Comments and Addenda

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Leptonic signals for nonstandard heavy quarks

Douglas W. McKay and Herman J. Munczek
Department of Physics and Astronomy, The University of Kansas, Lawrence, Kansas 66045
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Alternatives to the standard sequential six-quark and six-lepton model of weak and electromagnetic interactions include several in which heavy quarks decay only semileptonically. The rates of inclusive and several semi-inclusive lepton-production channels in e^+e^- annihilation are estimated for such models and a comparison is made with the standard-model expectations. Consideration is given to lepton spectra, and it is pointed out that a hard spectrum could be the signal of purely leptonic decay of heavy, spinless hadrons. The latter process is predicted to be prominent in several alternative schemes, one of which is outlined here. The leptonic spectrum appears to provide a realistic method of detecting unexpected hadronic physics. Even if the b quark turns out to be of standard sequential type, it is stressed that it is important to test for anomalies in leptonic production rate and spectrum shape at higher PEP and PETRA energies.

In the literature on weak and electromagnetic gauge theories, various alternatives to the standard sequential model of six quarks and six leptons[1] have been put forward. Several examples[2-4] have the distinctive features that Cabibbo universality is exact, i.e., the heavy quarks do not mix with the light u, d, s, and c quarks, and that the weak decay pattern of the next flavor of hadrons heavier than charm is distinctively different from the pattern expected for b-quark decay in the standard six-quark model. As in the standard model,[1] the authors of the alternative models assume that the next flavor heavier than charm has already shown up indirectly as a quark constituent of Υ.[2-4] The new hadron mass scale is then assumed to start at about 5 GeV. The hadrons in the "nonstandard" b-quark[5] schemes would have no decays into states of purely light hadronic matter made of u, d, s, or c quarks, but would always decay semileptonically or, in some cases, purely leptonically. The data available at PETRA,[6] CESR, and PEP will make it possible to detect such new hadronic properties, and the purpose of this note is to review the salient features of these models and to offer several tests for the detection of hadrons whose decays always result in leptons in the final state. Even if the constituent of Υ should prove to have the standard properties,[7] we feel that it is worthwhile at this stage to review the properties of the semistable nonstandard heavy-quark alternative and to stress the importance of looking carefully for evidence of such new interactions at each new energy regime.

Exact Cabibbo universality in the light-quark sector requires a different source of CP violation from that of the standard six-quark model,[1] whose Cabibbo mixing includes the heavy b and t quarks and admits a CP-violating phase. The alternative models isolate the heavy quarks from the light ones by additional symmetries, and CP violation is produced by the same mechanism which allows the heavy quarks to decay. We believe that this feature of the nonstandard models adds theoretical interest to them, since a link is forged between the old, incompletely understood physics of CP violation and the new, yet-to-be-tested physics of the heavy-quark decays.

For orientation, let us consider a class of possibilities in which μ, e, and τ and their associated neutrinos are produced with about the same strength in the decays of the b quark, giving a branching fraction of $\frac{1}{3}$ to each of these leptons. We will consider the production of $b\bar{b}$ by e^+e^- annihilation. Several interesting final states will be $e^+ + e^- \to \mu$ or e + anything,[8] $e^+ + e^- \to \mu^\pm + e^\mp$ + anything,[9] $e^+ + e^- \to \mu^\pm + (e^\mp$ or hadron $^\mp)$ + missing energy and momentum (presumably carried off by neutrinos).[6] We can compare then the production cross section times branching ratios of the nonstandard, only semileptonic, b-decay alternative to those of the standard[1] b decays.

