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CHARM EXISTS - WHAT NEXT?*

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ABSTRACT

The most recent data on D-meson production in e^+e^- annihilation are analyzed by a simple model. The experimental and theoretical implications of the discovery of charmed particles are explained.

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I. A "CHARMED" NEW WORLD

The recent discovery of narrow states in the invariant mass spectra of the $K\pi$, $K2\pi$, and $K3\pi$ decay channels around 2 GeV in electron-positron initiated reactions¹ is commonly considered as conclusive evidence for the existence of a new quark which has been anticipated for a long time.² This piece of evidence does not leave much doubt about the existence of quarks and in particular of this new charmed quark.³ It is therefore natural to ask what consequences one may expect on the experimental as well as on the theoretical side from this discovery.

In this note we present a short "tour d'horizon" on the recent data,¹ on the theoretical questions arising from it⁴ and from the presently emerging picture of particle dynamics,⁵ and on the experiments which are expected to give further information on the characteristics of the charmed quark.⁶ Our aim is to expose the immediate impact of the discovery of a charmed quark on the theoretical and the experimental side and to point to possible further discoveries one may expect as we go to higher energies.

In Section II we sketch the anticipated framework for a description of interacting particles and review the arguments leading to the postulate of a charmed quark. Some earlier and the most recent experimental results giving evidence for such a new quark are discussed in Section III. The models and questions arising from the most recent data on charmed particle production are touched on in Section IV. What experimental implications are expected from the existence of a charmed quark? We attempt an answer to this question in Section V. In Section VI we discuss the theoretical implications of the charmed quark and point to missing pieces in the overall picture of particle dynamics. Section VII presents our conclusions.

- 2 -

II. THEORETICAL MOTIVATION FOR A NEW QUARK

Before presenting the motivations for introducing a new quark, we first take a brief look at the present picture of particle dynamics.

The weak and electromagnetic interactions have been successfully unified in a gauge theory,⁷ admitting charged as well as neutral currents, which does not violate the unitarity bound at large energies. It involves leptons, quarks, and gauge bosons which group into doublets and triplets, respectively.

The structure of non-Abelian gauge theories has many attractive features believed to be relevant in strong interaction dynamics, such as renormalizability,⁸ asymptotic freedom,⁹ possibly quark confinement,¹⁰ such that strong interaction dynamics is believed to be dominated by a field theory of this type too.⁵ There thus appears a strong similarity between strong and weak interactions in the sense:

weak + e.m. interactions \longleftrightarrow strong interactions

leptons	←→ quarks
gauge bosons	\longleftrightarrow gauge gluons
weak + e.m. charge	\longleftrightarrow color charge
?	\longleftrightarrow Pomeron
Higgs bosons	\longleftrightarrow ?

The above-sketched weak interaction framework does permit strangeness changing neutral currents $\Delta s = 1$ which, however, are not compatible with the experimental results. First clues on a charmed quark came from the study of the strangeness changing second-order weak processes, such as $K_L \rightarrow \mu^+ \mu^-$, $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and the $K_L K_S$ mass difference. In a unified gauge theory of weak and electromagnetic interactions, the magnitude of a second order weak amplitude is in general $G_{F^*} \alpha$, so, in order to explain the observed magnitude of the $K_L \rightarrow \mu \mu$ amplitude which experimentally is of the order $G_F \cdot \alpha^2$, a suppression mechanism is needed. In the Weinberg-Salam model, the charmed quark indeed does remove the strangeness changing neutral current effects in first order and in higher orders as well; this was the main reason for introducing a new quark.³

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III. EXPERIMENTAL EVIDENCE FOR A CHARMED QUARK

In this section we present briefly the early experimental evidence for the existence of a charmed quark and subsequently discuss the most recent discoveries of charmed mesons and baryons.

A. Earlier Indications

Further evidence on the existence of a new quark came from the rising ratio $R \equiv \sigma(e^+e^- \rightarrow hadrons)/\sigma(\mu^+\mu^-)$ in electron-positron initiated reactions¹¹ although at the time of the first experimental evidence of this fact many alternative explanations were offered such as color, statistical models, new Pomeron-like interactions, and others.¹² So far, the strongest piece of evidence in favor of charmed quarks came from the new resonances ψ and ψ ' and their radiative transitions, although many alternative explanations seemed to be possible in the time just after their discovery.¹² Experimental information from electron-positron annihilation reactions has meanwhile accumulated to such an extent¹³ that the existence of a charmed quark was almost undeniable and it was considered a matter of time until charmed mesons, bound states composed of a charmed quark and a conventional (u,d,s) quark, would be discovered.

