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NEW PARTICLE PHENOMENOLOGY*

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I. INTRODUCTION

Almost no one has further doubts: charm, in the sense of Glashow, Iliopoulos and Maiani[1] exists. In referring to a possible new quantum number carried by a fourth quark, the use of tentative phrases and saying it is only to be called "charm in the generic sense" are now unnecessary. This is so even though the purist's check involving semileptonic decay of a particle with charm ± 1 into a final state of strangeness ∓ 1 has yet to be done. Remarkably, the establishment of this new quantum number has taken place in the short span of 1-1/2 years from the discovery[2] of the first $c\bar{c}$ states in November, 1974 to that[3] of the $c\bar{u}$ ground state in May, 1976.

In this talk we will explore the consequences of having a new heavy quark (c) in addition to the u, d, and s quarks (sometimes denoted q), and particularly the resulting $c\bar{c}$, $c\bar{q}$, and cqq spectroscopy. We do so in the general framework of a picture of matter as composed of spin 1/2 leptons and quarks, the latter bound together by an SU(3) octet of vector gluons coupled to the three color degrees of freedom of the quarks to form the color singlet hadrons observed in Nature. Ultimately it is to be hoped that such a color gauge theory of the strong interactions (Quantum Chromodynamics or QCD) will be proven to exist with solutions which exhibit the properties of the hadrons, including the new ones under discussion here. Even now, without completely solving the theory, applications can be made to hadron spectroscopy and decays in certain regimes with appropriate assumptions. With this in mind we will be referring as often as possible to the predictions, qualitative and quantitative, that have been made employing QCD for the properties of the new hadrons. On occasion, we shall refer as well to the "old" spectroscopy for reinforcement and comparison with the "new". In this way, we use hadron spectroscopy, "old" and "new", to get at the dynamics and test our underlying theory of hadrons.

The past few years have taught us that a new heavy quark exists. Indeed, a key question at this conference is whether all the new phenomena reported are explainable by just charm. We review the growing evidence from e^+e^- annihilation for a heavy lepton and then examine the likelihood of even more heavy quarks and the resulting direction of spectroscopy in the future.

II. CHARMONIUM

The mesonic system consisting of a charmed quark and antiquark is often referred to as charmonium, without necessitating the dynamical viewpoint that such a system may be the QCD analogue[4] of positronium in QED. With even the barest knowledge of the "old" spectroscopy, the $c\bar{c}$ spectrum is expected to consist of at least orbital excitations with L=0, 1, 2, ... and total $\vec{J}=\vec{L}+\vec{S}$ where S, the total quark spin, is 0 or 1, plus corresponding radial excitations.

The observed spectrum,[5] of odd charge conjugation states consists of the J or $\psi(3095)$, $\psi(3684)$ or ψ', "$\psi(4100)$", and $\psi(4414)$ with no reason to suppose that the last of these $J^{PC}=1^{--}$ mesons, which are likely radial excitations of the ground state ψ, has been found. The "$\psi(4100)$" probably consists of several resonances and/or thresholds, likely interfering with each other.[6,21] The possible proliferation of states near 4 GeV may be evidence for more than just the $c\bar{c}$ spectrum expected from considering a nonrelativistic system and simple potential. Additional levels due to excitations of the quark binding mechanism, e.g., string modes,[7] or arising from two quark-two antiquark states[8] have been proposed to explain the data in this region.

The observations of possible even charge conjugation states[5,9] involve mesons X(2800), $\chi(3414)$, $\chi(3454)$, P_c or $\chi(3508)$, and $\chi(3552)$. Both the X(2800) and $\chi(3454)$ could use additional confirmation. The other three states are established: they are all observed (1) as bumps in the inclusive gamma ray spectrum[10,11] from the ψ', (2) decaying into hadrons,[12] and (3) decaying into $\gamma\psi$.[13,14,10]

The ψ, ψ', $\chi(3414)$, and $\chi(3552)$ are established as having isospin zero, and decaying into hadronic states with C=G conserved. All the other $c\bar{c}$ states are consistent with having zero isotopic spin. Although a lengthy discussion is not possible here, where testable at present these states are also found to be consistent[12] with being SU(3) singlets (as expected for a $c\bar{c}$ system), with a small amount of SU(3) breaking possibly occurring in the decay process at a level not unexpected from studies of the decays of ordinary mesons.

A property of the states below ~3.7 GeV, but not above, is that they are <u>all</u> known to be narrow, either by direct measurement or by deduction from the occurrence of substantial electromagnetic decay modes. Such narrow widths are expected from the Zweig rule[15] for $c\bar{c}$ states with masses below the threshold for decay into a pair of charmed mesons, i.e., 3.73 GeV for a natural spin-parity and 3.87 GeV for an unnatural spin-parity state. The breaking of Zweig's rule may be described within QCD in terms of annihilation of the $c\bar{c}$ system into gluons, [4,16] which ultimately manifest themselves by coupling to ordinary quarks, i.e., ordinary hadrons. Such a picture gives very different predictions for decay widths of odd and even charge conjugation states. It also predicts the mass dependence of the Zweig rule violating widths via the logarithmic decrease in the gluon coupling characteristic of an asymptotically free gauge theory. We will return to examine these predictions based on QCD in relation to the data in a moment.

The spin-triplet p-wave $c\bar{c}$ states all have even charge conjugation, as does the spin-singlet pseudoscalar partner of the ψ'. These $^3P_0$, $^3P_1$, $^3P_2$ and $^1S_0'$ levels are all expected to lie between the ψ and ψ'. If we assume these four are the only ones with even charge conjugation between the ψ and ψ', then experimental data now demands an almost unique J^P assignment for the four observed states.[5] The argument, in brief, is that the observed decays to $\pi\pi$ and to $K\bar{K}$ plus the angular distribution of the gamma ray in $\psi' \to \gamma\chi$ implies that $\chi(3414)$ and $\chi(3552)$ have $J^{PC}=0^{++}$ and 2^{++}, respectively. From the cascade gamma ray angular distribution in $\psi' \to \gamma\chi \to \gamma\gamma\psi$, there is strong evidence[17,18] that $J\neq 0$ for the $\chi(3508)$: it must then be the $J^{PC}=1^{++}$ level. By process of elimination, $\chi(3454)$ is the pseudoscalar $\left({}^1S_0'\right)$ partner of the ψ'. This is the same assignment of quantum numbers for the states between the ψ and ψ' arrived at earlier[19] by employing additional theoretical assumptions together with a subset of the presently available data.

