigenstates. For the 3 x 3 dimensionality U is characterized by 3 Euler-like angles and one phase. Specifically U can be written[88] as

$$U = \begin{pmatrix} c_1 & c_3 s_1 & c_1 s_3 \\ -c_2 s_1 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + c_3 s_2 e^{i\delta} \\ s_1 s_2 & -c_1 c_3 s_2 - c_2 s_3 e^{i\delta} & -c_1 s_2 s_3 + c_2 c_3 e^{i\delta} \end{pmatrix}$$

This scheme became more attractive as τ lepton gained respectability, insofar that equality of quark and lepton populations (with conventional charge assignments) is one way to remove the triangle anomalies. The scheme became the "new orthodoxy" with the discovery[89] of Υ at Fermilab and its subsequent confirmation[90] at DESY. I would like to review in this chapter the question as to how well this "new orthodoxy" is supported by the experimental data.

We may first ask how well is the existence of this new doublet established. There is now reasonably good circumstantial evidence that new flavor has been produced in the e^+e^- annihilations: from the Υ spectroscopy,[91] the excess electron[92] and kaon[93] production at the 4S Υ state, and the value of R at high energy.[74] On the other hand, it is not clear that any unambiguous naked beauty b signal has been seen as yet.[94] In summary, however, I think most people would agree that the evidence for existence of a b quark is quite good.

What about the top quark, t ? PETRA detectors have searched for the t quark up to the highest energies of that ring and see no evidence of t production.[95] This places an upper limit of $m_t \lesssim 18$ GeV. Should this be a source of worry to the advocates of the 6 quark model? The theoretical estimates are uncertain, but it appears that

t quark mass of around 40 GeV would not be too surprising.[96] A fair statement to make would probably be to say that even though there is no experimental evidence for the t quark, neither do the present searches speak strongly against the existence of a (t b) doublet.

I turn next to the possible alternative multiplet assignments of the b quark.[97] The Glashow-Weinberg theorem no longer guarantees automatic suppression of neutral currents,[50] and thus one might expect an appreciable decay rate into 2 charged leptons, i.e.

$$b \to e^+ + e^- + X$$

$$b \to \mu^+ + \mu^- + X$$

The exact prediction is impossible to make because it depends on the mixing parameters of the K-M matrix (the form of the matrix remains the same as for the 6 quark picture.) The requirement that $\Delta S=1$ neutral currents are absent forms now one of the constraints that have to be imposed in obtaining possible solutions of the K-M matrix. V. Barger and S. Pakvasa have examined the possible alternatives[99] and conclude that

$$B(b \to e^+e^-X) = B(b \to \mu^+\mu^-X) \gtrsim 1\text{-}2\% \quad ,$$

This prediction already appears to be in trouble with the latest results[100] from the Cornell e^+e^- work.

The other possible alternative away from the standard models is a $(c\ b)_R$ doublet. This doublet is hard to rule out experimentally because FC couplings can be strongly suppressed in this case;[97] only detailed study of b→c decays could exclude this possibility.

Thus it appears that $(t\ b)_L$ alternative is the most appealing one. I would like to end this chapter with a very brief discussion of how well the K-M parameters are determined. Any self-inconsistency in this determination would be evidence for necessary modifications or expansion of the K-M scheme (8 quarks?).

I have already discussed previously the determination of U_{cd}, U_{us}, U_{cs} elements (the subscripts refer to the 2 quarks linked by a given element). Until t quark is discovered, no direct information

on U_{td}, U_{ts}, and U_{cb} is possible. It remains to discuss U_{ud}, U_{ub}, U_{cb}, and the constraints on θ_1, θ_2, θ_3, and δ imposed by our information about these matrix elements.

The U_{ud} element is obtained by comparing the strength of the weak interaction constant as obtained from pure Fermi β decays to that obtained from μ decay. The most recent analysis gives[101]

$$|U_{ud}| = 0.977 \pm 0.0025 \quad .$$

At present there exists no experimental information on U_{ub} and U_{cb} separately. A lower (and not very useful) limit on the sum of their squares

$$|U_{cb}|^2 + |U_{ub}|^2 \gtrsim 10^{-4}$$

can be obtained from the upper limit on B lifetime ($\tau_B < 3 \times 10^{-11}$ sec) by assuming the spectator model, which does not appear to work too well in D decays.

