

## An Analysis of a New Quark Model of Hadrons\*

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We present a detailed analysis of our new quark model, which proposes an anti-triplet of new Heavy quarks in addition to the familiar  $u$ ,  $d$ , and  $s$  quarks. The suggestion of three new quarks is motivated by the existence of three  $\psi$ -particles and by the observed value of  $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ . We show that ours is the only model with three new quarks that is consistent with  $R \sim 5$  and with the relative leptonic widths of the  $\psi$ -particles. The structure of the weak currents in the model prevents  $|\Delta S| = 1$  neutral currents in a natural way. A spectrum of Heavy mesons and baryons is predicted and their decay modes, production, and experimental search are discussed. Radiative decays of  $\psi'$  (3700) into positive parity  $\psi$ -like states, which are predicted by the Charm scheme and are not found, are not predicted in our model. However, the hitherto unobserved pseudoscalar  $\psi$ -like particles predicted by all  $q\bar{q}$  schemes are also predicted by us.

## 1. INTRODUCTION

Recently, electron-positron collision experiments have provided us with two new exciting puzzles. The first is the discovery [1, 2] of two extremely narrow states  $\psi$  and  $\psi'$ , which are also observed in hadronic collisions [3] and photo-production [4]. The second is the behavior [5, 6] of the quantity  $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ , which seems to be approximately constant below  $W = 3.5$  BeV, and again more or less constant above  $W = 4.5$  GeV, with a clear transition occurring somewhere between these two energies (Fig. 1). To confuse us further, a third state (which we shall denote as  $\psi''$ ) is observed around 4.1 GeV [5]. This state is wide and it may be related to the  $\psi$  and  $\psi'$  or to the "threshold" in  $R$ , or to both phenomena.

Many theoretical ideas have been proposed to explain these experimental observations. Most of them are clearly unsatisfactory from an experimental or theoretical point of view (or both). Very few models, first among which is the

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Charm scheme [7], are quite attractive. However, even the Charm model suffers from several difficulties (all experimental) that we consider to be serious but not yet fatal.

In this paper, we propose a new quark model for hadrons [8]. We propose three new fractionally charged quarks that are heavier than the three usual quarks. The  $\psi$ -particles are bound states of such quarks and the threshold in  $R$  is related to the production of new Heavy mesons. Our model uses several ideas of the Charm scheme but it differs from it in many important respects. We do not claim or pretend that the model contains the answers to all of hadron physics. On the contrary, we are aware of its difficulties. However, we believe that our scheme is: (i) *certainly* an interesting exercise in model building; (ii) *probably* an improvement with respect to the Charm scheme, as far as comparison with experiment goes; (iii) *possibly* a correct basis for a description of the hadron spectrum.

A brief description of our model has already appeared [8]. In this detailed paper we examine its various theoretical and experimental implications and study several possible variations of the model.

In Section 2, we discuss the experimental hints that convince us that the  $\psi$ -particles and the behavior of  $R$  are related to the existence of new quarks. Section 3 outlines some of the difficulties of the Charm scheme. In Section 4, we introduce our model, emphasizing that it is the only scheme based on new quarks, which is consistent with the experimental value of  $R$  and with the relative leptonic widths of the  $\psi$ -particles. Section 5 discusses the symmetry of the model. Sections 6 and 7 are devoted to the meson spectrum. In Section 8, we study the weak currents. The decay patterns of our new mesons and baryons are analyzed in Sections 9 and 10. Finally, we summarize our scheme and discuss its advantages and its difficulties in Section 11.

## 2. WHY DO WE BELIEVE IN NEW QUARKS?

The energy dependence of the quantity  $R$  clearly indicates (Fig. 1) that somewhere around  $W \sim 4$  BeV a new threshold opens up and new states are being produced. The two simplest possibilities that come to mind in this connection are the following:

(i) More and more  $\psi$ -like resonances are being formed above 4 BeV. They all possess some new mysterious property, and are wide, numerous, and overlapping. Consequently, they are not identified as single states. If this explanation were true, we would expect to find a significant number of  $\psi$  or  $\psi'$  particles in the decay products of the alleged new  $\psi$ -like states. This does not seem to be the case.

