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A NEW MODEL OF WEAK CP VIOLATION^{*)}

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A B S T R A C T

We propose a new model of spontaneous weak CP violation. It is the result of considering that new vector-like quarks at the Fermi scale could induce the observed CP non-conservation.

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Since the discovery of CP violation in the kaon system¹⁾ no general agreement has been reached on its origin. The simplest and most widely accepted explanation is due to Kobayashi and Maskawa (KM)²⁾. In their model CP is explicitly broken by the Yukawa couplings and no other fields than those of the minimal Glashow - Salam - Weinberg (GSW) model³⁾ are required. Recent experimental results on the bottom lifetime⁴⁾, top mass⁵⁾, ϵ'/ϵ ⁶⁾ and the $b \rightarrow u/b \rightarrow c$ ratio⁷⁾ could be interpreted as pointing to an alternative explanation, although the KM picture is not excluded.⁸⁾⁻¹⁰⁾

Other models, as that of Weinberg¹¹⁾, with spontaneous CP violation seem to be more problematic. In contrast with the KM model where only one scalar doublet is needed, in Weinberg's model three scalar doublets are required. The Yukawa couplings of the scalar doublets to the quarks ensure that flavour changing neutral currents (FCNC) are absent at the free level and CP non-conservation arises purely from the exchange of Higgs bosons^{*)}.

We propose a new scenario where the observed CP violation is due to the presence of new vector-like quarks at the Fermi scale. We will concentrate on the simplest possible model. It results from adding a new vector-like down quark and two extra Higgs doublets to the minimal GSW model. CP is spontaneously broken. The new ingredient is that the KM matrix being real, this breaking is felt by the standard fermions through their mixing with the new quark. Then, as we shall see, CP violating effects are suppressed by powers of m'/M , where m' is of the order of a standard down quark mass and M is the mass of the new quark. This ratio, which is naturally small, explains the smallness of the observed CP violation.

The content of the model is then the same as Weinberg's model plus an extra down quark. The CP breaking in the Higgs sector is analogous, as three scalar doublets are also required. FCNC induced by Higgs exchange are suppressed because only one Higgs doublet couples efficiently to each type of standard fermion (tree level FCNC induced by the new vector-like quark are naturally suppressed by powers of m'/M). The main difference with Weinberg's model is that the same Higgs doublet gives mass to up and down quarks, invalidating the main source of CP violation in that model. However, due to the existence of the vector-like quark there is now a new source of CP violation, which we use to explain the observed CP non-conservation.

*) For other alternatives see Ref. 8) and references therein.

The net result of our study will be a slight improvement on the CP predictions of the standard model. When ε is adjusted to reproduce experiment, ε'/ε may be up to an order of magnitude smaller than expected in the KM model. On the other hand, the perturbative contributions to d_n are well below the experimental bound, whereas θ_{eff} is calculable and small but probably not as small as experimentally required ($\lesssim 10^{-9}$)¹²⁾ in a natural way.

Let us now discuss the model in some detail^{*)}. As stated above it contains

three standard families plus a new vector-like down quark D^4 . Its left-handed (LH) and right-handed (RH) parts belong to SU_2^L singlets. Thus, it admits a bare mass term unrelated to the GSW breaking^{**)}. In order to have spontaneous CP

violation the model also requires two extra Higgs doublets ϕ', ϕ'' . The three scalar doublets are coupled to the quarks through a Yukawa interaction of the form

$$\begin{aligned} \mathcal{L}_Y = & -\frac{1}{12} \left[\bar{\psi}_L^i \phi D_R^j c_{ij}^d \delta_{ij} + \bar{\psi}_L^i (c_{1i}^d \phi_1' + c_{2i}^d \phi_2') D_R^4 + \right. \\ & \left. + \bar{\psi}_L^i \tilde{\phi} U_R^j c_{ij}^u \right] - M \bar{D}_L^4 D_R^4 + h.c. \end{aligned} \quad (1)$$

where $\psi_L^i = \begin{pmatrix} U \\ D \end{pmatrix}_L^i$, U_R^i , D_R^i , $i = 1, 2, 3$,

are the three standard families and ϕ the standard Higgs, $\tilde{\phi} = i\tau^2 \phi^+$. The model has a discrete symmetry under which $\phi \rightarrow -\phi$, $\phi_L^i \rightarrow -\phi_L^i$ and $D_{L,R}^4 \rightarrow -D_{L,R}^4$ without changing the other fields^{***)}.

