ARCHIVES

Ref.TH.2065-CERN

NEGATIVELY CHARGED QUARKS AND THE NEW PARTICLES

F. E. Close *)
CERN - Geneva

and

E.W. Colglazier
CERN - Geneva
and
Institute for Advanced Study, Princeton **)

ABSTRACT

As an alternative to conventional charm and the U(6) model of Harari, we investigate the consequences of quark models (with hidden colour) which contain only negatively charged new heavy quarks. The interesting feature of schemes of this type is a signature for charmed particle production and decay which is different from conventional models. Both theoretical and phenomenological arguments suggest that there may be more than one such new quark, and, as one example, we discuss a U(6) model with heavy quark charges (-1/3,-4/3,-1/3). One serious problem with models of this type is that although strangeness changing neutral currents are constrained in a gauge theory framework to be absent in order G, they are suppressed only by $\sin^2\theta_C$ in order $G\alpha$ for $K_L \to \mu^+\mu^-$ and the K_L-K_S mass difference.

---

*) Address after September 1, 1975 : Rutherford Laboratory, Chilton, Didcot, Berks., England.

**) Research sponsored in part by the Atomic Energy Commission grant No AT(11-1)-2220.

Ref.TH.2065-CERN
19 August 1975

1. INTRODUCTION

A new degree of freedom beyond the Gell-Mann and Zweig quark model appears to be necessary for theoretical as well as experimental reasons. In particular, assuming that a quark framework (with hidden colour) is relevant, at least one new quark is required to permit either a phenomenological description of the new particles 1) or a means of suppressing strangeness changing weak neutral currents in a unified gauge theory 2). In the well-known and economical SU(4) charm scheme 3) the charmed quark (c) of charge +2/3 achieves both ends: suppressing $\Delta S \neq 0$ neutral currents via the GIM mechanism 4) and constructing ψ, ψ', etc., as $c\bar{c}$ bound states 5). Whether this model will survive the present intense experimental scrutiny remains to be seen.

As discussed recently by Goto and Mathur 6), there is another way that $\Delta S \neq 0$ neutral currents can be avoided in a four quark model and that is if the new quark has charge -4/3. However this model, as it stands, has the undesirable feature that universality of leptonic weak interactions with nucleon beta-decay is lost. In order to restore this universality one must introduce more leptons or more quarks into the theory. Nevertheless, the fact that the $\Delta Q = +1$ weak current transforms the new quark into the old quarks (n, λ) instead of vice-versa leads, as we shall see, to a phenomenology for the weak production and decay of charmed particles which is different from conventional models. Among these distinctive differences are:

(i) the dominant decay of the -4/3 charge charmed quark conserves strangeness which implies no increase in the K/π ratio in e^+e^- annihilation as the charmed particle production threshold is crossed 6) (Also, doubly charged charm particles should exist 6).)

(ii) $\Delta S = -\Delta Q$ is no longer expected as a dominant signature for charm in neutrinoproduction

(iii) dilepton production with opposite charges ($\mu^+\mu^-$) is expected (as with charm), and with more than one negatively charged heavy quark dileptons of the same sign as well as trileptons can occur (same sign suppressed relative to opposite sign and trileptons even more so)

(iv) at very high energies the $\bar{\nu}$ cross section is predicted to increase significantly (which for these theories had better be beyond present experimental reach)

Since these features provide a contrast with the predictions of the charm scheme 5) and perhaps are as compatible with present experiment (the last prediction being the most worrisome), then models with negatively charged new heavy quarks are sufficiently interesting to merit this closer examination.

Accomodating the phenomenology of the new particles will present rather severe constraints for any new quark framework. In fact there have been suggestions that more than one new quark may already be necessary to achieve compatibility with recent experimental results 7). For example, if the ratio

$$R = \sigma(e^+e^- \rightarrow \text{hadrons}) / \sigma(e^+e^- \rightarrow \mu^+\mu^-)_{QED} \qquad (1)$$

is assumed to be asymptotically constant and to measure the sum of the squares of the quark charges, then the present value of $R \simeq 5\text{-}6$ 8) suggests that there exist more heavy quarks (or an absolute charge larger than 2/3 if a single heavy quark.). Also the existence of the decay $\psi' \rightarrow \psi\eta$ with a branching ratio of a few percent 8,9) could be evidence for a significant SU(3) $\underset{\sim}{8}$ component of the ψ' again implying more heavy quarks. (However, see section 3 regarding important theoretical and phenomenological caveats concerning such a conclusion about the ψ'.) Although the SU(4) charm model is certainly experimentally viable at present, a convincing case can also be made for an enlarged scheme.

We set out to investigate models containing new negatively charged heavy quarks subject to the two previously mentioned constraints:

i) elimination of $\Delta S \neq 0$ neutral currents in leading order (in a gauge theory framework)

ii) compatibility with ψ phenomenology.

The purpose is to examine a class of models which provides an interesting contrast with conventional ones and to see if they possess either particular advantages or liabilities. In the next section we examine the restrictions on a theory with negatively charged new heavy quarks which follow from demanding that $\Delta S \neq 0$ neutral currents are absent in leading order. In section 3 we discuss the constraints imposed by incorporating the new particles into the same framework. As a specific example a model with an SU(3) $\underset{\sim}{\bar{3}}$ of heavy quarks having charges $-1/3, -4/3, -1/3$ 10) is explored, both for its own sake and as a vehicle for illustrating the phenomenology of the general class. In sections 4,5,6, concentrating mostly on the specific model, we discuss the predictions for spectroscopy, $e^+ e^-$ annihilation, and neutrinoproduction respectively. In the final section we discuss the phenomenological implications in higher orders of weak interactions (assuming the SU(2)xU(1) gauge framework to be valid). It is here that we find what are probably the strongest theoretical arguments against models with only negatively charged new heavy quarks.

2. SUPPRESSING $\Delta S \neq 0$ NEUTRAL CURRENTS

As discussed by Goto and Mathur,[6)] weak neutral currents can be eliminated at leading order in a gauge theory framework by using a fourth quark of charge -4/3 instead of the familiar +2/3. To see this one first requires the weak charged current J^+ and its hermitian conjugate J^- to form an SU(2) algebra with $[J^+, J^-]$ free of $\Delta S \neq 0$ neutral currents. When the charmed quark has a charge -4/3 this constrains J^+ to be of the form

$$J^+ = \sqrt{2}\,(\bar{p}\, n_c + \bar{n}_c f) \tag{2}$$

where $n_c = n \cos\theta_c + \lambda \sin\theta_c$, θ_c is the Cabbibbo angle and f is the new charmed quark. The first thing to notice is that, because of the $\sqrt{2}$, universality is lost between lepton and hadron weak decays. More precisely, the above form for J^+ implies in an SU(2)xU(1) gauge theory the following left-handed weak SU(2) triplet assignment:

$$\begin{pmatrix} p \\ n_c \\ f \end{pmatrix}_L \quad ; \tag{3}$$

and with the leptons and their neutrinos in SU(2) doublets, universality between muon decay and neutron beta decay is destroyed by a factor $\sqrt{2}$.

Universality can be restored by either enlarging the number of leptons to make weak SU(2) triplets or enlarging the number of quarks. Although either possibility is viable, we shall choose to introduce more quarks in contructing a specific scheme for investigation, being partially motivated by the subsequent section 3 on the new particles. However, much of the phenomenology for charmed particle production and decay is common to any scheme having only negatively charged heavy quarks and suppressing strangeness changing neutral currents.

