B-meson decays and the Weinberg Higgs-boson model of CP violation

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We study the predictions of the Weinberg Higgs theory for decays of B mesons, normalizing to the strength of the interaction in kaon decays. The process $b \to s+\text{gluon}$ is seen to have a lower bound on its branching ratio of about 1% to 15% depending on the masses of the Higgs bosons. This may be directly observable. Partial-rate asymmetries, indicative of CP violation, are large only in relatively rare modes and are no easier to detect than those of the Kobayushi-Maskawa model. However, the pattern of decays in the two models differs.

I. INTRODUCTION

The present status[1] of experimental CP-violation studies allows many possible origins for this phenomena. If the recent preliminary report[2] of a nonzero ϵ' measurement is validated, the CP-nonconserving interaction must also have a portion which occurs in the $\Delta S=1$ sector, which would rule out superweak models. However there still remain several theoretical possibilities. The most economical is undoubtedly the Kobayashi-Maskawa (KM) model[3] which has become the standard model for the subject. However, the origins of CP violation are tied up with the phenomena of symmetry breaking and the Higgs-boson interactions characteristic of the TeV energy scale. We know very little about these subjects, and much of the effort of the next decade will be devoted to trying to uncover this TeV-scale physics. It is not yet possible to have any confidence that the resolution of these studies will decide that the minimal KM model is the main source of CP violation. Alternate models remain serious possibilities.

In one such theory, introduced by Weinberg[4] and called simply the Higgs model below, CP violation is due to the interaction of charged Higgs bosons. This model could be generated by extra Higgs bosons common as fundamental scalars in supersymmetric models or as composite scalars in technicolor models. We will here explore the consequences of such a model in B-meson decay.

The characteristic feature of Higgs-boson couplings is that they grow with increasing quark mass. For the light quarks in the kaon system, Sanda and Deshpande[5] pointed out that the dominant interactions will be the "Higgs penguin" type, $s \to d+\text{gluon}$, illustrated in Fig. 1. This occurs because the inclusion of the intermediate charmed particle in the loop generates a quark-mass dependence roughly of the form $m_s m_c^2$ instead of being proportional to light-quark masses. This type of interaction remains dominant for the b-quark system, Fig. 2, because its coefficient scales up roughly to $m_b m_t^2$, an increase of strength of more than 10^4. We will normalize the strength of the CP-violating interaction using kaon decays and show that the same combination of factors is relevant for $b \to s+\text{gluon}$. The b-quark decay depends somewhat on the relative sizes of the Higgs-boson masses and the top-quark mass, and we will explore this dependence.

The result is that the decay $b \to s+\text{gluon}$ should have a sizable rate in B-meson decay, with a branching ratio of 1% to 15%. This might allow for direct observation of this process by the study of "two-jet" configurations with a leading strange particle. There will also be possible observations of CP violation. Despite the CP-nonconserving structure of the Higgs-boson interaction which generates $b \to s+\text{gluon}$, the decay does not readily lead to easy-to-measure observables because an interference with other diagrams is needed to generate a CP-odd signal. This need for interference forces the maximum signals to occur in relatively-low-branching-ratio processes. The end results are signal strengths comparable to those of the KM model, although we show how the two theories could be distinguished. Overall, B-meson decays could be a crucial proving ground for the Higgs model.

The plan of the paper is as follows. In Sec. II we spell out the structure of the Higgs model. Section III is devoted to making the connection between kaon decays and B-meson decays. In Sec. IV we explore the mass dependence and give the predictions for the $b \to s+\text{gluon}$ rate. The study of CP violation in B decays is given in Sec. V, while conclusions are discussed in Sec. VI.

II. THE HIGGS MODEL OF CP VIOLATION

Suppose there exist three doublets of complex Higgs fields. Of interest to us are the associated three non-

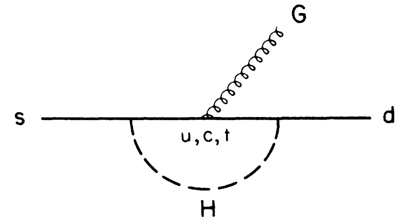

FIG. 1. The Higgs-boson-mediated transition $s \to d+G$, which is the dominant source of CP violation in the kaon system within the Weinberg Higgs model.

