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BOUNDS ON CHARGED HIGGS PROPERTIES FROM CP VIOLATION*

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ABSTRACT

We examine bounds from CP violation in the neutral K system on charged Higgs masses and couplings in models with two Higgs doublets. While CP violation is still due only to a non-zero phase in the Kobayashi-Maskawa matrix, there are additional short-distance contributions involving charged Higgs exchange rather than W exchange. By having CP violation in the mass matrix, but not in $K \to \pi\pi$ decay amplitude, largely due to Higgs exchange, it is possible to obtain a small value of ϵ'/ϵ.

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With the emergence of the standard model and its origin for CP violation in a phase within the Kobayashi-Maskawa[1] (K-M) matrix describing the weak couplings of quarks, it is of great importance to test whether this is the correct explanation of CP violation by delineating its consequences for as many specific cases as possible and by subjecting them to experimental test. Thus we have, for example, the attempts[2] to calculate the parameters ϵ and ϵ' of CP violation in the neutral K system in terms of the elements of the K-M matrix plus values of matrix elements of relevant operators and the recent experiments[3] to measure ϵ'/ϵ with high accuracy.

In a different vein, but also very much related to the standard model, there is much interest in the Higgs sector. The neutral Higgs boson remains as the one as yet undiscovered particle of that model, and there is also considerable speculation on whether the Higgs sector should be enlarged or even totally replaced by a dynamics. These latter possibilities affect the question of CP violation since the introduction of additional Higgs generates at a minimum extra diagrams involving Higgs exchange to be considered along with those involving W exchange. At most, in some models with three or more Higgs doublets,[4] the Higgs sector can become the sole source of CP violation.

Here we shall be interested in the extension of the minimal (standard) model to the case of two Higgs doublets rather than one, although many of our results can be generalized easily beyond the case of two doublets. We are concerned with what restrictions the observed CP violation in the neutral K system places on the couplings and masses of the charged Higgs bosons in such a theory. The restrictions which follow from the tiny $K_L^0 - K_S^0$ mass difference have already been studied,[5] but CP violating effects are even smaller (by $\sim 10^{-3}$) and emphasize different K-M angles and different quarks. Correspondingly we get even more sensitive bounds than obtained from the mass difference if we adopt the same kind of criteria.

Looked at another way, introducing additional Higgs bosons and therefore additional diagrams gives us more freedom in attempting to explain present observations. We shall also take this viewpoint and will find that it is possible for the Higgs exchange contribution to be the primary source of CP violation in the neutral K mass matrix (i.e., the parameter ϵ), while not being the dominant source of CP violation in K decay (i.e., the parameter ϵ'). Therefore, if the standard model runs into trouble accounting simultaneously for the values of both ϵ and ϵ', the introduction of another Higgs doublet with resulting heavy charged Higgs bosons could be a relatively "cheap" extension of the standard model that "decouples" the source of ϵ and ϵ' and allows for consistency with experiment.

Let us first follow the path toward achieving bounds that Abbott, Sikivie, and Wise[5] applied to the real part of the mass matrix. Namely, we adopt the philosophy that the imaginary part of the $K^0 - \overline{K}^0$ mass matrix element (proportional to ϵ) is "understood" as arising largely from the short distance contributions associated with the box diagram involving two W's and two heavy quarks. Correspondingly, the contribution from exchange of two Higgs bosons and from a W and a Higgs boson is assumed to be smaller than the standard one involving two W's, i.e.

$$\epsilon_{HH} + \epsilon_{HW} < \epsilon_{WW} \tag{1}$$

in order not to "spoil" the assumed approximate agreement with experiment of ϵ_{WW}.

