WIS-85/7/Feb-Ph

Weak Interactions of Quarks and Leptons (Theory)

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Lectures presented at the Twelfth Annual SLAC Summer

Institute on Particle Physics (Stanford, July 1984)

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1. The "Minimal" Standard Model. The *minimal* version of the standard model of electromagnetic, weak and color interactions is based on the gauge group SU(3)xSU(2)xU(1). It contains three generations of quarks and leptons: (u, d, ν_e, e); (c, s, ν_μ, μ); (t, b, ν_τ, τ). The model includes twelve gauge bosons ($W^+, W^-, Z^\circ, \gamma$ and eight gluons) as well as a physical scalar field φ°. The minimal number of fundamental parameters is 19:

(i) Six quark masses.

(ii) Three generalized Cabibbo angles in the quark sector.

(iii) One K-M phase in the quark sector.

(iv) Three charged-lepton masses.

(v) Three independent coupling constants (say α, θ_W and Λ_{QCD}).

(vi) M_W and M_φ.

(vii) An extra parameter θ multiplying the $F_c\tilde{F}_c$ term in the Lagrangian.

2. Extensions *Within* the Standard Model. The above list of particles, parameters and basic features refers to the most minimal and economic version of the model. It is, however, commonly accepted that several extensions of the minimal version may turn out to be experimentally necessary. This may happen in any of the following ways:

(*i*) Neutrinos may have masses. In this case we must immediately add at least seven additional parameters: Three neutrino masses, three generalized Cabibbo angles for the lepton sector and one generalized K-M phase for the lepton sector.

(*ii*) We may have several scalar fields. In such a case we must have not only additional neutral scalars but also physical charged φ^+ and φ^- particles. A number of additional parameters will then emerge in the Higgs sector.

(*iii*) It is even possible that an additional scalar multiplet will not be in an SU(2) doublet. In this case M_W, M_Z and θ_W become three independent parameters. However, the apparent success of the relation $M_W/M_Z = cos\theta_W$ indicates that this is not very likely. A scalar triplet may also induce Majorana masses for neutrinos, further increasing the number of parameters in the neutrino sector.

(*iv*) A fourth generation of quarks and leptons (and a fifth, etc.) may exist. In the quark sector we would then need seven additional parameters (two masses, three angles, two phases). In the lepton sector we may need at least one additional parameter, possibly seven.

All in all, the standard model, including possible "trivial" extensions, must involve at least 19 and possibly 30 or more independent free parameters.

3. Experiments Which May Contradict the Standard Model. The standard model is an incredible theoretical and experimental success. It is pointless to list, at this stage, the impressive set of experiments which have confirmed various aspects of the model. Except for the scalar φ°, all the particles of the model (quarks, leptons and gauge bosons) have now been apparently observed. Perhaps the most amazing proof of the

experimental success of the model, is the list of experiments which may necessitate new physics beyond the model. Such a list has been compiled from time to time, but so far it has never included even one fully established experimental fact. Our version of this list in the summer of 1984 is extremely short:

(*i*) If the universe has now a nonvanishing baryon number, and if it had no baryon number at the big bang (two reasonable but not absolutely certain assumptions) then we must have baryon number violation. The standard model does not forbid it, but does not provide any mechanism for it. Any B-violation requires physics beyond the standard model.

(*ii*) Recent measurements of the b-quark lifetime and branching ratios, the t-quark mass and the ϵ'-parameter in CP-violating K^{o}-decays,[1] indicate that the K-M mechanism and the standard model may not be able to account for all CP-violations. Better measurements are needed before we can be convinced that we have here a definite problem. If we do, we may need some new physics which goes beyond the standard model. We return to this issue in great detail in Sections 18-21.

(*iii*) A large sample of unexplained events has been accumulated at the UA1 and UA2 experiments at the CERN $\bar{p}p$ collider.[2] They include Z^{o} decays into $e^{+}e^{-}\gamma$, single jet events, single photon events, and other interesting events, all unexplainable within the framework of the standard model. It is unlikely that all of these effects are real. It is equally unlikely that all of them represent experimental errors and/or wild statistical fluctuations. Consequently, it appears that at least some of the peculiar collider events may represent new physics.

(*iv*) The recently observed[3] $\varsigma(8.3)$ peak at the single photon spectrum coming from Υ decay, does not seem to be consistent with the minimal version of the standard model. The ς cannot be the single φ^{o} scalar of the minimal scheme. It could possibly be one of several scalar particles. If the existence of the ς is confirmed, it may represent either a more complicated Higgs sector, or some new physics beyond the standard model. (A few weeks after the above paragraph was written, new data[3] indicate that the ς may have been a statistical fluctuation. It is amazing how often experiments which cannot coexist with the standard model, turn out to be erroneous).

The brevity of the above list and the doubts accompanying each of its items are perhaps the strongest testimony for the impressive experimental validity of the standard model!

4. Why Go Beyond the Standard Models? The main reasons for demanding new physics beyond the standard model are based on theoretical prejudices and on the traditional urge for a short and simple list of basic forces, building blocks and parameters. The list of motivations is, by now, very familiar. Let us remind ourselves once more:

(*i*) Whether 19 or 30, the number of fundamental free parameters in the standard model is too large. We feel that we should be able to compute many of them, starting from a smaller number of constants.

(*ii*) The triplications of generations is clearly a puzzle in search of an explanation, and the explanation can only be found beyond the standard model.

(*iii*) The subtle correlation between quark properties and lepton properties cannot be accidental (simple electric charge ratios; identical SU(2) behavior; color-charge correlations; anomaly cancellation of quarks against leptons). Any deep quark-lepton connection must be beyond the standard model.

(*iv*) Now that all interactions are gauged, the old desire to unify as many interactions as possible, becomes an extremely sensible goal. This can be achieved only beyond the standard model.

(*v*) The "hierarchy problem" (or the "fine tuning problem") are serious theoretical problems if the next physics scale is the Planck mass scale. These problems disappear (or get postponed) if the next scale of physics is around 1-10 TeV. However, such a nearby scale would clearly imply that new physics, beyond the standard model, is around the corner.

In addition to the above standard list, we may mention issues such as parity violation (explicit or spontaneous?), strong and weak CP-violation, connection to gravity, etc. The more we look at the standard model, the more we are impressed with its success and the more we are convinced that the new physics beyond the model is inevitable.

5. Classes of "Beyond the Standard Model" Theories. Six main classes of directions have been pursued:

(a) Left-right symmetric theories.

(b) Horizontal symmetries.

(c) Technicolor (and extended technicolor) schemes.

(d) Supersymmetry (SUSY).

(e) Composite models.

(f) Grand unified theories (GUTS).

Needless to say, in each of these directions, many different models have been pursued. Furthermore, it is very reasonable to consider combinations such as supersymmetric composite models or left-right symmetric grand unified theories or a theory incorporating GUTS, SUSY, horizontal symmetry and technicolor. The total number of different attempts must be well over a hundred, by now. We do not plan to cover all of them or even many of them, in these lectures. Instead, we wish to study some of their main features and touch upon several phenomenological issues which are common to many of the models which go beyond the standard model.

6. Which Class of Models Addresses Which Problem? At the risk of being somewhat superficial we present here a table which briefly summarizes the relations between the five reasons which send us "beyond the standard model" and the six classes of models which have been pursued (see Table 1). It is clear from the table that no single remedy cures all diseases. If the correct solution is contained within the six classes of models, it is likely to require a combination of two or more ingredients.

	Left-right Symmetry	Horizontal Symmetry	Techni-color	SUSY	Composite Models	GUTS
1. Too many parameters	Somewhat more than standard model	Somewhat less than standard model	More than standard model	More than standard model	! (in principle)	More than standard model
2. Generation puzzle	—	! (in principle)	—	—	! (in principle)	—
3. Quark-lepton connection	—	—	—	—	!	!
4. Unification	—	—	New force required	—	New force required	!
5. Hierarchy problem (fine tuning)	—	—	! (temporarily)	!	—	—
-Other issues	! Parity & CP	—	—	Possible gravity connection	—	—

Table 1: Classes of "beyond standard" directions and their relation to the open questions of the standard model.

A closer inspection of the six available directions of model building reveals that, as far as the basic physics ideas are concerned, there are only two major options:

(*i*) Compositeness. Quarks, leptons, Higgs particles and possibly W and Z, are composite. At least one new fundamental interaction is needed. Any possible unification may only happen beyond the level of the new Lagrangian involving the new subparticles.

(*ii*) GUTS. All particles of the standard model (with the possible exception of the Higgs particle) are the ultimate fundamental objects. The next progress is in unifying all interactions (possibly except gravity).

The four other classes of ideas (left-right symmetry, horizontal symmetry, technicolor and SUSY) are extremely important but they must play supporting roles either to a GUT or to a composite scheme. Compositeness and GUTS are not strictly contradictory, but it appears to be very difficult to reconcile them. We feel that progress must happen either in the direction of compositeness or in the direction of GUTS, but not both.

7. Plan of Lecture Notes. Having set the stage for the open questions of the standard model and the directions to be pursued beyond it, we are now ready to outline the general plan of these lectures on the theory of weak interactions of quarks and leptons.

We start with a discussion of the mass and angle parameters of the model and possible relations among them. We then continue with a discussion of the generation puzzle, horizontal symmetries, possible models for the quark mass matrix, etc.

We then move on to the question of CP-violation and its possible sources within and outside the standard model. The recent measurements of the b-quark lifetime and branching ratio and of the ϵ'/ϵ ratio of CP-violation parameters, lead us to a potential difficulty of the standard model. A possible way out may be the left-right symmetric theory which we then discuss, especially as a source of CP-violation. We also review the available bounds on the mass of a possible right-handed W-boson.

We then move on to a general discussion of experimental tests of theories beyond the standard model. We distinguish between high energy tests which can be performed at the energy scale of the new physics and low energy precision experiments which probe high-dimension terms in a low-energy effective Lagrangian. We review the present bounds of a long list of such low-energy experiments, producing a "reference chart" for the most important tests. Our phenomenological discussion is relevant to all new directions beyond the standard model.

Our final topic is the interesting possibility that the W and Z bosons are composite and that the weak interaction is a residual interaction of a more fundamental force, appearing in a new high-energy basic Lagrangian of a new theory of subparticles. We discuss several phenomenological aspects and experimental tests of this idea.

We conclude our lectures with a brief overview of the phenomenological frontiers of the standard model.

8. Masses and Angles: An Important Clue. It is often stated that the main reason for our inability to produce a satisfactory theory which goes beyond the standard model, is the total absence of experimental clues. However, it is not true that we have no experimental clues. If we argue that one of the main motivations for new physics is the large number of unexplained mass and angle parameters in the standard model, we must hope that a future model will allow us to calculate all of these parameters, starting from a small set of new fundamental constants. *In that case, the known experimental values of quark and lepton masses and Cabibbo angles must already provide us with extremely important clues for the physics beyond the standard model.* It is surprising how little is the attention which is presently being paid to these important clues. Very few authors have been discussing the systematics and possible relations among the known mass and angle parameters. We believe that the masses and angles are clues to one of the most important problems in all of physics. Let us review what we know about them.

9. Quark and Lepton Masses. The known mass values for quarks and charged leptons and the known upper bounds for neutrinos are shown in Figure 1. A few comments:

(i) The mass values for the three light quarks are somewhat uncertain. Well known chiral symmetry arguments tell us that $M_u/M_d \sim 0.55$, $M_d/M_s \sim 0.05$. Since $(M_d - M_u)$ must be of order of a few MeV's and since $(M_s - M_d)$ is likely to be around 150 MeV, we obtain the popular set of values $M_u \sim 4MeV$, $M_d \sim 7MeV$, $M_s \sim 150MeV$. However, various authors have used somewhat larger values.[4] (ii) There is also some theoretical uncertainty concerning M_c, M_b but it is much less significant than in the case of the light quarks. (iii) The recent experimental indications for the top quark[5] place its mass somewhere between 30 and 60 GeV. We will arbitrarily use $M_t = 45 \pm 15GeV$.

(*iv*) An interesting scaling relation may hold between second and third generation quarks: $M_s/M_b \sim M_c/M_t \sim 0.03$. Note, however, that $M_\mu/M_\tau \sim 0.06$. (*v*) All neutrinos are still consistent with being massless. We do not know whether they are exactly massless or just extremely light. In both cases some profound reason is necessary. The fact that the hierarchy of bounds on the masses of the different neutrinos resembles the hierarchy of masses of the corresponding charged leptons, is due to experimental constraints. Consequently, even if neutrino masses are not zero, they need not be related to their corresponding lepton masses.