More useful information exists on the ratio of these 2 matrix elements, $|U_{ub}/U_{cb}|$, from the study of the details of b decay. A relatively large value of U_{cb} would result in a larger numbers of K's and a lower energy charged lepton spectrum, than one would have if U_{ub} dominated. The experimental situation on the electron spectrum strongly[92,101] supports the large U_{cb} element (shown in Fig. 21).

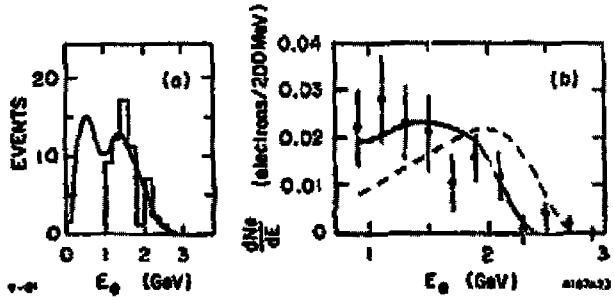

Fig. 21. The observed experimental energy spectrum of electrons from the 2 CESR detectors taken at the 4S T: a) data from CLEO detector with 1 GeV experimental cutoff. The curve corresponds to the spectrum expected on the basis of b→c decay. b) data from CUSB detector compared with $B \to e\nu(D,D^*)$ prediction (solid curve) and $B \to e\nu X$ (M_X = 1 GeV) prediction (dashed curve).

A quantitative interpretation of these plots is difficult because of the uncertainties about the mass of the final state hadronic system. Thus the CUSB group[102] obtains for $\Gamma(B\to eX_u)/\Gamma(B\to e\nu D,D^*)$

$\lesssim 0.23$ (90% C.L) if X_u = 50% (π,η) and 50% (ρ,ω)

≤ 0.32 (90% C.L) if X_u = 1 GeV .

Similarly the measured number of K's/event[93] is $2.5 \pm 0.5 \pm 0.5$ to be compared with the prediction of the standard model[103] of

$N_K = 1.5$ for b→c transition

$N_K = 0.7$ for b→u transition

Superficially, at least, both pieces of evidence support predominance of the b→c decay mode.

We finally interpret these results on the U matrix elements in terms of the 4 basic parameters. Logically the steps are as follows:

a) from U_{ud} that measures c_1 one can deduce that

$$s_1 = 0.23 \pm 0.01$$

b) U_{ud} and U_{us} $(c_3 s_1)$ give the relation

$$c_1^2 + s_1^2 c_3^2 = 1 - s_1^2 s_3^2 = 0.996 \pm 0.004$$

or $$s_1^2 s_3^2 = 0.004 \pm 0.004$$

yielding $$s_3 = 0.27^{+0.12}_{-0.27}$$

c) U_{cd} $(s_1 c_2)$ then gives

$$s_1 c_2 = 0.265 \pm 0.07$$

or $$s_2 \leq 0.57$$

d) $U_{c'}$ $(c_1 c_2 c_3 - s_2 s_3 e^{i\delta})$ imposes a coupled constraint on s_2 and s_3 which for small θ_2 and θ_3 can be approximated as

$$\theta_2^2/2 + \theta_3^2/2 + \theta_2\theta_3 \leq 0.4 \quad \text{for } \delta=0$$

$$\theta_2^2/2 + \theta_3^2/2 - \theta_2\theta_3 \leq 0.4 \quad \text{for } \delta=\pi$$

e) $|V_{ub}/V_{cb}|$ ratio ($|s_1 s_3/(c_1 c_2 s_3 + c_3 s_2 e^{i\delta})|$) can also be translated into a constraint in the s_2, s_3 plane.

The 4 constraints of s_2 and s_3 are illustrated graphically in Fig. 22, for 2 specific values of δ, i.e. 0 and π.