In a model with extra Higgs doublets we want to preserve the property that there are no flavor changing neutral currents at tree level. This can be accomplished[6] by having one neutral Higgs field coupled to charge 2/3 quarks and another Higgs field coupled to charge -1/3 quarks. In this case the coupling of the physical charged Higgs bosons is given by[5]

$$\mathcal{L}_{\rm int} = \frac{g\phi^+}{2\sqrt{2}M_W}\,\overline{U}\left[\frac{\xi}{\eta}\,M_u K(1-\gamma_5) + \frac{\eta}{\xi}\,K M_d(1+\gamma_5)\right] D + \text{H.c.}\,, \tag{2}$$

where η and ξ are the vacuum expectation values of the Higgs fields coupled to charge 2/3 and -1/3 quarks, respectively. The 3×3 matrix K is the K-M matrix[1] and M_u and M_d are diagonal mass matrices for charge 2/3 and -1/3 quarks U and D, respectively.

Alternatively, one can avoid flavor changing neutral currents by having just one of the two Higgs doublets couple to quarks.[7] In this case the neutral Higgs couplings are diagonalized along with the mass matrix and the charged Higgs couplings are given by[5,7]

$$\mathcal{L}_{\rm int} = \frac{g}{2\sqrt{2}M_W}\,\phi^+\overline{U}\left[\frac{\xi}{\eta}\,M_u K(1-\gamma_5) - \frac{\xi}{\eta}\,M_d(1+\gamma_5)\right] D + \text{H.c.}\,. \tag{3}$$

Since for the heavy quarks the mass of the charge 2/3 quarks is much greater than that of the charge -1/3 quarks in the same generation, it is the term proportional to $(\xi/\eta)M_u$ in either Eq. (2) or (3) which gives the best possibility of significant Higgs couplings between light and heavy quarks. Therefore, from here on, we concentrate only on this term with $\xi/\eta > 1$.

The imaginary part of the $\Delta S = 2$ effective Hamiltonian responsible for

$K^0 - \overline{K}^0$ mixing then has the form

$$\text{Im H} = \text{Im H}_{WW} + \text{Im H}_{WH} + \text{Im H}_{HH} \ , \tag{4}$$

where[5]

$$\text{Im H}_{WW} = \frac{g^4 s_1^2 s_2 s_2 s_\delta}{2^8 \pi^2 M_W^4} \left\{ -m_c^2 + m_c^2 \ell n \frac{m_t^2}{m_c^2} + s_2(s_2 + s_3 c_\delta) m_t^2 \right\}$$

$$\times \left[\bar{s}\gamma_\mu(1-\gamma_5)d\right] \left[\bar{s}\gamma^\mu(1-\gamma_5)d\right] \ , \tag{5a}$$

$$\text{Im H}_{WH} = \frac{g^4 s_1^2 s_2 s_3 s_\delta}{2^6 M_W^4} \left(\frac{\xi}{\eta}\right)^2 \left\{ - m_c^4 (8M_W^2 I_2(m_c) + 2I_3(m_c)) \right.$$

$$+ m_c^2 m_t^2 (8M_W^2 I_5 + 2I_6)$$

$$\left. + s_2(s_2 + s_3 c_\delta) m_t^4 (8M_W^2 I_2(m_t) + 2I_3(m_t)) \right\}$$

$$\times \left[\bar{s}\gamma_\mu(1-\gamma_5)d\right] \left[\bar{s}\gamma^\mu(1-\gamma_5)d\right] \ , \tag{5b}$$

and

$$\text{Im H}_{HH} = \frac{g^4 s_1^2 s_2 s_3 s_\delta}{2^6 \, M_W^4} \left(\frac{\xi}{\eta}\right)^4$$

$$\times \left\{ - m_c^4 I_1(m_c) + m_c^2 m_t^2 I_4 + s_2(s_2 + s_3 c_\delta) m_t^4 I_1(m_t) \right\} \tag{5c}$$

$$\times \left[\bar{s}\gamma_\mu(1-\gamma_5)d\right] \left[\bar{s}\gamma^\mu(1-\gamma_5)d\right] \ .$$

