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1. Introduction

The measurement of CP asymmetries in neutral B meson decays [1] will provide a crucial test of the Kobayashi-Maskawa (K.M.) mechanism of CP violation [2]. This test is specially important in view of the scarcity of experimental information on CP violation [3], which so far has only been observed in the decay of neutral kaons [4]. On the other hand, the understanding of CP violation may have profound implications for cosmology, since CP breaking is one of the essential ingredients [5] to generate baryon asymmetry in the universe. The fact that the amount of CP violation present in the Standard Model (SM) is probably not sufficient [6] to generate the observed baryon asymmetry, provides motivation to consider other sources of CP breaking.

We will consider a simple extension of the SM leading to CP asymmetries in B^0 decays that may drastically differ from those predicted by the SM. The model consists of adding to the SM an extra charge $-1/3$ quark which is isosinglet but which can mix with the standard quarks. One of the salient features of the model is the presence of Z -mediated flavor-changing neutral currents (FCNC) and deviations from unitarity

of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. An attractive aspect of models with isosinglet quarks is that although FCNC and deviations from unitarity arise and may have an important effect on CP asymmetries, they are naturally suppressed. As a result, these models can accommodate, without fine-tuning, the present experimental bounds on FCNC.

2. The Model

We will consider the standard $SU(2) \times U(1)$ gauge theory and for simplicity we will introduce only one charge $-1/3$ isosinglet quark. The quark field content of the model is thus:

$$(u^0 d^0)_L,; \quad u_{R,i}^0 \quad i = 1, 2, 3$$

$$d_{R,\alpha}^0, \quad D_L^0 \quad \alpha = 1 \dots 4,$$

where D denotes the isosinglet quark and $d_{4R}^0 \equiv D_R^0$. For our analysis, it is not necessary to specify the Higgs sector of the model. In fact, the usual Higgs doublet Yukawa couplings together with $SU(2) \times U(1)$ invariant mass terms of the type $\bar{D}_L^0 d_{R,\alpha}^0$ are sufficient to give appropriate mass to all quarks. However, the addition of an isosinglet complex scalar gives on the one hand the possibility of having spontaneous CP violation [7] and provides on the other hand a simple

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solution to the strong CP problem [8], [9]. Independently of the Higgs content of the model, the quark mass terms can be written:

$$\mathcal{L}_M = \bar{u}_{L_i}^0 (m_u)_{ij} u_{R_j}^0 + \bar{d}_{L_i}^0 (m_d)_{i\alpha} d_{R_\alpha}^0 + \bar{\tilde{D}}_L^0 (M_d)_\alpha d_{R_\alpha}^0 + h.c. \quad (1)$$

The weak gauge currents are given by [10]

$$\begin{aligned} \mathcal{L}_g &= \mathcal{L}_W + \mathcal{L}_Z \\ \mathcal{L}_W &= \frac{g}{\sqrt{2}} \bar{u}_{L_i} V_{i\alpha}^{CKM} \gamma^\mu d_{L_\alpha} W_\mu \\ \mathcal{L}_Z &= \frac{g}{2 \cos \theta_W} [\bar{u}_{L_i} \gamma^\mu u_{L_i} - Z_{\alpha\beta}^d \bar{d}_{L_\alpha} \gamma^\mu d_{L_\beta} - \sin^2 \theta_W J_{em}^\mu] Z_\mu \end{aligned} \quad (2)$$

where u_i , d_α are quark mass eigenstates. If we start the diagonalization of the mass matrices of Eq(1) from the weak-basis where the up-quark mass matrix is diagonal, the 3×4 CKM matrix is given by:

$$(V^{CKM})_{i\beta} = W_{i\beta} \quad (3)$$

where W is the unitary matrix relating the weak and mass eigenstates of the $Q = -1/3$ quarks:

$$\begin{bmatrix} d_i^0 \\ D^0 \end{bmatrix}_L = W \begin{bmatrix} d_i \\ B \end{bmatrix}_L \quad (4)$$

