Flavor-Changing Interactions Mediated by Scalars at the Weak Scale

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The quark and lepton mass matrices possess approximate flavor symmetries. Several results follow if the interactions of new scalars possess these approximate symmetries. Present experimental bounds allow these exotic scalars to have a weak-scale mass. The Glashow-Weinberg criterion is rendered unnecessary. Finally, rare leptonic B meson decays provide powerful probes of these scalars, especially if they are leptoquarks.

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As more and more tests of the standard model confirm its predictions to ever higher accuracy, it becomes tempting to believe that new physics, especially if it involves flavor-changing neutral currents, can only occur at energy scales very much larger than the weak scale. For example, $\Delta S=2$ four-fermion operators with coefficients $1/\Lambda^2$ give a K_L-K_S mass difference $\Delta m_K/m_K \simeq (f_K/\Lambda)^2$ implying that $\Lambda \gtrsim 1000$ TeV. The purpose of this paper is to show that it is perfectly natural for physics involving new heavy scalars to occur at scales as low as the weak scale, 250 GeV, and to show that rare leptonic B meson decays will provide an excellent probe of this new physics.

In this paper we introduce a specific form for the way that approximate flavor symmetries act on quarks and leptons. We then use this as a guide to infer the expected size of couplings between the known fermions and hypothetical, heavy scalar particles. The scalar mass M is then the only unknown parameter in the coefficient of the four-fermion interactions induced by the exchange of this scalar. We derive the experimental limits on M from a variety of rare processes. The most powerful of these limits are of order the weak scale, giving hope to the possibility that we may discover physics at the weak scale to be much richer than in the minimal standard model. There are two important advantages of our general approach. The scalar mass limits depend only on symmetry arguments and not on any specific model. Second, we can identify the most promising processes for discovering new physics in the next few years. In particular we find that rare leptonic B decays are a very powerful probe of these new scalar interactions. For the case of leptoquarks, these B decays will probe masses far above the present experimental limits.

An important application of our results is to flavor-changing effects in models with many Higgs doublets [1]. We find that the approximate flavor symmetries, which we already know must be a part of any successful model of particle physics, are sufficient to make it natural to have any number of Higgs doublets coupling to up- and down-type quarks. In other words, it is completely unnecessary to introduce discrete symmetries which act on Higgs doublets, as is so frequently done.

Approximate flavor symmetries.—In the standard model, the gauge interactions of the fermions,

$$\mathcal{L}_0 = i\bar{Q}\not{D}Q + i\bar{U}\not{D}U + i\bar{D}\not{D}D + i\bar{L}\not{D}L + i\bar{E}\not{D}E\,, \qquad (1)$$

have a global symmetry $U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E$, where Q_i and L_i are SU(2) doublet quarks and leptons while U_i, D_i, and E_i are SU(2) singlets and $i=1,2,3$ is a generation label.

The Yukawa couplings,

$$\mathcal{L} = \mathcal{L}_0 + \left\{ \lambda_{ij}^U \bar{Q}_i U_j \frac{\tilde{H}}{\sqrt{2}} + \lambda_{ij}^D \bar{Q}_i D_j \frac{H}{\sqrt{2}} + \lambda_{ij}^E \bar{L}_i E_j \frac{H}{\sqrt{2}} + \text{H.c.} \right\}, \qquad (2)$$

break the symmetry by varying degrees down to $U(1)_e \times U(1)_\mu \times U(1)_\tau \times U(1)_B$. We parametrize the approximate flavor symmetries by a set of small parameters $\{\epsilon\}$, one for each of the above chiral fermion fields, which describes the breaking of phase rotation invariance on each fermion. Thus λ_{ij}^U is suppressed by both ϵ_{Q_i} and ϵ_{U_j}. The idea is that the pattern of fermion masses and mixing angles can be described by the set $\{\epsilon\}$. However, this is not a precise numerical theory for fermion masses; equations of the form $\lambda_{ij}^U \approx \epsilon_{Q_i}\epsilon_{U_j}$ are only meant to be order of magnitude relations.

The Yukawa matrices $\lambda^U, \lambda^D, \lambda^L$ contain a great deal of information about the form of the breaking of flavor symmetry. Unfortunately, we cannot reconstruct these matrices from the information which can be obtained from experiments, namely, from the fermion masses (i.e., the Yukawa matrix eigenvalues) and the Kobayashi-Maskawa (KM) matrix. This information is insufficient to derive the form of the approximate flavor symmetries which the underlying theory must have. Nevertheless it provides a strong guideline for giving a simple predictive ansatz for the symmetry-breaking parameters.

The lightness of the up quark tells us that flavor symmetries strongly suppress the $\bar{Q}_1 U_1$ operator. However, the mass eigenvalue does not allow us to infer whether this is because the approximate flavor symmetry is acting only on Q_1, only on U_1, or on both. However, we need to know whether the coefficient of a scalar coupling to $Q_1 X$

(where X is any fermion other than U_1) is strongly suppressed because the up quark is very light.

