LEFT-RIGHT SYMMETRY AND CP VIOLATION[†]

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ABSTRACT. Left-right symmetric electroweak theory is reviewed. Experimental consequences and constraints on its parameters are discussed. From K_L-K_S mass difference one finds that $M_R \gtrsim 1.6$ TeV and the mixing angle $\zeta \lesssim .06$. Implications for CP violation especially for the electric dipole moment of the neutron, ε'/ε parameter for kaon decays and heavy quark decays are discussed.

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Following is the outline of this talk:

1. A brief introduction to Left-Right Symmetric electroweak models.
2. Experimental consequences of and constraints on LR Symmetry.
3. CP violation in LRS models and comparison with other models. Herein we will deal with (a) the electric dipole moment of the neutron, (b) the ε' parameter from $K \to 2\pi$ decay, and (c) CP asymmetry in heavy quark (especially b quark) decays.
4. Summary.

Introduction.[1]

Left-Right Symmetric electroweak models explain parity violation as the low energy behavior of a spontaneously broken theory, and as such provide an aesthetically appealing alternative to the standard model. They also provide a possible alleviation of the experimental desert by Grand Unified extensions of the standard model. The gauge group for LRS models is taken to be $G = SU_L(2) \times SU_R(2) \times U(1)_{B-L}$ where we take $g_R = g_L$. Fermions transform as doublets under the gauge group: $(\overline{\nu_e}\ \ \overline{e})_{L,R}\ldots$; $(\overline{u}\ \ \overline{d})_{L,R}\ldots$. The minimal Higgs sector consists of:

$$\begin{pmatrix} \chi^+ \\ \chi^o \end{pmatrix}_{L,R} , \quad \Phi = \begin{pmatrix} \phi_1^{\ o} & \phi_2^{\ +} \\ \phi_3^{\ -} & \phi_4^{\ o} \end{pmatrix} , \quad \tilde{\Phi} = \tau_2\, \Phi^* \tau_2 \tag{1}$$

where Φ transforms under G as $\Phi \to U_L\, \Phi\, U_R^{-1}$. On symmetry breaking the scalars develop vacuum expectation value,

$$\langle\chi_L\rangle = \begin{pmatrix} 0 \\ V_L \end{pmatrix} ; \quad \langle\chi_R\rangle = \begin{pmatrix} 0 \\ V_R \end{pmatrix} ; \quad \langle\Phi\rangle = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' \end{pmatrix} . \tag{2}$$

The gauge fields $W_{L,R}$ that couple to the L,R charged currents are not, in principle, mass eigenstates. Rather one has:

$$\begin{aligned} W_L &= W_1 \cos\zeta + W_2 \sin\zeta \\ W_R &= -W_1 \sin\zeta + W_2 \cos\zeta \end{aligned} \tag{3}$$

where W_1, W_2 are mass eigenstates with masses M_1, M_2 given by ($V_L \to 0$ Limit):

$$M_1^{\ 2} = \frac{g^2}{4} \left\{ |\kappa|^2 + |\kappa'|^2 + \frac{1}{2} |V_R|^2 - \left[\frac{1}{4} |V_R|^4 + 4|\kappa^*\kappa'|^2 \right]^{1/2} \right\} \tag{4}$$

$$M_2^{\ 2} = \frac{g^2}{4} \left\{ |\kappa|^2 + |\kappa'|^2 + \frac{1}{2} |V_R|^2 + \left[\frac{1}{4} |V_R|^4 + 4|\kappa^*\kappa'|^2 \right]^{1/2} \right\} \tag{5}$$

and $\zeta = \tan^{-1}[4|\kappa^*\kappa'|/|V_R|^2]/2$. The observed parity violation at "low" energy is then a consequence of having $M_L^{\ 2} \ll M_R^{\ 2}$, $\tan\zeta \ll 1$ or equivalently