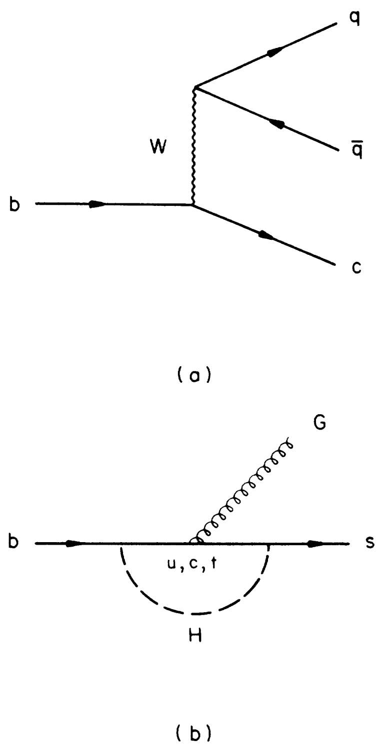

FIG. 2. (a) Standard B-meson decay due to W exchange. (b) The Higgs-boson-mediated transition $b \to s + G$.

Hermitian charged Higgs fields ϕ_k^+ $(k=1,2,3)$. Mixing occurs among these just as it does between massive fermions of a given charge. The basis of fields which diagonalizes the charged-Higgs-boson mass matrix is denoted by ϕ_W^+, H_i^+ $(i=1,2)$ where ϕ_W^+ gets absorbed by the charged W gauge bosons during symmetry breaking. The mixing matrix in the charged Higgs sector has the same structure as the KM matrix, viz., a CP-violating angle δ^H and CP-conserving angles θ_k^H $(k=1,2,3)$.

In a realization where neutral-Higgs-boson exchange must respect flavor conservation, a natural scheme is to couple ϕ_1 to right-handed down-type quarks and ϕ_2 to right-handed up-type quarks. It is straightforward to show that the coupling between quarks and the physical charged Higgs fields $H_{1,2}^+$ is then[6]

$$\begin{aligned} L_{QQH} = {} & 2^{3/4} G_F^{1/2} \bar{U}_L V M_D D_R (\alpha_1 H_1^+ + \alpha_2 H_2^+) \\ & + 2^{3/4} G_F^{1/2} \bar{U}_R M_U V D_L (\beta_1 H_1^+ + \beta_2 H_2^+) \\ & + \text{H.c.} \,, \end{aligned} \tag{1}$$

where

$$\begin{aligned} & \alpha_1 = s_1^H c_3^H / c_1^H, \quad \alpha_2 = s_1^H s_3^H / c_1^H \,, \\ & \beta_1 = [c_1^H c_2^H c_3^H + s_2^H s_3^H \exp(i\delta^H)] / s_1^H c_2^H \,, \\ & \beta_2 = [c_1^H c_2^H s_3^H - s_2^H c_3^H \exp(i\delta^H)] / s_1^H c_2^H \,. \end{aligned} \tag{2}$$

In Eq. (1), U represents quarks u,c,t, D represents quarks d,s,b, V is the 3×3 KM quark mixing matrix, and $M_{U,D}$ are the respective diagonal quark mass matrices.

The Lagrangian of Eq. (1) when used together with the QCD Lagrangian can generate a gluon emission vertex which changes quark flavor.[5,7] This is depicted in Fig. 1, and can be cast in the form of an effective Lagrangian for the transition $Q \to Q' + G$,

$$L_{QQ'G} = i\tilde{f} \bar{Q}' \sigma^{\mu\nu} (1-\gamma_5) \lambda^A Q F_{\mu\nu}^A \,, \tag{3}$$

where $F_{\mu\nu}^A$ is the gluon field tensor, λ^A are the color matrices of SU(3), and $\tilde{f}$ is the coupling strength:[8]

$$\tilde{f} = \frac{G_F}{\sqrt{2}} \frac{(4\pi\alpha_s)^{1/2}}{32\pi^2} m_Q \sum_{i=1}^{2} \sum_{k=1}^{3} \gamma_i \rho_{Q_k}(Q) F_{Q_{k},i} \,. \tag{4}$$

In Eq. (4) m_Q is the mass of quark Q (we have assumed $m_{a'} \ll m_a$), the γ_i contain Higgs-boson mixing angles

$$\gamma_i \equiv \alpha_i \beta_i, \quad i=1,2 \,, \tag{5}$$

where the index i labels the charged Higgs particles, $\rho_{Q_k}(Q)$ contains quark mixing angles

$$\rho_{Q_k}(Q) \equiv V_{Q_k Q} V_{Q_k Q'}^* \,, \tag{6}$$

where index k labels the three flavors of intermediate quarks in Fig. 1 and

$$F_{Q_{k,i}} = \frac{m_{Q_k}^2}{m_{H_i}^2 - m_{Q_k}^2} \left[\frac{m_{H_i}^4}{(m_{H_i}^2 - m_{Q_k}^2)^2} \ln \frac{m_{H_i}^2}{m_{Q_k}^2} - \frac{m_{H_i}^2}{m_{H_i}^2 - m_{Q_k}^2} - \frac{1}{2} \right] . \tag{7}$$

