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Abstract: Mass mixing and CP-violation in the B^0-$\bar{B}^0$ system are calculated in a recently proposed "horizontal" extension of the standard electroweak theory. The model allows practically complete mixing of B_s^0-$\bar{B}_s^0$ with aproximately 10% CP-impurity. The lepton charge asymmetry arising from the semi-leptonic decays of B_s^0 and $\bar{B}_s^0$, pair produced in e^+e^- annihilation, could be as large as $\sim 4\%$ to be contrasted with its small value ($< 1\%$) in the Kobayashi-Maskawa scheme.

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The early observation [1] that CP-violation in the b-quark sector could be large within the standard Kobayashi-Maskawa (KM) scheme [2] has recently led to systematic studies [3-5] showing that the KM scheme cannot simultaneously accommodate a large CP-violation and an appreciable mixing in the B^0-$\bar{B}^0$ system. Thus even though the former could be large, its experimental observation does not seem feasible. In this letter, we consider a model [6] which allows for an almost completely mixed B_s^0-$\bar{B}_s^0$ system containing at the same time, a rather large CP-impurity.

The model [6] is an extension of the standard Glashow-Weinberg-Salam theory and is based on the gauge group $SU(2)_L \times U(1)_Y \times O(3)_{RH}$. The additional $O(3)_{RH}$ describes interactions between right-handed members of different generations, each of which is characterized by the same set of quantum numbers with respect to $SU(2)_L \times U(1)$. Details of the model are worked out in ref. [6]. Here we only note its features relevant to the present analysis. Besides the superweak CP-violations in K^0-$\bar{K}^0$ system it can accommodate larger CP-violations in the third generation (characterized by the strength $G_H \sim 10^{-5}$ times the Fermi coupling constant G_F). Interactions between the left-handed fermions are CP conserving at the tree level i.e. the matrix analogous to the KM-matrix is real. Both these feature are also present in a larger class of models first proposed by Davidson and Wali [7]. We expect that our conclusions are valid in this more general class of "horizontal" CP-violation models but, for definiteness, here we concentrate on the model of ref. [6].

CP-violation in the mixing of neutral pseudoscalar measons (such as B^0-$\bar{B}^0$) introduces an asymmetry a in the inclusive production of the like-charge dimuons in e^+e^- annihilation. This asymmetry is related to the ratios r and $\bar{r}$ defined [8] as follows:

$$r \equiv \frac{N(B^0 \to \ell^+ + \cdots)}{N(B^0 \to \ell^- + \cdots)} = \eta \frac{\Delta M^2 + 1/4\,(\Delta\Gamma)^2}{2\Gamma^2 + \Delta M^2 - 1/4\,(\Delta\Gamma)^2} \,, \tag{1}$$

$$\bar{r} \equiv \frac{N(\bar{B}^0 \to \ell^- + \cdots)}{N(\bar{B}^0 \to \ell^+ + \cdots)} = \frac{1}{\eta} \frac{\Delta M^2 + 1/4\,(\Delta\Gamma)^2}{2\Gamma^2 + \Delta M^2 - 1/4\,(\Delta\Gamma)^2} \,. \tag{2}$$

ΔM and $\Delta\Gamma$ respectively denote the mass and decay-width differences for the B^o-$\bar{B}^o$ system. Γ is the total decay width. η characterizes the CP-violation in B^o-$\bar{B}^o$ mixing and is given [5] in terms of the standard variable ε as $\eta = \left|\frac{1-\varepsilon}{1+\varepsilon}\right|^2$.

The dilepton charge asymmetry a has the following expression [3-5] in terms of r and $\bar{r}$:

$$a = \frac{r-\bar{r}}{r+\bar{r}} = \frac{|\Gamma_{12}|/|M_{12}| \sin(\theta-\Phi)}{1. + 1/4 \left|\frac{\Gamma_{12}}{M_{12}}\right|^2} \quad . \tag{3}$$

Γ_{12} and M_{12} appearing here are, respectively, elements of the width and mass matrices, govering the evolution of the B^o-$\bar{B}^o$ complex. The phases are defined by $M_{12} = |M_{12}|\, e^{i\theta}$ and $\Gamma_{12} = |\Gamma_{12}|\, e^{i\Phi}$. The values of Γ_{12} and M_{12} determine ΔM and $\Delta\Gamma$ [4]. The asymmetry a depends only on the parameter η and hence truly reflects the amount of CP-violation. In contrast, the total single-lepton charge asymmetry ℓ [4] signals the experimental observability of the CP-violation as it depends on the amount of B^o-$\bar{B}^o$ mixing also:

$$\ell \equiv \frac{r-\bar{r}}{2+r+\bar{r}} \quad . \tag{4}$$

In the standard KM scheme, one infers M_{12} from the calculation [4,9] of the dispersive part of the famous box-diagram [9]. Γ_{12} is obtained from the absorptive part of the latter [4], or from the analysis [3,5] of the decay channels common to B^o and $\bar{B}^o$. We shall choose the former approach. The leading contribution to the ratio $|\Gamma_{12}/M_{12}|$ in the KM model [4] is sensitive only to the masses of the bottom and the top quarks and approaches approximately 10% for $m_t \sim 30$ GeV. However, one does not obtain such a large dilepton asymmetry a because the phases θ and Φ of the leading contributions to M_{12} and Γ_{12} are identical. Therefore a of eq. (3) arises only from the sub-leading contributions down by powers of the ratios of the light to the heavier quark masses [4].

The situation is quite different if the main source of CP-violation is provided by the horizontal interactions of the type proposed in ref. [6,7]. The horizontal gauge bosons-unlike the vertical ones-can generate neutral flavour changing transitions and hence exchange of a single such boson can mix states like B^o-$\bar{B}^o$ in a manner shown in fig. 1. This diagram can contribute only to M_{12}. Im Γ_{12} receives contribution through two such exchanges and hence it is very small compared to ImM_{12}. The contributions of ordinary weak interactions to M_{12} and Γ_{12} are purely real. As a result, unlike in the standard model, the phase cancellation in eq. (3) does not take place and it is possible to obtain a rather large dilepton asymmetry.

In the quantitative analysis of B^o-$\bar{B}^o$ mixing we shall assume, following ref. [6], a hierarchy in the masses of horizontal gauge bosons and take the boson H_1, generating transitions among the second and third generation to be the lightest one. The effective strength of interactions mediated by H_1, is characterized by a coupling $G_H \sim 10^{-5}\ G_F$. This is consistent with the CP-violation in K^o-$\bar{K}^o$ mixing [6] and with the limits coming from various neutral flavour changing transitions [10].

Neglecting contributions from the heavier horizontal gauge bosons, the effective Hamiltonian for transitions among charge 1/3 quarks is given [6] as follwos:

$$\mathcal{H}_{eff.} = \frac{G_H}{\sqrt{2}} (\bar{\chi}_R \gamma_\mu \hat{T}_1 \chi_R)(\bar{\chi}_R \gamma^\mu \hat{T}_1 \chi_R) \tag{5a}$$

with

$$\hat{T}_1 \equiv U_R T_1 U_R^\dagger \quad . \tag{5b}$$

χ_R denotes the column vector of physical charged 1/3 states d,s and b. T_1 is the generator in the vector respresentation of $O(3)_{RH}$. U_R is a mixing matrix and is the product of an orthogonal matrix O_R with a diagonal phase matrix F. O_R takes the following explicit form if the simplest possible Higgs-sector that allows CP-violation is assumed:

$$O_R = \begin{pmatrix} \cos\beta_R & -\sin\gamma_R \sin\beta_R & -\cos\gamma_R \sin\beta_R \\ 0 & \cos\gamma_R & -\sin\gamma_R \\ \sin\beta_R & \sin\gamma_R \cos\beta_R & \cos\gamma_R \cos\beta_R \end{pmatrix} \qquad (6)$$

γ_R and β_R resp. govern the mixing of the second and the first generation with the third one. In what follows we shall assume the typical values $\gamma_R \sim 10^{-1}$ and $\beta_R \sim 10^{-2}$. These are consistent with K^O-$\bar{K}^O$ mixing [6]. Moreover, these are typical values of the corresponding angles in the left-handed sector [11].

ImM_{12} for the B^O-$\bar{B}^O$ system can be calculated from $\mathcal{H}_{eff}$ by using the vacuum saturation assumption [9] with the appropriate colour factors [12]. It can be seen from the explicit form of O_R and eqs. (5) that ImM_{12} is zero for $B_d^O \sim (d\bar{b})$ meson. Hence one does not expect any CP-violation in B_d^O-$\bar{B}_d^O$ mixing in the model. For the $B_{os} \sim (s\bar{b})$ system, M_{12} has an imaginary part which is given in terms of the B-decay constant f_{B_s} and it's mass m_{B_s} as:

$$(Im\, M_{12})_{B_s} = \frac{G_H}{3\sqrt{2}} f_{B_s}^2 m_{B_s} \cos^2\beta_R \cos 2\gamma_R \sin 2(\varphi_2 - \varphi_3) \quad . \qquad (7)$$

