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FINAL STATES IN CHARMED PARTICLE DECAYS

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ABSTRACT

It is shown how weak decays of charmed particles provide information on the isospin properties of the charm-changing weak interactions, multi-particle production, enhancement of nonleptonic weak interactions, unseen decay modes of known charmed particles and best ways in which to discover new ones, and possible new weak currents and new fermions.

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1. INTRODUCTION

In the period between the discovery of the J/ψ ^{1,2} and that of charmed³⁻⁵ mesons at 1.87 GeV/c²,⁶⁻¹⁰ a good deal has been learned about the weak decays¹¹ of heavy particles. This talk - which might be subtitled "An Appreciation of Charm" - is an attempt to show some of the uses of that information.

We begin (Section II) with a list of the expected properties of charmed particles:^{3, 12-14} their masses, and the states to which they decay. Section III presents some results of isospin restrictions on the final states, mentioning both rigorous consequences of the form of H_{weak} and predictions based on statistical models.^{15, 18-21} These results apply to decays to a fixed number of particles, giving the distribution of charges of these particles.

In Section IV we discuss the branching ratios of charmed particles to final states of various multiplicities. Clues can be taken^{13, 22} from statistical models, and predictions compared with results on $\bar{N}N$ and e^+e^- annihilations²⁶⁻²⁹ at center-of-mass energies similar to the charmed particle masses.

There remain questions of the applicability of symmetries beyond isospin to charmed particle decays, especially the nonleptonic ones.^{13, 30-33} These are discussed in Section V. Answers to these questions may shed light on the way in which the nonleptonic decays of strange particles appear to be enhanced.

The results of Secs. III-V are combined into sets of branching ratios for charmed particle decays. Such predictions can help

interpret present data (Sec. VII), including those experiments which directly detect particles with lifetimes of 10^{-12} - 10^{-14} sec.,³⁴⁻³⁸ and other experiments which observe multi-particle decays of charmed mesons⁶⁻¹⁰ or candidates for charmed baryons.³⁹⁻⁴² The estimates of branching ratios also are used to predict new decay modes of known charmed particles, and to suggest the best modes in which to observe predicted particles like F^+ (2000).^{13, 14, 43}

In proceeding from the expected behavior of charmed particles to the totally unknown world of heavy leptons and new (charmless) heavy quarks, one may be able to use many of the results of Secs. III-VI. Some suggestions are made in Sec. VII. Particular attention is directed to the chance that some of the new objects may be present in the final states of charmed-particle weak decays. Sec. VIII summarizes.

II. CHARMED PARTICLE PROPERTIES

We shall assume the "standard" four quarks are coupled to left-handed charged currents as shown in Table I.³

Table I. Properties of four quarks

Name	Charge	Strangeness	Charm	Currents	θ = Cabibbo Angle ($\approx 15^\circ$)
u	2/3	0	0	$\begin{pmatrix} u \\ d' \end{pmatrix}_L$	$d' = d \cos \theta + s \sin \theta$
d	-1/3	0	0		
c	2/3	0	1	$\begin{pmatrix} c \\ s' \end{pmatrix}_L$	$s' = -d \sin \theta + s \cos \theta$
s	-1/3	-1	0		

The J/ψ mass was an important factor in setting the masses

expected for charmed particles.^{13, 14, 43, 44} The estimates of Ref. 14 were notably successful for S-waves. On the basis of the observed charmed particles, these estimates can be adapted to predict the masses of the remaining singly-charmed S-wave mesons and baryons;^{43, 22} the results are shown in Table II. (Masses in parentheses denote predictions.)

In Table II only the underlined states are expected to be weakly decaying. Others can decay to the underlined ones via photon emission, pion emission, or both.

Our major concern will be with weak decays not involving powers of $\sin \theta$. Consequently, the semileptonic decays we shall discuss involve the transitions

$$c \rightarrow s l^+ \nu_l : \Delta S = \Delta C, \Delta I = 0 \quad (II. 1)$$

while the nonleptonic decays involve

$$c \rightarrow s u \bar{d} : \Delta S = \Delta C, \Delta I = \Delta I_3 = 1 \quad (II. 2)$$

All we say will be valid for antiparticles as well, and they will not be discussed separately. The quantum numbers of hadronic systems to which (II. 1) and (II. 2) give rise have been listed in Refs. 13 and 16.

III. ISOSPIN

As a result of Eqs. (II. 1) and (II. 2), all particles in Table II decay to final states with definite isospin, with the exception of D^0 and A^0 final states, which have a mixture of $I=1/2$ and $I=3/2$. Some restrictions which follow from these total isospin values are noted in Refs. 15-17.

Table II. Observed and predicted charmed particles
(singly charmed S-wave mesons and baryons)

Quark content	Name (Ref. 13)	Mass (MeV/c ²)	References	Remarks
$\bar{c}u$	$\underline{1S_0} \quad \underline{D^0}$	1867 ± 3	6-10, 45	
	$3S_1 \quad D^{*0}$	2005.5 ± 1.5	6-10, 45	
$\bar{c}d$	$\underline{1S_0} \quad \underline{D^+}$	~ 1872	6-10, 45	Sum of masses: 3880 ± 5 . (Ref. 45)
	$3S_1 \quad D^{*+}$	~ 2010	6-10, 45	
$\bar{c}s$	$\underline{1S_0} \quad \underline{F^+}$	(1975)	14, 43	{ Not yet observed }
	$3S_1 \quad F^{*+}$	(2060)	14, 43	
cud	$2S_{1/2} \quad \underline{C_0^+}$	2260 ± 10	39-41	$I = 0$
cuu, cud, cdd	$2S_{1/2} \quad C_1^{++,+,0}$	~ 2420	39-41	{ $I = 1$. See Refs. 22, 43 for interpretation }
	$4S_{3/2} \quad C_1^{*,+,+,0}$	~ 2480	40, 41	
$c\bar{u}, c\bar{d}$	$2S_{1/2} \quad \underline{A^{+,0}}$	(2480)		{ Not yet observed. Mass predictions are those of Ref. 14, adjusted upward by 60 MeV to fit the C_0^+ mass. See Refs. 22, 43. }
$c\bar{u}, c\bar{d}$	$2S_{1/2} \quad S^{+,0}$	(2570)		
	$4S_{3/2} \quad S^{*,+,0}$	(2640)		
$c\bar{s}$	$2S_{1/2} \quad \underline{T^0}$	(2740)		
	$4S_{3/2} \quad T^{*0}$	(2780)		

A. Exact relations.

The decay $D^0 \rightarrow K^- \pi^+$ has been seen⁶⁻¹⁰ Purely because of (II. 2), the amplitude for this process is related to that for two others by^{16, 30, 31}

$$A(D^0 \rightarrow K^- \pi^+) + \sqrt{2} A(D^0 \rightarrow \bar{K}^0 \pi^0) = A(D^+ \rightarrow \bar{K}^0 \pi^+) \quad (III. 1)$$

At least one of the two decays involving $\bar{K}^0$ must occur.

The constraint due to (III. 1) may be expressed geometrically the ratios $\Gamma(D^0 \rightarrow K^- \pi^+)/\Gamma(D^0 \rightarrow \bar{K}^0 \pi)$ and $\Gamma(D^+ \rightarrow \bar{K}^0 \pi^+)/3\Gamma(D^0 \rightarrow \bar{K}^0 \pi)$ lie inside an ellipse.¹⁶ The first ratio is clearly bounded between 0 and 1. That the second also lies between 0 and 1 is a special case of^{16, 17}

$$0 \leq \frac{\Gamma(D^+ \rightarrow X^+)}{\Gamma(D^0 \rightarrow X^0)} \leq 3 \quad (III. 2)$$

where (X^+, X^0) denote the totality of charge distributions of a multi-particle final state with (positive, zero) charge, e.g., $X^+ = (\bar{K} + n\pi)^+$, $X^0 = (\bar{K} + n\pi)^0$. The lower (upper) bound in (III. 2) is attained when $I=3/2$ ($I=1/2$) final states are suppressed. While the $I=1/2$ and $I=3/2$ contributions to $D^0 \rightarrow X^0$ do not interfere in the total rate, they may do so for individual charge states

The D^+ and D^0 semileptonic decays to $l^+ \nu_l \bar{K} + (\geq 0 \text{ pions})$ obey pairwise equalities as a result of (III. 1), e.g.,

$$\Gamma(D^0 \rightarrow l^+ \nu_l K^-) = \Gamma(D^+ \rightarrow l^+ \nu_l \bar{K}^0) \quad (III. 3)$$

Consequently, the branching ratios for the final states in (III. 3),

or for any other pair of isospin-related final states, obey

$$B(D^0)/B(D^+) = \tau(D^0)/\tau(D^+) \quad (III. 4)$$

allowing the ratio of lifetimes τ to be measured.¹⁷

B. Bounds on charge distributions.

While $\Gamma(D^0 \rightarrow K^- \pi^+)/\Gamma(D^0 \rightarrow \bar{K}^0 \pi)$ is restricted to lie only between 0 and 1 in the absence of further information, many other such ratios obey less trivial bounds. For charmed-particle decays,¹⁶ these are useful when one can detect only certain charge states, permitting estimates for the rates at which others are produced. Similar considerations have been applied to decays of the J/ψ and other $c\bar{c}$ states.⁴⁵⁻⁴⁷ A sample of such bounds is presented in Table III. These are the lowest-multiplicity ones for which the bounds aren't either (i) 0 and 1, or (ii) calculable with the help of the most elementary Clebsch-Gordan coefficients.