In order to carry out the restoration of universality by introducing new quarks, then at least one new heavy quark with charge -1/3 is needed. Anticipating the subsequent discussion of ψ phenomenology, we shall introduce two such quarks. This leads to a new heavy antitriplet of quarks with the following charges

$$n' = -1/3 \;, \; f = -4/3 \;, \; \lambda' = -1/3 \tag{4}$$

(the n' and f forming the upper and lower components of an isospin doublet). The left-handed weak SU(2) triplet with universality restored (albeit in an ad hoc way) becomes

$$\begin{pmatrix} p \\ \frac{n_c + n_c'}{\sqrt{2}} \\ f \end{pmatrix}_L \tag{5}$$

where $n_c' = n'\cos\phi_c + \lambda'\sin\phi_c$ and ϕ_c is an arbitrary angle (which need not have the same magnitude as the familiar Cabibbo angle). An SU(2)xU(1) gauge theory can now be constructed in a manner similar to the Weinberg-Salam [2)] model (with the previous triplet as the only non-trivial representation of weak SU(2) for quarks). Strangeness changing weak neutral currents are indeed eliminated in leading order as is most easily seen by the explicit expressions for the weak currents

$$J_\mu^+ = \bar{p}\gamma_\mu(1-\gamma_5)(n_c+n_c') + (\bar{n}_c+\bar{n}_c')\gamma_\mu(1-\gamma_5)f \tag{6}$$

$$J_\mu^{\text{neutral}} = \bar{p}\gamma_\mu(1-\gamma_5)p - \bar{f}\gamma_\mu(1-\gamma_5)f - 2\sin^2\theta \; J_\mu^{em} \tag{7}$$

where θ is the analog of the Weinberg angle and J^{em} is the electromagnetic current, i.e.,

$$J_\mu^{em} = \frac{2}{3}\bar{p}\gamma_\mu\bar{p} - \frac{1}{3}(\bar{n}\gamma_\mu n + \bar{\lambda}\gamma_\mu\lambda + \bar{n}'\gamma_\mu n' + \bar{\lambda}'\gamma_\mu\lambda') - \frac{4}{3}\bar{f}\gamma_\mu f \tag{8}$$

The coupling and mass of the charged weak boson are adjusted as usual so that the effective coupling of the charged current in leading order is

$$\frac{G_F}{\sqrt{2}} \; J^+ J^- \tag{9}$$

For the weak neutral current, however, the effective coupling (related to the mass and coupling of the weak neutral boson) depends on exactly how the gauge symmetry is spontaneously broken by the Higgs particles. The simplest choice, a complex doublet of scalar fields, would also lead to the effective coupling $G_F/\sqrt{2}$, as in the Weinberg-Salam model. Yet without a complete specification of all the leptons and scalars in the theory, this relation is not certain 11). Consequently we shall assume an arbitrary parameter (of the order of unity) times $G_F/\sqrt{2}$ for the effective coupling of $J^{\text{neutral}} J^{\text{neutral}}$. Furthermore, in order to construct a completely renormalizable theory the cancellation of triangle anomalies must be ensured 12). However, we shall ignore this constraint[*] since we are not constructing a complete theory (being interested only in a class of models). In particular the anomalies can always be altered by fundamental fields much higher in mass which may not be relevant for present phenomenology. Of course, the conventional SU(4) charm model is especially attractive because all the necessary requirements for a complete theory are met. Other constraints of weak interaction phenomenology, in particular higher order effects, will be discussed in section 7.

Before moving to the new particles, two important differences should be noted between the charged current in equation (6) and the one in the conventional model: (i) $\Delta H = -\Delta Q$ for the f quark (where we have substituted the name "heaviness" for charm) as opposed to $\Delta H = \Delta Q$ for the c quark (ii) $\Delta S = 0$ is the Cabibbo favoured mode of the f quark instead of $\Delta S = \Delta H$ for the c quark. These two small differences lead to a very different phenomenology.

3. PHENOMENOLOGY OF THE NEW PARTICLES

The phenomenology of the ψ particles expected in the SU(4) charm model is so well known 5) (and similar to any model with only one new quark) that we shall not review it here. As an alternative, Harari recently introduced a six quark model 7) which was strongly motivated by several pieces of existing data: primarily the large value of R but also the failure at that time to see radiative cascade decays of the ψ' (which is no longer the case according to recent discoveries at DORIS 13)) and, perhaps, the existence of the decay $\psi' \to \psi\eta$ at a rate suggesting that there is no SU(3) suppression[**] (although this decay

---

*) If the constraint is imposed, then many new leptons are required.

**) Recall that $\eta \simeq \eta_1 \sin 10^\circ + \eta_8 \cos 10^\circ$ from the quadratic octet mass formula and hence $\Gamma(\psi' \to \psi\eta)$ would include a factor $\sin^2 10^\circ$ if ψ, ψ' are both SU(3) $\underset{\sim}{1}$'s and SU(3) is conserved in the decay.

is unsuppressed only in an O(6) version of Harari's model which is not compatible with a weak gauge theory [7]). Because this model is an interesting generalization of ordinary charm, we shall briefly review Harari's conclusions concerning his model in the following subsection.

(i) Harari's Model [7]

The heavy quarks in Harari's model are in a $\underset{\sim}{\bar{3}}$ of SU(3) with charges (2/3, -1/3, 2/3), the ψ and ψ' are chosen as the I=0 SU(3) $\underset{\sim}{1}$ and $\underset{\sim}{8}$ states, respectively, with the I=1 state presumably the wide enhancement around 4.2 GeV. The value of R in e^+e^- annihilation is expected to be 5 beyond the threshold for the production of the new hadrons containing the heavy quarks; the ratio of leptonic couplings is predicted to be

$$\Gamma_{\psi\to e\bar{e}} : \Gamma_{\psi'\to e\bar{e}} : \Gamma_{\psi''\to e\bar{e}} = 6:3:9 \qquad (10)$$

(both sets of predictions being in good agreement with the data [1,8]). As usual, Zweig's rule must be invoked to "explain" the narrow widths of the ψ particles. The only C=+ states *a priori* expected in this mass range, and hence could be seen in the ψ or ψ' radiative decays, would be the pseudoscalar partners of the vector states.

As Harari shows, the weak interactions can be incorporated in an SU(2)xU(1) gauge framework with a generalization of the GIM mechanism to suppress off-diagonal neutral currents. Although there is greater freedom than in the four quark model, the signatures for charmed particle production and decay (such as the K/π ratio) are very similar (except for dilution of the cross section among three times as many charmed states).

The question of whether the decay $\psi'\to\psi\eta$ is, or is not, suppressed relative to $\psi'\to\psi\pi\pi$ depends on the relative breaking of light and heavy SU(3) ($SU(3)_{L,\,H}$ respectively) versus their diagonal sum (which is ordinary SU(3)). In a U(6) scheme both $SU(3)_L$ and $SU(3)_H$ are contained as separate symmetries and even the decay $\psi'\to\psi\pi\pi$ can proceed only by breaking of $SU(3)_H$ (since $\psi'\epsilon\ \underset{\sim}{8}$ of $SU(3)_H$). The same is true of $\psi'\to\psi\eta$ but in this case one *also* requires the breaking of $SU(3)_L$ *or* the decay must proceed entirely through the singlet piece of the η *. With a smaller symmetry O(6) (where diagonal SU(3) is the only good symmetry) the decay $\psi'\to\psi\eta$ is allowed, however, a gauge theory for the weak interactions cannot be constructed because some of the required weak currents are outside the O(6).

---

*) In the usual SU(4) charm, $\psi'\to\psi\pi\pi$ is allowed by SU(3) while $\psi'\to\psi\eta$ must go via SU(3) breaking or the singlet piece of the η .

