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Enhanced charged Higgs boson effects in $B^- \to \tau\bar{\nu}$, $\mu\bar{\nu}$ and $b \to \tau\bar{\nu}+X$

Wei-Shu Hou

Department of Physics, National Taiwan University, Taipei, Taiwan 10764, Republic of China

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Charged Higgs boson effects are not helicity suppressed in the decays $B^- \to \tau\bar{\nu}$, $\mu\bar{\nu}$, and $e\bar{\nu}$, and could enhance or suppress these modes without violating lepton universality. The present limit of $B(B^- \to \mu\bar{\nu}) < 2.0\times 10^{-5}$ is more stringent than the measurement $B(b \to \tau\bar{\nu}+X) = (4.20^{+0.72}_{-0.68}\pm 0.46)\%$, while a factor of 2 improvement in the present limit of $B(B^- \to \tau\bar{\nu}) < 1.2\%$ would be comparable. There is much room for discovery as one pushes the latter limit down to the standard model expectation of order 10^{-4}. A value below this may be explained without requiring $f_B|V_{ub}|$ to be unduly small.

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Recently, the ALEPH Collaboration at the CERN e^+e^- collider LEP has measured the $b \to c\tau\bar{\nu}$ branching ratio [1],

$$B(b \to \tau\bar{\nu}+X) = (4.20^{+0.72}_{-0.68}\pm 0.46)\% \ , \tag{1}$$

while the CLEO Collaboration at the Cornell Electron Storage Ring (CESR) has searched for the $B^- \to l\bar{\nu}$ type of modes, setting the preliminary 90% C.L. limits [2]:

$$B(B^- \to \tau\bar{\nu}) < 1.2\% \ , \tag{2}$$

$$B(B^- \to \mu\bar{\nu}) < 2.0\times 10^{-5} \ , \tag{3}$$

and

$$B(B^- \to e\bar{\nu}) < 1.3\times 10^{-5} \ .$$

We combine these numbers to constrain the charged Higgs-boson sector. Somewhat surprisingly, the most stringent bound at present comes from $B^- \to \mu\bar{\nu}$, but future prospects are brightest for the $B^- \to \tau\bar{\nu}$ mode. The interest in the latter is traditionally in its simple relation to $f_B|V_{ub}|$.

The $b \to c\tau\bar{\nu}$ mode is kinematically suppressed compared to the modes $b \to cl\bar{\nu}$, $l = e,\mu$. In the standard model (SM), $B(b \to c\tau\bar{\nu})$ is expected at the 2–3% level. Coupled with its rather poor experimental signatures, it has never been explicitly searched for until the ALEPH measurement. It was known [3,4], however, that charged Higgs-boson effects may enhance this mode greatly, if the parameter $R \equiv \tan^2\beta m_b m_\tau/m_{H^-}^2$ is large. This mechanism was invoked recently [5,6] as a possible means for suppressing the B meson semileptonic branching ratio from the usual expectation of 12% or more, down to the currently observed 10% or so. The ALEPH measurement, Eq. (1), being consistent with the SM, certainly rules out this explanation. Note, however, that the central value is more than one σ above SM expectations. Improvement in this mode is therefore desired, but it may be limited by systematics. In light of this, we find the CLEO measurements summarized in Eqs. (2) and (3) rather interesting.

It was noted in Refs. [5,6] that, as accompanying evidence for a greatly enhanced $b \to c\tau\bar{\nu}$ mode due to charged Higgs effects, the $B^- \to \tau\bar{\nu}$ mode is further enhanced by a factor of m_B^2/m_τ^2 in rate, since the $H^\pm$ mediated channel is not helicity suppressed. With the $b \to c\tau\bar{\nu}$ mode capped by the ALEPH measurement, it is this additional enhancement factor, *together with* the prospects of rapid experimental development, that draws our attention to the decay modes $B^- \to l\bar{\nu}$.