The sin $2(\varphi_2-\varphi_3)$ factor in this equation arises from the phase matrix F present in U_R [6]. We shall assume maximal CP-violation setting this factor to 1. Contribution of $\mathcal{H}_{eff}$ to $(ReM_{12})_{B_s}$ then turns out to be negligible. The latter as well as Γ_{12} do, however, receive contributions comparable to eq. (7) from the ordinary weak interactions. They can be obtained from the corresponding expressions [4] in the standard model. The only change that occurs in our case is the replacement of KM-matrix by a 3 x 3 orthogonal matrix O_L. We adopt the following parametrization for O_L suggested by Maiani [13]:

$$O_L = \begin{pmatrix} \cos\beta\cos\theta & -\sin\theta\cos\gamma - \sin\beta\sin\gamma\cos\theta & \sin\gamma\sin\theta - \sin\beta\cos\gamma\cos\theta \\ \cos\beta\sin\theta & \cos\gamma\cos\theta - \sin\beta\sin\gamma\sin\theta & -\sin\gamma\cos\theta - \cos\gamma\sin\beta\sin\theta \\ \sin\beta & \sin\gamma\cos\beta & \cos\gamma\cos\beta \end{pmatrix} . \qquad (8)$$

θ in eq. (8) is the Cabibbo angle, while β and γ are analogous to the other two KM angles [2].

Using O_L instead of the KM-matrix in calculations of Hagelin [4] we get the following expressions for the real parts of M_{12} and Γ_{12}, respectively:

$$(ReM_{12})_{B_s} = \frac{G_F^2 f_{B_s}^2 m_{Bs}}{12\pi^2} \left\{ \xi_t^2 \left(m_t^2 + \tfrac{1}{3} m_b^2 + \tfrac{3}{4} m_b^2 \ln \frac{m_t^2}{m_b^2} \right) + O\left(m_c^2, \frac{m_b^4}{m_t^2}\right) \right\}, \qquad (9a)$$

$$(Re\,\Gamma_{12})_{B_s} = -\frac{G_F^2 f_{B_s}^2 m_{Bs}}{8\pi} \left\{ \xi_t^2 m_b^2 + \tfrac{8}{3} \xi_t \xi_c m_c^2 + O\left(\frac{m_c^4}{m_b^2}\right) \right\} \qquad (9b)$$

with

$$\xi_t \equiv \sin\gamma\cos\gamma\cos^2\beta \qquad (10a)$$

and

$$\xi_c \equiv \tfrac{1}{2} \sin 2\gamma (\sin^2\theta \sin^2\beta - \cos^2\theta) - \tfrac{1}{2} \sin 2\theta \cos 2\gamma \sin\beta \quad . \qquad (10b)$$

In order to complete the analysis, we now need the total decay width Γ_{B_s}. This has been calculated by Leveille [14] combining various models proposed to describe the B-decays. Again replacing in his formula KM matrix elements by the corresponding elements of O_L we get:

$$\Gamma_{B_s} = \frac{G_F^2 m_b^5}{192\,\pi^3} \left(8.67 \sin^2\beta + 3.75 \sin^2\gamma \cos^2\beta \right) \quad . \qquad (11)$$

This and similar expressions for other mesons could serve also to infer about the angles β and γ. We shall use the bounds obtained by the JADE group [11] in the numerical analysis that follows.

We adopt the values $f_{B_s} \sim 0.3$ GeV and $m_{B_s} \sim 5.2$ GeV for the decay constant and the mass of B_s^0, respectively, and choose two characteristic values (20 and 30 GeV resp.) for the top quark mass m_t. The asymmetries a and ℓ are not much sensitive to the values of β, while with respect to γ they have the variations displayed in fig. 2. One obtains rather large dilepton asymmetry within the allowed values [11] of γ. This arises because of the significant difference in the phases of M_{12} and Γ_{12} and because of the large values for the ratio $|\Gamma_{12}|/|M_{12}|$. We find that the coefficient of η in eq. (3) - characterizing the mixing of B_s^0-$\bar{B}_s^0$ - stays close to 1 indicating almost complete mixing of the system. Coexistence of the large values of a with the complete mixing results in rather large values of ℓ as shown on fig. 2. One should compare this with the value ($<$ 1%) obtained [4] in the KM model for similar values of the top quark mass.