Ignoring the purely leptonic decays, to which we return later, let us focus on the two cases $(\mu+X)$ and (μ^+ charged hadron or e).[9] Comparison between the standard and nonstandard model will give an indication of the difference in event rate which one might expect. Estimates of the semileptonic-decay branching ratio of standard b quarks are in the vicinity of 10% for each type of lepton,[10] while the nonstandard b quarks always decay semileptonically. The ratio, then, is simply given by

$$\frac{[\sigma B(e^+e^-\to b\bar{b}\to\mu+X)]_{\text{nonstandard}}}{[\sigma B(e^+e^-\to b\bar{b}\to\mu+X)]_{\text{standard}}}\simeq\frac{0.33}{0.10}=3.3\,, \tag{1}$$

since the production cross sections are the same in each case and we have assumed approximately equal coupling of μ, e, and τ to the weak interaction which is responsible for the nonstandard b decay. The direct processes

$$e^+e^-\to\tau+\bar{\tau}\longrightarrow\text{anything}\qquad\tau\searrow\mu+\nu+\bar{\nu}$$

and

$$e^+e^-\to\bar{c}+c\longrightarrow\mu+\text{anything}\qquad\bar{c}\searrow\text{anything}$$

will be backgrounds to these events. However, kinematic cuts and hadron multiplicity cuts have been successful in distinguishing between τ and charm decays at lower energies.[11] Comparing raw event rates, assuming no cuts on the data, one would estimate the ratio between $\mu+X$ in the nonstandard, all-semileptonic-decay case and the standard-model case to be

$$\frac{\sum_i[\sigma B(e^+e^-\to i\to\mu X)]_{\text{nonstandard }b}}{\sum_i[\sigma B(e^+e^-\to i\to\mu X)]_{\text{standard }b}}=\frac{0.16+\frac{4}{3}0.1+\frac{1}{3}0.33}{0.16+\frac{4}{3}0.1+\frac{1}{3}0.1}\simeq1.25\,, \tag{2}$$

where i runs over $\tau\bar{\tau}$, $c\bar{c}$, and $b\bar{b}$ and where 0.1 is the measured charm semileptonic branching ratio,[8] the same value is assumed for b in the standard model, 0.16 is the $\tau\to\mu+\nu+\bar{\nu}$ measured branching ratio,[12] and $\frac{4}{3}$ and $\frac{1}{3}$ are the charm and b-quark charge factors, respectively. Considering that the estimates of the standard b-quark semileptonic branching ratios are guesses based on experience with charm decays and estimates of mixing angles in the six-quark model, our estimate, Eq. (2), of the enhancement of the inclusive μ signal expected in the nonstandard models over that of the standard model is a crude one. It does show that one does not expect a very dramatic effect in overall inclusive muon (or electron) event rate even if the nonstandard b quark, with its 100% semileptonic decay, is being produced rather than the standard b quark, which has nonleptonic modes available as well. The problem, of course, is the factor $\frac{1}{3}$ due to the b-quark charge, which will make any b signals harder to detect than in the case of charm, and it will make decay modes harder to pin down.

The $\mu+h$(or e) + missing ν's final states are interesting ones because the only way that a single hadron or electron can appear in conjunction with a μ is by $\tau\bar{\tau}$ production and decay or by $q\bar{q}$ production and purely leptonic decay. The latter is only large if the decay occurs via spin-zero-mediated processes as in several versions of the nonstandard heavy-quark models.[2-4] The W-boson-mediated, purely leptonic modes are severely suppressed[13] by angular momentum conservation, of course. Therefore, we have a nonstandard b-quark and τ confusion by the possibilities

$$e^++e^-\to\tau_{\searrow\mu\nu\bar{\nu}}+\bar{\tau}_{\searrow\bar{e}\nu\bar{\nu},\ \searrow h\bar{\nu}}\,, \tag{3a}$$

$$e^+e^-\to B_{\searrow\mu\nu}+\bar{B}_{\searrow e\nu,\ \searrow\nu+\tau_{\searrow e\nu\bar{\nu}}}\qquad(\mu e\text{ final state})\,, \tag{3b}$$

and

$$e^++e^-\to B_{\searrow\mu\nu}+\bar{B}_{\searrow\nu+\tau_{\searrow h\nu}}\qquad(\mu h\text{ final state})\,, \tag{3c}$$

where B stands for a spin-zero, heavy meson with "b" flavor. Comparing the τ as a source of μ/e and μ/h signal and the nonstandard b-quark source for the same final state, we have