Due to the presence of the isosinglet quark, there are FCNC which are closely related to the deviations of unitarity in the CKM matrix:

$$Z_{\alpha\beta}^d = [(V^{CKM})^\dagger (V^{CKM})]_{\alpha\beta} = \delta_{\alpha\beta} - W_{4\alpha}^* W_{4\beta} \quad (5)$$

More explicitly, one has:

$$\begin{aligned} V_{ud}^* V_{us} + V_{cd}^* V_{cs} + V_{td}^* V_{ts} &= Z_{ds} \\ V_{us}^* V_{ub} + V_{cs}^* V_{cb} + V_{ts}^* V_{tb} &= Z_{sb} \\ V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} &= Z_{bd} \end{aligned} \quad (6)$$

One can readily show [10],[11] that both FCNC and deviations from unitarity are naturally suppressed by the ratio m^2/M^2 , where m denotes a standard quark mass and M is the isosinglet quark mass. The analysis can be readily extended to the case where there are more than one isosinglet quark or to the case where both $Q = -1/3$ and $Q = 2/3$ isosinglet quarks are introduced [10].

3. Experimental constraints on FCNC

Before analysing the impact of FCNC on CP asymmetries, it is useful to review the present experimental restrictions on FCNC. The coupling Z_{ds} leads to a Z -exchange contribution at tree level to the $K^0 - \bar{K}^0$ transition and then the size of the $K_L - K_S$ mass difference leads to a limit on $|\text{Re } Z_{ds}|$. On the other hand, the strength of CP violation measured by the parameter ε_K , limits $|\text{Im } Z_{ds}|$. Altogether one has [12]:

$$\begin{aligned} |\text{Re } (Z_{ds})| &\leq 2.4 \cdot 10^{-5} \\ |\text{Im } (Z_{ds})| &\leq \min\{6.4 \cdot 10^{-4}, 1.3 \cdot 10^{-9}/|\text{Re } (Z_{ds})|\}. \end{aligned} \quad (7)$$

The recent experimental search for the decays $B \rightarrow X \mu^+ \mu^-$ by the UA1 collaboration [13] puts a bound on the couplings Z_{bd} , Z_{bs} . From the upper bound $Br(B \rightarrow X \mu^+ \mu^-) \leq 5 \cdot 10^{-5}$, one derives the limits [10]:

$$\left| \frac{Z_{bd}}{V_{cb}} \right| \leq 0.029, \quad \left| \frac{Z_{bs}}{V_{cb}} \right| \leq 0.029. \quad (8)$$

It is worth recalling that in the SM, the above ratio is predicted [14] to be $Br(B \rightarrow X \mu^+ \mu^-) \approx 6 - 8 \cdot 10^{-6}$, i.e. one order of magnitude smaller than the present experimental upper bound.

The crucial point is that in spite of the stringent bounds of Eq. (8), FCNC can contribute to $B^0 - \bar{B}^0$ mixing with sufficient strength to lead to predictions for CP asymmetries in B^0 decays which differ significantly from those of the SM.

4. CP Asymmetries in B^0 decays

In the SM, the dominant contribution to $B^0 - \bar{B}^0$ mixing arises from the top-quark contribution to the box diagram. Let us assume that the off-diagonal element of $B_q^0 - \bar{B}_q^0$ is changed by a factor Δ_{qb} , as a result of a new contribution from physics beyond the SM:

$$M_{12} = M_{12}^{(0)} \Delta_{qb} \quad (q = d, s) \quad (9)$$

where $M_{12}^{(0)}$ is the box diagram contribution. We will consider decays where the dominant amplitudes contributing to the decay have the same CKM phase. We will further assume that $\Gamma_{12}^{(0)} \ll$