The function $F_{Q_{k,i}}$ has the following limiting forms:

$$F_{Q_{k,i}} \frac{m_{Q_k}^2}{m_{H_i}^2} \left[\ln \frac{m_{H_i}^2}{m_{Q_k}^2} - \frac{3}{2} \right], \quad m_{Q_k} \ll m_{H_i} \,, \tag{8a}$$

$$F_{Q_{k,i}} \sim \frac{1}{3} - \frac{1}{2} \left[\frac{1 - m_{Q_k}^2}{m_{H_i}^2} \right], \quad m_{Q_k} \simeq m_{H_i} \,, \tag{8b}$$

$$F_{Q_{k,i}} \frac{1}{2} - \frac{1}{2} \frac{m_{H_i}^2}{m_{Q_i}^2}, \quad m_{Q_k} \gg m_{H_i} \,. \tag{8c}$$

For the purposes of this paper we are assuming that CP violation arises from the Higgs sector, i.e., we ignore the KM angle δ. If so, the CP-conserving and CP-violating content of $\tilde{f}$ arise from the real and imaginary parts of the γ_i, respectively. From Eqs. (2) and (5) we see that $\mathrm{Im}\gamma_2 = -\mathrm{Im}\gamma_1$. Given the limiting constant behavior in

Eqs. (8b) and (8c), it is therefore important to bear in mind the possibility of cancellations.

III. KAON *CP* VIOLATION AND *B*-MESON DECAY

In Ref. 7, the dominant Higgs-boson-induced *CP*-violating source in K^0-$\bar{K}^0$ mixing is shown to reside in the η' pole, viz., $\bar{K}^0 \to \eta' \to K^0$. The associated K-to-η' matrix elements are induced by the effective Lagrangian of Eq. (3). This is summarized in Fig. 3. In practice, only the c-quark and t-quark contributions can be appreciable. From the analysis of Ref. 7, we infer

$$\sum_i \mathrm{Im}\gamma_i[\rho_c(s)F_{c,i}+\rho_t(s)F_{t,i}]=5.2\times 10^{-3} . \tag{9}$$

The dependence in Eq. (9) is upon $\mathrm{Im}\gamma_i$ because the effect being fit is *CP* violating. Equation (9) is the input we shall use for our analysis of B decays. Let us postpone the issue of estimating the relative size of the c-quark and t-quark contributions to Eq. (9) and instead turn to computing the B-decay amplitude.

In the following we restrict our attention to nonleptonic weak transitions of the b quark only. The standard W-exchange amplitude for the transition $b \to c\, d\bar{u} + cs\bar{c}$ yields a decay rate

$$\Gamma_W(b) \simeq \frac{G_F^2 m_b^5}{64\pi^3} \mid V_{bc}\mid^2(\mid V_{cs}\mid^2+\mid V_{ud}\mid^2) . \tag{10}$$

In the Higgs model there is necessarily a distinct mechanism for a nonleptonic b-quark transition, $b \to sG$, with a corresponding decay rate

$$\Gamma_H(b)=\frac{16 m_b^3}{3\pi}\bar{f}^{\,2} . \tag{11}$$

For both Eqs. (10) and (11) we treat the b quark as a free particle and employ a phase space appropriate to massless final-state particles. This procedure is adequate to our needs as we shall be interested in ratios of Eqs. (10) and (11). Finally, it is easy to see in the Higgs-boson-induced transition $b \to sG$ that the top-quark intermediate state is by far the most important. Equation (11) then becomes

$$\Gamma_H(b)=\frac{G_F^2 m_b^5 \alpha_s}{96\pi^4} \mid \rho_t(b)\sum_i \gamma_i F_{t,i}\mid^2 \tag{12}$$

so that in ratio form we have

$$\frac{\Gamma_H(b)}{\Gamma_W(b)}=\frac{\alpha_s}{3\pi}\frac{\mid \rho_t(b)\sum_i \gamma_i F_{t,i}\mid^2}{\mid V_{cb}\mid^2} , \tag{13}$$

where the running QCD fine-structure constant is evaluated at the energy scale of the b-quark mass, $\alpha_s \simeq 0.2$.