We now argue that the approximate symmetries act on both left- and right-handed fields:

(i) The flavor symmetries do not act just on the right-handed fields because otherwise $U_3 \approx t_R$ couples to $(\alpha Q_1^u + \beta Q_2^u + \gamma Q_3^u) = t_L$ and $D_3 \approx b_R$ couples to $(\alpha' Q_1^u + \beta' Q_2^u + \gamma' Q_3^u) = b_L$, where $\alpha, \beta, \gamma, \alpha', \beta', \gamma'$ are arbitrary mixing angles of order 1, so that t_L and b_L would have no reason to be very nearly in the same $SU(2)_L$ doublet.

(ii) The flavor symmetries do not act just on the left-handed fields because in this case the approximate flavor symmetries make no distinction between λ^U and λ^D. A large m_t/m_b ratio could be due to a large ratio of vacuum expectation values v_2/v_1 in a two-Higgs-doublet theory, but this would lead to an unacceptably large m_u/m_d ratio. In addition, the KM angles are given by linear mass relations such as $\theta_c \approx m_d/m_s$ rather than the more successful square root form $\theta_c \approx (m_d/m_s)^{1/2}$.

Therefore we conclude that *the underlying theory must have approximate flavor symmetries that act on both left- and right-handed fields.*

The approximate flavor symmetries and the associated set of small symmetry-breaking parameters $\{\epsilon\}$ are defined on flavor eigenstates. In practice it is much more useful to know what suppression factors are induced on the mass eigenstates. Consider the up-type quarks. Assume that $\epsilon_{Q_i} \ll \epsilon_{Q_j}$ and $\epsilon_{U_i} \ll \epsilon_{U_j}$ for $i<j$, as suggested by $m_{U_i} \ll m_{U_j}$. Then the mass matrix is diagonalized by unitary rotations on the Q_i by a matrix with elements $|V_{ij}| \approx \epsilon_{Q_i}/\epsilon_{Q_j}$ $(i<j)$ and on the U_i by a matrix with elements $|V_{ij}^R| \approx \epsilon_{U_i}/\epsilon_{U_j}$ $(i<j)$. Relations between flavor and mass eigenstates (Q_i') are of the form $Q_1' = Q_1 + O(\epsilon_{Q_1}/\epsilon_{Q_2})Q_2 + O(\epsilon_{Q_1}/\epsilon_{Q_3})Q_3$. This shows the important result that the flavor-breaking parameters $\{\epsilon\}$ apply to mass eigenstates as well as to flavor eigenstates. For example, the three flavor-eigenstate contributions to Q_1' all carry the same approximate-flavor-symmetry suppression factor of ϵ_{Q_1}.

The actual structure of the approximate low-energy flavor symmetries is likely to involve many parameters: The fermion masses and mixing angles have very few obvious regularities. A simple predictive ansatz is shown in Table I. It involves both left- and right-handed fermions and is predictive because it only involves quark and lepton masses.

TABLE I. The ansatz for flavor-symmetry-breaking parameters associated to the chiral fermion fields. $\eta_i = (m_{U_i}/v_2)^{1/2}$ and $\xi_i = (m_{D_i}/v_1)^{1/2}$.

Field	Flavor-symmetry-breaking parameter
Q_i	$(\eta_i \xi_i)^{1/2}$
U_i	$(\eta_i/\xi_i)^{1/2}\eta_i$
D_i	$(\xi_i/\eta_i)^{1/2}\xi_i$
L_i, E_i	$(m_{E_i}/v_1)^{1/2}$

The rationale behind our choice is as follows. For the leptons the flavor symmetries on L_i and E_i are equally responsible for suppressing the Yukawa couplings. For quarks, we have again tried to have both left- and right-handed flavor symmetries equally responsible for suppressing Yukawa couplings. However, since Q_i appears in both up and down mass operators, we have taken the symmetry-breaking parameter ϵ_{Q_i} to be the geometric mean of that expected from m_{U_i} and that expected from m_{D_i}. Note that we have allowed for a two-Higgs-doublet model. With only one Higgs boson $v_1 = v_2 = 250$ GeV.

The ansatz gives reasonable values for the Cabibbo-Kobayashi-Maskawa mixing angles.

$$V_{ij} \approx \epsilon_{Q_i}/\epsilon_{Q_j} \approx (m_{U_i} m_{D_i}/m_{U_j} m_{D_j})^{1/4}, \quad i<j,$$

which is correct at the factor-of-2 level.

One must keep in mind that the ansatz, despite its simplicity, is hardly unique. A more complicated ansatz might use the KM matrix as input as well as the fermion masses. However, this extra complexity is not warranted since our ansatz is quite consistent with the KM matrix. We use the ansatz only to *estimate* the magnitudes of unknown Yukawa couplings.

