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Electroweak interference in a new model of b and τ interactions

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A recently proposed model, where the b quark couples to the c quark through a second W boson, is analyzed. In a two-generation version of this model, enhanced Yukawa couplings to new particles are considered for a unified account of the observed forward-backward asymmetry in $e^+e^-\to\bar{b}b$ and in $e^+e^-\to\tau^+\tau^-$. Copious production of new particles in e^+e^- annihilation well below 100 GeV is predicted.

I. INTRODUCTION

In a recently proposed model[1] inspired by the particle content of supersymmetric E_6 gauge models as the low-energy manifestation[2] of the heterotic superstring,[3] the b quark is assumed not to decay via the standard W boson according to the conventional analysis based on the Kobayashi-Maskawa mixing matrix.[4] Instead, it is supposed to decay mainly into the c quark through a second W boson with a right-handed coupling. Constraints from precise e^+ spectrum measurements in polarized μ^+ decay[5] and the b lifetime[6] together with an estimate[1] of the Michel parameter in semileptonic b decay indicate that the mixing angle ζ between the two W's is of the order -0.015 and that the mass of W_2 is not too far above 400 GeV. In the framework of the $SU(3)\times SU(2)_1\times SU(2)_2\times U(1)$ subgroup of E_6, this is realized by assigning $(c,b)_R$ as a doublet under $SU(2)_2$, while keeping $(u,d)_L$ and $(c,s)_L$ as doublets under $SU(2)_1$ as usual. Now b_L can also be part of an $SU(2)_1$ doublet, i.e., $(t,b)_L$, in which case the assumption that b_L does not couple to c_L or u_L becomes rather *ad hoc*, but this assignment will certainly be necessary if the experimental evidence[7] for the existence of the t quark is confirmed. A more interesting scenario is for b_L to be a singlet under both $SU(2)_1$ and $SU(2)_2$. In that case, it can be accommodated as one of the extra states available in the fundamental **27** representation of E_6, and a third generation will not be needed, assuming now of course the absence of a t quark. However, if b_L and b_R are both singlets under $SU(2)_1$, b will have no axial-vector coupling to the standard Z boson. The same thing will also happen to the τ lepton, because τ_L and τ_R are then both $SU(2)_1$ doublets if a third **27** is not available. Hence the observed forward-backward asymmetry[8] in $e^+e^-\to\bar{b}b$ and in $e^+e^-\to\tau^+\tau^-$ will have to be explained in some other way. This is the subject matter of the present paper.

In Sec. II the model is described in some detail. In particular, the lepton assignment will be slightly changed from that of Ref. 1, and will be more in keeping with the expectation that b and τ should be together. In Sec. III the issue of electroweak interference is fully discussed. It will be shown that a one-loop amplitude involving a new scalar boson and a new charged lepton, both belonging to a **27** supermultiplet of E_6 is a possible way to account for the observed forward-backward asymmetry in $e^+e^-\to\bar{b}b$ and in $e^+e^-\to\tau^+\tau^-$. These new particles should be relatively light, say about 30 GeV, and have enhanced couplings to electrons. In Sec. IV their possible copious production in e^+e^- annihilation is briefly discussed. Finally, in Sec. V, there are some concluding remarks.

II. DESCRIPTION OF THE MODEL

The fundamental **27** representation of E_6 can be decomposed according to its [SO(10),SU(5)] content as

$$27=(16,\bar{5})+(16,10)+(16,1)+(10,\bar{5})+(10,5)+(1,1)\ . \tag{1}$$

Each combination of $\bar{\mathbf{5}}$ and **10** of SU(5) contains one complete generation of the usual quarks and leptons. Although **10** appears only once in the decomposition of **27**, $\bar{\mathbf{5}}$ appears twice. This allows for the existence of something like half a generation. Consider two **27**'s. The first two generations of quarks and leptons are assigned as

$$(u^c;u,d;e^c)_L:\ (16,10)\ , \tag{2}$$

$$(c^c;c,s;\mu^c)_L:\ (16,10)\ , \tag{3}$$

$$(d^c;\nu_e,e)_L:\ (16,\bar{5})\ , \tag{4}$$

$$(s^c;\nu_\mu,\mu)_L:\ (10,\bar{5})\ . \tag{5}$$

The subscript L refers to the left-handed chiral projection; the superscript c denotes the charge-conjugate state so that ψ_L^c can be interpreted as ψ_R. At the $SU(3)\times SU(2)_L\times U(1)_Y$ level, the above assignment is exactly the same as in the standard model. Hence all interactions involving only the first two generations will be unchanged. The difference comes in when one tries to place a third generation. Since both (16,10)'s are used up, there is no slot for the t quark. As for the b quark and the τ lepton with its associated neutrino, the following assignment is quite natural:

