Relating the long B lifetime to a very heavy top quark

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(Received 30 June 1989)

The long B lifetime is related to the heaviness of the top quark by a particular mass-mixing ansatz. The u-type quark mass matrix is of the Fritzsch form, while for the d type it is diagonal except in the d-s plane, which generates the Cabibbo rotation. We predict $m_t \gtrsim 200$ GeV from $V_{cb} \lesssim 0.06$. One gets "maximal CP violation," and the relations $|V_{ub}/V_{cb}| = \sqrt{m_u/m_c}$, $|V_{td}/V_{cb}| = \sqrt{m_d/m_s}$, and $|V_{ts}| = |V_{cb}|$ are close to exact. An interesting Wolfenstein pattern emerges. We discuss the viability and implications of having such a heavy top quark (such as lower M_Z), and the possibility of a vanishing V_{ub} and its impact on CP violation.

When the long B-meson lifetime was discovered,[1] it came as a total surprise to the physics community. One did not suspect that V_{cb} and V_{ub} would be much smaller than the Cabibbo angle $V_{us} \simeq V_{cd} \simeq 0.22$. By now we know that there appears to be a hierarchy of mixing angles, which can be intuitively understood as some kind of "decoupling," in that heavier quarks do not play a major role in low-energy physics (involving light quarks).

The hierarchy of quark mixing angles, taken together with the hierarchy of quark masses between generations, have prompted numerous discussions of mass-mixing relations. Indeed, the most successful mass-mixing relation is actually the 20-year-old[2] $\lambda \equiv \sin\theta_C \simeq \sqrt{d/s}$ (Ref. 3). With three generations, the most popular and still viable ansatz is due to Fritzsch.[4] However, this ansatz is not particularly natural in its explanation for the smallness of V_{cb}. A double fine-tuning is needed to achieve a factor of 3–7 cancellation. This is because, as a generalization of the original 2×2 ansatz, $\sqrt{s/b} \sim \sqrt{d/s}$ is large compared to V_{cb}. Thus, to account for the smallness of V_{cb}, only certain values of m_t is allowed, in addition to the phase difference, such that $\sqrt{c/t}$ may cancel against $\sqrt{s/b}$. This brings us back again to the question of why B lifetime is so long. Is it just an accident?

It will be nice to justify the Fritzsch ansatz by a dynamical principle (e.g., such as the axion for the strong CP problem). Alternatively, it would be interesting if one can find another ansatz that resolves this issue in a more appealing way. We do not have an answer in the first sense. But by noting that the culprit is the rather large $\sqrt{s/b}$, we propose an ansatz that drops the s-b mixing term altogether, resulting in $V_{cb} = \sqrt{c/t}$, and the question above gets rephrased: Is the long B lifetime a first indication that the top quark is very heavy?

This type of question could not have been asked at the time of discovery of the long B lifetime, since at that time it was widely believed that the top quark would soon be found, and even a 20-GeV value seemed high.[5] The situation has changed dramatically in the past couple of years. The top quark still has not been seen and direct searches already yield lower bounds that are much heavier than what was anticipated. What is more important is the unexpectedly large B_d mixing,[6] which was another surprise from the B-meson system. If one takes central (mostly theoretical) values for various not-so-well-known parameters, indeed one finds that a very heavy top is needed. Thus, we proceed to pursue the question of whether the long B lifetime can be related to the top being very heavy.

We begin by briefly reviewing the Fritzsch ansatz.[4] The u- and d-type quark mass matrices are assumed to be of the form

$$m_U \sim \begin{bmatrix} 0 & a & 0 \\ a & 0 & b \\ 0 & b & c \end{bmatrix} , \tag{1}$$

where a,b,c are complex, and m_D is of similar form with $\tilde{a},\tilde{b},\tilde{c}$ as elements. It is then easy to show that the charge-current quark mixing matrix is of the form

$$V = U^T P D , \tag{2}$$

where $P = \mathrm{diag}(1, e^{i\sigma}, e^{i\tau})$ is a diagonal phase matrix, while D is an orthogonal matrix of the form

