PHYSICAL REVIEW D VOLUME 24, NUMBER 11 1 DECEMBER 1981

Charged Higgs boson with $m_H < m_B$?

D. R. T. Jones, G. L. Kane, and J. P. Leveille
Randall Laboratory of Physics, University of Michigan, Ann Arbor, Michigan 48109
(Received 16 July 1981)

We argue that the existence of charged Higgs bosons with $m_{\text{Higgs}} < m_B$ is subject to severe constraints from B decays. Our analysis is performed using a model (involving a Higgs triplet) with a pseudo-Goldstone charged Higgs boson whose mass is predicted to be 3.5 GeV, with phenomenological remarks about charged Higgs bosons in general. Although allowed by present experimental limits, this model could be ruled out by attainable limits from B decays.

I. INTRODUCTION

Modifications of the standard $SU(2)\times U(1)$ electroweak model involving nonminimal Higgs structure[1] result inevitably in the existence of physical charged Higgs scalars. The detection of such particles has been considered,[2] but detailed predictions are difficult to give in view of the fact that in the models usually considered both the masses of the hypothetical particles and their couplings to fermions are functions of (unknown) parameters in the Higgs potential and hence are essentially arbitrary. In this paper we reexamine the question of whether a charged Higgs boson $H^\pm$ might exist in the range $m_H < m_B$. The phenomenological considerations of Sec. III below are essentially model independent and general formulas are given which allow the extension to arbitrary cases. Our investigation is made in the context of the standard model with the usual Higgs doublet ϕ and in addition a triplet η with zero hypercharge; detailed numerical values are given for this case, with ranges stated for more general situations.

An objection to such a Higgs sector is that it modifies the successful[3] prediction of the standard model that $\rho = M_W{}^2/M_Z{}^2\cos^2\theta_W = 1$ to $\rho = 1 + 4\langle\eta\rangle^2/\langle\phi\rangle^2$. We are therefore forced to fine-tune the Higgs potential so that $\langle\eta\rangle/\langle\phi\rangle \lesssim 10^{-1}$ to avoid conflict with experiment. Nevertheless, we believe the model is worth considering because, if we impose invariance under the discrete symmetry $\eta \to -\eta$, the mass of the charged Higgs particle $H^\pm$ is predicted, independent of the values of the parameters in the Higgs potential, to be 3.5 GeV. This comes about because $H^\pm$ is in fact a pseudo-Goldstone[4,5] boson whose mass arises from radiative corrections involving the vector bosons. The coupling of H^+ to fermions is also predicted up to an overall suppression factor $\tan\delta = 2\langle\eta\rangle/\langle\phi\rangle$.

A good place to look for a charged Higgs boson in this mass range is B decay. As we shall see, B decay can in fact easily give a more stringent upper bound on δ than the limit from ρ already discussed. Since there is also evidently a lower bound on δ coming from the requirement that the lifetime τ_H be not so great as to give rise to visible tracks in e^+e^- annihilation experiments it is clear that the model has at least the merit of falsifiability.

In the next section we discuss the model in more detail; then Sec. III is devoted to phenomenological considerations.

II. THE MODEL

With a doublet of $\phi(Y=1)$ and a self-conjugate triplet $\eta(Y=0)$ the general form of the Higgs potential is

$$V(\phi,\eta) = -m^2\phi^\dagger\phi - \tfrac{1}{2}\mu^2\eta^2 + \lambda_1(\phi^\dagger\phi)^2 + \frac{\lambda_2}{4}(\eta^2)^2 + \lambda_3\phi^\dagger\phi\eta^2\,, \qquad (1)$$

where we have imposed invariance under $\eta \to -\eta$.