The method employed in Ref. 16 for obtaining the bounds in Table III is quite straightforward and general. It involves the expansion of the decay amplitude in terms of a set of invariant isospin amplitudes. The expansion coefficients, when this amplitude is squared and summed over kinematic configurations, define a symmetric matrix whose maximum and minimum eigenvalues directly yield the required upper and lower bounds. As the algebra is performed numerically, we have been able to obtain bounds for up to seven particles in the final state.

C. Bounds on the average number of charged particles.

The above methods apply to any quantity linear in branching ratios. One such quantity is the average number $\bar{n}_c$ of charged tracks

Table III. Some isospin bounds on final states in charmed-particle decays

Decaying particle	Final state	Relative to:	Lower bound	Upper bound	Statistical ^{a)} value
D^0	$K^- \pi^+ \pi^- \ell^+ \nu_\ell$	$\bar{K} 2\pi \ell^+ \nu_\ell$	1/3	2/3	1/2
C_o^+	$\Lambda 2\pi^+ 2\pi^- \ell^+ \nu_\ell$	$\Lambda 4\pi \ell^+ \nu_\ell$	1/3	8/15	2/5
D^0	$K^- 2\pi^+ \pi^-$	$\bar{K} 3\pi$	0	4/5	4/15
D^+	$K^- 2\pi^+$	$\bar{K} 2\pi$	0	4/5	2/5
F^+	$\bar{K}^0 K^0 \pi^+$ $+ K^- K^+ \pi^+$	$\bar{K} K \pi$	1/2	1	3/4
C_o^+	$\Lambda 2\pi^+ \pi^-$ or $\Sigma^+ \pi^+ \pi^-$	$\Lambda 3\pi$ or $\Sigma 3\pi$	1/2	4/5	3/5
C_o^+	$K^- p \pi^+$	$\bar{K} N \pi$	0	3/4	3/8

seen in an experiment. Let us assume that an experiment sees all the charged products of K_S^0 and neutral hyperon decays. Then

$$n_c = n_{pc} + 2 n_V \quad (III.5)$$

where n_{pc} is the number of prompt charged tracks and n_V is the number of K_S^0 and neutral hyperons observed to decay to pairs of charged tracks. Fig. 1 shows bounds on $\bar{n}_c$ for D semileptonic and nonleptonic decays.

In Fig. 1a, 1b, the tight bounds for semileptonic decays arise because the $I=1/2$ final state obeys $n(\pi^0) = [n(\pi^+) + n(\pi^-)]/2$, so 2/3 of the pions must be charged.^{15, 48} Thus the variations come entirely from the kaons. The lax bounds in Fig. 1c reflect the large number of isospin amplitudes ($I = 1/2, 3/2$) that can contribute to D^0 nonleptonic

Fig. 1. Bounds on $\bar{n}_c$ for D decays. $\bar{n}_c$ includes charged tracks from K_S^0 decays. n denotes total multiplicity of final state. Black dots denote predictions of statistical model (Sec. III, E). (a) D^0 semileptonic, (b) D^+ semileptonic, (c) D^0 nonleptonic, and (d) D^+ nonleptonic decays.

decays. If $I=3/2$ final states were suppressed, these bounds would be tighter. For $I=0$ final states (arising in some semileptonic decays) one has precise expressions for $\bar{n}_c$, e.g.,

$$\bar{n}_c(C_0^+ - l^+ \nu, \Lambda + n\pi) = -\frac{4}{3} + \frac{2}{3}n, \quad (\text{III. 6})$$

the first term coming from l^+ , the second from Λ , and the third from the pions.

D. Simultaneous bounds.

In many instances two different charge states of the same multiplicity can be observed, but these still do not exhaust all possible charge states of that multiplicity. Thus, for example, the decays $F^+ \rightarrow \bar{K}^0 K^0 \pi^+$, $K^- K^+ \pi^+$ might be observed, but the decay $F^+ \rightarrow \bar{K}^0 K^+ \pi^0$ would be missed if neutral pions were not detected. Since the allowed values of the $\bar{K}^0 K^0 \pi^+ / \bar{K} K \pi$ and $K^- K^+ \pi^+ / \bar{K} K \pi$ ratios must lie in the interior of an ellipse,¹⁶ an improvement on the bound in row 5 of Table III is possible. A similar conclusion holds for any other pair of charge states, with the exception that the ellipse is replaced by a convex figure containing straight-line and curved segments. As an example, the allowed values of

$$X_{\Sigma 2\pi} = \frac{(C_0^+ - \Sigma^+ \pi^+ \pi^-)}{(C_0^+ - \Sigma^+ 2\pi^+)} \quad (\text{III. 7})$$

and

$$Y_{\Sigma 2\pi} = \frac{(C_0^+ - \Sigma^+ 2\pi^+)}{(C_0^+ - \Sigma^+ 2\pi^+)} \quad (\text{III. 8})$$

lie within the convex hull of an ellipse defined by $I_{\pi\pi} = \text{even}$ (amplitudes relatively real) and the point $X_{\Sigma 2\pi} = 1/2$, $Y_{\Sigma 2\pi} = 0$, corresponding to $I_{\pi\pi} = 1$. All the bounding curves in Ref. 15 appear to be the convex hulls of ellipses and points, but we do not yet have a general proof that this should be so.⁴⁹ This is because our method¹⁶ allows the direct

numerical construction of the bounding curves: we bound

$$X_\theta = X \cos \theta + Y \sin \theta, \quad (\text{III. 9})$$

vary θ , and make use of the convexity of the bounding curve to construct the figure using the same eigenvalue procedure described in Sec. III. B.

The simultaneous-bound method also allows one to relate D^+ and D^0 decays to $\bar{K} + n\pi$,¹⁶ thus generalizing to all n the ellipse mentioned below Eq. (III. 1). (This ellipse is replaced by a different convex figure for each n and for each pair of charge states.)

E. Statistical model.

In a multi-particle decay, the number of invariant isospin amplitudes grows rapidly with the number of particles.¹⁹ It was suggested some time ago¹⁸ that the charge distribution in a multi-particle process be calculated by letting each of these amplitudes have equal magnitude, and by assuming that the interference terms vanish when averaged over kinematic variables. Some results of applying this postulate to the decays of charmed particles are shown in Fig. 2. (The entries are rational numbers, explicit results may be found in Ref. 16.)

In Fig. 2 note the statistical suppression of multi- π^0 states,⁵⁰ and the importance of states with $n(\pi^0) \leq 1$. The neglect of interference between amplitudes may be a poor approximation for low n : for $n = 1$, no kinematic averaging can occur, and the statistical prediction is more a reflection of ignorance than of anything else. Another point of caution is that Fig. 2 ignores η , η' production. (However, we shall estimate

Fig. 2. Fractions of $D = \bar{K} + \pi^+$ decays giving $n\pi^0$, one π^0 , etc., on basis of statistical isospin postulate.

In Sec. V, C that the states with η and η' should comprise only about 1/5 of D^0 nonleptonic decays.

The checking of statistical isospin models is illustrated in Refs. 21, 27, and 45-47. From known experimental rates, one uses results such as shown in Fig. 2 to predict rates for unseen modes. These predicted rates imply distributions in the number of observed tracks which may be checked with experiment. Moreover, the branching ratios thus

constructed should add up to 1. In this manner one finds no clear-cut difficulty with the statistical model for J/ψ decays. However, for pionic $\bar{N}N$ annihilations at rest, the model appears to underestimate the production of neutral particles.⁵¹ Whether this shortcoming is due to η and η' , final-state photons, or a fundamental inaccuracy of the model²⁷ is unknown. Charmed-particle decays should be very helpful in shedding further light on the question.

IV. MULTIPLICITIES

When a charmed particle decays, how many particles emerge? What is the shape of the distribution in the number of particles?

