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Weak Decays of Charmed Particles and Heavy Leptons

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WEAK DECAYS OF CHARMED PARTICLES
AND HEAVY LEPTONS

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Invited Talk

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Photon Interactions at High Energies

I. Introduction

We now believe that charm [1] is in broad outline correct. You have heard the evidence in the experimental talks. Despite the successes of the theory, weak decays of charm may still surprise us. If charm is to fit into a larger world including τ [2] and T [3], it is unlikely that the 1970 charm theory is correct in all particulars. So we should examine the basis of charm and ask where new post-1970 physics may turn up. Much of this talk is therefore concerned with what we do not know about charm: the chirality of the $\Delta C = 1$ current, the Cabibbo suppressed decays, and $\Delta C = 1$ nonleptonic decays generally.

With the τ we are faced with basic issues: what is the neutral particle "ν_τ" appearing in τ decay? Does τ decay via the old weak current or a new one? Where does τ fit into the lepton world? There are partial answers to the first two questions (with one disturbing element: $\tau \to \nu_\tau \pi$ is not seen). The last question will surely occupy us for years, and we may face dramatic surprises. Perhaps we already have one, in the two mysterious HPWF super trimuon events.

II A. Charm's Chirality

Direct lepton production in $\nu_\mu N$, $\bar{\nu}_\mu N$ and e^+e^- annihilation is evidence for charm. However, we still have no solid evidence for the chirality of the $\Delta C = 1$ current [1]. Where should we look?

[+] permanent address

1. Distributions

In dimuon production by ν_μ off d or s quarks (or $\bar{\nu}_\mu s$) [4]

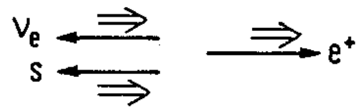
$$\nu_\mu d \to \mu^- c \searrow \mu^+ \nu_\mu s \text{ or } d \quad (\propto \sin\theta_c);\ \nu_\mu s \to \mu^- c \searrow \mu^+ \nu_\mu s \text{ or } d \quad (\propto \cos\theta_c) \qquad (1)$$

ν_μ is left handed and so is d or s in the 1970 GIM theory. The μ^- distribution is thus isotropic in the $\nu_\mu d$ rest frame. Boosted to the lab frame this gives a flat distribution in fractional muon energy loss or fractional hadron shower energy $y = 1 - E_\mu - /E_\nu = E_{had}/E_\nu$. If the struck quark were right handed, angular momentum shows that it would go backward in the rest frame and have a lower lab energy, the μ_2 carrying off the greater part (the y distribution is, of course, $(1-y)^2$).

Experimentally we have the claim of the CDHS group that the overall dimuon distribution is compatible with being flat [5], as expected for a V-A $\Delta C = 1$ current (V+A is thus ruled out). However, the group does not give upper limits on the amount of s_R (from low x events) or d_R (from high x or valence quark events) allowed in the $\Delta C = 1$ current.

There is another application [6] of these ideas. Namely in

$$e^+e^- \to D\bar{D} + \ldots$$
$$\searrow e^+ \nu_e + \begin{cases} K \text{ (V current) (2)} \\ K^* \text{ (V,A currents)} \\ \vdots \end{cases}$$



the kinematic configuration with maximum e energy is forbidden by angular momentum for a left handed s_L (see the figure). So we expect soft e^+ with $\bar{K}$. For s_L and s_R appearing symmetrically in the current [6], the maximum e^+ energy is allowed, and a harder spectrum will result.

Experimentally, it does not yet appear possible to decide the issue; we need more data on D decays at the $\psi(3772)$ [7].

2. Polarization

Neither of the above tests is satisfying; it would be better to infer the s polarization from the polarization of a Λ^o containing it.

Consider neutrino production of the charmed baryon $C_o^+(cud)$

$$\nu_\mu n \rightarrow \mu^- C_o^+ \searrow e^+ \nu_e \Lambda^o \qquad (3)$$

studied by G. Köpp et al.[8] In general $C_o^+(c\ ud)$ will be polarized (in the production plane, by T-invariance). Because $d_L \rightarrow c_L$ is proportional to $\sin\theta_c$, this polarization is very sensitive to any d_R admixture in the current.

Turning to the Λ^o polarization, the authors of (8) find nearly complete longitudinal polarization, using the 1970 GIM theory. If the transitions $c \rightarrow s_L$ and $c \rightarrow s_R$ were equally strong and in phase[6], the current would be pure vector, and $\langle P''_{\Lambda^o}\rangle = 0$.

Another place to look for longitudinal Λ^o polarization:

$$e^+e^- \rightarrow C\bar{C} + \ldots \searrow e^+ \nu_e\ \Lambda^o + \ldots \qquad (4)$$

(or equivalently $e^-\bar{\Lambda}^o + \ldots$, where C is now a generic charmed baryon). Because of 1γ exchange, C is now unpolarized. A nonzero longitudinal polarization is thus, of course, evidence for parity violation.

Cross sections for $C\bar{C} + \ldots$ as large as several percent of σ_{tot} are credible theoretically and experimentally[9]. With $B(C \rightarrow e^+\nu\Lambda^o + \ldots) \approx 10\ \%$, about 1 in 10^3 e^+e^- events above $E_{CM} \sim 4.5$ GeV will contain $e^+\Lambda^o$. Of course $e^+\Lambda^o$ from an exclusive channel like $C_o^+\bar{C}_o^-$ will be less frequent. Because $C\bar{C} + \ldots$ is an inclusive process, we should not expect $\langle P''\rangle_{\Lambda, e^+\Lambda}$ as large as in (3). Of course, observation of any nonzero polarization would be of great significance.