Here the integrals $I_1, \ldots, I_6$ are defined in Abbott, Sikivie and Wise.[5] Knowing that the K-M angles θ_1, θ_2, and θ_3 are all small,[8] we have used the very good approximation that $\cos\theta_i = 1$. (But the CP violating phase δ may well be large, so we keep both $\cos\delta = c_\delta$ and $\sin\delta = s_\delta$.) As the subscripts imply, H_{WW}, H_{WH}

and H_{HH} arise from the short distance box graph involving exchange respectively of two W's (the standard contribution[9]), a W and a charged Higgs boson and two charged Higgs bosons. The imaginary part of H and hence CP violation in the neutral K system arise entirely because of a non-zero K-M phase δ in each term of Eq. (4). When $\delta = 0$ there is no CP violation inherent in the Higgs sector itself, as there may be in models with three or more Higgs doublets.[4]

We now impose the condition in Eq. (1). Since Im $\mathrm{H} \propto \epsilon$ and the effective Hamiltonians in Eqs. (5a), (5b) and (5c) all involve the same four-quark operator, the matrix element of that operator cancels out of the resulting equation along with the weak coupling g and the common factor $s_1^2 s_2 s_3 s_\delta$. Inasmuch as we are interested in bounding ξ/η when $M_H^2 \gg m_t^2$, and since $m_t \gg m_c$, a good first approximation to the resulting inequality is obtained by only keeping the term proportional to $m_t^4(\xi/\eta)^4$ in Eq. (5c) and that involving m_t^2 in Eq. (5a). This results in

$$\left(\frac{\xi}{\eta}\right)^2 < 2\left(\frac{M_H}{m_t}\right) \tag{6}$$

when we use the expression[5] for $I_1(m) = (16\pi^2 M_H^2)^{-1}$ valid to $\mathcal{O}(m^2/M_H^4)$.

The exact bound following from the full expression, a quadratic in $(\xi/\eta)^2$, is not much harder to compute. While the factor $g^4 s_1^2 s_2 s_3 s_\delta$ still cancels out, there is now a dependence on the K-M angles through the quantity $s_2(s_2 + s_3 c_\delta)$ which enters Eqs. (5) in the terms arising purely from t quark exchange. An example of the bound on $(\xi/\eta)^2$ for a typical value[10] of $s_2(s_2 + s_3 c_\delta) = 2.5 \times 10^{-3}$ and for $m_t = 45$ GeV is shown in Fig. 1. Varying $s_2(s_2 + s_3 c_\delta)$ from 1×10^{-3} to 5×10^{-3} changes this upper bound by $\sim 30\%$ (downward). The bound (Eq. (6)) obtained by keeping only the leading terms in m_t (the dashed line in Fig. 1) is obviously a good approximation to the exact bound (the solid curve).

The upper bound on $(\xi/\eta)^2$ obtained here is much stronger (by a factor of ~ 20) than that[5] obtained from the real part of the $K^0 - \overline{K}^0$ mass matrix under analogous assumptions on the relative size of the Higgs and W contributions. For example, instead of[5] $(\xi/\eta)^2 \lesssim 200$ at $M_H = 150$ GeV, we have $(\xi/\eta)^2 \lesssim 10$. Even for charged Higgs bosons with masses of a sizeable fraction of a TeV, Fig. 1 implies $(\xi/\eta)^2 \lesssim 25$. Thus within the constraint imposed by adopting Eq. (1), enhancement[11] of the Higgs coupling to quarks by more than a factor $\xi/\eta \sim 5$ is ruled out for "reasonable" charged Higgs masses.

We now change our viewpoint and adopt an alternative philosophy, allowing the diagrams involving charged Higgs exchange rather than W exchange to be the main source of CP violation in the neutral K mass matrix. We replace Eq. (1) by

$$\epsilon_{WW} + \epsilon_{WH} + \epsilon_{HH} = \epsilon \; , \tag{7}$$

and use the experimental value[8] of 2.27×10^{-3} on the right-hand side. Depending on the values of the K-M angles, Higgs parameters, etc., either the terms involving Higgs exchange or those involving W exchange on the left-hand side of Eq. (7) could be the primary source of ϵ.