A. Statistical (thermodynamic) model for $\bar{n}$.

Imagine the hadronic debris of a charmed-particle decay to be confined to a sphere of radius $R_0 \approx 1$ at a temperature T .^{22, 23} Assume the matter to evolve into $\bar{n}$ pions and the minimum number of additional particles necessary to conserve energy, momentum, and any other quantum numbers. (Hence a 2-body decay corresponds here to $n = 0$.) Then calculate $\bar{n} \sim VT^3$ and the total energy $\bar{E} \sim VT^4$ available to the $\bar{n}$ particles. (Here $V = 4\pi R_0^3/3$.) Eliminate T ; the result is²²

$$\bar{n} = 0.528 (E/E_0)^{3/4} \quad (IV.1)$$

$$(E_0 = \hbar c/R_0 = 200 \text{ MeV.})$$

We interpret²²

$$E = M + M_1 + M_2 \quad (IV.2)$$

for a particle of mass M decaying to particles of mass M_1 , M_2 , and n additional pions, thus the total multiplicity $\bar{n}_{\text{tot}}$ is

$$\bar{n}_{\text{tot}} = \bar{n} + 2 \quad (\text{IV. 3})$$

In this manner one is led to expect values of $\bar{n}_{\text{tot}}$ around 4 for nonleptonic D , F , and C_0 decays.

Eq. (IV. 1) is not expected to hold for values of E so high that the anisotropies seen in e^+e^- annihilations ("jet structures"⁵²) may occur.^{53, 54} However, below $E = 4$ GeV it seems to describe e^+e^- annihilations as well as the conventional formula²⁹

$$\bar{n}_c = 1.93 + 1.5 \ln E_{c, m} \quad (\text{IV. 4})$$

if suitably interpreted.⁵⁵ Thus Eq. (IV. 1) probably can be applied with equal accuracy to weak decays of all particles in Table II.

B. Shapes of Distributions.

Two simple multiplicity distributions for $D \rightarrow \bar{K}\pi + n\pi$ whose shapes are specified by $\bar{n}$ alone are shown in Fig. 3. One is a Poisson distribution in n . The other is obtained by assuming that the Lorentz-invariant matrix element for $D \rightarrow \bar{K}\pi + (n+1)\pi$ is a constant times that for $D \rightarrow \bar{K}\pi + n\pi$, and neglecting the masses of the final hadrons. Then one finds,¹³ for the probability $P_n(n)$ of seeing $D \rightarrow \bar{K}\pi + n\pi$ when the average value of n is $\bar{n}$, the relation

$$P_n(n+1) / P_n(n) = c^2 / [(n+1)(n+2)] \quad (\text{IV. 5})$$

with c a constant fixed by $\bar{n}$.

Fig. 3. Two multiplicity distributions for $D \rightarrow \bar{K}\pi + n\pi$, with $\bar{n} = 2.07$ (Ref. 22). Solid line: Poisson distribution in n , $P_n(n) = \bar{n}^n e^{-\bar{n}} / n!$. Dashed line: distribution of Eq. (IV. 5). (See Refs. 13, 56.)

The distributions of Fig. 3 give a first impression of the charmed-particle decay multiplicity one might expect.⁵⁷ They may be combined with statistical isospin predictions^{16, 18-20} to yield branching ratios for any charge state. As the distribution of (IV. 5) should be corrected for particle masses,^{58, 59} I will not use it further except to note that it is narrower than the Poisson distribution, and gives smaller two-body branching ratios. In this talk I shall present some tables of branching ratios based on Poisson distributions²² in n , with $\bar{n}$ fixed by (IV. 1).

The branching ratios for D nonleptonic decays, relative to all $\bar{K}\pi + n\pi$ decays, are shown in Tables IV and V. The underlined charge states have been observed in Refs. 6-10 (solid) and 41 (dashed).

Table IV. Predicted branching ratios for specific charge states of $D^0 \rightarrow \bar{K} + \text{pions}$, in percent. Statistical isospin model used.

$n(\pi^\pm) =$	0	1	2	3	4	≥ 5	Sum (Poisson)
$K = \bar{K}^0$	K^-	$\bar{K}^0$	K^-	$\bar{K}^0$			
$\bar{K}\pi$	6	<u>6</u>					12.6
$\bar{K}2\pi$	4	10	<u>12</u>				26.1
$\bar{K}3\pi$	2	5	13	<u>7</u>			27.0
$\bar{K}4\pi$	~ 0	2	6	7	<u>4</u>		18.6
$\bar{K}\geq 5\pi$	~ 0	1	2	4	5	3	15.7
Sum	12	25	33	18	9	3	100

Table V. Same as Table IV for $D^+ \rightarrow \bar{K} + \text{pions}$.

$n(\pi^\pm) =$	1	2	3	4	≥ 5	Sum (Poisson)
$K = \bar{K}^0$	K^-	$\bar{K}^0$	K^-			
$\bar{K}\pi$	13					12.6
$\bar{K}2\pi$	15	<u>10</u>				26.1
$\bar{K}3\pi$	8	9	11			27.0
$\bar{K}4\pi$	2	4	9	4		18.6
$\bar{K}\geq 5\pi$	1	1	3	4	3	15.7
Sum	40	24	25	8	3	100

We may construct a Poisson distribution for the decays

$D = l^+ \nu_l \bar{K} + n\pi$ by starting from the observation that one expects^{13, 33}

$$\frac{\Gamma(D = l^+ \nu_l \bar{K})}{\sum_{n \geq 0} \Gamma(D = l^+ \nu_l \bar{K} + n\pi)} \approx 0.3 \quad (\text{IV. 6})$$

A much larger number would be ruled out by the softness of the observed direct lepton spectrum in multi-particle events observed at DESY⁶⁰ and at SPEAR^{45, 61}. A much smaller number would be hard to reconcile with separate estimates^{13, 33} for three-body and inclusive semileptonic decays.⁶²

Eq. (IV. 6) may be taken as the first term in a Poisson distribution with $\bar{n} = -\ln(0.3) \approx 1.2$. The resulting branching ratios are shown in Table VI.

Table VI. Predicted branching ratios for specific charge states of $D = l^+ \nu_l \bar{K} + \text{pions}$, as percent of all such decays. Statistical isospin model used.

$n(\pi^\pm) =$	0	1	2	≥ 3	Sum (Poisson)
$D^0: \bar{K} =$	K^-	$\bar{K}^0$	K^-		
$D^+: \bar{K} =$	$\bar{K}^0$	K^-	$\bar{K}^0$		
$l^+ \nu_l \bar{K}$	30				30
$l^+ \nu_l \bar{K}\pi$	12	24			36
$l^+ \nu_l \bar{K}2\pi$	4	7	11		22
$l^+ \nu_l \bar{K}\geq 3\pi$	~ 0	2	5	5	12
Sum	46	33	16	5	100

C. Inclusive variables.

The branching ratios in Tables IV-VI may be condensed into a form more easily compared with present data. The numbers at the bottom of each column, for example, give distributions of kaons and charged pions. These are, of course, compatible with the bounds of Ref. 15. It is interesting that D^+ nonleptonic decays lead in the model to relatively few neutral pions and charged kaons: $\bar{n}(\pi^0)/\bar{n}(\pi^\pm) = 0.5$ (bounds of Ref. 15: 0 to 3/2), and $\bar{n}(K^-)/\bar{n}(K^0) = 0.5$ (bounds of Ref. 15: 0 to 4).

If the neutral kaons in D decays are visible as two charged particles 1/3 of the time and invisible the other 2/3 of the time, as occurs in certain experiments,^{6-10, 41} Tables IV-VI imply the distributions of observed charged particles shown in Table VII.

Table VII. Predictions of percentage of D decays leading to n_c observed charged particles, when decays of short-lived neutral kaons are taken into account.

	$n_c = 0$				$\bar{n}_c$
D^0 semileptonic	69	29	2		2.7
D^0 nonleptonic	9	51	35	5	2.7
	$n_c = 1$				
D^+ semileptonic	31	59	10		2.6
D^+ nonleptonic	26	55	18	1	2.9

The values of $\bar{n}_c$ in Table VII may be compared with $\bar{n}_c = 3.1$ for pionic NN annihilations at rest,²⁷ and $\bar{n}_c = 2.9$ obtained by extrapolating

the expression (IV.4) down to $E_{c.m.} = 1.87$ GeV.

A $D\bar{D}$ pair thus should contribute about 5.4 to $\bar{n}_c$ (cf. Ref. 63). The masking of this effect just above charm threshold has been attributed⁶³ to the production of heavy lepton pairs,⁶⁴ which contribute a nearly compensating number of events with low charged-particle multiplicity.

When discussing F^+ or C_0^+ decays, we cannot identify a single channel which, when summed over pions, is expected to be dominant. Thus, $F^+ = \bar{K}K + \text{pions}$, $F^+ = (\eta \text{ or } \eta') + \text{pions}$, and $F^+ = \text{pions}$ all are possible in principle (though the last may be suppressed, see Refs. 35 and 65.) Similarly C_0^+ can decay to many different types of $S = -1$ baryonic channels. Relations among such decays occur in the next section.

V. SYMMETRIES BEYOND ISOSPIN

A. Semileptonic decays.

The isospin method¹⁷ noted in Sec. (III A) for obtaining $\tau(D^0)/\tau(D^+)$ can be generalized¹⁷ to yield $\tau(F^+)/\tau(D^+)$ if one is willing to trust the $SU(3)$ prediction

$$\frac{\Gamma(F^+ \rightarrow \ell^+ \nu_\ell \eta)}{\Gamma(D^+ \rightarrow \ell^+ \nu_\ell K^0)} = \frac{2}{3} \quad (V.1)$$

This prediction will be modified slightly by singlet admixture in the η ,⁶⁶ and by phase space and form factor differences.