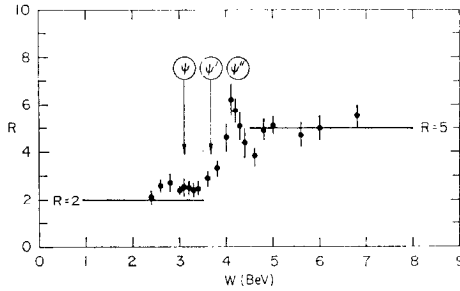


FIG. 1. Experimental data for  $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$  versus the c.m. energy  $W$ . Data are from [5, 6]. The predicted values of  $R = 2$  (below the Heavy meson threshold) and  $R = 5$  (above threshold) are marked.

(ii) Pairs of new particles carrying a new quantum number are being produced above the new threshold. Such particles could a priori be new hadrons, leptons, or an entirely new breed of particles. Do we have any evidence for the production of such pairs? Direct searches have failed to uncover such evidence. However, we do have an extremely interesting *indirect* indication that such pairs may be produced. The inclusive spectra [9] of charged particles in  $e^+e^-$  collisions below ( $W = 3$  BeV) and above ( $W = 4.8$  BeV) the “new threshold” are shown in Fig. 2. An inspection of these inclusive distributions reveals that for  $x > 0.5$  scaling is obeyed while in the region  $x < 0.5$  no scaling pattern exists. In other words, the large increase in  $R$  between 3.0 and 4.8 BeV is entirely due to events in which all charged tracks have  $x < 0.5$ .

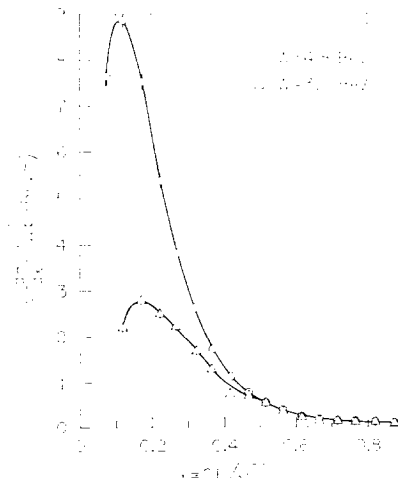


FIG. 2. Inclusive charged particle distributions at  $W = 3.0$  BeV and  $W = 4.8$  BeV representing data below and above threshold, respectively (from [9]).

What could lead to such a behavior? Consider the production of a pair of new particles at threshold. They are produced at rest, each carrying half of the total energy. If each of these particles then decays, it is clear that the momentum of any single decay product cannot exceed one-quarter of the total energy. In other words, all such decay products will have  $x < 0.5$ . If the pair of new particles is produced slightly above threshold, a few decay products may have  $x > 0.5$ , but their effect should be completely negligible and our argument is still valid. Therefore, we speculate that the difference between the inclusive distributions at  $W = 4.8$  GeV and  $W = 3.0$  BeV (Fig. 3) is limited to the  $x < 0.5$  region because it is entirely given by the decay products of pairs of new particles.

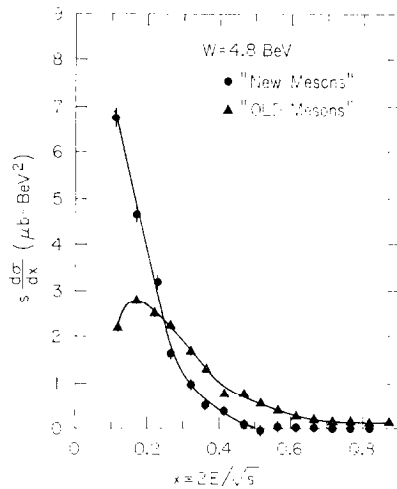


FIG. 3. Assuming that the inclusive distribution at  $W = 3.0$  BeV scales and represents the production of ordinary hadrons at all energies, the  $W = 4.8$  BeV inclusive distribution is divided into the contribution of new particles and old particles. The areas under the two curves are comparable but the shapes are completely different. The new particle distribution vanishes beyond  $x \sim 0.5$ .

