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Charged Higgs bosons, charged hyperpions, and the nonleptonic decays of heavy-flavored mesons

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We find that the existence of charged Higgs bosons $H^{\pm}$ or charged hyperpions $P^{\pm}$ may enhance the nonleptonic decays of the pseudoscalar t-flavored mesons T_q. This, in turn, would induce a difference in the average kaon multiplicities expected for two-jet events in T_b and T_b^* decays and therefore provide a possible way to discriminate between T_b and T_b^* production in e^+e^- annihilation.

I. INTRODUCTION

It was recently pointed out[1] that the weak interactions are expected to dominate the decays of the heavy-flavored mesons T_q and T_q^*, which are composed of the hypothetical heavy t quark and light quark q. This result arises from the estimates that the vector T_q^* and pseudoscalar T_q states are separated by less than a pion mass, the strong decay $T_q^* \rightarrow T_q\pi$ is then kinematically forbidden, and the electromagnetic transition $T_q^* \rightarrow T_q\gamma$ is strongly suppressed, yielding widths of just few eV. On the other hand, in the valence-quark approximation, the weak hadronic total decay rate is simply given by the t-quark cascade transition $t \rightarrow b\sum(q\bar{q}'+l\nu)$, the light quark q acting as spectator, which yields widths of order a few keV (Ref. 1). Corrections to this approximation are given by nonspectator contributions, which are in general negligible except for the T_q^* mesons, where the annihilation of the $t\bar{q}$ system in the s channel through the exchange of a W boson gives a sizable contribution.[2] In the scenario outlined above, the final states in $e^+e^- \rightarrow T_q\bar{T}_q$, $T_q^*\bar{T}_q^*$ would be essentially identical to those in the $e^+e^- \rightarrow t\bar{t}$ continuum above threshold, and it would be very difficult to discriminate between T_q and T_q^* production.

In the present note we study the effect of charged Higgs bosons $H^{\pm}$ and charged pseudo-Goldstone bosons $P^{\pm}$ (hyperpions) on the nonleptonic decays of the T_q^* and T_q mesons. These particles are predicted in most extensions of the standard electroweak model,[3] in all its supersymmetric versions, and in the extended hypercolor (EHC) models.[4] If these particles exist with mass lower than the mass of the t quark and their coupling to fermions is proportional to the mass of the heaviest fermion available, it is known[2,5,6] that the decay of the t quark will be dominated by the production of real $H^{\pm}$ $(P^{\pm})$. In this case, both T_q and T_q^* mesons will decay predominantly into $H^{\pm}(P^{\pm})+X$, the final states in $e^+e^- \rightarrow T_q\bar{T}_q$, $T_q^*\bar{T}_q^*$ will be again identical to those in $e^+e^- \rightarrow t\bar{t}$ continuum above threshold, and it would be also very difficult to distinguish between T_q and T_q^* production.

In a previous note,[7] one of us studied the purely leptonic decays of the T_q and T_q^* mesons in the framework of some models which predict $H^{\pm}$ $(P^{\pm})$ particles. It was pointed out that since only "light" leptons can be produced in these decays, helicity suppression is active, and the leptonic T_q^*-meson decays then will proceed via weak annihilation into $W^{\pm}$, while the leptonic T_q-meson decays will proceed through $H^{\pm}$ $(P^{\pm})$ annihilation. Even though it was found that some of the leptonic decays of the T_b meson could be comparable to the leptonic T_b^* decays, a measurement of these decay modes would not discriminate between T_b and T_b^* production. In the present note we will find that if $H^{\pm}$ $(P^{\pm})$ exists with $m_H < m_t$, they will induce measurable effects in the nonleptonic decays of T_b^* and T_b mesons. Although these effects are expected to be too small to be used as an evidence for the existence of $H^{\pm}$ $(P^{\pm})$, they can be used to discriminate between T_b and T_b^* production. In particular, we have found that the presence of $H^{\pm}$ $(P^{\pm})$ may enhance some of the nonleptonic annihilation decays of the T_b meson. This in turn will induce that the average kaon multiplicity expected for two-jet events in T_b decay is slightly greater than the one expected for two-jet events in T_b^* decays. The production of either T_b or T_b^* is expected to have a very small cross section in almost any reaction, except, perhaps, in the case[1,2] that a t-quarkonium state decays by a spectator mechanism into $(t\bar{t}) \rightarrow (t\bar{b}) + W^-$ virtual (H^- real), where the $(t\bar{b})$ system will fuse to form a T_b state 26% of the time and a T_b^* state 74% of the time. Therefore, if the production of T_b and T_b^* is experimentally feasible in this way, one could distinguish between T_b and T_b^* production by studying the average kaon multiplicities in events like $e^+e^- \rightarrow$ two jets $+\, l\nu$ (large p_T).