B. Recent Discoveries

Indeed experimental evidence for narrow bumps in the $K\pi$, $K3\pi$, and $K2\pi$ channels of electron-positron initiated reactions now exists¹ and there is little doubt that the expected charmed mesons D^{0} , D^{\pm} , as well as D^{*0} , $D^{*\pm}$, ³ have been discovered. There is further evidence of charmed baryons $C_{0} \equiv (cud)$ and $C_{1} \equiv (cuu)$ in photoproduction.¹⁴

In the following we present the characteristics of the data which seem to emerge. The $K^{\pm}\pi^{\mp}$ and $K^{\pm}\pi^{\mp}\pi^{\pm}\pi^{\mp}$ invariant mass spectra show a peak at 1.87 GeV/c² which is assigned to the neutral charmed meson $D^{O} \equiv (c\bar{u})$; its mass is

- 5 -

 $1865 \pm 15 \text{ MeV/c}^2$ (Fig. 1). Similarly a further narrow state was reported in the invariant mass distribution of the $K^{\text{F}} \pi^{\pm} \pi^{\pm} \pi^{\pm}$ exotic decay channel with mass $1876 \pm 15 \text{ MeV/c}^2$. In charm spectroscopy this state is assigned to be the charged partner $D^+ \equiv (c\bar{d})$ of the above neutral charmed meson D^0 . Both of the above states appear in association with a system having a mass of approximately 2 GeV. The $K\pi$ recoil spectrum shows two pronounced peaks at ~ 2010 MeV/c^2 and ~ 2150 MeV/c² of roughly equal height with an almost equal number of events under the two peaks (Fig. 2). Below and above this region events are scattered, which is partially attributed to background; one might speculate on the existence of a small peak at ~2600 GeV/c². The K3 π recoil spectrum shows the same characteristics with the 2150 MeV/c^2 peak more pronounced. The D^{0} -momentum spectrum shows two narrow peaks around ~ 180 MeV/c and ~ 550 MeV/c which are interpreted as reflections of the $D^{0*}\overline{D}^{0*}$ and $D^{0}\overline{D}^{0*}$ production channels respectively (Fig. 3). The $D^{0*} \rightarrow D^{\pm 0} \pi^{\mp 0}$ decay modes certainly exist and if $D^{0*} \rightarrow D^{0}\gamma$ is important it will lead to a broadening of the momentum spectrum. The analogous recoil-mass and momentum spectra for charged D^{\pm} -production are shown in Figs. 4 and 5. One notices that the $D^{\pm}D^{*\mp}$ reflection is more pronounced in comparison to the $D^{*\pm}D^{*\mp}$ peak and a clear $D^{* D^{*}}$ signal in the momentum spectrum is missing.

IV. THEORETICAL MODELING AND PROBLEMS

The experimental results have recently been analyzed by De Rujula, Georgi, and Glashow¹⁵ and by Eichten and Lane¹⁶ by model calculations. Both groups qualitatively account for the striking predominance of the associated D* production over D (at $\sqrt{s} = 4.03$ GeV) by a sequential production of the quark pair in which the more massive cc contribution is produced initially through the virtual photon and subsequently an uncorrelated pair of lighter quarks is produced having no direct interaction with the photon. The ratios $\sigma_{\rm D\bar{D}}:\sigma_{\rm D\bar{D}}*+\bar{\rm D}{\rm D}*:$ $\sigma_{\rm D}*\bar{\rm D}*=1:4:7$ for both the neutral and charged cases are then obtained using the above assumptions, angular momentum conservation, and the traditional method of counting statistical weights of the allowed final angular momentum states with the implied assumption that the electromagnetic coupling to each allowed spin state is equivalent.