As already mentioned, this explicit model also predicts the absence of CP-violations in B_d^0-$\bar{B}_d^0$ sector. This may not persist in more general horizontal models. Recall that in ref. [6] the lowest two generations remain massless in the tree approximation because of the simplest possible Higgs structure adopted. These light masses can arise either from the radiative corrections e.g. in the manner of ref. [15] or from a more complicated Higgs structure. It was shown in ref. [6] that it is possible to introduce more Higgs multiplets in such a way that the reality of the KM matrix at the tree level is not spoiled and at the same time the light quarks and leptons receive masses. The only change

that occurs is the replacement of O_R in eq. (6) by a general orthogonal matrix like the one given in eq. (8). This modified mixing matrix allows CP-violation in both B_d^0-$\bar{B}_d^0$ and B_s^0-$\bar{B}_s^0$ and can also account for the CP-violations in K^0-$\bar{K}^0$. The details depend upon one more completely unknown mixing angle θ_R.

The experimental observation of the lepton asymmetry in B_s^0-$\bar{B}_s^0$ seems hard since they can presumably be produced only in the continuum. The measurement in the B_d^0-B_d^0 system is comparitively easier and can be done on the Υ(4S) resonance at 10.55 GeV [16] decaying predominently into $b\bar{b}$ channel. Assuming e.g. a single-lepton asymmetry of 5% in B_d^0-$\bar{B}_d^0$ decay one would need several ten thousand events on the Υ(4S) in order to observe it. The measurement of the corresponding 10% dilepton asymmetry could be harder since that would require several hundered thousand events on the Υ(4S).

In summary, we have pointed out the possibility of observable CP-violations in the B^0-$\bar{B}^0$ systems within the horizontal gauge models [6,7] with real Kobayashi-Maskawa matrix. Details are worked out in a specific model which predicts large CP-violation in B_s^0-$\bar{B}_s^0$ system but none in B_d^0-$\bar{B}_d^0$. The predictions are admittedly model-dependent in their details. Nevertheless, they indicate that horizontal interactions could provide a source of relatively large CP-violations in the B^0-$\bar{B}^0$ system.

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Figure Captions:

Fig. 1 The graph contributing to CP-violation in mixing of B_s^o-$\bar{B}_s^o$ states.

Fig. 2 Magnitude (in %) of the predicted dilepton (solid curve) and the single lepton (broken curve) charge asymmetry coming from the semi-leptonic decays of B_s^o and $\bar{B}_s^o$ produced in e^+e^- annihilation as functions of $|\sin\gamma|$ for m_t = 20 GeV and 30 GeV, respectively.

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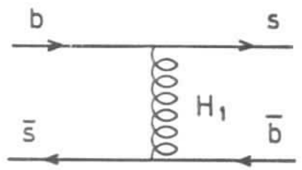
b
s
H1
s̄
b̄

Fig. 1

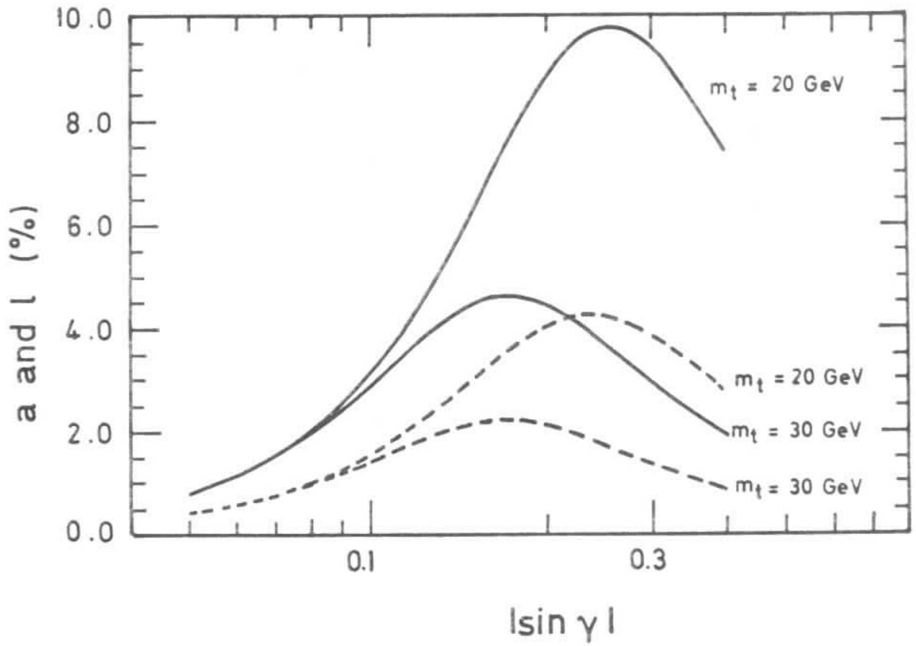
10.0
8.0
6.0
4.0
2.0
0.0
0.1
0.3
a and l (%)
|sin γ|
m_t = 20 GeV
m_t = 20 GeV
m_t = 30 GeV
m_t = 30 GeV

Fig. 2