$$\frac{\sigma B(e^+e^-\to\tau\bar{\tau}\to\mu+e\text{ or }h)}{\sigma B(e^+e^-\to B\bar{B}\to\mu+e\text{ or }h)}=(0.16\times0.26)/|F(Q^2)|^2\tfrac{1}{3}[(0.33\times1.16)^2+(0.33)^2\times1.16\times0.10]B(l\nu)^2\,, \tag{4}$$

where $F(Q^2)$ is a B electromagnetic form factor and $B(l\nu)$ in the denominator stands for the branching ratio of the lightest, presumably charged, new flavored meson into $l+\nu$. As before, we assume for definiteness that μ, e, and τ couple the same to the decay-producing current and give 33% each to the final states. The factor 1.16 in the brackets of the denominator accounts for the possibility that a μ or e comes from τ decay and 0.10 is the (approximate) τ branching fraction to a single, stable hadron (π or K).[14] If a spinless weak-boson exchange is responsible for the B decay, then the purely leptonic mode (which comes from quark annihilation) can easily be 50%, as we argue later. Because the spinless, semistable mesons B must be produced directly for the signal in question and not be the end product of a cascade from heavier particles, the form factor $F(Q^2)$ will almost surely suppress this signal severely except, perhaps, in the $B\bar{B}$ threshold region where, as in charm production, hadron dynamics (resonances) might enhance b production. This form-factor suppression eliminates the purely leptonic mode of a nonstandard b quark from competition with the $\tau\bar{\tau}$ signal at high energies (~30 GeV), but might admit an important contribution not far from $b\bar{b}$ threshold. A limit on the branching ratio can be obtained by analyzing PETRA data[7] at 13 and 29 GeV. We find that the τ signal's agreement with QED requires that

$$|F(Q^2)|B(B^\pm \to e^\pm \nu) \leq \begin{cases} 1 \text{ at } 13\text{ GeV} \\ 0.2 \text{ at } 29\text{ GeV}. \end{cases} \tag{5a}$$

For orientation we note that a similar consideration of the D data[15] at 3.771 GeV leads to the limit

$$B(D^\pm \to l^\pm + \nu) < 0.5\%. \tag{5b}$$

The D production cross section is measured directly, so the value of the form factor has been used to determine the limit on $B(D\to l+\nu)$ in Eq. (5b).

Rate considerations do not reveal a sharp distinction between the standard model and nonstandard ones in which the b quark decays only semileptonically. Equations (2) and (5a) indicate the weakness of these effects. The shape of the lepton spectrum has been useful in analyzing the structure of τ (Ref. 14) and D decays,[15] and the two-body decay discussed above will have a distinctive hard spectrum shape. This would reveal its presence if it were a prominent decay mode. Qualitatively, this is shown in Fig. 1, where the well-known three-body and two-body spectrum shapes are contrasted for the case of a decay in flight of a particle with energy E and momentum p.

After summarizing a nonstandard model, in

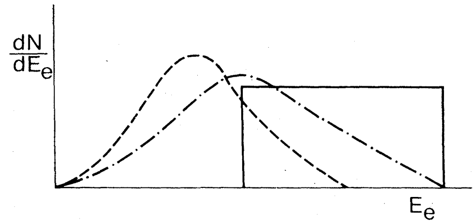

FIG. 1. Illustration of the leptonic spectrum shapes of two-body decay (solid), three-body decay into all massless particles (dashed), and three-body decay into one massive and two massless particles (dot-dashed).

which the b decays semileptonically by a spin-zero (S and P) interaction, and discussing the decay rates to be expected in the model, we will return to a quantitative account of the hard spectrum expected from purely leptonic meson decays. We propose this spectrum test as a realistic and promising one for detection of nonstandard quark properties.

A NONSTANDARD MODEL

Works which differ from each other in symmetry structure and representation content but which share the feature that the light u, d, s, and c quarks have exact Cabibbo mixing and the b quark does not communicate with them through the usual weak currents are the ones by McKay and Munczeck,[2] Derman,[3] and Georgi and Glashow.[4] In each example, the b-quark candidate decays only semileptonically. The possibilities discussed by Derman and by Georgi and Glashow have some lepton-number and/or baryon-number-violating modes with all charged particles in the final state (no missing neutrinos), while the models considered by McKay and Munczek do not involve such modes.