For completeness, one should mention that a limit on θ_2 can be obtained from theoretical arguments based on the K_L^0-K_S^0 mass difference.[104] We recall that the original estimate[105] for the mass of the charm quark came by estimating the $\Delta m(K_L$-$K_S)$ from box-diagrams in Fig. 23. Of course, in those days the t quark was not included in such calculations, but the fact that the mass of the c quark came surprisingly close to the theoretical expectations, argues that the contribution of the t quark to the mass difference cannot be too large. Very roughly that contribution is

$$\Delta m\,(K_L\text{-}K_S) \propto m_t^2 \times \text{strength of } \bar{t}d\text{-}\bar{t}s \text{ couplings}$$

Arguing that contribution due to t quark should not be greater than that due to c quark leads to inequality

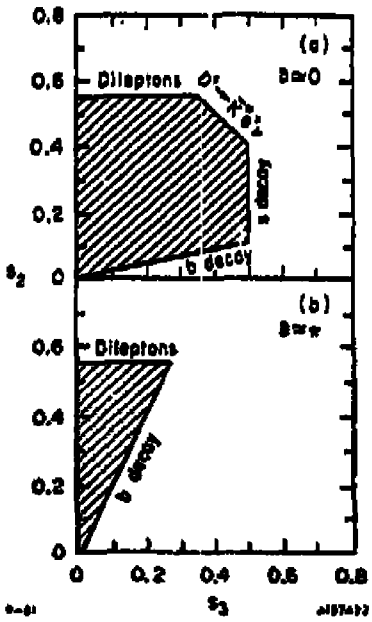

Fig. 22. Constraints imposed on $\sin\theta_2$ and $\sin\theta_3$ by different experiments (from Sakurai).

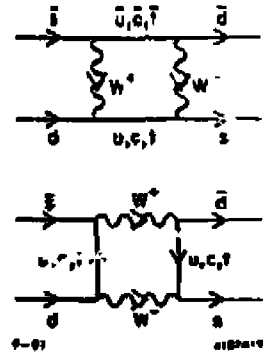

Fig. 23. Box diagrams contributing to the K_L^0-K_S^0 mass difference.

$$\tan\theta_2 \lesssim \frac{m_c}{m_t} \lesssim 0.3 .$$

It is instructive to look at the K-M matrix by using the values of s_1, s_2, and s_3 derived from the arguments applied above. I reproduce below the matrix as derived by Sakurai[7] from his typical values for $\delta=0$, i.e.

$$s_1 = 0.227 \quad s_2 = 0.250 \quad s_3 = 0.262$$

He then obtains

$$U = \begin{pmatrix} 0.974 & 0.219 & 0.059 \\ -0.213 & 0.845 & 0.488 \\ 0.057 & 0.489 & 0.870 \end{pmatrix}$$

The values (especially the last decimal figures) should not be taken literally. They are useful, however, to illustrate the feature that the couplings tend to get smaller as we get further away from the diagonal.

6. CP VIOLATION

Very little has happened experimentally in this field since the review article of K. K. Kleinknecht.[106] The general situation can be summarized very succinctly as follows:

a) CP violation has been observed[107] in the K_L^0-K_S^0 system.

b) CP violation in K_L^0-K_S^0 system is consistent with Wolfenstein's[108] superweak theory (Fig. 24).

c) No CP violation effect has been seen in any other system.[109]

On the other hand there is now a renewed interest in studying the CP violation and several precise experiments are in the running or planning stage that may shed new light on this old problem.

This revival of the experimental interest has been stimulated to a large extent by the theoretical work attempting to answer the questions posed by the CP violation either within the framework of the standard model or by applying some variant thereof.

The 2 acid tests of the different theories appear to be the ratio $|\epsilon'/\epsilon|$ that can be measured by comparing the magnitudes of

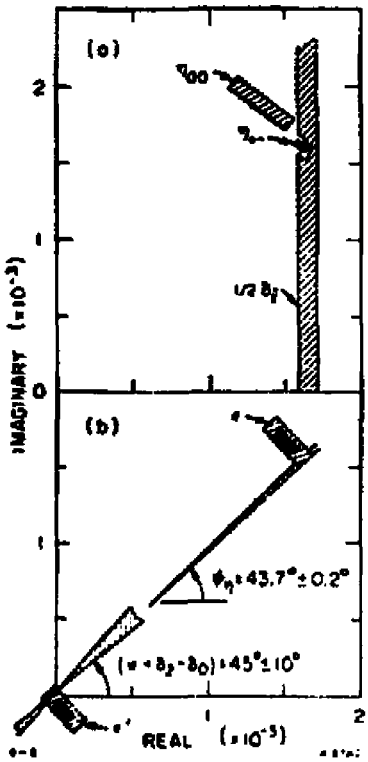

Fig. 24. Summary of measured (a) and derived (b) CP violation parameters in K_L^o-K_S^o system (from Cronin, ref. 106).