The model in Ref. 15 parametrizes the integrated cross sections or the resulting ratios, $R \equiv \sigma_h / \sigma_\mu$, by their threshold rise and a subsequent falloff due to the form factor which accounts for binding effects between the quarks. Their form is:

$$R_{D\overline{D}} \propto 1 \cdot p^{\frac{3}{2}} \cdot e^{-\gamma p^2}$$
(4.1)

$$R_{D\overline{D}^* + \overline{D}D^*} \propto 4 \cdot p^{\frac{3}{2}} \cdot e^{-\gamma p^2}$$
(4.2)

$$R_{D*\overline{D}*} \propto 7 \cdot p^{\frac{3}{2}} \cdot e^{-\gamma p^2}$$
(4.3)

$$p = \sqrt{\frac{[s - (m_1 + m_2)^2][s - (m_1 - m_2)^2]}{4s}}$$
(4.4)

where p is the c.m. momentum of the produced charmed meson pair with

- 7 -

masses m_1 and m_2 . In Fig. 6 we have drawn the curves resulting from Eqs. (4.1-4.3) for the above three channels with the mass values given by Goldhaber et al.:¹

$$m_{D^{0}} = 1865 \pm 15 \text{ MeV/c}^{2}, \quad m_{D^{+}} = 1876 \pm 15 \text{ MeV/c}^{2}$$

$$m_{D^{0}*} = 2007 \pm 20 \text{ MeV/c}^{2}, \quad m_{D^{+}*} = 2010 \pm 20 \text{ MeV/c}^{2}.$$
(4.5)

In Fig. 6a we show the cross-section shapes without any form factor damping $(\gamma = 0, \text{ dash-dotted curves})$; subsequently we introduce the exponentially falling form factor with different values for the parameter γ_{\circ} $\gamma = 4 \text{ GeV}^{-2}$ (short dashed curves) corresponds to the value $\Gamma\sim 1~{\rm GeV}^2$ used in Ref. 15. The sensitive dependence of these curves on the charmed particle masses is exhibited by the shaded area. Its left boundary corresponds to m = 1865 - 15 MeV, D^{0} $m_{D^{0}*} = 2007 - 20$ MeV, and its right boundary was determined using $m_{D^{0}} = D^{0}$ 1865 + 15 MeV, m = 2007 + 15 MeV. One notices in particular that the in- $D^{0}*$ tersection of the left boundary with the vertical line at $E_{c.m.} = 4.03$ GeV is at almost the same height as the DD* cross section. $D\overline{D}$ production is small in comparison to $D\overline{D}^*$ or $D^*\overline{D}^*$ production; it peaks around $E_{c_0,m_0} = 3.9$ GeV and gradually falls off with increasing energy. $D\overline{D}^*$ production dominates around 4.05 GeV where the $D^*\overline{D}^*$ mode has its threshold onset. Due to its steep rise $D^*\overline{D}^*$ production is very sensitive to the initial c.m. energy as well as the D^* mass and dominates D production around 4.2 GeV through $D^* \rightarrow D\pi$ decay. Introducing a stronger exponential damping with $\gamma = 16 \text{ GeV}^{-2}$ (long dashed curves) shifts the maxima of all three D-production cross sections substantially to the left. Fig. 6b compares the cross-section shapes in Eqs. (4.1-4.3) with the experimental $E_{c_{o}m_{o}}$ -dependence of $R \equiv \sigma_{h}/\sigma_{\mu}$. We notice structure in

the region 3.8-3.9 GeV which cannot be explained by the above ansatz although the model predicts some $D\overline{D}$ -production in that area. The bump between 3.9 and 4.0 GeV can be explained by the threshold onset of DD^* -production. The point at 4.03 GeV is measured with high accuracy and there is little room left for an interpretation excluding a resonance (with width ~ 20 MeV). There is a further bump with maximum at 4.1 GeV which, according to the model, must be identified with the $D^*\overline{D}^*$ threshold onset. The solid lines in Fig. 6b correspond to $\gamma = 8 \text{ GeV}^{-2}$. At $E_{c.m.} = 4.028 \text{ GeV}$ (where most of the data have been taken) the production ratios are

$$\mathbf{R}_{\mathbf{D}^{\mathbf{O}}\overline{\mathbf{D}}^{\mathbf{O}}}:\mathbf{R}_{\mathbf{D}^{\mathbf{O}}\overline{\mathbf{D}}^{\mathbf{O}}*+\overline{\mathbf{D}}^{\mathbf{O}}\mathbf{D}^{\mathbf{O}}*}:\mathbf{R}_{\mathbf{D}^{\mathbf{O}}*\overline{\mathbf{D}}^{\mathbf{O}}*}=1:4.5:0.7$$
(4.6)

