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ABSTRACT

K_L-K_S mass difference and the CP violation parameter, ϵ, of the K^o-$\overline{K^o}$ system are used to set bounds on the right-handed Cabibbo-like angle and the CP violating phase angle in the left-right symmetric electroweak model of four quarks. The corresponding mixing and phase angles in typical left-right asymmetric models ($g_L \neq g_R$) are also determined.

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I. INTRODUCTION

In spite of the remarkable successes of the standard $SU(2)_L \times U(1)$ model of the electroweak interactions [1] there has been a growing interest in the left-right symmetric model (L-R model) [2] based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. An aesthetic reason for this stems from the belief that physics (unlike many physicists!) at the fundamental level does not discriminate between left and right and that the violation of parity is only a low energy consequence of the spontaneous symmetry breakdown. The L-R model is also a subgroup of the Pati-Salam group, $SU(2)_L \times SU(2)_R \times SU(4)_c$, which naturally emerges in many grand unifying models. From the experimental standpoint, the L-R model holds the promise of an enriched particle content, some of which could well be within the striking range of the CERN $\bar{p}p$ collider.

In the context of the L-R model, it has been usual to interpret the left-handed nature of the observed weak interactions as a consequence of the large mass of the right-handed gauge bosons ($m_{W_R} >> m_{W_L}$) though an examination of the different weak processes resulted in a comparatively low bound of $m_{W_R} > 2.8\, m_{W_L}$ [3]. Recently it has become clear that if neutrinos are Majorana rather than Dirac fermions then several attractive features follow. For our purposes, the important outcome is that one is naturally led to a heavy ν_R of mass $\sim M_R$ ($\approx m_{W_R}$) associated with a light ν_L of mass $\sim m^2/M_R$, where $m (<< M_R)$ is a typical Dirac fermion mass [4]. In such a scenario, the r-h leptonic and semileptonic weak interactions are kinematically suppressed by the heavy ν_R and it is possible to envisage a situation with $m_{W_R} \approx m_{W_L}$. This is extremely interesting from the experimental point of view since the charge vector bosons ($W_R^{\pm}$, $W_L^{\pm}$) and the <u>two</u> weak neutral vector bosons (Z_1 and Z_2) are all within the range of the $\bar{p}p$ collider and ISABELLE. Of course, one must ensure that the model does not conflict with the known experimental data. Rizz and Senjanović [5] have made an analysis of the neutral current phenomenology of model and have found many allowed solutions with low M_R *).

As a further test of this model one can confront it, in the nonleptonic sector, with the K^o-$\overline{K^o}$ system. It has been found [7] that in the case of

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*) As a word of caution we must add that Barger, Ma and Whisnant in a recent analysis of the data [6] find more stringent bounds <u>at the one standard deviation</u> level.

"manifest" left-right symmetry (i.e. the same Cabibbo angle in the left- and right-handed sectors) in the four quark model, one must have $m_{W_R} \gtrsim 20\, m_{W_L}$ ($\sim$ 1.6 TeV) in order to have Δm_K of the right sign. However, if the W_R is actually of the same order of mass as the W_L then it implies a breaking of manifest left-right symmetry with interesting implication for charmed particle decays [8]. A detailed calculation of this process has been used to set bounds on the right-handed Cabibbo angle (θ_R) [9].

In this work, we consider the prediction of the L-R model for the CP violation in the K^o-$\overline{K^o}$ system. The basic CP violating mechanism in this model has been examined by Mohapatra and Pati [10]. Unlike the standard models even in the four quark case this model allows CP violation through the mass matrix and here we use the K^o-$\overline{K^o}$ system to set bounds on the CP violating phase. (In the standard model the K^o-$\overline{K^o}$ system has been often used to set bounds on the Kobayashi-Maskawa mixing angles and phase for the six quark model [11]). As a byproduct we find some new allowed ranges of θ_R not included in [9] where the CP violating phase was dropped.