$v_R^2 \gg |\kappa^*\kappa'|,\ v_L^2$. Note that for this minimal Higgs sector one gets a useful theoretical constraint:

$$\frac{1}{2}\tan 2\zeta \leq \beta/(1-\beta) \Longrightarrow \zeta \lesssim \beta\ ,\quad \beta,\zeta \to 0 \tag{6}$$

where $\beta \equiv M_L^2/M_R^2$. The theory thus has two characteristic parameters: ζ and β. However, in making contact with experiment there is the additional complication of quark mixing angles. In general, the right-handed quark mixing matrix is independent of the left-handed mixing matrix. For three generations of quarks one then has altogether six angles and six phases rather than three angles and one phase as in the standard model. Beg[2] et al. proposed that the theory should be "manifest" left-right symmetric (MLRS) i.e. that the charged currents be invariant under $\gamma_5 \leftrightarrow -\gamma_5$ reflection. This results in the angles and phases in the right-hand sector being identically equal to those in the left-hand sector, making the theory considerably more manageable. One can show that manifest LRS emerges as a natural consequence if one requires Φ to have the LR Symmetry transformation

$$L \leftrightarrow R \qquad \Phi \leftrightarrow \Phi^\dagger\ . \tag{7}$$

The resulting theory is not only simple and elegant but can also be extended to resolve the strong CP problem without the need for axions.

Experimental Consequences and Constraints.

Bég[2] et al. were the first to consider the constraints on a MLRS theory coming from existing data on e^- polarization and the Michel parameter in mu decay, beta decay of O^{16} etc. They concluded that

$$\beta \lesssim .13 \Longrightarrow M_R \gtrsim 2.8\ M_L \tag{8}$$

and

$$\zeta \lesssim .06\ . \tag{9}$$

An important shortcoming of Bég et al.'s analysis is that it assumes light right-handed neutrinos (specifically $\nu_{\mu R}$ and ν_{eR}). If the ν_R have large Majorana masses (as would be the case in several theoretical scenarios) then Bég et al.'s bounds become invalid. Gobbi[3] et al. have analyzed new data which leads to the bound $M_R > 450$ GeV, $|\zeta| < .046$, however their analysis suffers from the same dependence on neutrino masses.

Recently[4] the K_L-K_S mass difference has been used to constrain the parameters of MLRS models. In the calculation of the diquark transition $(d\bar{s} \to \bar{d}s)$ to construct the effective $\Delta s = 2$ Hamiltonian, one has to evaluate eight scattering graphs (shown in Figure 1) plus the corresponding eight annihilation graphs.

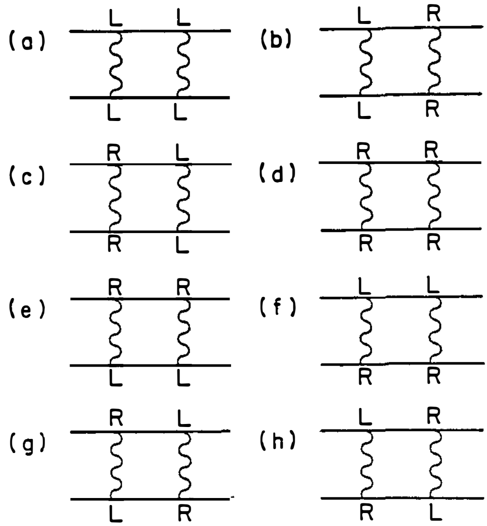

Figure 1. W_L, W_R exchange graphs that contribute to ΔM_K.

If the external momenta are taken to be negligible, the scattering and the annihilation graphs are found to make equal contributions. In our published calculation[4] we assumed $\zeta = 0$. If we now include the contribution for finite ζ as well, again using vacuum saturation to evaluate $\langle K_o | H_{eff} | \overline{K^o} \rangle$, we find:[1]

$$\begin{aligned}\Delta M_K \simeq \frac{G_F^2}{6\pi^2} f_K^2 M_K \Big\{ & \lambda_c^2 m_c^2 \Big[1 + (6y+1)\Big(1 + \ell n \frac{m_c^2}{M_L^2} \Big) \beta + \beta^2 \\ & + \Big(4y - 4 + (4y+1)\, \ell n \frac{m_c^2}{M_L^2} \Big) t^2 \Big] \\ & + \lambda_t^2 m_t^2 \Big[1 + (6y+1)\Big(1 + \ell n \frac{m_t^2}{M_L^2} \Big) \beta + \beta^2 \\ & + \Big(4y - 4 + (4y+1)\, \ell n \frac{m_t^2}{M_L^2} \Big) t^2 \Big] + 2\lambda_c \lambda_t m_c m_t \Big[\omega + (6y+1)\, \ell n \frac{m_t^2}{M_L^2} \beta + \omega \beta^2 \\ & + \Big((4y+1)\, \ell n \frac{m_t^2}{M_L^2} - (4y+6)\, \omega \Big) t^2 \Big] \Big\} , \end{aligned} \tag{10}$$

where $y \equiv M_K^2/(m_s+m_d)^2$, $\omega \equiv (m_c/m_t)\, \ell n\, m_t^2/m_c^2$, $t = \tan\zeta$ and $\beta, \zeta \ll 1$.