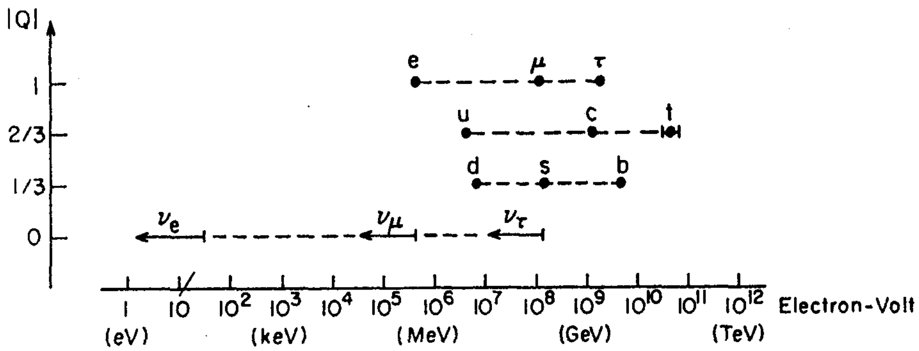

Figure 1: Mass values of quarks and leptons.

10. Neutrinos Are Massless or Extremely Light. Why? Let us consider the two possibilities. If neutrinos are exactly massless, an exact symmetry principle must be at work here. We do not know any such principle. In the minimal standard model we simply declare that all neutrinos are left-handed. We assume that there is no right-handed neutrino. Hence, we cannot write a Yukawa coupling of the SU(2)-doublet Higgs to two neutrinos and no neutrino mass emerges. The situation here is self-consistent but we have simply traded the zero-mass assumption with the essentially equivalent statement of "no right-handed neutrino." This hardly explains anything. In models which go beyond the standard model the situation is similar although, in some cases, the absence of a right-handed neutrino may appear a little more natural. This is the case, for instance, in the SU(5) model where the $10+\bar{5}$ multiplet allows all quarks and leptons to have left *and* right-handed components while neutrinos are only left-handed. However, a right-handed neutrino can be easily added as an SU(5) object. Here, the assumption of massless neutrino is traded for the assumption that the relevant reducible representation is $10+\bar{5}$ rather than $10+\bar{5}+1$.

If neutrinos are extremely light rather than massless, we do not require an exact selection rule but we must still have a convincing explanation for the many orders of magnitude which distinguish between, say, M_e and M_{ν_e}. A simple explanation emerges in models in which neutrinos have a Majorana as well as a Dirac mass. The argument goes as follows: We assume that we have both right-handed and left-handed neutrinos, with Dirac masses which are comparable to the masses of charged leptons, and which are generated by the same mechanism. We also have a parity violating mechanism for producing a Majorana mass term at a higher energy scale Λ. This can easily happen in a Left-Right-Symmetric model (see Section 23) but also in Grand Unified Theories, Horizontal Symmetry schemes, etc. The left- and right-handed neutrinos then obtain a mass matrix of the general form[6]:

$$\begin{pmatrix} 0 & M_\ell \\ M_\ell & \Lambda \end{pmatrix}$$

where M_ℓ is a typical charged-lepton Dirac mass, and Λ is the Majorana mass for the right-handed neutrino (dictated by some new physics scale). The mass eigenvalues are: $M(\nu_L) \sim M_\ell^2/\Lambda$; $M(\nu_R) \sim \Lambda$. Assuming $M_\ell \ll \Lambda$ we then have $M(\nu_L) \ll M_\ell$, $M(\nu_R) \gg M_\ell$, and the left-handed neutrino must be much lighter than the charged lepton. Notice that in this case we must have a symmetry reason for the vanishing, or for the smallness, of the other Majorana mass term (the zero in the matrix). This follows naturally in the Left-Right Symmetric theory (Section 23) but, again, we seem to have traded one puzzle for another.

The puzzle of neutrino masses is, therefore, still unsolved. A detection of a nonvanishing neutrino mass and the related observation of neutrino mixing angles and neutrino oscillations should provide us with important experimental clues for the physics beyond the standard model.

11. The Generalized Cabibbo Matrix. As a "warmup" exercise let us consider the possibility that the quark mass matrices are symmetric and real (of course, they need not be!). We then have two real symmetric 3x3 matrices, one for the up-sector and another for the down-sector. Each matrix is completely characterized by 6 parameters. Hence: 12 parameters determine the quark mass matrices. However, an arbitrary common orthogonal rotation of both matrices cannot change any physical quantity. It simply redefines the arbitrary basis in which we study our three equivalent SU(2)-doublets of quarks. Such an arbitrary orthogonal rotation can be characterized by three independent parameters. We therefore conclude that of the 12 parameters, 3 are unphysical and 9 are physically measurable. Among these 9, we find the six quark masses obtained by diagonalizing each matrix separately, and the three generalized Cabibbo angles which define the relative rotation between the diagonalizing matrices in the up and down sectors, respectively.

If the original mass matrices in an arbitrary basis are M^U and M^D, we have:

$$U^{-1}M^U U = \begin{pmatrix} M_u & 0 & 0 \\ 0 & M_c & 0 \\ 0 & 0 & M_t \end{pmatrix} ;$$
$$D^{-1}M^D D = \begin{pmatrix} M_d & 0 & 0 \\ 0 & M_s & 0 \\ 0 & 0 & M_b \end{pmatrix} ;\text{and}$$
$$C = U^{-1}D \ .$$

Here C is the generalized Cabibbo matrix which is real and orthogonal. Each of the nine matrix elements of C can be measured directly in experiments but all of them can be expressed in terms of three real parameters (essentially Euler angles).

Note that in this section we are deliberately ignoring the existence of complex phases, a *unitary* (*rather than orthogonal*) C-matrix and *much* more complicated mass matrices (which are neither real nor symmetric). We do it for the sake of simplicity, and will return to the relevant complex phases in our discussion of CP-violation in Section 17.

Our present knowledge of the Cabibbo matrix is summarized by the following approximate parametrization and values:

$$C = \begin{pmatrix} 1-\frac{1}{2}\theta_{12}^2 \sim 0.97 & \theta_{12} \sim 0.22 & \theta_{13} \sim O(\theta_{12}\cdot\theta_{23}) < 0.01 \\ -\theta_{12} \sim -0.22 & 1-\frac{1}{2}(\theta_{12}^2+\theta_{23}^2) \sim 0.97 & \theta_{23} \sim 0.05 \\ O(\theta_{13}) < 0.01 & -\theta_{23} \sim -0.05 & 1-\frac{1}{2}\theta_{23}^2 \sim 0.999 \end{pmatrix}$$

A few comments are necessary: (*i*) The θ_{12} is the "old" Cabibbo angle. (*ii*) The θ_{23} corresponds to a certain combination of the θ_2 and θ_3 angles of Kobayashi and Maskawa[7] or to the angle γ of Maiani.[8] It is essentially determined by the b-quark lifetime and is presently known within a 25% ambiguity. (*iii*) In the K-M parametrization θ_{13} is given as $\theta_1 \cdot \theta_3$. The upper limit for it is obtained from the present upper limit on $\Gamma(b \to u + \ell + \nu)$. The order of magnitude relation $\theta_{13} \sim \theta_{12}\theta_{23}$ follows from the orthogonality of the matrix and the smallness of θ_{12} and θ_{23}. (*iv*) There are no significant measurements, at present, for the matrix elements C_{22}, C_{31}, C_{32} and C_{33}. Our information on them follows entirely from the orthogonality of the matrix.

We see that the C-matrix is not very different from the unit matrix. All angles are small. Matrix elements connecting adjacent generations are larger than the matrix element connecting generations 1 and 3.

When we include CP-violating effects, one additional complex phase will appear in several places in the matrix. However, the absolute magnitude of the matrix elements will remain unchanged.

12. Single-Generation Standard Model. We now turn to the discussion of possible relations among masses and angles in the standard model. As a first step, let us consider a hypothetical universe in which only the *first-generation quarks and leptons exist*, together with all the gauge bosons and Higgs fields of the standard model. Such a universe should not be very different from the real one, in the sense that almost all matter around us consists of the first-generation fermions u, d and e. What would be the difference between the single-generation universe and the real universe? We would have a modification of a few percent in the rates for neutron β-decay, and $\nu_e - e$ elastic scattering. We do not expect any change in all QCD interactions of u and d quarks and no noticeable change in nuclear structure, patterns of N^* and Δ resonances, etc. Even proton decay could proceed, if SU(5) is valid. The only important effect may be related to CP-violation. The standard K-M mechanism for weak CP-violation cannot work with less than three generations. Hence, the neutron dipole moment may be smaller or absent and it is not clear

whether the observed baryon number of the universe could have been created with the prevailing modified CP-violation mechanism.

The question which interests us here is, however: Given that a single-generation universe is a good approximation of the real universe and given some new theory which goes beyond the standard model and which enables us to compute quark and lepton masses, could we calculate the observed masses of u,d,e,ν_e? We do not know the answer to this hypothetical question but we wish to draw attention to two different possible situations:

(*i*) All higher-generation effects provide only minor perturbations to the hypothetical single-generation universe. In this case we should be able to approximately compute the masses of u,d,e,ν_e without paying too much attention to the complexities of Cabibbo angles, higher masses, etc.

(*ii*) The fundamental mass scale is the mass of the highest generation and all lighter generations are obtained as higher order corrections, either from higher order loop diagrams or from higher powers of Higgs vacuum-expectation-values. In that case, the masses of u,d,e,ν_e cannot be calculated or understood without a complete understanding of the entire multigeneration picture.

There is an important difference between the two scenarios. If all quarks and leptons are fundamental (as they are in GUTS) we would definitely expect all of them to be equally important and any possible mass calculation should probably consider all generations. On the other hand, in some composite models, it is conceivable that higher generations are some kind of excitations of the first one. Such excitations may be interesting but their understanding may not be crucial to the understanding of the fundamental properties of the first generation, in the same way that the existence of hypernuclei is not very crucial to the understanding of ordinary nuclei.

Somehow we believe that it would seem more appropriate to understand the first-generation fermions, from which we are all made, without too much reference to the higher generations. Whether this will actually be the case, only time will tell.

13. Mass-Angle Relations in a Two-generation Model. In a two-generation standard model we have four quark masses and one mixing angle – the original Cabibbo angle θ_c. Historically, the charmed quark mass was predicted from the observed $K_S^o - K_L^o$ mass difference.[9] The familiar "box diagram" of Figure 2 contributes to the mass difference, yielding an expression of the general form:

$$\Delta M = K_1 B sin^2\theta_c \cos^2\theta_c (M_c^2 - M_u^2)$$

where K_1 is a known constant depending (among other parameters) on g_W and M_W. An unknown factor of order one, B, is defined as:

$$B = \frac{< K^o|\bar{d}\gamma_\mu(1+\gamma_5)s\bar{d}\gamma_\mu(1+\gamma_5)s|\bar{K}^o >}{\frac{8}{3}F_K^2 M_K^2} .$$

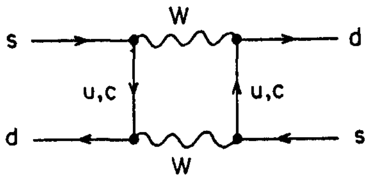

Figure 2: The classical "Box Diagrams" for $\Delta M(K_S^o - K_L^o)$.

In the approximation in which the vacuum contribution saturates the matrix elements, B=1 a somewhat more reliable calculation yields B~ 0.4. However, there is still a considerable uncertainty about the value of B and no value between 0.3 and 1 can be ruled out, at present. We will return to the problem of the B-parameter in Section 18.

The above calculation of M_c yields numbers which are consistent with the observed value. Hence, we may safely assume that no other contribution to $\Delta M(K_S^o - K_L^o)$ will yield values which are larger than the contribution of the above box diagram. This constraint turns out to be a formidable obstacle to many theoretical models, providing bounds on quantities such as the mass of the top-quark, the mass of a possible right-handed W_R, masses of various Higgs particles, mass differences of SUSY squarks, etc.

Does the physics of a hypothetical two-generation universe resemble the real universe? The answer is definitely yes, with the possible exception of CP-violation effects. It is unlikely that any quantity related to the second-generation quarks and leptons has a substantial dependence on the parameters or even on the existence of the third generation. Even a tiny quantity such as $\Delta M(K_S^o - K_L^o)$ is properly accounted for by a two-generation calculation and does not seem to allow for substantial third-generation contribution.

Arbitrarily assuming real symmetric mass matrices, the most general form of the matrices is:

$$M^U = \begin{pmatrix} X_U & Y_U \\ Y_U & Z_U \end{pmatrix}; \; M^D = \begin{pmatrix} X_D & Y_D \\ Y_D & Z_D \end{pmatrix} \quad .$$

We have here six parameters, of which one is unphysical. An arbitrary simultaneous rotation of both matrices can be parametrized in terms of one parameter, and it does not represent a physically detectable change.