As for nonleptonic decays,³² a number of $SU(3)$ -related channels appear in multi-hadron final states of semileptonic decays.⁶⁷ It requires phase-space and form-factor calculations to assess their importance.⁵⁸

Parity violations in semileptonic decays of charmed particles,⁶⁸ as in $C_0^+ \rightarrow l^+ \nu_l \Lambda$, can test for right-handed currents involving charmed and strange quarks. The Λ polarization is affected substantially if such currents are present.⁶⁹

B. I -, U -, and V -spin for nonleptonic decays.

The weak nonleptonic Hamiltonian (II, 2) must transform either as a $\bar{6}$ or a 15 of $SU(3)$,³⁰⁻³³ as shown in Fig. 4.

Fig. 4. $\bar{6}$ and 15 representations of $SU(3)$. The part of $H_{\text{weak}}^{n.l.}$ giving rise to $c \rightarrow su\bar{d}$ is shown by an arrow.

As Fig. 4 shows, the crucial distinction between the $\bar{6}$ and 15 contributions lies in their V -spins. Both representations have the same I -spin and U -spin properties. We shall describe some tests of the

suggestions that (i) the $\bar{6}$ part may be enhanced,³⁰⁻³³ and (ii) decays into non-exotic final states may be enhanced.¹³ Two-body decays of charmed pseudoscalar mesons provide a clear-cut distinction between these two possibilities. (For a related discussion, including estimates of branching ratios, see Ref. 33.)

C. Meson $\rightarrow 2$ mesons.

The I -spin properties of $H_{\text{weak}}^{n.l.} (\Delta S = \Delta C)$ lead to the relation (III, 1). The U -spin properties can be seen to lead to

$$\Gamma(D^0 - \bar{K}^0 \eta) = \frac{1}{3} \times 0.9 \times \Gamma(D^0 - \bar{K}^0 \pi^0) \quad (V.2)$$

$$A(F^+ - \bar{K}^0 K^+) + (3/2)^{1/2} A(F - \eta \pi^+) = A(D^+ - \bar{K}^0 \pi^+) \quad (V.3)$$

Note the presence of $A(D^+ - \bar{K}^0 \pi^+)$ on the right-hand sides of (III, 1) and (V, 3). The (spatially symmetric) $\bar{K}^0 \pi^+$ system must be in a 27 . It cannot be reached from the D^0 (which belongs to $\bar{3}$) via the $\bar{6}$ piece of $H_{\text{weak}}^{n.l.} (\Delta S = \Delta C)$. Thus, one might expect $\Gamma(D^+ - \bar{K}^0 \pi^+)$ to be small in comparison with partial widths on the left-hand sides of (III, 1) and (V, 3) either because of $\bar{6}$ enhancement or because of non-exotic final state enhancement. In either case, if $\Gamma(D^0 - \bar{K}^0 \pi^+) \neq 0$, we have

$$\Gamma(D^0 - \bar{K}^0 \pi^0) = \frac{1}{2} \Gamma(D^0 - K^+ \pi^+) \quad (V.4)$$

$$\Gamma(F^+ - \eta \pi^+) = \frac{2}{3} \times 1.06 \times \Gamma(F^+ - \bar{K}^0 K^+) \quad (V.5)$$

A specific test of the $\bar{6}$ enhancement mechanism is provided by the relation

$$\Gamma(\bar{D}^+ \rightarrow K^+ \bar{K}^0) = 0.88 \times \Gamma(D^0 \rightarrow K^- \pi^+) \quad (V.6)$$

which may be derived with the $\Delta V = 0$ property of the $\bar{6}$.

The symmetries mentioned above do not predict $\Gamma(D^0 \rightarrow \bar{K}^0 \eta')$. The following remarks are based on the assumption, still open to question, that the nonleptonic D^0 decay proceeds through an octet $s\bar{d}$ state. If one can use a nonet ansatz to relate $\Gamma(D^0 \rightarrow \bar{K}^0 \eta)$ to $\Gamma(D^0 \rightarrow \bar{K}^0 \eta')$, one finds^{32, 89}

$$\Gamma(D^0 \rightarrow \bar{K}^0 \eta') = \frac{8}{21} \times 0.74 \times \Gamma(D^0 \rightarrow \bar{K}^0 \eta) \quad (V.7)$$

The rates for $D^0 \rightarrow 0^- 0^-$ are then in the ratios

$$\begin{aligned} \Gamma(D^0 \rightarrow K^- \pi^+) : \Gamma(D^0 \rightarrow \bar{K}^0 \pi^0) : \Gamma(D^0 \rightarrow \bar{K}^0 \eta) : \Gamma(D^0 \rightarrow \bar{K}^0 \eta') \\ = 1 : 0.50 : 0.15 : 0.88 \quad (V.8) \\ (0.22) \end{aligned}$$

Similar methods apply to decays to $0^+ 1^-$ and $1^- 1^-$ final states,^{30-32, 71}

In the absence of clear-cut evidence for quasi-two-body decays of this sort, we may instead estimate the multi-body decays of D^0 involving $\bar{K}\eta + n\pi$ and $\bar{K}\eta' + n\pi$ as in Sec. IV, and find

$$\begin{aligned} \Gamma(D^0 \rightarrow \bar{K}\pi + (\geq 0 \text{ pions})) : \Gamma(D^0 \rightarrow \bar{K}\eta + (\geq 0 \pi)) : \Gamma(D^0 \rightarrow \bar{K}\eta' + (\geq 0 \pi)) \\ = 0.8 : 0.05 : 0.15 \quad (V.9) \\ (0.9) \quad (0.04) \end{aligned}$$

In addition, D^0 should have a branching ratio of a few percent to $K\bar{K}\bar{K} + (\geq 0 \text{ pions})$.

D. Meson - 3 mesons.

The best-studied three-body decay of a charmed meson at present

is $D^+ \rightarrow K^+ 2\pi^+$.⁷⁻¹⁰ The three particles appear to be in a spatially symmetric state. On the assumption of $\bar{6}$ dominance, these particles must lie in a $\bar{10}$ of $SU(3)$. Then one expects³²

$$\begin{aligned} \Gamma(D^+ \rightarrow K^+ 2\pi^+) : \Gamma(D^+ \rightarrow \bar{K}^0 \pi^+ \pi^0) : \Gamma(D^+ \rightarrow \bar{K}^0 \pi^+ \eta) : \Gamma(D^+ \rightarrow K^+ 2\bar{K}^0) \\ = 1 : 1/4 : (3/4) \times 0.45 : 1 \times 0.17 \quad (V.10) \end{aligned}$$

The proportion of $D^+ \rightarrow \bar{K}^0 \pi^+ \pi^0$ is much smaller than in the statistical isospin model (cf. row 2 of Table V), and in fact is as low as it can be.

E. Baryon - baryon + meson.

Another relation implied by $\bar{6}$ enhancement is

$$\sqrt{2} A(C_0^+ \rightarrow p \bar{K}^0) + \sqrt{3} A(C_0^+ \rightarrow \Lambda \pi^+) + A(C_0^+ \rightarrow \Sigma^0 \pi^+) = 0 \quad (V.11)$$

easily derived from V-spin. Eq. (V.11) implies that $\Lambda \pi^+$ cannot be the only 2-body nonleptonic channel of C_0^+ . The maximum of the ratio of $\Lambda \pi^+$ to $(\Lambda \pi^+) + (p \bar{K}^0) + (\Sigma^0 \pi^+) + (\Sigma^+ \pi^0)$ rates, subject to (V.11) and without regard to phase space differences, is 5/11. From this we are tempted to generalize to multi-body decays: it is unlikely that $C_0^+ \rightarrow \Lambda + \text{pions}$ accounts for more than half of all C_0^+ nonleptonic decays.

VI. SOME EXPERIMENTAL IMPLICATIONS

A. Short-track detection.

The event of Ref. 34 was the first to be interpreted in terms of possible charm production. It involves the production of a pair of short-lived tracks. So, too, does the event of Ref. 35,³⁷ which can be inter-

puted as $C_0 \bar{C}_0$ pair production.^{22,38} Both these events occurred in cosmic ray exposures. By contrast, at the lower energy of 300 GeV, a sample of 60,000 proton interactions has yielded no candidates for associated charm production, and a corresponding upper limit on the cross section of 1.5 $\mu\text{b}/\text{nucleon}$.⁷²

The prospects for charm production in neutrino physics look much brighter: a recent emulsion exposure³⁶ has obtained one candidate for charm production in only 16 neutrino interactions. This is not far from the expected rate (far above threshold) of $\sin^2 \theta \approx 1/18$. Since the emulsion stack may contain a total of as many as 200 neutrino interactions, a check of the total rate for short-track production indeed should be possible.