We then regard the $\chi(3414)$, P_c or $\chi(3508)$, and $\chi(3552)$ as being fairly firmly identified as the ${}^3P_0$, ${}^3P_1$, and ${}^3P_2$ levels of the $c\bar{c}$ system, respectively. The branching ratios[10,11] for $\psi' \to \gamma + {}^3P_J$ are each from 5 to 10%. The relative rates are consistent with being proportional to $(2J+1)k_\gamma^3$, as required for the electric dipole transitions expected in the charmonium picture.[20] The absolute rates for $\psi' \to \gamma + {}^3P_J$ are within a factor two or better of the values predicted on the basis of a sophisticated calculation which takes into account the coupling of the $c\bar{c}$ states to the charmed particle continuum.[21,22]

Information on the relative rates for (Zweig rule violating) hadronic decays of the ${}^3P_J$ states can now be derived[19] from available experimental data. We assume that both the $\psi' \to \gamma + {}^3P_J$ and ${}^3P_J \to \gamma\psi$ transitions are electric dipole in character, something consistent with experiment for the former set of decays as noted above. Then the measured branching ratios for $\psi' \to \gamma + {}^3P_J \to \gamma\gamma\psi$ may be employed to tell us the <u>relative</u> total widths of the ${}^3P_J$ states. As the relative rates for ${}^3P_J \to \gamma\psi$ are given to us by the electric dipole assumption, we then get the <u>relative</u> rates for ${}^3P_J \to$ hadrons. The important conclusion[19] from this exercise is that the width for ${}^3P_1 \to$ hadrons is a small fraction of that for ${}^3P_0$ or ${}^3P_2 \to$ hadrons, i.e., less than (1/4) $\Gamma\left({}^3P_2 \to \text{hadrons}\right)$ and less than (1/5) $\Gamma\left({}^3P_0 \to \text{hadrons}\right)$. This agrees with the prediction from the gluon annihilation picture of Zweig forbidden hadronic decays where even charge conjugation states decay into two (massless) gluons. This is allowed for J=0 or 2, but forbidden for J=1 by a familiar argument using Bose statistics and angular momentum considerations. On this basis one expects ${}^3P_0$ or ${}^3P_2 \to$ gluon + gluon ($\to$ hadrons), but not ${}^3P_1 \to$ gluon + gluon, and hence a suppression in relative hadronic decay width in the latter case, as observed.

There is no measurement of the <u>absolute</u> rate for any decay of a ${}^3P_J$ state. But we may get at them by making an estimate for the absolute rate for ${}^3P_J \to \gamma\psi$. A naive estimate can be obtained by assuming the same electric dipole matrix element as for $\psi' \to \gamma + {}^3P_J$. This leads to widths which are ~10 times bigger than those for $\psi' \to \gamma + {}^3P_J$, i.e., hundreds of keV, simply because of the increased phase space. A much more sophisticated analysis has been performed by Jackson,[23] who employs sum rules to get both upper and lower bounds on $\Gamma\left({}^3P_J \to \gamma\psi\right)$. Again, the values of $\Gamma\left({}^3P_J \to \gamma\psi\right)$ are found to lie in the hundreds of keV range.

The known branching ratios[5,10] for ${}^3P_J \to \gamma\psi$ plus these bounds yield bounds on the <u>absolute</u> total widths for the ${}^3P_J$ states. Except for the ${}^3P_1$ state, these widths are mostly due to the hadronic decays of the ${}^3P_J$ states: they turn out to be in the multi-MeV range, which is one and a half orders of magnitude bigger than $\Gamma(\psi \to \text{hadrons})$. Again this is expected from the gluon annihilation picture where for ${}^3P_{0,2} \to$ hadrons compared to $\psi \to$ hadrons one gains, (1) by the phase space of two gluons rather than three and (2) by the presence of one less power of the squared gluon coupling, α_S, which is estimated to be considerably less than unity at the ψ or ^3P_J masses. In fact, the absolute widths for $^3P_J \to$hadrons estimated from experiment as above agree with the detailed calculations based on the charmonium and gluon annihilation picture carried out by Barbieri et al.[24]

More problematic for the theory are the splittings in mass between the ^3P_J states. They are an order of magnitude larger than those originally predicted on the basis of single gluon exchange at short distances.[20,25] One must clearly incorporate the effects of the confining "potential" as well as the short distance coulomb-like effect on the "fine structure" of charmonium. A natural first attempt in this direction is to approximate the multi-gluon confining forces by an effective vector exchange.[26] This yields bigger mass splittings, but it also limits their relative size[26]:

$$0.8 \leq \frac{M\left(^3P_2\right) - M\left(^3P_1\right)}{M\left(^3P_1\right) - M\left(^3P_0\right)} \leq 1.4 \quad .$$

The assignment of ^3P_J states to the observed levels as given before results in a value for this ratio of mass splittings of 0.4 to 0.5.

Several ways out of this quandry have been suggested. One possibility is to give the quarks a (color) anomalous magnetic moment, but retain the effective vector exchange nature of the confining force.[27] With a choice of the moment of ~1 quark magneton, one gets "qualitative agreement" with the observed mass differences. Alternately, one may use an effective scalar exchange, which gives rise to a spin-orbit potential of opposite sign. Within the framework of a relativistic Bethe-Salpeter calculation, Henriques et al.[28] have obtained a reasonable ^3P_J spectrum with such a scalar confining potential (plus a strong coulomb-like potential at short distances). However, at this point we are getting to be a long way from the basic theory of QCD. One is led to ask at what point one is learning as much about the underlying theory as about our ability to find an effective potential model with several free parameters which can be adjusted to fit the data.

These problems and questions are compounded in the case of the candidates for pseudoscalar partners of the ψ and ψ', the possible states X(2800) and $\chi(3454)$. In their proposed role as η_c and η_c', respectively, they both suffer three faults:

1. The rates for $\psi \to \gamma + X$ and $\psi' \to \gamma + \chi(3454)$ are too small. In the case of $\psi \to \gamma + X(2800)$, the upper limit on this branching ratio[5, 11] implies the rate must be too small by at least an order of magnitude compared to a naive charmonium calculation.[29]
2. The hadronic widths are too small. From the claimed branching ratio[9] for $\psi \to \gamma X \to \gamma\gamma\gamma$ and the upper limit[5, 11] on $\psi \to \gamma X$, we have $\Gamma(X \to \gamma\gamma)/\Gamma(X \to \text{hadrons}) \gtrsim \frac{1}{2} \times 10^{-2}$. Similarly,[19, 22] $\Gamma(\chi \to \gamma\psi)/\Gamma(\chi \to \text{hadrons}) \gtrsim 10^{-1}$. Therefore both have estimated hadronic widths of tens of keV to hundreds of keV. This is an order of magnitude smaller than expected on the basis of the gluon annihilation picture.[4, 16, 20] There, both pseudoscalars annihilate into two gluons giving hadronic widths of several MeV, as indeed we found was likely for the $^3P_0$ and $^3P_2$ states.
3. The mass splittings from their vector partners (both ~250 MeV) are too large. From color gluon exchange at short distances,[25] or simply from the observed K-K* and D-D* (see below) mass differences, one expects the η_c-ψ or η_c'-ψ' mass difference to be in the 50-100 MeV range. There is no spin-orbit potential contribution to this "hyperfine" mass splitting. Of course, the (color) anomalous quark moment[27] used to try and fit the ^3P_J splittings

would also increase the predictions for the present mass differences, giving a unified explanation of both effects. This does not in itself remove difficulties (1) and (2) however.

Harari[30] has recently offered an alternative "way out" by emphasizing the possible presence of a $^1D_2$ $c\bar{c}$ state ($J^{PC}=2^{-+}$) between the ψ and ψ'. In this case, $\chi(3454)$ might be identified with this $^1D_2$ level, leaving the η_c' to be discovered in the future. This obviously still leaves all the problems listed above for the X(2800) as well as implies another large "hyperfine" splitting, but this time for the d-wave states inasmuch as all estimates put the ^3D states above the ψ' in mass. However, irrespective of the solution of the immediate problem at hand with the pseudoscalars, it is important to keep in mind the possible presence of such a $^1D_2$ state to make a total of five states between the ψ and ψ'.