This paper is organized in the following manner. In Sec.II we summarize the calculation of the K_L-K_S mass difference and the CP violating phase in the four quark L-R model. In the next section we use the known neutral kaon parameters to set bounds on the mixing angles and the phase angle. We end in Sec.IV with our discussions.

II. CP VIOLATION AND THE K_L-K_S MASS DIFFERENCE IN THE L-R MODEL

In the standard $SU(2)_L \times U(1)$ model the charge $-\frac{1}{3}$ quark weak interaction eigenstates are related to the mass eigenstates through an orthogonal transformation parametrized by the Cabibbo angle, θ_c. In the L-R model the left and right-handed weak eigenstates are related to the mass eigenstates by, in general, different unitary transformations [10]:

$$U_L = \begin{pmatrix} \cos\theta_L & \sin\theta_L\, e^{i\delta_L} \\ -\sin\theta_L\, e^{-i\delta_L} & \cos\theta_L \end{pmatrix}, \quad U_R = \begin{pmatrix} \cos\theta_R & \sin\theta_R\, e^{i\delta_R} \\ -\sin\theta_R\, e^{-i\delta_R} & \cos\theta_R \end{pmatrix}, \tag{1}$$

where $\theta_L = \theta_c$. Manifest left-right symmetry corresponds to setting $\theta_L = \theta_R$. The existence of the phase factors δ_L and δ_R makes the possibility of CP

violation in this model obvious.

The K^o-$\overline{K^o}$ system involves an effective $\Delta S = 2$ Hamiltonian. In the L-R model the lowest order contribution to this piece is generated through the box diagremas shown in Fig.1(a)-(c). (We have not exhibited the "crossed" diagrams associated with these diagrams which have also been included in the calculation.) In the standard model only Fig.1(a) is present. Once the $\Delta S = 2$ effective Hamiltonian is obtained, the two relevant parameters $\Delta m_K = m_{K_L} - m_{K_S}$ and $\mathrm{Im}\, m_{12}$ are extracted using

$$\Delta m_K = 2\,\mathrm{Re} < \overline{K^o} \,|\, H_{eff} \,|\, K^o > , \tag{2}$$

$$\mathrm{Im}\, m_{12} = \mathrm{Im} < \overline{K}_o \,|\, H_{eff} \,|\, K^o > . \tag{3}$$

The extraction of these matrix elements is complicated by the presence of strong interaction effects. We follow the time-honoured practice of assuming that the insertion of the vacuum intermediate state in all possible ways saturates the matrix element [12]. A colour factor of $\frac{4}{3}$ has been included in the result. Bag model calculations tend to agree with this result up to O(1) factors [13].

The calculations have been described in great detail in Ref.[9] taking into account the possibility of mixing between W_L and W_R for the special case of $\delta_L = \delta_R = 0$. In this paper for the simplicity of presentation we ignore the W_L-W_R mixing which is, anyway, constrained to be small [3]. Furthermore, we redefine the phase of the s-quark through the transformation $s \rightarrow e^{i\delta L}\, s$. This transformation has no observable consequence but it allows us to write the final expressions in a simpler form. Following the steps of [9], we find in a straightforward manner

$$\begin{aligned}(\Delta m_K) = (\Delta m_K)_{std}\Big[1 &+ \frac{R^2}{\mu^2 r^2}\cos 2\delta \\ &+ \frac{1}{r}\Big\{6\left(\frac{m_K}{m_s+m_d}\right)^2 + 1\Big\}\Big\{\frac{1}{\mu}\cos\delta\left(f_c + \frac{m_u^2}{m_c^2} f_u\right) \\ &- \frac{m_u}{m_c}\left(\frac{C_R^2}{C_L^2} + \frac{S_R^2}{S_L^2}\cos 2\delta\right)(f_c - 1)\Big\}\Big] ,\end{aligned} \tag{4}$$

$$\mathrm{Im}\, m_{12} = -\frac{1}{2}(\Delta m_K)_{std}\Big[\frac{R^2}{\mu^2\gamma^2}\sin 2\delta + \frac{1}{\gamma}\Big\{6\Big(\frac{m_K}{m_s+m_d}\Big)^2+1\Big\}\times$$