II. NONLEPTONIC ANNIHILATION DECAYS

A simple analysis of the mass dependence of QCD effects in t-quark decays indicates that one can safely neglect strong effects and use simple W-exchange diagrams.[2,8] Consequently, the spectator model for T-meson decays is well justified and only the vector meson T_b^* may have a sizeable nonspectator component through annihilation via W exchange.[2] We will assume that the heavy t quark exists with $m_t < M_W$ in the context of the three-generation extension of the standard model.[9] For simplicity, we assume that nature uses either elementary Higgs fields or the hypercolor scheme but not both, and that the $H^{\pm}(P^{\pm})$-fermion couplings can be parametrized as

$$L_{\rm eff}=i(\sqrt{2}G_F)^{1/2}H^+\{\bar{u}[C_1U_{\rm KM}M_d(1+\gamma_5)+C_2M_uU_{\rm KM}(1-\gamma_5)]d+C_3M_e\bar{\nu}(1+\gamma_5)e\}+\text{H.c.}\;, \tag{2.1}$$

where the symbols u, d, ν, and e refer to the conventional type of fermions of charges 2/3, −1/3, 0, and −1, respectively, $M_{u,d,e}$ are the corresponding diagonalized mass matrices, and $U_{\rm KM}$ is the conventional Kobayashi-Maskawa matrix.[9] The coefficients C_i in Eq. (2.1) are rather model dependent. They are of order unity in some "monophagic" hypercolor models,[6] and for the standard model with two Higgs doublets, $C_i=\eta_1/\eta_2$, η_2/η_1, or 1, where η_1 and η_2 are the respective Higgs-field vacuum expectation values.[10]

We are going to take separately the two possibilities that $H^\pm$ ($P^\pm$) exists with either $m_H>m_t$ or $m_H<m_t$. In the first case, the decay widths of both T_q and T_q^* mesons are determined mainly by the spectator diagram shown in Fig. 1(a), and it is given by

$$\Gamma_S\left[t\to b\sum(q\bar{q}'+l\nu)\right]\cong\frac{3G_F^2m_t^5}{64\pi^3}\left[1+\frac{192C_2^2m_t^2(C_1^2U_{cb}^2m_b^2+C_2^2U_{cs}^2m_c^2+C_3^2m_\tau^2)}{206m_H^4}\right]\;, \tag{2.2}$$

where the second term in the large parentheses is the $H^\pm$-exchange contribution and in general is negligible. In the second case, if $m_H<m_t$, the decay widths of both T_q^* and T_q are now determined by the diagram shown in Fig. 1(b) for the creation of a real $H^\pm$:

$$\Gamma_H(t\to bH^+)\cong\frac{\sqrt{2}G_FC_2^2U_{tb}^2m_t^3}{16\pi}\;. \tag{2.3}$$

The nonleptonic decays of the charged mesons T_q^* and T_q will have characteristic three- or two-jet events depending if they arise through spectator [Fig. 1(a)] or annihilation [Fig. 1(c)] diagrams, respectively. In the last case, since only "light" quarks can be produced, helicity suppression is active, the exchange of $H^\pm$ ($P^\pm$) is helicity suppressed for the vector state, and $T_{q_1}^*\to q_2\bar{q}_3$ is determiend only by $W^\pm$