In order to obtain a relationship among the four masses and one angle which are experimentally measurable, we must have some constraint on the X_i, Y_i and Z_i parameters. Such a constraint can come, for instance, from a selection rule governing the couplings of the Higgs field to the quarks of different generations. The relevant selection rule must be based on some new quantum number which distinguishes among generations and which is based on some new physics beyond the standard model.

A particularly interesting example of such a selection rule has been considered by several authors.[10] They assume some new symmetry which dictates that, in a given basis for the mass matrix, $X_U = X_D = 0$. In such a case we are left with four independent parameters Y_U, Z_U, Y_D, Z_D. We can therefore derive one relationship among masses and angles, enabling us to compute the Cabibbo angle, from the experimental values of the four quark masses. The relation is:

$$\theta_c \sim \sqrt{\frac{M_d}{M_s}} - \sqrt{\frac{M_u}{M_c}} \ .$$

If we repeat the calculation in a more realistic framework in which we do not insist on a real symmetric matrix, extra complex phases appear in the matrix. The resulting condition for θ_c is, in this case, an inequality[11]:

$$\sqrt{\frac{M_d}{M_s}} - \sqrt{\frac{M_u}{M_c}} \leq \theta_c \leq \sqrt{\frac{M_d}{M_s}} + \sqrt{\frac{M_u}{M_c}} \ .$$

Experimentally $\sqrt{\frac{M_d}{M_s}} \sim 0.22$, $\sqrt{\frac{M_u}{M_c}} \sim 0.05$, and $\theta_c \sim 0.22$. Our trivial exercise has certainly landed us in the right ballpark.

It is interesting to note that the above calculation indicates that, if we could somehow increase the masses of second-generation quarks, while keeping M_u, M_d fixed, we would find a decreasing Cabibbo angle. In such a case the five mass and angle parameters are not independent. We cannot ask questions such as: What would happen to $\Delta M(K_S^o - K_L^o)$ if M_s, M_c were made very large while M_u, M_d and θ_c remained fixed. On the other hand, in the standard model all five parameters are fundamental and the variation of one of them need not influence the others.

The simple $X_U = X_D = 0$ scheme is not necessarily the right one. We have mentioned it here only as a simple example for the kind of constraint that we could obtain by considering certain physics ingredients which originate beyond the standard model. In this case, we use an additional symmetry and obtain a relation which reduces the number of independent free parameters in the standard model.

14. Mass-Angle Relations in a Three-Generation Model. In the realistic case of three generations we have six quark masses, three generalized Cabibbo angles and one K-M phase. Of these, two masses, two angles and one phase appear on the scene only when we add the third generation.

Does the third generation influence the physics of the first two generations?

We consider here three aspects of this interesting question:

(*i*) We must have some very small effects, induced by the third-generation quarks, in ordinary weak transitions involving the first two generations. For instance, in a two-generation world the weak transition amplitudes for $c \to d$ and $s \to u$ should have the same absolute magnitude (except for phase-space factors). The contribution of the third generation will presumably cause a minor deviation from this equality.

(*ii*) The top quark contribution to the $K_S^o - K_L^o$ mass difference is related to the usual "box diagram" contribution by the ratio[12]:

$$\frac{\Delta M_t}{\Delta M_{\rm Box}} \sim \sin^4\theta_2 \left(\frac{M_t}{M_c}\right)^2 + 2\sin^2\theta_2 \ell n \left(\frac{M_t}{M_c}\right)^2$$

where $\Delta M_t, \Delta M_{\rm Box}$ are the two contributions and θ_2 is the second angle in the standard K-M choice of angles. The above relation holds for $M_c <$

$M_t < M_W$. Experimentally, our present knowledge of θ_2 and M_t yields: $\Delta M_t/\Delta M_{\rm Box} \sim 1\%$. Consequently, the third generation has practically no influence on low energy quantities such as $\Delta M(K_S^o - K_L^o)$.

Theoretically, we learn here a very interesting lesson.[13] Let us ignore all experimental information for a moment. The expression for ΔM_t indicates that for larger and larger M_t, the top-quark contribution to $\Delta M(K_S^o - K_L^o)$ becomes larger. In particular, for $M_t \to \infty$, ΔM_t becomes the dominant contribution to ΔM. (Actually, when $M_t \to \infty$ the above equation which is valid only for $M_t < M_W$ must be replaced by another expression but the argument remains valid). Our physical intuition would certainly rebel against such a picture. It is totally unacceptable to have a picture in which a static quantity related to a 500 MeV particle depends mostly on the properties of a remote quark at 50 or 100 GeV. There is only one simple and elegant way to avoid this: If $\sin\theta_2 \to 0$ when $M_t \to \infty$, the product $sin^4\theta_2(M_t/M_c)^2$ may be bounded and no dominant third-generation effect will ever exist. Such a scenario is extremely plausible: A mixing angle which mixes the third generation with earlier generations becomes smaller when the inter-generation mass difference grows. In the standard model such a connection cannot be obtained. All masses and angles are independent free parameters and there are no relations among them. However, we expect any scheme which goes beyond the standard model to yield mass-angle relations of the type advocated here.

(iii) Another amusing conclusion can be drawn when we study the actual numerical form of the quark mass matrices. Let us choose the basis in which the down-sector mass matrix is diagonalized:

$$M^D = \begin{pmatrix} 7 & 0 & 0 \\ 0 & 150 & 0 \\ 0 & 0 & 4500 \end{pmatrix} .$$

In that basis, we obtain

$$M^U = C \begin{pmatrix} M_u & 0 & 0 \\ 0 & M_c & 0 \\ 0 & 0 & M_t \end{pmatrix} C^{-1} \sim \begin{pmatrix} 70 & 300 & 430 \\ 300 & 1340 & 2200 \\ 430 & 2200 & 45000 \end{pmatrix} .$$

where we have used $M_u = 4$, $M_c = 1300$, $M_t = 45000$ and C is a real generalized Cabibbo matrix given by:

$$C = \begin{pmatrix} 0.97 & 0.22 & < 0.01 \\ -0.22 & 0.97 & 0.05 \\ < 0.01 & -0.05 & 1 \end{pmatrix} .$$

If we now truncate the third generation and continue to use the basis in which M^D is diagonal, we obtain:

$$M^U = \begin{pmatrix} 67 & 280 \\ 280 & 1220 \end{pmatrix} .$$

Hence, the influence of the third generation on the 2x2 mass matrices obtained in the truncated scheme is quite small (10% or less for all matrix elements). This remarkable conclusion follows from the simple relation

$$sin^2\theta_{23} < \frac{M_c}{M_t}$$

where $\sin\theta_{23} \sim 0.05$ is the matrix element C_{23}, measured from the b-quark lifetime. *The existence of the third generation does not seem to have any substantial impact on the physics of the first two generations* (except for CP-violation effects, to be discussed in Sections 17-19).

A specific scheme for relating masses and angles in a three-generation model was proposed several years ago by Fritzsch.[11] He assumed that, in some basis, the mass matrices have the form:

$$M^U = \begin{pmatrix} 0 & X_U & 0 \\ X_U & 0 & Y_U \\ 0 & Y_U & Z_U \end{pmatrix} \; ; \qquad M^D = \begin{pmatrix} 0 & X_D & 0 \\ X_D & 0 & Y_D \\ 0 & Y_D & Z_D \end{pmatrix}$$

with possible complex phases entering in the X_i, Y_i, Z_i matrix elements. The vanishing matrix elements of M^U and M^D are presumably due to some new symmetry principle which labels the different generations.

The Fritzsch scheme allows for a determination of the parameters X_i, Y_i, Z_i in terms of the six quark masses. We obtain:

$$|Z_U| \sim m_t \; ; \; |Y_U| \sim \sqrt{m_c m_t} \; ; \; |X_U| \sim \sqrt{m_u m_c} \; ;$$

$$|Z_D| \sim m_b \; ; \; |Y_D| \sim \sqrt{m_s m_b} \; ; \; |X_D| \sim \sqrt{m_d m_s} \; .$$

Using the above values we can now obtain constraints on the three generalized Cabibbo angles and the single K-M phase. It is interesting to note that, in the general case of complex mass matrices of the above form, all present data are still consistent with the Fritzsch ansatz.

A particularly attractive feature of the above exercise is the fact that, in the limit of $m_b, m_t \to 0$, we obtain: $\theta_2, \theta_3 \to 0$ (in the K-M notation) or $\theta_{23}, \theta_{13} \to 0$ (in the notation of Section 11).

The above discussion provides us with a simple example for the kind of constraints which we can obtain by postulating a simple generation symmetry. Such a symmetry must emerge from a new theoretical structure which goes beyond the standard model. Various authors have tried to suggest schemes which yield constrained mass matrices of one type or another. While we do not find any of these attempts to be particularly convincing, we believe that the problem itself is extremely important and it deserves much more attention.

15. Mechanisms Leading to Mass-angle Relationships. In order to obtain any kind of relation among quark masses, Cabibbo angles and the K-M phase, we must have some input which goes beyond the standard model. The most general set of quark mass matrices must clearly have ten independent parameters, leaving the six masses, three angles and one phase unrelated. Any constraint on the mass matrices (such as relations among matrix elements, vanishing of certain matrix elements, etc.) would impose mass-angle relations. The most reasonable approach would prob-

ably be to invoke some new symmetry, lying outside the standard model, in order to impose certain conditions on the mass matrices. The obvious advantage of such an approach is the fact that such a symmetry is needed anyhow in order to provide us with a label which distinguishes among the different generations.

Such symmetries are usually referred to as "horizontal symmetries" and we will discuss them briefly in our next section. However, here we wish to make a few general comments concerning such symmetries:

(*i*) Each quark and each Higgs particle in the standard model Lagrangian should presumably be an eigenstate of the new symmetry. Consequently, certain Yukawa couplings which are otherwise allowed, would be forbidden by the new symmetry. This could yield zeros in the quark mass matrices, leaving a smaller number of independent parameters and leading to mass-angle relations.

(*ii*) One of the main puzzles of the mass pattern is the different orders of magnitude of masses corresponding to different generations. This indicates that the correct relations among masses are not likely to follow from some Clebsch-Gordan coefficients of a new symmetry. There are at least three "popular" classes of "explanations" for the mass hierarchy of the three generations: (a) The different mass scales are due to the different vacuum expectation values (v.e.v.) of three different Higgs fields. (This, of course, simply postpones the question rather than solving it.) (b) The different mass scales are due to matrix elements which come from different-order loop corrections to the quark masses. (c) Different scales are due to matrix elements which reflect different powers of the same v.e.v. of a given Higgs field. Several models of each type have been proposed, but none of them appear to be really convincing. We briefly mention some such models in Section 16.

(*iii*) Since the matrices M^U and M^D can be arbitrarily rotated by a common matrix without causing any detectable changes, the explicit form of the mass matrices will have a different structure in different bases. For instance, in the example of Section 13, if $X_U = X_D = 0$ in one basis, we clearly lose that relation in any other basis. As long as we stay within the standard model, all bases are equally legitimate. Only a symmetry which is due to some new physics, can dictate a convenient physical basis which would, hopefully, exhibit a set of simple mass matrices.

(*iv*) An attractive working hypothesis is to assume that the mass ratio of quarks belonging to two adjacent generations is of the order of some small parameter ϵ^2, while the angles which mix adjacent generations are of order ϵ. We then obtain the following general form of the mass and angle matrices:

$$M^{U,D} = m_{t,b}\cdot \begin{pmatrix} O(\epsilon^4) & O(\epsilon^3) & O(\epsilon^2) \\ O(\epsilon^3) & O(\epsilon^2) & O(\epsilon) \\ O(\epsilon^2) & O(\epsilon) & O(1) \end{pmatrix} \; ; \quad C = \begin{pmatrix} O(1) & O(\epsilon) & O(\epsilon^2) \\ O(\epsilon) & O(1) & O(\epsilon) \\ O(\epsilon^2) & O(\epsilon) & O(1) \end{pmatrix} .$$

Clearly, matrix elements which are claimed here to be of order ϵ^k could vanish or be much smaller than ϵ^k as a result of some symmetry. If

$\epsilon \sim 0.1 - 0.2$ we find that, experimentally, the C-matrix has the form suggested above. The matrices discussed in the examples of Sections 13 and 14 are clearly very special cases of our mass matrix here.

The forms of $M^{U,D}$ and of C which we have suggested here are clearly consistent with each other. It should be worthwhile to study the general features of such matrices.