Note that in $e^+\bar{\Lambda}^o$ analogous to (4), e^+ tags a semileptonic decay of C, whereas $\bar{\Lambda}^o$ comes from a (mostly nonleptonic) decay of $\bar{C}$. As a result, it will also be interesting to examine $\langle P^{\mu}_{\Lambda^o}\rangle_{e^+\bar{\Lambda}}$. Maybe it will tell us something about chirality in $\Delta C = 1$ nonleptonic decays.

II B. Cabibbo's Angle

The dominance of kaons in charm decays is a dramatic confirmation of the $\Delta C = \Delta S = \pm 1$ rule[10]. Now we need to look for violations of this rule. The 1970 theory predicts that $\Delta C = \pm 1$, $\Delta S = 0$ decays will take place at a rate $\sim \tan^2\theta_c$ times the rate of $\Delta C = \Delta S = \pm 1$ decays. Deviations from this prediction will be evidence for something new in charm decay.

1. Semileptonic Processes

Tests of the charm current are cleanest in semileptonic processes, since the hadronic current appears once, multiplying a known leptonic

current. The leading $\Delta C = \Delta S = \pm 1$ piece has $\Delta I = 0$, leading to $\Gamma(D^o \rightarrow \ell^+ \nu K^-) = \Gamma(D^+ \rightarrow \ell^+ \nu \bar{K}^o)$. It may be possible to test this by looking for decays in emulsions. This consequence of the $\Delta I = 0$ rule may also be useful in normalizing the relative total D^o and D^+ decay rates as seen in e^+e^- annihilation[11].

decay	amplitude	ΔS	ΔI
$c \rightarrow l^+\nu_l s$	$\cos\theta_c$	1	0
$c \rightarrow l^+\nu_l d$	$-\sin\theta_c$	0	1/2

The specific Cabbibo structure of the current appears in

$$\frac{\Gamma(D^o \rightarrow e^+\nu\pi^-)}{\Gamma(D^o \rightarrow e^+\nu K^-)} = \frac{BR(D^o \rightarrow e^+\nu\pi^-)}{BR(D^o \rightarrow e^+\nu K^-)} = \begin{bmatrix} 1.6 \\ 2.0 \end{bmatrix} \tan^2\theta_c \qquad (5)$$

which can be measured in e^+e^- annihilation. (The numbers in the bracket are calculated using $F_+(Q^2) = F_+(0)$, giving the 1.6, and $F_+(Q^2) = (1 + Q^2/M^2_{D,F})^{-1}F_+(0)$, giving 2.0. SU_3 for $F_+(0)$ has also been used, from the Ademollo-Gatto theorem[12]. Significant violation of (5) would indicate a new piece in the hadronic $\Delta C = 1$ current.

Notice that (5) only checks whether d and s are mixed as the 1970 theory predicts - not whether the decaying c quark is entirely the 1970 charmed quark. Suppose c'' entered (5) rather than c, where

$$\begin{pmatrix} c'' \\ t'' \end{pmatrix} = \begin{pmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} c \\ t \end{pmatrix} \qquad (6)$$

(t being a new $e_t = 2/3$ quark, probably with its own charge $-1/3$ partner b)[13]. Now (5) is unchanged, but c is now no longer the promised 100 % charmed quark (charm is distributed among c and t). We can check this by comparing

$$\nu_\mu d \rightarrow \mu^- c \searrow \mu^+ \nu\ s \text{ or } d \quad \text{and} \quad e^+e^- \rightarrow c + \bar{c} \searrow \mu^+ \nu\ s \text{ or } d \qquad (7)$$

For the latter, σ_{charm} is known, and DASP gives us the semileptonic branching ratio $B_e = 11 \pm 3\ \%$[14]. The former (from dimuon data at large x where valence d quarks dominate) gives $B^e \sin^2\theta_c \cos^2\phi$. The CDHS group have not analyzed their data with this in mind. They do claim that a credible s to d ratio, ≈15 % B^e and $\sin^2\theta_c = .05$ (no factor $\cos^2\phi$) agrees with their data [5]. Probably $\cos^2\phi$ as small as ∿ 1/2 is not yet excluded. This should be looked at more carefully.

2. ΔC = 1 Nonleptonic Decays

The nonleptonic decay Hamiltonian transforms as a sum of the symmetric 20 and 84 representations of SU_4 (see section IIIC). An immediate consequence of this and SU_3 invariance is

decay	amplitude	ΔS	ΔI
$c \to u\bar{d}s$	$\cos^2\theta_c$	1	1
$c \to u\bar{d}d$	$-\cos\theta_c \sin\theta_c$	0	1/2, 3/2
$c \to u\bar{s}s$	$\cos\theta_c \sin\theta_c$	0	1/2
$c \to u\bar{s}d$	$-\sin^2\theta_c$	-1	0,1

that for certain nonleptonic decays only <u>one</u> reduced matrix element contributes, and the ratio of Cabibbo suppressed to allowed decays is predicted to be [15]

$$\frac{\Gamma(D^o \to \pi^+\pi^-)}{\Gamma(D^o \to K^-\pi^+)} = 2\,\frac{\Gamma(D^+ \to \pi^+\pi^o)}{\Gamma(D^+ \to \bar{K}^o\pi^+)} = \frac{1}{2}\,\frac{\Gamma(F^+ \to K^o\pi^+)}{\Gamma(F^+ \to \eta\pi^+)} \tag{8}$$

$$= 2\,\frac{\Gamma(F^+ \to K^+\pi^o)}{\Gamma(F^+ \to \bar{K}^o K^+)} = \text{R.M.F.}\ \tan^2\theta_c$$

(the above uses Isgur's wave function $\eta = \frac{1}{2}(u\bar{u} + d\bar{d} - \sqrt{2}s\bar{s})$ [16], and R.M.F. stands for relative momentum factors--phase space times barrier penetration factors or form factors). Simple S-wave phase space gives < 20 % corrections to (8); this is probably the order of magnitude of SU_3 violations also). Large violations of (8) would mean

(i) There is a new piece in the ΔC = ± 1 weak current, <u>or</u>

(ii) The still poorly understood nonleptonic decay dynamics [17] induces representations other than 20 and 84 in H_{NL}.