$M_{12}^{(0)}$. In this case the CP asymmetry is given by:

$$a \equiv \frac{\Gamma(B^0 \rightarrow f) - \Gamma(\bar{B}^0 \rightarrow f)}{\Gamma(B^0 \rightarrow f) + \Gamma(\bar{B}^0 \rightarrow f)} \simeq -\sin(\Delta M t) \sin \phi, \quad (10)$$

where

$$\begin{aligned} \phi &= \phi^{(0)} + \arg \Delta_{bq}, \\ \Delta_{bq} &= \Delta_{qb}^*, \\ \phi^{(0)} &= \arg \left[\left(\frac{q}{p} \right)^{(0)} \frac{\bar{A}(f)}{A(f)} \right], \\ \left(\frac{q}{p} \right)^{(0)} &= \left[\frac{M_{12}^{(0)*}}{M_{12}^{(0)}} \right]^{1/2}. \end{aligned} \quad (11)$$

The index (0) denotes the contributions arising within the three generations SM, and $A(f)$, $\bar{A}(f)$ stand for the decay amplitudes from the initial state $|B^0\rangle$, $|\bar{B}^0\rangle$ to a CP eigenstate $|f\rangle$. From Eq. (11) it is clear that there are two ways in which new physics may change the SM prediction for CP asymmetries:

- (i) A non-vanishing Δ_{bq} , which determines the deviation from the box diagram contribution $\phi^{(0)}$. There will be different new physics contributions for B_d and B_s , if $\arg \Delta_{bd} \neq \arg \Delta_{bs}$.
- (ii) Although the expression for $\phi^{(0)}$ is the one given by the SM, the actual numerical value of $\phi^{(0)}$ may differ from the SM prediction. This is due to the fact that models beyond the SM allow in general for a different range of the CKM matrix elements.

The parametrization of Eq. (9) may be useful in general to characterize the effect of new physics on CP asymmetries. We will now specialize to the model with an isosinglet quark, where the new contribution to the $\Delta B = 2$ effective Hamiltonian arises from Z -exchange tree graphs. The same analysis applies in the case of more than one charge $-1/3$ isosinglet quark. It is obvious that $\Gamma_{12}^{(0)}$ is not significantly changed. One readily obtains [10]:

$$\Delta_{bq} = 1 + r_q e^{2i\theta_{bq}}$$

$$\begin{aligned} r_q &= \frac{1}{\nu |\bar{E}(x_t)|} \left| \frac{Z_{bq}}{V_{tb} V_{tq}^*} \right|^2 \\ \theta_{bq} &= \arg \left[\frac{Z_{bq}}{V_{tq} V_{tb}^*} \right] \end{aligned} \quad (12)$$

where $\nu = \alpha/4\pi \sin^2 \theta_W$ and $\bar{E}(x_t) = \left(\frac{m_t}{M_W} \right)^2$ is an Inami-Lim function for the top quark box diagram. For $m_t = 140$ GeV, $\nu \bar{E}(x_t) = -0.0046$.

The experimental value of B_d^0 - $\bar{B}_d^0$ mixing fixes the allowed range for the product $|V_{td} V_{tb}|^2 \cdot |\Delta_{bd}|$ through the relation:

$$|V_{td} V_{tb}|^2 |\Delta_{bd}| = \left[\frac{6\pi^2}{G_F^2 \eta_{\text{QCD}} M_W^2 M_B} \right] \cdot \frac{x_d}{\tau_B B_B f_B^2} \frac{1}{|\bar{E}(x_t)|} \quad (13)$$

where we have used standard notation. For a given value of r_d , θ_{bd} , one obtains $\arg \Delta_{bd}$, $|\Delta_{bd}|$ from Eq. (12) and then Eq. (13) fixes the allowed range of $|V_{td} V_{tb}|$. It is useful to consider the following two cases, in the study of CP asymmetries:

- (a) $r_q \gg 1$ — Z -exchange gives the dominant contribution to B_q^0 - $\bar{B}_q^0$ mixing.
- (b) $r_q \approx 1$ — Z -exchange and box diagrams give comparable contributions to B_q^0 - $\bar{B}_q^0$ mixing.