The event found in Ref. 36 consisted of (i) an interaction in the emulsion at a point "A", giving rise to some heavy tracks and five light ones, (ii) the materialization of one of the light tracks into three light ones at a point "B", 182 μm from A, and (iii) an apparent two-body decay ("V⁰") of a neutral strange particle, 34 cm downstream from points A and B. If the V⁰ is a Λ , it has survived two mean lifetimes, and if it is a K_S^0 , it has survived three.

Let us assume that the strange particle comes from the vertex B, as would be expected for the decay of a charmed particle. By arguments of momentum balance,³⁶ it is possible to rule out certain possibilities like $C_0^+ \rightarrow \Lambda 2\pi^+ \pi^-$ or $D^+ \rightarrow K_S^0 2\pi^+ \pi^-$. The asymmetric decay of the V⁰, as well as its lifetime, suggests that it may be a Λ .

We have checked that the decays

$$C_0^+ \rightarrow \Lambda 2\pi^+ \pi^- \pi^0 \quad (\text{VI.1a})$$

$$C_0^+ \rightarrow \Lambda 2\pi^+ \pi^- \eta \quad (\text{VI.1b})$$

$$C_0^+ \rightarrow \Lambda \tau^+ \pi^- \ell^+ \nu_\ell \quad (\text{VI.1c})$$

all give acceptable kinematic fits,⁷³ using the momentum measurements of Ref. 36 based on multiple scattering. Eqs. (VI.1) yield a C_0^+ with momentum

$$2.7 \text{ GeV}/c \leq p_{\text{lab}} \leq 6.8 \text{ GeV}/c, \quad (\text{VI.2})$$

and hence lifetime

$$2 \times 10^{-13} \text{ sec.} \leq t \leq 5 \times 10^{-13} \text{ sec.} \quad (\text{VI.3})$$

The two C_0 ($\bar{C}_0$) candidates^{22,38} in Ref. 35 live about 7×10^{-13} sec. and 5×10^{-12} sec. if they really are C_0 tracks.³⁸

The decay $C_0^+ \rightarrow \Lambda 2\pi^+ \pi^-$ already may have been observed.³⁹⁻⁴¹

By the methods of Secs. III and IV, we have estimated that this decay is 0.16 of all $C_0^+ \rightarrow \Lambda + (\text{pions})$ decays. Interestingly, because of a favorable statistical isospin factor, $C_0^+ \rightarrow \Lambda 2\pi^+ \pi^- \pi^0$ also should be a significant mode: 0.13 of all $C_0^+ \rightarrow \Lambda + (\text{pions})$ decays. Perhaps this is what has been observed in Ref. 36. Unfortunately, it will be impossible to tell from the event in question: there are two solutions for the π^0 momentum, one of which involves a π^0 backward in the laboratory and thus totally undetectable in the present experiment.⁷³

It is easier to find charged short-lived particles than neutral ones in emulsions. However, there are several possibilities for charged particles with lifetimes around 10^{-13} sec.: D^+ , F^+ , C_0^+ , and the heavy lepton L^+ . These particles should decay into 1 or 3 charged particles. The D^0 is harder to look for, but among the particles we have discussed it is the only neutral one, and so its signal should be more characteristic. It should decay predominantly to two or four charged particles, according to Table VII. If neutral heavy leptons exist (Sec. VII), they, too, should show up in emulsions.

B. Other charmed-particle experiments.

At $E_{c.m.} = 4.028$ GeV, SPEAR has measured⁹

$$\begin{aligned} 2B(D^0 \rightarrow K^- \pi^+) \quad \sigma(D^0) &= 0.52 \pm 0.05 \text{ nb} \\ 2B(D^0 \rightarrow \bar{K}^0 \pi^+ \pi^-) \quad \sigma(D^0) &= 0.80 \pm 0.21 \text{ nb} \\ 2B(D^0 \rightarrow K^- 2\pi^+ \pi^-) \quad \sigma(D^0) &= 0.72 \pm 0.18 \text{ nb} \\ 2B(D^+ \rightarrow K^- 2\pi^+) \quad \sigma(D^+) &= 0.27 \pm 0.05 \text{ nb} \quad (\text{VI.4}) \end{aligned}$$

with additional systematic uncertainties of 50%.⁷⁴ The D^0 data are compatible with the predictions of Table IV, if we regard $\sigma(D^0)$ as unknown. If we estimate $\sigma(D^0)$ independently,⁴⁵ we find all the experimental D^0 branching ratios implied by the above numbers are slightly smaller than the corresponding entries in Table IV.

Note the small value of $B\sigma$ for $D^+ \rightarrow K^- 2\pi^+$, in comparison with the value for $D^0 \rightarrow \bar{K}^0 \pi^+ \pi^-$. These are decays of the same multiplicity, and the statistical isospin factors¹⁶ are almost the same: 0.4 for the former, and 0.45 for the latter. The disparity

may indicate (i) $\sigma(D^0) > \sigma(D^+)$ ⁴³ (cf. the estimate $\sigma(D^0) \approx \frac{2}{3} \sigma(D)$ in Ref. 45), (ii) a smaller branching ratio for $D^+ \rightarrow \bar{K} + \text{pions}$,¹³ (iii) a shortcoming of the model, or (iv) any combination of the above.

An estimate of the $D^+ \rightarrow \bar{K}^0 \pi^+$ signal expected on the basis of the statistical isospin model is possible, if we use the D^0 branching ratios in (VI.4) to obtain a direct estimate of the relative probabilities of 2-body and 3-body decays, and apply this estimate to D^+ decays as well. The resulting prediction, for SPEAR data at 4.028 GeV, is

$$2B(D^+ \rightarrow \bar{K}^0 \pi^+) \quad \sigma(D^+) = 0.39 \pm 0.13 \text{ nb} \quad (\text{VI.5})$$

This signal should be detectable. If it is much smaller, the $\bar{K}^0 \pi^+$ mode is undergoing a particular suppression not experienced by the final state $K^- 2\pi^+$. Both are exotic, but the former must belong to a 27 whereas the latter may belong to a $\overline{10}$. Only the latter could be produced if $H_{\text{weak}}^{n.l.}$ transformed as $\bar{5}$. (See Sec. V.)

The photoproduction experiment of Ref. 41 detects a small $D^0 \rightarrow \bar{K}^0 2\pi^+ 2\pi^-$ signal. One expects from Table IV a small branching ratio into this channel: $\approx 4\%$ of $D^0 \rightarrow \bar{K} + \text{pions}$. By contrast, according to Table V, the channel $\bar{K}^0 2\pi^+ \pi^-$ should be $\approx 11\%$ of $D^+ \rightarrow \bar{K} + \text{pions}$. Its absence could be due to any of the factors (i) - (iv) mentioned above.

C. New modes, new charmed particles.

Secs. III-V suggest some interesting new decay modes in which to observe the known charmed particles. Many of these will require the detection of single neutral pions or the imposition of kinematic fits

to compensate for single missing neutral particles. Tables IV-VI suggest some prominent modes of D decay. In addition, using a Poisson distribution in n for $C_0^+ \rightarrow \Lambda + n\pi$, with $\bar{n}$ set by (IV.1), one finds that²²

$$C_0^+ - \left\{ \begin{array}{l} \Lambda \pi^+ \\ \Lambda \pi^+ \pi^0 \end{array} \right\} = \left\{ \begin{array}{l} 17\% \\ 30\% \end{array} \right\} \text{ of } C_0^+ \rightarrow \Lambda + \text{pions} \quad (VI.6)$$

Moreover, according to (V.11), if $\bar{b}$ enhancement is valid, we should expect at least one of the modes $C_0^+ \rightarrow p\bar{K}^0$, $(\Sigma^+)^+$ to be visible once $C_0^+ \rightarrow \Lambda\pi^+$ is seen.

Many suggestions have been given in Refs. 13 and 43 for observing the F^+ and the remaining particles in Table II. Proceeding from Eq. (IV.1), we would expect

$$F^+ \rightarrow \eta \pi^+ = 12\% \text{ of } F^+ \rightarrow \eta \pi + (\geq 0\pi) \quad (VI.7)$$

$$F^+ \rightarrow \eta' \pi^+ = 20\% \text{ of } F^+ \rightarrow \eta' \pi + (\geq 0\pi) \quad (VI.8)$$

$$F^+ \rightarrow \bar{K}^0 K^+ = 17\% \text{ of } F^+ \rightarrow \bar{K} K + (\geq 0\pi) \quad (VI.9)$$

Recalling (V.5) and using a nonet ansatz³² to relate $F^+ \rightarrow \eta \pi^+$ to $F^+ \rightarrow \eta' \pi^+$,⁸⁹ we then would find roughly equal rates for $F^+ \rightarrow \eta \pi + (\geq 0\pi)$, $F^+ \rightarrow \eta' \pi + (\geq 0\pi)$, and $F^+ \rightarrow \bar{K} K + (\geq 0\pi)$.⁸⁹ Let us assume this to be so, and let us neglect^{33, 65} the decays $F^+ \rightarrow \text{pions}$. Then we find the F^+ branching ratios listed in Table VIII. The large number of channels available in the nonleptonic decay of F^+ makes it hard to detect in any one of them, though $\bar{K}^0 K^+$ and $K^- K^+ \pi^+$ look most promising. We shall mention another possibility in the next section.