Experimentally, we only know that $\Gamma(D^o \to \pi^+\pi^-)/\Gamma(D^o \to K^-\pi^+) < 8\ \%$.

3. D^o-$\bar{D}^o$ Mixing and ΔC = -ΔS Decays

The 1970 theory predicts small D^o-$\bar{D}^o$ mixing [1],[18]. A produced D^o

decays promptly in ∿ 10^{-13} sec. to mesons and possibly leptons. There is no time for mixing with $\bar{D}^o$. The mixing must compete with ΔC = -ΔS decays at a fractional level of order $\theta_c^4 \sim 10^{-3}$.

A very clean way of looking for mixing or a ΔC = -ΔS decay is through production and decay of ψ(3772) [15],

$$e^+e^- \to \psi(3772) \to D^o + \bar{D}^o \to \begin{cases} K^\pm K^\pm + \ldots \\ e^\pm e^\pm + \ldots \end{cases} \tag{9}$$

The final state with $K^\pm K^\pm$ arises through mixing and ΔC = -ΔS decay; $e^\pm e^\pm$ solely through mixing provided the semileptonic ΔQ= ΔC rule is valid. Experimentally we know that in e^+e^- annihilation a D^o decays as a $\bar{D}^o$ less than 18 % of the time [20] (same sign dimuon data [5] appear to lead to a similar but more model dependent number) .

While this data excludes the existence of an order G_F ΔC = 0 neutral current (which would give complete mixing) [15], we are still 2 orders of magnitude away from the prediction of the 1970 theory [1]. Activity in this unexplored range would be evidence for something new. Notice in particular that we have no bounds or data on final states (9) with same sign electrons. DELCO should be able to deliver on this.

II C. Nonleptonic Decays: Models

Can we expect to improve our understanding of nonleptonic weak interactions by studying charm decays? This is not obvious: final state multiplicities are large and information may be washed out by final state interactions. (This does not apply to selection rules respected by the strong interactions, of course.) Probably we should only accept as potential weak interaction physics those things which deviate significantly from what would be expected in a statistical or thermodynamic model [21]. The relative decay rates into two body channels seems an ideal place to look. Remember that at Frascati energies $\sigma(e^+e^- \to \pi^+\pi^-) \sim \sigma(e^+e^- \to K^+K^-)$ [22] (evidence for the SU(3) classification of the photon), but that inclusively few heavy particles are produced (information on SU(3) is lost) [23]. Here H_{NL} will play the role γ has in e^+e^- annihilation. Let us look at some options.

1. Sextet Dominance

H_{NL}^{quark} (ΔC = 1), broken down into SU(4) and SU(3) representations is shown in the table. It is the sum of two pieces [24]:

(i) an SU(3) V-spin singlet in an SU(3) 6 which in turn is in an SU(4) 20 and

(ii) a V-spin triplet in an SU(3) 15, buried in an SU(4) 84

$\Delta C = 1$	SU_4	SU_3	V spin	comment
$(\bar{s}c)(\bar{u}d) - (\bar{u}c)(\bar{s}d)$	$\underset{\sim}{20}$	$\underset{\sim}{6}$	0	$\Delta C = 0$ is pure octet
$(\bar{s}c)(\bar{u}d) + (\bar{u}c)(\bar{s}d)$	$\underset{\sim}{84}$	$\underset{\sim}{15}$	1	$\Delta C = 0$ is octet plus $\underset{\sim}{27}$

Many authors observed that the $\underset{\sim}{84}$ contains a $\Delta C = 0$ piece with $\Delta I = 3/2$, whereas the $\underset{\sim}{20}$ has a pure octet $\Delta C = 0$ ($\Delta I = 1/2$)piece (24). Accepting exact SU(4), they concluded that the octet enhancement of nonleptonic strange particle decays implied an enhancement of the SU(4) 20-plet (or perhaps suppression of the $\underset{\sim}{84}$, or both simultaneously). Then $H_{NL}^{effective}$ ($\Delta C = 1$) transforms as an SU(3) $\underset{\sim}{6}$ and charm decays satisfy a $\Delta V = 0$ rule. Thus follows

$$\Gamma(D^+ \to \bar{K}^o \pi^+) = 0 \qquad (10)$$

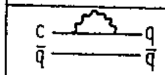
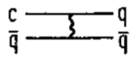
(among other relations) (24).

Actual enhancement of the nonleptonic $\underset{\sim}{6}$ would naturally lead to a large nonleptonic decay rate and a small semileptonic branching ratio (and perhaps a difference in D^o and D^+ lifetimes).

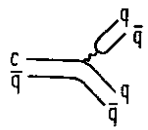
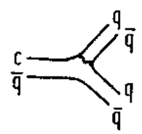
None of the above has come to pass. From the DASP group we have $BR(D \to e\,\nu + \ldots) = 11 \pm 3$ % (14) (confirmed within errors by DELCO and SPEAR experiment SP-26). This is not small. SP-26 has reported the first clean evidence for $D^+ \to K^- \pi^+$ at this conference. They quote $BR(D^+ \to \bar{K}^o \pi^+) = 1.5 \pm .6$ % and $BR(D^o \to K^- \pi^+) = 2.2 \pm .6$ %. It does not seem likely that $\underset{\sim}{6}$ dominance will play a role in the future. We must look elsewhere.

