DOES A LOW MASS RIGHT-HANDED VECTOR BOSON IMPLY A DEPARTURE FROM MANIFEST LEFT–RIGHT SYMMETRY?

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We examine the $K^0 - \bar{K}^0$ complex for constraints on the left–right symmetric model of the electroweak interactions. A light right-handed vector boson is found to require a strong departure from manifest left–right symmetry. The effect on charmed particle decays and other nonleptonic processes are discussed.

Gauge models of the electroweak interactions with left–right (L–R) symmetry have been widely discussed in the literature [1,2]. The currently popular view [3], that the left and right-handed neutrinos are Majorana fermions, with ν_R superheavy, provides a kinematic mechanism of suppression of leptonic and semileptonic charged current right-handed interactions thereby preserving the successes of the (V – A) theory in these sectors in spite of a low M_R. The mixing between W_L and W_R can, in principle, lead to deviations from the (V – A) structure in semileptonic processes. But it has been shown [4,5] that the mixing angle is constrained to be small by phenomenology and throughout this letter we will neglect such mixing ‡1 (a detailed discussion including mixing effects has been presented elsewhere [6]). The neutral current sector of the L–R symmetric model has also been examined in detail. It has been found [7] that the model can fit all neutral current data and allows a wider range for the Weinberg angle than the standard $SU(2)_L \times U(1)$ model. The L–R symmetric gauge model with a low M_R is thus a viable alternative to the standard model as far as the charged *and* neutral leptonic and semi-leptonic weak interactions are concerned.

In this letter we consider nonleptonic processes in the context of this model. We find, from an analysis of the $K_L - K_S$ mass difference, new and interesting correlations between the ratio M_R/M_L and the deviation from "manifest" [4] left–right symmetry. For simplicity we assume that the t-quark coupling to the light quark sector is negligibly small and we restrict ourselves to a four quark model. In the left–right symmetric model, unless special symmetries are imposed, the left- and right-handed weak charged current eigenstates are different. They are related to the mass eigenstates by different unitary transformations C_L and C_R which can be parametrised by *two* rotation angles and two phase angles δ_L and δ_R ‡2. The latter provide a mechanism for *CP* violation in the weak

‡1 In the presence of such mixing, in the case $\cos\theta_R \approx 0$ which leads to significant cd coupling (to be discussed later), this model might predict interesting phenomenological consequences for charm production in neutrino–hadron scattering.

‡2 In the weak interaction basis the mass matrices M_u and M_d (of charge 2/3 and –1/3 quarks) are, in general, not diagonal. They are diagonalised by bi-unitary transformations of the form $M_u^{diag} = U_L M_u U_R^+$ and $M_d^{diag} = D_L M_d D_R^+$. Then the generalisations of the Cabibbo rotation are the unitary matrices $C_L = U_L D_L^+$ and $C_R = U_R D_R^+$. In the four quark case, after using the freedom to absorb phases in the quark fields, each of them can be parametrised by a Cabibbo-like angle θ_L, θ_R and a phase angle δ_L, δ_R. "Manifest" left–right symmetry ($\theta_L = \theta_R$) corresponds to M_u and M_d being hermitian ($\delta_L = \delta_R = 0$) or complex symmetric ($\delta_L \neq \delta_R$).

interactions. In fact, it has been shown [8] that in the presence of $W_L - W_R$ mixing the prediction of this model for the electric dipole moment of the neutron is several orders larger than that of the Kobayashi–Maskawa model of *CP* violation and is closer to the experimental bound. In this letter we do not pursue the question of *CP* violation and drop the phase angles. We do allow the Cabibbo-like angles θ_L and θ_R to be different. It may be recalled that the left–right symmetry is anyway broken in the leptonic sector since $m_{\nu_R} \gg m_{\nu_L}$.

The $K^0 - \bar{K}^0$ mixing via the box diagram was first studied by Gaillard and Lee [9] in the standard $SU(2)_L \times U(1)$ model. In models with right-handed gauge bosons (but no mixing between W_L and W_R) two more diagrams also contribute to the process. In a straightforward manner we obtain the contribution from these diagrams to the effective $\Delta S = 2$ lagrangian:

$$\mathcal{L}_{\text{eff}}^{\text{LL}} + \mathcal{L}_{\text{eff}}^{\text{RR}} = (m_c^2 g_L^4 s_L^2 c_L^2 / 512\pi^2 M_{W_L}^4)\{\bar{s}\gamma_\mu(1+\gamma_5)d\}^2 + [L \to R, \gamma_5 \to -\gamma_5], \tag{1a}$$