^{*)} Full detail of the model will be given elsewhere.¹³⁾

^{**)} It is known that even in the absence of extra symmetries these fermions with $\Delta I=0$ masses can be added to the standard model evading experimental bounds, in particular on FCNC, and without running into conflict with naturalness¹⁴⁾.

^{***)} In fact (1) has three global U_1 ; baryon number, hypercharge which is of course gauged and an extra U_1 . The last one is broken by terms like $\phi_1'^+ \phi \phi_2'^+ \phi$ in the Higgs potential, leaving only that discrete symmetry.

The lepton sector which we will not discuss in detail is similar to that of the standard model. The lepton Yukawa couplings reduce to

$$\mathcal{L}_Y = - \frac{1}{f_2} \bar{\chi}_L^i \phi E_R^j c_i^e \delta_{ij} + h.c. \quad (2)$$

due to the previous discrete symmetry $\phi \rightarrow -\phi$, $\chi_L^i \rightarrow -\chi_L^i$ where $\chi_L^i = \begin{pmatrix} N \\ E \end{pmatrix}_L^i$. The lepton Yukawa interactions have been written in the basis where e, μ , τ lepton numbers are apparently preserved. Analogous freedom in the quark sector allowed us to assume c^d diagonal in (1) and CP conservation is made explicit by choosing the phases of the fields in such a way that all Yukawa couplings in (1) and (2) are real.

The Higgs potential is the most general one consistent with the former discrete symmetry. Then, in general, the vacuum will break CP

$$\langle \phi^0 \rangle = v, \quad \langle \phi_{1,2}'^0 \rangle = v_{1,2}' e^{i\alpha_{1,2}} \quad (3)$$

where we choose $\langle \phi^0 \rangle$ real^{*)}. Once CP is broken by the vacuum (3), the standard fermions know of this breaking mainly through their mixing with the new heavy quark. This is our main point and the reason for (1). It is natural to take the mass of the new quark of the order of the Fermi scale, $M \sim 10^2-10^3$ GeV. This large value of M tells us that the mixing of the new quark with the standard down quarks will be very small. This follows from the diagonalization of the corresponding mass matrix [according to (1)]

*) In order to have CP spontaneously broken we need at least three Higgs doublets. In the case of two doublets ϕ , ϕ' the most general Higgs potential consistent with the discrete symmetry $\phi \rightarrow -\phi$ allows us only for very definite values of α_1 in (3), $\alpha_1 = n(\pi/2)$. But for these values there is a redefinition of fields [see (1)] which makes CP invariance manifest.

$$\mathcal{M}^d = \begin{pmatrix} m_1 & & 0 & m'_1 e^{i\beta_1} \\ & m_2 & & m'_2 e^{i\beta_2} \\ & 0 & & m'_3 e^{i\beta_3} \\ \hline & & 0 & M \end{pmatrix}$$

(4)

where $m_j = \frac{1}{\sqrt{2}} c_j^d v$, $m'_j e^{i\beta_j} = \frac{1}{\sqrt{2}} (c_{1j}^d v'_1 e^{i\alpha_1} + c_{2j}^d v'_2 e^{i\alpha_2})$

and m_j , m'_j are typically of the order of a standard down quark mass (0.1-5 GeV). The mass matrix can then be diagonalized order by order in m/M , m'/M . Up to corrections of order m'^2/M^2 the masses of the down fermions are m_i ($i=1,2,3$ correspond to d,s,b , respectively) and M (mass of the new vector-like quark $\tilde{d}$).

It must be noted that the determinant of $\mathcal{M}^d$ is real. This is a nice feature of the model, θ_{QCD} is zero by CP and then θ_{eff} is zero at tree level, getting corrections only at higher orders (see below).

In order to analyze the predictions of the model it is more convenient to rewrite gauge and Yukawa couplings in a mass eigenstate basis. For instance,

$$\mathcal{L}_Z = \frac{(g^2 + g'^2)^{1/2}}{2} Z_\mu (\bar{u}_L^i \gamma^\mu u_L^i - a_{\alpha\beta} \bar{d}_L^\alpha \gamma^\mu d_L^\beta - 2 \sin^2 \theta_W J_{em}^\mu) \quad (5)$$

where u^i , d^α stand for u,c,t and $d,s,b,\tilde{d}$, respectively and

$$a_{jk} = \delta_{jk} - \frac{m'_j m'_k}{M^2} e^{i(\beta_j - \beta_k)}, \quad a_{j4} = a_{4j}^* = \frac{m'_j}{M} e^{i\beta_j}, \quad a_{44} = \frac{\sum m_i'^2}{M^2}.$$

In general, gauge couplings among light fermions violate CP at most at the order of m'^2/M^2 [see (5)]. In particular the KM matrix is real up to this order. Yukawa

couplings are as usual extra suppressed^{*)}.