The overall situation with regard to the even charge conjugation $c\bar{c}$ states might then be summarized as follows: Even though the original predictions[20] for the p-wave states had the rates for $\psi' \to \gamma + {}^3P_J$ an order of magnitude too large, the mass splittings an order of magnitude too small,[20, 25] and the wrong dominant decay modes[20] ($\gamma\psi$ rather than hadrons), the observed states are a great triumph. They establish unambiguously the existence of an orbitally as well as radially excited $c\bar{c}$ spectroscopy. If there were any doubts they also do the same for the $q\bar{q}$ system—don't let anyone tell you there is no A_1, when its $c\bar{c}$ analogue $\chi(3508)$ exists! The ^3P states also support in both their relative and, as well as can be estimated, in their absolute hadronic widths the gluon annihilation picture of Zweig rule violating decays.

On the other hand, if X(2800) and $\chi(3454)$ are the pseudoscalar partners of the ψ and ψ', they are a quantitative failure of the theory. Their rates for radiative formation from ψ and ψ', their hadronic decay widths, and their mass splittings do not fit into the simple charmonium and gluon annihilation picture. If these states are confirmed as the η_c and η'_c, respectively, then some serious rethinking of the whole picture needs to be done, for we must be doing something really wrong in treating the $c\bar{c}$ system as a nonrelativistic one with the physics of decays occurring at sufficiently short distances that it is tractable within the framework of QCD with a small number of gluons.

III. CHARM

The lowest mass charmed mesons are the D^0 at[3] 1865 ± 15 MeV and the D^+ at[31] 1876 ± 15 MeV. The recoil spectra in e^+e^- annihilation near 4 GeV, to be discussed below, show clear evidence[3, 31, 32, 33] for a charged and neutral D*, both near 2010 MeV.

With the initial discovery came the observation of the $K^-\pi^+$ and $K^-\pi^+\pi^+\pi^-$ modes[3] of the D^0 and the $K^-\pi^+\pi^+$ mode[31] of the D^+. We have heard at this conference of the observation of $D^0 \rightarrow K^0_S\pi^+\pi^-$ from SPEAR[33] and the indications of photoproduction of D^0 followed by its decay into $K^0_S\pi^+\pi^-\pi^+\pi^-$ at Fermilab.[34] All these decays are consistent with being the leading Cabibbo allowed nonleptonic decays expected for charmed mesons. There are no significant bumps reported in purely multipion modes, and an examination of $\pi^+\pi^-$ compared to $K^{\mp}\pi^{\pm}$ for the D^0 ($\bar{D}^0$) indicates that it is at most not much bigger than expected for such a Cabibbo suppressed mode.[32] The mean charged multiplicity in D decay is obtainable from the e^+e^- annihilation data near 4 GeV: it is about two or a little larger.[35] This means the total mean multiplicity is likely between three and four, and that three and four body decays are very probably the most common ones.

As noted by Glashow,[36] if a charmed quark becomes a strange quark (not antiquark) in nonleptonic decays, then the charges of the D's decaying in K^-'s tells us the charmed quark charge, given the u and d charges. It is +2/3.

A preliminary study[32] of the Dalitz plot for $D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$ shows that the density does not vanish on the boundary and therefore that the final particles are in a state of unnatural spin-parity.[37,38] Since $D^{o} \to K^{-}\pi^{+}$ has a final state with manifest natural spin-parity, if the D's are in the same isomultiplet than parity violation in the decay of at least one of the D's is implied: hence the decay occurs by the weak interaction. The establishment of the spin of the D^{o} as zero, plus the already observed decays $K^{-}\pi^{+}$ and $K_{S}^{o}\pi^{+}\pi^{-}$, would accomplish the proof of a weak decay without the assumption that D^{o} and D^{+} are in the same isomultiplet.

Independent evidence that the D's decay weakly is provided by the observation of semileptonic decays of new hadrons in neutrino induced dilepton events[39] and by the detection of inclusive electrons, correlated with kaons, in the 4 GeV center-of-mass energy region of $e^{+}e^{-}$ annihilation at DORIS.[40,41] The size of these signals leads one to estimate a semileptonic branching ratio of at least 10% for some <u>average</u> of D^{o} and D^{+}: it is important to note that one of the D's may have a branching ratio much larger than the other.

This bears on the important theoretical issue of whether the nonleptonic decays of charmed particles are enhanced over the magnitude expected in a naive current-current form for the effective nonleptonic Hamiltonian. Such is clearly the case for strange particles, and on this basis early estimates[42] of the semileptonic branching ratio for charmed mesons were 5 to 10%. The experimental indications, although very preliminary, are of a number bigger than this, lending support to later arguments[43] that the nonleptonic enhancement factor is less for charm changing than for strangeness changing decays. Presently available data does not even rule out a semileptonic (electronic plus muonic) branching ratio as high as the 40% found by simply assuming that the charmed quark inside a hadron decays as if free in the ratios

$$c \to s + e\nu : c \to s + \mu\nu : c \to s + u\bar{d}$$
$$\approx \quad 1 \quad : \quad 1 \quad : \quad 3$$

i.e., without any nonleptonic enhancement factor at all.

Another very interesting theoretical issue is that of D^0-$\bar{D}^0$ mixing. In the so-called "standard model" with four quarks, such mixing is a very small effect[44]: a D^0 will decay into a final state including a wrong sign kaon (a K^+) only at the level of doubly Cabibbo suppressed decays, i.e., $\approx \tan^4 \theta_c$. However it is possible to have large D^0-$\bar{D}^0$ mixing, a possibility both realized in various models[45] and pointed out for experimental testing by a number of authors.[46] Glashow and Weinberg[47] have reemphasized recently in a more general context that large D^0-$\bar{D}^0$ mixing (and charm changing neutral currents) is expected in any theory where the weak isospin T, and its third component, T_3, are not the same for each quark with charge +2/3 (like the c quark). Such large mixing would mean that a D^0 decays roughly equally into final states with a K^+ or a K^-. Distinguishing between the extreme cases of very small or very large mixing should be possible rather soon in e^+e^- annihilation: one need only compare the charge of the kaon arising from a detected D^0 decay with that of the accompanying kaon (from the other D) using a large enough data sample to give a statistically significant result.

Although much remains to be learned about the D's, the study of charmed mesons has already graduated to the D*'s and their properties. Without further justification[48] we will assume that like the π and ρ or K and K*, the D and D* have $J^P = 0^-$ and 1^- respectively. The D*, being heavier, will decay by strong or electromagnetic interactions into the D. Since from the previously noted masses,

$$M^* - M \simeq m_\pi \quad ,$$

pionic decay will be inhibited by phase space and possibly even forbidden. To get an idea of the kind of widths we should be expecting, we concentrate on the D^{*0} and start from the measured[49] $\Gamma(K^* \to \pi^0 K)$ and assume that $\Gamma \propto g^2 p_\pi^3$: we find on relating the $K^* \to \pi K$ coupling to that for $D^* \to \pi D$ that[50]

$$\Gamma(D^{*0} \to \pi^0 D^0) \simeq 0.1 \text{ MeV} \left(\frac{M^*-M-m_\pi}{10 \text{ MeV}}\right)^{3/2} .$$

Assuming $\Gamma \propto g^2 p_\pi^3/M^2$ leads to a smaller width, while a PCAC approach (relating axial-vector couplings for zero mass pions) yields a bigger one. But no matter what you do it is hard to get widths larger than a fraction of an MeV.