16. Horizontal Symmetries. These are symmetries which enable us to distinguish among otherwise identical generations. A horizontal symmetry cannot be exact. If it were exact, all Cabibbo angles would vanish. We therefore usually assume that the horizontal symmetry is spontaneously broken and the mass matrices contain terms connecting states with different eigenvalues of the horizontal symmetry.

Horizontal symmetries could be discrete, global or gauged. Discrete symmetries are the simplest. They lead us to no theoretical difficulties but they usually appear to be artificial (unless dictated by some other physics reason, such as a composite model[14]). Global symmetries require physical Goldstone particles which should have been observed. Gauged symmetries larger than U(1) usually lead to anomaly problems. A gauged U(1) (or $U(1)^N$) horizontal symmetry leads to no great difficulties and usually avoids anomaly problems without too much trouble.

It therefore appears that a discrete horizontal symmetry or a gauged U(1) or $(U(1))^N$ horizontal symmetry is the most likely candidate, at present.

Horizontal symmetries are likely to be axial,[15] i.e. $X(f_L) = -X(f_R)$, etc. where $f_{L,R}$ are the left- and right-handed components of the same fermion (quark or lepton). This is necessarily the case in most GUTS and in many composite models. Mass matrices of the forms discussed in Sections 13, 14, 15 are most likely to follow from an axial horizontal symmetry.

A simple example of a horizontal symmetry which yields, in lowest order, a three-generation mass matrix of the Fritzsch type (see Section 14) is the following. Assume an U(1) or a $Z_N (N \geq 8)$ horizontal symmetry under which:

$$X(t_L, b_L) = 0 \; ; \; X(c_L, s_L) = 1 \; ; \; X(u_L, d_L) = 2 \; ; \; X(f_L) = -X(f_R) \; ;$$
$$X(\phi_1) = 3 \; ; \; X(\phi_2) = 1 \; ; \; X(\phi_3) = 0$$

where ϕ_i are SU(2)-doublet Higgs fields. In lowest order, the quark mass matrices will have the form:

$$M^{U,D} = \begin{pmatrix} 0 & h_1 < \phi_1 > & 0 \\ h_1 < \phi_1 > & 0 & h_2 < \phi_2 > \\ 0 & h_2 < \phi_2 > & h_3 < \phi_3 > \end{pmatrix}$$

where h_i are Yukawa couplings. If $< \phi_2 > / < \phi_3 > \sim O(\epsilon)$; $< \phi_1 > / < \phi_2 > \sim O(\epsilon^2)$, we obtain the correct hierarchy and general features.

Other scenarios lead to matrices in which different powers of the v.e.v. of the same Higgs field appear in different places. A particularly interesting example was studied by Dimopoulos et al.[16] In their scheme, the mass matrices have the form:

$$M^{U,D} = m_{t,b} \begin{pmatrix} 0 & K^3 < \phi >^3 & 0 \\ K^3 < \phi >^3 & 0 & K < \phi > \\ 0 & K < \phi > & 1 \end{pmatrix}$$

where K is a constant involving the v.e.v. of Higgs fields other than ϕ. Here the mass hierarchy follows from the relation $K < \phi > \sim \epsilon$ and the zeros in the matrix are due to horizontal selection rules.

We cannot present here a comprehensive review of all attempts to obtain mass-angle relations. We have only tried to mention some of the general directions which have been followed by various authors, so far without clear success.

17. CP-violation in the Standard Model. In the minimal standard model (i.e. one Higgs doublet) there is only one possible source for weak CP-violation: the Kobayashi-Maskawa phase. Let us remind ourselves how we obtain such a phase. In a standard model with N identical generations we have an NxN unitary C-matrix representing the relative rotation between the diagonalizing matrices for M^U and M^D. Such a matrix has, in general, N^2 parameters. However, each of the 2N quark fields can be arbitrarily redefined using a phase transformation $q_i \rightarrow q_i e^{i\phi_i}$. We then have 2N unphysical phases. Each row or column in the unitary NxN matrix C corresponds to a quark field. Each matrix element therefore contains an arbitrary phase difference $e^{i(\phi_i - \phi_j)}$. There are (2N-1) such phase differences. Hence, the actual number of physical parameters is not N^2 but $N^2 - (2N-1) = (N-1)^2$. Of these, $\frac{1}{2}N(N-1)$ can always be chosen as real rotation angles, leaving $\frac{1}{2}(N-1)(N-2)$ physical arbitrary phases. For two generations we have one Cabibbo angle and no phase; for three generations – three (generalized Cabibbo) angles and one (Kobayashi-Maskawa) phase; for four generations – six angles and three phases, etc.

The complex phases which appear for the first time in the three-generation case are the source of CP-violation. The full matrix can be explicitly parametrized in many different ways. The original K-M choice chooses the first row and the first column of the matrix to be real. Other choices have been suggested. The physics results are, of course, independent of the convention chosen. In these lectures we usually use the standard K-M choice.

18. The ϵ-Parameter. The only well-measured CP-violating quantity is the ϵ parameter in the K° system: $|\epsilon| = 2.3\text{x}10^{-3}$. The standard model expression for $|\epsilon|$ is given by:

$$\epsilon = KBs_2s_3s_\delta \left(-\eta_1 + \eta_2 \left(\frac{M_t}{M_c}\right)^2 (s_2^2 + s_2s_3c_\delta) + \eta_3 \ell n \left(\frac{M_t}{M_c}\right)^2\right) + L \cdot D.$$

Here $s_i = sin\theta_i (i = 1,2,3)$; $s_\delta = sin\delta$; $c_\delta = cos\delta$. We have used the approximation $cos\theta_1 = cos\theta_2 = cos\theta_3 = 1$. The coefficient K is known:

$$K = \frac{s_1^2 G_F^2 F_K^2 M_K M_c^2}{6\sqrt{2}\pi^2 \Delta M_K} \quad , \text{ and}$$

B is the factor defined in Section 13. The coefficients $\eta_i (i = 1,2,3)$ are QCD corrections which are presently believed to be $\eta_1 = 0.7$, $\eta_2 = 0.6$, $\eta_3 = 0.4$. The term L.D. denotes unknown long distance effects which are believed to be small. The parameters $\theta_2, \theta_3, \delta$ are constrained by measurements of the b-quark lifetime and branching ratio. The world average of b-lifetime measurements is now approximately[17] $(1.2 \pm 0.2)10^{-12}$ sec. The present upper limit for the b-quark branching ratio is [18]

$$\frac{\Gamma(b \to u)}{\Gamma(b \to c)} \lesssim 0.04 \ .$$

These numbers restrict the allowed range of θ_2, θ_3 values according to Figure 3.[19] For each θ_2, θ_3 value the angle δ is determined as shown in the figure.

If we arbitrarily select a set of "best values" M_t=45 GeV, B=0.4, s_3=0.025, s_2=0.06, $\delta = 100°$ we obtain:

$$\left| \frac{\epsilon_{\text{calculated}}}{\epsilon_{\text{experimental}}} \right| = 0.6 \ .$$

However, if we allow B, M_t, s_3, s_2 to increase to their present upper limits we can still account for the observed value of ϵ. The allowed region in the $s_2 - s_3$ plane which is consistent with the experimental value of ϵ is a small region near $s_3 \sim 0.03$, $s_2 \sim 0.06$. However, the most sensitive parameter is still the unknown theoretical parameter B which may be anywhere between 0.3 and 1 (perhaps even higher).

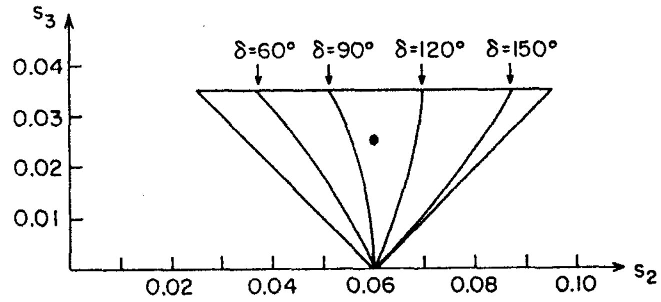

Figure 3: The allowed range of θ_2, θ_3 values after the recent measurements of the b-quark lifetime and branching ratio. Each point in the $\theta_2 - \theta_3$ plane dictates a specific value of δ. The dot in the center of the triangle is arbitrarily chosen as a "best value." The value of ϵ prefers the region in the center of the top part of the triangle. The figure follows the presentation of Reference 19.

Theoretical attempts to calculate B from bag model considerations have yielded a wide range of results. Most recent analyses regard these values as totally unreliable. A beautiful phenomenological analysis by Donoghue, Golowich and Holstein[20] (DGH) using chiral symmetry, soft pion techniques, "flavor SU(3)" and QCD has led to the conclusion that B is somewhere around 0.3-0.4. However, recent arguments[21] indicate that the next perturbative corrections to the chiral DGH calculation are substantial and may increase B towards larger values.

The theoretical understanding of the B-parameter is extremely crucial since it may determine whether or not the minimal standard model can account for the best determined CP-violating quantity ϵ.

19. The Ratio ϵ'/ϵ. Another crucial parameter is the ratio ϵ'/ϵ. In the minimal standard model we obtain:

$$\frac{\epsilon}{\epsilon} = F \cdot s_2 s_3 s_\delta \quad .$$

The coefficient F has been estimated by various authors using the famous "Penguin diagram." A typical calculation yields[22]:

$$F \sim 8 \left(\frac{C_6}{0.1}\right) \left(\frac{<\pi\pi(I=0)|Q_6|K^\circ>}{1.4GeV^3}\right) \quad .$$

The quantities C_6, Q_6 are defined by the Wilson expansion of the effective ΔS=1 weak Hamiltonian:

$$H_{eff}^{\Delta S=1} \propto \sum_{i=1}^{6} C_i Q_i \quad ,$$

where C_i are the Wilson coefficients and Q_i are the renormalized four-quark operators. In particular, Q_6 is given by:

$$Q_6 = (\bar{s}d)_{V-A} \cdot (\bar{u}u + \bar{d}d + \bar{s}s)_{V+A} \quad .$$

Theoretical estimates give $C_6 \sim 0.1$, $<\pi\pi(I=0)|Q_6|K^\circ> \sim 1.4GeV^3$. The favored value of the coefficient F is around 8, but it could easily be smaller by factors of, at least, 2. If we return to our "best values" of $s_3 = 0.025$, $s_2 = 0.06$, $\delta = 100°$ we obtain the theoretical prediction:

$$10^3 \cdot \frac{\epsilon'}{\epsilon} = +12 \quad .$$

The recent experimental result gives[23]:

$$10^3 \frac{\epsilon'}{\epsilon} = -4.6 \pm 5.3 \pm 2.4 \quad .$$

A serious discrepancy may develop here if the negative experimental value of ϵ'/ϵ is confirmed. Note that the analysis of the previous section has taught us that in order to obtain agreement with the experimental value of ϵ we need the expression $s_2 s_3 s_\delta$ to be as large as possible within its present experimental bounds. On the other hand, any increase in $s_2 s_3 s_\delta$ will only make the discrepancy in ϵ'/ϵ worse!

It is entirely possible that the "Penguin" calculation is wrong by a factor 5 or 10 and that the ϵ'/ϵ problem is not serious. However, if the "Penguin" contribution is *much smaller* than present estimates, the old unsolved problem of the $\Delta I = \frac{1}{2}$ enhancement in nonleptonic K-decays becomes much more serious than is presently believed.

20. Do We Have a Serious Discrepancy? The recently obtained bounds on M_t, s_2, s_3 and δ have created a serious problem for the minimal standard model in connection with CP-violation. It seems difficult, but still possible, to accommodate the well known value of ϵ and the poorly known value of ϵ'/ϵ. We definitely have here a serious threat to the minimal

standard model. The remaining ambiguities are both theoretical and experimental.

On the theoretical side, the B-parameter in the calculation of ϵ and the F-parameter in the calculation of ϵ'/ϵ are unknown to within factors of 2 or more. They depend on what is perhaps the least understood part of the standard model, namely – the physics of nonleptonic weak amplitudes. The subtle interplay of the electroweak interactions and QCD in these amplitudes has never been satisfactorily understood.

On the experimental side, better determinations of the top-quark mass, the b-quark lifetime and the $(b \to u)/(b \to c)$ branching ratio will certainly be helpful in further restricting the allowed range of the relevant parameters.

We believe that this situation should be very closely watched in the next year or two. It seems to be the only serious potential problem for the standard model, at the present time.