Because the interaction which violates CP conservation and mediates b-quark decay in the models of McKay and Munczek is neither a gauge boson nor Higgs boson in origin, we briefly review this model in order to provide the setting for subsequent discussion.

Our model is based on the gauge group SU(2) ×U(1) with the standard W, Z, and γ gauge particles, and parity is violated spontaneously. Global or discrete γ_5 symmetries are imposed on the Langrangian so that mass terms for the neutrinos are avoided. Soft breaking terms are added to the potential in the case of continuous symmetries so that Goldstone bosons are avoided. After spontaneous symmetry breaking, each fermion SU(2) representation splits into a light sector and a heavy sector. Light fermions are identified as the right-handed singlet and left-handed doublet components and vice versa for heavy fermions. Neither Higgs-boson nor gauge-boson interactions cause heavy-light transitions or mixings. In versions where the minimum of two Higgs doublets is used, the symmetries are so restrictive that CP violation cannot occur. The simplest way—the one which introduces the fewest new particles and interactions—in which CP violation can be included is to introduce a single, charged spin-zero boson which couples light quarks to heavy quarks. The leptonic couplings of this charged, spin-zero boson (which we call χ) can be arranged so that light lepton couplings to χ can occur. The χ-boson couplings therefore admit both CP-violating phases and leptonic and semileptonic decays of heavy hadrons. A scheme which we have found[16] to allow the b quark to be the lightest of the $V+A$ coupled heavy quarks (while leaving arbitrary the masses of the other, heavy quarks) has lepton-number-violating interactions of the type

$$B^+(\bar{b}u) \to \chi \to \bar{\nu}e^+,$$

where B^+ is a $J^P=0^-$ heavy hadron. This lepton-number violation is too subtle for direct observation, but the scalar nature of the interaction means that the rate can be sizable, not suppressed by angular momentum conservation as is the case for $V\pm A$ interactions.

Finally, the minimal new particle content of schemes which we have investigated is three new neutrinos, three charged leptons with $V+A$ interactions, and three heavy quarks besides b which, like b, have $V+A$ interactions with the W boson. Anomalies are canceled between heavy/light partners of opposite chirality without the usual family-structure requirements of the standard model.

We reiterate that, like the other models of this class, the physics of the low-energy u, d, s, c, μ, e, and τ is the same as that in the successful standard $SU_L(2)\times U(1)$ model.[1] The alternative models have exact Cabibbo universality in the light-quark sector and a new interaction which admits CP violation and heavy-quark semileptonic decay. The new interaction can be mediated by Higgs particles,[3] by the χ which we described above,[2] or by gauge bosons associated with a larger group.[4]

LIFETIMES OF HEAVY HADRONS

We next consider the restrictions on couplings, and therefore on lifetimes, of heavy-quark decays, which are imposed on models which, like ours, have exact Cabibbo universality among light quarks.[2] We require that the standard Glashow-Iliopoulos-Maiani (GIM[1]) suppressed box diagrams[17] with W exchange are the principal mechanism for K^0-$\bar{K}^0$ mixing, and the CP violation in the K^0-$\bar{K}^0$ mass matrix is due to the new forces. Roughly speaking, this means that

$$\theta_C^{\,2}G_F^{\,2}M_c^{\,2} > \theta_N^{\,2}G_N^{\,2}M_N^{\,2} \gtrsim 10^{-3}\theta_C^{\,2}G_F^{\,2}M_c^{\,2},$$

where θ_C, G_F, and M_c are the usual Cabibbo angle, Fermi decay constant, and charmed-quark mass and θ_N, G_N, and M_N are the nonstandard mixing angles, decay constant, and mass scale appropriate to the heavy quarks and CP-violating forces. Assuming that mixing angles are small (we have verified that this is so in our model), this means that decay lifetimes would be roughly

$$10^{-14} < \tau < 10^{-11}\ \text{sec}. \tag{6}$$

However, the quark interaction need not be the same strength as the lepton interactions if the mediating particle is spin zero. Therefore the decay rates, which are determined by leptonic and semileptonic processes, could easily differ from the rough bounds of Eq. (6), which consider only nonleptonic constraints, by an order of magnitude at either end.