We shall take the so-called model II of two Higgs doublet models [7], where u-type quarks get mass from one doublet, wide d-type quards and charged leptons get mass from the other doublet. Charged Higgs Yukawa couplings are controlled by the parameter $\tan\beta = v_2/v_1$, the ratio of vacuum expectation values of the two doublets, normally expected to be of order m_t/m_b. Although model II is realized in minimal low-energy supersymmetric models, we shall not make such an explicit assumption. Hence, the mass of the charged Higgs boson is taken as arbitrary. We remark that for model I [7], where all fermions get mass from one and the same doublet, there is no interesting effect. The same can be said about models where d-type quarks and charged leptons derive mass from different doublets.

For our concern, the $W^\pm$ and $H^\pm$ effectively induce the four-Fermi interaction

$$(G_F/\sqrt{2})V_{ib}\{[\bar{u}_i\gamma_u(1-\gamma_5)b][\bar{l}\gamma_u(1-\gamma_5)\nu] - R_l[\bar{u}_i(1+\gamma_5)b][\bar{l}(1-\gamma_5)\nu]\} \ , \tag{4}$$

where

$$R_l = \tan^2\beta(m_b m_l/m_{H^-}^2) \ . \tag{5}$$

The standard V-A term induces $B^- \to l\bar{\nu}$ decay via the axial-vector current, with

$$\langle 0|\bar{u}\gamma_\mu\gamma_5 b|B^-\rangle = if_B p_B^\mu \ , \tag{6}$$

while the pseudoscalar coupling of the $H^\pm$ boson is simply related,

$$\langle 0|\bar{u}\gamma_5 b|B^-\rangle = -if_B(m_B^2/m_b)\ , \tag{7}$$

where we have ignored m_u compared to m_b. One easily arrives at the amplitude

$$\mathcal{M}_{B^-\to l\bar{\nu}} = -(G_F/\sqrt{2})V_{ub}f_B[m_l - R_l(m_B^2/m_b)] \times \bar{l}(1-\gamma_5)\nu\ , \tag{8}$$

where the SM term is proportional to m_l (helicity suppression), while the charged Higgs term is proportional to R_l. The relative sign is negative, similar to the case of $B\to D\tau\bar{\nu}$ transition [6], and follows from Eq. (4). Using Eq. (5), m_l can be factored out while the explicit quark mass dependence in m_b cancels, and we find

$$B(B^-\to l^-\bar{\nu}) = B_{\rm SM} r_H\ , \tag{9}$$

where $B_{\rm SM}$ is the standard model expectation:

$$B_{\rm SM}(B^-\to l^-\bar{\nu}) = \frac{G_F^2 m_B m_l^2}{8\pi}\left[1-\frac{m_l^2}{m_B^2}\right]^2 (f_B^2|V_{ub}|^2\tau_B)\ . \tag{10}$$

The $H^\pm$ boson simply modifies the SM expectation by the m_l-independent factor

$$r_H = [1-\tan^2\beta(m_{B^-}^2/m_{H^-}^2)]^2\ , \tag{11}$$

and lepton universality is retained. This may be surprising at first sight, but is easily understood. Although not helicity suppressed, the $H^\pm$ term contains a dynamical coupling to the lepton mass. The absence of helicity suppression does lead to a physical effect, and $m_b m_l$ of Eq. (5) is now replaced by m_B^2. Hence, enhancement in $B^-\to l\bar{\nu}$ is even more pronounced than the $b\to c\tau\bar{\nu}$ case [5,6].

$H^\pm$ effects do not modify the ratio

$$B(B^-\to\mu\bar{\nu})/B(B^-\to\tau\bar{\nu})\ ,$$

but all the $B^-\to l\bar{\nu}$ modes can be enhanced or suppressed by the same factor r_H. For enhancement, $r_H > 1$,

$$\tan\beta = (1+\sqrt{r_H})^{1/2}(m_{H^-}/m_{B^-})\ . \tag{12}$$

Thus, enhancement requires

$$\tan\beta > \sqrt{2}(m_{H^-}/m_{B^-}) \simeq 0.27(m_{H^-}/1\ \text{GeV})\ . \tag{13}$$

Below this, the destructive interference leads to suppression; i.e., for $r_H < 1$, there are two solutions:

$$\tan\beta = (1\pm\sqrt{r_H})^{1/2}(m_{H^-}/m_{B^-})\ . \tag{14}$$

For $r_H \simeq 1$, one could either have a vanishing charged Higgs effect, or it is twice as strong as the SM contribution in amplitude.