$$D \simeq \begin{bmatrix} 1 & \sqrt{d/s} & \sqrt{d/b}\, s/b \\ -\sqrt{d/s} & 1 & -\sqrt{s/b} \\ \sqrt{d/b} & \sqrt{s/b} & 1 \end{bmatrix} , \tag{3}$$

and U is likewise with obvious substitutions. We have kept only leading orders in mass ratios. At this point we note the standard values[7]

$$\begin{aligned} d/s &\simeq (\tfrac{1}{21} - \tfrac{1}{18}) \gg u/c \sim (\tfrac{1}{390} - \tfrac{1}{200}) , \\ s/b &\simeq (\tfrac{1}{40} - \tfrac{1}{25}) > c/t \lesssim \tfrac{1}{30} , \\ d/b &\sim (\tfrac{1}{450} - \tfrac{1}{860}) \gg u/t \lesssim \tfrac{1}{9000} . \end{aligned} \tag{4}$$

What is unknown is the top-quark mass, although individual light-quark masses are also quite uncertain. Note that $\sqrt{d/s} \sim \sqrt{s/b}$, so the rotation in d-s and s-b planes are both of order of the Cabibbo angle. Note also that $\sqrt{u/c} \sim d/s$ and the rotation in the u-c plane seems to be of order Cabibbo angle squared. For the bulk of our discussion, we shall assume the values quoted above, and return to discuss possible modifications later.

With these mass ratios in mind, one can discuss the virtues and problems of the Fritzsch ansatz. The mixing matrix takes the form

$$V \sim \begin{bmatrix} 1 & \sqrt{d/s} - \sqrt{u/c}\, e^{i\sigma} & \sqrt{s/b}\sqrt{u/c}\, e^{i\sigma} - \sqrt{u/t}\, e^{i\tau} + \sqrt{d/b} \\ -\sqrt{d/s} + \sqrt{u/c}\, e^{-i\sigma} & 1 & -\sqrt{s/b} + \sqrt{c/t}\, e^{i(\tau-\sigma)} \\ -\sqrt{d/b} + \sqrt{d/s}\sqrt{c/t}\, e^{i(\sigma-\tau)} & \sqrt{s/b} - \sqrt{c/t}\, e^{i(\sigma-\tau)} & 1 \end{bmatrix}, \tag{5}$$

where any term that is necessarily very small compared to the leading term has been dropped. Note the approximate relations $V_{ub} \simeq \sqrt{u/c}\, e^{i\sigma} V_{cb} + \sqrt{d/b}\; s/b$, $V_{td} \simeq -\sqrt{d/s}\, V_{cb}^*$, and $V_{ts} \simeq -V_{cb}^*$, so

$$|V_{ub}/V_{cb}| \sim \sqrt{u/c}\,, \quad |V_{td}/V_{cb}| \sim \sqrt{d/s} \tag{6}$$

is expected; hence, the smallness of V_{ub} as compared to V_{cb} is quite natural. However, the real problem with the Fritzsch ansatz is the smallness of V_{cb} itself. As stated earlier, $\sqrt{s/b} \sim \sqrt{d/s}$, is of order 0.16–0.20. This is a factor of 3–7 larger than the measured value of $|V_{cb}| \simeq 0.03$–0.06 ($\sim d/s$). Thus, the following is true.

(a) As a prerequisite, the phase difference $\tau - \sigma$ [in the conventions of Eq. (5)] has to be close to zero to even allow for cancellation.

(b) Even if this is true, m_t has to be tuned to ensure sufficient cancellation between $\sqrt{c/t}$ and $\sqrt{s/b}$. This does lend predictive power to the ansatz, but can also be criticized as arbitrary.

(c) Since $\sqrt{d/s}$ is so close to the Cabibbo angle already, while $\sqrt{u/c}$ is a sizable fraction, to be compatible with the Cabibbo angle (V_{us}), $\sqrt{d/s}$, and $\sqrt{u/c}$ have to be combined as close to quadratic as possible. Thus,

$$\sigma \approx \pm\pi/2 \tag{7}$$

is necessary. This seems to be a nice feature in fixing a *CP*-violating phase. However, (a) only implies $|\tau - \sigma| \lesssim 15°$. The result is that the actual *CP*-violating phase in V is not predicted at all, and depends on accidents of mass ratios.