A firm numerical value for ΔM_K cannot be deduced from this calculation at present due to our lack of knowledge of m_t and of some of the mixing angles. Let us instead examine the four-quark contribution

$$\Delta M_K^{4q} \simeq 3.4 \times 10^{-12}\ \text{MeV}[1 - 420\beta - 290\zeta^2] \tag{11}$$

which we compare to the experimental value

$$\Delta M_K\ (\text{expt.}) = (3.521 \pm .014) \times 10^{-12}\ \text{MeV}\ . \tag{12}$$

Thus, in the standard model, the four-quark contribution (given by the first term in (11)) essentially equals ΔM_K (expt.). This can be understood in two ways: (1) Terms proportional to β, ζ or those containing the top quark (in Eq. (10)) or other contributions arising from the exchange of Higgs scalars but not shown in (10) are all very small in comparison to ΔM_K^{4q}. (2) Some of the individual contributions, which are functions of several unknown parameters (namely two K-M angles, the t-quark mass, and the mass of the Higgs) are actually large but the values of the unknown parameters are such that these contributions cancel. Since the second possibility would require seemingly contrived cancellations among unrelated factors, we regard it as implausible and do not consider it further. Even under the first set of assumptions, however, there remain considerable uncertainties due to the effects of strong interactions. To be conservative, we assume only that the LR contributions are not dominant which would give the wrong sign for ΔM_K. We thus obtain the bound:

$$420\beta + 290\zeta^2 < 1 \tag{13}$$

which yields a contour in β, ζ plane representing the asymptotic constraint:

$$\beta \lesssim 1/420 \implies M_R \gtrsim 1.6\ \text{TeV} \tag{14}$$

and

$$\zeta \lesssim .06\ . \tag{15}$$

Figure 2 exhibits the constraints on MLRS models coming from various existing experiments and compares them with those resulting from the K_L-K_S mass difference. Figure 3 compares the K_L-K_S constraint with those anticipated from forthcoming high precision experiments. Note that if we accept the theoretical constraint $\zeta \leq \beta$ (Eq. (6)), we get a much tighter constraint on ζ

$$\zeta \lesssim 1/420\ . \tag{16}$$

Recently there have been several related works,[5-9] all of which have assumed $\zeta = 0$ so that they involve the calculation of graphs 1(a-d) only. In that limit all of these works reproduce the result given in Eq. (10). Some of these

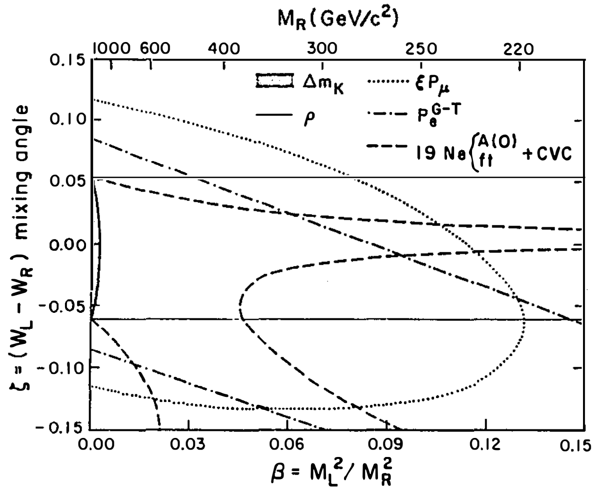

Figure 2. Comparison of the bounds set on β and ζ from ΔM_K to those deduced from leptonic and semileptonic decays.

