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POSSIBLE INTERPRETATION OF CABIBBO-SUPPRESSED NON-LEPTONIC CHARM DECAYS AS EVIDENCE FOR CHARGED HIGGS BOSONS*

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ABSTRACT

It is suggested that the recent anomalous data on Cabibbo-suppressed charm decays can be interpreted as a manifestation of a charged Higgs boson. If this were true, it would be the first experimental detection of a Higgs contribution. At the least, it demonstrates that large, interesting Higgs (i.e., scalar) contributions are consistent with present experimental constraints. Predictions are given for τ and heavy quark decays.

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INTRODUCTION In this note we consider the possibility that charged Higgs particles or effective scalar currents contribute significantly to particle interactions. In particular, Cabibbo-suppressed charm non-leptonic decays have recently been reported,[1] with

$$\Gamma(D^o \to K^+K^-)/\Gamma(D^o \to K^+\pi^-) = 11.3 \pm 3\%$$
$$\Gamma(D^o \to \pi^+\pi^-)/\Gamma(D^o \to K^-\pi^+) = 3.3 \pm 1.4\% \quad .$$

It was expected[2] that these ratios would be equal (apart from a 15% reduction of $K^+K^-/\pi^+\pi^-$ due to phase space). Although the errors are not small, it is very interesting to consider the implications if a significant enhancement of K^+K^- is present.

The larger rate occurs for the final state with strange quarks, which have larger mass. It is natural to ask if a Higgs contribution, which is expected to couple more strongly to heavier particles, could explain this result. We will see that it is possible, although the dependence on mass turns out to be subtle.

In the standard Weinberg-Salam $SU(2)\otimes U(1)$ theory,[3] there is a single complex Higgs doublet. Many authors have considered theories with more than one Higgs doublet. If the masses of fermions and of gauge bosons, with their quite different scales, originate in physically different ways, it will require two (or more) Higgs doublets. In an otherwise standard theory, two complex doublets lead to five physical Higgs particles: $H^{\pm}$, and three neutral ones. In addition to $H^{\pm}$, another qualitatively new feature occurs. There are two vacuum expectation values, V_1 and V_2, and it is possible that $V_2/V_1 \ll 1$. The Higgs-fermion couplings can be enhanced by $(V_2/V_1)^{-1}$ compared to those of the standard theory.[4] Higgs-fermion couplings many times those of the standard theory are allowed[4] by present experiments.

<u>CHARGED HIGGS MODEL</u> Consider the following charged Higgs-fermion interaction

$$\mathscr{L} = \frac{g}{2\sqrt{2}\,\beta\, M_W} \sum_{q,\ell} A_{\bar{q}q}\, \bar{q}_{2/3}\left[m_{q1/3}\left(1-\gamma_5\right) + m_t\left(1+\gamma_5\right)\right] q_{1/3} H^+ + \text{H.C.} \qquad (1)$$

For quarks $A_{\bar{q}q}$ are the appropriate elements of the Koyayashi-Maskawa[5] matrix. For leptons $m_{q1/3} = m_e, m_\mu, m_\tau$; $m_{q2/3} = m_t = 0$; and $A_{\bar{q}q} = 1$. Here g is the usual gauge coupling, and $\beta = V_2/V_1$ is the ratio of vacuum expectation values; this analysis is most interesting for $\beta \ll 1$, which is consistent with present experiments.[4] We have not so far found a symmetry which makes this interaction technically natural. The choice of m_t is made to be definite in a six-quark model; only $(m_t/\beta m_H)$ finally enters for quarks. The asymmetry in choice between the q = 2/3 and q = -1/3 quarks is not unique, but has been done this way in order to maintain the analogy between q = -1/3 quarks and the charged leptons. A detailed discussion of the derivation of (1) and its implications will be given in a separate paper.

One nice feature of having a common large mass m_t for the q = 2/3 quark is that a GIM mechanism[6] operates for the charged Higgs couplings. Another is the symmetry between q = 0 leptons (neutrinos) and q = 2/3 quarks: as seen by a Higgs, all neutrinos have a common interaction (zero, assuming $m_\nu = 0$) and all q = 2/3 quarks have a common interaction ($\sim m_t$).