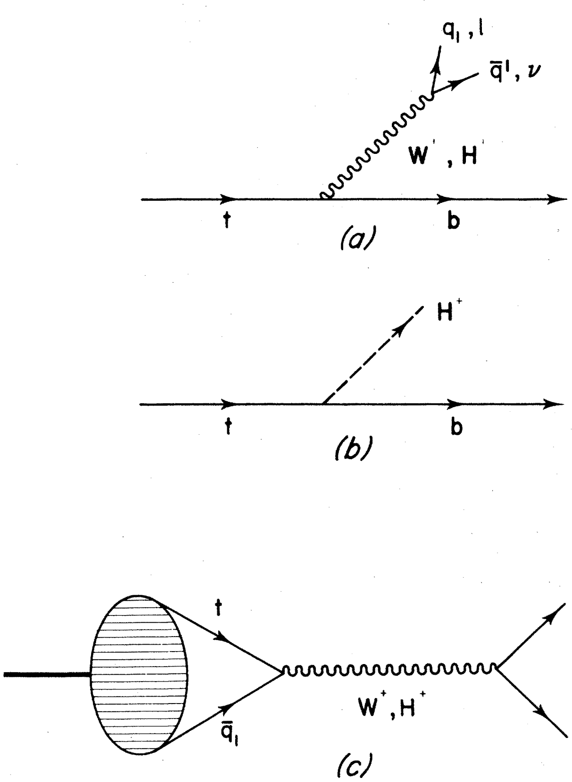

FIG. 1. Dominant Feynman diagrams involved in the weak decay of T mesons: (a) spectator diagram, (b) decay into a real $H^\pm$, and (c) annihilation diagram.

exchange:

$$\Gamma_a(T_{q_1}^*\to q_2\bar{q}_3)\cong\frac{G_F^2f_V^2U_{t1}^2U_{23}^2M_T^3}{4\pi(1-M_T^2/M_W^2)^2}\;, \tag{2.4}$$

where $M_t\simeq m_t+m_{q_1}$ and $f_V(T_q^*)$ is proportional to the T_q^* wave function at the origin. Simple potential-model calculations indicate[1] that $f_V(T_b^*)\simeq 700$ MeV, $f_V(T_s^*)\simeq 90$ MeV, and $f_V(T_d^*)\simeq 70$ MeV. On the other hand, the exchange of $W^\pm$ is helicity suppressed for the pseudoscalar state and $T_{q_1}\to q_2\bar{q}_3$ is determined only by $H^\pm$ exchange:

$$\Gamma_a(T_{q_1}\to q_2\bar{q}_3)\cong\frac{3G_F^2f_V^2U_{t1}^2U_{23}^2M_T^3(C_1m_1-C_2m_t)^2(C_1^2m_4^2+C_2^2m_3^2)}{8\pi(M_T^2-m_H^2)^2}\;, \tag{2.5}$$

where $f_V(T_q)\simeq f_V(T_q^*)$.

A simple comparison of Eq. (2.2)–(2.5) shows that the annihilation branching ratios for T_q^* and T_q are negligible except in the case that $m_H>m_t$ for T_q^*, and for the T_q meson in the case that $M_T\sim m_H$, where we would have a resonancelike phenomenon. In spite of this, there is the interesting possibility that for some channels the T_b and T_b^* annihilation widths might be comparable if $m_H<m_t$. In particular, we expect the most striking effects in the decay channels $T_b,T_b^*\to c\bar{s},c\bar{b}$. If we take as a maximal choice $C_2\approx 10$ and the experimental bound[11] $m_H\geqslant 15$ GeV, then from Eqs. (2.4) and (2.5) it follows that[12] $\Gamma(T_b\to c\bar{s})/\Gamma(T_b^*\to c\bar{s})\sim 65$ if $m_t=25$ GeV, $m_H=15$ GeV; and $\Gamma(T_b\to c\bar{s})/\Gamma(T_b^*\to c\bar{s})\sim 15$ if $m_t=40$ GeV, $m_H=25$ GeV. We obtain similar results in the case $\Gamma(T_b\to c\bar{b})/\Gamma(T_b^*\to c\bar{b})$.

III. KAON MULTIPLICITIES

In this section we explore the possibility that the nonleptonic annihilation channels of T_b could be comparable to those of the vector meson T_b^*. As far as the purely leptonic channels are concerned, it was pointed out[1,7] that the most striking signatures in the production of T_b and T_b^* are expected in the leptonic and semi-inclusive decays $T_b,T_b^*\to l\nu$, (large p_T) $l\nu$+few soft hadrons. We now study the average kaon multiplicities expected for two- and three-jet events in T_b and T_b^* decays as a possible way of distinguishing between T_b and T_b^* production.

It was pointed out by Bigi and Krasemann[1] that the annihilation decays of T_b^* should differ from cascade decays in their flavor content. In particular, they found that, if one considers only the effect of virtual W exchanges, then the average kaon multiplicities expected in these decays differ by about one unit. In order to get this result, it is necessary to assume that in the annihilation reaction the decay proceeds via a W boson which fragments into three color doublets of $u\bar{d}$ and $c\bar{s}$ each and into three lepton doublets $e\nu$, $\mu\nu$, and $\tau\nu$. The further development into the observed final state is assumed to be driven by only soft gluons, whose transition into $s\bar{s}$ is suppressed. Thus the annihilation picture leads to the following chains:

$$T_b^* \to \begin{cases} u\bar{d} + 5 \text{ gluons} , \\ c\bar{s} + 4 \text{ gluons} \to s\bar{s} + 4 \text{ gluons} + W_{\text{soft}} , \end{cases} \tag{3.1}$$

which has to be compared with the following cascade chains:

$$T_b^*(T_b) \to b\bar{b} + W_{\text{hard}} \to c\bar{c} + 3W_{\text{hard}} \to s\bar{s} + 2W_{\text{soft}} + 3W_{\text{hard}} . \tag{3.2}$$