(d) Finally, when the top becomes very heavy, e.g., $m_t \gtrsim M_W$, then even the fine-tunings of (a), (b), would not suffice to account for the smallness of V_{cb} and the model will get ruled out. In some sense, this is the predictive power of the ansatz. But, if it does get verified in nature, it would still be nicer if one could *dynamically* account for this tuning. This would be a very challenging and interesting task, perhaps similar to the exclusion principle explanation of the periodic table, although comparatively, this time the data set is too small.

Lacking good ideas in this direction, and keeping in mind that the Fritzsch ansatz may get ruled out altogether if the top turns out to be very heavy (and therefore will take a while for its discovery), we propose an alternative ansatz that seems to explain the smallness of V_{cb} in a more natural way, and with greater predictive power.

We have noted that the culprit is that $\sqrt{s/b}$ is way too large and does not by itself leave much room for tuning. Inspecting the Fritzsch form of the mass matrices, one notices, however, that if the $\sqrt{s/b}$ term was simply absent, then the smallness of V_{cb} can be related to the heaviness of top. To simplify, and to be more consistent, we therefore postulate that there is no s-b or d-b mixing, while d-s mixing is retained as is. Thus, the d-type mass matrix has the form[8]

$$m_D \sim \begin{vmatrix} 0 & \tilde{a} & 0 \\ \tilde{a} & \tilde{b} & 0 \\ 0 & 0 & \tilde{c} \end{vmatrix}, \tag{8}$$

while m_U retains the Fritzsch pattern. The diagonalization is very similar as before, and one immediately sees that the phase angle τ can be absorbed into the b-quark field, and one single phase remains. To get the mixing matrix, all one needs to do, then, is to set $\sqrt{d/b}, \sqrt{s/b}$ to zero in Eq. (5). We thus arrive at the mixing matrix within our ansatz,

$$V \sim \begin{bmatrix} 1 & \sqrt{d/s} - \sqrt{u/c}\, e^{i\sigma} & -\sqrt{u/t}\, e^{i\sigma} \\ -\sqrt{d/s} + \sqrt{u/c}\, e^{-i\sigma} & 1 & \sqrt{c/t} \\ \sqrt{d/s}\sqrt{c/t} & -\sqrt{c/t} & 1 \end{bmatrix}, \tag{9}$$

in a slightly different phase convention.

We now explore the consequences of this ansatz.

(i) The most important, of course, is the relation $|V_{cb}| = \sqrt{c/t}$. We shall take into account QCD corrections to the masses only, ignoring the potentially more important weak corrections, since the mass generation mechanism itself is at issue here. With QCD corrections only, one gets the relation

$$m_t(\mu) = m_c(\mu)/|V_{cb}|^2\,, \tag{10}$$

which holds for arbitrary scale μ, while V_{cb} is more or less scale independent. Using the central value of m_c (1 GeV) $= 1.35 \pm 0.05$ GeV, and the range $0.03 \lesssim |V_{cb}|$

$\lesssim 0.06$ (Ref. 9), we find 350 GeV$\lesssim m_t$ (1 GeV) $\lesssim 1400$ GeV. The physical "on-shell" mass [defined via $m_t(m_t)=m_t$] is then found by solving'

$$m_t(m_t) \approx 0.746[\ln(m_t/\Lambda_5)/\ln(2m_b/\Lambda_5)]^{-12/23} \times m_c(m_c)/|V_{cb}|^2 , \quad (11)$$

where we take $2m_b \equiv 2m_B \simeq 10.56$ GeV, $2m_c \equiv 2m_D \simeq 3.73$ GeV for the intermediate scales, following Ref. 7 for the n_f flavor Λ scales, with $\Lambda_5 = 65$ MeV. Taking the central value for $m_c(m_c) = 1.27 \pm 0.05$ GeV, we "predict" that physically

$$200 \text{ GeV} \lesssim m_t \lesssim 750 \text{ GeV} \quad (12)$$

is indeed to account for the measured range of V_{cb}. This seems to be barely allowed by the ρ parameter[10] and neutral-current data.[11] We will come back later to give a detailed discussion of the viability of this result. At present we comment that, indeed, it is rather difficult to account for the smallness of V_{cb}. We do, however, eliminate the double fine-tuning of the Fritzsch ansatz, since V_{cb} carries no phase. Note the curious result that, for $V_{cb} = 0.055$, we get $m_t(m_t) \simeq$ vacuum expectation value (VEV); i.e., the top-quark mass would be the same as for the electroweak symmetry-breaking scale.