The Higgs-boson angles which are present in γ_i are not known. However the value of $\mathrm{Im}\gamma_i$ is constrained by kaon *CP* violation, Eq. (9). This allows us to obtain a lower bound on $\Gamma_H(b)$ for a given set of masses. Let us define

$$\eta=\frac{\sum_i \gamma_i \rho_t(b) F_{t,i}}{\sum_i \mathrm{Im}\gamma_i[\rho_c(s)F_{c,i}+\rho_t(s)F_{t,i}]} . \tag{14}$$

The advantage of this parameter is that

$$\mathrm{Im}\eta=\frac{\sum_i (-1)^{i+1}\rho_t(b)F_{t,i}}{\sum_i (-1)^{i+1}[\rho_c(s)F_{c,i}+\rho_t(s)F_{t,i}]} \tag{15}$$

is independent of the Higgs-boson angles, since $\mathrm{Im}\gamma_1=-\mathrm{Im}\gamma_2$, and

$$\mid \eta\mid^2 \geq \mid \mathrm{Im}\eta\mid^2 . \tag{16}$$

In terms of this parameter we find

$$\frac{\Gamma_H(b)}{\Gamma_W(b)}=\frac{\alpha_s}{3\pi}\frac{(5.2\times 10^{-3})^2}{\mid V_{cb}\mid^2}\mid \eta \mid^2$$

$$=2.3\times 10^{-4}\mid \eta\mid^2 . \tag{17}$$

This might seem likely to produce an insignificant branching ratio. However, η can be large.

The nonleptonic decay of the b quark is known to go predominantly into the creation of c quarks. Therefore the ratio of Eqs. (13) and (17) must be bounded. Interestingly however, there is now a question of what value to take for the empirical bound. Over the past several years evidence has accumulated of a deficiency in the number of c quarks observed per decay b quark compared to that expected from theory.[9] However this putative deficiency depends on such factors as the branching ratio for $D \to \pi\bar{K}$ and the ratio $\Gamma(b \to u)/\Gamma(b \to c)$. Indeed recent reanalysis of the Mark III double-tagged $D \to \pi\bar{K}$ events has essentially removed the deficiency from ARGUS data.[10] However for CLEO data, the deficiency remains and is at the level $N_{\mathrm{ch}}(\text{observed}) \simeq 0.6 N_{\mathrm{ch}}(\text{expected})$. In view of this, let us employ

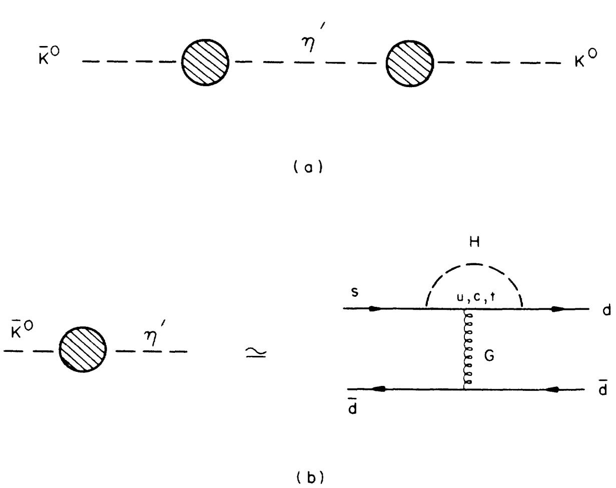

FIG. 3. The $K^0 \to \eta'$ transition generates K^0-$\bar{K}^0$ mixing in second order. In the Higgs model this transition violates *CP* and generates ϵ.

$$\left.\frac{\Gamma_H(b)}{\Gamma_W(b)}\right|_{\rm expt} \lesssim \gamma \ , \tag{18}$$

where the value of γ is likely to become better determined by future analysis. At present, for definiteness we take $\gamma \simeq 0.2$. As γ decreases, our analysis is correspondingly strengthened. It is of course amusing to note that, if instead it becomes clear that the c-quark deficiency is a real one, the Higgs model provides a natural explanation for the effect.

IV. PREDICTIONS FOR $b \to sG$

We now turn to the exploration of the available parameter space and to the predictions of the decay rate. In order to illustrate that the decay rate can be sizable, it is useful to first calculate the rate for a "typical" value of the parameters. For example, consider $m_t \approx 50$ GeV, $m_{H_1} \approx m_W$, $m_{H_2} \approx 2m_W$. In this case the parameters responsible for the $s \to dG$ transitions are

$$\begin{aligned}\sum_{i=1}^{2} (-1)^{i+1}\rho_c(s)F_{c,i} &= V_{cd}^* V_{cs} \sum_{i=1}^{2} (-1)^{i+1}\frac{m_c^2}{m_{H_i}^2}\left[\ln\frac{m_{H_i}^2}{m_c^2} - \frac{3}{2}\right] \\ &= 3.5\times 10^{-4} \ ,\end{aligned} \tag{19}$$