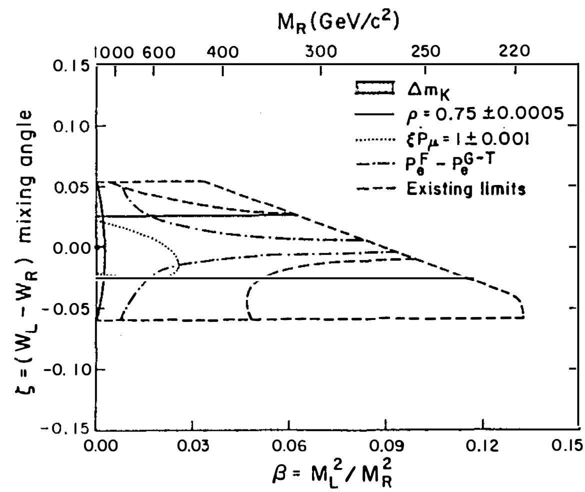

Figure 3. Comparison of the bounds set on β and ζ from ΔM_K to those anticipated from upcoming experiments.

authors[7] have interpreted the bounds from the K_L-K_S mass difference to be bounds on the mixing angles in the right-handed quark sector (that is, they do not assume MLRS) in order to acquire a light W_R. This possibility cannot be discounted, but it requires a more complicated model while substantially reducing predictive ability. The possible resolution of the strong CP problem (without axions) previously noted is also lost.[10] Evaluation of hadronic matrix elements has been studied by Trampetic[5] in the context of ΔM_K and non-leptonic weak decays using various harmonic oscillator quark models. His results are in agreement with our bound (14) deduced using vacuum saturation. Senjanovic, Mohapatra and Tran[8] have done a detailed (once again in the $\zeta = 0$ limit only) calculation in the six-quark model including the contribution from Higgs exchange. They also find that, in a MLRS model, to have values of M_R lower than (14) there have to be delicate cancellations between various contributions not explicitly written down in Eq. (10).

Another constraint on ζ has been deduced by Bigi and Frere[9] who study weak non-leptonic decays of hyperons in a LR Symmetric model. They include QCD corrections to LL and LR currents and show that compatibility with experiment demands $\zeta \lesssim$ a few percent. We emphasize that their bounds on β as well as our bounds on β and ζ (Eqs. (14), (15)) are independent of ν_R mass.

Implications for GUT's.

The bound (14) on M_R has additional implications if one embeds the LR Symmetric group in a grand unifying group such as SO(10). Neglecting the small Higgs contribution, one finds[11]

$$\sin^2\theta_W(M_L) = \frac{3}{8} - \frac{11\alpha(M_L)}{3\pi}\left[\frac{5}{8}\,\ell n\,\frac{M_u}{M_L} - \frac{3}{8}\,\ell n\,\frac{M_u}{M_R}\right] \tag{17}$$

where M_u is the unification mass. The second term in the parenthesis is seen to increase the value of $\sin^2\theta_W$ above the SU(5) prediction. If, however, $M(Z_R^o) \gtrsim M_R \gtrsim 300$ GeV, as is indicated by (14), then the contribution of Z_R^o to the neutral current is negligible and one finds from the neutral current data $\sin^2\theta_W \simeq .22$-$.23$ as in the standard model. Taken with (17), this requires $M_R > 10^9$ GeV. This result can be weakened somewhat if one allows the LR Symmetric group to break through the steps $SU(2)_L \times SU(2)_R \times U(1) \xrightarrow[2M_R]{} SU(2)_L \times U(1)_R \times U(1) \xrightarrow[2M_L]{} SU(2)_L \times U(1)$ with $M(Z_R^o) \simeq M_L$. A careful analysis including the contribution from scalars gives[12] $M_R \gtrsim 10^6$ GeV.

CP Violation.

There are potentially six relative phases entering the quark mixing matrices in an LRS model.[1] For simplicity we will consider two natural but somewhat restricted models: (a) Manifest Left-Right Symmetry (MLRS). This case, which arises when one takes complex Yukawa couplings and real scalar VEV's, has equal left and right quark mixing matrices, i.e. $U_R = U_L$, and hence only one phase. It is generally difficult to distinguish from the standard model. (b) Pseudo-Manifest Left-Right Symmetry (PLRS).[1] If one breaks CP spontaneously by having real Yukawa couplings and complex scalar VEV's one gets PLRS with $U_R = U_L^*$. This model has four relative phases which, on one hand, make it easy to distinguish from the standard model while, on the other hand, make it difficult to make definite predictions. Both of these models assume that the 2×2 scalar multiplet has the LR transformation $L \leftrightarrow R$, $\phi \leftrightarrow \phi^\dagger$.