η_{+-} and η_{oo} and the electric dipole moment of the neutron. The importance of these two quantities stems partly from the fact that different theories have at least a fighting chance of making a prediction about them and partly from the fact that the present experimental limits are very close to at least some of the recent predictions. The present experimental limits are:

$$|\epsilon'/\epsilon| \lesssim 0.02 \quad [110]$$

$$d_n = (0.4 \pm 1.5) \times 10^{-24} \text{ e cm} \quad [111]$$

Within the framework of the standard model the ϵ parameter is given by [104]:

$$|\epsilon| \propto \frac{1}{\sqrt{2}} \sin\theta_2 \cos\theta_2 \sin\theta_3 \sin\delta \times F(\theta_2, m_c^2/m_t^2)$$

where the last factor is a slowly varying function of θ_2 and quark masses. Since no one knows how to calculate δ, the above equation can be viewed as a means of measuring δ (provided that there are no other contributions to CP violations). That will be possible once better knowledge of θ_2 and θ_3 will be available.

It does appear that the ratio $|\epsilon'/\epsilon|$ can be calculated within the K-M model, and the consensus of different calculations is that [112]

$$1/500 \lesssim |\epsilon'/\epsilon| \lesssim 1/50 ,$$

i.e. on the verge of experimental detectability. As for the dipole moment, however, the prediction is far away from the present limits, namely

problems.[115]

On the experimental side a highly incomplete list of topics that need to be investigated might be:

a) search for t quark
b) observation of τ neutrino
c) observation of $W^{\pm}$, Z^0, Higgs scalars
d) determination of ν masses and the ν mixing parameters
e) determination of K-M matrix parameters
f) better measurement of CP violation parameters
g) search for additional generations
h) better limits on all the couplings
i) proton stability question

plus many others.

On the theoretical side many questions remain also:

a) why is there a quark-lepton similarity?
b) is there a larger group than SU(2) x U(1)?
c) why are there only certain color-charge combinations?
d) how many generations are there? why?
e) what causes CP violation?
f) why is there left-right asymmetry? is it just a low energy phenomenon?
g) are quarks and leptons fundamental?

plus many others.

One could also ask a general question: Do we have an ultimate theory of weak interactions? I do not want to answer it, but would like to remind the reader about the existence of the large number of free parameters in the theory:

3	GWS model parameters (e, G_F, $\sin^2\theta_W$)
10	K-M matrix and quark mass parameters
10	lepton sector parameters
1	mass of Higgs scalar
1	number of generations
1	number of Higgs doublets
26	minimum total number of parameters.

If the number of Higgs doublets, number of generations, or the size of the gauge group are larger, the number of parameters can grow to a significantly higher number. Whether a theory with so many parameters can be called truly fundamental is at least partly a subjective question, that cannot be answered on any absolute scale. Most of us, however, would probably answer it in the negative.