Table VIII. Model for F^+ nonleptonic branching ratios, in percent.

$F^+ \rightarrow \text{pions}$ neglected. Poisson distributions in n . Statistical isospin model used.

$\eta \pi + n\pi$ ($\bar{n} = 2.16$) 33 % (44%) ⁸⁹			$\eta' \pi + n\pi$ ($\bar{n} = 1.63$) 33 % (41%) ⁸⁹		
$\eta \pi^+$	4	(5)	$\eta' \pi^+$	7	(2)
$\eta \pi^+ \pi^0$	8	(12)	$\eta' \pi^+ \pi^0$	11	(3)
$\eta 2\pi^+ \pi^-$	5	(7)	$\eta' 2\pi^+ \pi^-$	6	(2)
$\eta \pi^+ 2\pi^0$	4	(5)	$\eta' \pi^+ 2\pi^0$	3	(1)
$\eta (\geq 4\pi)$	12	(15)	$\eta' (\geq 4\pi)$	7	(3)
$\bar{K} K + n\pi$ ($\bar{n} = 1.78$) 33 % (44%) ⁸⁹					
$\bar{K}^0 K^+$	6	(8)	$K^- K^0 2\pi^+$	1	(2)
$\bar{K}^0 K^+ \pi^0$	2	(3)	$K^+ K^+ \pi^+ \pi^0$	2	(3)
$K^- K^+ \pi^+$	4	(5)	$\bar{K}^0 K^0 \pi^+ \pi^0$	2	(3)
$\bar{K}^0 K^0 \pi^+$	4	(5)	$\bar{K}^0 K^+ 2\pi^0$	1	(1)
$\bar{K}^0 K^+ \pi^+ \pi^-$	3	(4)	$\bar{K} K (\geq 3\pi)$	8	(12)

VII. NEW OBJECTS

It is amusing that just as a quantum number was discovered which restored lepton-hadron symmetry,³⁻⁵ evidence has appeared for new heavy leptons and for possible new quarks which threw the situation off balance again.^{45, 60, 64, 75-78}

A. Charm = heavy leptons.

If a charged heavy lepton $L^\pm$ of mass $L \approx 95 \text{ GeV}/c^2$ ^{64, 60} is coupled via a charged weak current to a massless neutrino ν_L and the F^+ has mass $2 \text{ GeV}/c^2$, the decay $F^+ \rightarrow L^+ \nu_L$ is just barely possible.⁷⁹

Similarly, there is the barest possibility that a neutral heavy lepton could be present in F^+ decay. The process $\mu \rightarrow e \gamma$, whose possible observation has been discussed elsewhere at this conference (refs. 80, 75, 76) is allowed at a level of 10^{-10} or greater^{80, 75, 76} if there exist neutral heavy leptons N_1 and N_2 coupled via right-handed currents:

$$\begin{pmatrix} N_1 \cos \phi + N_2 \sin \phi \\ e^- \end{pmatrix}_R \quad \begin{pmatrix} -N_1 \sin \phi + N_2 \cos \phi \\ \mu^- \end{pmatrix}_R \quad (\text{VII. 1})$$

The present experimental lower limit on the mass of the lightest such lepton N is set only by the absence of the decay $K^+ \rightarrow e^+ N$.⁸¹ As long as $m_N < m_F - m_e$, the decay $F^+ \rightarrow N e^+$ can occur, provided the value of ϕ does not prevent it. If $m_N < m_F + m_\mu$, at least one of the decays $F^+ \rightarrow N \mu^+$, $N e^+$ must be quite substantial, independent of ϕ , as we now show.

The decay of a pseudoscalar meson of mass M into leptons of mass m_1, m_2 via a $V \pm A$ current involves a Lorentz-invariant matrix element whose square is $M^2(m_1^2 + m_2^2) - (m_1^2 - m_2^2)^2$. For $M = 2 \text{ GeV}/c^2$ this factor, multiplied by the appropriate phase space term, is the same to within 5% for $F \rightarrow N e$ and $F \rightarrow N \mu$ when m_N varies between $0.5 \text{ GeV}/c^2$ (its present lower bound⁸¹) and $1.75 \text{ GeV}/c^2$. Consequently, we shall neglect both the electron and muon masses in what follows. By an elementary calculation, relating the decays $F \rightarrow N (e \text{ or } \mu)$ to $K \rightarrow \mu \nu$, we find

$$\frac{\Gamma(F \rightarrow Ne) + \Gamma(F \rightarrow N\mu)}{\Gamma(K \rightarrow \mu\nu)} = (f_F/f_K)^2 K_K(m_N), \quad (\text{VII. 2})$$

with the function $K_K(m_N)$ shown in Fig. 5.

Fig. 5. Kinematic factor describing $F \rightarrow N (e \text{ or } \mu)$ via Eq. (VII. 2).

Note in (VII. 2) the absence of ϕ , the result of summing over e and μ . The ratio of f_F to f_K is unknown. It would be 1 in the $SU(4)$ limit.⁸² Since $\Gamma(K \rightarrow \mu \nu) \approx 5 \times 10^{-7} \text{ sec}^{-1}$, one has

$$\begin{aligned} \Gamma(F \rightarrow Ne) + \Gamma(F \rightarrow N\mu) &\geq 2 \times 10^{11} \text{ sec}^{-1} (f_F/f_K)^2 \\ (1 \text{ GeV}/c^2 \leq m_N \leq 1.3 \text{ GeV}/c^2) \end{aligned} \quad (\text{VII. 3})$$

and the sum of these partial widths still is appreciable over most of the remaining allowed kinematic range.⁸³ Fig. 5 also applies to the decay⁷⁹ $F^+ \rightarrow L^+ \nu_L$: for $m_L = 1.95 \text{ GeV}/c^2$, $m_{\nu_L} = 0$, and $m_F = 2 \text{ GeV}/c^2$, one finds a value (very sensitive to $m_F - m_L$) of

$$\Gamma(F^+ \rightarrow L^+ \nu_L) \approx 3 \times 10^9 \text{ sec}^{-1} (I_F/I_K)^2 \quad (\text{VII. 4})$$

An estimate of the total decay rate of F^+ , taking account of possible nonleptonic enhancement effects,³³ is $\Gamma(F^+) \approx 8 \times 10^{12} \text{ sec}^{-1}$ for m_c (the mass of the charmed quark) $= 2 \text{ GeV}/c^2$, and less for smaller values of m_c . Thus, for a wide range of values of m_N , the branching ratio

$$\frac{\Gamma(F \rightarrow N\pi) + \Gamma(F \rightarrow N\rho)}{\Gamma(F)} \geq (\text{several } \%) \quad (\text{VII. 5})$$

as long as $I_F/I_K \geq 1$.

In turn, we have estimated the total decay rate of N and its decay into $(e \text{ or } \mu)^+ + \pi^+$ via standard methods,^{81, 33, 13} to obtain branching ratios varying from 40 % to 10% into the latter channel as m_N varies from 1 to 2 GeV/c^2 .

Consequently, the branching ratio for

$$F^+ \rightarrow \pi^+ (e \text{ or } \mu)^+ (e \text{ or } \mu)^- \quad (\text{VII. 6})$$

if we sum over e and μ , could easily exceed a percent if the heavy lepton N were to lie in the right mass range (m_N around $1 \text{ GeV}/c^2$). Depending on detection capabilities, the channel (VII. 6) even could become competitive with those listed in Table VIII as a way of looking

for the F^+ .

A neutral heavy lepton produced with a branching ratio of several percent in F decays could, in principle, be responsible for anomalous leptons of the same sign as the lepton associated with the incident neutrino in high-energy neutrino reactions.^{84, 85} An example of such a process is

$$\nu_\mu X \rightarrow \mu^+ F^+ Y \rightarrow \begin{cases} N(\mu^+ \text{ or } e^+) \\ (\mu^- \text{ or } e^-) + \left\{ \begin{array}{l} \pi^+ \\ \text{multi-hadrons} \\ (\mu^+ \text{ or } e^+) + \nu \end{array} \right\} \end{cases} \quad (\text{VII. 7})$$

By means of this reaction, a neutral heavy lepton can yield up to four observed leptons in the final state.

Further suggestions for producing neutral heavy leptons have been given.^{81, 76} We have concentrated on ways associated with charmed-particle decays: if the F^+ can be produced abundantly in any reaction, its decays will help raise the experimental lower limit on the lowest-mass lepton (if any exists) coupled via Eq. (VII. 1). (A similar argument could have been given for D^+ decays, but the corresponding rates would have been suppressed by $\tan^2 \theta \approx 1/18$.)