In addition to phases in the quark mass matrix one can also have a phase in the W mixing matrix:[13]

$$W_L = W_1 \cos\zeta + W_2 \sin\zeta\, e^{i\lambda} \;, \quad W_R = -W_1 \sin\zeta\, e^{-i\lambda} + W_2 \cos\zeta \;. \tag{18}$$

This phase is equivalent to an overall phase in the quark mixing matrices for hadronic and semi-leptonic interactions. However, it can also cause CP violating effects in purely leptonic processes independent of the value of M_ν. There is, of course, the possibility of additional phases from scalar mixing given an enlarged scalar sector. We do not consider this possibility.

Let us now consider the implications of LRS models of CP violation for (a) the electric dipole moment of the neutron (μ_n^e), (b) the ε' parameter of kaon decay and (c) heavy quark decays.

<u>The Electric Dipole Moment of the Neutron (μ_n^e).</u>[13]

We parameterize the quark charge-current gauge interaction in the form:

$$L_{cc} = \sum_{\substack{i,j \\ i \neq j}} \sum_{k=1,2} \overline{\psi}_i \gamma_\mu (a^k_{ij} + b^k_{ij}\gamma_5)\, \psi_j W_k^\mu + \text{h.c.} \tag{19}$$

The one-loop contribution to the electric dipole moment (edm) of a quark is then seen to be:

$$\mu_q^e \propto \text{Im}(a^k_{ij} b^{k*}_{ij}) \tag{20}$$

which vanishes in the standard model where $a = b$. Shabalin[14] has shown, furthermore, that the quark edm in the standard model vanishes even to two loops. It has been pointed out,[15,16] however, that CP-violating diquark transitions lead to a neutron edm at one loop. When including the contribution of penguin-like diagrams, calculations of the neutron edm yield:[17]

$$\mu_n^e \sim 10^{-32} \text{ ecm} \;.$$

We recall that the current experimental bound is given by:[18]

$$\mu_n^e \leq 6 \times 10^{-25} \text{ ecm} \qquad \text{(expt)} \tag{21}$$

and one anticipates an improvement of about two orders of magnitude in the next few years. The prediction of the standard model is thus some seven orders of magnitude smaller than the present experimental bound and beyond any anticipated improvements.

In models of CP violation other than the standard model one does not in general expect the one-loop contribution to the edm to vanish and one therefore expects $\mu_n^e >> 10^{-30}$ ecm. Specifically, for an LRS model the quark edm receives a contribution from Figure 4 and one has:[1]

$$\mu_n^e = \frac{eg^2}{72\pi^2}\sin 2\zeta\left(\frac{1}{M_R^2} - \frac{1}{M_L^2}\right)\{(5m_u - m_d)\, c_{1L}c_{1R}s_{\lambda'} + (5m_c c_{2L}c_{2R}s_{(\delta_2+\lambda')}$$

$$- m_s c_{3R}c_{3L}s_{(\delta_1+\lambda')} + (5m_t s_{2L}s_{2R}s_{(\delta_4+\lambda')} - m_b s_{3L}s_{3R}s_{(\delta_3+\lambda')})\, s_{1L}s_{1R}\} \tag{22}$$

where

$$c_{iL,R} \equiv \cos\theta_{iL,R}\ , \quad s_{iL,R} \equiv \sin\theta_{iL,R}\ , \quad s_{\lambda'} \equiv \sin(\lambda + \delta_{oL} - \delta_{oR})\ ,$$

$$s_{(\delta_i+\lambda')} \equiv \sin(\delta_{iL} - \delta_{iR} + \lambda + \delta_{oL} - \delta_{oR})\ . \tag{23}$$