We conclude that the $D\overline{D}^*$ mode outweighs the $D^*\overline{D}^*$ mode by a factor 6 at this energy point which is clearly in disagreement with the experimental D^0 recoil spectrum; this data shows equal amounts of $D^*\overline{D}^*$ and $D\overline{D}^*$ production, roughly. Variation of γ can shift the peaks of the curves and modify the relative contributions at $E_{c.m.}^{=4.03}$ GeV; however, reasonable choices cannot explain the recoil spectrum since the cross section for $D^*\overline{D}^*$ is substantially smaller than the cross section for $D\overline{D}^* + \overline{D}D^*$. Ways out of this discrepancy are:

- 1. The peak at $E_{c.m.} = 4.03$ GeV in the experimental data is due to the $D^*\overline{D}^*$ threshold onset. Such interpretation, however, has to explain the large value of R and shifts the $D\overline{D}^*$ peak to $E_{c.m.} = 3.92$ GeV, which is slightly too low. (See Fig. 6a.) In addition, the 4.1 GeV peak lacks interpretation.
- 2. One can assume that the DD** channel has a strong influence and is mainly responsible for the second peak in the recoil spectrum;¹⁷ however, the D** mass appears then unexpectedly low.

3. A resonance at 4.03 GeV which favors substantially the $D^*\overline{D}^*$ mode might

be another explanation; dynamical and/or higher symmetry motivations for such a point of view are lacking so far.

- 4. The reasoning that a shift of the D^{0*} mass does substantially change the threshold onset of the $D^*\overline{D}^*$ channel (see Fig. 6a) can be excluded by the following arguments. In Fig. 7 we have drawn the s-dependence of the momenta using the mass values given in Eq. (4.5). We subsequently varied the masses of the D-mesons by adding and subtracting their error values (shaded areas). One notices that $p_{D^*\overline{D}^*}$ varies very sensitively around $E_{c.m.} \sim 4.03 \text{ GeV}$. The momentum spectrum (Fig. 3) of the D-meson shows a peak around $\sim 180 \text{ GeV/c}$ which fixes the momentum value and in turn the mass m_{D^*} . This method can also be applied to p_{DD^*} and leads to the same value $m_{D^*} = 2007 \text{ MeV/c}^2$.
- 5. The most likely explanation is that the form factors depend very sensitively on the charmed particle's momentum.

We would like to add a brief comment on the widths of the bumps in the recoil spectrum (Figs. 2 and 4). As the c.m. energy increases the recoil bumps due to reflection become broader; their lower boundaries vary relatively little whereas their upper boundaries increase. The amount of broadening depends on the exact masses of D and D* (see Fig. 8) in particular at larger values of $E_{c.m.}$. The widths of the recoil peaks thus provide further checks.

In the model presented above the photon coupling to the lighter $q\bar{q}$ -pair and subsequent c-quark association was ignored; this assumption was motivated by the phenomenological fact that the creation of a quark-antiquark pair out of the vacuum is less likely with increasing quark mass. Eichten and Lane¹⁶ in their coupled channel model find a suppression of ~ $(m_q/m_c)^4$ for diagram b in Fig. 9; this result is however only reliable for small charmed meson momenta where their theory applies. In order to find the structure of the cross sections we have calculated¹⁸ the influence of both diagrams in Fig. 9 in a free quark model assuming that the D-meson wave functions are linear combinations of spinors with the current operator

$$J^{\mu} = ie \left[Q_{c} \bar{\psi}_{c} \gamma^{\mu} \psi_{c} + Q_{q} \bar{\psi}_{q} \gamma^{\mu} \psi_{q} \right]$$
(4.7)