A similar approach for the radiative widths starts from the measured rate[49] for $\omega \to \gamma\pi$ and relates its magnetic dipole amplitude using the quark model to that for $D^* \to \gamma D$. With $\Gamma \propto \mu^2 k_\gamma^3$ we find:

$$\Gamma(D^{*0} \to \gamma D^0) \simeq 70 \text{ keV} \quad \text{(SU(4) symmetry)}$$

$$\simeq 18 \text{ keV} \quad \text{(only the } \bar{u} \text{ quark moment in the } D^* \text{ is active)} .$$

While one may criticize the detailed assumptions in the phase space factor, coupling constant determination, etc. in these calculations, three things are clear before we know any more about experimental results:

1. The D^* widths are of order 100 keV and perhaps less;
2. The decay mode $D^* \to \gamma D$ is competitive with $D^* \to \pi D$ even though the latter is a strong decay;
3. Electromagnetic mass differences between the charged and neutral D's and the charged and neutral D^*'s are very important simply because pionic transitions allowed by selection rules can be forbidden due to lack of phase space.

This naturally brings us to the subject of electromagnetic mass differences. In a constituent model where hadrons are composed of quarks, one writes

$$\Delta M_{em} = \begin{pmatrix}\text{contribution from} \\ \text{quark } \Delta m\end{pmatrix} + \begin{pmatrix}\text{coulomb} \\ \text{contribution}\end{pmatrix} + \begin{pmatrix}\text{magnetic} \\ \text{contribution}\end{pmatrix} \quad .$$

Only the last term is different for the D and D* (which both have L=0, but S=0 and 1, respectively). An indication of its importance can be gained from the old spectroscopy[49]:

$$\Delta M(K^o\text{-}K^+) = 4.0 \pm 0.1 \text{ MeV}$$

$$\Delta M(K^{*o}\text{-}K^{*+}) = 4.1 \pm 0.6 \text{ MeV}$$

We could feel completely reassured in dropping it, but for the only baryons (which are L=0 "hyperfine" partners) measured with sufficient accuracy[49]:

$$\Delta M(\Xi^o - \Xi^-) = 6.4 \pm 0.6 \text{ MeV}$$

$$\Delta M(\Xi^{*o} - \Xi^{*-}) = 3.3 \pm 0.7 \text{ MeV} \quad .$$

In any case this last (magnetic) term is dropped in most calculations and for the D's or D*'s probably is not dominant over the first two.[51]

It is important to note that the first two terms contribute with opposite sign to the K^o-K^+ electromagnetic mass difference, while they have the same (positive) sign for D^+-D^o. Thus it is difficult for any calculation of this kind to predict that $\Delta M(D^+\text{-}D^o)$ is smaller than $\Delta M(K^o\text{-}K^+) \simeq 4$ MeV. In just a few months a whole theoretical literature[52] and controversy, mostly at Harvard, has sprung up on the electromagnetic mass differences of charmed particles. It is an interesting subject in itself, but we merely note here that the predictions for $\Delta M(D^+\text{-}D^o)$ and $\Delta M(D^{*+}\text{-}D^{*o})$ in the literature range all the way from 4 MeV to 15 MeV.

Our prospects for learning experimentally about the decay modes of the D*'s and about electromagnetic mass differences are much improved over the short term because of the proximity of thresholds for various charmed meson channels to center-of-mass energies where large amounts of data now exist from e^+e^- annihilation. In particular, at $\sqrt{s} = 4.028$ GeV the missing mass spectrum recoiling against a D^0 shows[32, 33] peaks just above 2 GeV and near 2.15 GeV. With the detected D^0 mass constrained, the latter peak is spectacular, falling mostly in one 10 MeV mass bin.[32] While the peak near 2 GeV must be partly due to a real resonance, the D^{*0}, the more impressive peak near 2.15 GeV could be entirely a reflection of the D^*D^* channel, as was realized immediately by the experimentalists who first observed it. Not to call one of the most impressive peaks on any invariant mass plot in recent years a resonance at first seems outrageous. So we will spend a little time in what follows on reflectionology,[53] thereby (we hope) explaining why those who propose that the peak at ~2.15 GeV is a reflection are not completely crazy. The key points are the nonrelativistic kinematics, because of the heavy D mass, and the effects of the edge of phase space. These yield characteristic effects which turn out to be of very important diagnostic value for sorting out the properties of the D-D* system.

First, it is important to think in terms of momentum of the detected D, which is what is really measured: put aside missing mass plots, which can be quite misleading. To be specific we consider a detected D^0 and its momentum spectrum. We start by approximating $D^* \to \pi D$ decays as having no Q-value (which turns out to be a rather good approximation) and neglecting the $D^* \to \gamma D$ decays. We will lift these restrictions in a moment. For $\sqrt{s}$ values just above 4 GeV we expect peaks in the momentum spectrum as in the following table (assuming $M_{D^o} = 1.865$ GeV and $M_{D^{*o}} = 2.005$ GeV):

Source	Momentum of Detected D^o	At $\sqrt{s} = 4.028$ GeV Momentum (MeV)	Missing Mass (GeV)
$D^o\bar{D}^o$	$p = \frac{1}{2}(s - 4M^2)^{\frac{1}{2}}$	760	1.865
$D^o\bar{D}^{*o}$	$p^* = \frac{[(s-(M+M^*)^2)(s-(M-M^*)^2)]^{\frac{1}{2}}}{2s^{\frac{1}{2}}}$	558	2.005
$D^{*o}\bar{D}^o$ $\hookrightarrow \pi^o D^o$	$\frac{M}{M^*}\, p^*$	519	2.027
$D^{*+}D^-$ $\hookrightarrow \pi^+ D^o$	Near the above peak, but shifted slightly below in momentum (and above in missing mass) if the charged D and D* are heavier than the neutral D and D*, respectively.		
$D^{*o}\bar{D}^{*o}$ $\hookrightarrow \pi^o D^o$	$\frac{M}{M^*} \cdot \frac{(s-4M^{*2})^{\frac{1}{2}}}{2}$	177	2.148
$D^{*+}D^{*-}$ $\hookrightarrow \pi^+ D^o$	Near the above peak, but at lower momentum (and higher missing mass). May not be kinematically allowed at $\sqrt{s} = 4.028$.		