B. Charged heavy lepton decays.

Here we have only a few minor comments, as these decays are well-discussed elsewhere.^{45, 63, 76, 81, 96}

The statistical isospin model of Sec. III can be applied to those decays involving multi-hadron final states. For example, the pions in

$L^- \rightarrow \nu_L + (3\pi)^-$ should all be charged 4/5 of the time. Many other such applications are possible, but decay rates into specific channels like $\nu_L \pi^-$, $\nu_L \rho^-$, and $\nu_L A_1^-$, which probably make up the bulk of the hadronic decays, can be estimated directly.^{81, 86}

Both charmed particles and heavy charged leptons are sources of massive charged weak currents when they decay. As discussed, these currents can be used to test for new couplings and leptons, as in Eq. (VII.1). Another possibility for the heavy lepton decays is to use their massive weak currents to test for second-class currents of hadrons,⁸⁷ via final states of definite G-parity. In this context we note that the decay

$$L^- \rightarrow \nu_L \eta \pi^- \quad \text{(VII.8)}$$

is absolutely forbidden for first-class currents: only the vector current can contribute to the production of a pair of 0^- particles, but the first-class vector current has $G = +$, while $\eta \pi$ has $G = -$.⁸⁸

C. Heavy-quark decays.

These are discussed in Refs. 45, 54, 75, and 76. The statistical considerations of Secs. III and IV are relevant once the appropriate hadronic quantum numbers are changed, except that for sufficiently massive quarks, jet structure of the final state may be appreciable,⁵⁴ and Eq. (IV.1) may not apply. The authors of Ref. 54 have stressed that charmed particles may be important intermediates in the decays of hadrons containing heavy quarks. The nonleptonic decays are likely to be affected seriously by right-handed currents, and one

should not necessarily expect the semileptonic branching ratios of heavier hadrons to be the same as for charmed ones.

VIII. SUMMARY

The discovery of charmed particles has been a tremendous source of encouragement in constructing unified gauge theories of the weak, electromagnetic, and (perhaps) strong and gravitational interactions. This work is proceeding at an extraordinary rate.

Here, other aspects of charmed particles have been discussed. Their decays provide information on multi-body production. This can be helpful in deciding how hadronic systems evolve, in finding new charmed particles, and in knowing what to look for in the decays of hadrons containing new, heavier quarks. Charmed particles also can provide some insight into the physics of nonleptonic weak interactions. Their decays (and those of heavy leptons) provide massive charged weak currents - a charged version of electron-positron collisions.

From what we have heard from other speakers at this conference, it looks like there is a whole new realm of particle physics associated with the mass scale of $2 \text{ GeV}/c^2$. Charm may be just the first hint of this physics. The year and a half it took us to discover it, after we knew it should be there, has provided theorists and experimentalists with some experience which should be very worthwhile in the near future.

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REFERENCES

1. J. J. Aubert et al, Phys. Rev. Letters 33, 1404 (1974).
2. J. -E. Augustin et al., Phys. Rev. Letters 33, 1406 (1974).
3. S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D2, 1285 (1970).
4. The hadronic weak currents of Ref. 3 were first proposed by M. Gell-Mann and S. L. Glashow, 1961 (unpublished); M. Gell-Mann, Phys. Letters 8, 214 (1964); Z. Maki and Y. Ohnuki, Prog. Theor. Phys. 32, 144 (1964); Y. Hara, Phys. Rev. 134, B701 (1964); and B. J. Björken and S. L. Glashow, Phys. Letters 11, 255 (1964), in which "charm" is named.
5. General quartet schemes for hadrons have been considered by the authors of Refs. 3, 4, as well as by Y. Katayama et al., Prog. Theor. Phys. 28, 675 (1962); P. Tarjanne and V. L. Teplitz, Phys. Rev. Letters 11, 447 (1963); Z. Maki, Prog. Theor. Phys. 31, 331, 333 (1964); and D. Amati, H. Bacry,

- J. Nuyts, and J. Prentki, Phys. Letters 11, 190 (1964).
6. G. Goldhaber, F. M. Pierre, et al., Phys. Rev. Letters 37, 255 (1976).
7. I. Peruzzi, M. Piccolo, G. J. Feldman, H. K. Nguyen, J. E. Wiss, et al., Phys. Rev. Letters 37, 569 (1976).
8. G. Goldhaber, "Study of Charmed Mesons at SPEAR", Lawrence Berkeley Laboratory report LBL-5534, presented at 1976 SLAC Summer Institute on Particle Physics.
9. R. Schwitters, in Proceedings of Division of Particles and Fields American Physical Society Divisional Meeting, Brookhaven National Laboratory, October, 1976, edited by Ronald F. Peierls, Brookhaven Natl. Lab. report BNL-50598, February, 1977.
10. J. E. Wiss, G. Goldhaber, et al., Phys. Rev. Letters 37, 1531 (1976).
11. A description of tests for weak decays of heavy mesons is given by Benjamin W. Lee, C. Quigg, and Jonathan L. Rosner, Comments in Nuclear and Particle Physics, to be published. The most conclusive of these tests makes use of the Dalitz-plot analysis of Charles Zemach, Phys. Rev. 133, B1201 (1964), and has been used in Ref. 10 to infer that the D is decaying weakly.
12. S. L. Glashow, in Experimental Meson Spectroscopy - 1974, edited by D. A. Garelick, American Institute of Physics, New York, 1974, p. 387.
13. Mary K. Gaillard, Benjamin W. Lee, and Jonathan L. Rosner,

- Rev. Mod. Phys. 47, 277 (1975).
14. A. De Rújula, Howard Georgi, and S. L. Glashow, Phys. Rev. D12, 147 (1975).
  15. O. Nachtmann and A. Pais, Phys. Letters 65B, 59 (1976).
  16. Murray Peshkin and Jonathan L. Rosner, "Isospin Restrictions on Charge Distributions in Charmed Particle Decays," Institute for Advanced Study report COO-2220-93, December, 1976, to be published in Nuclear Physics B.
  17. A. Pais and S. B. Treiman, "Charmed Meson Lifetime Ratios and Production in e^+e^- Collisions," Rockefeller University report no. COO-2232B-112, to be published in Phys. Rev. D.
  18. E. Fermi, Phys. Rev. 92, 452 (1953), 93, 1434(E) (1954).
  19. A. Pais, Ann. Phys. (N. Y.) 9, 548 (1960), *Ibid.*, 22, 274 (1963).
  20. F. Cerulus, Nuovo Cimento (Suppl.) 15, 402 (1960).
  21. A. Pais, Phys. Rev. Letters 32, 1081 (1974).
  22. Benjamin W. Lee, C. Quigg, and Jonathan L. Rosner, to be published in Phys. Rev. D15 (1977).
  23. E. Fermi, Prog. Theor. Phys. 5, 570 (1950).
  24. Some early work in this area is reviewed by A. Jabs, Nucl. Phys. B34, 177 (1971), and by D. Q. Lamb, in Proceedings of the Colloquium on High Multiplicity Hadronic Interactions, École Polytechnique, 1970, edited by A. Krzywicka et al., p. IV. 69.
  25. R. Hagedorn, Nuovo Cimento (Suppl.) 3, 147 (1965), S. C. Frautschi, Phys. Rev. D3, 2821 (1971), C. J. Hamer and S. C. Frautschi, Phys. Rev. D4, 2125 (1971).

26. C. J. Hamer, Nuovo Cimento 12A, 162 (1972).
27. S. J. Cráncidia and V. Rittenberg, Nucl. Phys. B59, 570 (1973).
28. B. Jean-Marie et al., Phys. Rev. Letters 36, 291 (1976).
29. Gary J. Feldman and Martin L. Perl, Phys. Letters 19C, 233 (1975).
30. G. Altarelli, N. Cabibbo, and L. Maiani, Nucl. Phys. B88, 285 (1975), Phys. Letters 57B, 277 (1975).
31. R. L. Kingsley, S. B. Treiman, F. Wilczek, and A. Zee, Phys. Rev. D11, 1919 (1975).
32. M. B. Einhorn and C. Quigg, Phys. Rev. D12, 2015 (1975), Phys. Rev. Letters 35, 1114(C) (1975).
33. J. Ellis, M. K. Gaillard, and D. V. Nanopoulos, Nucl. Phys. B100, 313 (1975).
34. K. Niu, E. Mikumo, and Y. Maeda, Prog. Theor. Phys. 46, 1644 (1971).
35. H. Sugimoto, Y. Sato, and T. Saito, Prog. Theor. Phys. 53, 1541(L) (1975), and in Proceedings of the 14th International Cosmic Ray Conference, Munich, Aug. 15-29, 1975, Max-Planck-Institut, 1975, paper no. HE 5-6, p. 2427.
36. E. H. S. Burhop et al., Phys. Letters 65B, 299 (1976).
37. Early emulsion events, including those of Refs. 34 and 35, are discussed by K. Hoshino et al., in Proceedings of the 1975 Cosmic Ray Conference (op. cit. Ref. 35), papers no. HE 5-11, p. 2442, and HE 5-12, p. 2448, and by G. B. Yodh, in Proceedings of the 1975 Cosmic Ray Conference (op. cit. Ref. 35), p. 3936. The importance of associated production in reducing background

from nuclear interactions is stressed by Yodh and in Ref. 38.