Thus, as Harari concludes, in the model with heavy quark charges 2/3,-1/3, 2/3, the constraint that one can build a weak and electromagnetic gauge theory with a generalized GIM mechanism requires the U(6) scheme, in contrast to the O(6), with the result that $\psi' \to \psi\eta$ should be suppressed relative to $\psi' \to \psi\pi\pi$.

(ii) A model with a negatively charged heavy quark antitriplet

The experimental data are very restrictive for hidden colour quark models similar to Harari's. For example, it can be shown [10] that if ψ and ψ' contain large $SU(3)_H$ $\underset{\sim}{1}$ and $\underset{\sim}{8}$ components, respectively, with the quark charges constrained such that R is less than 10 and $\frac{1}{2} < \Gamma_{\psi \to e\bar{e}} / \Gamma_{\psi' \to e\bar{e}} < 8$ (and $\Gamma_{\psi'' \to e\bar{e}}$ of the same order), then the model with hidden colour and the fewest new quarks is either Harari's or the one with heavy quark charges -1/3,-4/3,-1/3. With ψ a pure $SU(3)_H$ singlet, the second model gives

$$\Gamma_{\psi \to e\bar{e}} : \Gamma_{\psi' \to e\bar{e}} : \Gamma_{\psi'' \to e\bar{e}} = 24 : 3 : 9 \qquad (11)$$

which is not really satisfactory since experimentally [8] $\Gamma_{\psi \to e\bar{e}} : \Gamma_{\psi' \to e\bar{e}} \simeq 2$. However, with a small amount of singlet-octet mixing between the ψ' and ψ' the ratio of leptonic widths is considerably improved. For example, mixing by an angle of arctan($-\sqrt{2}/5$), so that

$$\psi' = \frac{1}{3\sqrt{3}} \left(5\, \psi_{\underset{\sim}{1}} - \sqrt{2}\, \psi_{\underset{\sim}{8}} \right) , \qquad (12)$$

changes the ratio of leptonic widths to

$$\Gamma_{\psi \to e\bar{e}} : \Gamma_{\psi' \to e\bar{e}} : \Gamma_{\psi'' \to e\bar{e}} = 18 : 9 : 9 \qquad (13)$$

Concerning R, which is 8 in this model, the full asymptotic value may not be reached until all the new states can be pair produced which requires center of mass energy above 8 GeV. One interesting feature of this model is that, unlike Harari's, <u>all of the weak currents are contained in the smaller O(6) symmetry.</u>

The $SU(3)_H$ assignment of the ψ and ψ' is the crucial assumption in limiting six quark models to only Harari's and the one with negatively charged quarks. Consequently, the degree to which the data support these assignments should be mentioned. The decays of the ψ which are forbidden to an SU(3) $\underset{\sim}{1}$, such as $K\bar{K}$, $K^*(890)\bar{K}^*(890)$, $K^{**}(1420)\bar{K}^{**}(1420)$, $K\bar{K}^{**}(1420)$, are indeed not observed experimentally, while decays which are allowed, such as $K\bar{K}^*(890)$ and $K^*(890)\bar{K}^{**}(1420)$ are seen [8].

This strongly suggests a singlet assignment for the ψ (or at least a singlet component in the ψ which the decay mechanism favors). On the other hand the ratio of $\Gamma(\psi\to\pi^{\pm}\rho^{\mp})/\Gamma(\psi\to K^{\pm}K^{*\mp})$, which should be unity for a singlet ψ, is approximately 3:1 (for each charge state) [8]. However, a small amount of SU(3) breaking in the amplitude or singlet-octet mixing between ψ and ψ' could radically change the $\pi\rho$ to KK^* ratio as required while still suppressing the forbidden decays (since singlet-octet interference affects only the former). For example, in the model with heavy quark charges -1/3, -4/3, -1/3 and mixing as in equation (12) plus diagonal SU(3) the only good symmetry (as in an O(6) scheme), the $\pi\rho$ to KK^* ratio and the suppression of the KK, etc., are consistent if the intrinsic singlet and octet reduced matrix elements are not too dissimilar. With either conventional SU(4) charm or a U(6) model the data would have to be explained by a small amount of SU(3) breaking.

The SU(3) assignment for the ψ' is more controversial. The decay $\psi'\to\psi\eta$ would be SU(3) forbidden if the η were a pure octet state and the ψ' and ψ singlets. Yet $\psi'\to\psi\eta$ (which is a p wave decay with not much phase space) is only a factor of twelve smaller than $\psi'\to\psi\pi\pi$ [8]. Naively a singlet admixture in the η does not alone seem sufficient to explain the $\psi\eta$ decay if the ψ' is an SU(3) singlet, and so this could be an indication that a non-singlet, in particular $\underset{\sim}{8}$, piece is present in the ψ'. However, there are two important caveats. First, one cannot eliminate the possibility that both ψ and ψ' are SU(3) singlets and that the deviation of the $\pi\rho/KK^*$ ratios from unity and the large $\psi'\to\psi\eta$ decay rate are both due to SU(3) breaking pieces in the Hamiltonian, which is what is required for an SU(4) or U(6) model. Secondly, the way that strong interaction symmetries are generated in the conventional unified gauge theory framework* is via the quark mass matrix. Consequently the six quark models automatically possess both $SU(3)_L$ and $SU(3)_H$ as well as diagonal SU(3) symmetry which forbids the $\psi'\to\psi\eta$ decay. Although the (-1/3, -4/3, -1/3) model needs only an O(6) symmetry for incorporating the weak interactions, there is no way consistent with the usual assumptions to break the U(6) symmetry down to O(6).[15]

---

*) The overall group is assumed to be the direct product of a non-abelian strong gauge group and a weak gauge group. The gauge bosons of each group are neutral under the other group, and the only scalar fields are neutral under G_S and spontaneously break G_W. Relaxation of these assumptions usually leads to disastrous consequences such as strong parity violation. See ref. 14.

Consequently, as concluded by Nanopoulos and Ross 15), the decay $\psi' \to \psi\eta$ can only proceed through SU(3) violation in the conventional gauge framework. *Because of the previous two caveats and our prejudice for a gauge theory, we feel that neither $SU(3)_H$ $\underset{\sim}{1}$ or $\underset{\sim}{8}$ assignment for the ψ' can be favoured over the other* (since $\psi' \to \psi\eta$ is suppressed either way).[*]

Consequently, in seeking a reason to go beyond conventional charm we are forced to rely heavily on the large value of R. With negatively charged quarks, the minimal model is SU(4) with the fourth quark having charge -4/3. In this case, $R \to 7\,{}^1\!/_3$ and the heavy hadron spectrum is similar to that of conventional charm 6), but new leptons are needed to restore universality. If, instead, $\psi' \in \underset{\sim}{8}$ of $SU(3)_H$, the minimal model is U(6) with charges (-1/3,-4/3,-1/3) 10). In the absence of further information about the $\underset{\sim}{1}$ or $\underset{\sim}{8}$ nature of the ψ', we shall examine the phenomenology of both of these models although concentrating on the latter since many of the predictions are similar.

4. SPECTROSCOPY AND DECAY MODES OF THE NEW MESONS

A. One heavy quark charge -4/3 6)

Just like the familar charm model one will have new mesons with hidden heaviness ($f\bar{f}$) which are indentified with the new ψ states (including the interpretation of the ψ', ψ'', etc., as radial excitations plus the other features of the charmonium picture 5)). New states carrying heaviness +1 will be as follows: $R^-(f\bar{n})$, $R^{--}(f\bar{p})$, and $Q^-(f\bar{\lambda})$ which are the analogues of the states $D^+(c\bar{n})$, $D^0(c\bar{p})$, and $F^+(c\bar{\lambda})$ of the familar charm model. The existence of doubly charged states is an interesting feature of the model with the f quark 6).