$$(b^c;\nu_\tau,\tau)_L:\ (16,\bar{5})\ , \tag{6}$$

$$(b;\tau^c,N_\tau^c)_L:\ (10,5)\ . \tag{7}$$

To round out the two **27**'s, there should be extra quarks and leptons; namely,

$$(h^c;\nu_E,E)_L:\ (10,\bar{5})\ , \tag{8}$$

$$(h;E^c,N_E^c)_L:\ (10,5)\ , \tag{9}$$

$$(N_e^c)_L,(N_\mu^c)_L:\ (16,1)\ , \tag{10}$$

$$n_L,n_L':\ (1,1)\ . \tag{11}$$

Consider first τ decay. As long as N_τ is heavier than τ, the latter will decay only into ν_τ via the standard W boson, exactly as the standard model. On the other hand, the neutral-current interaction of τ is different from that of the standard model, because τ_R is now part of a doublet instead of a singlet. The axial-vector coupling g_A^τ to the Z boson is now zero, instead of $-\frac{1}{2}$. The same problem also occurs for g_A^b, because b_L is now a singlet as well as b_R, so again g_A^b is zero in this model, instead of $-\frac{1}{2}$. As for b decay, although it cannot proceed at the SU(2) $\times$U(1) level, it will do so at the next level, through a second SU(2). To see this in more detail, consider the SU(3)$\times$SU(2)$_1\times$SU(2)$_2\times$U(1) decomposition of the two **27**'s:

$$(u,d)_L,(c,s)_L:\ (3,2,1,\tfrac{1}{6})\ , \tag{12}$$

$$(d^c,u^c)_L,(b^c,c^c)_L:\ (\bar{3},1,2,-\tfrac{1}{6})\ , \tag{13}$$

$$(\nu_e,e)_L,(\nu_\tau,\tau)_L:\ (1,2,1,-\tfrac{1}{2})\ , \tag{14}$$

$$(e^c,N_e^c)_L,(\mu^c,N_\mu^c)_L:\ (1,1,2,\tfrac{1}{2})\ , \tag{15}$$

$$h_L,b_L:\ (3,1,1,-\tfrac{1}{3})\ , \tag{16}$$

$$h_L^c,s_L^c:\ (\bar{3},1,1,\tfrac{1}{3})\ , \tag{17}$$

$$\begin{bmatrix}\nu_E & E^c\\ E & N_E^c\end{bmatrix}_L,\ \begin{bmatrix}\nu_\mu & \tau^c\\ \mu & N_\tau^c\end{bmatrix}_L:\ (1,2,2,0)\ , \tag{18}$$

$$n_L,n_L':\ (1,1,1,0)\ . \tag{19}$$

The above assignment differs from that of Ref. 1 in the switch of $(\nu_\tau,\tau)_L$ with $(\nu_\mu,\mu)_L$ so that b_L^c combines with $(\nu_\tau,\tau)_L$ in one $(16,\bar{5})$ as shown earlier. The phenomenology of b decay remains the same, as was fully discussed in Ref. 1. On the other hand, there is now an interesting change in the neutrino sector: ν_e still combines with N_e^c to form a Dirac neutrino. This means that ν_τ is capable of producing μ^- via a right-handed charged current. Alternatively, in semileptonic b decay, the neutrino associated with μ^- is capable of reproducing τ^+ via the usual left-handed charged current. Furthermore, since $(\tau^c,\nu_\mu)_L$ couples to W_2, there is a neutrino component in τ^- decay which is capable of producing μ^+ as well. These and other similar considerations will be relevant for future beam-dump experiments. The other neutral lepton that τ is coupled to via W_1 is N_τ, which is assumed heavier than τ, so it will have to be observed in W or Z decay if kinematically allowed.

