IC/87/184

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INTERNATIONAL
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1987 MIRAMARE-TRIESTE

IC/87/184

International Atomic Energy Agency
and
United Nations Educational Scientific and Cultural Organization

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CP-VIOLATION AND MIXING IN A SUPERSTRING INSPIRED MODEL *

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ABSTRACT

Superstring theories lead to supersymmetric E_6 based models which contain exotic charge -1/3 quarks, h. We find that if the h mixes with the b quark then CP-violation and mixing are dramatically affected.

MIRAMARE-TRIESTE
July 1987

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* To appear in the Proceedings of the 'San Miniato Conference on Heavy Flavours', 1987.
Work partially supported by the Indian National Science Academy, University Grants Commission, India.

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Superstring theories are of great current interest. (If you do not feel terribly enthusiastic jump to the next paragraph.) We would like to discuss in this talk CP-violation and mixing predictions in an E_6 model of the type that is expected to be the low energy relic of superstring theory. The heterotic string on compactification to four dimensions yields an E_6 grand unified theory with N=1 Supersymmetry (SUSY). The string model constrains the massless excitations (i.e. the physical particles) to lie in the $\underline{\mathbf{27}}$ representations of E_6. In terms of SO(10) representations it contains a $\underline{\mathbf{16}}$, a $\underline{\mathbf{10}}$ and a $\underline{\mathbf{1}}$. Under SU(5) the $\underline{\mathbf{27}}$ of E_6 decomposes into $\underline{\mathbf{10}} + \underline{\bar{\mathbf{5}}} + \underline{\mathbf{1}} + \underline{\mathbf{5}} + \underline{\bar{\mathbf{5}}} + \underline{\mathbf{1}}$. The standard quarks and leptons of one generation (including the right-handed neutrino) are contained in the $\underline{\mathbf{16}}$ of SO(10) i.e. in $\underline{\mathbf{10}} + \underline{\bar{\mathbf{5}}} + \underline{\mathbf{1}}$ of SU(5). The additonal $\underline{\mathbf{10}}$ of SO(10) – equivalently the $\underline{\mathbf{5}}$ + $\underline{\bar{\mathbf{5}}}$ of SU(5) – contains an extra colour triplet charge (-1/3) quark - h . There is one such exotic d-type quark in each generation.

In this talk we consider the mixing of an h-quark with the b-quark and discuss its implications on CP-violation, $B^0 - \overline{B^0}$ and $D^0 - \overline{D^0}$ mixing[1,2]. The possibility of mixing of the h quarks (we will generically call them h irrespective of their generation) with the d-quark has already received quite a bit of attention for its possible effects on neutral currents, top quark mass, h-quark decay and sneutrino vev. Due to the high precision to which the Cabibbo angle is known, there is no room for a large h-d mixing. Consequently it has no significant implication for CP-violation. The same situation obtains for h-s mixing. On the other hand, the b-quark couplings are known with relatively less precision[3] and h-b mixing can be quite substantial and still be consistent with current experimental data. The small deviation of the Kobayashi-Maskawa (KM) mixing matrix from unitarity[4] provides an added motivation[5] for consideration of the mixing of an additional quark with the three standard ones. We find that h-b mixing can affect CP-violation rather dramatically. The key point is that the KM mixing angles θ_2 and θ_3 are now allowed to be much larger by the data. Since CP-violation involves the quantity $s_2 s_3 s_\delta$ the effects are striking: the lower bound on the top quark mass set by ϵ is removed and ϵ'/ϵ is smaller. For $B^0 - \overline{B^0}$ mixing the predictions are similar to that in the standard model but CP-violation is smaller. Supersymmetric gluino loop graphs enhance $D^0 - \overline{D^0}$ mixing to values close to the experimental upper bound.