The last four peaks are manifestly not due to real resonances recoiling against the detected D^o. But in our approximation of zero Q-value in D* decays they give peaks whose widths are determined just by the intrinsic D and D* widths (i.e., negligible) and the resolution of the apparatus. The effect of nonzero Q-value is easily inserted: since all velocities of the D's arising from reflections are nonrelativistic we may to good approximation use Galilean relativity and add (vectorially) the momentum arising from nonzero Q-value, to that in the table. For $D^* \to \pi D$, $|\Delta\vec{p}| \simeq 16$ MeV $(Q/\text{MeV})^{1/2}$, while $|\Delta\vec{p}| \simeq 135$ MeV due to $D^* \to \gamma D$. It is clear that for Q-values in the expected range of 10 MeV or less for $D^* \to \pi D$, the spread of the "reflection" peaks is comparatively small, and for example, a relatively "narrow" (reflection) peak due to $\bar{D}^o D^{*o}$ ($D^{*o} \to \pi^o D^o$), centered ~40 MeV in momentum below the (true resonance) peak due to $D^0\bar{D}^{*0}$, should be visible in the D^0 momentum spectrum. On the other hand, if $D^{*0} \to \gamma D^0$ were the only D^{*0} decay, the corresponding "reflection" peaks are very much spread out, particularly those at lower D^0 momentum, so that they will no longer even be recognizable as "peaks". This is borne out by explicit Monte Carlo calculations.[32] Note also that the position of the peak in D^0 momentum due to $D^{*0}\bar{D}^{*0}$ is very sensitive to the D^{*0} mass at $\sqrt{s} = 4.028$ GeV: a shift in D^* mass of 2 MeV changes the momentum of the D^0 by ~20 MeV.

Preliminary data on both the D^0 and D^+ momentum spectra at $\sqrt{s} = 4.028$ GeV have been presented at the SLAC Summer Institute on Particle Physics[32] and at this conference.[33] With the background material discussed above, we see that these data, first of all, give us a D^{*0} mass accurate to a few MeV from the position of lower momentum D^0 peak (due to $D^{*0}\bar{D}^{*0}$). Second, the narrowness of this peak means that $D^{*0} \to \pi^0 D^0$ has a small Q value—several MeV at most. Therefore $D^{*0} \to \pi^- D^+$ is very likely forbidden by lack of phase space, since $m_{\pi^\pm} - m_{\pi^0} = 4.6$ MeV and M_{D^+} is probably greater than M_{D^0}. There are indications for $D^{*0} \to \gamma D^0$, but it can't completely dominate D^{*0} decays or there would be no sharp lower momentum peak at all. Third, and with less certainty, $D^{*+} \to \pi^+ D^0$ is not the overwhelmingly dominant D^{*+} decay. For if it were $\bar{D}^0 D^{*0}$ ($D^{*0} \to \pi^0 D^0$ or γD^0) and $D^- D^{*+}$ ($D^{*+} \to \pi^+ D^0$) would <u>each</u> contribute as many events to their respective reflection peaks as found in the direct peak due to $D^0\bar{D}^{*0}$. There are not enough events in the reflections for this. Thus $D^{*+} \to \pi^0 D^+$ or γD^+ are non-negligible D^{*+} decay modes. Aside from being of immediate interest for the D^+ momentum spectrum and untangling D^{*+} decays, this also bears on the electromagnetic mass difference question discussed earlier. For if $\Delta M(D^+ - D^0)$ were at the upper end of the predicted range, i.e.,

$\approx$ 15 MeV, then indeed we would expect $D^{*+} \rightarrow \pi^+ D^0$ to strongly dominate $D^{*+} \rightarrow \pi^0 D^+$ (as well as $D^{*+} \rightarrow \gamma D^+$) as it would be greatly favored by phase space as well as by a factor of 2 from Clebsch-Gordan coefficients. Thus we would guess that the D^+-D^0 electromagnetic mass difference is nearer the lower end of the range of predictions, i.e., probably lies between 5 and 10 MeV.

In our reflectionology discussion we have not yet dealt with the relative size of the $D\bar{D}$, $D\bar{D}^* + D^*\bar{D}$ and $D^*\bar{D}^*$ channels, which obviously enters any detailed attempt to understand the D momentum (or recoil mass) spectra. A simple model based on creation of a $c\bar{c}$ pair by the virtual photon in e^+e^- annihilation, followed by combination with an ordinary $q\bar{q}$ pair produced out of the vacuum to form charmed mesons, yields a "raw" ratio[53] of 1:4:7 for $D\bar{D}:D\bar{D}^* + D^*\bar{D}:D^*\bar{D}^*$.

Unfortunately the D and D* have different masses, and, particularly in the 4 GeV region, account must at least be taken of the different thresholds for each channel. Since all these channels involve p-waves, this is most naively done by including a factor of p^3, which nonrelativistically is proportional to $Q^{3/2}$, where Q is the available energy (Q-value) for a given channel. But no channel cross section grows like this forever: it must be cut off somehow, say by a factor e^{-Q/Q_0}. This is in essence the model with which De Rujula et al.[53] have tried to understand the observed spectra. With the choice of a parameter which is equivalent to $Q_0 \simeq 250$ MeV, and an assumed set of D and D* masses they have calculated the missing mass spectra at a nominal value of $\sqrt{s} = 4.05$ GeV and found a result[53] which looks rather like the older data obtained in a range of $\sqrt{s}$ centered near 4.1 GeV. However, comparing their model (even with changed D and D* masses) with the large bloc of data at $\sqrt{s} = 4.028$ GeV shows that the predicted peak resulting from $D^*\bar{D}^*$ is much too small compared to that from DD^*.[54]

One would need to change Q_0 to a value well below 100 MeV to fit the data. But then one finds that everything is really depending on Q_0, i.e., on the dynamical suppression of $D\bar{D}$ and DD^* by an order of magnitude, and not on the basic input of 1:4:7 which we would like to test. This is all aside from the high likelihood that the treatment of the dynamics is way oversimplified and probably doesn't represent what is happening in this region of coupled channels, thresholds, and direct channel resonances.[55] $\psi(4028)$ may just love $D^*\bar{D}^*$!

A cleaner test of spin factors like the 1:4:7 used above will be in $e^+e^- \to D\bar{D}^{**}$, where D^{**} is one of the expected L=1 $c\bar{q}$ states. If the $c\bar{c}$ pair comes from the virtual photon while the $\bar{q}q$ arises from the vacuum, it can be shown[56] that production of the $J^P = 2^+$ D^{**} in this manner is forbidden, while one of the $J^P = 1^+$ states is allowed. The clear absence of a channel like $D\bar{D}^{**}(2^+)$ should be much easier to establish than trying to make comparisons of several allowed channels with quite different thresholds.

With all this discussion of reflections in the D^0 momentum or missing mass spectrum caused by $D^*\bar{D}^*$ we should comment that the possibility of a real resonance, D^{**}, at ~2.15 GeV is certainly not ruled out. It could explain part, or even all, of the peak we have been attributing to $D^*\bar{D}^*$. Possible values of J^P, limited in part by the need to keep this "D^{**}" relatively narrow, are 0^- and 1^+. In particular, the latter has been proposed by Suzuki.[57] The crucial test of course is that the $D^*\bar{D}^*$ reflection moves upward in missing mass (slowly) with increasing $\sqrt{s}$, while a real resonance doesn't.

Finally, please find the F^+, i.e., $c\bar{s}$ meson! The corresponding F^{*+} decays to γF. All estimates put the F^+ near 2 GeV in mass. It should decay to $\bar{K}^0K^+$, $K^+K^-\pi^+$, etc. Although it was supposed to have been discovered this past July, its nonappearance is not yet a cause for major worry. But it would be nice to fill in this last big gap in the spectroscopy of charmed mesons.