What is the nature of these particles? The rise in  $R$  could easily be due to the production of new heavy leptons or other particles that do not interact strongly. However, it is almost certain that the wide bump at 4.1 GeV cannot be related to nonstrong effects. It is equally clear that if  $\psi$  and  $\psi'$  are bound states of a fermion and an antifermion, the binding must be significantly stronger than an electromagnetic binding. Consequently, if the new threshold in  $R$  is related to the  $\psi$ -particles, and if pairs of new particles are produced above this threshold, they are likely to be new hadrons.

Since the building blocks of hadrons are presumably quarks, we are led to the

following qualitative picture. A set of (one or more) new Heavy quarks exists, in addition to the usual quarks  $u$ ,  $d$ , and  $s$ . The  $\psi$  and  $\psi'$  particles, as well as the  $\psi''$ -bump, are states of a new quark and a new antiquark. The constant  $R$  below  $W = 3.5$  BeV reflects the charges of the "old" quarks. The constant  $R$  above  $W = 4.5$  BeV reflects the charges of the combined set of new and old quarks. Pairs of new mesons, each containing one new quark (or antiquark) and one old antiquark (or quark), are abundantly produced above the new threshold. They account for the rise in  $R$  (Fig. 1) as well as for the rise in the inclusive distribution (Fig. 2). The decays of  $\psi$  and  $\psi'$  into the new mesons are energetically forbidden. Their decay into ordinary mesons are inhibited by the quark-diagram rule ("Zweig rule" [10]). This is the "explanation" for the narrow width of  $\psi$  and  $\psi'$ . On the other hand,  $\psi''$  presumably decays into pairs of new mesons via an ordinary strong decay and has a normal hadronic width. Therefore, the threshold for the production of at least some of the new mesons must be below 4.1 BeV.

We believe that this qualitative picture is essentially correct. However, within its general framework, many different models are still possible. The best known among these is the Charm scheme [7, 11] and we now turn to discuss its experimental difficulties.

### 3. DIFFICULTIES WITH CHARM

The Charm scheme is extremely attractive from the theoretical point of view. It is designed to eliminate strangeness-changing neutral weak currents and it achieves this goal in an elegant and minimal way.

The basic ingredient is, of course, a fourth quark  $c$ , with electric charge  $Q = +\frac{2}{3}$ . It is an  $SU(3)$  singlet, and it carries one unit of a new additive quantum number, Charm. The modified Gell-Mann-Nishijima formula is:

$$Q = I_z + \frac{1}{2}Y + \frac{2}{3}C$$

and the relevant algebra is  $SU(4)$ .

What are the experimental difficulties of the Charm scheme?

(i) The value of  $R$  is predicted to be  $3\frac{1}{3}$ . Experimentally [5, 6], it is around 5 and it is approximately constant in energy above  $W = 4.5$  GeV. There is no indication of a gradual decrease towards  $R = 3\frac{1}{3}$ . This is the most serious difficulty, in our opinion.

(ii) The Charm scheme has no natural explanation for the existence of three  $\psi$ -particles. It can accommodate them easily as radial excitations of a  $c\bar{c}$  vector meson, but the number of such levels is not predicted. This point is essentially a matter of taste and we do not assign great importance to it.

(iii) The identification of  $\psi'$  as a radially excited state leads to the prediction [11] of  $p$ -wave  $c\bar{c}$  bound states with  $J^{PC} = 0^{++}, 1^{++}, 2^{++}$ . Their masses should be between those of the  $\psi$  and  $\psi'$ . The  $\psi'$  is predicted to decay via a radiative  $E1$  transition into each one of these states. The predicted partial widths are substantial [11] and the decays should be detected easily as narrow peaks in the momentum spectrum of photons that are emitted in  $\psi'$ -decay. Such peaks have not been observed and the present upper limits on them [12] are significantly lower than the predictions of the Charm model.

(iv) No direct evidence for the existence of charmed particles has been found. The present upper limits [13] on their production and decays are below the expected values for  $e^+e^-$  collisions, but it is quite possible that our theoretical understanding of the nonleptonic decay patterns of such particles should be reexamined.