With h-b mixing parametrised by an angle α, the KM mixing matrix is of the form (note there are still three u-type quarks)

$$V = \begin{bmatrix} c_1 & -s_1 c_3 & -s_1 s_3 c_\alpha & s_1 s_3 s_\alpha \\ s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & (c_1 c_2 s_3 + s_2 c_3 e^{i\delta}) c_\alpha & -(c_1 c_2 s_3 + s_2 c_3 e^{i\delta}) s_\alpha \\ s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 e^{i\delta} & (c_1 s_2 s_3 - c_2 c_3 e^{i\delta}) c_\alpha & -(c_1 s_2 s_3 - c_2 c_3 e^{i\delta}) s_\alpha \end{bmatrix}$$

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

The small deviation of the (3×3) KM matrix from unitarity sets the bound $\cot\,\alpha \lesssim 0.11$ [90 % c.l.]. We use $\cot\,\alpha = 0.11$ later. As in the standard model, the bottom lifetime τ_B and $\overline{R} = \Gamma(b \to u l \nu)/\Gamma(b \to c l \nu)$ can be used to fix θ_3 and relate the allowed values of θ_2 and δ. We find

$$s_3 = (s_3)_{std}/c_\alpha \tag{1}$$

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

where $a = c_3^2 - c_1^2 s_3^2$, $b = -2c_1 s_3 c_3$ and $c = c_3^2 + s_3^2(c_1^2 - 5.78)$. Here we have chosen $\overline{R}$ =0.04 – a rather low value – motivated by the fact that a situation difficult to accomodate in the standard model may be quite consistent in this new model. For the same reason we choose to work with the so-called 'bag factor' B = 0.33 later on. We find that for τ_B ranging from 0.8 to 1.4 ps, s_3 varies between 0.37 and 0.24 – about one order of magnitude larger than in the standard model. The CP-violation parameter ϵ is given by

$$|\epsilon| = 3.82 \times 10^4 B[Im\lambda_t \; Re\lambda_t]s(m_t)\eta \tag{3}$$

where $\lambda_t = V_{td}^* V_{ts}$, η is a QCD correction factor (≈0.6) and s(x) a monotonically increasing function that arises from standard box-diagram integrals. In writing eq. (3) we have dropped the negligible contributions involving the c and u quarks. The KM angle dependent factor in brackets peaks for some value of δ – for this choice, one gets the minimum allowed top mass (using s(m_t)). In the case under consideration, the bracketed expression is much larger than in the standard model due to the bigger KM angles and consequently s(m_t) can now be two orders of magnitude smaller – this translates into an insignificant (~ 1 GeV) lower bound on m_t. In fact, if one chooses a realistic top mass (~ 40 GeV) then from eqs. (1-3) one gets two solutions both with sin$\delta \approx 0$. Among the two solutions the one with δ in the second quadrant gives too large V_{cd} and is inconsistent with experimental results on neutrino production of charm. The allowed range of sinδ as a function of τ_B is shown in Fig. 1.

Once the KM angles are fixed from ϵ one can estimate ϵ'/ϵ. From an evaluation of the penguin diagram one obtains

$$\epsilon'/\epsilon = 15.6 H s_2 c_2 s_3 s_\delta \tag{4}$$

with $H = 0.54^6$. The results for ϵ'/ϵ are shown in Fig. 2. The experimental bound from a combination of the BNL-Yale and Saclay-Chicago results is also shown.

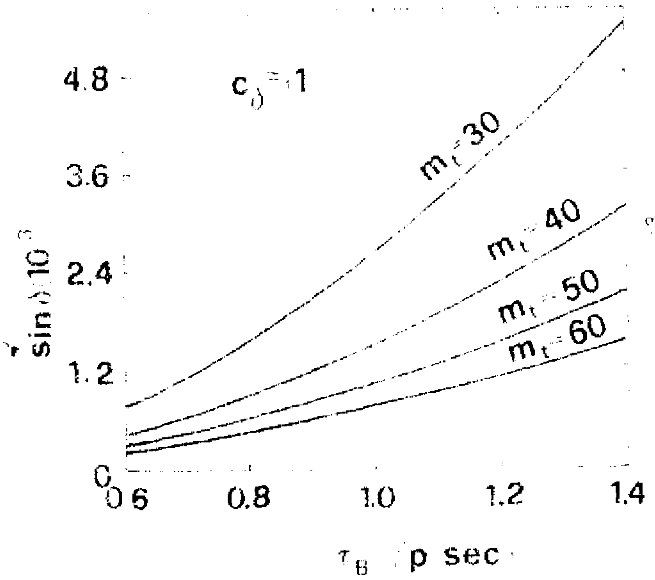

Figure 1: sinδ as a function of τ_B for different m_t(GeV).