Like charmed mesons, the discovery[58] of charmed baryons permits us to use the properties of the observed states to get at the dynamics of the strong interaction, as well as electromagnetic and weak interactions in a hadronic setting. The lowest mass baryon was expected to be the Λ_c (or C_0^+ in Ref. 42), i.e., the charmed analogue of the Λ obtained by replacing the s quark by the c quark. Experimentally the $\bar{\Lambda}_c$ is presumably to be identified with the state at 2.25 GeV observed in the (nonleptonic) decay mode $\bar{\Lambda}\pi^+\pi^-\pi^-$ via photoproduction at Fermilab.[58,34]

In the same experiment, combining the $\bar{\Lambda}_c$ with an additional $\pi^{\pm}$ gives indications of an enhancement near 2.5 GeV: this presumably is the Σ_c and/or Σ_c^*, the charmed analogues of the Σ and $Y_1^*(1385)$, respectively. The coincidence in masses with the earlier Brookhaven neutrino event[59] containing a charmed baryon candidate event is striking: a $\Lambda\pi^+\pi^+\pi^+\pi^-$ mass of 2.426 GeV, and with removal of one of the three π^+ mesons a $\Lambda\pi^+\pi^+\pi^-$ mass of 2.244 GeV—probably two new particles in one picture!

With the Σ_c and/or Σ_c^* heavier than the Λ_c by more than a pion mass,[60] $\Sigma_c \to \pi\Lambda_c$ or $\Sigma_c^* \to \pi\Lambda_c$ proceed by strong interactions. But the Λ_c, being the lowest mass charmed baryon, must decay weakly. That the decay $\Lambda_c \to \Lambda\pi^+\pi^+\pi^-$ is in fact due to weak interactions would follow immediately from establishment of a nonzero longitudinal polarization of the final Λ. Present data[58] are still not statistically conclusive, but should become so in the future.

Aside from $\Lambda\pi\pi\pi$, and other nonleptonic modes like $\Lambda\pi$, $\Lambda\pi\pi$, $\Sigma\pi\pi$, ... which surely must exist, at some level one expects semileptonic decays as well.[60] Some of the neutrino induced dilepton events seen in bubble chambers[39] to be accompanied by a Λ may well represent charmed baryon production followed by semileptonic decay. If so the semileptonic branching ratio of the Λ_c is much larger than for strange baryons. This of course brings us again to the question of the degree of enhancement of nonleptonic decays and whether it is as large as for strangeness changing weak decays.

The (strong interaction) mass differences of the Λ_c and Σ_c or Λ_c and Σ_c^* provide a very important testing ground for ideas about the dynamics. We assume that the Λ_c is at 2.25 GeV, the Σ_c at 2.42 (from the BNL neutrino event[59]) and the Σ_c^* at ~2.5 GeV, with both the Σ_c and Σ_c^* subsumed in the ~2.5 GeV bump seen at Fermilab.[58] The mass differences of these singly charmed baryons then are in rather good agreement with the predictions of De Rujula et al.,[25] based on taking only single gluon exchange at short distances and making a nonrelativistic reduction of the quark-quark interaction into a Breit Hamiltonian form. This agreement is entirely nontrivial: after all, the $\Lambda_c - \Sigma_c$ mass splitting is larger than that of Λ and Σ. This comes about in the theory because the mass splitting is due to color magnetism and is proportional to the difference of two terms, each inversely proportional to a corresponding quark mass. With a charmed quark replacing a strange one, the cancellation between the two terms is smaller and the mass difference larger. But this success (and also good agreement with the D-D* mass difference using the same model[25]) must be contrasted with its miserable failure in the $c\bar{c}$ system where it *a priori* should have worked best! I don't think we can claim that the baryon mass splittings are well understood theoretically in this way when at the same time we have the $c\bar{c}$ skeleton in the closet.

IV. MORE LEPTONS AND QUARKS

For more than a year it has been known that there is a class of events of the form[61]

$$e^+e^- \to e^{\mp}\mu^{\pm} + \geq 2 \text{ undetected neutrals}$$

which have no conventional explanation. Several lines of argument, which we will not repeat here, suggested that rather than charmed particle production and their semileptonic decay, it was production and subsequent purely leptonic decay of a pair of heavy leptons that was the correct explanation for these events.[62] Further experimental work, with more data, has been used to rule out various other specific hypotheses for the origin of these events.[63] More recently events of the form

$$e^+e^- \rightarrow \mu^\pm \text{ hadron}^\mp + \text{neutrals}$$

have also been discussed.[64] They occur at a rate consistent with that expected from pair production of heavy leptons, with the purely leptonic decay of one and the "semihadronic" (neutrino + hadrons) decay of the other. The mass of the lepton lies between 1.6 and 2.0 GeV, with values in the upper half of that range more likely.[64]

With the discovery of charmed mesons with masses in this range, one might naively feel that the case for a heavy lepton has been weakened. In fact, I would argue it is stronger. Before charm was actually found, all kinds of wild hypotheses about its production and decay were possible. We know now experimentally that one does not produce $D\bar{D}$, but rather DD^*, D^*D^*, etc. for $\sqrt{s} \gtrsim 4$ GeV, so that D and $\bar{D}$ are rarely produced without other hadrons and photons, some of which would generally be detected (and not all be "undetected neutrals"); that D decays involve K's, as charm says they should; that the leptonic momentum spectrum in semileptonic D decays is relatively soft (from both e^+e^- and neutrino experiments); etc. All these characteristics when contrasted with the features of the data, especially at high values of $\sqrt{s}$ (say 6 to 8 GeV), argue against interpreting these events as arising from charm.

It is also to be remembered that after correcting for acceptance, cuts, etc. the observed $e^{\pm}\mu^{\mp}$ events, interpreted as coming from pair produced point heavy leptons, correspond to branching ratios for $L^- \to \nu_L \mu^- \bar{\nu}_\mu$ or $L^- \to \nu_L e^- \bar{\nu}_e$ of ~17%.[63] The cross section for $e^{\mp}\mu^{\pm}$ events is big! Since charm is presumably produced with a cross section ~4/3 times the point cross section at large $\sqrt{s}$, some of the semileptonic decay modes of charmed particles (which are to be imitative of heavy leptons) must have branching ratios at least as big as this if the $e\mu$ events come from charm production.

Note that the balance between heavy lepton and charm production is very different outside of e^+e^- annihilation. For example, in photoproduction the charm production cross section may well be 10^4 times bigger than the Bethe-Heitler cross section for making heavy lepton pairs, so that D decay modes with miniscule branching fractions may result in $e^{\mp}\mu^{\pm}$ events far in excess of anything from a heavy lepton.[65]

The case for more quarks (than u, d, s, and c) is at present mostly indirect.[66] Given a heavy lepton (and its corresponding neutrino) one may argue from quark-lepton symmetry or from cancellation of triangle anomalies for more quarks. If one did not have a heavy lepton, then the value of $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ of more than 5 at the highest SPEAR energies compared to the ~3-1/3 expected from the u, d, s and c quarks argues for additional quarks.