'sandwiched' in between. Q_c and Q_q are the charges of the charmed and lighter quarks in units of e. The resulting cross section ratios then are

$$\sigma_{D\overline{D}} : \sigma_{D\overline{D}} : \sigma_{D\overline{D}} : \sigma_{D} : \overline{D} * : \overline{D} : \overline{D$$

where kinematical factors due to phase space have identical forms in all three channels and have been ignored. The form factors F_c and F_q are momentumdependent, thus $F_{c,q} \equiv F_{c,q}(p)$, and give the relative size of the contributions due to diagrams a and b in Fig. 9. One notices that the DD-channel has an electric coupling whereas the form of $\sigma_{D\overline{D}^*+\overline{D}D^*}$ reflects a magnetic coupling and $\sigma_{D^*\overline{D}^*}$ has both. If $F_q \equiv 0$ we are back at the 1:4:7 ratio as was found earlier in Refs. 15 and 16. The form of the cross sections (Eq. (4.8)) gives us the possibility to test experimentally whether $F_q \leq F_c$. The cross sections of the three channels are measured at one and the same momentum value p which means at different energy points:

$$\sigma_{\mathrm{D}\overline{\mathrm{D}}}(\mathbf{s}_{1}), \ \sigma_{\mathrm{D}\overline{\mathrm{D}}^{*}+\overline{\mathrm{D}}\mathrm{D}^{*}}(\mathbf{s}_{2}), \ \sigma_{\mathrm{D}^{*}\overline{\mathrm{D}}^{*}}(\mathbf{s}_{3})$$
(4.9)

We then form the combination

$$\sigma_{D*\overline{D}*} - 3\sigma_{D\overline{D}} - \sigma_{D\overline{D}*+\overline{D}D*} \propto F_{c}(p) \circ F_{q}(p)$$
(4.10)

and thus we can experimentally test whether the above assumption is correct. This test, although quite general, is however only applicable in a region where no resonance is present. A similar technique can also be used to determine the ratio formed by the electric and magnetic form factors. ^{18,19,20}

V. EXPERIMENTAL IMPLICATIONS OF CHARMED QUARKS

In this section we discuss other experimental tests which are being carried out at present in order to obtain more information on the nature of the charmed quark and we will point to missing pieces in the overall charm picture.

A. Prompt Leptons in e⁺e⁻ Annihilation

Experiments at DESY measure the inclusive production of $e^+e^- \rightarrow e^\pm X$ and $e^+e^- \rightarrow e^\pm KX$ at 3.6, 4.1, and 4.4 GeV with the results:²¹

- (i) Inclusive electron signals are found at 4.1 and 4.4 GeV, but not at 3.6 GeV, indicating a new particle production threshold.
- (ii) The multiplicity for these events peaks at n ≈5-6 at 4.1 GeV indicating that the source is not heavy lepton production, for which n ≈2-2.5 is pre-dicted.
- (iii) An eK signal is found at 4.1 GeV; the signal is suppressed at 4.4 GeV.
 This suggests that D and F semileptonic decays are being observed at 4.1
 GeV, while charmed baryon production and decay does set in and possibly contributes to inclusive e[±] production only above 4.52 GeV.
- (iv) The electron energy distributions measured at 4.1 GeV peak at low E_e with no events observed for $E_e > 0.7$ GeV; this is quite compatible with charmed particle decays $D \rightarrow Ke\bar{\nu}_e$, $K\pi e\bar{\nu}_e$, $K\pi\pi e\bar{\nu}_e$ (see Fig. 10).
- B. Deep Inelastic Neutrino Experiments

The dilepton events found in neutrino initiated deep inelastic experiments indicate the production and subsequent semileptonic decay of new particles which are compatible with being charmed mesons (see Fig. 11).²²

C. Photoproduction Experiments

The energy dependence of the differential cross section of $\gamma N \rightarrow \psi + X$ near threshold shows an unusually flat onset but rises steeply from $E_{\gamma} \sim 12$ GeV on (Fig. 12). This suggests that there is a pseudothreshold at this energy corresponding to the production of charmed particles. Prompt lepton measurements in this process show a significant excess of leptons at $E \sim 20$ GeV with a ratio $\mu/\pi = (1.4 \pm 2.5) \cdot 10^{-4}$ whereas no excess is observed at $E_{\gamma} = 8$ or 12 GeV.²³ This fact again is attributed to charmed mesons decaying semileptonically. Measurements in photon initiated reactions at Fermilab with energies $\langle E_{\gamma} \rangle \sim 120$ GeV have led to the discovery of a charmed baryon state with mass near 2.26 GeV/c² which is identified with C_0^+ , ³ and the experimental results are consistent with the anticipated two next higher states C_1 and C_1^* near 2.42 and 2.48 GeV/c².