38. T. K. Gaisser and F. Halzen, Phys. Rev. D14, 3153 (1976).
39. E. G. Cazzoli et al., Phys. Rev. Letters 34, 1125 (1975).
40. B. Knapp et al., Phys. Rev. Letters 37, 882 (1976).
41. B. Knapp, in 1976 DPF Proceedings (op. cit. Ref. 9).
42. S. J. Barish et al., to be published in Phys. Rev. D15 (1977).
43. A. De Rújula, Howard Georgi, and S. L. Glashow, Phys. Rev. Letters 37, 398, 785(G) (1976).
44. A. W. Henry and D. B. Lichtenberg, Phys. Rev. D12, 2756 (1975).
45. Frederick J. Gilman, these proceedings, and in 1976 DPF Proceedings (op. cit. Ref. 9).
46. Frederick J. Gilman, in High Energy Physics and Nuclear Structure - 1975 (AIP Conference Proceedings No. 26), edited by D. E. Nagle et al., New York, American Institute of Physics, 1975, p. 331.
47. F. Vannucci et al., "Mesonic Decays of the $\psi(3095)$," SLAC and LBL report SLAC-FUB-1862, LBL-5595, December, 1976, submitted to Phys. Rev.
48. M. Peshkin, Phys. Rev. 121, 636 (1961).
49. I thank S. Nussinov for proofs of some special cases.
50. I thank A. Pais for a discussion of this point.
51. Using data quoted in Ref. 27 on up to 7-prong annihilations, I have checked that the sum of all pionic annihilations constructed with the help of tables of Ref. 19 is only about 2/3 of the actual total.
52. Gail Hanson et al., Phys. Rev. Letters 35, 1609 (1975).
53. This possibility has been raised in Ref. 54 for decays of hadrons

containing heavier quarks.

55. Benjamin W. Lee, C. Quigg, and Jonathan L. Rosner, unpublished. In this work one finds a substantial range of overlap between (IV.1) with $E_0 = 225$ MeV, $E = E_{c.m.} - 2m_\pi$, $\bar{n}_{tot} = n + 2$, and (IV.4), with $\bar{n}_{tot} = \frac{3}{2} \bar{n}$.
56. I thank C. Quigg for pointing out that Eq. (IV.5) entails $P_n(n) = c^{2n-1} / [n!(n+1)! I_1(2c)]$, where I_1 is a modified Bessel function, and $\bar{n} = c I_2(2c) / I_1(2c) = c - 3/4 + 3/(32c) + O(1/c^2)$.
57. I thank D. Horn for a discussion of more general parametrizations, including the Gaussian distribution. A Gaussian would be suitable for describing the distribution if its center and width were fixed by the data. With present uncertainties in branching ratios (see Ref. 9), this is not possible.
58. Benjamin W. Lee, C. Quigg, and Jonathan L. Rosner, in progress.
59. The table of branching ratios for $D \rightarrow K\pi + n\pi$ in Ref. 13 contains an additional assumption which is not compatible with present data (see Refs. 6-10) or with the discussion of Sec. IV. A, namely, the fixing of c in Eq. (IV.5), and hence of $\bar{n}$, a priori.
60. H. Meyer, these proceedings. W. Braunschweig et al., Phys. Letters 63B, 471 (1976). J. Burmaster et al., Ibid. 64B, 369 (1976).
61. Gary J. Feldman, F. Bulos, D. Lüke, et al., Phys. Rev. Letters 38, 117 (1977).
62. For further considerations, see M. Bourquin and J.-M. Gaillard, Nucl. Phys. B114, 334 (1976). I. Hinchcliffe and C. H. Llewellyn Smith, Nucl. Phys. B114, 45 (1976). V. Barger, T. Gottschalk,

- and R. J. N. Phillips, Phys. Letters 64B, 333 (1976), and Univ. of Wisconsin report COO-569, August, 1976, to be published, and M. Gronau et al., DESY report 76/62, November, 1976, to be published.
63. See, e.g., Frederick J. Gilman, in Proceedings of the 1975 International Symposium on Lepton and Photon Interactions at High Energies, Stanford University, August 21-27, 1975, edited by W. T. Kirk, Stanford Linear Accelerator Center, Stanford, Calif., 1975, p. 131, and H. Harari, *Ibid.*, p. 317.
  64. M. L. Perl et al., Phys. Rev. Letters 35, 1489 (1975), Phys. Letters 63B, 466 (1976).
  65. S. Nussinov, Institute for Advanced Study report COO-2220-85, September, 1976, to be published in Phys. Rev.
  66. According to H. Lapkin (these proceedings), this singlet admixture may not have predictable effects.
  67. These have been worked out by C. Quigg (private communication).
  68. A. J. Buras, Nucl. Phys. B109, 373 (1976).
  69. A. J. Buras and John Ellis, Nucl. Phys. B111, 341 (1976).
  70. The decimal factor is a phase space correction.
  71. S. R. Borchardt and V. S. Mathur, Phys. Rev. Letters 36, 1287 (1976).
  72. G. Coremans-Bertrand et al., Phys. Letters 65B, 480 (1976).
  73. I thank C. Quigg for checking the kinematic solutions.
  74. The factor of 2 on the left of Eq. (VI.4) comes from our assumption of CP invariance, since only the sum for particles and antiparticles is quoted. Tests of CP invariance in decays of charmed particles are noted by A. Pais and S. B. Treiman, Phys. Rev. D12, 2744

- (1975), and Maurice Goldhaber and Jonathan L. Rosner, to be published in Phys. Rev. D15 (1977). For an extensive review of a class of models for CP violation see H. Harari, "Beyond Charm", lectures delivered at Les Houches Summer School, August, 1976, Weizmann Institute report WIS-76/54 PH, to be published
75. H. Fritzsch, these proceedings.
  76. R. M. Barnett, these proceedings, and in 1976 DPF Proceedings (op. cit. Ref. 9).
  77. F. Gürsey, these proceedings, and in 1976 DPF Proceedings (op. cit. Ref. 9).
  78. S. L. Glashow, these proceedings.
  79. I. Karliner, Phys. Rev. Letters 36, 759 (C) (1976).
  80. T. P. Cheng and Ling-Fong Li, "Nonconservation of Separate μ - and e - Numbers in Gauge Theories with V+A Currents," December, 1976, to be published. T. P. Cheng, these proceedings.
  81. J. D. Bjorken and C. H. Llewellyn Smith, Phys. Rev. D7, 887 (1973).
  82. Since $f_K = 1.28 f_\pi$, these constants might indeed be increasing slightly with mass. The value of f_F may be useful for distinguishing among quark models: see C. H. Llewellyn Smith, Ann. Phys. (N.Y.) 53, 521 (1969). For an extreme view of symmetry-breaking effects, see J. Kandaswamy, J. Schechter, and M. Singer, Phys. Rev. D13, 3151 (1976).
  83. The maximum in Fig. 5 occurs for $m_N = m_F/\sqrt{3} = 1.16 \text{ GeV}/c^2$.
  84. A. Benvenuti et al., Phys. Rev. Letters 34, 419 (1975), *Ibid.*, 34, 597 (1975), *Ibid.*, 35, 1199 (1975), *Ibid.*, 35, 1249 (1975), D.

Cline, 1976 DPF Proceedings (op. cit. Ref. 9).

85. B. Barish et al., Calif. Inst. of Technology report CALT 68-567, presented by O. Fackler at 1976 DPF Meeting (op. cit. Ref. 9).
86. Y. S. Tsai, Phys. Rev. D4, 2821 (1971).
87. A. Pais and S. B. Treiman, Phys. Rev. D14, 293 (1976).
88. I am indebted to Arthur Halprin for suggesting this test.
89. Note added: (I am indebted to S. Nussinov for discussions leading to the following remarks): An alternative version of the meson ansatz, consistent with the $\bar{6}$ dominance assumption, is the following: If $D^0 = c\bar{u} \rightarrow s\bar{u} \bar{d} \bar{u} \rightarrow \bar{K}^0 + (\eta \text{ or } \eta')$, the η and η' must be produced through the $u\bar{u}$ state, so that one finds the ratio listed in parentheses in Eq. (V.7). This then leads to the alternative conclusions in parentheses in Eqs. (V.8) and (V.9). Similarly if $F^+ = c\bar{s} \rightarrow s\bar{u} \bar{d} \bar{s} \rightarrow \pi^+ + (\eta \text{ or } \eta')$, the η and η' must be produced through the $s\bar{s}$ state, leading to a ratio of $\Gamma(F^+ \rightarrow \pi^+ \eta') / \Gamma(F^+ \rightarrow \pi^+ \eta)$ which is 1/4 that obtained in Ref. 32. The numbers in parentheses in Table VIII are based on the assumption that the η and η' are produced via the $s\bar{s}$ state.

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