$$\mathcal{L}_{\text{eff}}^{\text{LR}} = (m_c^2 g_L^2 g_R^2 s_L c_L s_R c_R / 64\pi^2 M_{W_L}^2 M_{W_R}^2)[\ln(m_c^2/M_{W_L}^2) + 1]\,[\bar{s}(1-\gamma_5)d\bar{s}(1+\gamma_5)d$$
$$+ \tfrac{1}{4}\bar{s}\sigma_{\mu\nu}(1-\gamma_5)d\bar{s}\sigma^{\mu\nu}(1+\gamma_5)d], \tag{1b}$$

where $s_L = \sin\theta_L$ etc. and we have used $M_{W_L}, M_{W_R} \gg m_c \gg m_u$. Assuming [9] that the insertion of the vacuum intermediate state in all possible ways saturates the matrix element $\langle K^0| - \mathcal{L}_{\text{eff}}|\bar{K}^0\rangle$ we obtain the following expression for the $K_L - K_S$ mass difference:

$$\Delta m_K = (m_c^2 m_K f_K^2 g_L^4 s_L^2 c_L^2 / 192\pi^2 M_{W_L}^4)\{1 + (M_{W_L}/M_{W_R})^4 (g_R^4/g_L^4)\, s_R^2 c_R^2 / s_L^2 c_L^2$$
$$+ (M_{W_L}/M_{W_R})^2 (g_R^2/g_L^2)(c_R s_R / c_L s_L) \ln(m_c^2/M_{W_L}^2 + 1)\{6[m_K/(m_s + m_d)]^2 + 1\}\}, \tag{2}$$

f_K is the kaon decay constant: $\langle 0|\bar{s}\gamma^\mu\gamma_5 d|K^0\rangle = f_k P^\mu$. In deriving eq. (2) we have taken the colour degree of freedom into account and also made use of

$$\bar{\psi}_1\gamma_5\psi_2 = -i\partial_\mu(\bar{\psi}_1\gamma^\mu\gamma_5\psi_2)/(m_1 + m_2). \tag{3}$$

The standard model result [9] is obtained by taking the $M_{W_R} \to \infty$ limit. Eq. (2) also reproduces the result of Beall et al. [10] in the limit of manifest left–right symmetry ($\theta_L = \theta_R$) with $g_L = g_R$. Substituting the standard numerical values we get

$$\Delta m_K = 2.0 \times 10^{-5}\,(\text{GeV})^5 (g_L^4 s_L^2 c_L^2 / M_{W_L}^4)[1 + (M_{W_L}/M_{W_R})^4\, g_R^4 s_R^2 c_R^2 / g_L^4 s_L^2 c_L^2$$
$$- 436.7\,(M_{W_L}/M_{W_R})^2\, g_R^2 s_R c_R / g_L^2 s_L c_L]. \tag{4}$$

In deriving eq. (4) we have set $M_{W_L} = 90$ GeV in the logarithm. Since $M_{W_L} < M_{W_R}, g_R \approx g_L$ and $s_R c_R \leqslant \frac{1}{2}$, the second term in the bracket can be neglected in comparison with the third. Although the magnitude of Δm_K predicted by the above equation should not be taken too seriously because of the inherent ambiguities of strong interaction calculations, the demand for the correct sign of the $K_L - K_S$ mass difference seems to be quite logical. This corresponds to $g_L^2 s_L c_L M_{W_R}^2 > 436.7\, g_R^2 s_R M_{W_L}^2$. In the limit of manifest left–right symmetry and $g_L = g_R$, as discussed in ref. [11], this implies $M_{W_R} \geqslant 20.9\, M_{W_L}$. Here we are interested in the low M_{W_R} scenario. Substituting $\theta_L = \theta_{\text{Cabibbo}}$ and $g_L \approx g_R$ we get $s_R c_R < (1.1 \times 10^{-3})(M_{W_R}^2/M_{W_L}^2)$. This constrains θ_R to regions such that $\sin 2\theta_R$ is very small. Thus low M_{W_R} goes in conjunction with strong deviations from manifest left–right symmetry. $\sin 2\theta_R \approx 0$ can be achieved either through (i) $\sin\theta_R \approx 0$ or (ii) $\cos\theta_R \approx 0$. In case (i) the coupling of the u(c) quark to the s(d) quark in the right-handed sector is very small. On the other hand in case (ii), unlike in the left-handed sector the u(c) quark couples predominantly to the s(d) quark. This case therefore could provide clean signatures in favour of the light W_R since Cabibbo suppressed left-handed processes would become Cabibbo favoured through the right-handed current.