REFERENCES

1. The interested reader is referred to a report by Mary K. Gaillard, Weak Decays of Heavy Quarks, FERMILAB-Conf-78/64-THY, lecture presented at the 1978 SLAC Summer Institute. See also SLAC Report No. 215, p. 397.
2. R. P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1958); E. C. G. Sudarshan and R. E. Marshak, Phys. Rev. 109, 1860 (1958); J. J. Sakurai, Nuovo Cimento 7, 649 (1958).
3. S. L. Glashow, Nucl. Phys. 22, 579 (1961); S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam, Elementary Particle Theory, ed. N. Svartholm (Almquist and Wiksell, Stockholm, 1968), p. 367.
4. S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D2, 1285 (1970).
5. M. Kobayashi and T. Maskawa, Progr. Theoret. Phys. 49, 652 (1973).
6. F. Scheck, Phys. Rep. C44, 187 (1978).
7. J. J. Sakurai, The Structure of Charged Currents, Rapporteur talk presented at Neutrino '81, International Conference on Neutrino Physics and Astrophysics, Wailea, Maui, Hawaii, July 1-8, 1981.
8. J. E. Kim, P. Langacker, M. Levine, H. H. Williams, Rev. Mod. Phys. 53, 211 (1981).
9. T. D. Lee and C. N. Yang, Phys. Rev. 104, 254 (1956).
10. For a review of some of the upcoming experiments see M. Strovink, Possible Deviations from (V-A) Charged Currents: Precise Measurement of Muon Decay Parameters, paper presented at the Workshop on Weak Interactions and Grand Unification, VPI, Blacksburg, Va., December 3-6, 1980, LBL-12275.
11. M. Bardon et al., Phys. Rev. Lett. 14, 449 (1965); J. Peoples, Ph.D. thesis, Columbia University, Nevis Cyclotron Laboratory Report No. 147 (1966).
12. S. Berenzo, Phys. Rev. 181, 1854 (1969).
13. D. Fryberger, Phys. Rev. 166, 1379 (1968).
14. V. V. Akhmanov et al., Sov. J. Nucl. Phys. 6, 230 (1968).
15. J. Egger, Nucl. Phys. A335, 91 (1980).
16. I was informed at the Santa Cruz Conference that the new data taken by the ETH-SIN-Mainz Collaboration and presented at the 1981 Versailles Conference has allowed them to reduce the errors on β and β' by approximately a factor of 2. The central values are still consistent with zero (M. Strovink - private communication).
17. C. Jarlskog, Nuov. Cim. Lett. 4, 377 (1970).
18. N. Armenise et al., Phys. Lett. 84B, 137 (1979).
19. Reported by G. Barbiellini, ν_N: Structure of weak interactions, rapporteur talk given at the 1981 International Symposium on Lepton and Photon Interactions at High Energies, Bonn, August 24-29, 1981.
20. M. Jonker et al., Phys. Lett 86B, 229 (1979).
21. V. Amaldi (private communication); also G. Barbiellini (ref. 19).
22. G. Feinberg and S. Weinberg, Phys. Rev. Lett. 6, 38 (1966).