III. ELECTROWEAK INTERFERENCE

In e^+e^- colliders, the forward-backward asymmetries in $\bar{b}b$ and $\tau^+\tau^-$ production have been measured[8] and found to be in fair agreement with the standard-model prediction of $g_A^b=g_T^\tau=-\frac{1}{2}$. Therefore, there is a serious discrepancy with the present model where these couplings are zero, unless some other mechanism can be found within the model able to account for the data. The first thing to consider is the effect of the possible neutral vector gauge bosons. However, there are phenomenological mass limits on these in either the SU(2)$_L\times$SU(2)$_R\times$U(1) extension[9] or the SU(2)$_L\times$U(1)$_Y\times$U(1) extension,[10] and a simple analysis shows that the effect is always much too small, and often of the wrong sign.

The next thing to consider is the exchange of scalar bosons in the t channel. Since the model has supersymmetry, there are many new scalar bosons which can have substantial Yukawa couplings to the known quarks and leptons. A Fierz rotation of the scalar or pseudoscalar interaction may then generate an effective axial-vector contribution to $e^+e^-\to\bar{b}b$ and $e^+e^-\to\tau^+\tau^-$. Unfortunately, this effect turns out to be always of the wrong sign. Actually, this mechanism is rather unattractive for $e^+e^-\to\bar{b}b$ in the first place, because it would require a scalar leptoquark boson with a mass of the order 10^2 GeV.

Consider now the one-loop diagrams of Fig. 1. The interaction Lagrangian is given by

$$L_{\rm int}=\phi(g_1\bar{E}_Re_L+g_2\bar{\tau}_R\tau_L+g_3\bar{b}_Rb_L)+\text{H.c.}\ , \tag{20}$$

where the scalar boson ϕ transforms as (16,1) and every single term in the above is of the form $(16,1)(16,\bar{5})(10,5)$, as allowed in the $\mathbf{27}\times\mathbf{27}\times\mathbf{27}$ product. Let $\sqrt{s}$ be the center-of-mass energy of the e^+e^- collision, θ the angle of the outgoing τ^- or b relative to the incoming e^-, m_ϕ the mass of ϕ, m_E the mass of E; then the one-loop amplitudes of Fig. 1 involve integrals of the form

$$I=\int\frac{dz_1dz_2dz_3dz_4\delta(1-z_1-z_2-z_3-z_4)}{(z_1+z_2)m_\phi{}^2+z_3m_E{}^2-s[z_1z_2-z_3z_4(1\pm\cos\theta)/2]}\ . \tag{21}$$

To get an idea of the size of this contribution, assume for simplicity $m_\phi=m_E=m$, and expand I in powers of $s/4m^2$. The resulting asymmetry for $e^+e^-\to\tau^+\tau^-$, normalized to the standard-model prediction, is then given by

$$A_\tau=\left[\frac{g_1{}^2}{4\pi}\right]\left[\frac{g_2{}^2}{4\pi}\right]\left[\frac{\sqrt{2}}{8m^2G_F}\right]\left[1-\frac{s}{M_Z{}^2}\right]\left[1+\frac{1}{9}\left[\frac{s}{4m^2}\right]+\frac{7}{135}\left[\frac{s}{4m^2}\right]^2\right]\ . \tag{22}$$

The expression for A_b is the same except g_2 is replaced by g_3. Since A_τ and A_b are both experimentally known to be consistent with being one, the phenomenological requirement is clearly

$$\left[\frac{g_1{}^2}{4\pi}\right]\left[\frac{g_2{}^2}{4\pi}\right]\frac{1}{m^2}\simeq\frac{8G_F}{\sqrt{2}}\ , \tag{23}$$

and $g_3\simeq g_2$. Now m has to be greater than 23 GeV in or-

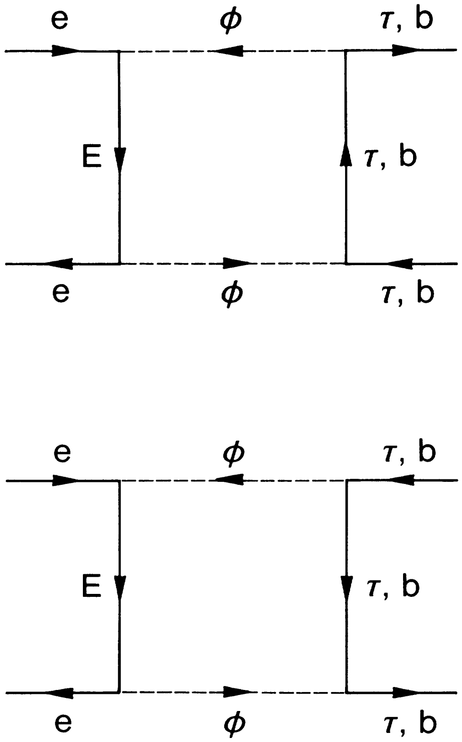

FIG. 1. One-loop amplitudes contributing to $e^+e^-\to\tau^+\tau^-$ and $e^+e^-\to\bar{b}b$. The neutral scalar boson ϕ and the charged heavy lepton E are new hypothetical particles.