Before turning to other processes, we make a few remarks:
(i) from eq. (4) it is clear that the choice $\sin 2\theta_R < 0$ also permits a low M_{W_R}. We have not pursued this choice any

further. (ii) QCD corrections to the above calculation have been estimated and found to be unimportant [10]. Also, the results do not alter significantly if the MIT Bag model is used instead of the vacuum saturation approximation to extract the matrix elements [10]. As in ref. [10] we have assumed that the t-quark contribution in the box diagrams is negligible. This is not inconsistent with the present bounds on the couplings of the t-quark to the d and s quarks. We have also dropped the contributions from graphs where the vector bosons are replaced by Higgs Scalar fields. In the absence of the t-quark the contribution of these graphs which depends on quark masses is small [11].

It is clear that in all nonleptonic processes with amplitudes $\alpha \sin\theta_c \cos\theta_c$ the results of the standard model will be reproduced in this model. For example, the asymmetry parameter in the radiative decay of hyperons [12] is found to be $\alpha = (1-c^2)/(1+c^2)$ with

$$c = (g_R/g_L)^2 (M_{W_L}/M_{W_R})^4 (\sin 2\theta_R/\sin 2\theta_L)[\ln(M_{W_L}/m_c)/\ln(M_{W_R}/m_c)] . \quad (5)$$

But $c \approx 0$ when $\sin 2\theta_R \approx 0$. Thus the result of the standard model ($\alpha \approx 1$) [12] is reproduced. It has been noted [13] that the $\Delta S = 1$, $\Delta C = 0$ piece of the weak nonleptonic hamiltonian is required by kaon and hyperon nonleptonic decays to be predominantly left-handed. Since this piece is also proportional to $\sin\theta_c \cos\theta_c$ the constraints of ref. [13] are well satisfied. The enhancement of the $\Delta I = \frac{1}{2}$ piece via QCD [14] will also be valid in this model for similar reasons.

The alternative situation of manifest left–right symmetry with a large M_{W_R} will pass all the tests that we have discussed thus far. However, in the latter situation *all* right-handed weak interactions are suppressed by the ratio $(M_{W_L}/M_{W_R})^2$ ($\leqslant 1/400$). On the other hand, in the model with breaking of manifest left–right symmetry ($\sin 2\theta_R \approx 0$), the "Cabibbo favoured" processes ($\sim\cos^2\theta_R$ (case i) or $\sim\sin^2\theta_R$ [case (ii); see eqs. (6) and (7) below] will be of roughly the same strength as the ordinary left-handed weak interactions. These processes therefore provide crucial tests of the model. Consider, for example,

$$\text{(a)} \quad \mathcal{H}_{\text{eff}}^{(\Delta S = \Delta C = 0)} = (g_L^2 c_L^2/8M_{W_L}^2)\, \bar{u}\gamma_\mu(1+\gamma_5)\, d\bar{d}\gamma^\mu(1+\gamma_5)u + (L \to R, \gamma_5 \to -\gamma_5) + \text{h.c.} \quad (6)$$

This piece of the hamiltonian along with the neutral current contribution is responsible for parity violation in nuclear physics. In case (i), parity violation will be small, while in case (ii), the interaction is almost purely left-handed. Of course, in the simplest situation studied, the photon polarisation asymmetry in thermal neutron capture ($np \to \gamma d$), theory and experiment are in disagreement by several orders [15]. Thus this piece of the hamiltonian may not be of immediate importance as a test of the model.

$$\text{(b)} \quad \mathcal{H}_{\text{eff}}^{(\Delta S = -1, \Delta C = -1)} = (g_L^2 c_L^2/8M_{W_L}^2)\, \bar{u}\gamma_\mu(1+\gamma_5) d\bar{s}\gamma^\mu(1+\gamma_5)c + (L \to R, \gamma_5 \to -\gamma_5) + \text{h.c.}, \quad (7a)$$

$$\text{(c)} \quad \mathcal{H}_{\text{eff}}^{(\Delta S = 1, \Delta C = -1)} = (g_L^2 s_L^2/8M_{W_L}^2)\, \bar{u}\gamma_\mu(1+\gamma_5) s\bar{d}\gamma^\mu(1+\gamma_5)c + (L \to R, \gamma_5 \to -\gamma_5) + \text{h.c.} \quad (7b)$$

The above pieces of the effective hamiltonian lead to charmed particle decays. The disagreement between theory and experiment in this area is well-known [16]. We point out a few consequences of this model for this topic.