Non-trivial differences with the charm model emerge when the weak decays of these states are considered. These differences are due to the two features of the weak current described in section 2. First, the conventional charm weak current $J^+ \sim \bar{p}n_c + \bar{c}\lambda_c$ has the property $\Delta H = \Delta Q$ (again substituting the name "heaviness" for charm). The present model has $J^+ \sim \sqrt{2}(\bar{p}n_c + \bar{n}_c f)$ and hence $\Delta H = -\Delta Q$ (remembering that the leptons must also be in weak SU(2) triplets to restore universality). Also, the charm weak current contains a piece $\Delta S = \Delta H$

---

[*] Cahn and Chanowitz make the interesting conjecture that circumstantial evidence concerning the isospin and SU(3) properties of all the new vector mesons may be determined from the relative rates of $\psi \to \pi^0\gamma, \eta\gamma, \eta'\gamma$. See ref. 16.

with strength $\cos\theta_c$ in amplitude which in turn leads one to expect K mesons to be important in the decay products of the heavy states. In the present model, on the other hand, the $\Delta S = \Delta H$ arises only at strength $\sin\theta_c$, and $\Delta S = 0$ is the favoured mode with a corresponding suppression of the kaon yield in the heavy decays relative to the charm model expectation 6).

If only one new quark is required to describe the phenomenology of the new states, then the above two features can help to distinguish the present model from the charm model as they lead to observable differences in both e^+e^- and ν interaction phenomenology.

B. Heavy antitriplet charges -1/3, -4/3, -1/3 10)

Since the model consists of six quarks there will be 36 meson states for each J^P value. These six quarks separate into a triplet of light quarks (q_L) and an antitriplet of heavy quarks (q_H) and, but for the charges of the heavy quarks, are identical to those of Harari 7). Consequently the group structures of this and Harari's model are identical, specifically: (i) nine "familiar" mesons with H = 0 ($q_L\bar{q}_L = \underset{\sim}{3}\times\underset{\sim}{\bar{3}} = \underset{\sim}{1} + \underset{\sim}{8}$), (ii) nine new mesons with "hidden heaviness" and H = 0 ($q_H\bar{q}_H = \underset{\sim}{\bar{3}}\times\underset{\sim}{3} = \underset{\sim}{1} + \underset{\sim}{8}$), (iii) nine heavy mesons with H = +1 ($q_H\bar{q}_L = \underset{\sim}{\bar{3}}\times\underset{\sim}{\bar{3}} = \underset{\sim}{\bar{6}} + \underset{\sim}{3}$) and their nine antiparticles with H = -1.

There should be pseudoscalar and vector versions of each state, and three of the vectors (ψ, ψ', ψ'') couple to the photon. The only C = +1 states naively expected in the 3-4 GeV mass range and which could appear in the ψ or ψ' radiative decays are the pseudoscalars.

Since the average charge of our quark antitriplet is one unit less than Harari's, so in turn our heavy mesons have one unit less charge than their analogues in the Harari model. The H = +1 $\underset{\sim}{\bar{6}}$ and $\underset{\sim}{3}$ mesons are exhibited in Figure 1. We have labelled these states P, Q, and R to facilitate rapid comparison with the Harari model (our notation n', f, λ' corresponds to his t, b, r). Note that the f quark only occurs in states R^-, R^{--}, Q^- and hence the extension from the model with only one heavy quark (f) is readily seen. Considerable mixing might occur between the relevant members of the $\underset{\sim}{\bar{6}}$ and $\underset{\sim}{3}$.

So far the differences with the Harari model are trivial. Non-trivial differences emerge when we discuss the weak decays (the lowest lying H = ± 1 mesons are presumably stable against strong and electromagnetic decays), and the reasons are identical to those mentioned in section 4A.

The weak decays are as follows:

(i) leptonic decays

The following quark combinations decay to a lepton and neutrino with rates proportional to the following factors *

$$R_1^-(f\bar{n}) \sim \cos^2\theta_c \qquad Q_1^-(f\bar{\lambda}) \sim \sin^2\theta_c$$
$$R_2^-(n'\bar{p}) \sim \cos^2\phi_c \qquad Q_2^-(\lambda'\bar{p}) \sim \sin^2\phi_c \tag{14}$$

Unless the R states in $\underset{\sim}{3}$ and $\underset{\sim}{\bar{6}}$ are "ideally" mixed into the 1,2 combinations above, their decays will be dominated by the R_1 or R_2 piece depending on the relative size of θ_c and ϕ_c (similarly for the Q states).

If $\phi_c \simeq \theta_c$ then

$$\Gamma_{K_2} : \Gamma_{Q^-} : \Gamma_{R^-} = 1 : \frac{m_Q}{m_K} : \frac{m_R}{m_K}\cot^2\theta_c \simeq 1 : 4 : 80 \tag{15}$$

(where K_2 represents $K\rightarrow \ell\nu$) by analogy with the estimates made in Gaillard, et. al. [3).]. If $\theta_c << \phi_c < \frac{\pi}{2}$ then

$$\Gamma_{K_2} : \Gamma_{Q^-} : \Gamma_{R^-} = 1 : \frac{m_Q}{m_K}\,\frac{\sin^2\phi_c}{\sin^2\theta_c} : \frac{m_R}{m_K}\cot^2\theta_c \simeq 1 : 80 : 80 \tag{16}$$

Hence a comparison of Q and R leptonic widths could distinguish between $\phi_c \sim \theta_c$ or $\phi_c >> \theta_c$. Since $\Gamma_{K_2} \sim 0.5\times 10^8$ sec^{-1}, then one expects

$$\Gamma_{R^-} \sim 4\times 10^9\ \mathrm{sec}^{-1} \quad ; \quad \Gamma_{Q^-} \sim 2\times 10^8\ \mathrm{sec}^{-1}\ \text{to}\ 4\times 10^9\ \mathrm{sec}^{-1} \tag{17}$$

if the Q and R masses are around 2 GeV.

(ii) semileptonic decays

The decays $H \rightarrow M\ell^-\bar{\nu}$ are as follows (for H → M) with the strength $\cos^2\theta_c$ or $\sin^2\theta_c$ in the rate as indicated

$$\left.\begin{array}{l} R^{--} \rightarrow \pi^- \\ R_1^- \rightarrow \pi^0 \\ Q_1^- \rightarrow K^0 \end{array}\right\} \cos^2\theta_c \qquad \left.\begin{array}{l} R^{--} \rightarrow K^- \\ R_1^- \rightarrow \bar{K}^0 \\ Q_1^- \rightarrow \eta \end{array}\right\} \sin^2\theta_c \tag{18}$$

These also obtain in the model containing only a single f quark.

---

*) In general there may be mixing between states common to $\underset{\sim}{\bar{6}}$ and $\underset{\sim}{3}$. Hence we refer to $R^-_{1,2}$, etc., as the quark combinations with, without the f quark. R_1^- and Q_1^- are identical to the states in the single heavy quark model.

The following only arise if n', λ' quarks are also present.

$$\left.\begin{array}{l} R^0 \to \pi^+ \\ R_2^- \to \pi^0 \\ Q^0 \to K^+ \end{array}\right\} \cos^2\phi_c \qquad \left.\begin{array}{l} Q^0 \to \pi^+ \\ Q_2^- \to \pi^0 \\ P^0 \to K^+ \end{array}\right\} \sin^2\phi_c \tag{19}$$

Computing these rates by comparing with $K_{\ell 3}$ weighted by (mass)^5 phase space and assuming that the masses are about 2 GeV leads one to expect rates of order 10^{11} sec^{-1} for R^-, R^{--}, Q^-, Q^0 independent of whether ϕ_c is large or small. However, if either $\cos^2\phi_c$ or $\sin^2\phi_c$ is small, <u>one</u> of the states P^0 or R^0 will have a similar rate (10^{11} sec^{-1}) while the other may be around 6 x 10^9 sec^{-1}.