$$\times\Big\{\frac{1}{\mu}\sin\delta\Big(f_c + \frac{m_u^2}{m_c^2}f_u\Big) - \frac{m_u}{m_c}\frac{S_R^2}{S_L^2}\sin 2\delta\,(f_c-1)\Big\}\Big] \quad (5)$$

with

$$(\Delta m_K)_{std} = \frac{m_c^2 f_K^2\, m_K\, \alpha^2 S_L^2 C_L^2}{12\, m_{W_L}^4 \sin^4\theta} \quad (6)$$

$$f_c = \Big(\ln\frac{m_c^2}{m_{W_L}^2} + 1 + \frac{\ln\gamma}{\gamma-1}\Big); \quad f_u = f_c\,(c\rightarrow u) \quad (7)$$

$$\mu = \frac{S_L C_L}{S_R C_R}; \quad \gamma = \frac{m_{W_R}^2}{m_{W_L}^2}; \quad R = \frac{g_R^2}{g_L^2}; \quad \delta = \delta_R - \delta_L \quad (8)$$

$$S_L = \sin\theta_L, \quad C_R = \cos\theta_R \text{ etc.}$$

A few words of explanation are possibly called for. $(\Delta m_K)_{std}$ is the result obtained using the standard model (i.e. Fig.1(a) only) and is the only surviving contribution in the $m_{W_R} \rightarrow \infty$ or $g_R \rightarrow 0$ limit. The terms proportional to $1/\gamma^2$ come from Fig.1(b) while those proportional to $1/\gamma$ are from Fig.1(c). The factor $\{6(\frac{m_K}{m_s+m_d})^2+1\}$ arises from the matrix elements of $H_{eff}(\Delta s = 2)$ of the $(s-p)(s+p)$ type Dirac structure obtained from Fig.1(c) as compared to the $(V\pm A)(V\pm A)$ form from Figs.1(a) and 1(b). The factors involving f_c, f_u emerge from the loop momentum integration. External particle momenta are neglected since it has been shown that these contributions are negligible in the K^0-$\overline{K^0}$ mixing problem [14] and $m_{W_L} >> m_c >> m_u$ has been used to simplify the integrals.

III. COMPARISON WITH EXPERIMENTAL NUMBERS

In order to get a feeling for the relative sizes of the various terms in Eqs.(4) and (5) we consider the actual numerical values in a typical situation We use m_{W_L} = 77.6 GeV, m_K = .497 GeV, m_c = 1.6 GeV, m_s = .15 GeV, m_d = 5 MeV and f_k = 1.23 m_π. For $\sin^2\theta_W$ = .23, γ = 4, R = 1 we find

$$(\Delta m_K) = 4.2\times10^{-15}\Big[1 + \frac{1}{16\mu^2}\cos 2\delta$$

$$-103.1\Big\{\frac{1}{\mu}\cos\delta\Big(1+2.8\,\frac{m_u^2}{m_c^2}\Big) - 1.15\,\frac{m_u}{m_c}\Big(\frac{C_R^2}{C_L^2}+\frac{S_R^2}{S_L^2}\cos 2\delta\Big)\Big\}\Big]\,\mathrm{GeV} \quad (9)$$

$$\mathrm{Im}\, m_{12} = -2.1\times10^{-15}\Big[\frac{1}{16\mu^2}\sin 2\delta$$

$$-103.1\Big\{\frac{1}{\mu}\sin\delta\Big(1+2.8\,\frac{m_u^2}{m_c^2}\Big) - 1.15\,\frac{m_u}{m_c}\frac{S_R^2}{S_L^2}\sin 2\delta\Big\}\Big]\,\mathrm{GeV} \quad (10)$$