23. S. E. Willis et al., Phys. Rev. Lett. 44, 522 (1980) and 903 (E), (1980).
24. An experiment by V. A. Lubimov et al., Phys. Lett. 94B, 266 (1980), however, reports $14 < m_{\nu_e} < 46$ ev at the 99% C.L.
25. For a recent review of this subject see D. Bryman and C. Picciotto, Rev. Mod. Phys. 50, 11 (1978).
26. M. K. Moe and D. D. Lowenthal, Phys. Rev. C22, 2186 (1980).
27. W. C. Haxton, G. J. Stephenson, Jr., and D. Strottman, Phys. Rev. Lett. 47, 153 (1981).
28. M. L. Perl, Ann. Rev. Nucl. Part. Sc. 30, 299 (1980).
29. W. Bacino et al., Phys. Rev. Lett. 42, 749 (1979).
30. See G. Feldman's review at this Conference for the details of this argument.
31. R. Hollebeek, Recent results from PEP on hadronic final states and weak interference effects; talk given at the 1981 International Symposium on Lepton and Photon Interactions at High Energies, Bonn, August 24-29, 1981.
32. See ref. 2 and S. S. Gerstein and J. B. Zeldovitch, Z. Eksperim. Teor. Fiz. 29, 698 (1955).
33. V. L. Highland et al., Preliminary Report on a New Pion Beta Decay Experiment, paper submitted to 9-ICOHEPANS, Versailles, France, July 5-12, 1981.
34. J. Dorfan, Proceedings of the XX International Conference on High Energy Physics, Madison, Wisconsin (L. Durand and L. G. Pondrom, editors), p. 368.
35. Y. S. Tsai, SLAC-PUB-2450.
36. Quoted by G. Barbiellini (ref. 19).
37. N. Cabibbo, Phys. Rev. Lett. 10, 531 (1963).
38. M. Ademollo and R. Gatto, Phys. Rev. Lett. 13, 264 (1964).
39. S. Shrock and L.-L. Wang, Phys. Rev. Lett. 41, 1692 (1978).
40. M. Bourquin et al., Bristol-Geneva-Heidelberg-Orsay-Rutherford-Strasbourg (UA2 Collaboration), contributed paper to Intern. Conference on High Energy Physics - Lisbon (Portugal), 9-15 July, 1981, Université Paris-Sud reprint, LAL 81/18.
41. J. M. Dorfan et al., Phys. Rev. Lett. 46, 215 (1981); see also G. Feldman's report at this Conference.
42. H. E. Haber, G. L. Kane, and T. Sterling, Nucl. Phys. B161, 493 (1979).
43. B. McWilliams and L.-F. Li, Nucl. Phys. B179, 62 (1981).
44. M. A. Bég et al., Phys. Rev. Lett. 38, 1252 (1977).
45. B. R. Holstein and S. B. Treiman, Phys. Rev. D16, 2369 (1977).
46. F. W. Koks and J. van Klinken, Nucl. Phys. A272, 61 (1976).
47. For a general introduction to gauge theories see for example H. Quinn, Gauge Theories of the Weak Interactions, SLAC Report No. 215 p. 167; S. Weinberg, Rev. Mod. Phys. 46, 255 (1974); E. S. Abers and B. W. Lee, Phys. Rep. 9C, 1 (1973).
48. J. Bjorken and C. H. Llewellyn Smith, Phys. Rev. D7, 887 (1973).
49. M. Holder et al., Phys. Rev. Lett. 39, 433 (1977).
50. S. L. Glashow and S. Weinberg, Phys. Rev. D15, 1958 (1977).
51. P. Q. Hung and J. J. Sakurai, Phys. Lett. 69B, 323 (1977).
52. F. Reines, H. S. Gurr, and H. W. Sobel, Phys. Rev. Lett. 37, 315 (1976).

53. H. Jonker et al., CERN-EP/81-66, submitted to Phys. Lett.
54. E. H. Heisterberg et al., Phys. Rev. Lett. 44, 635 (1980).
55. For a more detailed discussion see L. Wolfenstein, AIP Proceedings No. 23, Division of Particles and Fields, Williamsburg, Sept. 1974 (C. E. Carlson, editor), p. 84.
56. J. G. Branson, Electro weak tests, rapporteur's talk a. the 1981 International Symposium on Lepton and Photon Interactions at High Energies, Bonn, August 24-29, 1981.
57. M. Pohl, Review talk given at the XVIth Rencontre de Moriond, Les Arcs, March, 1981: Aachen Report 81/10, April, 1981.
58. L. F. Abbott and R. M. Barnett, Phys. Rev. D18, 3214 (1978).
59. H. Jonker et al., Phys. Lett 99B, 265 (1981) and Phys. Lett. 102B, 67 (1981); P. Coteus et al., Phys. Rev. D24, 1420 (1981); R. Mariah et al., AIP Proceedings No. 68 (XX International Conference, Madison, Wis.), p. 741.
60. For a more detailed discussion of this problem see e.g. L. Wolfenstein, Phys. Rev. D19, 3450 (1979).
61. S. L. Adler et al., Phys. Rev. D13, 1216 (1976) and the earlier references cited in this work; see also ref. 58.
62. E. Fasierb et al., Phys. Rev. Lett. 43, 96 (1979).
63. C. Y. Prescott et al., Phys. Lett. B72, 489 (1978) and Phys. Lett. B84, 524 (1979).
64. R. N. Cahn and F. J. Gilman, Phys. Rev. D17, 1313 (1978).
65. For some of the older theoretical calculations see E. M. Henley and L. Wilets, Phys. Rev. A14, 1411 (1976) and M. W. S. M. Brimicombe et al., J. Phys. B9, 49 (1976). For more recent calculations see M. J. Harris et al., J. Phys. B11, L749 (1980) and P. G. H. Sanders, Phys. Scr. 21, 284 (1980). Part of the change in the theoretical results is due to a different value of $\sin^2\theta_W$ used in the original calculations (0.35 rather then 0.23 commonly used now). That alone accounted for 21% reduction in theoretical expectation.
66. P. H. Buckshaum et al., Phys. Rev. D24, 1134 (1981) and Phys. Rev. Lett. 46, 640 (1981).
67. L. L. Lewis et al., Phys. Rev. Lett. 39, 795 (1977).
68. J. H. Hollister et al., Phys. Rev. Lett. 46, 643 (1981).
69. L. M. Barkov and M. S. Zolotorev, Phys. Lett. 85B, 308 (1979).
70. P. E. G. Baird et al., Phys. Rev. Lett. 39, 798 (1977).
71. Preliminary result of a new experiment of P. E. G. Baird et al., quoted by E. N. Fortson and L. Wilets, Advances in Atomic and Molecular Physics, Vol. 16, p. 319 ff (1980).
72. Y. V. Bogdanov et al., JETP Lett. 31, 214 (1980).
73. The basic point here is that the interactions coupled to nuclear density are coherent and thus dominate over interactions coupled to nuclear spin which is of order unity; see L. Wilets, Neutrino '78, edited by E. C. Fowler (Purdue U., West Lafayette, Indiana) p. 437 (1978) or E. M. Henley, Comments Nucl. Part. Phys. 7, 79 (1977).
74. D. P. Barber et al., Phys. Rev. Lett. 46, 1663 (1981).
75. For a recent analysis of this kind see P. Q. Hung and J. J. Sakurai, Phys. Lett. 88B, 91 (1979).
76. A. R. Clark et al., Phys. Rev. Lett. 46, 299 (1981).