In particular, the $K^0 - \overline{K}^0$ matrix element of $[\bar{s}\gamma_\mu(1-\gamma_5)d]\,[\bar{s}\gamma^\mu(1-\gamma_5)d]$ no longer cancels out, nor does the characteristic combination of mixing angles $s_1^2 s_2 s_3 s_\delta$. Defining in a conventional way the parameter B as the ratio of the actual matrix element to its vacuum-insertion value, the factor $B\, s_1^2 s_2 s_3 s_\delta$ is common to all terms on the left-hand side of Eq. (7). The resulting equation is a quadratic in $(\xi/\eta)^2$ whose solutions we can parametrize in terms of $B\, s_1^2 s_2 s_3 s_\delta$,

M_H/m_t and $s_2(s_2 + s_3 c_\delta)$.

At one extreme we have solutions where, as before, $\epsilon_{WW} \gg \epsilon_{WH} + \epsilon_{HH}$. The relevant domain of parameters may be obtained by noting that there is a constraint following from the condition that $(\xi/\eta)^2 \geq 0$ for the solutions of Eq. (7), treated as a quadratic equation in $(\xi/\eta)^2$. For $s_2(s_2 + s_3 c_\delta) = 2.5 \times 10^{-3}$, we find[12] $B\, s_1^2 s_2 s_3 s_\delta \leq 2.14 \times 10^{-5}$ independent of M_H/m_t, with the equality holding when there is no Higgs contribution in Eq. (7). As shown by the solid curve in Fig. 2, for a value of $B\, s_1^2 s_2 s_3 s_\delta = 2.1 \times 10^{-5}$ (just lightly less than the bound) the solutions to Eq. (7) involve relatively small values of $(\xi/\eta)^2$ and have only a mild dependence on M_H/m_t. In this particular example ϵ_{WW} is the source of 98% of ϵ.

At the other extreme, when $B\, s_1^2 s_2 s_3 s_\delta$ is much smaller than its maximum, one has contributions from Higgs exchange as the dominant source of ϵ. When for example, $B\, s_1^2 s_2 s_3 s_\delta = 1 \times 10^{-6}$, ϵ_{WW} supplies only 5% of ϵ and $(\xi/\eta)^2$ is large and depends almost linearly on M_H/m_t (as shown by the dashed curve in Fig. 2.). Thus the short-distance contribution due to Higgs exchange could be the dominant contribution to CP violation in the neutral K mass matrix. Associated with this situation is a small value of $B\, s_1^2 s_2 s_3 s_\delta$ (as compared with its value when the usual W exchange contribution is the primary source of ϵ).

At the same time we may consider what happens to the other parameter of CP violation in the neutral K system, ϵ'. This measures CP violation in the $K \to \pi\pi$ decay amplitude and originates[13] primarily from so-called "penguin" diagrams. Here also we will have an additional diagram obtained by replacing W exchange with charged Higgs exchange. Their amplitudes can be related[5] by a Fierz transformation and their relative contributions to ϵ' are in the ratio

$$\frac{\epsilon'_H}{\epsilon'_W} \approx \frac{A_H^{\text{Penguin}}}{A_W^{\text{Penguin}}} \approx -\frac{1}{2}\left(\frac{\xi}{\eta}\right)^2 \frac{m_t^2}{M_H^2}\,\frac{\ell n\,(M_H^2/m_t^2)}{\ell n\,(m_t^2/m_c^2)}\ . \tag{8}$$

Comparing this to the leading (in m_t) contributions to ϵ:

$$\frac{\epsilon_{HH}}{\epsilon_{WW}} \approx \left[\frac{1}{2}\left(\frac{\xi}{\eta}\right)^2 \frac{m_t}{M_H}\right]^2 , \tag{9}$$

we see that aside from logarithms, the ratio of the Higgs contribution to the W contribution in ϵ' is down by a factor m_t/M_H as compared to the situation in $\epsilon^{1/2}$. Therefore if $(\xi/\eta)^2(m_t/M_H)$ is $\mathcal{O}(1)$ or less, as it is when $\epsilon_{WW} > \epsilon_{WH} + \epsilon_{HH}$, then the Higgs exchange contribution to ϵ' is an order of magnitude or more smaller than that of W exchange in the domain $m_t^2/M_H^2 \ll 1$ that we are considering. But even when $(\xi/\eta)^2(m_t/M_W)$ is large (say ~ 10) and Higgs exchange gives by far the dominant contribution to ϵ, the contribution from Higgs exchange to ϵ' is at most comparable in magnitude to that of W exchange.[14]