21. Other Possible Sources of CP-violation. In the minimal standard model, CP-violating amplitudes are the only low energy quantities whose leading contributions depend on the existence of the third generation. In other words, these are the amplitudes which are most sensitive to physics effects which are due to a relatively high mass scale. It is perfectly reasonable to expect such amplitudes to provide us with the first indications for physics beyond the minimal standard model. Almost any extension of the standard model may lead to additional sources of CP-violation. We now review briefly some of the possibilities:

(*i*) If we have a sufficiently complicated Higgs sector we may get additional CP violating effects.[24] We do not know how to obtain a reliable estimate of the magnitude of these effects. However, in such a scheme there is no reason for a small value of ϵ'/ϵ. The "natural" value for ϵ'/ϵ is around 0.05, reflecting the relative strength of the $\Delta I = 3/2$ and $\Delta I = 1/2$ amplitudes in $K \to 2\pi$ decay. Since experimentally, $\epsilon'/\epsilon \ll 0.05$, there must be a convincing reason for the smallness of ϵ'. In the minimal standard model we do obtain a small (perhaps not sufficiently small) ϵ'. If the main source of CP-violation is the Higgs sector, we do not expect[25] a small ϵ'.

(*ii*) Another simple extension of the standard model is the introduction of a fourth generation, yielding six generalized Cabibbo angles and three generalized K-M phases. With so many parameters, we clearly have the freedom to fit ϵ, ϵ' etc. However, we believe that all mixing angles which connect the first two generations to the hypothetical fourth generation must be extremely small (see our discussion in Section 15). It is therefore extremely unlikely that the possible existence of a fourth generation will have a substantial influence on any low energy quantity, including ϵ and ϵ'. We therefore believe that this is an unlikely solution to the potential CP problem.

(*iii*) The possible existence of supersymmetric partners for all fermions and gauge bosons of the standard model would also lead to additional CP-violating effects. Here, again, the absolute size of the effects cannot be estimated at present. Again, most simple considerations have led to ϵ'/ϵ values which are too large. In this case, however, it is entirely possible that a mechanism which contributes to ϵ and, at the same time, produces a small ϵ', will be found.

(*iv*) An extremely simple and attractive source of CP-violations could be the existence of right-handed weak currents, due to a "right-handed" W_R-boson.(26) This happens in all Left-Right Symmetric (LRS) models. The typical size of CP-violating amplitudes is then linked to the strength of right-handed currents. In LRS models it is easy and natural to obtain small ϵ'/ϵ values. If the minimal standard model fails to explain the observed values of ϵ and ϵ', we should probably consider the LRS model as the prime suspect for a major additional source of CP-violating amplitudes.

We now turn to study the LRS model.

22. Motivation for a Left-Right Symmetric Theory. The standard model for electroweak interactions violates parity. We observe only left-handed charged currents. All right-handed quarks and leptons are singlets under the weak SU(2). The violation of parity could, in general, be either explicit or spontaneous. In the standard model, all other broken symmetries are broken spontaneously, while parity is explicitly violated. It would therefore be interesting to try to construct a simple extension of the standard model in which parity is fundamentally conserved and all parity violating effects are due to spontaneous symmetry breaking. The same arguments apply to Charge Conjugation symmetry. The standard model does not respect it. A C-invariant Lagrangian with spontaneous breaking of Charge Conjugation would be an interesting possibility.

It turns out to be relatively easy to produce a Left-Right Symmetric (LRS) theory, possessing the following properties:

(*i*) The Lagrangian of the theory conserves Parity and Charge Conjugation.

(*ii*) At a certain energy scale Λ_R, C and P are spontaneously broken, together with a part of the original gauge symmetry.

(*iii*) At energies below Λ_R, the entire phenomenology of the standard model is reproduced. In fact, we may write a "low energy" ($E < \Lambda_R$) effective Lagrangian which is obtained from the original LRS Lagrangian and is identical to the standard model Lagrangian.

Such a theory would be consistent with all present experiments. It can be tested either by performing experiments at energies approaching Λ_R or by observing indirect effects of Λ_R in precision measurements of low energy quantities.

An important question in any LRS theory is the size of the scale Λ_R. We will show below that it is likely to be above 1 TeV, and that a favored range would be around 10 TeV.

23. A "Minimal" Version of the LRS Theory. We now introduce a "minimal" version of the LRS theory which has the following features:

(i) The Lagrangian conserves both P and C. (Many authors have been considering a C-violating version known in the trade as "manifest" LRS. We see no good reason to violate Charge Conjugation in a LRS Lagrangian.)

(ii) The Higgs sector is minimal in the sense that one Higgs multiplet is responsible to all Λ_R effects and another Higgs multiplet provides the usual SU(2)xU(1) breaking.

(iii) Neutrinos have Majorana masses emerging from the Λ_R scale.

The model is based on the gauge group $SU(2)_L x SU(2)_R x U(1)$. There are three gauge couplings g_{2L}, g_{2R}, g_1. We assume: $g_{2L} = g_{2R}$. There are seven gauge bosons, corresponding to the seven generators of $SU(2)_L x SU(2)_R x U(1)$. We denote them as $W_L^+, W_L^3, W_L^-, W_R^+, W_R^3, W_R^-, B^o$. All left-handed quarks and leptons and right-handed antiquarks and antileptons are in $(\frac{1}{2},0)$ representations of the gauge group. All right-handed quarks and leptons and all left-handed antifermions are in $(0,\frac{1}{2})$ representations. The electric charge is given by:

$$Q = I_{3L} + I_{3R} + \frac{1}{2}Y \quad .$$

It is immediately clear[27] that the U(1) generator Y is identical to B-L (B=Baryon number; L=Lepton number).

The minimal Higgs sector includes the following multiplets:

(i) A complex ϕ-field belonging to the $(\frac{1}{2},\frac{1}{2})_o$ representation. All components of ϕ transform as doublets under $SU(2)_L$. The ϕ-field has the right quantum numbers for coupling to quarks or leptons, as well as to all gauge bosons. Consequently, its vacuum expectation values contribute to all masses. We denote the relevant v.e.v. by:

$$<\phi> = \begin{pmatrix} k & 0 \\ 0 & k' \end{pmatrix} \quad .$$

Note that k, k' are, in general, complex.

(ii) A complex Δ-field[28] belonging to the $(1,0)_2 + (0,1)_2$ representation. Here the subscript denotes Y=B-L. We must clearly also have the antiparticles in the $(1,0)_{-2} + (0,1)_{-2}$ multiplet. The charges of the Δ-triplet are $\Delta^{++}, \Delta^+, \Delta^o$. The v.e.v. are:

$$<\Delta_L> = \begin{pmatrix} 0 \\ 0 \\ U_L \end{pmatrix} \; ; \text{ and } <\Delta_R> = \begin{pmatrix} 0 \\ 0 \\ U_R \end{pmatrix} .$$

It is here that we introduce the spontaneous breaking of LRS by assuming $U_R \neq U_L$. In particular, we must assume:

$$|U_R|^2 \gg |k|^2 + |k'|^2 \gg |U_L|^2 \quad .$$

It will become clear that ϕ induces all the usual effects of the standard model while Δ_R is responsible to all other phenomena which are special to the LRS theory.

The masses of the charged gauge bosons are given by the matrix:

$$M^2(W^{\pm}) = \frac{1}{2}g^2 \begin{pmatrix} 2|U_L|^2 + |k|^2 + |k'|^2 & -2k'k^* \\ -2kk'^* & 2|U_R|^2 + |k|^2 + |k'|^2 \end{pmatrix} .$$

Neglecting U_L and assuming a large U_R we conclude that, to a good approximation, $M(W_L^{\pm})$ is given by the ϕ field (which belongs to an $SU(2)_L$ doublet) while $M(W_R^{\pm})$ is of order U_R. The actual physical gauge bosons are $W_L - W_R$ mixtures:

$$W_1 = W_L cos\xi + W_R e^{i\eta} sin\xi \text{ , and}$$

$$W_2 = -W_L e^{-i\eta} sin\xi + W_R cos\xi \quad .$$

However, the mixing angle ξ must be small. We have:

$$|\xi| \sim \left|\frac{2kk'}{k^2 + k'^2}\right| \left(\frac{M(W_L)}{M(W_R)}\right)^2 \quad .$$

For $M(W_R) \sim O(1TeV)$ we obtain $\xi \lesssim 0.01$, even if $k \sim k'$. Some authors prefer $k \ll k'$ for various theoretical reasons. In that case ξ would be even smaller.

We therefore conclude that the physical, charged W's are almost identical to W_L and W_R, and their mixing is negligible.

The three physical neutral gauge bosons are Z_2 (with mass of order U_R), Z_1 (essentially the usual Z°) and the photon. They form linear combinations of W_L^3, W_R^3 and B° with coefficients depending on the usual weak angle θ_W. The masses of $W_L^{\pm}$ and Z_1 are entirely contributed by the v.e.v. of the ϕ-field. Since ϕ is a $SU(2)_L$ doublet, the usual Weinberg mass relation:

$$\left(\frac{M(W_L^{\pm})}{M(Z_1)}\right)^2 = cos^2\theta_W$$

is maintained. The heavy bosons $W_R^{\pm}$ and Z_2 are also related[28] by a simple function of θ_W:

$$\left(\frac{M(W_R^{\pm})}{M(Z_2)}\right)^2 = \frac{cos2\theta_W}{2cos^2\theta_W} \sim 0.35 \quad .$$

This relation is an important experimental test of the minimal Higgs version of $SU(2)_L x SU(2)_R x U(1)_{B-L}$.

The masses of all charged quarks and leptons are contributed by the ϕ-field (or fields, in the case of several multiplets corresponding to the $(\frac{1}{2},\frac{1}{2})_o$ representation). However, the case of the neutrino is different. The ϕ-field contributes an ordinary Dirac mass to the neutrino. At the same time, the Δ-fields contribute a Majorana mass through the $SU(2)_L x SU(2)_R x U(1)_{B-L}$ invariant couplings $\Delta_L \nu_L \nu_L + \Delta_R \nu_R \nu_R$. The neutrino masses are then given by a 2x2 matrix of the form:

$$M(\nu) \propto \begin{pmatrix} O(U_L) & O(k,\ k') \\ O(k,\ k') & O(U_R) \end{pmatrix} \quad .$$

Each matrix element is accompanied by unknown Yukawa couplings which are not necessarily of order one. The actual orders of magnitude of the four matrix elements are therefore undetermined, except for the general understanding that the final matrix must have a form

$$M(\nu) \propto \begin{pmatrix} a & b \\ b & c \end{pmatrix} .$$

where $a \ll b \ll c$ and b is a Dirac mass which is not very different from the mass of the corresponding charged lepton. The eigenvalues of the mass matrix are:

$$M(\nu_L) \sim b^2/c \ll b; \quad M(\nu_R) \sim c .$$

Consequently, the left-handed neutrino is predicted to be much lighter than the corresponding charged lepton (but not massless!) and the right-handed neutrino is much heavier, possibly as heavy as $M(W_R)$. Note that the actual mass eigenstates are approximately, but not exactly, ν_L and ν_R. The mechanism discussed here is a special case of the general scenario[6] which we mentioned in Section 10.

The minimal LRS model contains quite a number of physical Higgs particles including neutral, singly-charged and doubly-charged states. Only one Higgs particle is expected to correspond to the W_L mass scale. All other Higgs particles are likely to be heavy and to be associated with the right-handed scale U_R. Some of the heavy neutral Higgs particles could induce flavor changing neutral currents, which we discuss in the next section.

24. Cabibbo Angles and Complex Phases in LRS Theory. In principle, a LRS theory describing N generations leads to two different NxN unitary matrices C_L and C_R. However, in the C-conserving model that we have been describing here, there is always a basis for choosing the generation phases in which the left- and right-handed Cabibbo matrices are related[29]:

$$C_L = C_R^* .$$

This means that the real angles must be the same in the right- and left-handed sectors while the complex phases may be different. In the case of two generations, C_L can be chosen as the usual 2x2 Cabibbo matrix, depending on one angle θ_c. The C_R matrix will then contain arbitrary complex phases, leading to CP-violation effects which are entirely induced by the right-handed currents and are therefore of the general order of magnitude of right-handed amplitudes.[26] Note that in the LRS theory, CP-violation need not depend on the existence or the parameters of the third generation of quarks and leptons.

25. Experimental Lower Bounds on the Mass of W_R. The simplest searches for right-handed currents involve possible deviations from "good old V-A theory." Accurate measurements of μ-decay, neutron β-decay, π^+ decay, etc. could provide us with limits on the possible existence of right-handed currents. However, all of these experiments involve light neutrinos. Since the right-handed neutrino is presumably heavy and W_R

couples only to ν_R and not to ν_L, such low energy neutrino experiments do not give us much information on $M(W_R)$. The only contribution on right-handed currents which could be detected in such experiments is due to $W_L - W_R$ and $\nu_L - \nu_R$ mixing. However, these are known to be extremely small effects and even if we could measure them we would not be able to determine $M(W_R)$.