The pseudoscalar state η_c , an important missing piece in the overall charm picture, will perhaps be discovered by the Primakoff production process (Fig. 13). The characteristic energy and Z-dependence of this strongly forward-peaked process open it to a very selective observation. η_c is expected to decay significantly into two photons.^{24,6}

D. Hadron Experiments

In purely hadronic processes, charmed particles have not yet been discovered but their production cross sections have been estimated by supposing a Drell-Yan type mechanism²⁵ (Fig. 14).²⁶ One possible experiment is to look for dileptons coming from the charmed particle decays. Another type of experiment triggers on leptons and looks for bumps in the reconstructed invariant mass of the final state hadrons which are expected to be mainly of strange type. A third type of experiment searches for the occurrence of sharp mass peaks associated with kaons, for two simultaneously occurring particle combinations.⁶ Although not impossible, charmed particle detection in purely hadronic processes will be much more difficult than in weak and electromagnetic production processes since the conventional hadronic processes are strongly competing. What is missing in the charm picture? The state at 2.8 GeV in electronpositron annihilation, seen at DESY and conjectured as paracharmonium η_c does not fit too well in the overall picture; it is expected to be much closer to ψ_{\circ} The F = (cs) mesons are still missing and a number of charmed baryons are waiting to be detected (Fig. 15).²⁷ The anticipated higher cc resonances have to be experimentally confirmed as for instance the 3 ${}^{3}S_{1}$ -resonance which is placed at 4.03 GeV by Eichten and Lane.¹⁶

Since charmed particles now exist one wonders about their properties. Do they violate parity in their decays, or CP-invariance perhaps? We briefly indicate proposed tests:

(a) P-violation

Parity violation in the weak decays of the charmed D-mesons can be determined by the following three methods:

(i) The simultaneous appearance of the decay modes $K^+\pi^-\pi^-$ and $K_S^0\pi^-$ or $K^+\pi^-$, $K^-\pi^+\pi^+\pi^-$ and $K_S^0\pi^+\pi^-$ indicates P-violation.²⁸ (ii) If the $K^{\pm}\pi^{\mp}$ and $K^{\pm}\pi^{\mp}\pi^{\mp}$ peaks belong to the same isospin multiplet with J = 0 then parity is violated. If instead $J^P(K\pi) = 0^+, 1^-, 2^+, \ldots$ and $K\pi\pi$ does not vanish on the Dalitz plot boundary, then again parity is violated.²⁹ (iii) Measurement of the momentum of two or three particles in an inclusive decay and formation of

$$A \equiv \vec{p} \cdot (\vec{K}_1 \times \vec{K}_2) \cdot (\vec{K}_1 - \vec{K}_2) \cdot \vec{p}$$

$$B \equiv \vec{K}_1 (\vec{K}_2 \times \vec{K}_3)$$
(5.1)

indicates P-violation if the average value <A> or is nonvanishing.³⁰ (b) CP-violation³¹

CP-invariance could also be tested using for example the leptonic decay modes: $D^{\circ} \rightarrow K^{-}\mu^{+}\nu_{\mu}^{\circ}$. Let us denote by $N^{\pm\pm}$ decays like $(K^{\pm}\mu^{\mp}\bar{\nu}_{\mu})(K^{\pm}\mu^{\mp}\bar{\nu}_{\mu})$ and similarly N^{+-} for decays like $(K^{+}\mu^{-}\bar{\nu}_{\mu})(K^{-}\mu^{+}\nu_{\mu})$. CP-violation would give a charge asymmetry

$$\delta \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}} \simeq 4 \operatorname{Re} \epsilon$$
 (5.2)

where ϵ is the CP-violation parameter in the wave functions of the D_s and D_L mesons formed by linear combinations of D_1 and D_2 which are pure CP-eigenstates. Estimates, however, indicate that the effect will be almost unmeasurably small.