The following crude estimates for the probabilities for a gluon turning into $s\bar{s}$ and for the fragmentation $W_{\text{hard}} \to c\bar{s}$,

$$P(g \to s\bar{s}) \sim \tfrac{1}{6} - \tfrac{1}{9} , \tag{3.3}$$

$$P(W^+_{\text{hard}} \to c\bar{s}) \sim \tfrac{1}{3} , \tag{3.4}$$

lead to different average kaon multiplicities:[1] $\langle N_K \rangle = \langle N_{\bar{K}} \rangle \sim 0.7$–$0.9$ for the annihilation chains (3.1), and $\langle N_K \rangle = \langle N_{\bar{K}} \rangle \sim 2$ for the cascade chain (3.2). Incorporating the charged Higgs boson $H^{\pm}$ $(P^{\pm})$ into the picture, we have to add the cascade chain

$$T_b^*(T_b) \to b\bar{b} + H^+_{\text{hard}} \to s\bar{s} + 2W_{\text{soft}} + 2W_{\text{hard}} + H_{\text{hard}} , \tag{3.5}$$

and the annihilation chain:

$$T_b \to c\bar{s} + 4 \text{ gluons} \to s\bar{s} + 4 \text{ gluons} + W_{\text{soft}} . \tag{3.6}$$

According to the couplings given in (2.1), the $H^{\pm}$ boson will fragment essentially into three $c\bar{s}$ color doublets and one lepton doublet $\tau\nu$; then we have $(H^+ \to c\bar{s}) \sim 3/4$.

If we now take into account the chains (3.5) and (3.6), the average kaon multiplicities become $\langle N_K \rangle = \langle N_{\bar{K}} \rangle = 1.1$–$1.3$ for the T_b annihilation mechanism, and $\langle N_K \rangle = \langle N_{\bar{K}} \rangle = 4.4$ for both T_b and T_b^* cascade mechanisms. Therefore, we have that including the new channels open by the possible existence of $H^{\pm}$ $(P^{\pm})$ with $m_H < m_t$, there is a difference of about half unit between the average kaon multiplicites expected for the two-jet events in T_b and T_b^* decays. On the other hand, if $H^{\pm}$ $(P^{\pm})$ does not exist or $m_H > m_t$, then the only available channels arise through chains (3.1) and (3.2) and we should expect an average kaon multiplicity of about 0.7–0.9 for the two-jet events coming from T_b^* decays.

Finally, we would like to comment on the possibility that the annihilation channels T_b^*, $T_b \to c\bar{b}$ might be also important. In this case we have to include two more annihilation chains:

$$T_b^*(T_b) \to c\bar{b} + 2 \text{ gluons} \to s\bar{s} + 2 \text{ gluons} + 2W_{\text{soft}} + W_{\text{hard}} . \tag{3.7}$$

In this condition, the probabilities (3.3) and (3.4) have to be modified to

$$P(W^+_{\text{hard}} \to c\bar{s} \text{ ro } c\bar{b}) \sim \tfrac{1}{4} , \tag{3.8}$$

$$P(H^+_{\text{hard}} \to c\bar{s} \text{ or } c\bar{b}) \sim \tfrac{3}{7} . \tag{3.9}$$

As a consequence, the total average kaon multiplicities expected for two-jet (annihilation) events become $\langle N_K \rangle = \langle N_{\bar{K}} \rangle \sim 0.9$–$1.0$ for T_b^* decays, and $\langle N_K \rangle = \langle N_{\bar{K}} \rangle \sim 1.2$–$1.3$ for T_b decays if $m_H < m_t$. The cascade chains (3.2) and (3.5) remain unaltered even if these new channels are opened, and their average kaon multiplicities are again given by $\langle N_K \rangle = \langle N_{\bar{K}} \rangle \sim 2$ if there is no $H^{\pm}$, and $\langle N_K \rangle = \langle N_{\bar{K}} \rangle \cong 4.4$ if there is a $H^{\pm}$ with $m_H < m_t$.

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