High energy weak interaction experiments could provide a more direct test for the contributions of W_R in $\bar{p}p$ colliders (once we get to $E_{c.m.} \gtrsim 3M(W_R)$) and ep scattering experiments such as the ones planned for the HERA machine.

The strongest experimental bound on $M(W_R)$ is obtained, however, from our old friend the $K_S^o - K_L^o$ mass difference. In addition to the standard box diagram (Figure 2, Section 13) we must now consider two additional types of contributions:

(*i*) Neutral Higgs exchanges (Figure 4(a)). Assuming that these contribute less than the standard box diagram, we get a lower bound on the mass of the heavy neutral Higgs particle[30]

$$M_H \gtrsim 5\,TeV \ .$$

Assuming that M_H is not too different from $M(W_R)$ we deduce that $M(W_R)$ is not likely to be far below 5 TeV. However, we know so little about the masses of Higgs particles, that the argument is not very convincing.

(*ii*) A much more important bound is obtained when we assume that the $W_L - W_R$ "box diagram" (Figure 4(b)) contributes to $\Delta M(K_S^o - K_L^o)$ less than the standard "box diagram."[31] We then obtain the relation[32]:

$$430\left(\frac{M(W_L)}{M(W_R)}\right)^2 cos\gamma \lesssim 1$$

where γ is an unknown arbitrary relative phase between the right- and left-handed Cabibbo angles and the factor of 430 emerges[31] from several "factors of order one" which happen to pile up on top of each other. Since the phase γ is unknown, we seem to have learned nothing new here.

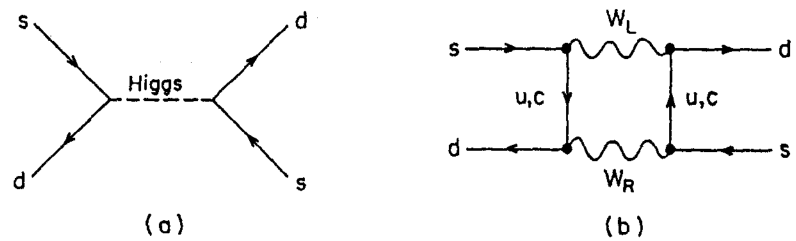

Figure 4: Diagrams contributing to the $K_S^o - K_L^o$ mass difference in a LRS model.

However, we can also calculate the contribution of the same diagram to the CP-violating parameter ϵ. We find:

$$2\sqrt{2}\epsilon_{LR} \sim 430\left(\frac{M(W_L)}{M(W_R)}\right)^2 sin\gamma \ .$$

Here ϵ_{LR} is the contribution of the diagram of Figure 4(b) to ϵ. The last two relations teach us that[32]:

$$430 \left(\frac{M(W_L)}{M(W_R)} \right)^2 \lesssim 1 + 8\epsilon_{LR}^2 \sim 1$$

where we have used $\epsilon_{LR}^2 \ll 1$. Consequently[31]:

$$M(W_R) \gtrsim 20 M(W_L) \sim 1.7 \; TeV.$$

Note, however, that the actual lower limit is likely to be even higher than 1.7 TeV. In order to maintain $M(W_R)$=1.7 TeV we would need $\gamma \lesssim 0.5°$. Such a small value of γ requires some reason. We are not aware of any good reason for a tiny phase-angle γ. If γ is larger, W_R must be heavier (e.g. for $\gamma \sim 10°, M(W_R) \gtrsim 7$ TeV).

We therefore conclude[32]:

(*i*) $M(W_R)$ must be above 1.7 TeV.

(*ii*) M_H is above 5 TeV, hinting that $M(W_R)$ is not far from that value.

(*iii*) $M(W_R)$ may be of order 10 TeV if γ is not particularly small.

26. A Possible Bound on $M(W_R)$. If we had only two generations, the K-M phase would not have existed and the minimal standard left-handed model would not have allowed any weak CP-violation. The LRS theory would then lead to a CP-violation given by:

$$2.3 \text{x} 10^{-3} = \epsilon \sim 150 \left(\frac{M(W_L)}{M(W_R)} \right)^2 sin\gamma \; .$$

Since $|sin\gamma| \leq 1$, we would then be able to derive an ***upper bound*** on $M(W_R)$:

$$M(W_R) < 21 \; TeV \; .$$

In the real world we do have three generations. If we have a LRS theory, we may then have at least two different sources of CP-violation: (*i*) The standard K-M phase. (*ii*) The relative phases between the two 3x3 matrices C_L and C_R.

If the contribution of the LR diagram to CP-violation is negligible, we obtain no useful upper bound on $M(W_R)$. However, if ϵ_{LR} is a substantial part of ϵ, we immediately recover our upper bound. In particular, if we define

$$\epsilon = \epsilon_{K-M} + \epsilon_{LR} \quad \text{and}$$
$$\lambda = \frac{\epsilon}{\epsilon_{LR}}$$

we obtain:

$$M(W_R) \; < \; \sqrt{\lambda} \cdot 21 \; TeV \; .$$

Hence, if ϵ_{LR} is, say, 50% of ϵ, we obtain $M(W_R)$ <30 TeV, etc.

In Sections 18 and 19 we have discussed the possibility that the parameters ϵ and ϵ' cannot be accounted for by the minimal standard model.

If future experiments and theoretical analysis confirm this suspicion, the most likely candidate for explaining CP-violation is probably the LRS theory. In that case $M(W_R)$ *must* be within, say, a factor of 2-3 from 10 TeV. Furthermore, it has been shown that the LRS theory naturally leads to $\epsilon'/\epsilon = 0$!

27. Summary: LRS Theory. The possibility of a Left-Right Symmetry is the simplest extension of the standard model. As we discussed in Section 6, the LRS theory addresses only the questions of the origin of P, C and CP-violation and does not answer any of the fundamental problems of the standard model.

The LRS theory is a necessary ingredient in some GUTS such as SO(10) and E(6) and in some composite models. Alternatively, it may exist on its own, unrelated to any further developments.

The mass scale of W_R is at least a few TeV, most likely O(10 TeV), possibly much more. High energy tests at HERA and future hadron colliders may reveal the existence of W_R. It may play a very important role in explaining CP-violation, especially if the minimal standard model fails to explain the observed values of ϵ and ϵ'.

28. Classes of Experimental Tests Beyond the Standard Model. In earlier sections we have mentioned the motivations for going beyond the standard model and the classes of models which deal with the expected new physics. We have also discussed several "minor" extensions of the standard model such as adding extra Higgs particles, additional generations, horizontal symmetries and left-right symmetries. The limited scope of these lectures does not allow us a detailed discussion of GUTS, composite models or SUSY. We will limit ourselves here to a brief discussion of general experimental tests which can probe the physics beyond the standard model. Most of the tests can provide indications for the new energy scale, regardless of the type of model involved.

The general line of thinking is the following: We assume that some new physics exist beyond the standard model, characterized by a new energy scale Λ (or several new energy scales, among which Λ is the lowest). At $E \sim \Lambda$ we must therefore have a new theory, presumably involving a new Lagrangian, new particles and possibly new interactions. The new particles may be leptoquarks, horizontal gauge bosons, preons, techniquarks, etc. The new high-energy Lagrangian may or may not include all or some of the particles of the standard model. In GUTS it will include all of them. In Technicolor theories it will not include Higgs particles. In Composite Models it will not include quarks and leptons (and perhaps even W and Z). Some of the new particles will always have masses of order Λ. Other new particles may be massless or light relative to Λ.

In all cases we expect that the physics for energies $E \lesssim 100$ GeV will be described, to a good approximation, by the standard model. Consequently, the new Lagrangian must yield, at $E \ll \Lambda$, an effective Lagrangian which is approximately equal to the standard model Lagrangian, at least for the interactions and masses of the particles of the standard model.

We may schematically refer to four different parts of the low energy effective Lagrangian:

$$L_{eff} = L_{SM} + L_{LP} + L_{HD} + L_G \ , \text{ where}$$

(i) L_{SM} is the Lagrangian of the *minimal* standard model.

(ii) L_{LP} is the contribution of additional Light Particles which have not yet been observed and which have "ordinary" couplings (remaining finite for $\Lambda \to \infty$). This could be (a) additional Higgs multiplets within the standard model; (b) additional generations of quarks and leptons; and (c) supersymmetric partners of all standard model fermions, gauge bosons and Higgs fields. All such particles and their interactions should be treated on the same footing as the standard model particles. Their masses are expected to be below Λ and their interactions do not explicitly contain powers of Λ. The normal reason for not observing such particles in present experiments is the possibility that their masses are, say, between 25 and 200 GeV (well below a new Λ but above present experimental capabilities).

(iii) L_{HD} is the effective contribution of High Dimension terms such as four-fermion operators. All parts of L_{HD} are preceded by coefficients of order Λ^{-n} (n positive). The most common type of L_{HD} terms has the form

$$\frac{g^2}{\Lambda^2}\bar{f}_1 f_2 \bar{f}_3 f_4$$

where f_i are quarks and/or leptons and Λ represents the new scale, reflecting the exchange of a heavy horizontal gauge boson, a leptoquark, an extended techniboson, etc. All L_{HD} terms vanish in the limit $\Lambda \to \infty$, but they involve only light ($M < \Lambda$) particles.

(iv) L_G represent interactions involving Goldstone or pseudo-Goldstone particles with masses $M \ll \Lambda$, representing symmetry breaking at scales $E \gtrsim \Lambda$. Such particles are light but their Yukawa couplings to ordinary light fermions are of order $1/\Lambda$. Typically:

$$L_G \propto \frac{M_F}{\Lambda}\chi \bar{f} f$$

where χ is a Goldstone particle and M_f is the mass of a standard model quark or lepton.

The above schematic breakdown of the low energy effective Lagrangian leads us to a simple classification of the types of experiments which can probe the physics beyond the standard model. We must first distinguish between low energy ($E < \Lambda$) experiments and high energy ($E \gtrsim \Lambda$) experiments. Low energy experiments can probe three types of new phenomena:

(i) The existence of new light ($M < \Lambda$) particles, appearing in L_{LP} (SUSY partners, fourth generation, etc.). This is usually done by a straightforward direct search for the particles, knowing that their couplings are "normal" and that their masses (if they exist) are likely to be at the highest available energies but well below any new Λ-scale. Even if such particles are found, we may remain completely ignorant about the value of Λ.

(*ii*) Deviations from standard model predictions in precision measurements of low-energy phenomena. This is the only method of probing terms appearing in the L_{HD} component of the effective Lagrangian. This class of experiments includes two subclasses: (a) Searches for new processes which can proceed only via L_{HD}. Examples: $\mu \to e + \gamma$, proton decay, $K \to e + \mu$, etc. (b) Searches for deviations from the standard model predictions in well known quantities such as $\Delta M(K_S^\circ - K_L^\circ)$, $g-2, e-\mu$ universality, Michel parameters in weak decays, Bhabha scattering, etc.

At present, all information on the lower bounds for the new scale Λ is obtained from (negative) experimental searches for terms in L_{HD}.

(*iii*) Searches for possible Goldstone particles with ultra-weak couplings, appearing in L_G.

The high energy experiments must wait for future accelerators. Conceptually, such experiments are simple. We must search for direct evidence for new particles with mass M$\sim$ Λ and for indirect evidence for confined particles whose mass may be anywhere from zero to O(Λ) but their confinement scale is Λ. Such confined particles can be "observed" only at energies well above Λ, in the form of jets or evidence for pointlike behavior. Examples are techniquarks, preons, leptoquarks, etc.

If we now review the above list of experiments we notice that at present energies (E< Λ), information about the new scale Λ can be obtained only from probing high-dimension terms in L_{HD}. We now turn to a discussion of such experimental tests.