VI. CHARMED QUARKS - WHAT NEXT?

In the preceding sections we have limited ourselves to the immediate theoretical and experimental implications of the charmed quark discovery. In this section we would like to go beyond this limit by presenting the arising new questions and by pointing to missing pieces of the gauge theory approach to particle dynamics.

A. How Many Quarks are There?

Since four elementary constituents (quarks) now seem to exist, the question naturally arises: why not more? The introduction of a fourth quark into the strong interaction scheme established a close resemblance between weak and strong interaction theory

$$\begin{pmatrix} \nu_{e} \\ e^{-} \end{pmatrix} \begin{pmatrix} \nu_{\mu} \\ \mu^{-} \end{pmatrix} \longrightarrow \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$$
(6.1)

besides solving a number of deeper problems; for instance the cancellation of anomalies. Moreover the generalization to schemes with four quarks became evident. The extension of weak interaction theory to six quarks has been investigated by a number of authors³² which could show that such a step, although not unique, does not lead to any obvious difficulties. Indeed, there are experimental indications and theoretical arguments which give hints at a six quark scheme:

(i) The μe events at SPEAR indicate that charged heavy leptons L^{\pm} exist with decay modes: $L^{-} \rightarrow e^{-} + \overline{\nu}_{e} + \nu_{L}$, $\mu^{-} + \overline{\nu}_{\mu} + \nu_{L}$. If this interpretation is correct and if the leptons decay weakly via V-A interaction, they are most likely grouped in three SU₂ doublets of left-handed leptons instead of two:

$$\begin{pmatrix} \nu_{e} \\ e^{-} \end{pmatrix} \begin{pmatrix} \nu_{\mu} \\ \mu \end{pmatrix} \begin{pmatrix} \nu_{L} \\ L \end{pmatrix} \longrightarrow \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$
(6.2)

which on the hadronic side, by analogy, makes it plausible to expect six quarks.

- (ii) In the four-quark scheme the asymptotic hadron to μ -pair production ratio in electron-positron initiated reactions is $R = 3\frac{1}{3}$ whereas the experimental value above $E_{CM} = 4.5$ GeV is between 5 and 5.5. This discrepancy cannot be explained without additional quarks.
- (iii) Deep inelastic neutrino processes also give indications for a six quark scheme. The ratio $\sigma(\overline{\nu}N \rightarrow \mu^+ + X)/\sigma(\nu N \rightarrow \mu^- + X)$ seems to rise from 0.4 at low energies to 0.6-0.7 at higher energies whereas a four-quark model with the usual small component of qq-pairs in the large t nucleon, predicts a ratio 1/3.
- (iv) There exist further theoretical reasons. 33

It thus appears quite possible that, as we go to higher energies, more ψ - like $t\overline{t}$ or $b\overline{b}$ narrow resonances as well as $(b\overline{u}), (b\overline{d}), \dots (b\overline{c}), \dots (t\overline{c}), \dots (t\overline{b})$ bound states, will be found — a wealth of new particles!

B. Where are the Gluons?

What are the interacting forces between the quarks — gluons? If quantum chromodynamics is the underlying theory dominating the interaction between quarks, as charmonium-type calculations motivated by asymptotic freedom arguments indicate, one should be able to find measurable consequences of gluons.

If gluons are confined, only indirect tests are possible. If they are unconfined, they might have escaped detection. In the latter case their masses (widths) have been estimated in the energy range 2-3 GeV (1-few MeV) and a number of measurable predictions such as decay channels, branching ratios, etc., exist. ³⁴ In a theory with Han-Nambu quarks, the ratio R in e^+e^- annihilation is unaffected if the gluon mass is much bigger than the momenta under consideration. However if the gluon mass is small we have

where $m_{\chi} \ge 2.5$ GeV is the mass of a neutral field. M_{G} is the mass of the produced gluons. The structure function \overline{F}^{2} describing $e^{+}e^{-} \rightarrow p + X$ is also proportional to $(m_{\chi}/M_{G})^{4}$ whereas \overline{F}^{1} is unaffected by the produced gluons.³⁵ Let us look for other measurable consequences:

- (i) Heavy lepton pair production in hadron collisions, described by the
 Drell-Yan process, will show logarithmic deviations from scaling.³⁶
- (ii) Large-p_T hadrons (with respect to the main jet axes) in e⁺e⁻ initiated reactions could predominantly be produced by hard gluon bremsstrah-lung giving rise to three-jet final states.³⁷
- (iii) In deep-inelastic experiments color excitation which manifests itself by gluon terms is predicted to lead to a 15% change in the momentum conservation sum rule if color threshold is passed. ³⁸
- (iv) Hadron multiplicities in hadron and lepton initiated reactions are the same. Furthermore, in the central region the jet structure and

associated hadron multiplicities are the same in e^+e^- annihilation in deep inelastic scattering and in forward hadron collisions. $\overset{39}{\cdot}$

(v) Spin measurements in ψ - photoproduction will reveal almost exact s-channel helicity conservation even in the threshold region if gluons are responsible for the diffractive characteristics of this process.⁴⁰

Gluons are a characteristic ingredient of gauge theories and therefore should be looked for in nature.

C. What More?

Intermediate vector bosons are waiting to be discovered⁴¹ and more leptons still might exist. Speculations ranging from new leptonic interactions up to leptonic quarks still exist.¹² This list of open questions could be continued for quite a while and shows that many of the fundamental problems still are unsolved even after the discovery of the charmed quark.

VII. CONCLUSION

In this paper we have presented the consequences of the discovery of a charmed quark. We have presented the most recent experimental results on D-production in e^+e^- annihilation and we have analysed the data by simple model calculations. The experimental search for more information on the characteristics of charmed particles has been indicated and some of the fundamental theoretical questions awaiting more information from the experiments were discussed.

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Figure Captions

- 1. Invariant mass spectrum of the $K\pi$ channel in e^+e^- annihilation at $E_{CM} = 4.03$ GeV.
- 2. $D^{O}(K\pi)$ recoil spectrum in $e^{+}e^{-}$ annihilation in the energy range 3.9 GeV $\leq E_{CM} \leq 4.6$ GeV.
- 3. $D^{O}(K\pi)$ momentum spectrum at $E_{CM} = 4.03$ GeV.
- 4. $D^{\pm}(K\pi\pi)$ recoil spectrum in $e^{+}e^{-}$ annihilation in the energy range 3.9 GeV $\leq E_{CM} \leq 4.6$ GeV.
- 5. $D^{\pm}(K\pi\pi)$ momentum spectrum at $E_{CM} = 4.03$ GeV.
- 6. Cross section ratio $R \equiv \sigma_h / \sigma_\mu$ of the channels $D\overline{D}$, $D\overline{D}^*$, $D^*\overline{D}^*$ in the model of Ref. (15) near threshold.
- Energy and (D-meson) mass dependence of the CM-momenta corresponding to the channels DD, DD* and D*D*.
- 8. Kinematical upper and lower limits of the reflection bumps in the invariant mass spectrum as a function of the CM-energy and the D-meson masses.

curve 1: $m_D = 1.865 \text{ GeV}$, $m_{D^*} = 2.007 \text{ GeV}$ curve 2: $m_D = 1.880 \text{ GeV}$, $m_{D^*} = 2.027 \text{ GeV}$ curve 3: $m_D = 1.850 \text{ GeV}$, $m_{D^*} = 1.987 \text{ GeV}$.

- 9. Quark diagrams for electromagnetic D-pair production.
 - (a) Photon c-quark coupling and $q\overline{q}$ association.
 - (b) Photon q-quark coupling and cc association.
- 10. Energy spectrum of direct electrons coming from D-mesons at rest.
- 11. Momentum and invariant mass spectrum of the dilepton events observed in deep-inelastic neutrino reactions.

- 12. Threshold onset of the differential cross section for ψ -photoproduction.
- 13. η_c -production using the Primakoff effect.

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- 14. Drell-Yan production mechanism of charged particles in hadron initiated reactions.
- 15. Threshold onset of charmed baryon-antibaryon pair produced in e^+e^- -annihilation.



Fig. 1







Fig. 3



I

2





Fig. 5



Fig. 6





Fig. 8







Fig. 9

(b) _{3056A10}





Fig. 11



L

Fig. 12





 $\in \mathbb{Z}_{+}^{r}$







Fig. 15