In this model, the main contribution to ϵ comes from the diagram in Fig. 1, where a single Z^0 is exchanged. We work in the standard phase convention¹⁵⁾ in which imaginary parts are small and $|\text{Im } M_{12}/\text{Re } M_{12}| \gg |\text{Im } A_I/\text{Re } A_I|$ (see below), then

$$\epsilon \approx \frac{e^{i\pi/4}}{\sqrt{2}} \frac{\text{Im } M_{12}}{2 \text{Re } M_{12}} \quad (6)$$

$\text{Re } M_{12}$ has a contribution from the box diagram (see Fig. 2),

$$[\text{Re } M_{12}]_{\text{box}} = - \frac{G_F^2}{12 \pi^2} f_K^2 m_K B s_1^2 c_1^2 \left(m_c^2 + s_2^4 m_t^2 + 2 s_2^2 m_c^2 \ln \frac{m_t^2}{m_c^2} \right) \quad (7)$$

where $c_i = \cos \theta_i$, $s_i = \sin \theta_i$ and θ_i ($i=1,2,3$) are the three angles which appear in the real part of the KM matrix, and B is defined by

$$\langle K^0 | (\bar{d}_L \gamma^\mu s_L) (\bar{d}_L \gamma_\mu s_L) | \bar{K}^0 \rangle = - B \frac{1}{3} f_K^2 m_K \quad (8)$$

However, it is not clear at present whether there are large long-distance contributions to $\text{Re } M_{12}$. Therefore we will use in the calculation of ϵ $\text{Re } M_{12} = (\Delta M/2)^{15)}$ with ΔM taken from experiment.

On the other hand $\text{Im } M_{12}$, which comes essentially from the diagram of Fig. 1, can be calculated using (5)

$$\text{Im } M_{12} = - \frac{G_F}{\sqrt{2}} \frac{2}{3} f_K^2 m_K B \left(\frac{m'_1 m'_2}{M^2} \right)^2 \sin 2(\beta_1 - \beta_2) \quad (9)$$

^{*)} CP phases are apparent after mass eigenstate fermion and scalar fields are considered. The scalar diagonalization modifies the CP phases in CP violating Yukawa vertices but it does not introduce new relevant CP violating vertices. Then the relevant CP violating Yukawa couplings are also suppressed by factors m'/M . For this reason one has only to worry about gauge interactions. However, there is one exception, the neutral Yukawa couplings of $\phi^0 = \phi_R^0 + i\phi_I^0$ which are diagonal and complex due to the $\phi_R \leftrightarrow \phi_I$ mixing. But this will be only relevant for processes which do not require change of flavour, for instance in the calculation of d_n . We will come back to this later.

Going back to (6) and comparing with the experimental value of ϵ we find

$$\frac{\text{Im } M_{12}}{\text{Re } M_{12}} = 4 \times 10^7 B \left(\frac{m'_1 m'_2}{M^2} \right)^2 \sin 2(\beta_1 - \beta_2) = 6.48 \times 10^{-3}, \quad (10)$$

and for the relevant CP violating parameter in the kaon system

$$\eta \equiv \frac{m'_1 m'_2}{M^2} \sin(\beta_1 - \beta_2) = \pm 9 \times 10^{-6} \sqrt{\tan(\beta_1 - \beta_2)/B} \quad (11)$$

where the $\pm$ sign corresponds to $\beta_1 - \beta_2 \in [0, \pi/2]$ ($[\pi, 3\pi/2]$). Considering now (10) together with the bound on $m'_1 m'_2 / M^2$ from $K_L^0 \rightarrow \mu^+ \mu^-$ ¹⁴⁾ ($m'_1 m'_2 / M^2 < 2 \times 10^{-5}$) we get

$$4 \times 10^{-6} B^{-1/2} \leq |\eta| \leq 2 \times 10^{-5} B^{-1/2} \quad (12)$$

with $\beta_1 - \beta_2$ lying in $[\delta, \pi/2 - \delta]$ ($[\pi + \delta, 3\pi/2 - \delta]$) where $\delta = 0.21$.