29. Low Energy Probes for the High Energy Scale of the New Physics.

One of the most remarkable achievements in physics is the magnificent agreement between theory (QED+standard model) and experiment in the measurements of the anomalous magnetic moments of the muon and the electron. We denote the possible discrepancy between experiment and theory by Δ_ℓ (for $\ell = e, \mu$):

$$\Delta_\ell = (g-2)_\ell^{EXP} - (g-2)_\ell^{TH} \quad .$$

We know that $\Delta_e \lesssim 5 \cdot 10^{-10}$; $\Delta_\mu \lesssim 3 \cdot 10^{-8}$. These results lead us to bounds on the scale of possible new physics. The bounds can be obtained by considering dispersion relations for the lepton form factor[34] or for the low energy Compton scattering amplitude.[35] In both cases we obtain an order of magnitude estimate:

$$\Delta_\ell \sim a_1 \left(\frac{M_\ell}{\Lambda}\right) + a_2 \left(\frac{M_\ell}{\Lambda}\right)^2 + \cdots$$

where a_1, a_2 are expected to be of order 1. In general, this gives $\Lambda > 1$ PeV(=1000 TeV) for the electron and Λ >3 PeV for the muon. However, in some types of models (especially in composite models) we may have a chiral symmetry which is responsible for keeping M_e and M_μ well below Λ. In that case, $a_1 = 0$ and:

$$\Delta_\ell \sim O\left(\frac{M_\ell}{\Lambda}\right)^2 \quad .$$

The obtained bounds are then much lower (but less model dependent!). We find: $\Lambda_e \gtrsim 20GeV$; $\Lambda_\mu \gtrsim 600GeV$. Even these bounds could easily be wrong by factors of 2 or π. Consequently, (g-2) "sends" us towards a scale of TeV or so, but Λ-scales of a few hundreds of GeV cannot be completely excluded.

A similar conclusion is obtained from Bhabha scattering. In addition to the usual QED and weak contributions, the amplitude for $e^+e^- \to e^+e^-$ could have a contribution from a term of the form[36]:

$$L_{HD} = \frac{g^2}{\Lambda^2} e^+e^-e^+e^-$$

where $g^2/4\pi \sim O(1)$ and Λ is the new scale. Here, again, the analysis of the data indicates $\Lambda \gtrsim O(1TeV)$ but factors of 2 or π cannot be excluded. The four-electron effective interaction with $g^2/4\pi \sim 1$ is essentially unavoidable in composite models for the electron.[36] It is not a necessary ingredient in other theories, but we may have such terms in a variety of extended technicolor models, horizontal symmetry schemes and other theories.

Deep inelastic experiments such as eN and νN scattering as well as $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \tau^+\tau^-$ and the hadronic R-value in e^+e^- scattering, all indicate a pointlike structure for quarks and leptons. A new Λ-scale may lead to a deviation from pointlike behavior. Hence, any "measurement" of the pointlike nature provides an indirect lower bound on Λ. Most such bounds are around 1 TeV or less and they are model dependent.

Another important class of model dependent bounds emerges from searches for the processes: $K_L^\circ \to \mu^\pm + e^\pm$, $K^+ \to \pi^+\mu^+e^-$, $\mu N \to eN$, $\mu \to e\gamma$, $\mu^+ \to e^+e^+e^-$ and from the observed small value of $\Delta M(K_S^\circ - K_L^\circ)$. In all of these cases we may parametrize the new effects in terms of an effective term of the form:

$$L_{HD} = \frac{4\pi\eta}{\Lambda^2} \bar{f}_1 f_2 \bar{f}_3 f_4$$

where $\eta = \frac{g^2}{4\pi}$ and f_i are quarks or leptons. For instance, in $K^\circ \to \mu e$ we have $\bar{f}_1 f_2 \bar{f}_3 f_4 = \bar{s} d e^+ \mu^-$. The parameter η could be O(1) if the process is strong (say, in hypercolor models); it could be suppressed by factors of α or α^2 as a result of some dynamics or selection rules; it could also be suppressed by factors of $\sin\theta$ or $\sin^2\theta$ where θ is some inter-generation mixing angle such as the Cabibbo angle (say $\theta \sim O(1/10)$). We could therefore easily find η values ranging from 1 to 10^{-5} in various models. We cannot even exclude the possibility of an exact selection rule, dictating $\eta = 0$ for one or few of the above processes. Each experimental bound on the rate for these processes can only lead to an upper bound on η/Λ^2. For smaller and smaller η-values, the relevant bounds on Λ become less and less significant, and for η=0 the absence of a given process teaches us nothing about Λ.

We summarize the present experimental situation on a chart, displaying several bounds(37) on a diagram in the $\Lambda - \eta$ plane (Figure 5). For each theory beyond the standard model, we must consider each process, determine the expected value of η and read the corresponding lower bound for Λ from the chart.

Proton decay can be discussed in terms of the same type of phenomenological analysis. However, we must remember that in the case of proton decay, several models(38) forbid a four-fermion term but allow higher order terms of six or more fermions leading to contributions which are proportional to Λ^{-4} or Λ^{-6} in the Lagrangian. We therefore show the Λ-values obtained from the present bound on the proton lifetime for highest order, second order and third order terms.

We wish to emphasize that all the experimental measurements discussed in this section are equally important. We cannot declare one process to provide a "better bound" for Λ than other processes. In different models there may be different suppression factors and different selection rules acting in different terms in the effective Lagrangian.(39) Consequently, some processes provide the most sensitive bounds for one model, while other amplitudes are more sensitive in another model.

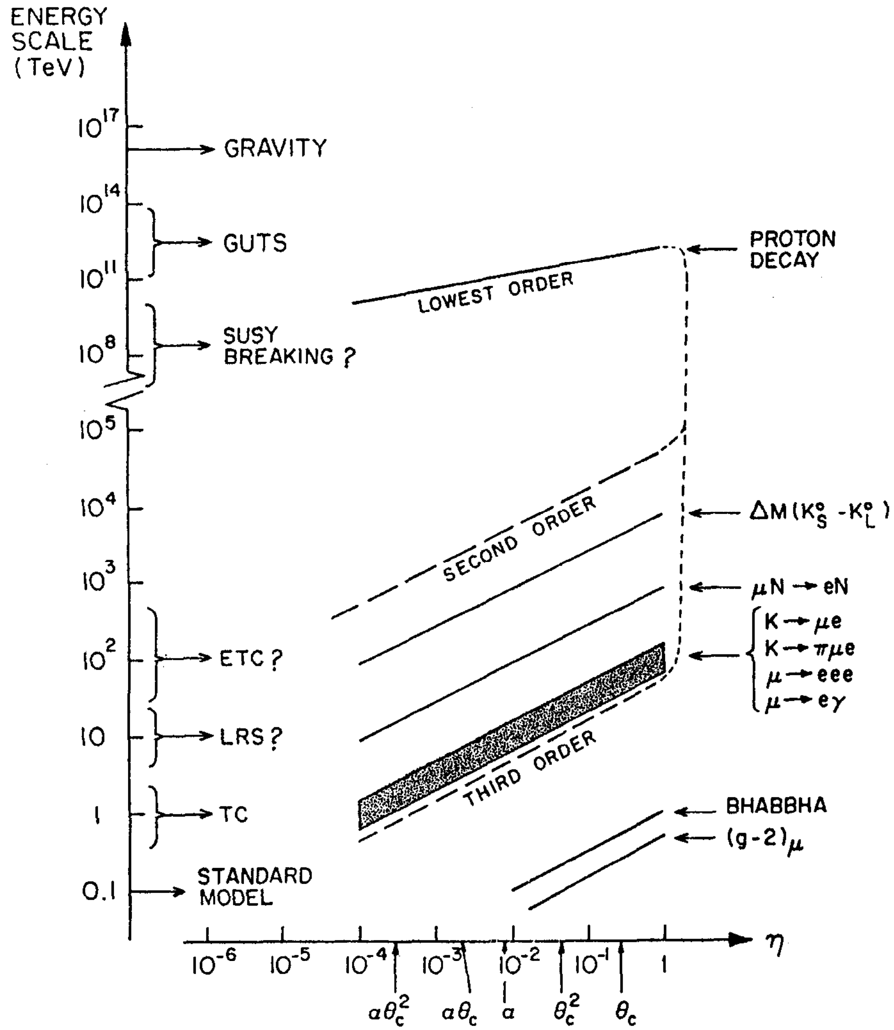

Figure 5: A chart indicating various bounds on the scale Λ of new physics beyond the standard model, as a function of a "strength parameter" η (see text).

We urge our experimentalist colleagues to continue vigorously in the somewhat thankless pursuit of improved experimental bounds in each and every process. One of these processes *must* yield a nonvanishing result, hopefully in the near future.

30. Different Scales of New Physics?[40] So far we have only mentioned "a new energy scale" Λ. It is possible that there are several new energy scales. We may discover that the inverse size of the electron and the muon is around TeV, but only at the PeV($=10^3$ TeV) scale we can tell an electron from a muon. It is possible that the "Horizontal scale" leading to generation-changing processes such as $\mu \to e\gamma$ or $K \to e\mu$ is 100 TeV while the GUTS scale is 10^{11} TeV. We must keep in mind that no one (except the orthodox priests of GUTS) guarantees that there is only one new scale of physics below the Planck mass. In fact, if history is to be used as a guide, we expect new significant physics for every increase in energy by a factor of 10-100.

31. Is the Weak Interaction Fundamental? We cannot conclude these lectures on the weak interactions without considering the possibility that the weak interaction is *not* one of the fundamental forces of nature.[41]

Among the four interactions which are presently considered fundamental, three correspond to unbroken gauge symmetries, and possess massless gauge bosons. Only the weak interaction corresponds to a spontaneously broken gauge symmetry and is mediated by a massive gauge boson.

In all previous cases, short-range interactions always turned out to be the residual effects of a more fundamental force. This was the case for the Van-der-Waals force and for the strong nuclear force ("Strong Interactions"). Will the weak interaction have the same fate?

We can suggest several hand-waving arguments for the following hypothesis: The weak interaction is not fundamental. It is a residual effect of another new fundamental interaction. *The W and Z bosons are composite and they do not appear in the fundamental Lagrangian.*

The arguments are:

(*i*) The simplest way to avoid the "fine tuning" problem is to assume that all Higgs particles are composite.[42] Since the longitudinal components of W and Z are "born" from the Higgs field, they would also be composite. This does not necessarily require that the transverse W and Z are composite, but it is certainly suggestive.

(*ii*) Assume that quarks and leptons are composite. In that case, there must exist a new interaction which is responsible for the binding of preons inside a quark or a lepton. Presumably, the composite quark or lepton is neutral with respect to the new interaction, or else we would have already detected it. An obvious example is a confining hypercolor interaction among preons with a hypercolorless quark or lepton. In any such model we may consider, for instance, the interaction of two neutrinos. At short distances, we expect residual $\nu - \nu$ interactions which are "leftover" effects of the internal preonic interactions within each neutrino (in complete analogy to residual color effects among two nucleons). The existence of a residual short-range interaction among two neutrinos is an extremely plausible consequence of any composite model of leptons. The only remaining question is this: Is the ordinary weak interaction identical to, or does it form a part of, the residual $\nu - \nu$ interaction or do we have here two separate unrelated $\nu - \nu$ forces? It is attractive to suggest[41] that the W and Z exchange is the "long range tail" of the residual $\nu - \nu$ interaction which emerges from the now preonic binding force. Such a hypothesis would be somewhat analogous to the role of the one-pion – exchange contribution, as the "long-range tail" of the residual color interaction among two nucleons.

(*iii*) A much more dubious argument which we cannot resist, is the following: We have fermions of charges $0, \pm\frac{1}{3}, \pm\frac{2}{3}, \pm 1$. It seems obvious that the fundamental electric charge is $\frac{1}{3}e$. All massless gauge bosons are neutral. It is unlikely that a charged (the only charged!) fundamental gauge boson has a charge of three fundamental units. If W and Z are not fundamental, we have no problem here.

If quarks and leptons are *not* composite, the above arguments will convince no one. However, if quarks, leptons and Higgs particles are composite, the possibility of composite W and Z and the hypothesis of residual weak interactions should be taken seriously and studied carefully.

32. Composite W and Z: Problems and Solutions. Let us now assume that quarks, leptons and Higgs particles are composite and that their compositeness scales is Λ. We know that Λ is probably above 1 TeV. If there are several new scales, we denote the lowest one by Λ.

Within the framework of such a scheme we now wish to consider the possibility that W and Z are also composite, presumably consisting of the same type of preons which exist within the quarks and the leptons. The most natural guess for the mass of a composite boson would be $M_W, M_Z \sim \Lambda$. If $M_W, M_Z \ll \Lambda$, some new symmetry principle should probably "protect" M_W, M_Z. We are not aware of any such principle. We therefore conclude that there are three logical possibilities:

(A) The W and Z are not composite.

(B) The W and Z are composite on a scale $\Lambda \gg 100$ GeV. No explanation exists for the relation $\Lambda \gg M_W, M_Z$.

(C) The W and Z are composite. The scale Λ is not too far from 100 GeV.