These quantities have to be compared with the experimental values. $\mathrm{Im}(m_{12})$ is related to the K^0-$\overline{K^0}$ CP violating parameter ϵ through

$$\epsilon = \frac{i\ \mathrm{Im}\, m_{12} + \frac{1}{2}\mathrm{Im}\,\Gamma_{12}}{i\,\frac{1}{2}\Delta\Gamma - \Delta m_K}\ .$$

Neglecting Γ_{12} which is small and using the experimental result $\Delta\Gamma \sim \Gamma_s$ = .477 Δm_k, one finds from the experimental value of ϵ [15]

$$\frac{\mathrm{Im}\, M_{12}}{\Delta m_K} = 3.25\times10^{-3}\ . \quad (11)$$

Also [16]

$$\Delta m_K = 3.52\times10^{-15}\ \mathrm{GeV}. \quad (12)$$

In the typical case of Eqs.(9) and (10), one has to look for suitable choices of θ_R and δ ($\theta_L = \theta_c$, of course) such that (11) and (12) are satisfied. Solutions can, in principle, exist in any of the four quadrants for each of θ_R δ. However, the analysis is somewhat simplified by noting that θ_R enters only in the combination $S_R C_R$ in the dominant terms, so it is enough to consider only the range $0 \leq \theta \leq \pi$ and for every θ_R that is allowed $(\theta_R + \pi)$ is also allowed. (In the terms involving S_R^2 or C_R^2 there is actually also no change by this shift of θ_R.) Moreover, changing the sign of δ only flips the sign of Im m_{12} keeping Δm_k unchanged. The sign in Eq.(11) thus helps to reduce the freedom on δ. Now, from Eq.(9) it is clear that if the signs of C_R and $\cos\delta$ are both changed simultaneously then Δm_k does not change. The change in Im m_{12} can be compensated by changing at the same time the sign of $\sin\delta$.

Thus if C_R, cos δ and sin δ form an acceptable solution then so do $-C_R$, -cos δ and -sin δ. It is therefore enough just to present the results for (i) $C_R > 0$, $\cos\delta > 0$ and (ii) $C_R > 0$, $\cos\delta < 0$.

Because of its large coefficient, the term in the curly brackets in Eq.(9) is usually dominant. The small amount of CP violation in the K^o-$\overline{K^o}$ system restricts sin δ close to zero ($\cos\delta \approx 1$). It turns out that if $\cos\delta > 0$, $C_R > o$ then the right hand side of Eq.(9) (and also of Eq.(4)) monotonically increases as $S_R C_R$ is decreased. Δm_k is initially negative but eventually becomes positive. There are significant cancellations between the two terms within the curly brackets in Eq.(9) and the ratio $\mu = S_L C_L / S_R C_R$ does not have to be too large. The results for this case are presented in Table I. Actually we have not required that the solution exactly satisfy Eq.(12) but only that it reproduces the standard model prediction for (Δm_k); i.e. the bracketed expression multiplying $(\Delta m_k)_{std}$ in Eq.(4) be unity. We have considered $m_{W_R}/m_{W_L} = 2,3$ and 4 which seems to cover the allowed range for low m_{W_R}. For the sake of completeness we have also considered the left-right asymmetric model [17]. This model is known to fit low energy neutral current data [18] with a low M_R. We have considered the choices $g_L/g_R = \sqrt{2}$ and 2. It may be noted that the $g_L \neq g_R$ possibility may be naturally realized in grand unified theories but for g_L/g_R as large as $\sqrt{2}$ or 2 this would imply $m_{W_R} >> m_{W_L}$. Therefore the asymmetric models we consider here cannot emerge from grand unified theories

For case (ii) ($C_R > 0$, $\cos\delta < 0$), the two terms in the curly brackets of Eq.(9) are of the same sign and there is no cancellation. In this case as $\mu = S_L C_L / S_R C_R$ is increased, Δm_k decreases monotonically from a large positive value. Δm_k can reduce to the standard model value only for $\mu = \infty$ and μ has to be greater than even 500 in order for Δm_k to be within 10% of the standard model prediction. This practically corresponds to setting $C_R = 0$ or $S_R = o$ in which situation there will be no CP violation at all.