(ii) The relations in Eq. (6) that were only approximate in the Fritzsch ansatz becomes more exact. In our ansatz, only V_{cb} is related to third-generation quark mass(es), and once this is fixed, all the remaining terms are either close to 1 or are in terms of V_{cb} and quark mass ratios within the first two generations.

(iii) The single phase σ, as in the Fritzsch case, is fixed to be $\pm\pi/2$, to account for $V_{us} \simeq V_{cd}$. This is because of the closeness of $\sqrt{d/s}$ to the Cabibbo angle, and is actually the reason why we kept the d-s rotation in our ansatz. This fine-tuning of σ, however, contrasts with the Fritzsch case: there is only one single nontrivial phase. Identifying $V_{cb} = \sqrt{c/t}$, and using V_{us} or V_{cd} as input, the phase is also fixed, and the complete mixing matrix becomes determined in terms of "light"-quark mass ratios which are presumably calculable[7] by fitting the known hadronic spectrum. The Fritzsch ansatz uses eight parameters to account for the ten parameters characterizing quark masses and mixing, while the CP-violating phase, the elements V_{ub} and V_{td} are not completely determined. In our case, we use only seven parameters—six masses and a phase—while the phase is fixed to be $\pm\pi/2$, seemingly "maximal."

(iv) In fact, the phase is maximal in the strict sense. The invariant

$$\mathrm{Im}(V_{us}V_{ub}^* V_{cs}^* V_{cb}) \simeq \sqrt{d/s}\,\sqrt{u/t}\,\sqrt{c/t}\,(1+u/c)\sin\sigma \simeq |V_{us}|\,|V_{ub}|\,|V_{cs}|\,|V_{cb}|\sin\sigma \quad (13)$$

is just a product of the moduli of elements, so the phase $\sigma = \pm\pi/2$ is truly "maximal." With measured mixing elements, and the relation $|V_{ub}/V_{cb}| = \sqrt{u/c}$, one finds the phase invariant to be of order $(3\text{–}4)\times 10^{-5}$, where we have restricted V_{cb} to be greater than 0.05, and the uncertainty mostly reflects that of $\sqrt{u/c}$.

(v) Comparison with known data. Usual treatments of QCD corrections cannot be readily extended to our heavy top-quark mass value. However, recomputing all such corrections is clearly beyond the scope of our present paper. Therefore, in the following discussion, we shall take QCD corrections from published work. Using standard formulas, with QCD correction factor $\eta_{\mathrm{QCD}} \approx 0.8$, we find that $B_B f_B^2 \lesssim (120 \text{ MeV})^2$ is needed to account for the experimental value of $x_d = 0.70 \pm 0.13$. Given the present theoretical uncertainties of B_B and f_B, we conclude that we account for B_d mixing rather well. For ϵ we use the formulas of Ref. 12 and find that the kaon "bag" parameter $B_K \lesssim 0.4$ is needed to account for ϵ. For ϵ'/ϵ our result is consistent with the NA31 value,[13] except that in our case, the latter does not decrease with increase of m_t, since our CP invariant is fixed. However, the recent result[14] of $(-0.5\pm 1.5)\times 10^{-3}$ from Fermilab experiment E731 is considerably smaller than the NA31 value. This poses a problem even for the three-generation standard model itself. We will come back to the problem of CP violation later, together with a critique on our ansatz.