2. Quark Comics

Let us turn to a simple alternative: quark diagrams and H_{NL}^{quark} as a description for $\Delta C = 1$ two body decays. These comic book pictures are familiar by now and are shown in the tables: amplitudes are calculated using color factors and exact SU(3) and ignoring gluons (25). The resulting picture for $\Delta C = 1$ decays is certainly too naieve, but it is clear, uncomplicated and predictive. Seen this way, a D meson is a $c\bar{q}$ atom in which $\bar{q}$ is either captured by c or c decays ($c\bar{q} \to q\bar{q}$ or $c \to qq\bar{q}$, q being u, d or s). In the limit of zero q mass, quark capture vanishes by helicity: a V - A interaction gives q_L and $\bar{q}_R$ and a ^1S_o $c\bar{q}$ state cannot go to $q_L\bar{q}_R$ (spin 1) (26). Charm decays simply involve the decay of the c nucleus of the $c\bar{q}$ atom. The basic test of this is (25),(26)

picture	contributes to	comment
	$D^o \to \pi^+\pi^-$ $D^+ \to \pi^+\pi^o$	Cabibbo suppressed; zero in free quark model; ignore.
	$D^o \to K^-\pi^+$ $D^o \to \bar{K}^o\pi^o$	vanishes by helicity for $m_q = 0$; ignore
	$F^+ \to \pi^+\pi^+\pi^-$	vanishes by helicity for $m_q = 0$; absence of 3π mode tests idea

quark capture, $c\bar{q} \to q\bar{q}$

picture	contributes to	comment
	$D^+ \to \bar{K}^o\pi^+$ $D^o \to K^-\pi^+$ $F^+ \to \eta\pi^+$	color factor 3 in amplitude enhances rate; inclusively gives ratios $e\nu s$: $\mu\nu s$: $u\bar{d}s \sim 1 : 1 : 3$
	$D^+ \to \bar{K}^o\pi^+$ $D^o \to \bar{K}^o\pi^o$ $F^+ \to \bar{K}^o K^+$	no color factor in amplitude; rates not enhanced (alternatively, they are suppressed relative to e.g. $D^o \to K^-\pi^+$)

quark decay $c\bar{q} \to q\bar{q}q\bar{q}$

$$\frac{\Gamma(F^+ \to \pi^+\pi^+\pi^-)}{\Gamma(F^+ \to K^+K^-\pi^+)} << 1 \qquad (11)$$

(see the table; $\Gamma(F^+ \to \rho^0\pi^+) << \Gamma(F^+ \to \bar{K}^{*0}K^+)$ might prove a better test, as it involves two body decays). If (11) fails, the simple quark picture must be discarded.

Suppose (11) succeeds. We can then proceed. Notice that the first amplitudes in the quark decay table get a factor 3 from the sum over three colors of quark in one of the outgoing mesons. Because the colors must match in the second set of amplitudes, they receive no such enhancement. We immediately find many relations for Cabibbo allowed decays,

$$\Gamma(D^0 \to K^-\pi^+) = 2\Gamma(F^+ \to \eta\pi^+) = (3/4)^2\ \Gamma(D^+ \to \bar{K}^0\pi^+)$$
$$= 18\ \Gamma(D^0 \to \bar{K}^0\pi^0) = 9\Gamma(F^+ \to K^+\bar{K}^0) \qquad (12)$$

(it is easy to extend this to Cabibbo suppressed decays). Now we see that $D^+ \to K^+\pi^0$ is no longer suppressed, but $F^+ \to K^+\bar{K}^0$ is (27) (satisfying our condition that there must be deviations from a statistical model, for which $F^+ \to K^+\bar{K}^0$ is unsuppressed (21)).

If $F^+ \to K^+\bar{K}^0$ is indeed small, it would explain why F^+ has not so far been seen in this channel (a better charged mode for an F^+ search would be $K^+K^-\pi^+$). Further, (12) is consistent with the fact that $F^+ \to \eta\pi^+$ has been seen.

Quark decay naturally leads to equal semileptonic branching ratios for D^0, D^+ and F^+ (c knows nothing of the flavor of $\bar{q}$ in a $c\bar{q}$ state). The DELCO group has presented data bearing on this (14). They note that the semileptonic branching ratios from 2e events/1e events and 1e events/all charm at $\psi(3770)$ are equal. But it is easy to see that if $\sigma(D^0\bar{D}^0) = \sigma(D^+D^-)$; $\sigma(F^+F^-) = 0$,

$$\frac{B_{2e}}{B_{1e}} - 1 = \left(\frac{B_e(D^+) - B_e(D^0)}{B_e(D^+) + B_e(D^0)}\right)^2 \qquad (13)$$

and $B_{2e} = B_{1e}$ implies $B_e(D^+) = B_e(D^0)$. (At present the errors are rather big; hopefully we will soon have separate values for $B_e(D^+)$ and $B_e(D^0)$ (28).)

If this simple model turns out to have anything to do with real charm decays, it might help us on the way to a general understanding of non-leptonic decays. It may also be of some use in myopic futurism: guessing how final states will look above the threshold for producing the objects of which $\Upsilon(9.4)$ is made (if it is a quark-antiquark bound state) (29).

III. Tau

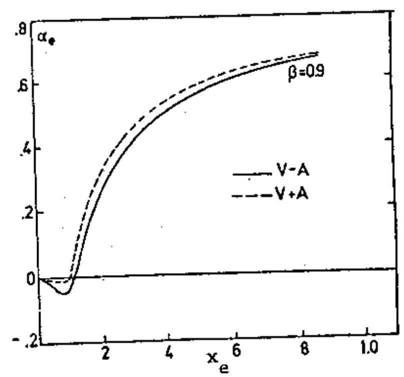
Persuasive evidence for a heavy lepton τ with pointlike e^+e^- production cross section has been presented at this conference and ably reviewed by Perl (2). The τ mass lies in the range 1.8 - 1.95 GeV, and lepton spectra and all branching ratios except $\tau \to \nu_\tau\pi$ agree with what is expected for a V - A τ with its own massless neutrino. In particular, $BR(\tau \to e\nu\nu) \sim B(\tau \to \mu\nu\nu) \sim$ 15-20 %.