The decay of the c-quark is supposed to be an important mechanism for charmed particle decays. In the standard model, this process contributes to nonleptonic *and* semileptonic decays with a strange particle ($S = -1$) in the final state. In the model under consideration, the right handed currents do not contribute to the semileptonic process, thus decreasing the semileptonic branching ratio B. Recall that experimentally $B(D^0) \approx 4\%$, $B(D^+) \approx 20\%$ while the standard model predicts $B(D^0) = B(D^+) \approx 10\%$. The L–R symmetric model prediction is thus very favourable for D^0 decay. (The enhancement of $B(D^+)$ is usually explained as due to destructive interference of two $\bar{d}$ quarks in the final state.) In case (i) one expects $S = -1$ particles in the final state also from r.h. interactions ($c \to su\bar{d}$). But in case (ii) the Cabibbo favoured r.h. interactions ($c \to du\bar{s}$) give $S = +1$ particles. Thus in this latter scenario, nonleptonic decays should contain roughly equal number of $S = +1$ (r.h. interactions) and $S = -1$ (l.h. interactions) final states while semileptonic decays should predominantly be to $S = -1$ final states.

In the decay of the F^+ meson one expects two strange particles ($S = 0$) in the final state in the standard model and also in case (i). In case (ii) about equal number of final states with $S = 2$ (r.h. interactions) and $S = 0$ (l.h. interactions) should be seen in nonleptonic decays.

The annihilation mechanism through W exchange suggested for D^0 decay ($c\bar{u} \to s\bar{d}$, gluons are not explicitly written) to explain $\tau(D^+) > \tau(D^0)$ etc., is enhanced in case (i) and one expects to find K^- and $\bar{K}^0$ mesons in the final state. In case (ii), the annihilation mechanism gives ($c\bar{u} \to d\bar{s}$) and thus one expects to see also K^+ and K^0 mesons in the final state. This could provide a clean test of the L–R symmetric model in case (ii) [‡3].

The interesting process of flavour annihilation of F^+ to nonstrange final states ($c\bar{s} \to u\bar{d}$) is enhanced in case (i). In case (ii) this process is Cabibbo suppressed in the r.h. interactions. In the standard model the F^+ flavour annihilation (unlike in the D^0 case) can also lead to semileptonic decay and thus B is increased. Since the right-handed semileptonic processes are kinematically forbidden, in case (i) one expects a decrease of B from the standard model value due to the r.h. interaction.

For charmed hyperon decays there is some evidence [16] in support of the diquark decay cd → su, which is Cabibbo favoured in the standard theory. cs → su is Cabibbo suppressed and hence in the standard model one expects $\tau(\mathrm{cus}) \gg \tau(\mathrm{cud})$. This result is also valid in case (i). In case (ii), cd → su is strongly suppressed ($\cos^2\theta_R \approx 0$) while cs → du is Cabibbo favoured by the r.h. interactions. In this case, one expects $\tau(\mathrm{cus}) \approx \tau(\mathrm{cud})$ since one is favoured by the r.h. interaction while the other is favoured by the l.h. interaction.

Finally, it is interesting that the L–R symmetric model is a low energy manifestation of some popular grand unifying models [18]. Thus even at the level of grand unification, this model provides an alternative to the standard model of the weak interactions.

In view of the analysis in ref. [10] and that of the present paper it appears that the $K_L - K_S$ mass difference constraint favours either a very heavy right-handed gauge boson in a "manifestly symmetric" model ($\theta_L = \theta_R$) or a model with a low right-handed mass scale and strong departure from manifest L–R symmetry ($\theta_L \neq \theta_R$). It should be emphasised that both these conclusions are based on a four-quark model and are reliable to the extent that our present experimental knowledge does not flatly contradict the assumption of a negligible t-quark coupling to the light quark sector. A more complete analysis in the six-quark model is therefore desirable. At this state this analysis, however, might turn out to be inconclusive since it would involve many additional parameters, e.g., m_t and Kobayashi–Maskawa like angles (θ_{iL} and θ_{iR}, $i = 1, 2, 3$), most of which are yet to be determined. If one introduces additional phenomenological inputs like dimuon production in neutrino/antineutrino–nucleon scattering, rare decay modes of K-mesons, the *CP* violation parameter ϵ and heavy quark (c and b) decays, some quantitative information may still be obtained [‡4]. A more detailed analysis along these lines is in progress and will be discussed elsewhere.

The above conclusions are also somewhat questionable because of the use of the vacuum saturation approximation. It should, however, be noted that standard model calculations using the MIT bag [20] or the relativistic harmonic oscillator quark model [21] or SU(3) and PCAC [22] does not change the results drastically.

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‡3 The total branching ratio for the Cabibbo favoured modes (in the standard model) is experimentally much smaller than anticipated [17].

‡4 Some of these inputs have already been used to fix similar parameters in the standard model [11,19].

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