(vi) Hierarchy of mixing elements. Note that, with $\lambda \equiv \sin\theta_C$, $V_{cb} \approx \lambda^2$, and $V_{ub}/V_{cb} = \sqrt{u/c} \approx \lambda^2$ in our ansatz. After certain phase redefinitions we get the interesting Wolfenstein form[15]

$$V \approx \begin{bmatrix} 1 & \lambda & \lambda^5 \mp i\lambda^4 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3(1\mp i\lambda) & -\lambda^2 & 1 \end{bmatrix} , \quad (14)$$

where we have kept only leading elements, and one can easily unitarize the matrix. We thus find that, in Wolfenstein's notation, $A \simeq 1$, $\rho \simeq \lambda^2$, and $\eta \simeq \pm\lambda$, which certainly is rather curious, and one may want to speculate about the underlying physics. Another curiosity worth mentioning is the rather small ratio $m_b(1 \text{ GeV})/m_t(1 \text{ GeV}) \approx \lambda^3 - \lambda^4$, which is nowhere used in the ansatz, but could be a clue to the underlying mechanism.

The upshot is that we have a rather peculiar ansatz for mass-mixing relations. The ansatz is completely predictive: very heavy top quark, maximal CP, and the quark mixing matrix is completely fixed (e.g, V_{cb} is close to its maximal allowed value). It is also "consistent" with present existing information, although both V_{cb} and m_t (related) and B_K (for ϵ) seem to live close to the margins of their allowed ranges, while ϵ'/ϵ seems to pose a problem. We therefore turn to a detailed discussion of these latter questions.

The main problem, of course, is the demand for $m_t \gtrsim 200$ GeV. A detailed study[11] of available neutral-current data and measurements of M_Z and M_W suggests that $m_t \lesssim 180$ GeV at the 90% confidence level, similar to the ρ parameter constraint.[10] This does not necessarily clash with our prediction for m_t because of its statistical nature. However, although viable, to rely on just statistical fluctuations does not serve to convince oneself. We therefore provide arguments for the possibility of having a top-quark mass heavier than this bound, in ascending order of the level of speculation involved. First of all, the above neutral-current bound depends on the input parameters, in particular, the UA1/UA2 value of

$M_Z = 91.8 \pm 1.8$ GeV (Ref. 16). If the input parameters are changed due to new measurements, the above bound may also change. In fact, it was pointed out[17] that if M_Z is lowered, the allowed range for m_t moves up, leaving the lower and upper bounds both higher. Indeed, the Mark II Collaboration at the SLAC Linear Collider finds the lower value $M_Z = 91.17 \pm 0.18$ GeV (Ref. 18). Although not very different from previous results, the 90%-C.L. upper limit on m_t becomes 220 GeV. Thus, the current M_Z value certainly does not rule out the possibility of having a very heavy top quark. Second, some recent work indicates that heavy fermion effects on the ρ parameter softens at the two-loop level,[19] which should translate into a weaker upper limit on m_t following the previous discussion. Third, a fine-tuned ρ parameter is possible if there are Higgs-boson triplets (or higher representations). Fourth, we point out that the mass-mixing game does not directly involve the mechanism for quark mass generation at or above the weak symmetry-breaking scale (VEV). For fermions with masses much smaller than the VEV scale (which includes all fermions except possibly the top quark), together with our knowledge of $V-A$ structure of weak interactions, we have built in the difference in representation structure for left- and right-handed fermions, such that one has an exact chiral-symmetry-forbidding fermion mass terms in the absence of scalar fields. The Yukawa couplings of the Higgs-scalar field to fermions thus serve as small but arbitrary parameters that break this chiral symmetry, and together with the weak symmetry breaking itself, give rise to the small observed masses. All this seems to be well satisfied in the observed spectrum. However, we are in the ambiguous situation that the resulting dynamical relation $m_f = \lambda_f \times \mathrm{VEV}$ cannot be tested (except, perhaps, in the K_L-K_S mass difference), since the Yukawa couplings (λ_f) for these light fermions are much weaker than the gauge couplings. The only place to test it is in the case of a heavy top quark, as seen from the aforementioned Z-boson mass shift, ϵ, B mixing, rare K, B, and Z decays, etc. But, for heavy fermions, there is no reason *a priori* why $m_Q = \lambda_Q \times \mathrm{VEV}$ should hold, since the fermion mass becomes similar to the VEV scale, and the chiral symmetry is badly broken. In other words, there is no reason why heavy fermions should have similar charge and representation assignments as the light ones. Nevertheless, because the top does seem to belong to a left-handed doublet with the b quark, it is not easy to evade the neutral-current bound. Still, efforts along this direction to find out the dynamical origin for (heavy) top-quark mass should be interesting, and may shed light on the overall mechanism of fermion mass generation.