The other, more experimental, argument for new quarks, and in particular one with charge -1/3 usually called b, comes from the anomalous distributions seen in deep inelastic scattering of antineutrinos.[67, 68] The existence of such a new quark might show up most spectacularly in e^+e^- annihilation as a narrow peak, like the ψ, due to a vector $b\bar{b}$ bound state. Such a narrow particle is ruled out at SPEAR except possibly between about 4.5 and 5.7 GeV where the bounds are marginal.[5] Alternately, if the $b\bar{b}$ state were slightly mixed (a few %) with $c\bar{c}$ it would decay into pairs of charmed particles with a more typical hadronic width (say, tens of MeV). Such a state could have gone undetected up to now fairly easily, particularly again, between 4.5 and 5.7 GeV. Since the rise in R due to a charge -1/3 quark is only 1/3, it is still possible that a fifth quark yet remains to be found at SPEAR energies.

V. CONCLUSION

We have seen that there is an emerging spectroscopy of $c\bar{c}$, $c\bar{q}$ and cqq states. In many cases, charm spectroscopy has already become the archetype example of various aspects of hadron spectroscopy and decays and the testing ground for the underlying dynamics. But there are still plenty of states and their properties to be delineated, starting with the F^+ meson.

It can be claimed with real justification that we have a qualitative understanding of the new states we are seeing. However, a great deal of the time this "understanding" can be obtained simply by hanging the new charm quantum number directly on the "old" spectroscopy.

Whether we have a quantitative understanding is much more questionable. Models which seem to work well in situations where their applicability is in doubt, yield predictions which are sometimes right but also sometimes wrong by an order of magnitude in the $c\bar{c}$ system where they *a priori* should work best. In short, it is not clear yet whether charmonium bears more resemblance to the hydrogen or bismuth atom problems *vis-a-vis* quantum mechanics.

There is not much question anymore about the existence of charm. Rather, it is whether all we have seen up to now is just explainable by four quarks and four leptons. Another charged lepton is, in my opinion, very likely. And although the arguments are less direct, I would bet on the existence of more quarks.

Our main problems then are, first, that of obtaining a quantitative understanding of the spectroscopy and decays, connected as much as possible to an underlying theory like QCD and with the fewest possible free parameters. Second, we need to understand the spectroscopy of quarks and leptons. In fact, over the past year or so a slow but definite change in viewpoint has entered particle physics. It is that one takes the spectroscopy of quarks and leptons as the primary one. Hadrons then form a secondary spectroscopy, nuclei and atoms tertiary, etc. We have gone to the next level of structure. The associated questions become: How many quarks and leptons are there? What principles govern their spectra? Are all neutrinos massless? Added to "why does the muon weigh?" are why does the heavy lepton weigh? and why are both quark and lepton mass ratios so large? And, even deeper, are the lepton and quark spectra related and if so, how?

REFERENCES

1. B. J. Bjorken and S. L. Glashow, Phys. Letters 11, 255 (1964); S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, 1285 (1970).
2. J. J. Aubert et al., Phys. Rev. Letters 33, 1404 (1974); J. E. Augustin et al., ibid., 1406 (1974); G. S. Abrams et al., ibid., 1453 (1974).
3. G. Goldhaber, F. M. Pierre et al., Phys. Rev. Letters 37, 255 (1976).
4. T. Appelquist and H. D. Politzer, Phys. Rev. Letters 34, 43 (1975).
5. G. Feldman, lectures at the SLAC Summer Institute in Particle Physics, August 2-13, 1976 (unpublished). We take all values for masses (in MeV), branching ratios, etc. from the review and compilation of data contained in these lectures.
6. See, for example, the discussion and fits in Y. Dothan and D. Horn, Tel Aviv University preprint, 1976 and paper No. 47 submitted to this meeting.
7. R. C. Giles and S.-H. H. Tye, Stanford Linear Accelerator Center preprint SLAC-PUB-1794 (1976)(unpublished).
8. M. Bander et al., Phys. Rev. Letters 36, 695 (1976); C. Rosenzweig, Phys. Rev. Letters 36, 697 (1976); Y. Iwasaki, Prog. Theoret. Phys. (Kyoto) 54, 492 (1975). Also, L. B. Okun and M. B. Voloshin, ITEP preprint (1976)(unpublished).
9. B. Wiik, rapporteur talk at the 18th International Conference on High Energy Physics, Tbilisi, USSR, July 15-21, 1976 (unpublished).
10. J. S. Whitaker, W. Tanenbaum et al., Stanford Linear Accelerator Center preprint SLAC-PUB-1817 and Lawrence Berkeley Laboratory preprint LBL-5382 (1976)(unpublished).
11. D. H. Badtke et al., paper submitted by the Maryland, Pavia, Princeton, UC San Diego, Stanford Linear Accelerator Center, Stanford collaboration

to the 18th International Conference on High Energy Physics, Tbilisi, July 15-21, 1976 (unpublished).

12. G. Trilling, talk at the Topical Conference of the SLAC Summer Institute on Particle Physics, August 2-13, 1976 (unpublished).
13. W. Braunschweig et al., Phys. Letters B 57, 407 (1975).
14. W. Tanenbaum et al., Phys. Rev. Letters 35, 1323 (1975).
15. S. Okubo, Phys. Letters 5, 165 (1963); G. Zweig, unpublished; J. Iizuka, Suppl. to Prog. Theor. Phys. 37-38, 21 (1966).
16. A. De Rujula and S. L. Glashow, Phys. Rev. Letters 34, 46 (1975).
17. H. Rieseberg, invited talk on results from the DESY-Heidelberg collaboration in Particle Searches and Discoveries-1976, R. S. Panvini, ed. (American Institute of Physics, New York, 1976), AIP Conference Proceedings No. 30, Particles and Fields Subseries No. 11, p. 274.
18. W. Tanenbaum, private communication, and Refs. 5 and 12.
19. M. S. Chanowitz and F. J. Gilman, Phys. Letters B 63, 178 (1976).
20. T. Appelquist et al., Phys. Rev. Letters 34, 365 (1975); C. Callan et al., ibid., 52 (1975); E. Eichten et al., ibid., 369 (1975); J. Borenstein and R. Shankar, ibid., 619 (1975); B. J. Harrington et al., ibid., 706 (1975).
21. E. Eichten et al., Phys. Rev. Letters 36, 500 (1976).
22. The theoretical situation with respect to radiative ψ and ψ' decays also was reviewed at the Tbilisi Conference by M. S. Chanowitz, Lawrence Berkeley Laboratory preprint LBL-5524 (1976)(unpublished).
23. J. D. Jackson, Lawrence Berkeley Laboratory preprint LBL-5369 (1976) (unpublished).
24. R. Barbieri et al., Phys. Letters B 60, 183 (1976) and 61, 465 (1975).

25. A. De Rujula, H. Georgi, and S. L. Glashow, Phys. Rev. D 12, 147 (1975).

26. H. J. Schnitzer, Phys. Rev. Letters 35, 1540 (1975); J. Pumplin et al., Phys. Rev. Letters 35, 1538 (1975).

27. H. J. Schnitzer, Brandeis University preprint (1976) (unpublished).

28. A. Henriques, B. Kellett, and R. Moorhouse, CERN preprint TH. 2176 (1976) (unpublished).

29. See, for example, J. D. Jackson, lectures at the SLAC Summer Institute on Particle Physics, August 2-13, 1976 (unpublished) and references therein.