Eq. (1) is not the interaction of Ref. 4; that one fails to explain the data, because it renormalizes f_π, f_K in the wrong direction,[7] and gives too large a $K_L - K_S$ mass difference.[8] Although it is not obvious, (1) is a solution to writing the most general $\mathscr{L}$ and requiring fermion masses to be correct and no flavor changing neutral currents at the tree level.

NON-LEPTONIC D DECAYS We want to calculate the decay $D^o \to P^+P'^-$ where P,P' are pseudoscalar mesons. Assume that the dominant[8] contribution is the graph of Fig. 1, for charmed and heavier quark decays. This is approximate but should be all right for estimates. Then, the matrix element from W and Higgs contributions is

$$M=\frac{G_F}{\sqrt{2}}\left[\bar{u}(4)\gamma_\mu(1+\gamma_5)u(1)\bar{u}(2)\gamma_\mu(1+\gamma_5)v(3)-\frac{m_t^2}{\beta^2 M_H^2}\bar{u}(4)(1-\gamma_5)u(1)\bar{u}(2)(1+\gamma_5)v(3)\right]. \tag{2}$$

The interference of pseudoscalar and axialvector is suppressed by a factor $m_1(m_2 + m_3)$ so care is needed in approximating matrix elements. We put the final $q_{2/3}\bar{q}_{1/3}$ in a pseudoscalar by setting $\gamma_\mu(1+\gamma_5) \to \gamma_4\gamma_5$ and $1 + \gamma_5 \to \gamma_5$ in (2). Now square and sum over spins, giving a rate

$$\Gamma \sim 1 - 4\varepsilon_H(m_2 + m_3)/m_1 + 4\varepsilon_H^2 m_P^2/m_1^2 \tag{3}$$

as our basic result, where 1 is the W contribution. $\varepsilon_H = m_t^2/\beta^2 m_H^2$ measures the Higgs coupling, and only this parameter enters to fit the two rates.

The interference is destructive but suppressed by the helicity structure. Whether a given decay is enhanced depends on the masses. While our interaction is no longer simply proportional to each quark mass, the masses still enter, mainly through m_P; the Higgs still couples more strongly to the heavier system.

For $D \to K^-\pi^+$ or $\pi^-\pi^+$, $m_2 + m_3 = m_u + m_d$, $m_1 = m_c$, $m_P = m_\pi$ so we still have ($s_1 = \sin\theta_1$, etc.)

$$\Gamma(D \to \pi^-\pi^+)/\Gamma(D \to K^-\pi^+) = [s_1 c_2/(c_1 c_2 c_3 - s_2 s_3 c_\delta)]^2 . \tag{4}$$

Using current algebra masses[10] ($m_u + m_d = 0.012$, $m_s = 0.15$, $m_c = 1.12$) in Eq. (3), $\Gamma_{\pi\pi}$ is enhanced by a factor $(1 - 0.001\ \varepsilon_H + 0.073\ \varepsilon_H^2)$. For $D \to K^+K^-$, $m_2 + m_3 = m_s + m_u$, $m_P = m_K$, so Γ_{KK} is enhanced by $(1-0.14\ \varepsilon_H + 0.83\ \varepsilon_H^2)$. Choosing $\varepsilon_H = 2$ gives $\Gamma_{K\pi}$ and $\Gamma_{\pi\pi}$ enhanced by a factor of 1.3, Γ_{KK} enhanced by a factor 4, and

$$\Gamma(D \to K^+K^-)/\Gamma(D \to \pi^+\pi^-) = 3.1 . \tag{5}$$

If we put $m_t = 15$ GeV, $\beta M_H = 10.6$ GeV; $\beta \lesssim 1$.

Thus for a charged Higgs mass in the range 10-100 GeV our results are reasonable, and can reproduce the current data. Clearly there is room for the numbers to vary somewhat, and better numbers can be determined if the data is confirmed with good statistics in the future. For quark masses different from the current algebra ones similar results are still obtained for somewhat different ε_H.

CHARGED HIGGS EFFECTS[11] IN OTHER EXISTING DATA It is necessary to check other experiments, to see that such a large Higgs coupling is not already excluded.