We notice that the Q^- and R^- have their leptonic rates much less than the semileptonic just as in the conventional charm picture.

(iii) nonleptonic decays

The dominant nonleptonic decay rates are given schematically as follows

$$\left.\begin{array}{l} R^{--} \to \text{"}\pi^-\pi^-\text{"} \\ R_1^- \to \text{"}\pi^-\text{"} \\ Q_1^- \to \text{"}(K^0\pi)^-\text{"} \end{array}\right\} \cos^4\theta_c \tag{20}$$

and

$$\left.\begin{array}{l} R^0 \to \text{"}\pi^0\text{"}, \text{"}\eta\text{"} \\ R_2^- \to \text{"}\pi^-\text{"} \\ Q^0 \to \text{"}K^0\text{"} \end{array}\right\} \cos^2\theta_c \cos^2\phi_c \tag{21}$$

or

$$\left.\begin{array}{l} Q^0 \to \text{"}\pi^0\text{"}, \text{"}\eta\text{"} \\ Q_2^- \to \text{"}\pi^-\text{"} \\ P^0 \to \text{"}K^0\text{"} \end{array}\right\} \cos^2\theta_c \sin^2\phi_c \tag{22}$$

Note that all of the heavy states can decay into light states.

Estimates of the nonleptonic decay rates are beset by the usual problems surrounding which amplitudes are enhanced, whether exotic decays ($\pi^-\pi^-$, $K^0\pi^-$) are suppressed, etc.* Qualitatively, as in the familiar arguments applied to the charm model $^{5)}$, we expect the nonleptonic rates to be

---

*) Note that the $\Delta I = \frac{1}{2}$ transition $(\bar f \lambda)(\bar n f)$ will help enhance $\Delta I = \frac{1}{2}$ in ordinary non-leptonic decays (assuming the H = ± 1 weak currents are O(6) generators, i.e., SU(3) $\underset{\sim}{3}$ and $\underset{\sim}{\bar 3}$).

larger than the semileptonic. Quantitatively, only experiment can decide. At present we would expect anything between 10-50% to be possible for the semileptonic branching ratio.

5. PHENOMENOLOGY OF e^+e^- ANNIHILATION

If one believes that

$$R \equiv \frac{\sigma(e^+e^-\to \text{hadrons})}{\sigma(e^+e^-\to \mu^+\mu^-)_{QED}} = \Sigma\, Q_i^2 \qquad (23)$$

indicates the sum of the squares of quark charges even in preasymptotic regions, then R will be 2 below threshold for producing states containing heavy quarks. Above this threshold R will rise to a value

$$R = 7\tfrac{1}{3} \qquad \text{(one heavy quark f)} \qquad (24)$$

or

$$R = 8 \qquad \text{(antitriplet of heavy quarks } h', f, \lambda'\text{)} \qquad (25)$$

In the latter case one might need energies of at least $E_{c.m.} \gtrsim 2 \times 4.2$ GeV due to the I=1 nature of $\psi''(4.2)$ in this model (so that pair production of its charged partners can occur).

If these lowest lying heavy mesons are in the vicinity of 2 GeV in mass then their pair production is responsible for the observed rise in R in the range 3 GeV $< E_{c.m.} <$ 5GeV. This means that approximately 10 nb of the $\sigma_{tot}(e^+e^- \to$ hadrons) at 4.8 GeV is due to pair production of these states. In the charm model one then anticipates the inclusive cross section for producing a heavy (i.e. charmed) meson or its antiparticle to be around 7 nb and the present upper limits on $K^-\pi^+\pi^+$, etc., branching ratios are about 7 or 8%. 17)

In the model with <u>one</u> heavy quark of charge -4/3 one would naively expect inclusive production of R^{--} (or R^{++}) to be four times as frequent as, say, R^- (R^+). However, due to the SU(4) breaking we anticipate these rates to be roughly equal (just like the nonsuppression of $D^0\bar{D}^0$ relative to D^+D^- in charm). Hence the same conclusions on cross sections and branching ratios follow here as in the charm model. However, one feels that the doubly charged states should be more easily recontructable due to the smaller variety of decay modes avaliable and it is this feature which may be a good test of the -4/3 charge quark hypothesis.

In the model with a heavy antitriplet, if all the P,Q,R states have equal mass the inclusive cross-sections for producing any individual heavy meson or its antiparticle can be estimated as follows. Estimating U(6) breaking by coupling the photon only to the heavy quark, the states containing an f quark will be produced about 16 times as readily as those containing n' or λ'. If the R^- and Q^- states in $\underset{\sim}{3}$ and $\underset{\sim}{\bar{6}}$ are not "ideally" mixed, then the production cross sections for R^{--}, R^-, Q^- will each be around 4 nb with the remaining states each around 1/4 nb. If so, then the present upper limits on $K^-\pi^+\pi^-$, etc., branching ratios will be of order 15%* as against 7-8% in the single heavy quark models.

We draw attention to the fact that the K/π ratio for the heavy meson decays in models with -4/3 charge quarks are <u>not</u> expected to be larger than below theshold (in contrast to the naive charm model estimates). Therefore, reconstructions of non-kaonic events may be useful in attempting to discover enchancements associated with the heavy mesons.

6. HIGH ENERGY NEUTRINO INTERACTIONS

There are already some hints that new phenomena are being observed in high energy neutrino induced reactions[18)], but it is not yet clear to what extent these observations are in accord with charm model predictions [5)]. In the present model the phenomenology is rather different from that of the ordinary charm and in some cases seems to be consistent with features of the data which are not natural in the conventional model. The phenomenology is outlined below and, at the least, is useful as a guide to experiment since to confirm the charm model, for instance, one must perform experiments sensitive enough to distinguish among the differing predictions of these various models. Hence, even if this model is not correct, it may be of use as a "foil" against which the charm interpretation of the data can be contrasted.

(i) Production of new states by ν and $\bar{\nu}$

The transitions between light and heavy quarks which lead to production of new states in charged current interactions are shown in equation 26.

---

*) For the R^{--}, R^-, Q^-. (The R^0, Q^0, P^0 will not be detectable at present if produced only at 1/4 nb level). If there is mixing between $\underset{\sim}{\bar{6}}$ and $\underset{\sim}{3}$ then production cross-sections as high as 6 nb could result for R^{--}, R^-, Q^-.

$$\begin{array}{ccc} \underline{\nu} & \qquad & \underline{\bar\nu} \\ n_c' \to p & & \bar n_c' \to \bar p \\ f \to n_c & & \bar f \to \bar n_c \\ \bar n_c \to \bar f & & n_c \to f \\ \bar p \to \bar n_c' & & p \to n_c' \end{array} \qquad (26)$$

In order to make predictions concerning the production of new states, we are forced to rely on a dynamic model. For that we shall use the parton model, which has been fairly successful for interpreting "low" energy lepton induced reactions. Although an onset of scaling is obviously required to apply the parton model, hopefully the predictions will be useful indicators of future trends even in a transition region.

For incident neutrinos on a nucleon target new effects are anticipated only for $x \lesssim 0.2$ since the transitions are triggered by interaction with antiquarks or heavy quarks. (Both of these types of quarks are expected to be in the sea of quark-antiquark pairs and hence significant only at small x.) This contrasts with the charm model where the n can be excited to c, though suppressed by $\sin^2\theta_c$ in rate, and hence can contribute at all x.