For the case of MLRS, there is, as in the standard model, only one phase and one finds that

$$\mu_n^e \text{ (to 1 loop)} = 0 \quad . \qquad \text{(MLRS)} \tag{24}$$

For PLRS the edm, given by (22), is non-vanishing to one loop but its numerical value is uncertain as so many of the parameters are unknown. In principle the edm can certainly be large. In particular, if one assumes t quark effects to be small, one can obtain a four-quark result:

$$|\mu_n^{e(4q)}| \simeq (10^{-21} \text{ ecm}) \tan\zeta\ (4.2 \sin(\lambda+2\delta_o) + 1.3 \sin(\lambda+2\delta_o+2\delta_1))\ , \tag{25}$$

where we have assumed $M_1^2 << M_2^2$ and used constituent quark masses. Using $\zeta < \beta < 1/420$ one finds

$$\mu_n^e(4q) < 10^{-23} \text{ ecm}\ . \qquad \text{(PLRS)} \tag{26}$$

Thus, to be consistent with experiment, we find that either the CP violating phases are very small (i.e. < 1/25) or $\tan\zeta$ is even smaller than deduced in (6).

The Weinberg model of CP violation also gives a one-loop contribution to a quark edm. Beall and Deshpande[19] have calculated the neutron's edm and find:

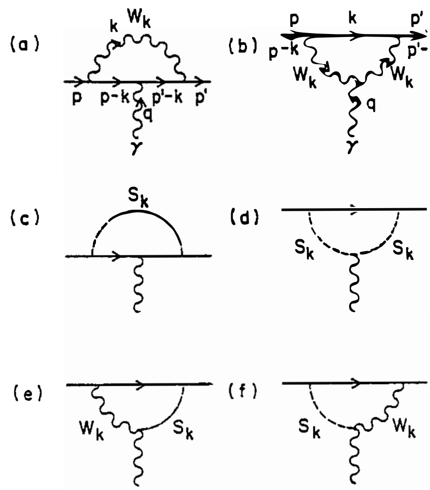

Figure 4. Vertex corrections contributing to the neutron's electric dipole moment in the 't Hooft-Feynman gauge. W here denotes the gauge fields and S the unphysical scalars.

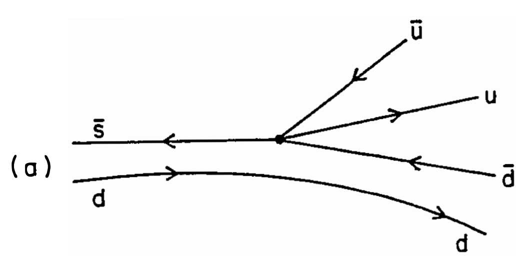

Figure 5. Diagram contributing to $K^o \to 2\pi$ decay.

$$\mu_n^e \sim (2 \text{ to } 4) \times 10^{-26} \text{ ecm} . \quad \text{(Higgs model)} \tag{27}$$

Thus we see that (1) two orders of magnitude improvement in the experimental result could rule out the Weinberg model, and (2) any observation of a positive result, in the next few years, would clearly demonstrate that the Kobayashi-Maskawa phase is not the sole source of CP violation

$\underline{\varepsilon'/\varepsilon}$.

The primary parameter characterizing CP violation, and the only one thus far to have a measured non-zero value, is ε, defined by

$$K^o_{L,S} = \frac{1}{\sqrt{2(1+\varepsilon^2)}} \left((1+\varepsilon)\, K^o \pm (1-\varepsilon)\, \overline{K}^o\right) .$$

Corrections in the LRS model to the standard model calculation of ε are small and depend sensitively on the mass and couplings of the t-quark.

We recall that

$$\varepsilon' \equiv \frac{i}{\sqrt{2}} \exp[i(\phi_2-\phi_o)]\ \text{Im}(A_2/A_o) \tag{28}$$

where

$$A_I e^{i\Phi_i} \equiv \langle 2\pi, I|T|K^o\rangle , \tag{29}$$

T is the $\Delta S = 1$ effective weak Hamiltonian, and $I = 0, 2$ is the isospin of the $\pi^+\pi^-$ or $\pi^o\pi^o$ system. In the standard model, estimates[20] range:

$$\varepsilon'/\varepsilon = 10^{-3} \text{ to } 10^{-2} . \qquad \text{(standard model)} \tag{30}$$