It can be readily seen that the bounds of Eq. (8), together with the quadrangular relations of Eqs. (6) imply that in the case of B_d^0 the dominant contribution to B_d^0 - $\bar{B}_d^0$ mixing may arise from Z -exchange, while for B_s^0 , Z -exchange can at most compete with the box-diagram contribution. Case (a) was studied in Ref. [12], where it was shown that the CP asymmetries $a(J/\psi K_s)$, $a(\pi^+ \pi^-)$ no longer measure the angles β and α , as it happens in the SM, but the angles β' , α' defined by Fig. (1), where a geometrical interpretation of the third line in Eq. (6) is given. Case (b) is somewhat more involved and it was studied in Ref. [10]. The crucial point is that even for relatively small values of r_q (i.e. non-dominant contribution of Z -exchange diagrams) the prediction for CP asymmetries can differ substantially from those of the SM. This is illustrated in Fig. (2)

Figure 1. The unitarity quadrangle in the B_d sector, corresponding to the third line in Eq(6).

where the regions in r_d, θ_{bd} space where the model predicts the sign of the asymmetry $a(J/\psi K_s)$ to be opposite to the one predicted by the SM are plotted.

Recently, it has been pointed out [15], [16] that, in the SM, there is a strong correlation between the CP-violating asymmetries in the decays $B_d^0 \rightarrow J/\psi K_s$ and $B_d^0 \rightarrow \pi^+ \pi^-$, leading to a very restricted allowed region for these asymmetries. In Fig. (3) we give the correlations for $a(J/\psi K_s)$, $a(\pi^+ \pi^-)$ for the SM, the superweak (SW) model [17] and the present model with an isosinglet quark for $r_d = 0.6$. It is clear that the study of these correlations is a powerful tool to test for new physics since models beyond the SM may give drastically different correlations.

The decays of B^0 mesons offer yet another possibility for detecting new physics through the measurement of the CP-violating leptonic charge asymmetry in the number of equal sign lepton pairs arising from the semi-leptonic decay of $B^0 - \bar{B}^0$ pairs:

$$A_{SL} = \frac{N_{++} - N_{--}}{N_{++} + N_{--}}. \quad (14)$$

It has been pointed out [18] that A_{SL} may play a crucial rôle in distinguishing the SM from the SW model. In the model with an isosinglet quark, it has been shown [19] that A_{SL} can be significantly larger than in the SM and that a study of the correlations ($A_{SL}, A_{\psi K_s}$) offers a promising way of detecting new sources of CP violation and in

Figure 2. The regions of r_d, θ_{bd} space where (a) the model predicts $a(J/\psi K_s)$ to be positive, thus contradicting the SM, (b) the model predicts $a(J/\psi K_s)$ to be negative, and (c) the unitarity triangle does not close. For this figure the values $m_t = 140 Ge$, $|V_{ud}| = 0.9744$, $|V_{ub}|/|V_{cb}| = 0.1$, $|V_{cd}| = 0.204$ and $(B_B F_B^2)^{1/2} = 0.2 Gev$ were used.

particular distinguishing the model from the SM and the SW model.

5. Conclusions

We have described a simple extension of the SM which predicts CP asymmetries in B^0 decays which may differ drastically from those expected in the SM. We have emphasized that B -physics at either $e^+ e^- B$ factories or at hadron colliders, provides an excellent opportunity to look for new physics and test some of the least known aspects of the electroweak theory, namely those having to do with Yukawa couplings and the closely related phenomenon of CP violation.

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Figure 3. $a(J/\psi K_s)$ versus $a(\pi^+ \pi^-)$ for $r_d = 0.6$. The solid line gives the prediction of our model with the choice of central values for the relevant physical parameters and $m_t = 140 \text{ GeV}$. The dashed line gives the SW prediction and the dotted line encloses the allowed region in the SM as obtained in Ref[15] when the penguin contribution to $a(\pi^+ \pi^-)$ is considered.

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