I have only two comments by way of introduction:

Firstly, there is a decisive test for a pointlike j = 1/2 τ. Measure $e^+e^- \to \tau^+\tau^- \to e^\pm$ + 1 prong, where

$$\frac{d\sigma_e}{d\Omega} \propto 1 + \alpha_e \left[\cos^2\theta_e + P^2 \sin^2\theta_e \cos 2\phi_e\right] \qquad (14)$$

(P is the $e^\pm$ polarization, θ_e the polar angle and ϕ_e the azimuth measured from the ring plane). Now, Pais and Trieman (30) pointed out that $\langle\alpha_e\rangle$ (α_e integrated over p_e) is independent of the τ decay interaction. It depends only on $\beta \cong p_\tau/E_B$ for a pointlike j = 1/2 τ and can be calculated exactly (e.g. $\langle\alpha_e\rangle$ = .25 for E_{beam} = 3.5 GeV). In addition $\alpha_e(x_e = P_e/E_B, E_B)$ can be calculated (31)(32) and turns out to be insensitive to the V,A structure of the τ-ν_τ vertex. (See the figure, from Ref. (31). It would be useful (if perhaps anticlimactic) to check this prediction.



Second remark: we know that charm is produced singly by the weak charged current in ν_μ interactions, and pairwise from 1γ in e^+e^- annihilation. By contrast, $\tau^+\tau^-$ is produced in e^+e^-, but not by a weak current striking a nucleon. This gives a consistency check on the belief that τ is a heavy lepton (and not, for example a liberated quark): the lepton spectra in

$$e^+e^- \to D + \ldots \to e^+ \text{ or } \mu^+ + \ldots \quad \text{and} \quad \nu_\mu N \to \mu^- D^+ \ldots \to e^+ \text{ or } \mu^+ + \ldots \qquad (15)$$

<u>should be the same</u> (the $\tau^+\tau^-$ contribution to the former can be <u>eliminated by demanding</u> high multiplicities). The comparison depends on the assumption that a charmed quark fragments the same way in e^+e^- and $\nu_\mu N$. It should be carried out at the same value of the parent quark momentum in both processes or, accepting scaling, by plotting e^+e^- and $\nu_\mu N$ data versus a common scaling variable (e.g. $z = p_e/p_{quark}$).

Data on inclusive muons in multiprong e^+e^- events has been published by the SLAC-LBL group for mean CM energy 6.9 GeV (33). This is easily plotted versus a scaling variable. Unfortunately, the μ^+ spectra in $\nu_\mu N \to \mu^-\mu^+ + \ldots$ have not yet been plotted this way, which makes comparison difficult. However, Odorico (34), in a contributed paper, points out that the energy distribution of the "soft" muon in dimuon events is well accounted for if one assumes a $D \to e\nu K$ decay and a charmed quark to D meson fragmentation function $D(z)$ = constant. Coincidentally, T.C. Yang and the present author have independently noted that the SLAC-LBL data on $e^+e^- \to \mu^\pm$ + multiprongs can be accounted for using the <u>same</u> constant fragmentation function. (35)

There is thus no evidence for a second "τ-like" component to the soft muon spectrum in dimuon events, and we have no reason from this corner to suspect that τ is anything but a heavy lepton. However, a direct comparison of data would be more satisfying.

To sum up: there are still unexplored issues, but every reason to believe that the heavy lepton τ exists. The remainder of this talk is about the physics issues arising from this fact.

III A. What is "ν_τ"?

We know little about the missing neutral in decays like $\tau^- \to e^-\bar{\nu}_e"\nu_\tau"$, $\mu^-\bar{\nu}"\nu_\tau"$. From PLUTO we have the mass limit $m_{\nu_\tau} < 540$ MeV,(36) and from the existence of μe events and nonexistence of μe plus further tracks it seems plausible that the lifetime is $c\tau_{\nu_\tau} > 10^2$ cm

It is not yet even established that "ν_τ" does not interact strongly with matter.

Let us <u>assume</u> that "ν_τ" is a light spin 1/2 weakly interacting neutral.

What can we say about the possibility that it is a known neutrino?

1. "ν_τ" is $\bar{\nu}_{eR}$ or $\bar{\nu}_{\mu R}$

Suppose "ν_τ" is the same as the right-handed antineutrino $\bar{\nu}_{e\,R}$ or $\bar{\nu}_{\mu\,R}$ appearing at the e or μ vertex in $\tau^- \to "\nu_\tau" e^-\bar{\nu}_e$ or $\tau^- \to "\nu_\tau"\mu^-\bar{\nu}_\mu$. There is then a statistics factor 2 in the rate for $\tau^- \to \bar{\nu}_{eR}\, e^-\bar{\nu}_{eR}$ or $\tau^- \to \bar{\nu}_{\mu R}\,\mu^-\bar{\nu}_{\mu R}$, <u>independent</u> of the τ lifetime (37),(38). There is

evidence against such a factor for "ν_τ" = $\bar{\nu}_{eR}$ and weaker evidence against such a factor for $\bar{\nu}_{\mu R}$ (2).

The fact that the reaction (39)

$$\nu_{\mu L}\, N \to \tau^+ + \ldots \qquad \tau^+ \to \mu^+ + \ldots \tag{16}$$

is not seen argues against $\bar{\nu}_{\mu R}$, provided the weak interaction in this process is order G_F.

Notice that neither of these arguments would apply if one supposed that "ν_τ" were a new <u>left-handed</u> antineutrino with the same lepton number as $\bar{\nu}_\mu$ or $\bar{\nu}_e$, but produced only in τ decay. In the following we follow Perl and (tentatively) discard "ν_τ" = $\bar{\nu}_{e\,R}$ or "ν_τ" = $\bar{\nu}_{\mu R}$.