$$\begin{aligned}\sum_{i=1}^{2}(-1)^{i+1}\rho_t(s)F_{t,i} &= V_{td}^* V_{ts}\sum_{i=1}^{2}(-1)^{i+1}F_{t,i} \\ &\le 1.2\times 10^{-4} \ ,\end{aligned}$$

where we have used $|V_{ts}| \approx |V_{cb}| = 0.05$, which follows from the unitarity of the KM matrix, and $|s_3| < 0.09$, which is required by the b lifetime and the $b \to u$ constraints.[11] On the other hand, for the transition $b \to sG$ we have

$$\begin{aligned}\sum_{i=1}^{2} (-1)^{i+1}\rho_t(b)F_{t,i} &= V_{ts}^* V_{tb}\sum_i(-1)^{i+1}F_{t,i} \\ &= 6.0\times 10^{-3}\end{aligned} \tag{20}$$

so that

$$|\operatorname{Im}\eta| > 170 \tag{21}$$

and

$$\frac{\Gamma_H(b\to sG)}{\Gamma_W(b)} \ge 0.04 \ . \tag{22}$$

Figure 4 displays the branching-ratio lower bound for many other values of the parameters. Recall that the lower bound is only a function of the masses and is independent of the Higgs-boson angle factors. Branching ratios of order 15% can be obtained for $m_1 = 180$ GeV, $m_2 = 200$ GeV, but more typical values lie in the $1 \to 10\%$ region. Although the functional dependence on the masses is quite complicated, there is an empirical pattern which indicates that the branching ratio rises with the mass of the lightest Higgs bosons. In fact the only region where very small branching ratios are expected is the region where both Higgs bosons are light and the top quark is heavy.

We can see that as the allowed amount of $b \to sG$ is decreased by lowering the experimental bound, greater regions of parameter space becomes ruled out. For example, a bound of $\gamma < 5\%$ [see Eq. (18)] would indicate that both charged Higgs bosons, could not be very heavy and would suggest that at least one charged Higgs boson is light. *A substantial decrease below this level would be very powerful, especially if combined with unsuccessful searches for charged scalars below a mass of M_z.*

V. *CP* VIOLATION

One might naively think that the situation described above could provide the ideal environment for the generation of large *CP*-violating signals. After all, one has a large *CP*-violating interaction which could contribute about 10% of the total rate. The difficulty, however, is that *CP*-violating signals require the interference of a *CP*-odd interaction with a *CP*-even one. The combination of the Higgs model with the standard model for the *CP*-conserving interactions does not readily yield such a large interference. The $b \to s +$gluon signal has most of its intensity in the two-jet final state with one of the jets being the s quark and the other being a $q^2 \approx 0$ gluon. The

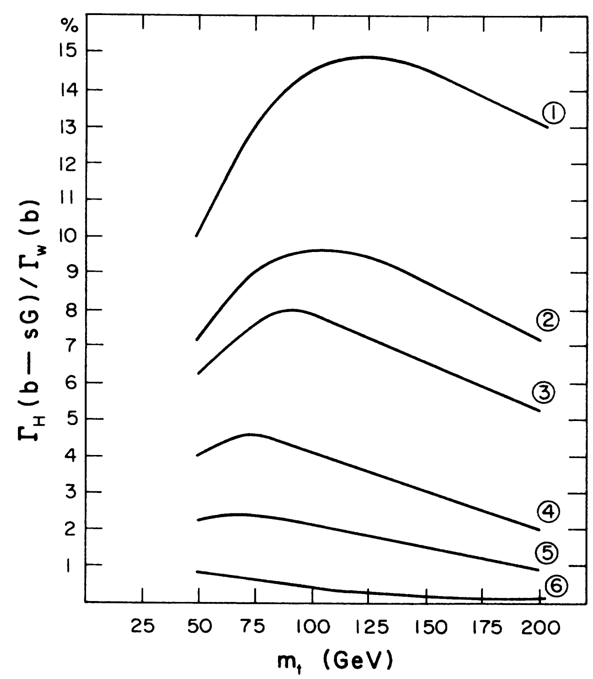

FIG. 4. The lower bound to the relative branching ratio $B_H(b\to sG)/B_W(b\to c\bar{c}s, c\bar{u}d)$, as a function of m_t. The various masses of Higgs bosons are (1) $m_1 = 180$ GeV, $m_2 = 200$ GeV; (2) $m_1 = 120$ GeV, $m_2 = 200$ GeV; (3) $m_1 = 120$ GeV, $m_2 = 160$ GeV; (4) $m_1 = 80$ GeV, $m_2 = 160$ GeV; (5) $m_1 = 50$ GeV, $m_2 = 200$ GeV; (6) $m_1 = 50$ GeV, $m_2 = 75$ GeV.

standard model $b \to s+$gluon is significantly smaller, and would not be likely to interfere because it has the same Lorentz structure and is also dominated by the top-quark intermediate state. The dominant standard-model decays either do not share the same quantum numbers in the final state, or are likely to have much of their strength in a different region of phase space. As an example of the latter statement, the transition for $b \to c\bar{c}s$ has the same final-state quantum numbers as $b \to s+$gluon, but the interference from inclusive three-jet $b \to c\bar{c}s$ decays with the two-jet $b \to s+$gluon process is not likely to be large because the configurations of the final particle is expected to be much different.