Thus even when the Higgs exchange contribution dominates ϵ, we still have $\epsilon' \approx \epsilon'_W$. But the absolute magnitude of ϵ'_W is proportional to a product of a $K \to \pi\pi$ matrix element of the penguin operator and of its coefficient, involving the overall factor $s_1^2 s_2 s_3 s_\delta$. When we go from the situation where W exchange contributions dominate ϵ to that where Higgs exchange contributions dominate, everything in the calculation of ϵ'_W remains the same except that $s_1^2 s_2 s_3 s_\delta$ decreases (proportionally) as ϵ_{WW}/ϵ decreases: by "tuning" up the portion of ϵ to be accounted for by Higgs exchange contributions rather than the standard W exchange contributions, we can reduce[14] the predicted value of ϵ'. Therefore, by extending the minimal model through the introduction of a second Higgs doublet involving heavy charged Higgs bosons with enhanced couplings, one could accommodate a very small value of ϵ'/ϵ.

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FIGURE CAPTIONS

1. Upper bound on $(\xi/\eta)^2$ as a function of M_H/m_t following from the condition $\epsilon_{HH}+\epsilon_{WH} < \epsilon_{WW}$. The resulting approximate bound in Eq. (6) is shown (dashed line), as well as the exact bound (solid curve) for $s_2(s_2+s_3c_\delta) = 2.5\times10^{-3}$, $m_c = 1.5$ GeV, $m_t = 45$ GeV.

2. Value of $(\xi/\eta)^2$ as a function of M_H/m_t needed to satisfy $\epsilon_{WW}+\epsilon_{WH}+\epsilon_{HH} = \epsilon$ when $B\,s_1^2 s_2 s_3 s_\delta$ equals 2.1×10^{-5} (solid curve), 8×10^{-6} (dotted curve), and 1×10^{-6} (dashed curve). The parameters $m_c = 1.5$ GeV, $m_t = 45$ GeV and $s_2(s_2+s_3c_\delta) = 2.5\times10^{-3}$.

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12. For $s_2(s_2 + s_3 c_\delta) = 1 \times 10^{-3}$ and 5×10^{-3}, we find $B s_1^2 s_2 s_3 s_\delta \leq 2.57 \times 10^{-5}$ and 1.67×10^{-5}, respectively.
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14. From Eq. (8) we note that the minus sign on the right-hand side makes $\epsilon' = \epsilon'_W + \epsilon'_H$ smaller in magnitude than ϵ'_W.