2. "ν_τ" is ν_{eL} or $\nu_{\mu L}$

Data presented at this conference bears on this question - in particular on the possibility that "ν_τ" = $\nu_{\mu L}$ (the left-handed neutrino in K^+ or $\pi^+ \to \mu^+\nu_\mu$). PLUTO has presented a 2 σ upper bound on the τ lifetime, $\tau_\tau < 1 \times 10^{-11}$ sec. (36) In the unit

$$\tau_o = \frac{1}{5}\,(1.90\ \mathrm{GeV}/m_\mu)^{-5}\ \tau_\mu = 2.3 \times 10^{-13}\ \mathrm{sec}$$

this is

$$\tau_\tau/\tau_o \;<\; 43 \tag{17}$$

In addition, both FNAL and CERN bubble chamber groups have looked for $\nu_{\mu L} + N \to \tau^- + \ldots$ with τ^- decaying to $e^- + \ldots$ (40). Their limits, expressed in the same unit, are

$$\tau_\tau(\nu_\mu)/\tau_o \;>\; \begin{cases} 12 & \text{FNAL} \\ 15 & \text{CERN} \end{cases} \tag{18}$$

($\tau_\tau(\nu_\mu)$ is the inverse of the rate to $\nu_\mu + \ldots$).

Evidently, events of this sort (soft e^- in a ν_μ beam) will be seen soon, or "ν_τ" = $\nu_{\mu L}$ ruled out. It is obviously much harder to rule out "ν_τ" $\equiv$ ν_{eL}, because of the low intensity of ν_e beams. In order to go beyond these considerations, we will have to turn to models (in section III C, D). From now on "ν_τ" = ν_τ; we assume a new neutrino.

III B. Testing the Current

We want to know whether or not the τ decays via the "known" vector and axial vector weak current, ignoring at first the possibility of S P T contributions to the vertex [31].

1. V, A Structure

The V, A structure of the τ-ν_τ vertex shows up in the decay spectrum $\tau \to e\nu\nu$ and in the angular correlation of $e\mu$ events [41)(42]. Theoretically, a V $\mp$ A τ-ν_τ vertex is most popular. It may be worth recalling that this is expressed in terms of the Michel parameter $\rho = 0$ for $(V \mp A)_\tau (V \pm A)_e$ and $\rho = 3/4$ for $(V \mp A)_\tau (V \mp A)_e$ (the subscripts refer to the vertex: τ for τ-ν_τ and e or μ for e-ν_e or μ-ν_μ) [31]. Consistency of the decay spectrum with $\rho = 3/4$ only implies a V − A τ-ν_τ vertex given the conventional ν_{eR} or $\nu_{\mu R}$ with e^- or μ^-. This amounts to assuming in advance that the old V − A current is responsible for τ decay. A new current coupling τ to ν_τ and e or μ to new left-handed antineutrinos would reverse the chirality of the τ-ν_τ vertex if we assume that $\rho = 3/4$. A polarization measurement would be needed in order to disentangle this.

It would be well to keep in mind that we have at present little evidence about the V, A structure of the τ decay interaction.

2. The Hadronic Current in τ Decay

The decay of τ to specific channels [43), (41), (42] is usually calculated from the known weak current

(i) whose leptonic part is the V − A theory with two component left handed neutrinos
(ii) whose vector hadronic part satisfies CVC, is of first class, and obeys Cabibbo universality
(iii) whose axial part is responsible for $\pi \to \mu\nu$ decay, is also first class and universal.

(Of course, the current-current Hamiltonian or W boson exchange is also used). While the decay rates to specific channels may be predicted accurately, branching ratios are more uncertain. This is because multibody decays are model dependent, and they enter branching ratios through the total rate. It is therefore important to emphasize our qualitative knowledge, and those places where the theory can be precisely tested.

Qualitatively, we know that e-μ universality is not violated by as much as a factor two [2], that vector and axial vector currents appear to be present (this depends on the impressive evidence presented by DASP and PLUTO for $\tau \to \nu_\tau\rho$ [14] and $\tau \to \nu_\tau A_1$ [36], respectively. The

latter corroborated by SP-26 [2]), and that with the exception of the branching ratio for $\tau \to \nu_\tau\pi$ [14], the predicted final states in τ decay are there at about the level expected for a sequential heavy lepton [2), (43), (41), (42].

We can test quantitatively whether τ decays via the conventional current. We assume

(i) The conventional weak current is solely responsible for τ decay
(ii) The weak τ-ν_τ vertex is <u>any</u> mixture of pointlike V and A (but these alone)
(iii) The mass of the τ associated neutrino is not too large (m_{ν_τ} < .7 GeV).

Eliminating the uncertain total τ decay rate by taking a ratio of branching ratios, we can then derive <u>lower bounds</u> for the quantities

$$\frac{BR(\tau^- \to \nu_\tau H^-)}{BR(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} > \begin{cases} 0.50 & H = \pi^- \\ 1.10 & H = \rho^- \end{cases} \qquad (19)$$

(The derivation is a straightforward application of formulae in refs. (37), (42)). The bound for ρ is uncertain to 10-20 % due to finite-width effects and errors on the experimental quantity $f_\rho^2/4\pi$ (the ρ-γ coupling). By contrast, the bound for π is good to a few percent as the pion decay constant f_π is well known. We heard from Yamada [14] that DASP finds no $\tau^- \to \nu_\tau\pi^-$ at a level 2-3σ below the lower bound (18). (The discrepancy is 3σ for a leptonic branching ratio 20 %, and 1.5σ for a 15 % $\tau \to e\nu\nu$ branching ratio; the DASP value is 20 $\pm$ 3 %). <u>If this is confirmed, τ cannot decay solely via the conventional weak current.</u> An <u>extraordinary result</u>, since apparently $\tau \to \nu_\tau\rho$ and $\tau \to \nu_\tau A_1$, and the branching ratios $\tau \to \nu_\tau\mu\nu$, $\nu_\tau e\nu$ are as predicted, and – a vital point in view of the nearby charm threshold – very few kaons appear in τ decay.