77. M. Veltman, Nucl. Phys. B123, 89, (1977); M. S. Chanowitz, M. A. Furman, and I. Hinchcliffe, Phys. Lett. 78B, 285 (1979).
78. B. J. Bjorken and S. L. Glashow, Phys. Lett. 11, 255 (1964).
79. For a remarkable and comprehensive discussion of these predictions, written before charm discovery, see M. K. Gaillard, B. W. Lee and J. L. Rosner, Rev. Mod. Ph. 47, 277 (1975).
80. See for example G. Goldhaber and J. E. Wiss, Ann. Rev. Nucl. Part. Sci. 30, 337 (1980), T. Appelquist, R. M. Barnett, K. Lane, Ann. Rev. Nucl. Part. Sci. 28, 387 (1978).
81. S. Pakvasa, S. F. Tuan, and J. J. Sakurai, Phys. Rev. D23, 2799 (1981).
82. G. S. Abrams et al., Phys. Rev. Lett. 43, 481 (1979).
83. For summary of lifetime data see G. Trilling, Proceedings of the XX International Conference, Madison, Wisconsin (AIP, N.Y., 1981). For branching ratio determination see W. Bacino et al., Phys. Rev. Lett. 43, 1073 (1979).
84. M. Jonker et al., Phys. Lett. 102B, 67 (1981).
85. K. K. Kleinknecht (private communication); also reported by G. Barbiellini, 1981 International Symposium on Lepton and Photon Interactions at High Energies, Bonn, August 24-29, 1981.
86. C. Baltay, Proceedings of Summer Institute on Particle Physics, July 9-20, 1979; SLAC Report No. 224, p. 388.
87. K. Niu, paper presented on behalf of experiment E531 at the XX International Conference, Madison, Wisconsin; p. 352 of the Proceedings (AIP, N.Y., 1981). The study in question concerned search for possible $\nu_\mu \rightarrow \nu_\tau$ oscillation. In a sample of 600 charged current events, no event was found which satisfied following criteria: no muon from the primary vertex, a charged trident decay or kink with P_T higher than 50 MeV/c and the secondary (if identified) was not a proton. Thus this search should be quite sensitive to D^0 decays produced by neutral current interactions.
88. I use the phase convention adopted by H. Harari, Phys. Rep. C42, 235 (1978) and since that time popularized by many others.
89. S. W. Herb et al., Phys. Rev. Lett. 39, 252 (1977).
90. C. Berger et al., Phys. Lett. 76B, 243 (1978).
C. W. Darden et al., Phys. Lett. 76B, 246 (1978).
91. D. Andrews et al., Phys. Rev. Lett. 44, 1108 (1980) and Phys. Rev. Lett. 45, 219 (1980)
T. Böhringer et al., Phys. Rev. Lett. 44, 1111 (1980)
C. Finocchiaro et al., Phys. Rev. Lett. 45, 222 (1980).
92. C. Bebek et al., Phys. Rev. Lett. 46, 84 (1981).
93. E. H. Thorndike (for the CLEO Collaboration) paper presented to the XX International Conference (Madison, Wisconsin 1980), p. 705.
94. M. Basile et al., Nuov. Cim. Lett. 31, 97 (1981); see also review talk given by F. Muller at this conference.
95. See for example D. P. Barber et al., Phys. Rev. Lett. 44, 1722 (1980).
96. See for example A. J. Buras et al., Phys. Rev. Lett. 46, 1354 (1981). This topic has been reviewed extensively at this Conference by Christopher Hill.