der to be consistent with the absence of ϕ or E production at present e^+e^- colliders. This puts a limit

$$\left[\frac{g_1{}^2}{4\pi}\right]\left[\frac{g_2{}^2}{4\pi}\right]\gtrsim 0.035\ . \tag{24}$$

Hence the Yukawa couplings g_1, g_2, and g_3 have to be enhanced relative to, say, $g_Z=e/\sin\theta_W\cos\theta_W$ by at least a factor of 2.

The coupling g_1 will appear in other processes as well. Its contribution to the anomalous magnetic moment of the electron is given by

$$a=\tfrac{1}{2}(g-2)=\frac{-g_1{}^2m_e{}^2}{192\pi^2m^2}\ . \tag{25}$$

Now even if $g_1{}^2/4\pi=1$ and $m=23$ GeV, a is only -3×10^{-12}, well short of the possible discrepancy[11] between theory and experiment of 3×10^{-10}. A more serious constraint comes from $e^+e^-\to e^+e^-$, where a diagram similar to those of Fig. 1 will contribute to the forward-backward asymmetry, but the effect here is roughly $2g_1{}^2/3g_2{}^2$ times that of A_τ; hence, it could be much smaller. Experimentally, the asymmetry A_e is not measured very accurately, because t-channel one-photon exchange, not possible in other processes, dominates here in the differential cross section. Therefore, a small change from the standard-model prediction cannot be excluded.

The measured asymmetries A_τ and A_b are mostly based on data taken at $\sqrt{s}=29$ and 34.5 GeV, hence the $s/4m^2$ correction in Eq. (22) is about 5% and 8%, respectively, if m is as low as 23 GeV, whereas the standard-model $s/M_Z{}^2$ correction is 10% and 14%. In the standard model, A_τ is equal to A_b naturally, and both are in agreement with data. In the present model, A_τ is equal to A_b only if $g_2=g_3$, and both magnitudes have to be adjusted to fit the data. Hence the standard model is clearly superior in this regard. On the other hand, the best measured asymmetry is in $e^+e^-\to\mu^+\mu^-$, and there has long been a hint of disagreement there with the standard-model prediction. Therefore, it cannot be ruled out that more precise determinations of A_τ and A_b will not find disagreement with the standard model. Now even if A_τ is normalized to one so that the forward-backward asymmetry is the same in this model as in the standard model for $e^+e^-\to\tau^+\tau^-$, there are still differences between the two models in that the effective $g_V^e g_A^\tau$ and $g_A^e g_V^\tau$ couplings are now $\frac{1}{4}$ and $\frac{1}{2}-\sin^2\theta_W$, respectively, instead of $\frac{1}{4}-\sin^2\theta_W$ for both. Preliminary measurements[12] of these quantities have errors of the order of their differences and cannot yet distinguish between the two models.

IV. PRODUCTION OF NEW PARTICLES

The proposed new particles ϕ and E should be much lighter than 10^2 GeV, or the Yukawa couplings g_1, g_2, and g_3 would have to be bigger and the considerations of the previous section become less likely as an alternative explanation of the electroweak-interference effect. Hence they are expected to be produced copiously at forthcoming e^+e^- colliders such as TRISTAN at KEK and SLC at SLAC.