We estimate the semileptonic decay rates in our model in a little more detail by comparing the rate of free, heavy-quark decay to that of μ decay. The free-quark estimates of semileptonic decay rates should be better than in the case of charm decay, where the comparison is simply $(M_c/M_\mu) \simeq (15)^5$ and is probably within a factor of 2 of the experimental values.[14,15,18] Taking $M_\chi \simeq M_N$, $g_{\chi e\nu}^{\,2} \simeq \frac{1}{10}g^2$, and $(g_{\chi q q'}/g)^2 \simeq (2\times10^{-5})^{1/2}$, where q' stands for a heavy quark and the latter estimate comes from CP-violation constraints discussed by us in Ref. 2, we find that

$$\sin^2\theta_C G_F^{\,2}M_c^{\,2} > \sin^2\theta_\chi G_\chi^{\,2}M_\chi^{\,2} \gtrsim \sin^2\theta_C G_F^{\,2}M_c^{\,2}\times10^{-3},$$

as required. Here G_χ is the effective scalar, χ-mediated, four-fermion weak-interaction coupling and θ_χ are quark mixing angles which enter the Yukawa couplings between heavy quarks, light quarks, and the χ particle. The values of the weak coupling g and of M_W are those of the standard model[1] and θ_C is the Cabibbo angle. With the above coupling choices, we find that

$$\frac{\tau(q'\to q\nu e)}{\tau(\mu\to e\nu\bar{\nu})} = \left(\frac{M_\mu}{M_{q'}}\right)^5\left(\frac{M_\chi}{M_W}\right)^4 g^4/g_{\chi e\nu}^{\,2}g_{\chi qq'}^{\,2} \simeq 7\times10^{-6},$$

or

$$\tau(q'\to q+\nu+e) \simeq 1.4\times10^{-11}\ \text{sec}. \tag{7}$$

A key factor in the estimate (7) is that the leptonic coupling to χ is not constrained by μ decay to be small because the Michel parameters in μ

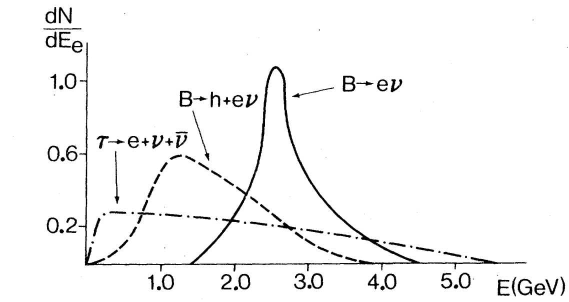

FIG. 2. Leptonic spectra of a heavy hadron of mass 5.1 GeV produced at 12 GeV cm e^+e^- energy or a τ produced at the same energy (dash-dotted curve). The solid curve is the purely leptonic spectrum with a constant fragmentation function, $D(z)=\text{constant}$. The dashed curve is a semileptonic spectrum with $D(z)=\text{constant}$ and the mass of the final-state hadron$=2.0$ GeV.

decay are the same for the χ-mediated interaction as those of a $V-A$ interaction. Only universality of weak-coupling strengths and the electron helicity measurement in μ decay constrain the χ couplings to leptons, and the upper bound is on the order of 5–10% in amplitude. It is the great precision of $\Delta S=2$ mass-splitting measurements which requires the χ coupling to quarks to be so small and which makes it a natural source of CP violation.[2]

Turning to the purely leptonic modes, we use the expression

$$\Gamma(B\to l\nu)=\frac{M_B}{\pi}\frac{(g_{e\nu\chi}g_{\chi qq'})^2}{M_\chi^4}\,|f_B|^2\,,$$

where M_B stands for the mass of a charged, quasistable meson and f_B is the counterpart of the pion decay constant (though with different dimensionality since this is a scalar interaction). With the values $M_B=5$ GeV, $g_{\chi e\nu}\simeq 10^{-1}$, $g_{\chi qq'}\simeq 2\times10^{-2}$, $M_\chi=M_W$, and $f_B=M_qM_{q'}\simeq 1\text{ GeV}^2$ we find