These considerations force one to study exclusive decays to specific few-body final states. Since there are expected to be a small fraction of the $b \to s+$gluon rate (perhaps $10^{-2} \to 10^{-3}$ of Γ_H), one is faced with small branching ratios (of the order of 10^{-3} to 10^{-4}) or small asymmetries (about 1% is typical). We will estimate these below. It will turn out that the nonzero signals are similar to those expected in the KM model. However the overall pattern of the signals does distinguish the two models, with the Higgs model predicting no signal in many cases where the KM model generates one. For example, the Higgs model has no signal in $B^0 \to D^+\pi^-$.

All estimates of hadronic matrix elements in B meson decay are extremely crude. Our estimates below will be no better. The reader should be warned that these "predictions" have considerable uncertainties (as do the corresponding ones in the KM model). However they will provide experimenters with a guide on where best to look for these effects. Our results are summarized in Table I.

A. Asymmetries in $B^0 \to K_S X_{c\bar{c}}$

In the B^0-$\bar{B}^0$ system mixing can occur and recent experimental indications are that the mixing is quite large.[12] States that start out as B^0 or $\bar{B}^0$ will evolve in time into mixed states of B^0, $\bar{B}^0$. Consider a final state f for which $B^0 \to f$ and $\bar{B}^0 \to f$ can occur. For the mixed states interference between $B^0 \to f$ and $\bar{B}^0 \to f$ can occur. Bigi and Sanda[13] show that

$$A_f = \frac{\Gamma(B^0(t) \to f) - \Gamma(\bar{B}^0(t) \to \bar{f})}{\Gamma(B^0(t) \to f) + \Gamma(\bar{B}^0(t) \to \bar{f})} = \frac{\sqrt{2r}(1-r)}{1+r} \mathrm{Im} \left[\frac{p}{q} \frac{A(\bar{B}^0 \to f)}{A(B^0 \to f)} \right], \tag{23}$$

where r is the mixing parameter defined by

$$r = \frac{\Gamma(B^0 \to e^+X)}{\Gamma(B^0 \to e^-X)} = \left| \frac{q}{p} \right|^2 \frac{x}{2+x^2} \tag{24}$$

and $p/q = 1$ if $B^0\bar{B}^0$ mixing conserves CP (as it does in the present case), and $x = \Delta m_B / \Gamma_B$. Experimentally the recent Argus result[12] implies $x = 0.73 \pm 0.18$, which is a very favorable number for those CP tests utilizing mixing.

The decay $b \to s+$gluon will dominantly populate states with one unit of strangeness. If one considers $B^0 \to K_S X$, $\bar{B}^0 \to K_S^0 X$, X having no net quantum numbers, one may have the type of mixing driven asymmetry of Eq. (23). The modes in this class with the largest CP-conserving rates are those from $b \to c\bar{c}s$, i.e., X containing a $c\bar{c}$. Examples are $B \to K_S^0 D\bar{D}$, $K_S^0 \psi$ plus modes with extra pions. The standard KM interaction for these is

$$H_W^{\mathrm{KM}} = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* \bar{s} \gamma^\mu (1+\gamma_5) c \, \bar{c} \gamma_\mu (1+\gamma_5) b \tag{25}$$

which is renormalized by QCD in the standard way. In order to produce the $c\bar{c}$ pair, the Higgs-model interaction must couple the gluon to the quark currents. In momentum space this yields

$$H \sim (4\pi\alpha_s)^{1/2} \tilde{f} \bar{s} \sigma^{\mu\nu} (1-\gamma_5) q_\nu \lambda^A b \frac{1}{q^2} \bar{c} \gamma^\mu \frac{\lambda^A}{2} c \,. \tag{26}$$

For our estimate of two- and three-body decay matrix elements we will replace q^2 by its rough average value $q^2 \approx m_B^2/2$, yielding a coordinate-space operator

$$H_H \approx \frac{(4\pi\alpha_s)^{1/2} \tilde{f}}{m_B^2} \bar{s} \sigma^{\mu\nu} (1-\gamma_5) \overleftrightarrow{\partial}_\nu \lambda^A b \bar{c} \gamma^\mu \lambda^A c \,. \tag{27}$$