It must be noted that box contributions to $\text{Im } M_{12}$ could be non-negligible, but an explicit calculation shows that they are typically one order of magnitude smaller than the tree-level diagram just considered. The reason is that although the box diagram contributions to $\text{Im } M_{12}$ should have a CP violating vertex of order η [to be compared with (9)], the GIM mechanism is not fully efficient (a logarithm is lost). Besides, one can try to play with m' [see (4)] to make the corresponding contributions larger. This, however, cannot change the results for any reasonable range of parameters.

Once we know the CP violating parameter required to reproduce the experimental value of ϵ [see (12)], we turn to the evaluation of ϵ'/ϵ . Following standard conventions^{8),15)}

$$\epsilon'/\epsilon \approx \frac{1}{\sqrt{2} |\epsilon|} \frac{\text{Re } A_2}{\text{Re } A_0} \left(\frac{\text{Im } A_2}{\text{Re } A_2} - \frac{\text{Im } A_0}{\text{Re } A_0} \right) \quad (13)$$

In contrast with the standard case, in this model there exist tree-level contributions to (13) (see Fig. 3) which have to be considered simultaneously with the usual penguin diagram contribution (Fig. 4). Let us consider $\text{Im } A_0 / \text{Re } A_0$ first. In this case the dominant contribution comes from Fig. 4. The result for the effective weak Hamiltonian reads

$$\text{Im } H_{eff} \simeq 2 \frac{G_F}{\sqrt{2}} \frac{4}{3} \frac{\alpha_s}{\pi} \ln \frac{M_W^2}{\mu^2} (\bar{s}_L \gamma_\mu T^a d_L) \cdot \\ \cdot (\bar{u} \gamma^\mu T^a u + \bar{d} \gamma^\mu T^a d + \bar{s} \gamma^\mu T^a s) \quad (14)$$

Comparing this result with the standard case¹⁶⁾, we see that the standard factor $s_1 s_2 c_2 s_3 s_8$ is replaced by 2η and due to the absence of the GIM cancellation the standard $\ln(m_t^2/m_c^2)$ is replaced by $\ln(M_W^2/\mu^2)$. Following the analysis of CP violation in the standard model⁸⁾ we make the approximation

$$\text{Im } H_{eff} \simeq - \frac{G_F}{\sqrt{2}} 2\eta y'_6 Q_6 \quad (15)$$

where the penguin operator Q_6 is defined

$$Q_6 \equiv \bar{s}_i \gamma_\mu (1-\gamma_5) d_j \left[\bar{u}_j \gamma^\mu (1+\gamma_5) u_i + \bar{d}_j \gamma^\mu (1+\gamma_5) d_i + \bar{s}_j \gamma^\mu (1+\gamma_5) s_i \right] \quad (16)$$

and the coefficient function y'_6 includes the strong interaction corrections to the effective weak Hamiltonian. The result in the leading logarithm approximation for the corresponding coefficient y_6 in the standard model is $y_6 \simeq -0.1$. In the absence of a similar calculation in this model, we estimate from (14)^{*)}

$$y'_6 \sim y_6 \frac{\ln M_W^2/\mu^2}{\ln m_t^2/m_c^2} \quad (17)$$

For the numerical analysis that follows we use as an upper limit $y'_6 = -0.2$. Using the experimental values for $|\epsilon| = 2.3 \times 10^{-3}$, $\text{Re } A_0 = 4.7 \times 10^{-7} \text{ GeV}$ and $\text{Re } A_2 = \text{Re } A_0/20$ we get^{**)}

$$|\epsilon'/\epsilon| \sim 108 |P| \quad (18)$$

where all our ignorance on non-perturbative effects has been absorbed in the matrix element $P \equiv \langle \pi\pi(I=0) | Q_6 | K^0 \rangle / 1 \text{ GeV}^3$. Present evaluations of matrix elements give $1/3 \lesssim B \lesssim 3/2$ ⁸⁾ which combined with (12) lead to

$$|\epsilon'/\epsilon| \sim (0.5 - 3.7) \times 10^{-3} |P| \quad (19)$$

*) A proper calculation is in progress¹³⁾.