For the LRS model, corrections to the standard model will be dominated by the graph shown in Figure 5. We find[1]

$$\varepsilon'|_{LR} = \frac{i}{\sqrt{2}} e^{i(\phi_2-\phi_o)} \times \text{Im}\left\{ \frac{(c_{LL}-c_{RR})\left(1+\frac{\sqrt{2}}{6}\right) + (c_{RL}-c_{LR})\left(1-\frac{z\sqrt{2}}{6}\right)}{(c_{LL}-c_{RR})\left(1-\frac{1}{6\sqrt{2}}\right) + (c_{RL}-c_{LR})\left(1+\frac{z}{6\sqrt{2}}\right)} \right\} \tag{31}$$

where

$$c_{LL} = U^{L*}_{us}\, U^L_{ud} \left(\frac{c^2_\zeta}{M_1^2} + \frac{s^2_\zeta}{M_2^2} \right) , \tag{32a}$$

$$c_{LR} = U^{L*}_{us}\, U^{R}_{ud}\, s_\zeta c_\zeta\, e^{-i\lambda}\left(\frac{1}{M_2^{\,2}} - \frac{1}{M_1^{\,2}} \right) , \tag{32b}$$

$$c_{RL} = U^{R*}_{us}\, U^{L}_{ud}\, s_\zeta c_\zeta\, e^{+i\lambda}\left(\frac{1}{M_2^{\,2}} - \frac{1}{M_1^{\,2}} \right) , \tag{32c}$$

$$c_{RR} = U^{R*}_{us}\, U^{R}_{ud}\left(\frac{c_\zeta^{\,2}}{M_2^{\,2}} + \frac{s_\zeta^{\,2}}{M_1^{\,2}} \right) , \tag{32d}$$

$c_\zeta \equiv \cos\zeta$, $s_\zeta \equiv \sin\zeta$, M_1 and M_2 are the W mass eigenstates, and U^L and U^R are the left- and right-handed quark mixing matrices and

$$z \equiv \frac{m_\pi^{\,2}}{(m_s - m_d)m_u} \simeq 30.5 \ . \tag{33}$$

As we expect, if we impose manifest LRS, this contribution is seen to vanish. If instead we assume PLRS ($U_R = U_L^*$), we find

$$\varepsilon'\big|_{LR} \simeq - \frac{(1+z)}{2\sqrt{2}\gamma}\, \frac{\zeta \cos\delta_1 \sin(2\delta_o + \delta_1 + \lambda)}{[1 - (1/6\sqrt{2})]^2} \tag{34}$$

where γ is a strong interaction enhancement factor anticipated to be of order 10. There are still too many unknown parameters in (34) to make a definite prediction for ε'. However, we see that even for $\zeta \leq \beta \lesssim 1/420$ this process could easily provide the dominant contribution to $|\varepsilon'/\varepsilon|$. In fact, as in the case of the neutron's edn, the experimental bound

$$|\varepsilon'/\varepsilon| \lesssim 0.02 \qquad \text{(expt)} \tag{35}$$

requires either that the CP violating phases are <<<1 or that ζ is much smaller even than the bound in (6).

Two experiments (FNAL #617 (Chicago-Stanford) and BNL #749 (BNL-Yale))[21,22] are underway for an improved measurement. These experiments are expected to improve (35) by about an order of magnitude in the near future.

Chang[23] has demonstrated recently that much of the uncertainty generated by the numerous phases in LR models can be eliminated if, in addition to assuming PLRS, one assumes the minimal Higgs sector. In that case there is only one independent CP-violating phase coming from the Higgs sector and all of the phases in the quark mixing matrices can be expressed in terms of it. In a four-quark model Chang finds

$$|\varepsilon'/\varepsilon| \simeq |\omega|\, \frac{8}{430}\, \frac{m_s}{m_c}\, \chi \simeq 10^{-4}\chi \tag{36}$$

where $|\omega| \simeq .05$ and χ is an enhanced matrix element estimated to be ~ 10. Calculation of ε'/ε in the Weinberg model[24] of CP violation through Higgs exchange gives[25]

$$\varepsilon'/\varepsilon = -\frac{1}{20}\left(\frac{2\xi}{2\xi+\varepsilon_m}\right)\frac{1}{(1+z)} \tag{37}$$

where $\xi << \varepsilon_m$[26] and z parameterizes long distance contributions and is presumed to be $|z| \lesssim 2$. In comparison with (35) we see that this model is again on the verge of being ruled out unless the experiments now in progress find a nonvanishing result for ε'/ε.