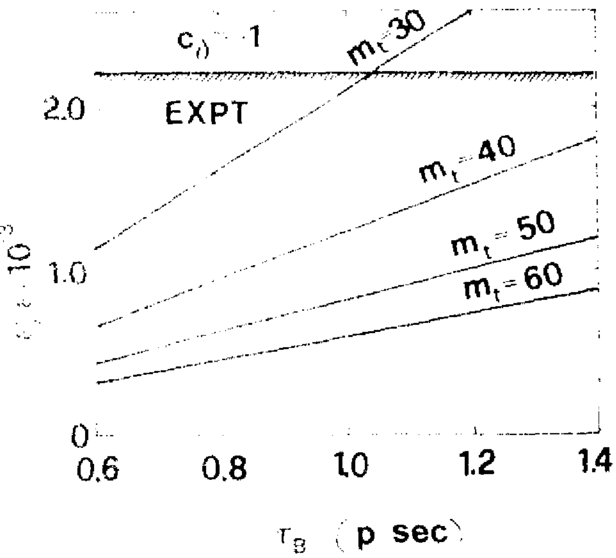

Figure 2: ϵ'/ϵ as a function of τ_B for different m_t(GeV).

Turning now to $B^0 - \overline{B^0}$ mixing, it is well known that in the standard model the dominant contribution comes from box-diagrams with t-quark internal lines. The results of this model can be obtained from those of the standard model[6] by simply substituting the new values of $\lambda_t^d = V_{td}^* V_{tb}$ and $\lambda_t^s = V_{ts}^* V_{tb}$ corresponding to the B_d and B_s systems respectively. It turns out that these combinations of angle factors do not change very much in going over to the new model. This can be traced to the fact that the enhancement obtained in V_{td} and V_{ts} through the larger KM angles is compensated by the additional factor of $\cos\alpha$ in V_{tb}. λ_t^d and λ_t^s remain similar to those in the standard model and are presented in Ref. 1. Consequently the predictions of this model for $B^0 - \overline{B^0}$ mixing are not significantly different from those of the standard model. However, since δ is now about three orders of magnitude smaller, CP-violation in the B-system will be very strongly suppressed.

Finally let us briefly consider $D^0 - \overline{D^0}$ mixing. In the standard model Δm_D is predicted[7] to be O(10^{-17} to 10^{-18} GeV) - about 4 to 5 orders below the current experimental upper bound. In the present model the main contribution comes from h-quark exchange in inner lines - much like the usual b-quark dominance in the standard model. Compared to the latter, the new contribution has an enhancement of O($\tan^2\alpha$) from the KM factors and a further factor of O(10) from the integrals. This gives a Δm_D about two orders of magnitude below the experimental limit. There is, however, an additional SUSY contribution in this case. It has its origin in the flavour violating *strong* interaction mediated by gluino exchange which is known to have important implications in CP-violation in the $K^0 - \overline{K^0}$ system[8]. The SUSY box diagrams have gluinos and u-type squarks in the internal lines. In the SUSY standard model this sort of flavour violation is not large for the $D^0 - \overline{D^0}$ system due to the smallness of the d-type quark masses compared to the top quark. With the exotic h-quarks as massive as the top, the situation is totally changed. The details are given in Ref. 2. It turns out that Δm_D increases with the h-quark mass and can be even as large as the experimental bound if the gluino and squarks are not too heavy.

In conclusion, superstrings lead to E_6 based models which have additional charge -1/3 quarks, h. After symmetry breaking these exotic quarks may mix with the standard d-type quarks. An alternative motivation for such mixing comes from the small deviation of the KM mixing matrix from unitarity. We find that if the h mixes with the b-quark (for other work on h-b mixing see refs. 4 and 9) then the lower bound on the top mass obtained from ϵ is removed and ϵ'/ϵ is lowered. $B^0 - \overline{B^0}$ mixing is unchanged but CP-violation in the B-system is strongly suppressed. For the $D^0 - \overline{D^0}$ system SUSY graphs involving the gluino now give a large contribution pushing Δm_D close to the experimental bound.

Acknowledgements

The author would like to thank Professor Abdus Salam, the International Atomic Energy Agency and UNESCO for hospitality at the International Centre for Theoretical Physics, Trieste. The work reported here was done in collaboration with Biswarup Mukhopadhyaya and Aditi Ray-Mukhopadhyaya.

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