97. See V. Barger, W. Y. Keung, R. J. N. Phillips, Phys. Rev. D24, 1328 (1981) for a discussion of details of b couplings in various models.
98. One should point out that in this model the triangle anomalies can still be removed by postulating additional quarks and/or leptons since the formal requirement is that $\sum_i Q_i^{\text{lepton}} + \sum_j Q_j^{\text{quark}} = 0$.
99. V. Barger and S. Pakvasa, Phys. Lett. B81B, 195 (1979).
100. K. Chadwick et al., Phys. Rev. Lett. 46, 88 (1981) quote $B(b \to \ell^+\ell^- X) < 1.3\%$ under certain rather reasonable assumptions. This limit has been reduced to 0.74% in the report of Sheldon Stone given at this Conference.
101. S. S. Shei, A. Sirlin, and H. S. Tsao, Phys. Rev. D19, 981 (1979).
D. H. Wilkinson and D. E. Alburger, Phys. Rev. C13, 2517 (1976).
102. L. J. Spencer et al., Phys. Rev. Lett. 47, 771 (1981).
103. S. Pakvasa, rapporteur talk at the XX International Conference (Madison, Wisconsin), 1980, (AIP No. 68, L. Durand and L. G. Pondrum, editors), p. 1165.
104. J. Ellis, M. K. Gaillard, and D. V. Nanopoulos, Nucl. Phys. B109, 213 (1976).
105. M. K. Gaillard, and B. W. Lee, Phys. Rev. D10, 897 (1974).
106. K. K. Kleinknecht, Ann. Rev. Nucl. Sci. 26, 1 (1976); see also James W. Cronin, Rev. Mod. Phys. 53, 373 (1981).
107. J. H. Christenson et al., Phys. Rev. Lett. 13, 138 (1964).
108. L. Wolfenstein, Phys. Rev. Lett. 13, 562 (1964).
109. One should mention, however, the recent theoretical speculations that the baryon-antibaryon asymmetry in the universe is due to CP violation.
110. M. Holder et al., Phys. Lett. 40B, 141 (1972).
M. Banner et al., Phys. Rev. Lett. 28, 1597 (1972).
111. W. B. Dress et al., Phys. Rev. D15, 9 (1979).
112. F. J. Gilman and M. Wise, Phys. Rev. D20, 2392 (1979).
B. Guberina and R. D. Peccei, Nucl. Phys. B163, 289 (1980).
113. D. V. Nanopoulos, A. Yildiz, and P. H. Cox, Phys. Lett. B87, 53 (1979)
B. F. Morel, Nucl. Phys. B157, 23 (1979).
114. For a general review of this topic and a list of original references, see: R. D. Peccei, Patterns of CP violation, Invited talk at the IV Warsaw Symposium on Elementary Particle Physics, Kazimiers, Poland, May 25-30, 1981. MPI-PAE/Pth 28/81. S. Pakvasa, ref. 102.
115. Similar points have been made many times before, see for example: H. Harari, Proceedings of Summer Institute on Particle Physics, July 28-August 8, 1980, SLAC Report No. 239.