CP-VIOLATION IN A SUPERSTRING INSPIRED MODEL WITH EXOTIC QUARKS

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Exotic charge $-1/3$ colour triplet (h) quarks are contained in E_6 models We examine the effects on *CP* violation resulting from h–b mixing and find that the lower bound on m_t is removed, ϵ'/ϵ is reduced and B^0–$\overline{B}^0$ mixing remains unchanged

An E_6 supersymmetric ($N=1$) grand unified theory (GUT) in four dimensions is known to emerge from the heterotic string after compactification on a Calabi–Yau manifold [1] The massless string excitation modes (relevant for low energy) are arranged in 27-plets of the gauge group The E_6 symmetry is subsequently broken to a rank $\geqslant 5$ group by Wilson loops related to the nonsimply connected nature of the Calabi–Yau manifold However, when no intermediate mass scales are present – as appears to be required on cosmological grounds [2] the whole 27-plet survives down to low energies Under SO(10) the 27 splits into a $16+10+1$ while under SU(5) it contains $\bar{5}+10+1+5+\bar{5}+1$ Thus in addition to the usual (including the right-handed neutrino) 16 fermions there are 11 others for each generation Of these, the ones on which we wish to focus our attention are the colour triplet charge $-1/3$ h-quark states contained in 5 and $\bar{5}$ of SU(5) [10 of SO(10)] When symmetry is broken they may mix with the d-type quarks Here we investigate the implications of such mixing on *CP* violation

In the standard three-generation model *CP* violation occurs through a phase δ in the Kobayashi–Maskawa (KM) quark mixing matrix V, which is unitary [3] Recent precise evaluation of the KM matrix elements [4] have indicated some deviations from unitarity – $|V_{ud}|=0\ 9729\pm0\ 0012$, $|V_{us}|=0\ 221\pm0\ 002$, $|V_{ub}|<0\ 0067$ (90% CL) [5] This has been taken by many as an indication for the existence of a fourth generation [6] On the other hand, it has been argued in the context of superstring models that a fourth generation may be phenomenologically unacceptable [2] Thus in these models the deviation of V from unitarity must be attributed to the mixing of h with d-type quarks, with $0\ 088>|V_{uh}|>0\ 045$ (90% CL) [4,7]

The implications on phenomenology of the mixing of exotic quarks in superstring models have recently received wide attention If the h mixes with the d alone, the mixing is constrained to be small since $|V_{ud}|$ has been measured to a high precision (see above) The consequences of such a d–h mixing have been examined for neutral currents [8], h-quark decay [9], top-quark mass [10], and sneutrino VEV [11] The smallness of this mixing makes it completely imperceptible in *CP* violation We do not consider h–s mixing either since it is constrained by the KM matrix to be almost of the same order as h–d mixing The remaining possibility is that of h–b mixing which can be rather large and has been shown [7] to have interesting signatures of its own Here we consider *CP* violation in the light of this mixing

Taking this mixing into account the KM matrix is generalised to the (3×4) matrix (no fourth u-type quark)

$$V=\begin{pmatrix} c_1 & -s_1c_3 & -s_1s_3c_\alpha & s_1s_3s_\alpha \\ s_1c_2 & c_1c_2c_3-s_2s_3\,e^{i\delta} & (c_1c_2s_3+s_2c_3\,e^{i\delta})c_\alpha & -(c_1c_2s_3+s_2c_3\,e^{i\delta})s_\alpha \\ s_1s_2 & c_1s_2c_3+c_2s_3\,e^{i\delta} & (c_1s_2s_3-c_2c_3\,e^{i\delta})c_\alpha & -(c_1s_2s_3-c_2c_3\,e^{i\delta})s_\alpha \end{pmatrix}, \tag{1}$$

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[1] For reviews see ref [1]

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where $c_1 = \cos\theta_1$, $s_1 = \sin\theta_1$, etc.

From the deviation of the KM matrix from unitarity one can conclude that $\cot\alpha = |V_{ub}|/|V_{uh}|$ is bounded by $\cot\alpha < 0.11$ (90% CL). The key idea of this paper is the following: the presence of $\cos\alpha$ in the third column implies that the stringent restrictions on θ_2, θ_3 and δ from the bottom lifetime τ_B and the ratio $\bar{R} = \Gamma(b \to u\ell\nu)/\Gamma(b \to c\ell\nu)$ are now relaxed. This will dramatically affect the *CP* predictions of the model.

Let us briefly outline the usual approach followed in the standard model [12]. For any τ_B and $\bar{R}$, θ_3 is fixed and θ_2 and δ get correlated. From the standard K^0–$\bar{K}^0$ box diagram calculation the ϵ parameter is given to a good approximation by

$$|\epsilon| = 3.82 \times 10^4 B[\mathrm{Im}\,\lambda_t\,\mathrm{Re}\,\lambda_t]s(m_t)\eta_2 , \qquad (2)$$

where B is the so-called "bag factor", $\lambda_t = V^*_{td}V_{ts}$, $s(m_t)$ is a monotonically increasing function whose explicit form is found in ref. [12] and $\eta_2 \simeq 0.60$ is a QCD correction factor. In writing eq. (2) we have dropped terms involving m_c and m_u which contribute negligibly. Given τ_B and $\bar{R}$, the angle-dependent factor enclosed in the brackets peaks for a certain value of δ (usually $c_\delta \simeq -0.6$) – this determines [from eq. (2)] the minimum allowed m_t for that particular τ_B and $\bar{R}$. For any m_t greater than this lower bound, δ (and θ_2) is determined from eq. (2). Once m_t and the KM matrix elements are fixed, one can use them to obtain ϵ'/ϵ and also mixing and *CP* violation in the B^0–$\bar{B}^0$ sector [13].