Let us just look at the relevant factors dimensionally. Taking the derivative in Eq. (27) to be of order m_B, the ratio of coefficients is

$$\frac{\dfrac{(4\pi\alpha_s)^{1/2}\tilde{f}}{m_B}}{\dfrac{G_F}{\sqrt{2}} V_{cb} V_{cs}^*} \approx \frac{\dfrac{\alpha_s}{8\pi} \sum_i \rho_t(b) F_{ti}}{V_{cb} V_{cs}^*} = \frac{\alpha_s}{8\pi} \frac{5.2 \times 10^{-3} \eta}{V_{cb} V_{cs}} \approx 10^{-3} \eta \approx \text{few} \times 10^{-2} \,. \tag{28}$$

This suggests that the asymmetry in these modes could be of order of a few percent, as there are no other factors which appear in these matrix elements which should modify the order of magnitude.

In the KM model[1,14] the branching ratio for these modes are expected to be about a percent, and the CP asymmetries could range from 1% to 20%. The branching ratio here should be the same and our estimate of the asymmetry is at the lower end.

TABLE I. The pattern of CP violation from the Higgs-boson interactions described in this paper.

Decays	Branching ratio	Partial rate asymmetries
$B^0 \to K_S D\bar{D}, K_S \psi$ $K_S D_s^+ D_s^-, K_S \psi\pi$	$\sim 10^{-2}$	$\sim 10^{-2}$
$B^0 \to K_S \pi, K_S \pi\pi$ $K_S \rho, K_S \phi$	$\sim 10^{-4}$	$\sim 10^{-1}$
$B^- \to K\pi, K\pi\pi$ $K\rho, K\phi$	$\sim 10^{-4}$	$\sim 10^{-1}$
$B^0 \to D^+\pi^-, D_s^+ K^-$ $D^0\pi^+\pi^-$ $B^- \to D\pi, D_s K$	$\sim 10^{-2}$	0

B. Asymmetries in $B^0 \to K_s X_{u\bar{u}}$

The Higgs-boson interaction produces $b \to su\bar{u}$ ($sd\bar{d}$) as readily as $b \to sc\bar{c}$ considered above. In the KM model, the dominant contribution to $b \to su\bar{u}$ ($sd\bar{d}, ss\bar{s}$) would come through the penguin interaction and would have strength (before QCD renormalization and including only the dominant logarithm term)

$$H_{\text{pen}} \approx \frac{G}{\sqrt{2}} V_{bc} V_{cs}^* \frac{\alpha_s}{12\pi} \ln \frac{m_t^2}{-m_b^2} \bar{s}\gamma^\mu (1+\gamma_5)\lambda^A b \times (\bar{u}\gamma_\mu \lambda^A u + \bar{d}\gamma_\mu \lambda^A d + \bar{s}\gamma_\mu \lambda^A s) \ . \tag{29}$$

This is to be contrasted with the Higgs-boson interaction (again with $q^2 = m_B^2/2$)

$$H_H \approx \frac{(4\pi\alpha_s)^{1/2}\tilde{f}}{m_B^2} \bar{s}\sigma^{\mu\nu}(1-\gamma_5)\overleftrightarrow{\partial}_\nu \lambda^A b \times (\bar{u}\gamma_\mu \lambda^A u + \bar{d}\gamma_\mu \lambda^A d + \bar{s}\gamma_\mu \lambda^A s) \ . \tag{30}$$

The ratio of coefficients now reads

$$\frac{\dfrac{(4\pi\alpha_s)\tilde{f}}{m_B}}{\dfrac{G}{\sqrt{2}} V_{bc} V_{cs} \dfrac{\alpha_s}{12\pi} \ln(m_t^2/m_b^2)} = \frac{3}{2} \frac{5.2\times 10^{-3}\eta}{V_{bc} V_{cs} \ln(m_t^2/m_b^2)} \approx 0.034\eta \approx \tfrac{1}{4} - \tfrac{3}{4} \ , \tag{31}$$

i.e., the interactions are roughly of the same strength. This is the most favorable case for generating asymmetries, and we could expect results at the tens of percent level.

The modes here could include $B^0 \to K_S\pi$, $K_S\pi\pi$, $K_S\rho$, $K_S\phi$, and the branching ratios have been estimated at the 10^{-4} level. The KM model is also expected to produce asymmetries at the 10% level.