Antineutrinos at any x can trigger heavy quark production from the n and p quarks with no suppression. This is in contrast with the charm model where antiquarks ($\bar n$, $\bar\lambda$) are required and so effects should be seen only for $x \lesssim 0.2$. Therefore, an important question is: Are new states produced as abundantly as conventional states in the region $x > 0.2$ by antineutrinos? A positive answer is certainly required for any type of model with only negatively charged new heavy quarks. For the particular six quark model, $\sigma^{\bar\nu N}$ should eventually equal $\sigma^{\nu N}$ ($\bar\nu$'s initiate $p \to n_c'$ and $n_c \to f$ as well as $p \to n$) somewhere beyond the threshold for the production of new states.

This prediction may already be in trouble, particularly in the differential form for $x > 0.2$ (where only valence quarks have significant contributions) which is as follows (N is an isoscalar target):

$$\left.\frac{d\sigma^{\bar\nu N}}{dy}\right|_{x>.2} \simeq 3(1-y)^2 \left.\frac{d\sigma^{\nu N}}{dy}\right|_{x>.2} \qquad (27)$$

for $W \gg W_{\text{threshold}}$, ($\left.\frac{d\sigma^{\nu N}}{dy}\right|_{x>.2}$ should be flat in y.). Whether there is a difficulty or not with the data depends on where the threshold is and how far above it one must go before the parton model prediction is realised. (A threshold effect first appears at large y and small x.) Moreover, for $W \simeq W_{\mathrm{threshold}}$ one anticipates charmed resonance production to be the dominant phenomenon. At low Q^2 this will be at small x, and to reach $x > 0.2$ one must increase Q^2 which should suppress resonance production due to form factor behaviour. For antineutrinos, new experimental phenomena are reported for $x<0.1$ and $E>30$ GeV [18]. Nevertheless, a naive look at $\bar{\nu}$ data for $x > 0.1$ does not support any deviation at all from the predictions of the simple three quark parton model. [18] If the parton predictions with heavy quarks are supposed to apply soon after the threshold for "heavy" particle production is passed, then the predicted rise in $\frac{d\sigma^{\bar{\nu}N}}{dy}$ for $x > 0.2$ can be put off only by pushing the threshold to a larger energy. A threshold of at least 7 GeV is necessary to be consistent with existing neutrino data. [19] Although one cannot be certain until the threshold energy for production of new states in antineutrino interactions is determined, we feel that the models with negatively charged quarks may be in some difficulty with their prediction of a large rise in $\frac{d\sigma^{\bar{\nu}N}}{dy}$ for $x > 0.2$.

(ii) Decay modes, dileptons, and $\Delta S = \pm \Delta Q$

In the ordinary charm model, a signal for the production of charm is observation of $\Delta S = -\Delta Q$ events in neutrino interactions. [5] These events proceed schematically through the following quark interactions:

$$\nu n \xrightarrow{\sin\theta_c} c\,\mu^- \qquad (28)$$

$$\hookrightarrow \lambda M^+ \quad \text{(dominant non-leptonic mode)}$$

and hence, $\Delta S = -\Delta Q$ events should be seen at finite x in νN according to conventional charm (though Cabibbo suppressed). With the negatively charged heavy quark models, the corresponding transition (occurring only with $\bar{\nu}$'s off valence quarks) is:

$$\bar{\nu} n \xrightarrow{\cos\theta_c} f\,\mu^+ \qquad (29)$$

$$\hookrightarrow \lambda M^- \quad (\sin\theta_c \text{ suppressed non-leptonic mode})$$

which is $\Delta S = +\Delta Q$ (competes with ordinary strangeness production, i.e. $\bar{\nu} p \rightarrow \lambda \mu^+$). Off quarks in the sea, both $\Delta S = \pm \Delta Q$ can be generated for ν's via the following:

$$\Delta S = +\Delta Q: \quad \nu \bar{n} \xrightarrow{\cos\theta_c} \bar{f}\,\mu^- \qquad (30)$$

$$\hookrightarrow \bar{\lambda} M^+ \quad (\sin\theta_c \text{ suppressed non-leptonic mode})$$

$$\begin{array}{ll} \Delta S = -\Delta Q: \; \nu\bar{\lambda} \xrightarrow{\sin\theta_c} \bar{f}\mu^- & \\ \qquad\qquad\qquad \hookrightarrow \bar{n}M^+ \; \text{(dominant non-leptonic mode)} & (31) \end{array}$$

and similarly for the $\bar{\nu}$'s . Thus, $\Delta S = -\Delta Q$ events arise only for $x \lesssim 0.2$ from strange quarks in the sea. Consequently, $\Delta S = -\Delta Q$ events will not be a dominant signal for charm production with only negatively charged heavy quarks.

Since the decay of the heavy quark in equations (29-30) could be semileptonic as well as non-leptonic , dilepton ($\mu^+\mu^-$) events will also be seen but suppressed by the branching ratio of heavy states into leptons. In $\bar{\nu}$ interactions, the dileptons can be produced off valence quarks, i.e.,for $x > 0.1$. (In the ordinary charm model, there is an extra sin θ_c suppression for $\mu^+\mu^-$ production by ν's off valence quarks.)

Also note that for $\bar{\nu}$'s off valence quarks, the following transitions occur

$$\begin{array}{ll} \bar{\nu}p \longrightarrow n_c'\mu^+ & \\ \qquad\quad \hookrightarrow p\mu^-\bar{\nu} & (32) \\ \qquad\quad \hookrightarrow f\mu^+\nu & \end{array}$$

Consequently, there will be dileptons produced with the same signs as well as opposite signs. However, dileptons of the same sign can be generated only by one heavy quark weakly decaying into another which should be considerably suppressed by phase space over the "heavy to light" transition (especially since the isodoublet n' and f are nearly degenerate and the mass formula for the ψ's suggests the λ' is lighter; 7) but, of course, there could be transitions between different SU(3) representations like $R_3^- \rightarrow R^{--}\mu^+\nu$). Note that dilepton production of the same sign could also occur in Harari's model except that in his model the p to n' transition is suppressed.

Off quarks in the sea, transitions leading to dileptons induced by ν's (similarly for $\bar{\nu}$'s) are:

$$\begin{array}{ll} \nu\bar{n}_c \rightarrow \bar{f}\mu^- & (33) \\ \qquad\quad \hookrightarrow \bar{n}\mu^+\nu & \end{array}$$

and

$$\begin{array}{ll} \nu\bar{p} \rightarrow \bar{n}_c'\mu^- & \\ \qquad\quad \hookrightarrow \bar{p}\mu^+\nu & (34) \\ \qquad\quad \hookrightarrow \bar{f}\mu^-\bar{\nu} & \end{array}$$

with the same comments as above regarding the relative rates.

Dilepton production of the same sign at finite x by ν's will be suppressed both because of the semi-leptonic branching ratio of heavy states and because of the small amount of antiquarks for $x > 0.1$.

Trileptons are also expected from the following sequential decay:

$$\begin{array}{l} \nu\bar{p} \longrightarrow \bar{n}_c' \mu^- \\ \qquad\quad \hookrightarrow \bar{f}\mu^-\bar{\nu} \\ \qquad\qquad\quad \hookrightarrow \bar{n}\mu^+\nu \end{array} \tag{35}$$

The rate for trilepton production should be down relative to dileptons of the same sign by the ratio of the semileptonic to non-leptonic decay of the heavy states (which contain the f).