In the standard model the experimental values of τ_B and $\bar{R}$ constrain θ_2 and θ_3 to very small values, leading to a significant lower bound on m_t and a rather large ϵ'/ϵ. Now with h–b mixing in operation the presence of the $\cos\alpha$ factor in the third column of V considerably relaxes the constraints on the angles. One now obtains

$$s_3 = (s_3)_{\mathrm{std}}/c_\alpha , \qquad (3)$$

and

$$\theta_2 = \tfrac{1}{2}[\cos^{-1}(c/\sqrt{a^2 + b^2 c_\delta^2}) + \sin^{-1}(b c_\delta/\sqrt{a^2 + b^2 c_\delta^2})] , \qquad (4)$$

where $a = c_3^2 - c_1^2 s_3^2$, $b = -2c_1 s_3 c_3$ and $c = c_3^2 + s_3^2\,(c_1^2 - 5.78)$. Since the allowed values of the mixing angles are now much larger [‡2], we have chosen to consider the situation which is most unfavourable for the standard model, namely $B = 1/3$. $\bar{R} = 0.04$ – a rather low value – has been used in line with ref. [5]. With this choice and with $\cot\alpha = 0.11$ we find that for τ_B ranging from 0.6 to 1.4 ps, s_3 varies from 0.370 to 0.245. We have used the upper bound of $\cot\alpha$, if it is smaller than this value then s_3 will turn out to be larger. Further, $\mathrm{Im}\,\lambda_t\,\mathrm{Re}\,\lambda_t$ peaks at $c_\delta \simeq -0.35$ which, taken in conjunction with eq. (2), yields an insignificantly small lower bound on m_t (which is already experimentally known to be heavier than 21 GeV). Thus even with the largest allowed value of $\cos\alpha$, the lower bound on m_t is removed in this model.

For any m_t in the range usually considered (30–60 GeV), eqs. (2)–(4) give us two solutions for δ which are very close to 0 and π. s_δ turns out to be at least two orders of magnitude smaller than in the usual case. In fig. 1 we have plotted $\sin\delta$ as a function of τ_B for four typical choices of m_t.

The other *CP*-violation parameter in the kaon system is ϵ'/ϵ. It is extracted from the penguin diagram and is given by

$$\epsilon'/\epsilon = 15.6 H s_2 c_2 s_3 s_\delta , \qquad (5)$$

with $H = 0.54$ [12]. Our results for ϵ'/ϵ are exhibited in fig. 2. Evidently these numbers, obtained for the most unfavourable choice of the bag factor B, are smaller than the corresponding values in the standard model. Also shown in fig. 2 is the experimental bound obtained by combining the results of ref. [14] and ref. [15].

Let us now turn to B^0–$\bar{B}^0$ mixing. A measure of mixing is provided by like-sign dileptons seen from B^0–$\bar{B}^0$

[‡2] In this work we have not considered the restrictions on the KM angles imposed by charm decay and neutrino production of charm. When these constraints [5] are included, only the solutions with δ in the first quadrant are allowed.

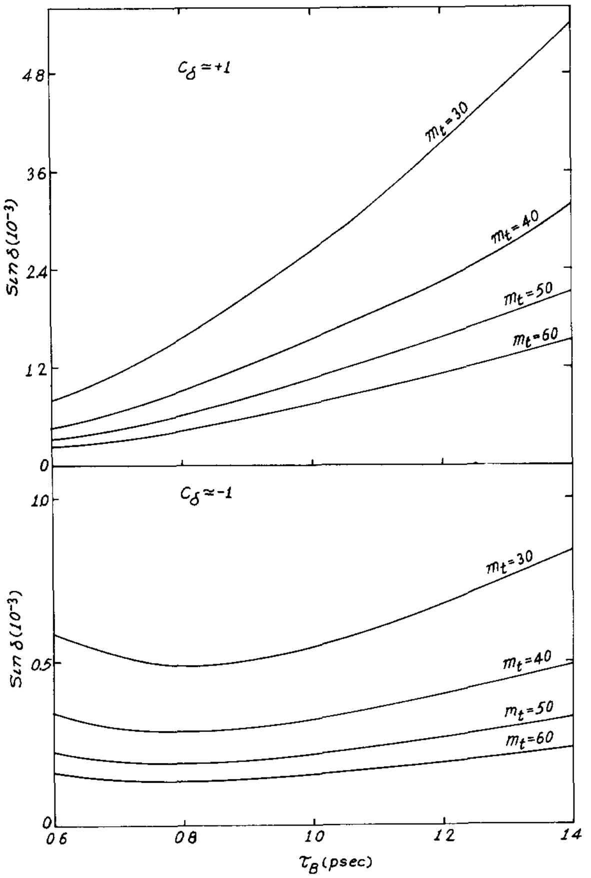

Fig. 1. sin δ as a function of τ_B for different values of m_t (GeV). $\bar{R}=0.04$, $B=1/3$.