It is easily seen that $V(\phi,\eta)$ is invariant under independent gauge transformations on ϕ and η; the representations are "unlocked" in the sense defined by Weinberg.[4]

It is easy to arrange the parameters in (1) so that both ϕ and η develop vacuum expectation values. However, it is easily seen that only the norms of ϕ and η are determined at the minimum. This is a direct consequence of the unlocking referred to above. It follows that a calculation of the effective potential to one loop is required to determine whether or not there is a residual U(1) (electromagnetism) after symmetry breaking. The calculation is standard[6] so we do not reproduce it here; the result is that a U(1) is indeed preserved; the vacuum expectation values can be chosen to be

$$\langle\phi\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}, \quad \langle\eta\rangle = \begin{pmatrix} 0 \\ 0 \\ w \end{pmatrix}. \qquad (2)$$

The vector-boson masses are given by

$$M_Z{}^2 = \tfrac{1}{4}g^2v^2\sec^2\theta_W\,, \quad M_W{}^2 = \tfrac{1}{4}g^2(v^2+4w^2) \qquad (3)$$

so

$$\rho = M_W^2/M_Z^2\cos^2\theta_W = 1+\tan^2\delta\,, \tag{4}$$

where

$$\tan\delta = 2\frac{w}{v}. \tag{5}$$

The resulting physical Higgs particles consist of two neutrals and a charged particle H^+ given by

$$H^+ = \cos\delta\,\eta^+ - \sin\delta\,\phi^+. \tag{6}$$

H^+ is massless in the tree approximation as a consequence of the unlocking of the two representations. The symmetry of the Higgs potential in Eq. (1) is $O(4)\otimes O(3)$. It is broken to $O(3)\otimes O(2)$, leaving $H^\pm$ as two pseudo-Goldstone bosons which would be truly massless in the absence of coupling to the gauge bosons. $H^\pm$ obtains a mass at the one-loop level from radiative corrections due to the gauge bosons. The calculation of the effective potential already described also yields the $H^\pm$ mass (for a calculation of pseudo-Goldstone–boson masses in an arbitrary gauge theory see Ref. 5). The result is

$$m_H^2 = \frac{3\alpha}{4\pi}\frac{M_Z^4\cos^2\theta_W}{M_Z^2-M_W^2}\ln\frac{M_Z^2}{M_W^2}\ . \tag{7}$$

In the limit $\delta \ll 1$ ($H^\pm$ purely η) this reduces to

$$m_H^2 = \frac{3\alpha^2}{4\sqrt{2}\,G_F}\csc^4\theta_W\ln\sec^2\theta_W\,. \tag{8}$$

Substituting the experimental value $\sin^2\theta_W = 0.23$ we obtain

$$m_H = 3.5\ \text{GeV}\,. \tag{9}$$

We will also require the coupling of H^+ to fermions. For the conventional N-generation model of left-handed doublets and right-handed singlets this is easily shown to be

$$-\sqrt{2}\,(\sqrt{2}G_F)^{1/2}\tan\delta\,H^+(\overline{u}_L C\,M_d d_R - \overline{u}_R M_u C d_L) + \text{H.c.}\,, \tag{10}$$

where M_d and M_u are the (diagonal) down- and up-quark mass matrices and C is the $N\times N$ generalized Cabibbo-Kobayashi-Maskawa (CKM) matrix.

In the next section we will apply (10) to $H^\pm$ production and decay and consider what limits can be placed on δ.

III. PHENOMENOLOGY

We have already emphasized that the experimental value of $\rho \approx 1\pm 0.01$ places a stringent upper bound on the triplet vacuum expectations value and on the coupling of the charged Higgs boson to the fermions. Now we investigate other ways of detecting the charged light Higgs boson.

Production of the charged boson in e^+e^- collisions gives little constraint. Indeed since the production would result only in a rise of $0.25R$ we only need to ensure that the charged scalar be short lived, since otherwise charged tracks would be visible in e^+e^- experiments. We assume $\tau_H \lesssim 10^{-10}$ s as a safe upper limit.