The ALEPH measurement of $b\to\tau\bar{\nu}+X$ has been used very recently to extract the bound [8]

$$\tan\beta \lesssim 0.54(m_{H^-}/1\ \text{GeV})\ , \tag{15}$$

at the 90% C.L. level, which can be easily obtained by comparing Eq. (1) with Ref. [4]. The errors in Eq. (1) have been combined linearly and $B_{\rm SM}$ $(b\to c\tau\bar{\nu}) = 2.7\%$ is taken. With new CLEO results on $B^-\to\tau\bar{\nu}$ and $\mu\bar{\nu}$ ($e\bar{\nu}$ mode is not competitive) given in Eqs. (2) and (3), we find, using Eq. (12) in the second step,

$$r_H(\tau) \lesssim 110 \Longrightarrow \tan\beta \lesssim 0.64(m_{H^-}/1\ \text{GeV})\ , \tag{16}$$

$$r_H(\mu) \lesssim 41 \Longrightarrow \tan\beta \lesssim 0.52(m_{H^-}/1\ \text{GeV})\ , \tag{17}$$

for the $\tau\bar{\nu}$ and $\mu\bar{\nu}$ modes, respectively. We have used $f_B = 170$ MeV, $V_{ub} = 0.005$ and $\tau_B = 1.40$ ps in Eq. (10). Note that the present limit on $B^-\to\mu\bar{\nu}$ is more stringent than $b\to\tau\bar{\nu}+X$ or $B^-\to\tau\bar{\nu}$. However, from Eq. (16) we see that a factor of 2 improvement in $B(B^-\to\tau\bar{\nu})$ would make it the most constraining mode.

As remarked earlier, the ALEPH measurement of $b\to\tau\bar{\nu}+X$ should be refined, but it may eventually be limited by systematics (it may be worthwhile to search for $B\to D\tau\bar{\nu}$ [6]). The present best limit of $B^-\to\mu\bar{\nu}$ would improve with data, but it is limited by statistics [9]. On the other hand, the present CLEO limit on $B^-\to\tau\bar{\nu}$ is based on 700 or so fully reconstructed $B^\pm$ mesons [2]. An analysis is underway [9] to use all data, of order one million B mesons, and there is clearly much room for improvement. At the same time, with proven capabilities in measuring $b\to\tau\bar{\nu}+X$, ALEPH would [10] also be attempting the measurement of $B^-\to\tau\bar{\nu}$, with the SM expectation of order 10^{-4} as the ultimate goal. Given the relatively high value of $B(b\to\tau\nu+X)$ from ALEPH, $B(B^-\to\tau\bar{\nu})$ may well be at the 10^{-3} level or above, which is still consistent with Eqs. (15)–(17). One should then find $B(B^-\to\mu\bar{\nu}) \simeq 0.0045\times B(B^-\to\tau\bar{\nu})$. This would be a clear departure from standard model expectations. Hence, new results from CLEO and ALEPH, as well as from other experiments, are eagerly awaited for.

If enhanced branching fractions are not discovered, the new limits would constrain the large $\tan\beta$/low m_{H^-} possibility. Given the plausible relation $\tan\beta \sim m_t/m_b \sim 15$–$30$, Eqs. (13) and (15)–(17) suggest the range of interest is $m_{H^-} \sim (2$–$4)\times\tan\beta$ GeV ~ 50–100 GeV, where even larger $\tan\beta$ values would permit higher m_{H^-}. This mass and $\tan\beta$ range is independently and directly studied in the search for $t\to bH^+$ mode via $H^+\to\tau^+\nu$. If $m_{H^+} < m_t - m_b < M_W$, this decay mode can evade the present Collider Detector at Fermilab (CDF) limit of $m_t \gtrsim 91$ GeV. Bounds have been given by UA1 and UA2 [11], while CDF results have not yet been reported. For $m_t > M_W + m_b$, the $t\to bH^+$ mode is subdominant, but the $H^+\to\tau^+\nu$ chain can still be searched for [12]. Thus, the search for $B^-\to l\bar{\nu}$ and $b\to\tau\bar{\nu}+X$ complements the direct search for $t\to bH^+$ at hadronic colliders. If enhancement is found in the former, it would imply that $t\to bH^+$ decay is likely to be seen.