(v) Along with the  $J^P = 1^- c\bar{c}$  states, the Charm scheme predicts  $J^P = 0^- c\bar{c}$  states. The mass of the lowest lying pseudoscalar should be well below the  $\psi'$ -mass. A radiative  $M1$  transition between  $\psi'$  and the pseudoscalar state is predicted and is not observed. However, this decay may be suppressed by the detailed wavefunctions of  $\psi'$  and the pseudoscalar state [11].

Among the above difficulties, (i) is special to the charm scheme and depends on its quark charges, (ii) and (iii) are related to each other and apply to any scheme with one additional quark, (iv) is relevant to any model with new quarks, but different schemes predict different production and decay properties for the missing mesons, and (v) is common to all models in which  $\psi$  is a bound state of a fermion and an antifermion.

The model proposed by us does not suffer from difficulties (i), (ii), and (iii). It is consistent with present upper limits, as far as (iv) is concerned, but it does suffer from difficulty (v). To our best knowledge, the model does not pose any new experimental difficulties.

#### 4. THE NEW MODEL: NOW WE ARE SIX

Two independent reasons encourage us to suggest three new quarks. The first is the existence of three  $\psi$  particles, which can be accommodated without radial or orbital excitations only if we have three quarks. The second is the observed value of  $R$ , which cannot be accounted for by the single additional quark of the Charm scheme and seems to require more quarks. Since the triplet is the smallest nontrivial  $SU(3)$  representation, we are naturally led to it when the singlet seems to fail.

The electric charges of three quarks in an  $SU(3)$  triplet are  $z, z - 1, z - 1$ , where  $z$  is arbitrary. If the quarks are in an antitriplet, their antiquarks are in a

triplet. In both cases we will have three objects (quarks or antiquarks) with charges  $z, z - 1, z - 1$  and three objects (antiquarks or quarks) with charges  $-z, 1 - z, 1 - z$ .

If all quarks come in the "usual" three colors [14], we have:

$$R = 2 + 3[z^2 + 2(z - 1)^2]$$

where the first term is due to the ordinary  $u, d, s$  quarks and the second term is due to the new Heavy quarks.

An inspection of  $R$  as a function of  $z$  (Fig. 4) indicates that  $R \leq 7$  can be achieved

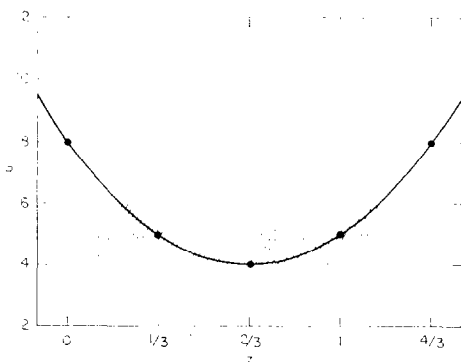


FIG. 4.  $R$  versus  $z$  in a model involving the  $u, d, s$  quarks and three additional quarks with charges  $z, z - 1, z - 1$ . All quarks come in three colors. For integer values of  $3z$  and  $R \leq 7$ , only  $z = \frac{1}{3}, \frac{2}{3}, 1$  are allowed.

only for  $z = \frac{1}{3}, \frac{2}{3}, 1$  (assuming that  $3z$  is an integer). The value  $z = 1$  for the Heavy quarks would mean that all mesons that are made out of a Heavy quark and an ordinary antiquark will have a noninteger charge. We reject this possibility [15].

Therefore, we are left with two possibilities:

(i)  $z = \frac{2}{3}$ . This would mean a triplet of Heavy quarks with charges identical to the  $u, d, s$  triplet. Such a model has been proposed by Barnett [16] and considered by many other people. In this case  $R = 4$ .

(ii)  $z = \frac{1}{3}$ . This would give integer charge mesons only if the quarks are in an  $SU(3)$  antitriplet with charges  $\frac{2}{3}, \frac{2}{3}, -\frac{1}{3}$  while the antiquarks are in a triplet with charges  $\frac{1}{3}, -\frac{2}{3}, -\frac{2}{3}$ . Here  $R = 5$ .

The observed value of  $R$  seems to favor the second possibility. However, a more decisive test is provided by the leptonic decay widths of the  $\psi$ -particles. Three neutral nonstrange vector mesons can be constructed from Heavy  $q\bar{q}$  pairs. Two of them are isoscalars and one is an isovector.