C. *CP* violation in charged-*B* decays

In addition to signals which utilize $B^0\bar{B}^0$ mixing, there can be tests of *CP* symmetry in the partial rate asymmetries of charged B mesons.[15] These require that there be two different mechanisms to reach a given final state, involving both (i) different *CP*-violating weak phases and (ii) different strong-interaction final-state interactions. In particular if the $B^- \to f$ and $B^+ \to \bar{f}$ amplitudes have the form

$$\begin{aligned} A(B^- \to f) &= |A_1| e^{i\phi_1} e^{i\delta_1} + |A_2| e^{i\phi_2} e^{i\delta_2} \ , \\ A(B^+ \to \bar{f}) &= |A_1| e^{-i\phi_1} e^{i\delta_1} + |A_2| e^{-i\phi_2} e^{i\delta_2} \ , \end{aligned} \tag{32}$$

where ϕ_i and δ_i are the *CP*-violating phase and strong final-state phase, respectively, then the partial rate asymmetry is

$$\frac{\Gamma(B^- \to f) - \Gamma(B^+ \to \bar{f})}{\Gamma(B^- \to f) + \Gamma(B^+ \to \bar{f})} = \frac{2|A_1|\,|A_2| \sin(\phi_1 - \phi_2)\sin(\delta_1 - \delta_2)}{|A_1|^2 + |A_2|^2 + 2|A_1|\,|A_2| \cos(\phi_1 - \phi_2)\cos(\delta_1 - \delta_2)} \ . \tag{33}$$

Of the various possibilities, only the modes which are generated by the penguin interaction, considered in Sec. V B above, seem promising. The Higgs penguin and the usual penguin diagrams are the interfering mechanisms. They clearly have different *CP* phases. In addition the usual penguin interaction has a final-state interaction phase which is calculable in perturbation theory. This is because the charmed-quark intermediate state in the penguin loop is below threshold for a real $b \to c\bar{c}s$ intermediate state, and hence the Feynman diagram picks up an absorptive part, given by the $\ln(-m_b^2)$ term in the coefficient of Eq. (29). That is, the final-state phase is

$$\delta_p \approx \frac{\pi}{\ln(m_t^2/m_b^2)} \approx \frac{2}{3} \ . \tag{34}$$

The Higgs-boson interaction, by contrast, has no such phase since only the top intermediate-state contributes, and it is above physical threshold.

Since our rough estimate of the amplitudes in Sec. V B indicated that $|A_1| \sim |A_2|$, the signals here could be maximally large, of order tens of percent. Again, however, the branching ratios involved are small. Modes such as $B^- \to K\pi$, $K\pi\pi$, $K\rho$, $K\phi$ all likely have 10^{-4} branching ratios. In the KM model, early estimates also had large asymmetries in these modes. However, if the constraints of $B\bar{B}$ mixing are included in the analysis,[11] it appears that the asymmetries are decreased, so that the large signal of the Higgs model could potentially help distinguish the theories.

VI. CONCLUSIONS

We have studied the Weinberg Higgs model of *CP* violation and discussed its predictions for B meson decay. The dominant interaction is the Higgs penguin diagram which generates $b \to s + \text{gluon}$. Normalizing the magnitude of the *CP*-violating interaction from its known strength in the kaon system leads to a lower bound on the branching ratio for $b \to s + \text{gluon}$ of from 1% to 15%, depending on the top and Higgs-boson masses. This prediction will hopefully become firmer as more information on mass bounds (or discovery) of the top and charged Higgs boson becomes available.

This process could become a testing ground, or at least a strong constraint, for the Higgs model as the experiment information improves. It is possible that the model could be ruled out in the future by this constraint.

Despite the fact that this decay is largely *CP* violating, the known *CP*-odd observables yield a small signal within the model. This is because the need to interfere with other amplitudes leads to sizable signals only in fairly rare modes. For those channels with a net strangeness in the final state and not net charm, the expected size of partial rate asymmetries is comparable to those of the KM model. Nevertheless, the Higgs model has its own distinctive pattern, with no *CP* violation expected in modes such as $D^+\pi^-$, $D_s^+K^-$, $D^0\pi^+\pi^-$ final states.

It is likely that the best way to confirm or refute this model is to look for the inclusive $b \to s+\text{gluon}$ rate directly. The main configuration for this process will be a two-jet signal, although the b mass may be a bit low to have extremely well-defined jets. Nevertheless the $s+\text{gluon}$ final state should be much less spherical than other standard decay channels, and should contain a hard strange particle. The combination of quantum-number counting and the configuration of the momentum (jettiness) should allow the present weak bound to be decreased into the region sensitive to the Higgs model. It would be amusing if this alternative model for *CP* violation were to be confirmed by a test which is not directly sensitive to the *CP* character of the interaction.

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