(iii) Neutral currents

Assuming the parton model, the prediction for the neutral current to charged current cross section ratio for deep inelastic neutrino (antineutrino) scattering off an isoscalar nucleus (R_ν and $R_{\bar{\nu}}$, respectively) is easily calculated for the model with -1/3,-4/3,-1/3 heavy quarks. As usual, the dominant contribution to the cross-section comes from the valence quarks. In the case of antineutrinos, the ratio $R_{\bar{\nu}}$ is different above and below the threshold for the production of new states(due to the expected rise in the charged current $\bar{\nu}N$ cross section), but only the prediction below threshold should be relevant at present. Since the absolute coupling of the neutral current has not been specified, there is an arbitrary parameter δ which sets the overall scale as well as the angle θ which is analogous to the Weinberg angle. With the current given in equation (7) and using only valence quarks, the predictions for R_ν and $R_{\bar{\nu}}$ are as follows:

$$R_\nu = \delta\left[1 - \frac{4}{3}\sin^2\theta + \frac{20}{27}\sin^4\theta\right] \qquad \text{all } W \tag{36}$$

$$R_{\bar{\nu}} = \delta\left[1 - \frac{4}{3}\sin^2\theta + \frac{20}{9}\sin^4\theta\right] \qquad W \ll W_{th} \tag{37}$$

$$R_{\bar{\nu}} = \frac{\delta}{3}\left[1 - \frac{4}{3}\sin^2\theta + \frac{20}{9}\sin^4\theta\right] \qquad W \gg W_{th} \tag{38}$$

With $\xi = 1$, there is no value of the angle θ which is consistent with the experimental data on deep inelastic ν and $\bar{\nu}$ scattering.[20] By adjusting the parameter $\xi \lesssim 1/2$, one can, of course, fit the data. Consequently, the neutral current data provide a rather strong constraint for models with only negatively charged heavy quarks (in particular on the mass squared ratio of the charged to neutral intermediate weak vector boson).

7. HIGHER ORDER WEAK EFFECTS

One of the nicest features of the conventional charm model is that not only are $\Delta S \neq 0$ neutral current effects eliminated at order G but also at order $G\alpha$ in the processes where such effects are not wanted.[21] In particular, suppression of $G\alpha$ effects in $K_L \to \mu^+\mu^-$ and the $K_L - K_S$ mass difference is achieved if the ratio of the mass squared of the charm quark to the charged intermediate boson is much less than one ($K_L \to \gamma\gamma$ is not suppressed, as required, if the ratio of the mass of p quark to charm quark is also much less than one). The cancellations would be exact in the SU(4) symmetry limit. A sufficient requirement for an automatic cancellation of the unwanted $G\alpha$ effects in the symmetry limit for the above models is that the anticommutator as well as the commutator of J^+ and J^- is free of $\Delta S \neq 0$ neutral currents. This requirement is obviously met by the GIM mechanism for SU(4) charm and by its generalization for Harari's model. In the case of negatively charged quarks, however, the anticommutator possesses $\Delta S \neq 0$ neutral currents. Consequently, the automatic suppression of $G\alpha$ effects in $K_L \to \mu^+\mu^-$ and the $K_L - K_S$ mass difference does not occur. Actually, in these models there is a suppression due to $\sin^2\theta_c$ but this is insufficient. In the $K_L - K_S$ mass difference, for example, the $G\alpha \sin^2\theta_c$ effect is m_W^2/m_c^2 $(\sim 10^3)$ times bigger than in the conventional charm model.* Even though nature could possibly find another means for suppressing these effects, it does not occur in the most natural and simple way as with conventional models. We consider this difficulty as a rather significant liability for the models with negatively charged heavy quarks.

---

*) However, the contribution to the $K_L - K_S$ mass difference is only an order of magnitude bigger than that in the model of De Rujula, Georgi and Glashow[22] which has a right handed (cn) doublet (using the estimate of reference 23).

7. CONCLUSIONS

We have studied the theory and phenomenology of quark models containing negatively charged quarks, in particular a quark with charge -4/3.

From a theoretical point of view, we were motivated by the desire to construct an alternative to the conventional charm scheme, especially one with a different signature for charmed particle production and decay. One such alternative had already been examined by Goto and Mathur [6)] who introduced the idea of a "charmed" quark of charge -4/3: however, this scheme lost universality between lepton and hadron weak decays. As one example, we restored universality by introducing two additional quarks with charge -1/3 and schematically constructed a unified gauge theory for weak and electromagnetic interactions. Also, we noted that the resulting antitriplet of charmed ("heavy") quarks was rather useful in connection with the phenomenology of the new particles being similar to the model proposed by Harari. [7)] One particular interesting feature was that the weak currents could be incorporated in an O(6) symmetry for the strong interactions, which would have allowed decays such as $\psi' \to \psi\eta$ except that in the conventional gauge framework the larger U(6) symmetry is automatically generated. We also found that the strangeness changing neutral currents which had been eliminated at order G reappeared at order $G\alpha \sin^2\theta_c$ for the $K_L - K_S$ mass difference and $K_L \to \mu^+\mu^-$. Although nature may be ingenious enough to find another means for suppressing the unwanted $G\alpha$ effects, we are doubtful that a fully satisfactory scheme can be built with only negatively charged heavy quarks.

From the phenomenological point of view, the negatively charged quark models have rather clear signals which could distinguish them experimentally from conventional charm models. First, in e^+e^- annihilation one should search for charge 2 states in pair production ; note that an increase in the K/π ratio on crossing the heavy threshold is not expected. [6)] In neutrino experiments, significant $\Delta S = -\Delta Q$ events should not be seen—the definitive signal should be a large rise in the $\bar{\nu}$ cross section somewhere beyond the threshold for production of the new states. However, a threshold of at least 7 GeV is necessary in order not to be in disagreement with existing data. Thus, although still viable at present, these models are on the verge of being eliminated experimentally.

From the above theoretical and phenomenological problems, we feel that negatively charged heavy quarks are unlikely to be the solution to the various questions that we have discussed. If this conclusion is correct, models with negatively charged heavy quarks still may be of some use phenomenologically since to confirm the charge +2/3 feature of charm quark one must be able to distinguish experimentally between the predictions of the two schemes.

[While writing up our investigation, we received a paper entitled "SU(4)/Z(2) Symmetry, Sextet Quarks and a U(2) Gauge Theory" by C.H. Albright and R.J. Oakes (Fermilab-Pub-75/53-THY, July 1975) which also presents a detailed study of the model with heavy quark charges -1/3,-4/3,-1/3 in a gauge theory framework. In particular, these authors include the necessary leptons to construct an example of a complete theory, and their prediction for the strength of the hadronic neutral current is in agreement with data.]

ACKNOWLEDGEMENTS

We are indebted to our colleagues in the CERN Theory Division for many fruitful discussions. In particular we would like to thank J. Cleymans, Y. Frishman, A. Hey, B.W. Lee, C.H. Lewellyn-Smith, D. Nanopoulos, J. Nuyts, R. Phillips, G. Ross, J. Prentki, and J. Weyers. One of us (EWC) would also like to thank CERN and the Rutherford Laboratory, where this work was begun, for their hospitality.

REFERENCES

1) J.J. Aubert et. al., Phys. Rev. Letters 33, 1404 (1974)
J.E. Augustin et. al., Phys. Rev. Letters 33, 1406 (1974)
G.S. Abrams et. al., Phys. Rev. Letters 33, 1453 (1974) and
Phys. Rev. Letters 34, 1181 (1975)
J.E. Augustin et. al. Phys. Rev. Letters 34, 764 (1975)
J.A. Kadyk, Proceedings of the Tenth Recontre de Moriond, Meribel-Les-Allues (France), ed. J. Tran Thanh Van (1975).

2) S. Weinberg, Phys. Rev. Letters 19, 1264 (1967)
A. Salam, Elementary Particle Physics, ed. N. Svartholm (Almguist and Wiksells, Stockholm), 367 (1968).