Clearly the third possibility is the only one which is worth pursuing in this section. If (A) is true – we say no more. If (B) is true, we are missing a critical theoretical ingredient and do not know how to proceed. If (C) is true, we may have a Λ-value within, say, a factor 2 from 1 TeV. The ratio M_W/Λ is of order 0.1, perhaps determined[43] by some dynamical factor of $1/(2\sqrt{3}\pi)$. No new symmetry is absolutely required. A Λ-scale of order TeV is also the expected scale for a composite Higgs.[42]

We therefore continue our discussion by considering (C) as our working hypothesis, assuming that quarks, leptons, W, Z and Higgs are all composite at an energy scale of order 1 TeV.

We must still demand that a low energy effective Lagrangian must exist which contains quarks, leptons, W, Z and perhaps Higgs fields, and is an extremely good approximation to the standard model Lagrangian. In the standard model, W and Z possess the properties of gauge bosons. Their couplings obey an SU(2) symmetry, they have universal couplings to all quarks and leptons, they do not induce flavor-changing neutral currents and they have specific three-boson and four-boson vertices whose couplings are dictated by the gauge symmetry. If W and Z are composite and do not correspond to a true fundamental gauge symmetry, why should they mimic all of these features?

Fortunately, the answer to these questions is not too difficult. First of all, we must assume a *global* SU(2) symmetry relating the charged and neutral composite vector bosons. Such a *global* symmetry may exist at the preon level[44] or may emerge at the composite level.[45] This is a necessary ingredient in any such theory but it poses no great difficulties. The global SU(2) determines the relations between Z and W couplings and leads to the Weinberg mass relation. The rest of the questions can be answered if we accept that $M_W/\Lambda \sim O(\frac{1}{10})$ and once we assume that all other possible composite vector bosons of the same quantum numbers are not lighter than Λ.

If Z° is much lighter than all "competing" vector bosons it is likely to "dominate" the electromagnetic currents of quarks and leptons in an analogous fashion to ρ-dominance in hadron physics. In other words, the photon couples to a composite quark or to a composite lepton by a form factor whose dispersion relation is dominated by the Z-pole. Still in other words: we can postulate a "field-current identity"[46] between the Z°-field and the $\bar{q}q$ or $\bar{l}l$ electromagnetic current.

The immediate consequence of such a situation is an *approximate* universality of Z° couplings to quarks, leptons and W-bosons.[47] In order to study this approximation quantitatively, we may do the following exercise: Assume that above the composite Z there is a composite Z' of mass M'. Assume that all Z' couplings are identical to the Z couplings. Consider the present upper limit on deviations from e-μ universality and from quark-lepton universality. Blame the deviations on the contribution of the Z' and find a lower limit for the Z'-mass. When we perform this exercise we find values around[48] $M(Z') \gtrsim 600\text{GeV}$. Consequently, if the next "action" is around TeV, all present universality relations of Z and W couplings are actually predicted by Z-dominance and the global SU(2) symmetry. *On the other hand, violations of universality may not be far beyond the accuracy of present experiments!*

We therefore conclude that the scenario of residual weak interactions and composite W and Z poses no new great difficulties if quarks and leptons are composite and if Λ is not much larger than 1 TeV. Needless to say, composite models for quarks and leptons have their own severe difficulties, but that is another story altogether.

33. Some Experimental Tests of Z Compositeness. We conclude our discussion of W and Z compositeness by describing some interesting tests of Z compositeness which will hopefully become feasible within the next few years.

The basic idea is due to Renard.[49] If Z° is a preon-antipreon bound state, and if the preons are electrically charged (some of them are likely to be or else how do we make a composite charged W?) we can have direct couplings of the photon to the preons inside the Z°. In that case, the decay Z° $\rightarrow 3\gamma$ can proceed via the diagram of Figure 6(b), as opposed to the lowest order standard model contribution of Figure 6(a).

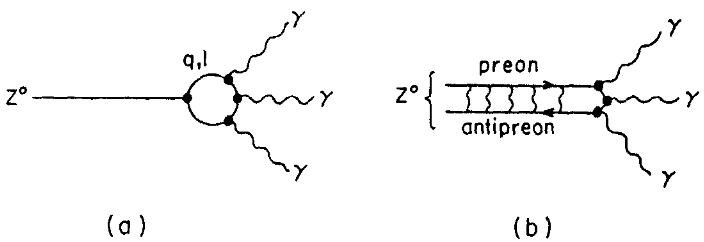

Figure 6: Leading diagrams contributing to $Z^\circ \rightarrow 3\gamma$ in the standard model (a) and in a composite-Z° scheme (b).

The actual calculation of the decay rate is subject to serious uncertainties due to our total ignorance of the inner structure of the Z°, the binding interaction among the preons, the preonic wave-function of the Z etc. However, in a simple model, Renard obtained an enhancement of up to four orders of magnitude in favor of the composite Z mechanism of Figure 6(b). The predicted branching ratios are[49]:

$$\frac{\Gamma(Z^\circ \rightarrow 3\gamma)}{\Gamma(Z^\circ \rightarrow any)} \sim \begin{cases} 10^{-5} & \text{(Composite-Z Model)} \\ 10^{-9} & \text{(Standard Model)} \end{cases} .$$

We do not necessarily trust the actual figure of 10^{-5}. However, once we have an e^+e^- collider at $E = M_Z$ and we start observing enormous numbers of Z°-decays, such 3γ events should be easy to detect. If the branching ratio is anywhere near 10^{-5} or 10^{-6}, the possibility of a composite Z would become likely. If the rate is lower, all options are still open.

If the preons within the Z° are colored, we would also expect an enhancement of [49] Z° $\rightarrow$ g+g+γ. However, the experimental signatures of this decay are easily confused with various decays involving quark jets and the experiment is not likely to be conclusive.

Note that the direct decay Z° $\rightarrow$3g is suppressed by the global SU(2) symmetry and therefore cannot provide an additional test of this hypothesis.[50]

An even more immediate test can be performed in p̄p colliders. Here we may look for[50]:

$$\bar{p} + p \rightarrow Z^\circ + \gamma + anything \quad ,$$

where γ is a hard photon with $p_T > 5$GeV. In the standard model such events are due to the subprocess

$$\bar{q} + q \to Z^\circ + \gamma$$

and the rate is approximately a factor α below "ordinary" Z°-production. If Z° is composite and if *its preons are colored and charged*, we also have a direct Z° $gg\gamma$ coupling and a possible substantial contribution from another subprocess:

$$g + g \to Z^\circ + \gamma \ .$$

Here, again, a convincing detailed calculation of the new subprocess is not possible, at present. However, using a crude model similar to that of Renard[49] we have found[50] that the second subprocess *may* contribute a much larger cross section than the standard model subprocess. The predicted cross sections are compared to each other in Figure 7, for a $\bar{p}p$ collider at $\sqrt{s}$ =540 GeV. Table 2 gives the numbers of expected $Z^\circ + \gamma$ events for $\sqrt{s}$=540 and 2000 GeV and for p_T^γ >10 GeV. The suggested enhancement of the $Z^\circ + \gamma$ cross section is remarkable.

The total number of such observable events in the CERN $\bar{p}p$ collider should have been, until now, 0.1 events. Hence, their absence teaches us nothing new. In fact, there is one event[2] with a hard photon and a large missing mass which could be due to $Z^\circ + \gamma$ followed by $Z^\circ \to \nu + \bar{\nu}$. There is also one $\mu^+\mu^-\gamma$ event[2] which could be Zo + γ followed by

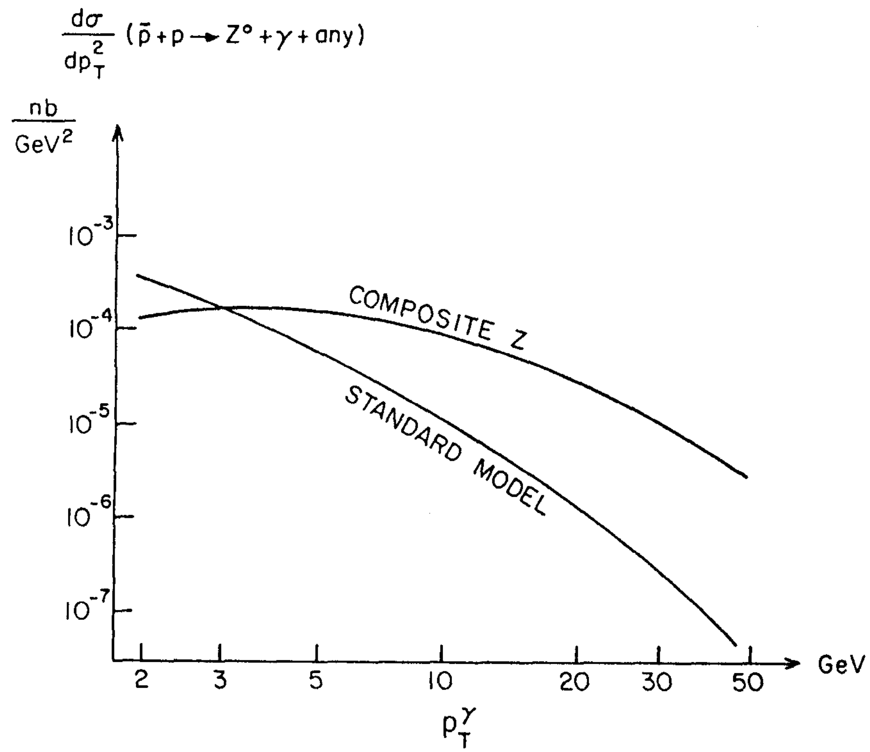

Figure 7: Predicted $Z^\circ + \gamma$ cross section in $\bar{p}p$ collisions at $\sqrt{s}$ =540 GeV for the standard model and for a specific simple ansatz in a composite-Z model (from Reference 50).

$Z^\circ \to \mu^+ + \mu^-$. Neither event is clean enough and one or two events would prove nothing, even if they are found.

If large numbers of $Z^\circ + \gamma$ events are observed at the CERN and

	Number of expected Z° $+\gamma$ events for $P_T^\gamma > 10 GeV$	
$\sqrt{s}$ (GeV)	Standard Model	Composite-Z° Model
540	15	300
2000	90	15000

Table 2: Number of Z° $+\gamma$ events per year in $\bar{p}p$ colliders with integrated luminosity of 10^{37} cm^{-2}.

Fermilab colliders within the next few years, the composite Z° hypothesis will be supported (although not confirmed. There may be other unknown reasons for $Z^\circ + \gamma$ production). If the $Z^\circ\gamma$ production rate is consistent with the standard model predictions we face three possibilities[50]:

(*i*) The Z° is not composite.

(*ii*) The Z° is composite but its preons are colorless.

(*iii*) The scale Λ is somewhat higher and/or our dynamical assumptions in the calculation led to an overestimate.

In any event, the detection of $Z^\circ + \gamma$ events is an obvious byproduct of any Z° search. It would be extremely interesting to watch for these events.

34. Physics Beyond the Standard Model: An Overview. Our main conclusions are two:

(a) There must be new physics beyond the standard model. There are many interesting ideas, models and theoretical directions. The new physics may first appear at a relatively near energy scale such as 1 TeV or at much higher scales. In both cases we may probe it by performing high accuracy low-energy experiments.

(b) The main key to further progress in understanding physics beyond the standard model is in the experimental clues. Among these we emphasize:

(*i*) The known quark and lepton masses and the generalized Cabibbo angles.

(*ii*) The possible problem for the standard model in explaining the CP-violating parameters ϵ and ϵ'.

(*iii*) The upper limits on possible standard model violations in g-2, Bhabha scattering, tests of V-A theory, Weinberg mass relation, $K_S^\circ - K_L^\circ$ mass difference, etc.

(*iv*) Continued search for "null processes" like p-decay, $\mu \to e\gamma$, $K \to e\mu$, $\mu N \to eN$, $\mu \to 3e$, $K \to \pi\mu e$.

(*v*) Search for "light" (M< Λ) particles such as Higgs particles, additional quarks and leptons and supersymmetric partners of the standard model particles.

The main open questions of weak interaction physics are:

(*i*) Is the electroweak group SU(2)xU(1), $SU(2)_L xSU(2)_R\, xU(1)_{B-L}$ or an even larger group? What is the origin of P, C and CP-violation?

(*ii*) Can the weak interaction or an extension of it help us to distinguish among different generations of quarks and leptons and to understand their mass spectrum?

(*iii*) Do Higgs particles exist? How many are there? Are they composite? Do their interactions become strong?

(*iv*) Is the weak interaction fundamental or residual? Are W and Z composite?

Let us hope that a new wonderful theory will soon answer all of these questions, and be confirmed by beautiful new experiments.

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