Is there a simple and plausible explanation for a small or vanishing $\tau \to \nu_\tau\pi$? Some exploratory options:

(i) The τ-ν_τ vertex is V and A but has structure. This contradicts our belief in a pointlike τ.
(ii) Besides the old current, a new pseudoscalar piece is present which interferes destructively with the old current in $\tau \to \nu_\tau\pi$. This strains credulity. And why then is the ratio $\pi \to e\nu/\pi \to \mu\nu$ small (it agrees with V − A theory)?

(iii) There is a new current in τ decay (e.g. V + A , mediated by a new W boson), and its axial piece is conserved or nearly conserved. This is not consistent with the axial quark current $\bar{u}\gamma_\alpha\gamma_5 d$. Its divergence is the same for the old and new currents. It looks hard to escape $\tau \to \nu_\tau \pi$ if $\tau \to \nu_\tau A_1$ is present.

We emphasize that it is not logically inconsistent to have $\tau \to \nu_\tau \pi$ but not $\tau \to \nu_\tau A_1$, but clearly dramatic steps will be necessary if the π decay is really small or zero. If τ is really very near in mass to D and refuses to decay as our preconceptions would have it, we could even be precipitated into a "D-τ puzzle".

It is very important to confirm the DASP result or to find the π decay.

From now on we assume that $\tau \to \nu_\tau \pi$ will be found at the expected level.

III C. A New Lepton Number for τ?

If τ is a sequential heavy lepton with its own massless neutrino, it automatically has a new lepton number. Then we already know a substantial fraction of what we will ever learn about τ. (Of course, τ-number violating decays $\tau \to e\gamma$ or $\mu\gamma$ and $\tau \to (e \text{ or } \mu) + (e^+e^- \text{ or } \mu^+\mu^-)$ may occur at some level (44))

Even if τ has a new lepton number, interesting things can happen.

1. A Massive Neutral Partner N_τ for τ

Suppose that τ follows the pattern of ν_e, e and ν_μ, μ except that its neutral partner is heavy, $M_{N_\tau} > M_\tau$ (45). In general, N_τ will mix with ν_e, ν_μ (which need not be massless) and the V - A doublet involving τ will be

$$\begin{pmatrix} N_\tau + \varepsilon_e\nu_e + \varepsilon_\mu\nu_\mu \\ \\ \tau^- \end{pmatrix}_L \qquad (20)$$

(plus mixed doublets involving e and μ).

Cabibbo universality (45),(46) and CVC are then generally assumed to give ε_e, $\varepsilon_\mu < .1$. The result is a long-lived τ,

$$\frac{\tau_\tau}{\tau_o} = \frac{1}{\varepsilon_e^2+\varepsilon_\mu^2} > 50 \qquad (21)$$

which modestly disagrees with the τ lifetime limit; any improvement would exclude this model with ε_e, $\varepsilon_\mu < .1$. If neutrino experiments are able to exclude $\varepsilon_\mu = 0$ (see Sec. IIIA) this model is presumably already defunct.

An interesting temporary escape from (21) has been noted by Glashow. (45) If the mixing in the lepton sector is the same as in the quark sector (by the Cabibbo angle θ_c), (21) is weakened to $\tau_\tau/\tau_o = 1/2\theta_c^2 = 9.5$. Then we expect τ production in $\nu_\mu N$ only a factor ~ 2 below the present FNAL and CERN limits.

2. Massive Neutrals and V + A Currents

Another possibility, suggested by Fayet (47) and applied to muon number nonconservation by Cheng and Li (44), is to add to each V - A lepton doublet $\begin{pmatrix} \nu_i \\ \ell_i \end{pmatrix}_L$ a V + A doublet $\begin{pmatrix} N_i \\ \ell_i \end{pmatrix}_R$ involving a heavy neutral lepton. (The neutral leptons will in general mix with one another). This model is theoretically interesting because of possible lepton number nonconservation (44). It is experimentally interesting because it predicts no parity violation in heavy atoms (47). It is also a useful paradigm in studying the production and experimental signatures of heavy neutral leptons which might be seen in $e^+e^- \to \bar{\nu}_e N_e + \nu_e \bar{N}_e$, (48) in $\tau \to e N_e \nu_\tau$ (49) (if $M_N < M_\tau$), followed by decay of N_i.

III D. An Old Lepton Number for τ?

It seems prodigal to introduce a new lepton number for each new lepton. An attractive alternative would be to give τ an old lepton number. This idea goes back to Konopinski and Mahmoud (50) who put μ^+, ν, e^- in a triplet with the same lepton number. Following up this possibility for τ within the framework of gauge theories opens some curious and exciting possibilities. We illustrate these possibilities by discussing some selected models:

1. Neutrino Swapping in $SU_2 \times U_1$

One can explore an option where μ^- and e^- share their neutral partners ν_μ, ν_e with the τ^-, which has no partner of its own. This offensive possibility is excluded in $SU_2 \times U_1$ gauge models (one W, one Z) because τ is then wholly unsure of its own lepton number, resulting in a bound (51)

$$BR(\tau \to e\,\ell^+\ell^- + \mu\,\ell^+\ell^-) \;>\; 5\,\% \qquad (1 = e \text{ or } \mu) \tag{22}$$

contradicting the PLUTO (SLAC-LBL) limits which require this branching ratio to be below (1 %) (.6 %)[2].