30. H. Harari, CERN preprint TH. 2222 (1976) (unpublished).

31. I. Peruzzi, M. Piccolo, G. J. Feldman, H. K. Nguyen, J. E. Wiss et al., Phys. Rev. Letters 37, 569 (1976).

32. G. Goldhaber, talk at the Topical Conference of the SLAC Summer Institute on Particle Physics, August 2-13, 1976 (unpublished).

33. R. Schwitters, invited talk at this conference.

34. B. Knapp, invited talk at this conference.

35. F. J. Gilman, in New Pathways in High Energy Physics II, A. Perlmutter, ed. (Plenum Press, New York, 1976), p. 1.

36. S. L. Glashow, talk at the Topical Conference of the SLAC Summer Institute on Particle Physics, August 2-13, 1976 and Harvard preprint HUTP-76/A162 (1976) (unpublished).

37. C. Zemach, Phys. Rev. B 133, 1201 (1964).

38. The Zemach analysis has been particularized to $D \to K\pi\pi$ by B. W. Lee, J. L. Rosner and C. Quigg, Fermilab preprint FERMILAB-Pub-76/73-THY (1976) (unpublished).

39. C. Baltay, H. Bingham, O. Fackler, and D. Cline, invited talks at this conference. See also P. Musset and W. F. Fry, talks at the Topical

Conference of the SLAC Summer Institute on Particle Physics, August 2-13, 1976 (unpublished), and references to specific experiments in these talks.

40. W. Braunschweig et al., Phys. Letters B 63, 471 (1976), and B. Wiik, Ref. 9. J. Burmester et al., PLUTO-Collaboration, DESY preprint DESY 76/50 (1976)(unpublished).

41. Semileptonic D decays have been examined phenomenologically recently by A. Ali and T. C. Yang, DESY preprints DESY 76/12 and DESY 76/39; I. Hinchliffe and C. H. Llewellyn Smith, Oxford preprint 23176 (1976) (unpublished); V. Barger, T. Gottschalk, and R. J. N. Phillips, University of Wisconsin preprint COO-569 (1976)(unpublished).

42. M. K. Gaillard, B. W. Lee, and J. L. Rosner, Rev. Mod. Phys. 47, 277 (1975).

43. J. Ellis, M. K. Gaillard, and D. V. Nanopoulos, Nucl. Phys. B 100, 313 (1975).

44. See, for example, T. Appelquist et al., Ref. 20; R. L. Kingsley et al., Phys. Rev. D 11, 1919 (1975).

45. A. De Rujula et al., Phys. Rev. Letters 35, 69 (1975); R. L. Kingsley et al., Phys. Rev. D 12, 2768 (1975); R. L. Kingsley et al., Phys. Letters B 61, 259 (1976); K. Kang and J. E. Kim, Brown University preprint COO-3130TA-330 (1976)(unpublished).

46. L. B. Okun et al., Letters Nuovo Cimento 13, 218 (1975); E. A. Paschos, talk at the Aachen Neutrino Conference, June 8-11, 1976 and BNL preprint BNL-21770 (1976)(unpublished); A. De Rujula, invited talk at the Aachen Neutrino Conference, June 8-11, 1976 (unpublished); R. L. Kingsley, Rutherford Laboratory preprint RL-76-065 (1976)(unpublished).

47. S. L. Glashow and S. Weinberg, Harvard preprint HUTP-76/A158 (1976) (unpublished). See also E. A. Paschos, BNL preprint BNL 21870 (1976) (unpublished).

48. See, however S. R. Borchardt and V. S. Mathur, University of Rochester preprint COO-3065-149 (1976)(unpublished).

49. T. G. Trippe et al., Review of Particle Properties, Rev. Mod. Phys. 48 (2), Part II (1976).

50. Note that in terms of quark diagrams, the c or s quark in $D^* \to \pi D$ or $K^* \to \pi K$, respectively, is inactive: it is the light u or d quark which "emits" the pion in both cases. We then have more justification than in many calculations which relate "new" and "old" particle amplitudes. Needless to say, similar calculations, published and unpublished, have been done by many people.

51. S. Ono, Phys. Rev. Letters 37, 655 (1976) however finds $(M_{D^+} - M_{D^o}) - (M_{D^{*+}} - M_{D^{*o}}) = 3.1$ MeV. A smaller value, ~ 0.8 MeV, is estimated by K. Lane (private communication).

52. A. De Rujula, H. Georgi, and S. L. Glashow, Phys. Rev. Letters 37, 398 (1976); K. Lane and S. Weinberg, Phys. Rev. Letters 37, 717 (1976); S. Ono, Ref. 51; H. Fritzsch, CERN preprint TH. 2191 (1976)(unpublished); W. Celmaster, Harvard preprint (1976)(unpublished); J. Sanchez Guillen, Harvard preprint HUTP-76/A170 (1976)(unpublished).

53. The recoil spectrum and the key role of reflection is stressed by A. De Rujula et al., Ref. 52 and also by K. Lane and E. Eichten, Phys. Rev. Letters 37, 477 (1976).

54. See also F. Close, Rutherford Laboratory preprint RL-76-112 (1976) (unpublished) and M. Suzuki and W. Wada, LBL preprint LBL-5477 (1976) (unpublished).

55. A complicated momentum dependence of the various channels is found by Eichten et al., Ref. 21, in their explicit calculations. This is discussed in K. Lane and E. Eichten, Ref. 53, and stressed by K. Lane, private communication.

56. A. De Rujula, H. Georgi, and S. L. Glashow, Phys. Rev. Letters 37, 785 (1976).

57. M. Suzuki, UC Berkeley preprint (1976)(unpublished).

58. B. Knapp et al., Phys. Rev. Letters 37, 882 (1976); W. Lee, talk at the Topical Conference of the SLAC Summer Institute on Particle Physics, August 2-13, 1976 (unpublished).

59. E. G. Cazzoli et al., Phys. Rev. Letters 34, 1125 (1975).

60. Theoretical expectations and experimental interpretations for charmed baryons are to be found in B. W. Lee, C. Quigg and J. L. Rosner, Fermilab preprint FERMILAB-Pub-76/71-THY (1976)(unpublished).

61. M. L. Perl et al., Phys. Rev. Letters 35, 1489 (1975).

62. See the talks of G. J. Feldman, F. J. Gilman, and H. Harari in Proceedings of the 1975 International Symposium on Lepton and Photon Interactions at High Energies, W. T. Kirk, ed. (Stanford Linear Accelerator Center, Stanford, 1975). For a contrary view, that these events originate from unconfined quarks, see J. Pati and A. Salam, Phys. Rev. Letters 36, 1229 (1976).

63. M. L. Perl, G. J. Feldman et al., Phys. Letters B 63, 466 (1976).

64. G. J. Feldman, Ref. 5, and the discussion and references to other data therein.

65. I thank Wonyon Lee for a stimulating discussion on this subject.

66. Arguments for more quarks are summarized by H. Harari, talk at the Storage Ring Meeting, Flaine, February, 1976 and Weizmann Institute preprint WIS-76/43-Ph (1976)(unpublished).

67. A. Benvenuti et al., Phys. Rev. Letters 36, 1478 (1976); B. Aubert et al., Phys. Rev. Letters 33, 984 (1974); A. Benvenuti et al., Phys. Rev. Letters 37, 189 (1976).

68. R. M. Barnett, invited talk at this conference.