Experimental consequences.— We use our ansatz to estimate the size of the Yukawa coupling and then the corresponding rates for various processes induced by the effective four-fermion couplings. In Table II we list the limits on the exchanged scalar mass [2] obtained from a variety of experiments. For now we assume the scalar exchange does induce each process and that the flavor symmetry acts only on fermions. Once again, we obtained these numbers using our ansatz to estimate the Yukawa couplings, so we expect the values to be reliable up to a factor of perhaps 2 or 3.

The factor κ represents the ratio of the matrix element of the new four-fermion operator relative to its vacuum insertion value. In the radiative μ decay, the τ-lepton contribution dominates in the loop because it has the largest Yukawa couplings.

First, we can see that these limits are nowhere near as strong as those for vector exchange [3]. Flavor-nonconserving theories at the weak scale are not ruled out at all. Second, if the uncertainty factors of 2 or 3 go the

TABLE II. Experimental lower limits on the exchanged scalar masses. BR≡branching ratio.

Process	$(M/\mathrm{GeV})(250\ \mathrm{GeV}/v_1)$
$\mu \to 3e$	1
$\mu \to e\gamma$	4
$\mu N \to eN$	10
$K_L^0 \to \mu^\pm e^\mp$	20
$B_d \to \tau^+\tau^-$	$20(10^{-4}/\mathrm{BR})^{1/4}$
$B_s \to \mu^+\mu^-$	$70(10^{-8}/\mathrm{BR})^{1/4}$
$\Delta m(B_d^0\text{-}\bar{B}_d^0)$	$400\sqrt{\kappa}$
$\Delta m(K^0\text{-}\bar{K}^0)$	$500\sqrt{\kappa}$

right way, it is possible that the rare leptonic B_s decay will be the first place to discover this new physics, considering that branching ratios 10^{-7}–10^{-8} will be obtained in the near future [4]. The branching-ratio prediction for $B_s \to \mu^+\mu^-$ is about 10^{-9} in the standard model, and in two-Higgs-doublet models with discrete symmetries [5].

There are cases where the scalar cannot induce all the processes considered, as in leptoquark models. The tree-level exchange of leptoquarks generates four-fermion operators which contain two quarks and two leptons. The limits from $K\bar{K}$ and $B\bar{B}$ mixing are therefore removed. In this case our results are particularly important: The rare leptonic B decay modes provide the most stringent test of models with scalar leptoquarks.

We discuss briefly the case in which approximate flavor symmetries act on the exchanged scalar too. Such is the case in R-parity-violating supersymmetric models [6], where the exchanged scalar is a slepton or a squark which carries the same approximate flavor symmetry as its fermion partners. Then in Table II all mass limits are lowered by an additional symmetry-breaking factor ϵ_a, where the approximate symmetry of type "a" is carried by the scalar. It is even less likely that such theories could have been excluded.

Glashow-Weinberg criterion for multi-Higgs-doublet models.— In this section we apply our results to the case of the minimal standard model extended only by the addition of an arbitrary number of Higgs doublets. In this case it is already known that, for the special case of Fritzsch-like Yukawa matrices, the additional scalars need not be heavier than a TeV [7]. However, our results are independent of the particular texture and depend only on the approximate flavor symmetry.

To avoid problems with large flavor-changing neutral currents, Glashow and Weinberg [1] argued that only one Higgs doublet could couple to up-type quarks and only one Higgs doublet to down-type quarks. However, this naturality constraint, known as the Glashow-Weinberg criterion, was based on an unusual definition of what is "natural." For them the avoidance of flavor-changing neutral currents was natural in a model only if it occurred for all values of the coupling constants of that model. For us a model will be natural provided the smallness of any coupling is guaranteed by approximate symmetries [8], and we find that this implies the Glashow-Weinberg criterion is not necessary.

In a model with many scalar doublets it is convenient to work in a basis where only one doublet, the Higgs doublet, acquires a vacuum expectation value, and all the others are massive scalar particles which play no role in the Higgs mechanism. The couplings of the Higgs meson are flavor diagonal at tree level, but in general the couplings of the other doublets are not. The limits on the mass M of these extra scalars are given in Table II. This shows that *approximate flavor symmetries are sufficient to allow extra scalar doublets with masses in the hundreds of GeV range; there is no need for additional symmetries to act on the scalar fields.*

One reason why this is important is that the vast majority of phenomenology on the multi-Higgs-doublet models has been done assuming symmetries which force only one Higgs doublet to couple to up-type and one to down-type quarks. We conclude that there is no good reason for accepting the predictions of these analyses, except in the case of supersymmetric models.

In conclusion, we have introduced a simple ansatz for the approximate flavor symmetries as shown in Table I. It reproduces the KM matrix elements at the factor-of-2 level. If the interactions of additional scalars respect these approximate symmetries, then the mass limits on the scalars from various experiments are shown in Table II. From this viewpoint, new flavor-changing physics at the weak scale is not excluded, and is natural. In particular, extra Higgs doublets can couple to both up- and down-type quarks; there is no need to impose additional discrete symmetries on the scalars. We find that rare leptonic B decay modes, such as $B_s^0 \to \mu^+\mu^-$, could uncover this new scalar-mediated physics in the coming years.

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