3) For references and review, see M.A. Beg and A.Sirlin, "Gauge Theories of Weak Interactions," Annual Reviews of Nuclear Science, vol. 24, 379 (1974); S. Weinberg, Rev. Mod. Phys. 46, 255 (1974) ; and M.K. Gaillard, B.W. Lee, J.L. Rosner, "Search for Charm," Rev. Mod. Phys. 47, 277 (1975).

4) S.L. Glashow, J. Iliopoulous, and L. Maiani, Phys. Rev. D2, 1285 (1970).

5) For example, see Gaillard, et. al., ref. 3. For the new particles, see also T. Appelquist and H.D. Politzer, Phys. Rev. Letters 34, 43 (1975); H. Harari, " Ψchology", SLAC-PUB-1514, 1974 (unpublished); CERN Theory Boson Workshop, CERN-TH-1964, 1974 (unpublished); T. Appelquist,et. al., Phys. Rev. Letters 34, 365 (1975); and E. Eichten,et. al., Phys. Rev. Letters 34, 369 (1975).

6) T. Goto and V.S. Mathur, "An Alternative Quark Model with Charm," University of Rochester report, 1975 (unpublished).

7) H. Harari, "A New Quark Model for Hadrons," SLAC-PUB-1568, March, 1975 (unpublished) and "An Analysis of a New Quark Model of Hadrons," SLAC-PUB-1589, May, 1975 (unpublished).

8) G. Feldman and V. Lüth, Invited Talks at the EPS Meeting on High Energy Physics, Palermo, June, 1975. For a recent discussion of implications of the data, see F.J. Gilman, "The New Particles," Invited Talk at VI International Conference on High Energy Physics and Nuclear Structure, Santa Fe, New Mexico, June, 1975 (SLAC-PUB-1600).

9) G. Wolf, Invited Talk at the EPS Meeting on High Energy Physics, Palermo, June, 1975.

10) E.W. Colglazier , K.J. Barnes, A.J.G. Hey, R.K.P. Zia, "Difficulties for SU(N) Quark Models of the New Particles," Rutherford Lab preprint RL-75-103, June 1975 (to be published in Acta Physica Polonica).

11) Weinberg, reference 3.

12) C. Bouchiat, J. Iliopoulos, and P. Meyer, Phys. Letters 38B, 519 (1972)
D. Gross and R. Jackiw, Phys. Rev. D6, 477 (1972)
H. Georgi and S.L. Glashow, Phys. Rev. D6, 429 (1972).

13) W. Braunschweig et. al. Phys. Letters 57B, 1975 (to be published).

14) S. Weinberg, ref. 3, and Phys. Rev. Letters 31, 494 (1973).
D. Nanopoulos, Nuovo Cimento Letters 8, 873 (1973).

15) We thank G. Ross and D. Nanopoulos for discussions and enlightment on this subject. See G. Ross and D.V. Nanopoulos, "SU(3) Properties of the New Particles—A Problem for Unified Gauge Theories?", CERN-TH-2061, August 1975 (unpublished).

16) R. Cahn and M. Chanowitz, "Radiative Decays as Tests of the Symmetries of the Ψ Particles," LBL preprint 3889, July 1975 (unpublished).

17) A.M. Boyarski, et. al., Phys. Rev. Letters 35, 195 (1975).

18) D. Cline and C. Rubbia, Invited Talks at the EPS Meeting on High Energy Physics, Palermo, June 1975.

19) We would like to thank V. Barger, R. Phillips and T. Weiler for trying various fits of this model to the data and informing us of the apparent consistency with $W_{th} \sim 7$ GeV.

20) For a review of the data, see the Plenary Report on Neutrino Physics by D.C. Cundy, XVII International Conference on High Energy Physics, London, 1974.

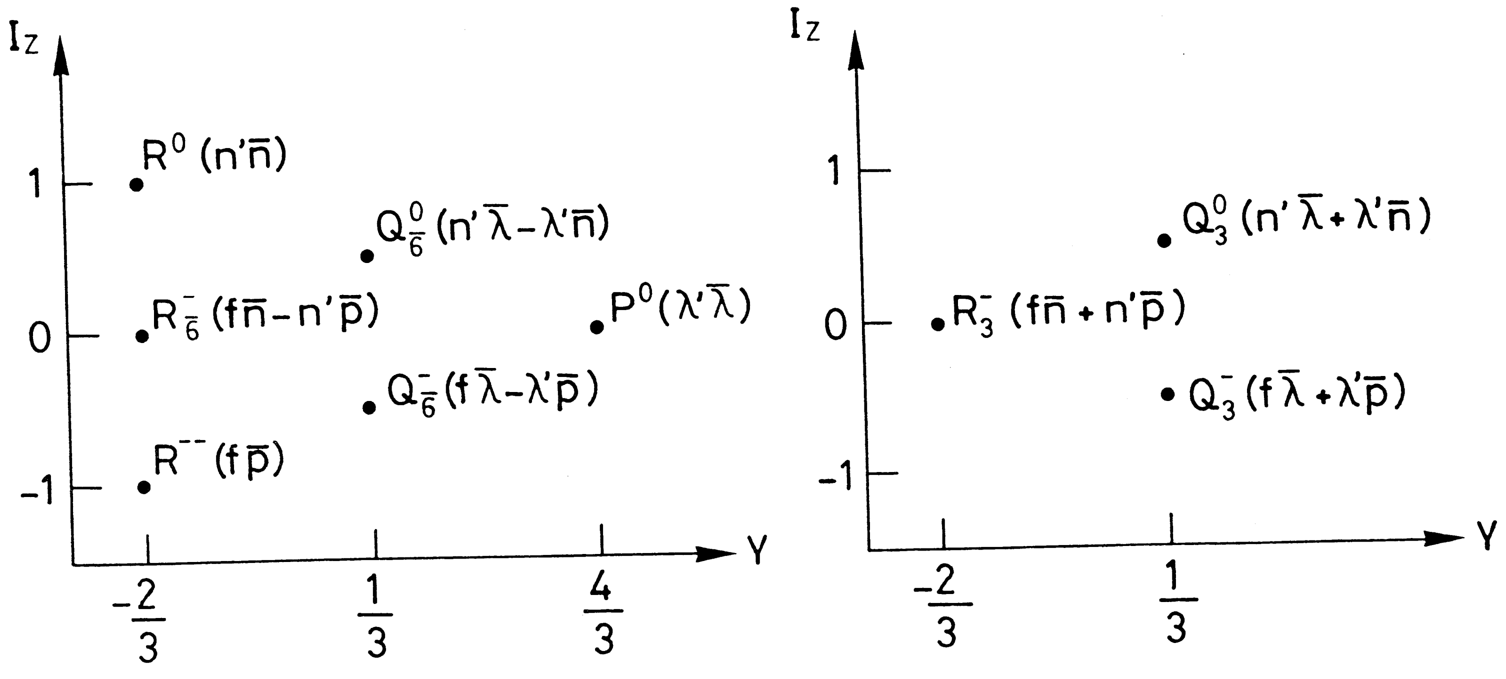
21) M.K. Gaillard and B.W. Lee, Phys. Rev. D10, 897 (1974).

22) A. De Rújula, H. Georgi, S. L. Glashow, Phys. Rev. Letters 35, 69 (1975).

23) F.A. Wilczek, A. Zee, R.L. Kingsley, and S.B.Treiman, "Weak Interaction Models with New Quark and Right-Handed Currents," Fermilab-Pub-75/44, June 1975 (unpublished).

FIGURE CAPTION

Fig. 1 : $\underset{\sim}{\bar{6}}$ and $\underset{\sim}{3}$ of H=+1 heavy mesons.



$\underset{\sim}{\bar{6}}$

$\underset{\sim}{3}$

FIG. 1