The interesting possibilities appear when we allow for the possibility that there are many weak bosons (gauge group bigger than $SU_2 \times U_1$).

2. $SU_3 \times SU_3$ Model of Bjorken and Lane

A theoretically respectable model which shows clearly what happens when there are few lepton multiplets but many weak bosons has been invented by Bjorken and Lane[52]. (The model uses a lepton classification due to Gursey and Sikivie[53]). This model has great phenomenological utility, whatever its experimental fate. The model has two octets of gauge bosons mediating the weak and electromagnetic interactions. The familiar W^+, W^- are in the first octet (together with other new charged and neutral bosons). The second octet contains no "known" charged boson. The neutral weak current is distributed among both octets. There is, of course, only one massless boson (the γ). Existing experiments require that many of the unseen weak bosons must be at least several times heavier than the $W^\pm$.

The leptons in this model are in $(\bar{3},3)$ representations with e and μ number. There are new neutrinos as well as new heavy leptons,

$$E = \begin{pmatrix} \bar{\tau}^o & e^+ & \tau^+ \\ e^- & \nu_e & \nu'_E \\ \tau^- & \nu_\tau & \tau^o \end{pmatrix}_L \qquad M = \begin{pmatrix} \bar{M}^o & M^+ & \mu^+ \\ M^- & M^o & \nu'_M \\ \mu^- & \nu_\mu & \nu_M \end{pmatrix}_L \tag{23}$$

The notation is as follows. The familiar $W^\pm$ causes transitions between the first two leptons in each row, and a new $V^\pm$ between the first and third leptons. A new neutral boson mediates the nondiagonal transitions between the second and third leptons. A second octet of bosons acts similarly on the leptons in columns.

The leptonic decay of τ takes place through the usual weak current ($\tau^- \leftrightarrow W^- \nu_\tau$) and for the final state with an electron via a new current (e.g. $\tau^- \leftrightarrow U^o e^-$). This new boson contributes incoherently and

$$\frac{BR(\tau^- \to \nu e \nu)}{BR(\tau \to \nu \mu \nu)} > 1 \tag{24}$$

- i.e. e-μ universality is violated in τ decay because τ has the lepton

number of e^+. The amount of violation is proportional to M_W^4/M_U^4.

The model also has $M_{\tau^o} = M_\tau$; τ^o might be seen via $F^+ \to \tau^o e^+$ followed by $\tau^o \to e^-\pi^+$ at a low rate[54]. It might be better to look for τ^o (or any other heavy neutral lepton with e or μ number) through the semileptonic decay of a heavy quark Q to a light one q, mediated by $W^\pm$ or a new gauge boson. In this model the situation is complicated. However,

$$Q \to \bar{\nu}_E \tau^o q$$
$$\to \nu_\tau \bar{\tau}^o q \tag{25}$$

are allowed if the neutral gauge boson is not very massive. Above the threshold for heavy quarks of mass 5 GeV in e^+e^- annihilation a crude estimate of the number of Q decays containing $\tau^o \to e\pi$ is 1-10 in 10^3. τ^o will also be produced via W exchange in $e^+e^- \to \nu_e \tau^o + \nu_e \bar{\tau}^o$, and $e^+e^- \to 1\gamma \to M^+M^-$ will provide the muonic partner of τ.

Muon neutrino beams will produce M^o by exchange of one of the new neutral weak bosons. Since this coupling involves a light and a heavy lepton, a heavy quark will be produced too,

$$\nu_\mu q \;\to\; M^o\,Q \tag{26}$$

The signature is, of course, a multimuon event[55] generated by the leptonic decay of M^o and the semileptonic decay of Q.

We now turn to a more ambitious (if theoretically less respectable) scheme which exhibits the same phenomenological features.

3. Octet Leptons

The idea that all leptons might be put together into an octet has been around for some time[56]. There is a contributed paper by Achiman[57] on an $SU_3^L \times SU_3^R$ model of this type. We will discuss here a simpler model

	left-handed				right-handed	
	$\bar{N}_e$	e^+			$\bar{\nu}_e$	e^+
τ^-	ν_τ, N_σ	σ^+		τ^-	ν_τ, N_σ	σ^+
	μ^-	ν_μ			μ^-	N_μ

due to Horn and Ross [56]. See the figure for the classification of left and right handed leptons. This time there are only 8 gauge bosons.

This model also shows the phenomenological features we can expect when we attempt to conserve on lepton numbers:

(i) e-μ universality is violated in τ decay due to the presence of new neutral bosons. (Constraints on weak boson or neutral lepton masses also arise from μ-decay and β-decay)

(ii) There is a heavy neutral lepton produced together with ν_e via the weak interactions in e^+e^- annihilation. It may also appear in semileptonic decays of a heavy quark. $\sigma^+\sigma^-$ will be produced via lγ in e^+e^-.

(iii) When new heavy quarks are added, they will be produced together with a new lepton by neutrino beams,

$$\nu_\mu q \to N_\mu Q$$

The signature here is again multimuon production.

We emphasize again that these models are illustrative and not exhaustive; other models exist which make predictions for τ decay [58]. The lesson these models pass on is that if the lepton world has a rich structure but few (or no) new lepton numbers, then we expect that e, μ and ν_e, ν_μ communicate with new leptons and new quarks. "Old" lepton beams will then prove to be a good source of "new" leptons.

Within the next few years we may learn from e^+e^- and neutrino experiments whether these ideas have anything to do with reality or not, and perhaps where the τ fits in the lepton world.

IV. Conclusion

Studies of the production and decay of charm and τ should be based on the conviction that they are only part of a larger reality. We don't understand why τ has appeared (with nearly the D mass!), and in view of the discovery of Υ, we ought to consider it surprising that charm seems to behave as was predicted it should. We have a lot to learn.

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