The Higgs coupling is $m_t g/\beta M_W$, compared to the W coupling of g. The effective W contribution is g^2/M_W^2, while the effective Higgs contribution is $(m_t^2/\beta^2 M_W^2)\ (g^2/M_W^2) = \varepsilon_H g^2/M_W^2 \simeq 2g^2/M_W^2$ from vertices and propagators. Typically spin effects favor W over H by a factor of 2-4, so the net H contribution to processes involving $q = 2/3$ fermions or heavy $q = -1/3$ fermions is of order 1/2-1 of the W contribution. This does not seem to be excluded by any experiments—some of the relevant analysis (e.g., for low mass leptons) is given in Ref. (4) and some below.

(a) The K_L-K_S mass difference[12] receives a contribution from H of order the W contribution. Since a GIM mechanism operates, the leading term is again of order M_c^2/M_W^2, multiplied by $\varepsilon_H^2 \approx 4$ but suppressed a similar amount by spin effects. Attempts to estimate quark mixing angles[13] would have to take account of the Higgs contribution if this interpretation of $D \to K^+K^-$ is eventually accepted.

(b) The π,K decay constants are renormalized[4,7] by the Higgs contribution. Here one can safely approximate the matrix elements, so for a decay $P \to \bar{\ell}\nu$, with quarks q_2 and $\bar{q}_1$ of charges 2/3 and 1/3 respectively in P,

$$f_P \to f_P[1 + (m_P^2/\beta^2 M_H^2)(m_t - m_1)/(m_2 + m_1)] \ . \tag{6}$$

The interference is constructive due to the sign structure of $\mathcal{L}$, since quarks are at one vertex and leptons are at the other. For f_π, f_K the enhancement is small, and uncertain due to lack of knowledge of light quark masses. For heavier mesons, from Eq. (6) we predict enhancements of 1.4, 1.5, 1.7 and 3 for f_D, f_F, f_B and f_T respectively.

(c) For inclusive D decays we simply calculate with Eq. (2), so $\Gamma \sim 4 + \varepsilon_H^2$. The interference term is negative for decay to hadrons and positive for semileptonic decays, but suppressed in both cases by the mass factors needed for scalar-vector interference. For $\varepsilon_H^2 = 4$ we have approximately equal W and Higgs contributions. This has important consequences:

(i) The D lifetime decreases by about a factor of 2.

(ii) Since Higgs mediated decay gives essentially no direct μ's or e's and only a few via τ's, the expected semileptonic decay is suppressed by almost a factor of 2 (consistent with experiment). Whether this is too much suppression when the usual (uncertain) amount of non-leptonic enhancement is included is difficult to determine without better models; in particular, the negative interference term can be important for $(m_u + m_d)/m_c \gtrsim 0.2$. Semileptonic decays are otherwise unaffected.

(d) There is an effect on conventional decays such as $K \to \pi^+\pi^-$. $\Lambda \to p\pi^-$, etc., e.g., $K \to \pi^+\pi^-$ is enhanced in rate by about a factor of 2.5 compared to the naive W contribution. Possibly a careful analysis of these decays could show an improvement in the situation with the $\Delta I = 1/2$ rule.

PREDICTIONS There are a number of distinctive predictions which will serve to test the present model.

(a) $\tau \to \pi\nu_\tau$ is enhanced by a factor $[1+\varepsilon_H m_\pi^2/m_t(m_u+m_d)]^2$. Using the numbers from f_π above, this is a factor of about 1.12.

(b) $\tau \to K\nu_\tau$ is enhanced by $[1 + \varepsilon_H m_K^2/m_t(m_s + m_u)]^2 \approx 1.43$.

(c) The Cabibbo suppressed decays $C_o^+ \to \Lambda K^+$, $F \to \phi K^+$ and similar ones are enhanced by precisely the same amount as $D \to K^+K^-$.

(d) $D^o \to K^o\overline{K}^o$ is not affected by these contributions and remains suppressed.

(e) The wrong-strangeness D decays are enhanced, giving

$$\frac{\Gamma(D^o \to K^+\pi^-)}{\Gamma(D^o \to K^-\pi^+)} = \sin^4\theta_1 \frac{\Gamma(D^o \to K^+K^-)}{\Gamma(D^o \to \pi^+\pi^-)} \simeq 3\sin^4\theta_1 \quad . \tag{7}$$

(Instead of $D^o \to K^-\pi^+$ one can rotate in isospin to $D^+ \to K^+\pi^o$.) However, the inclusive rates for $D^o \to K^-X$ and $D^o \to K^+X$ are affected identically so their ratio is unchanged.