Note that enhancement in $B^-\to l\bar{\nu}$ modes is limited by Eq. (13). To improve on this limit, one would need to probe $B(B^-\to\tau\bar{\nu})$ at the 10^{-4} level or below. Aside from experimental difficulties, one is limited by uncertainties in the SM expectation, i.e., f_B and V_{ub} values. Present lattice results [13] lead to f_B values that are slightly larger than 170 MeV. On the other hand, new findings of CLEO imply a smaller value for V_{ub} [14]. Hence, $f_B|V_{ub}|$ may well be lower than the value of

$f_B|V_{ub}| \simeq 0.85$ MeV that we have taken. As the standard model expectation for $B^- \to l\bar{\nu}$ is approached, one would need independent information on f_B and V_{ub} to be able to disentangle $H^{\pm}$ effects. If they can be reliably determined by other means, more stringent bounds on $\tan\beta/m_{H^-}$ than Eq. (13) can be achieved. However, if experiments are capable of establishing $B(B^- \to \tau\bar{\nu})$ to be much below 10^{-4} (a formidable feat), one need not conclude that $f_B|V_{ub}|$ is unduly small, but may explain it by the destructive interference between W and $H^{\pm}$ boson effects.

It may be asked whether there are analogous effects in other pseudoscalar meson decays. B^- decay is special because of the heavy m_B mass, so similar enhancements can be applied to the B_c meson [5,6]. For lighter mesons, the m_B^2 factor in r_H [Eq. (11)] is replaced by a much smaller value and one typically has at best a slight suppression. The $D_s \to \tau\nu, \mu\nu$ modes are actively searched for at present. For these modes, $m_{B^-}^2$ is replaced by $(m_s/m_c)m_{D_S}^2$. Thus, the impact of the $H^{\pm}$ effect on $D_s \to l\nu$ modes is rather small. An interesting effect may exist for $K \to \mu\nu$ and $e\nu$, modes that have been well measured and believed to be understood. The r_H factor has m_B^2 simply replaced by m_K^2. The limit of Eqs. (15)–(17) implies that f_K may well be larger than the usual value by 6.5%.

In summary, we find that charged Higgs boson effects may enhance $B^- \to l\bar{\nu}$ modes by a factor r_H [Eq. (11)] that is independent of m_l. At present, $r_H \sim 40$ is still allowed. Experimental studies of these modes and $b \to \tau\bar{\nu} + X$, $B \to D\tau\nu$ are encouraged, with rapid developments expected. If large enhancements of $B^- \to l\bar{\nu}$ is found, it would have interesting implications for the $t \to bH^+$ search at hadronic colliders, as well as H^+ properties. Very small branching ratios can be accounted for by destructive interference between W and $H^{\pm}$ effects, without requiring f_B or V_{ub} to be unduly small.

Note added. Since this paper was sent out for review, the CLEO Collaboration has made announcements on important progress. First, the new upper limit [15] of approximately 5×10^{-4} on the inclusive $b \to s\gamma$ mode now approaches standard model expectations. If the analysis of Hewett [16], made slightly earlier and concurrent with the present work, is correct, the $t \to bH^+$ decay mode of the top quark is kinematically forbidden $(m_{H^+} \gtrsim m_t)$. We note, however, that the $b \to s\gamma$ rate estimate depends on QCD corrections. In contrast, the $B \to \tau\nu$ mode is exceptionally clear from QCD effects; i.e., all strong interaction effects are summarized in the B meson decay constant f_B. The $b \to s\gamma$ limit does not explicitly exclude the possibility of an enhanced $B \to \tau\nu$ mode. Second, the experimental limit on $B \to \tau\nu$ has been advanced [17] by close to a factor of 2. Hence, the present limits on $b \to \tau\nu + X$ (ALEPH collaboration) and $B \to \tau\nu, \mu\nu$ (CLEO collaboration) are of equal sensitivity to $\tan\beta/m_{H^+}$. The range given by Eqs. (13) and (17) remains a window in which the $B \to \tau\nu$ and $\mu\nu$ modes may get greatly enhanced.

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