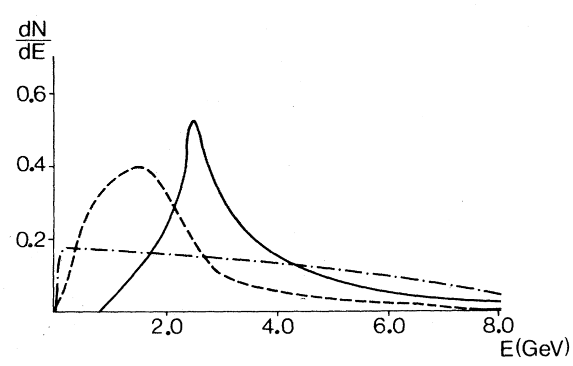

FIG. 3. The same spectra as in Fig. 2, except that the e^+e^- beam energy is 20 GeV.

$$\tau(B\to l+\nu)\simeq 2.4\times10^{-12}\text{ sec}\,, \tag{8}$$

which is a factor of about 5 shorter than the semileptonic decay estimate, Eq. (7). The charged, semistable pseudoscalar meson which carries the new b flavor is very likely to be the lightest, since it would be a $(\bar{b}u)$ composite. We expect, therefore, that the purely leptonic mode would be the dominant one for its decay. Unfortunately, the value of f_B used above is only a guess, so the estimate (8) should be viewed as a very rough guideline. In any case, a branching ratio such that

$$\Gamma(B\to l\nu)/\Gamma(B\to\text{all})\simeq 0.5$$

is a reasonable choice for purposes of illustration. The neutral meson will decay only semileptonically and should have a longer lifetime than the lightest, charged meson.

LEPTON SPECTRUM

The lepton energy spectrum might reveal the presence of unusual hadronic decays independent of the overall rate of lepton yield which, as we already noted, should be larger than expected if hadrons with no weak hadronic decay modes are being produced. The neutral, heavy mesons will decay semileptonically in the types of schemes we are interested in,[2] and the lepton spectrum should be similar to that of the usual $V-A$ interactions—softer than the electrons from τ decay—but the charged, heavy mesons can produce a hard

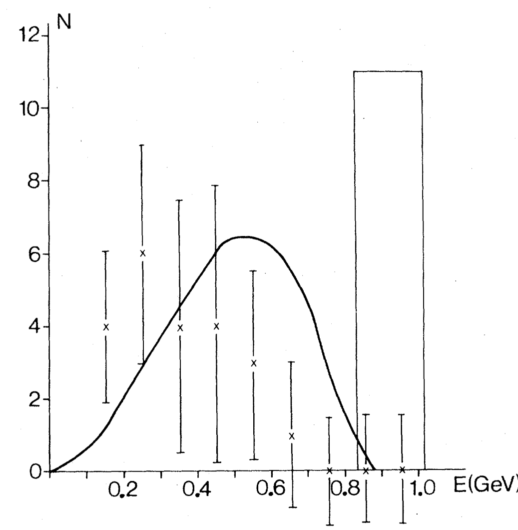

FIG. 4. Comparison of tagged $D^\pm$ electron decay spectrum from SPEAR at 3.771 GeV (Schindler, Ref. 15) with a $D\to Ke\nu$ spectrum (smooth curve) and a $D\to e\nu$ spectrum (flat curve). A bound on $D\to e\nu$ is discussed in the text.