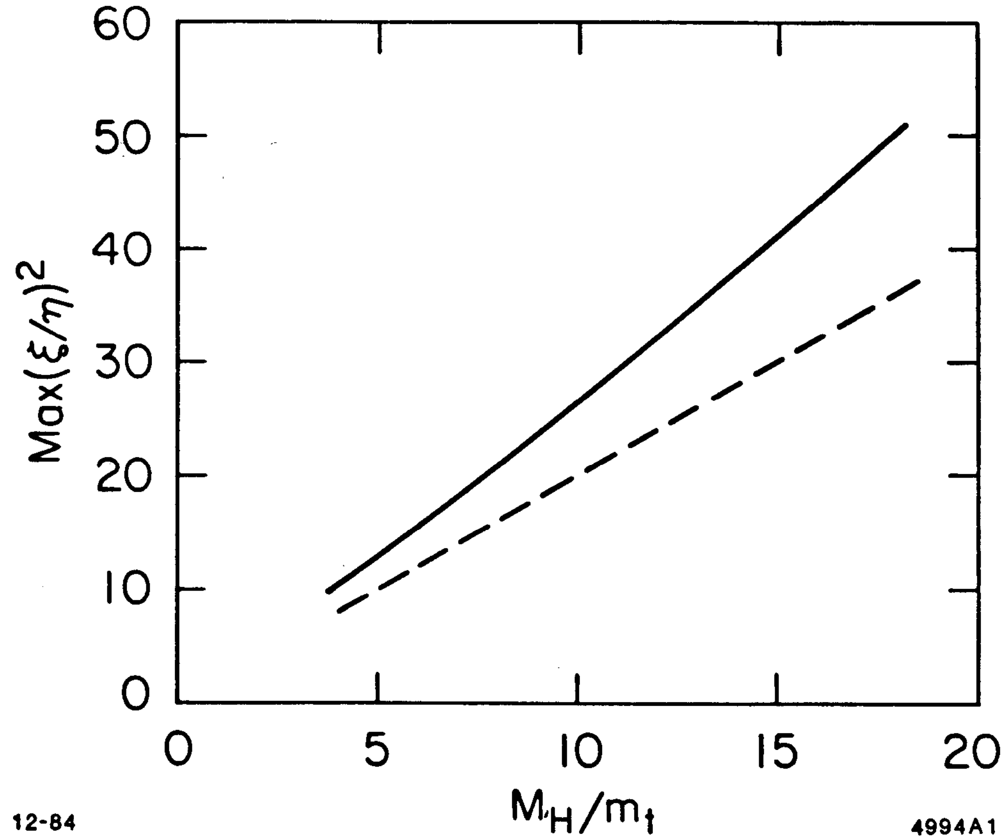

Fig. 1

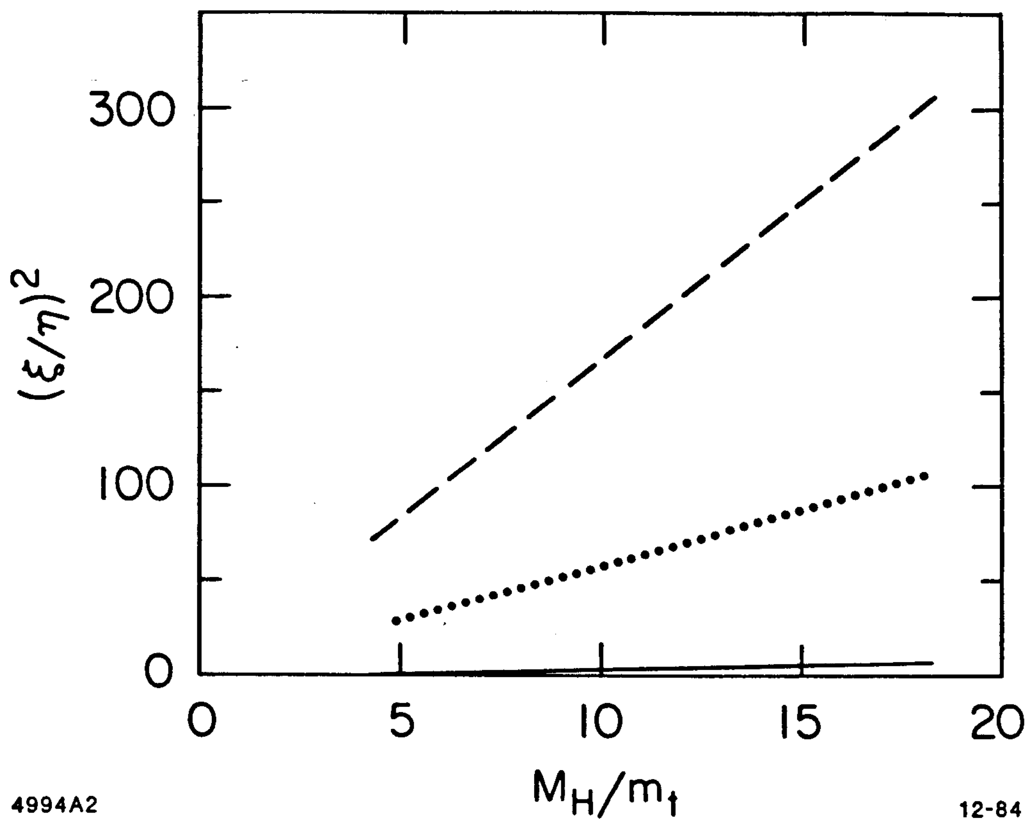

Fig. 2