**) η can have either sign [see (11)], so can ϵ'/ϵ .

The same analysis carried out in the standard model gives

$$\left| \frac{\epsilon'}{\epsilon} \right| \sim 6 \times 10^{-3} \left(\frac{s_2 s_3 s_8}{10^{-3}} \right) |P| \quad (20)$$

We see then that if a small value of $\left| \epsilon'/\epsilon \right|$ is confirmed ($\lesssim 0.003$), the standard explanation of CP violation would require a small value of the matrix element $|P|$ ($\lesssim 0.5$) which is not the case for the mechanism presented here.

On the other hand, for small values of P , ϵ'/ϵ is expected to be dominated by $\text{Im } A_2 / \text{Re } A_2$ in the present model¹³⁾. The relevant part of the weak Hamiltonian for the calculation of $\text{Im } A_2$ is at tree level given by (Fig. 3)

$$\begin{aligned} \text{Im } H_{\text{eff}} \simeq & \eta \frac{G_F}{\sqrt{2}} \left[2 \bar{s}_L \gamma_\mu d_L (\bar{u}_L \gamma^\mu u_L - \bar{d}_L \gamma^\mu d_L - 2 \sin^2 \theta_w J_{em}^\mu) + \right. \\ & \left. + 4 c_t^2 \bar{s}_L \gamma_\mu u_L \bar{u}_L \gamma^\mu d_L \right] \end{aligned} \quad (21)$$

Using the vacuum insertion approximation to evaluate the matrix elements of (21) we obtain a value for $\left| \text{Im } A_2 / \text{Re } A_2 \right|$ comparable to the previous value of $\left| \text{Im } A_0 / \text{Re } A_0 \right|$ with $|P| = 1$.

A strong limit on the amount of CP violation is also set in general by the electric dipole moment of the neutron, d_n ¹⁷⁾. In this model the largest perturbative contributions to d_n come from one-loop diagrams (see Fig. 5) with Higgs exchange (gauge bosons do not contribute to this order). We obtain adding (a), (b) and (c)

$$\begin{aligned} d_{up} = & \frac{m_u}{V} \frac{1}{16\pi^2} \left\{ - Q_u 2 \frac{m_u^2}{V} O_{5r}^T f_1(m_u, M_r) O_{r6} + R_{1k} m'_k \sin \beta_k R_{1e} \right. \\ & \left. + \frac{c_{al}}{\sqrt{2}} U_{3p}^+ \left[Q_d \tilde{f}_2(M, M_p) + \frac{Q_p}{2} f_3(M, M_p) \right] U_{pa} \right\} \end{aligned} \quad (22)$$

where $Q_u, \tilde{Q}_d, Q_p$ are the corresponding electric charges $2/3, -1/3, 1$ and $O(U)$ is the orthogonal (unitary) matrix that diagonalizes the mass matrix of the neutral (charged) scalars. The sums in r and p run over the physical neutral and charged Higgses, respectively, whereas the indices of the current neutral (charged) fields follow the ordering $\phi_{1R}^0, \phi_{1I}^0, \phi_{2R}^0, \phi_{2I}^0, \phi_R^0, \phi_I^0$ ($\phi_1^-, \phi_2^-, \phi^-$). R_{ij} is

essentially the KM matrix with real entries and f_i are the loop integral functions in the limit $m_u \ll M_{r,p} \sim M$

$$\begin{aligned} f_1(m_u, M_r) &= \frac{1}{M_r^2} \left(-\frac{3}{2} + \ln \frac{M_r^2}{m_u^2} \right) , \\ f_2(M, M_p) &= \frac{1}{(M^2 - M_p^2)^3} \left[(M^2 - M_p^2) \frac{M^2 - 3M_p^2}{2} + M_p^4 \ln \frac{M^2}{M_p^2} \right] , \\ f_3(M, M_p) &= \frac{1}{(M^2 - M_p^2)^3} \left[\frac{M^4 - M_p^4}{2} + M^2 M_p^2 \ln \frac{M_p^2}{M^2} \right] . \end{aligned} \quad (23)$$