spectrum of electrons by the purely leptonic mode. An unaccountably large number of high-energy secondary electrons or muons would be a signal for the presence of new, scalar-mediated interactions of the heavy quark. In Figs. 2 and 3 we show the electron spectrum computed for τ decay, $V-A$ semileptonic decay of a heavy meson, and purely leptonic decay of a heavy meson at energies of 12 and 20 GeV, respectively. Electron-positron annihilation is the production mechanism in each case, and total center-of-mass energies of 12 and 20 GeV are chosen. The heavy meson is assumed to fragment from the heavy quark,[10,19] and a distribution function which is a constant in z is chosen for illustration, where z is the fraction of quark momentum carried by the decaying meson. In Fig. 4, we show the situation which one would have for the charm decays, with data, to illustrate the diagnostic power of lepton spectra in discriminating between different decay mechanisms. As one sees in Figs. 2 and 3, the lepton spectrum peaks far enough toward high energies in the two-body, purely leptonic case so that one should be able to discern the presence or absence of new interactions, associated with different quark attributes and with CP violation, in CESR, PEP, and PETRA experiments in the 10–20 GeV range of total center-of-mass energies.

ACKNOWLEDGMENTS

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[3]E. Derman, Phys. Rev. D 19, 317 (1979).

[4]H. Georgi and S. Glashow, Nucl. Phys. B167, 173 (1980).

[5]We will refer to the Υ constituent, charge $\frac{1}{3}$, in the alternative schemes as "nonstandard b quarks". A different kind of nonstandard b-quark possibility is covered by the work of C. Quigg and J. Rosner, Phys. Rev. D 19, 1532 (1979). The b quark may mix sizably with light quarks in their analysis, but the weak decays are still W-mediated. Therefore, they obtain a variety of specific semileptonic final states for B decay but their signal does not include the possibility of a hard purely leptonic spectrum as does ours.

[6]The measurements of Barber *et al.*, Phys. Rev. Lett. 43, 1915 (1979), already put some constraints on the production and purely leptonic branching ratio of such objects as we discuss below.

[7]Data which might indicate the decay of mesons which contain b quarks into the nonleptonic $\psi K\pi$ mode have been presented by the GOLIATH collaboration at the 1979 EPS meeting. A hint that $b\bar{b}$ production is already showing up in the e^+e^- data at PETRA is discussed by A. Ali, J. Körner, J. Willrodt, and G. Kramer, Phys. Lett. 83B, 375 (1979).

[8]B. P. Kwan, Ph.D. thesis (SLAC Report No. 207, 1978) (unpublished). All of our discussions apply to either $e+$ other particles or $\mu+$ other particles in the final state.

[9]Barber *et al.*, Ref. 6; J. Kirkby, in *Neutrinos—'78*, proceedings of the International Conference for Neutrino Physics and Astrophysics, Purdue, 1978, edited by E. C. Fowler (Purdue University Press, West Lafayette, Indiana, 1979), p. 631; G. J. Feldman, *ibid.*, p. 647.

[10]A. Ali, Z. Phys. C 1, 25 (1979); A. Ali, J. Körner, G. Kramer, and J. Willrodt, Nucl. Phys. B168, 409 (1980).

[11]τ events have been selected in Ref. 6 by the choice of $e^+ + e^- \rightarrow \mu +$ charged hadron or e mode. This discriminates against standard heavy hadron decays. Purely leptonic hadron decay modes might have this signature, however, as we comment when we discuss the purely leptonic decays of nonstandard heavy hadrons below.

[12]J. Kirkby, talk presented at the International Symposium on Lepton and Photon Interactions at High Energies, Fermilab, Batavia, 1979 (unpublished).

[13]Estimates which have been made are ~15% for $F \rightarrow \tau + \nu$ and ~1% for $B \rightarrow \tau + \nu$. See D. Fakirov and B. Stech, Nucl. Phys. B133, 315 (1978); V. Barger, J. P. Leveille, P. M. Stevenson, and R. J. N. Phillips, Phys. Rev. Lett. 45, 83 (1980).

[14]The branching ratio of τ into a single hadron seems to be about 10%. See the review by Kirkby, Ref. 12.

[15]B. D. Kwan, Ref. 8; R. H. Schindler, Ph.D. thesis (SLAC Report No. 219, 1979) (unpublished).

[16]D. McKay and H. Munczek, Ref. 2, footnote 11. There should be bars above the $d_R^{(1)}$ and $d_L^{(1)}$ in the third term of the Lagrangian of this footnote, and the γ_5 phase of $u^{(1)}$ has the opposite sign to that shown.

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