Our ansatz could also run into difficulties with CP violation. Indeed, we need a relatively low (though allowed[12]) B_K, even for our lowest m_t values, while we seem unable to account for the low value of ϵ'/ϵ found by E731 (although we can account for the NA31 value). First, we note that for very large m_t values, a careful reanalysis is needed for QCD corrections, which we have not done. Regarding CP violation itself, it should be empoints to some underlying new dynamics. Given that CP violation is poorly understood, and presumably related to fermion mass generation, it is likely that this new dynamics could give rise to additional CP-violating sources. Thus, deviations in predictions for CP violation when playing the mass-mixing game does not automatically exclude the model. If this is not very assuring, we point out some interesting recent development. Note that our CP-violating phase factor ($e^{i\sigma}$) is always associated with $\sqrt{u/c}$, e.g., $V_{ub} = \sqrt{u/c}\, V_{cb} e^{i\sigma}$. Thus, in our model, CP violation vanishes with m_u (unlike the Fritzsch case). In our discussions above, we have used some standard values[7] for quark mass ratios. For the light fermions, these were computed from first-order chiral perturbation theory. Recently, it has been shown[20] that the u/d ratio may get large contributions from second-order chiral perturbation theory, and in fact, $m_u \to 0$ cannot be excluded. This solves the strong CP problem in a natural way, but in our ansatz, barring the aforementioned possible new sources of CP violation, CP would then be conserved. Thus, we do not advocate such a possibility, but just point to the fact that $\sqrt{u/c}$ could be much smaller than presented above, and without knowing precisely its value, one still has a lot of room to account for ϵ and ϵ', even if m_t is very heavy. One should note that the prediction for "maximal" CP becomes weakened as $\sqrt{u/c}$ is lowered.

In conclusion, we have proposed a new ansatz for mass-mixing relations. We modify the down-type quark mass matrix, keeping only Cabibbo mixing, while retaining the Fritzsch form for the up-type mass matrix. We thereby relate the smallness of V_{cb} to the heaviness of top, and predict that $m_t \gtrsim 200$ GeV, while V_{cb} should be close to its experimental upper limit. The quark mixing matrix is completely fixed, even the phase, and one finds maximal CP violation. An interesting hierarchy pattern of mixing angles emerges. There is no apparent contradiction with existing data, while predictions can be made for various processes, such as "maximal" B_s mixing, $B(K \to \pi\nu\bar{\nu})$ close to the 10^{-10} level, and $B(b \to s l^+ l^-)$, $B(b \to s\nu\bar{\nu})$ at the 10^{-5} and 10^{-4} level, respectively. If the top quark is found any time soon, with a mass value far below 200 GeV, our model will be ruled out. But if not, direct search would take a long time for such a large m_t value, possibly only when the Superconducting Super Collider becomes available. Why the top is so heavy compared to the bottom would be an interesting question calling for an answer.

Note added in proof. Recent theoretical work suggests that the standard model could account for a vanishing ϵ'/ϵ (even the opposite sign) in case m_t is very heavy. Thus, our ansatz is not in direct conflict with the E731 result, although the experimental situation needs to be clarified. Recent theoretical work on dynamical symmetry breaking via $t\bar{t}$ condensation, in which the top quark picks up a mass from unknown dynamics, also tends to suggest a very heavy top quark.

X.G.H. thanks the Max-Planck-Institut for hospitality during a short visit, out of which this project was initiated. W.S.H. wishes to thank Jean-Marc Gerard, Michael Gronau, Hans Kühn, and Paul Langacker for discussions.

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