IV. DISCUSSIONS

The bounds on the right handed Cabibbo angle, θ_R, and the phase angle $\delta = \delta_R - \delta_L$ set by the K^o-$\overline{K^o}$ system have been found. For this model as well as the left-right asymmetric models θ_R is found to be constrained to ranges

such that $\sin 2\theta_R$ is very small i.e. θ_R is either near 0 or near $\pi/2$. This implies that in the right-handed sector the u-quark (c-quark) couples almost to the pure d-quark (s-quark) or to the pure s-quark (d-quark). The latter alternarive has striking implications for charmed particle decays [8].

In this calculation the t-quark contribution has bot been considered. Even though it is yet to be experimentally detected the predominant feeling seems to favour the existence of the t-quark. This calculation may be extended to the six-quark system keeping the t-quark mass as a free parameter.

In conclusion, we find that the L-R model with low M_R requires strong breaking of manifest left-right symmetry in order to agree with the K_L-K_S mass difference. The CP violating phase in this model is constrained to be of roughly the same order as in the Kobayashi-Maskawa model.

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TABLE CAPTION

Table I The upper bound on $\sin\delta$ and the lower bound on $\mu = S_L C_L / S_R C_R$ allowed by the K_L-K_S mass difference and the CP violation parameter, ϵ. Case (A) corresponds to $\theta_R \approx \frac{\pi}{2}$ while case (B) corresponds to $\theta_R \approx 0$.

TABLE I

	g_L/g_R	1			$\sqrt{2}$			2		
	m_{W_R}/m_{W_L}	2	3	4	2	3	4	2	3	4
Ⓐ	μ	16	16	10	16	16	8	12	8	6
	$\sin\delta$	-1.5×10^{-3}	-2.5×10^{-3}	-1.4×10^{-3}	-1.5×10^{-3}	-4.3×10^{-3}	-9.7×10^{-3}	-3.1×10^{-3}	-14.2×10^{-3}	14.3×10^{-3}
Ⓑ	μ	72	40	40	48	16	14	24	12	8
	$\sin\delta$	$+.02\times10^{-3}$	$-.24\times10^{-3}$	-4.6×10^{-3}	1.0×10^{-3}	-1.5×10^{-3}	-0.9×10^{-3}	0.4×10^{-3}	0.7×10^{-3}	1.8×10^{-3}

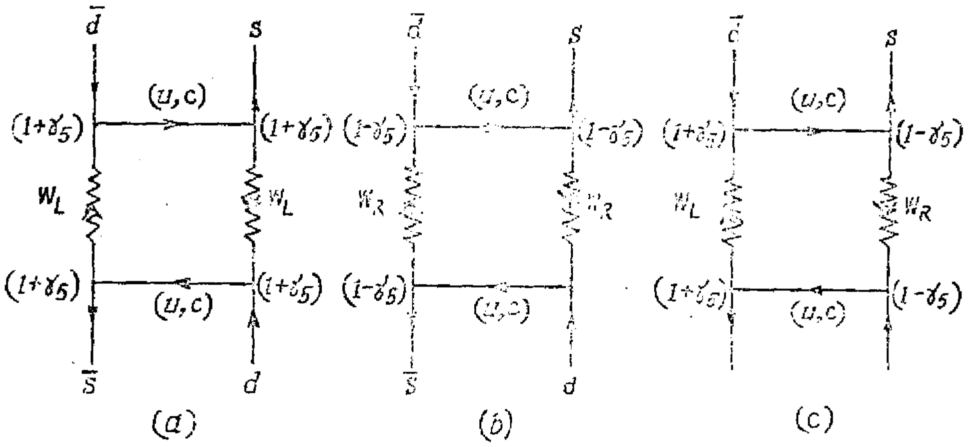

Fig.1 Diagrams which contribute to $\Delta s = 2$ H_{eff} to lowest order. The internal fermion line can be either an 'u' or a 'c' quark so that each of (a), (b) and (c) represent four diagrams.

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