Using Eq. (10) we may write the relevant couplings for the decay of the charged Higgs boson. We find

$$\begin{aligned}\mathcal{L}_{Hf\bar{f}} = -\frac{(G_F\sqrt{2})^{1/2}}{\sqrt{2}}\tan\delta\,H^+\{&-m_\tau\overline{\nu}_\tau(1-\gamma^5)\tau - m_\mu\overline{\nu}_\mu(1-\gamma^5)\mu - m_e\overline{\nu}_e(1-\gamma^5)e\\ &+V_{ud}\overline{u}[(m_d-m_u)+(m_d+m_u)\gamma^5]d + V_{us}\overline{u}[(m_s-m_u)+(m_s+m_u)\gamma^5]s\\ &+V_{ub}\overline{u}[(m_b-m_u)+(m_b+m_u)\gamma^5]b + V_{cd}\overline{c}[(m_d-m_c)+(m_d+m_c)\gamma^5]d\\ &+V_{cs}\overline{c}[(m_s-m_c)+(m_s+m_c)\gamma^5]s + V_{cb}\overline{c}[(m_b-m_c)+(m_b+m_c)\gamma^5]b+\cdots\}\,,\end{aligned}$$

where V_{ij} are the elements of the CKM matrix.

In a two-Higgs-doublet model, which also gives charged Higgs bosons, one obtains precisely the same form for $\mathcal{L}_{Hf\bar{f}}$ if the weakly interacting quark eigenstates are taken to be the usual Cabibbo-Kobayashi-Maskawa rotated ones and no flavor-changing neutral currents are allowed; $\tan\delta$ is again the ratio of the vacuum expectation values of the two Higgs fields. Our remarks in this section apply equally well to this model, with $\tan\delta$ appropriately reinterpreted.

We note that although the couplings to the quarks are proportional to the quark masses, they are suppressed by the CKM angles. In the mass range that we are considering, we only need to consider the decay modes $H^+\to\tau^+\nu$ and $c\overline{s}$, all others being suppressed by ratios of masses and angles. Using the rate [for a coupling $gH^+\overline{Q}(C_V+C_A\gamma^5)q$]

$$\Gamma(H\to Qq) = \frac{C}{8\pi}g^2(C_V^2+C_A^2)\frac{[m_H^2-(m_Q+m_q)^2]}{m_H}\times\left(\frac{\lambda(m_H^2,m_Q^2,m_q^2)}{m_H^4}\right)^{1/2},$$

where $C=1$ (3) for a lepton (quark) pair, we find the total rate (neglecting the strange-quark mass)

$$\Gamma_H = \frac{G_F\sqrt{2}\tan^2\delta\, m_H}{8\pi} \times\left[m_\tau^2\left(1-\frac{m_\tau^2}{m_H^2}\right)^2 + 3\,|V_{cs}|^2 m_c^2\left(1-\frac{m_c^2}{m_H^2}\right)\right]^2 .$$

Using $m_\tau = 1.784$ GeV, $m_c = 1.5$ GeV, and $m_H = 3.5$ GeV leads to a lifetime

$$\tau_H = \frac{4.76\times10^{-20}\ \text{sec}}{\tan^2\delta} .$$

Hence

$$\tan\delta \gtrsim \left(\frac{4.76\times10^{-20}}{10^{-10}}\right)^{1/2} \simeq 2\times10^{-5} .$$

If a shorter lifetime is excluded the lower bound on $\tan\delta$ is increased. In particular if this charged Higgs boson were produced in an emulsion experiment as a result of a B-meson decay, an upper limit to the lifetime of 10^{-14} sec could be achieved. This would bring the lower limit of $\tan\delta$ to 10^{-3}. Conventional accelerator experiments will surely get limits on charged tracks giving $\tau < 10^{-12}$ sec, or $\tan\delta > 6\times10^{-4}$. For charged Higgs bosons of different masses only the phase space changes, as shown in Γ_H, and the limit gets less stringent; to a good approximation it goes as $m_H^{1/2}$ so the numbers hardly change.

To obtain an upper limit for $\tan\delta$, we must look at the possible production processes for the charged Higgs boson. Since the couplings to fermions are proportional to the mass of the fermion, the standard lore of Higgs-boson physics indicates that we must look at reactions involving heavy quarks. B decays are the best source of information for charged Higgs bosons in the mass range $m_H < m_B$, so this part of the analysis holds for that range. The two-body decays of the b quark, $b\to Hq$, are semiweak and would dominate over the usual three-body modes. The Higgs boson would subsequently decay to $\tau\bar\nu$ or $c\bar s$ producing electrons and muons in the cascade chain. These leptons would be much softer than the ones resulting from the decay mediated by a W.