CP Violation in Decays of Heavy Quarks.

In gauge theories of CP violation there is no reason to expect CP nonconservation to be confined to the neutral kaon complex. Indeed it has been pointed out that in the standard model decays of charged or neutral mesons containing the b quark could exhibit appreciable CP asymmetries.[27,29] Since the CP violation really occurs at the quark level (i.e. in comparing CP conjugate decays such as $b \rightarrow d(s) + q + \bar{q}$ versus $\bar{b} \rightarrow \bar{d}(\bar{s}) + q + \bar{q}$, where q = u,d,s or c one expects nonvanishing asymmetry), it not only affects both charged and neutral B mesons but also inclusive and exclusive decay channels. The effects are supposed to be the most pronounced for Cabibbo suppressed decays. The precise magnitude of the asymmetries, being a function of the two unknown KM angles and the CP phase δ, is unknown but for many channels (such as $B \rightarrow \pi+X$, $3K+X$, $K\phi$, $D\bar{D}$, K_SK_SX ...) can be as large as a few percent to a few tens of percents. Theoretical studies also show that the b quark in the standard model is rather unique in this regard. For the t quark such asymmetries tend to vanish; that is, they have extra suppression factors $\sim$ (quark mass)$^2/m_t^2$. For the charm quark the asymmetry is expected to be $\sim 4\alpha_s\varepsilon/27$ (where $\varepsilon \sim 10^{-3}$ is the amplitude for CP violation in kaon decays) $< 10^{-4}$.[27] An observation of CP asymmetry significantly larger than this estimate (in charm quark decay) may signal breakdown of the standard model.

In other models of CP violation similar studies of asymmetries in heavy quark decays have not been done. For MLRS there is only one phase and the theory is expected to be very similar to the standard model in so far as decays of quarks are concerned (so long as $m^2_{quark} << m_L^2$).

Summary.

1. LRS provides an interesting and viable extension of the standard model. Current experiments indicate (under stated assumptions) $M_R \gtrsim 1.6$ TeV, $\zeta \lesssim .06$.
2. The information regarding CP violating parameters μ_n^e, t'/t and asymmetries in b (c) quark decays is summarized in the Table.

Table[a]

Quantity	Experiment	Standard Model	LRS[b] M	LRS[b] P	Higgs	Superweak (Ref. 31)
μ_n^e(ecm)	$\leq 6 \times 10^{-25}$	$\simeq 10^{-30}$	10^{-30}	($\lesssim 10^{-24}$)	$(2-6) \times 10^{-26}$	10^{-29}
$\|\varepsilon'/\varepsilon\|$	< .02	10^{-3}-10^{-2}	10^{-3}-10^{-2}	$0(10^{-3})$	.02-.05	0
a_b [c]	?	$\sim 10^{-2}$-10^{-1}	10^{-2}-10^{-1}	(?)	?	$\simeq 0$
a_c [c]	?	$\lesssim 10^{-4}$	$\lesssim 10^{-4}$	(?)	?	$\simeq 0$

a) ? indicates that the experimental or theoretical value for the parameter is not known at this time.

b) M stands for manifest left-right symmetry; P stands for pseudo manifest left-right symmetry.

c) a_b, a_c are CP asymmetries in b and c quark decays respectively.

Remarks.

(a) Theoretical calculations of ε' are rather messy involving many uncertainties. An order of magnitude improvement in the experimental bound (i.e. a null result) would convincingly rule out the Higgs model and may mean the failure of the standard model.

(b) The fact that the theoretical prediction for μ_n^e in the KM model is $0(10^{-32}$ ecm) means that an observation of a non-vanishing result in the next several years would unambiguously[30] signal the breakdown of the standard model. An order of magnitude improvement in the current bound (< 6 × 10^{-25} ecm) would rule out the Higgs model.

(c) There is every reason to expect a non-vanishing manifestation of CP violation outside the neutral kaon system involving $B^{\pm,o}$ meson decays. These as well as D decays need to be pursued experimentally. Asymmetries much larger than $\sim 10^{-4}$ in D decays again signal the breakdown of the KM model.

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