For the down quark only diagram (a) must be considered

$$\begin{aligned} d_{\text{down}} &= \frac{m_d}{V} \frac{1}{16\pi^2} Q_d \frac{m'_d}{f_2} f_2(M, M_r) \left\{ \sin \beta_1 \left[c'_{11} (O_{5r}^T O_{r1} - O_{6r}^T O_{r2}) + \right. \right. \\ &\quad + c'_{21} (O_{5r}^T O_{r3} - O_{6r}^T O_{r4}) \left. \right] - \cos \beta_1 \left[c'_{11} (O_{5r}^T O_{r2} + O_{6r}^T O_{r1}) + \right. \\ &\quad \left. \left. + c'_{21} (O_{5r}^T O_{r4} + O_{6r}^T O_{r3}) \right] \right\} . \end{aligned} \quad (24)$$

Using the additive quark model ($d_n = -1/3d_{\text{up}} + 4/3d_{\text{down}}$) and (22) and (24), we can now calculate d_n . However, many new parameters (mainly scalar masses and mixings) enter in the calculation, so that we can only give an order of magnitude estimate. Assuming $m_{u,d} \sim 10$ MeV, all heavy masses equal to $M \sim 100$ GeV, $m'_k \sim 0.4$ GeV and phases and mixings of order one, we get

$$d_n \sim 5 \times 10^{-28} \text{ e cm} , \quad (25)$$

which is three orders of magnitude below the experimental bound.

It should be noted that in this model there is also a non-zero electric dipole moment for the electron, d_e . This gets a one-loop contribution from a diagram analogous to diagram (a) for the up quark, which is due to the mixing of the real and imaginary parts of the neutral Higgs, $\phi^0 = \phi_R^0 + i\phi_I^0$. This contribution is equal to the first term in (22) but with m_u and Q_u replaced by m_e and Q_e , corresponding to an electric dipole moment for the electron

$$d_e \sim 10^{-32} \text{ e cm} , \quad (26)$$

safely below the experimental limit.

Coming back to d_n , one usually worries about possible contributions induced by $\theta_{\text{eff}} = \theta_{\text{QCD}} + \arg \det \mathcal{M}$, where $\mathcal{M}$ is the quark mass matrix^{12),17)}. In our model, CP is spontaneously broken and then θ_{QCD} is zero. On the other hand, $\arg \det \mathcal{M}$ is also zero at tree level as stated above [see (4)]. However, θ_{eff} gets one-loop corrections. The relevant diagrams are similar to those in Fig. 5 but without the photon insertion. Once the mass matrices at the tree level have been made real and diagonal, we calculate the corrections to the different entries. Off diagonal ones are not important, as they enter in the determinant by pairs and the corrections to real parts are also suppressed (at least by a loop integral factor). Besides, flavour changing contributions to imaginary parts are always suppressed by some power of η .

Diagonal entries are different. Higgs couplings are proportional to fermion masses and corrections to heavy flavour masses can be large. On the other hand, those (complex) corrections which are induced by the mixing of ϕ_R° and ϕ_I° (as for d_e) apparently cannot be suppressed. In fact, they are present in any model where CP is spontaneously broken at low energy. In our case, the largest contribution to θ_{eff} can be estimated using the diagram of Fig. 6 for the top quark, finding

$$\theta_{\text{eff}} \sim \frac{c_t^2}{16\pi^2} \xi \sim 10^{-3} \xi, \quad (27)$$

where ξ is a function of Higgs masses and mixing angles which is of order one when all masses are taken of the same order (~ 100 GeV) and all mixings are of order one. Other contributions are smaller and (roughly) compatible with the standard bound $\sim 10^{-9}$.

Other CP violating effects are at some extent model-dependent as essentially new parameters enter in the calculation. For instance, m' and β in Eq. (4) are relevant for the analysis of the bottom system. In this sense these effects deserve an independent study.

The result of our analysis is that vector-like fermions, which can exist¹⁴⁾ at the Fermi scale without upsetting experimental bounds, for instance on FCNC, or naturality requirements, could induce the observed CP violation. We have presented the simplest possible model with spontaneous CP violation.

The mass of the new quark is related to the amount of observed CP non-conservation, ε . Once ε is adjusted, ε'/ε can be predicted to some extent. It may be smaller (but not by much) than the present experimental limit. Perturbative

contributions to d_n are quite small, although larger than in the standard model. On the other hand, θ_{eff} is calculable (it appears at one loop). However, it is not obvious that it can be as small as 10^{-9} naturally.

We feel that given the present experimental situation it is interesting to consider alternative sources of CP violation beyond the KM model. Improvement on the limits of CP violation in the kaon system, as well as future experiments on other systems, could decide on the mechanism responsible for CP violation.

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FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6