Consider first $e^+e^-\to\phi^*\phi$. The differential cross section is easily calculated to be

$$\frac{d\sigma}{d\Omega}=\left[\frac{g_1{}^2}{4\pi}\right]^2\frac{p^3(1-\cos^2\theta)}{16E[2E(E+p\cos\theta)+m_E{}^2-m_\phi{}^2]^2}\ , \tag{26}$$

where $E=\sqrt{s}/2$ and $p=(E^2-m_\phi{}^2)^{1/2}$. This is to be compared with the standard $e^+e^-\to\mu^+\mu^-$ result from one-photon exchange:

$$\frac{d\sigma}{d\Omega}=\left[\frac{e^2}{4\pi}\right]^2\frac{1+\cos^2\theta}{16E^2}\ . \tag{27}$$

If g_1 is much greater than e, the production of $\phi^*\phi$ will become dominant above threshold. On the other hand, the production of a single ϕ or ϕ^* via $e^+e^-\to\phi(\phi^*)\tau^+\tau^-$ or $\phi(\phi^*)\bar{b}b$ may become important at a much lower threshold. Let $E_\phi(p_\phi)$ be the energy (momentum) of ϕ, and θ the angle it makes with e^-, then the differential cross section for $e^+e^-\to\phi\tau^+\tau^-$, assuming negligible the mass of τ, is given by

$$\frac{d\sigma}{dE_\phi d\Omega}=\frac{1}{4\pi}\left[\frac{g_1{}^2}{4\pi}\right]^2\left[\frac{g_2{}^2}{4\pi}\right]\frac{p_\phi{}^3}{16E^2}(1-\cos^2\theta)$$
$$\times\frac{E(E-E_\phi)+m_\phi{}^2/4}{(E-E_\phi)^2[2E(E_\phi+p_\phi\cos\theta)+m_E{}^2-m_\phi{}^2]^2}\ . \tag{28}$$

If m_ϕ is as low as 23 GeV, a rough numerical estimate shows that $g_1{}^2/4\pi \lesssim 0.2$ is required for the necessary suppression of ϕ (and ϕ^*) production at present e^+e^- colliders. This is compatible with Eq. (24), but since $g_2{}^2/4\pi$ should not be too big, $g_1{}^2/4\pi$ is not expected to be much smaller than about 0.1; hence, $e^+e^- \to \phi^*\phi$ above threshold will be at least one order of magnitude greater than $e^+e^- \to \mu^+\mu^-$ and should be readily observable. The decay of ϕ and ϕ^* will be prominently into $\tau^+\tau^-$ and $\bar{b}b$, and if kinematically allowed, into e^+E^- and e^-E^+, respectively.

Pair production of E^+E^- via e^+e^- annihilation has also a very large cross section above threshold. The differential cross section is given by

$$\frac{d\sigma}{d\Omega} = \left[\frac{g_1{}^2}{4\pi}\right]^2 \times \frac{p(E - p\cos\theta)^2}{16E[2E(E - p\cos\theta) + m_\phi{}^2 - m_E{}^2]^2} . \quad (29)$$

This is comparable to $\phi^*\phi$ production if m_E and m_ϕ are not too different. Single E production is presumably not favored by kinematics, because E does not have to couple strongly to low-mass states, as ϕ does to $\tau^+\tau^-$ and $\bar{b}b$. Once produced, E^- decays into ϕe^- if kinematically allowed, or $\tau^+\tau^-e^-$ and $\bar{b}be^-$ if ϕ is virtual. The branching fraction into the usual decay modes through the standard W boson will be highly suppressed.

V. CONCLUSION

If the t quark turns out to be absent, it will be very interesting to see if all the known particles can be accommodated into two **27** supermultiplets of a supersymmetric E_6 gauge model as inspired by superstring theory. The particles usually assigned to the third generation, i.e., b and τ, must then find new homes. This can be done rather easily within present experimental and phenomenological constraints as far as charged-current interactions are concerned.[1] However, it is unavoidable that the axial-vector couplings of both b and τ to the standard Z boson become zero instead of $-\frac{1}{2}$. Hence there is a need to account for the observed forward-backward asymmetry in $e^+e^- \to \tau^+\tau^-$ and in $e^+e^- \to \bar{b}b$ within the framework of this two-generation model. In this paper, a solution is put forward where two of the extra particles in a **27** supermultiplet, ϕ and E, with masses of the order 30 GeV, are supposed to have enhanced Yukawa couplings to e, τ, and b. Electroweak interference then comes from one-loop amplitudes with internal ϕ and E contributions. Consequently, forthcoming e^+e^- colliders such as TRISTAN at KEK with center-of-mass energy 60—70 GeV, and SLC at SLAC as well as LEP at CERN with energies 100 GeV or more, will certainly be able to produce these new particles ϕ and E and the cross sections will be at least an order of magnitude greater than the corresponding ones from quantum electrodynamics. There will be no difficulty then in deciding whether or not this model is correct.

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