(f) Since f_F is enhanced by 1.5, the rate for $F \to \nu\tau$ is enhanced by 2.25. This may be testable in beam dump experiments.[14]

(g) There are a number of predictions for B decays:[15]

(i) Since $W \to 3\bar{u}d$, $3\bar{c}s$, $\tau\bar{\nu}$, $\mu\bar{\nu}$, $e\bar{\nu}$ while $H \to 3\bar{u}d$, $3\bar{c}s$ and essentially $H \not\to \ell\bar{\nu}$, the expected semileptonic branching ratio for B decay is about $[1 + 1 + (0.4 + 0.6 + 0.6)/3]/(8 + 7/3) = 0.25$ using a factor of 1/3 for phase space suppression for $\bar{c}s$, $\tau\bar{\nu}$, $\varepsilon_H = 2$, and an inclusive rate proportional to $4 + \varepsilon_H^2$ as discussed above. For only W contributing it is about $2.3/6.3 = 0.37$. This difference should be detectable.

(ii) Further, the Higgs contribution gives no hard μ's or e's in B decay, so there is about a factor of two reduction in the number of these. This should be easy to find by cuts that will eliminate μ's or e's from τ or c decay.

(iii) Consider some exclusive B decays. Proceeding as above, from Eq. (4), we see that $B^o \to F^-D^+$ and $B^o \to F^-\pi^+$ are enhanced by the same amount, so the prediction for the ratio is unchanged.

An interesting mode[16] is $B \to \psi K^-$. This should be enhanced compared to other estimates by the Higgs by about a factor of 3. That could give it a several percent branching ratio, which might be very useful, as it is a good mode to measure the B mass, and probably an easy one to detect, via $\psi \to \ell^+\ell^-$.

(iv) The lifetime is decreased about a factor of 2.

(h) Similar results hold for t-quark decays. The SLBR is reduced and there are fewer decays to hard μ's, e's. The decay $T \to T\pi^+$ may be useful to find the T and to determine its mass, with $T \to \ell^+\ell^-$, unless the phase space is too large for it to be sizeable.

SUMMARY We have written a charged Higgs-fermion interaction and explored the implications of that interaction and the assumption that the Higgs-fermion coupling is of a strength comparable to that of the usual gauge coupling g. Not only is this not inconsistent with present data, it provides an interpretation of the recently reported result for Cabibbo suppressed D decays.[1]

If the data turned out to be a fluctuation, this analysis would still have demonstrated that large charged scalar effects could be present as far as is known. If the data were confirmed, and this explanation were to prove consistent with the predictions for other decays and with improved understanding of the dynamics of nonleptonic decays, this could be the first evidence for the existence of Higgs bosons (or at least effective spin zero weak currents). We are not aware of any alternative explanation of the data[17] at present.

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FOOTNOTES AND REFERENCES

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15. For the usual predictions see M. K. Gaillard, Ref. 9, and J. Ellis, M. K. Gaillard, D. V. Nanopoulos and S. Rudaz, Nucl. Phys. B131, 285 (1977).

16. After this was written I learned that H. Fritzsch has given a more thorough treatment of this mode in a recent CERN preprint.

17. L. Abbott, P. Sikivie, and M. Wise have observed that the dominant contribution to $D \to K^+K^-$ and $D \to \pi^+\pi^-$ are of opposite sign. Therefore another contribution (e.g., Penguin diagrams) which interferes but does not change sign could account for the data. However, it appears that all contributions one can write are too small to accomplish this. We assume large right-handed current effects are not present. It is easy to check that varying the KM mixing angles will not affect the $K^+K^-/K^-\pi^+$ ratio.

FIGURE CAPTION Fig. 1. This illustrates the dominant nonleptonic decay mechanism considered in the text. The numbers 1-4 label the particles and their momenta. The subscripts give the quark charges.

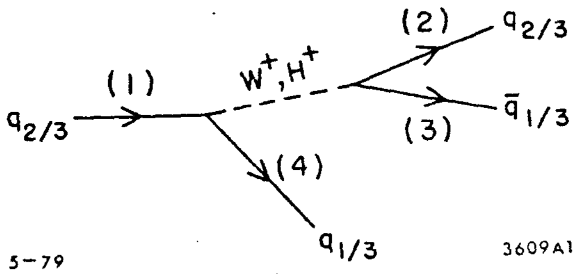

Fig. 1