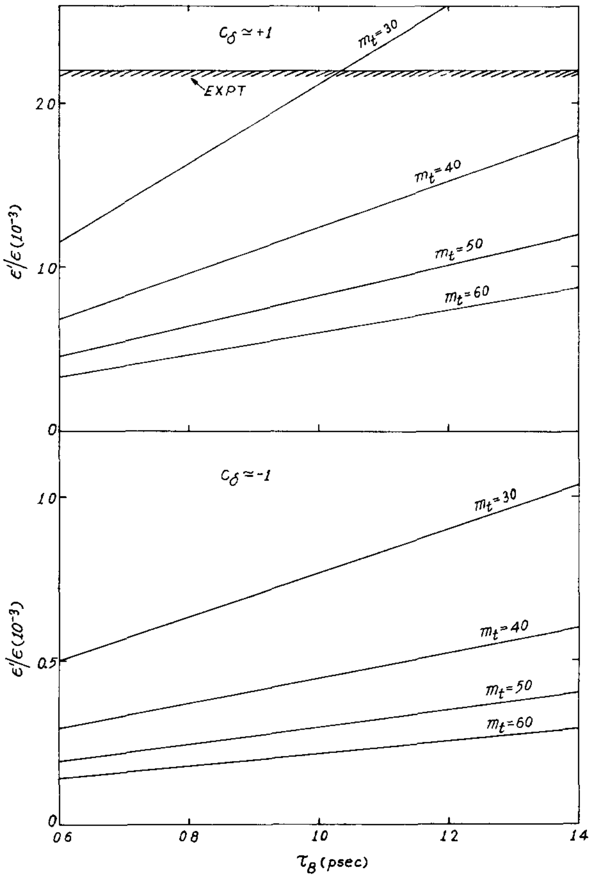

Fig. 2. ϵ'/ϵ as a function of τ_B for different values of m_t (GeV). $\bar{R}=0.04$, $B=1/3$. The experimental bound is also shown.

pair production. This and other observables which characterise the mixing, can be expressed in terms of the theoretically calculated quantity $x=\Delta M/\Gamma$. ΔM is estimated from box diagrams and it is found that the dominant contribution comes from t-quark exchange in the internal lines [13]. The predictions of this model can be obtained from those of the standard model by appropriately inserting our values for $\lambda_t^d=V_{td}^*V_{tb}$ and $\lambda_t^s=V_{ts}^*V_{tb}$ (corresponding to the B_d and B_s systems respectively) in the place of the ones for the standard model. $|\lambda_t^d|$ and $|\lambda_t^s|$ for different values of τ_B are presented in table 1, where we have set $s_\delta=0$ without affecting our results significantly. These numbers are of the same order of magnitude as the corresponding ones in the standard model. Hence the predictions for B^0–$\overline{B}^0$ mixing of the two models are similar. On the other hand, since s_δ is smaller by two orders of magnitude, all CP-violation parameters in this system will be strongly suppressed.

We have so far considered the mixing of one h-type quark with the b alone. There will actually be three h-type quarks for the three generations. As we have already pointed out, if the h- and d-type quarks mix in only one generation the significant contribution will come just from the mixing we have discussed.

In conclusion, we have studied the CP-violation consequences of the mixing of an exotic charge $-1/3$ colour triplet h quark with the b quark. We have found that the lower bound on m_t coming from ϵ is removed, even for the most unfavourable choice of the parameter B and a rather low value of $\bar{R}$. On the other hand ϵ'/ϵ is predicted to be significantly smaller than in the standard model and generally within the current experimental

τ_B(ps)	$c_\delta \simeq +1$		$c_\delta \simeq -1$	
	$\lvert\lambda_t^d\rvert (\times 10^{-3})$	$\lvert\lambda_t^s\rvert (\times 10^{-2})$	$\lvert\lambda_t^d\rvert (\times 10^{-2})$	$\lvert\lambda_t^s\rvert (\times 10^{-2})$
0 6	6 58	5 40	1 60	5 12
0 8	6 23	5 50	1 70	5 22
1 0	5 81	5 24	1 70	5 00
1 2	5 43	5 00	1 65	4 74
1 4	5 13	4 80	1 61	4 53

bounds This is true for h–b mixing at the upper bound of cos α, viz 0 11, for smaller cos α, ϵ'/ϵ is further reduced A way to distinguish this scenario from the standard model is provided by the B^0–$\bar{B}^0$ system, where the predictions for mixing are the same while *CP* violation is much smaller in this model Finally it should be pointed out that even though this work has been motivated by the recent interest in superstrings the results are more general and will hold in any model which has exotic h-type quarks that can mix with the b quark

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