This resulting increase in soft leptons and decrease in hard leptons is easily detectable, by comparing with a lepton spectrum generated from ordinary $b\to ql\nu$ modes and incorporating the charm leptons. The details are very sensitive to experimental cuts, however, and require a detailed Monte Carlo analysis, because most of the softer leptons are rejected by the cuts.

Exactly the opposite should occur for kaons. Indeed in the decay $H\to c\bar s$ a fast K (with energy ~1 GeV) will be produced, peaking the K distribution at the high-momentum end.

We now come back to the triplet model. Because of phase-space restrictions, the b quark can only decay to H^-u. We have

$$B(b\to H^+u) = \frac{\Gamma_H}{\Gamma_{\rm NH}+\Gamma_H}$$

with Γ_H the width into a Higgs boson,

$$\Gamma_H = \frac{G_F\sqrt{2}}{16\pi} m_b^3\left(1-\frac{m_H^2}{m_b^2}\right)^2 |V_{bu}|^2\tan^2\delta ,$$

and $\Gamma_{\rm NH}$ is the b width in the absence of a Higgs boson. For our purposes, it will be sufficient to consider only the spectator contributions to the b-quark width. We then find

$$B(b\to H^-u) = \frac{\tan^2\delta}{\tan^2\delta + [G_F m_b^2/12\pi^2(1-m_H^2/m_b^2)^2\sqrt{2}\,](7.7+3.1\,|V_{bc}|^2/|V_{bu}|^2)}$$
$$\approx \frac{\tan^2\delta}{\tan^2\delta + 7\times10^{-6}(1+0.4\,|V_{bc}|^2/|V_{bu}|^2)} .$$

Assuming a conservative estimate of $B(b\to H^-u) \lesssim 20\%$ since present data[7] shows hard leptons presumably not due to the decay via $H^\pm$, we see that for reasonable values of the ratio $|V_{bc}|^2/|V_{bu}|^2$ we expect $\tan\delta < 2\times10^{-3}$. Eventually a 1% branching-ratio limit will be obtainable, which would give $\tan\delta < 5\times10^{-4}$, which just overlaps with the lower limits estimated above from accelerator experiments, and easily overlaps with results from emulsion experiments. It is interesting that a rather loose bound on the decay mode $b\to Hu$ provides a much better restriction than the measurement of the ρ parameter, even for $|V_{bc}| \gg |V_{bu}|$.

We conclude by summarizing that present data conservatively constrains $\tan\delta$ to be in the range 10^{-5}–2×10^{-3}. Improvement of the lifetime bound either from e^+e^- data or emulsion experiments and a moderate improvement on the bound of $B(b\to H^-u)$ would either rule out or confirm this amusing model.

ACKNOWLEDGMENTS

Two of us (D.R.T.J. and J.P.L.) appreciate the hospitality of the Institute of Theoretical Physics, Santa Barbara, where part of this work was done. This work was supported in part by the U.S. Department of Energy.

[1]D. A. Ross and M. Veltman, Nucl. Phys. B95, 135 (1975).
[2]E. Golowich and T. C. Yang, Phys. Lett. 80B, 245 (1979); L. N. Chang and J. E. Kim, *ibid.* 81B, 233 (1979); H. E. Haber, G. L. Kane, and T. Sterling, Nucl. Phys. B161, 493 (1979); J. F. Donoghue and L.-F. Li, Phys. Rev. D 19, 945 (1979).
[3]For recent discussions of the data and fits see I. Liede and M. Roos, Nucl. Phys. B167, 397 (1980); J. E. Kim, P. Langacker, M. Levine, and H. H. Williams, Rev. Mod. Phys. 53, 211 (1980).
[4]S. Weinberg, Phys. Rev. Lett. 29, 1698 (1972).
[5]S. Weinberg, Phys. Rev. D 7, 2887 (1973).
[6]S. Coleman and E. Weinberg, Phys. Rev. D 7, 1888 (1973).
[7]K. Chadwick *et al.*, Phys. Rev. Lett. 46, 88 (1981).