Experimentally,  $\psi(3100)$  decays mostly to odd number of pions [17]. Therefore, we assume that it is an isoscalar state. The  $\psi'(3700)$  decays mostly into  $\psi\pi\pi$  [18]. We assume that it is another isoscalar state. The  $\psi''$  will therefore be an isovector state. The two isoscalars  $\psi$  and  $\psi'$  could a priori be octet-singlet mixtures with an arbitrary mixing angle. However, it is easy to see that regardless of the value of the mixing angle:

$$K = \frac{\Gamma(\psi \rightarrow e^+e^-) + \Gamma(\psi' \rightarrow e^+e^-)}{\Gamma(\psi'' \rightarrow e^+e^-)} = 6z^2 - 8z + 3.$$

We have ignored the mass differences among the  $\psi$ -particles.

Experimentally [17, 19]:

$$\Gamma(\psi \rightarrow e^+e^-) = 4.8 \pm 0.6 \text{ keV}$$

$$\Gamma(\psi' \rightarrow e^+e^-) = 2.2 \pm 0.5 \text{ keV}.$$

Using these values for  $z = \frac{2}{3}$ , we obtain  $\Gamma(\psi'' \rightarrow e^+e^-) \sim 21 \text{ keV}$ . For  $z = \frac{1}{3}$ , we have  $\Gamma(\psi'' \rightarrow e^+e^-) \sim 7 \text{ keV}$ . Experimentally [5],  $\Gamma(\psi'' \rightarrow e^+e^-) \sim 4 \text{ keV}$  (with very large errors of 50% or so). Hence, the  $z = \frac{2}{3}$  solution is totally unacceptable. The  $z = \frac{1}{3}$  solution is reasonable, especially if we remember that the  $\psi$ ,  $\psi'$ ,  $\psi''$  mass factors may contribute 20–30% corrections and that the experimental estimate of  $\Gamma(\psi'' \rightarrow e^+e^-)$  is extremely crude and will become more meaningful only when the detailed shape of the  $\psi''$  peak is better understood.

Therefore, we conclude that there is one and only one model of three Heavy quarks that is consistent with the experimental values of  $R$  and  $K$  and leads to integer-charge mesons. It is interesting that both  $R$  and  $K$  independently prefer the  $z = \frac{1}{3}$  solution!

An additional independent indication is provided by the assignment of the  $\psi$  and  $\psi'$ . Experimentally [17, 19],

$$\Gamma(\psi \rightarrow e^+e^-)/\Gamma(\psi' \rightarrow e^+e^-) \sim 2.$$

The  $z = \frac{2}{3}$  solution can accommodate this ratio only if  $\psi$  and  $\psi'$  have quark compositions analogous to those of  $\phi$  and  $\omega$ , respectively. In such a case,  $\psi'$  and  $\psi$  do not contain the same quarks. The decay  $\psi' \rightarrow \psi\pi\pi$  would be doubly forbidden by the Zweig rule, while  $\psi' \rightarrow$  ordinary hadrons is singly forbidden. It is then very difficult to understand why  $\psi' \rightarrow \psi\pi\pi$  is the dominant decay mode of  $\psi'$ .

On the other hand, the  $z = \frac{1}{3}$  solution accommodates the correct ratio for leptonic decays, if  $\psi$  is an  $SU(3)$  singlet and  $\psi'$  an octet state. In that case,  $\psi$  and  $\psi'$  contain the same quarks and the  $\psi' \rightarrow \psi\pi\pi$  transition is forbidden only once by the Zweig rule.

The "natural selection" process described here leaves us with our model.



We have three light quarks, the familiar  $u$ ,  $d$ ,  $s$  and three Heavy quarks. The Heavy quarks form an  $SU(3)$  antitriplet consisting of an isodoublet  $(t, b)$  with charges  $(\frac{2}{3}, -\frac{1}{3})$  and an isosinglet  $r$  with charge  $\frac{2}{3}$  (Fig. 5). The Heavy quarks possess a new additive quantum number, which we call Heaviness and denote by  $H$ . They have  $H = +1$  while the light quarks have  $H = 0$ .

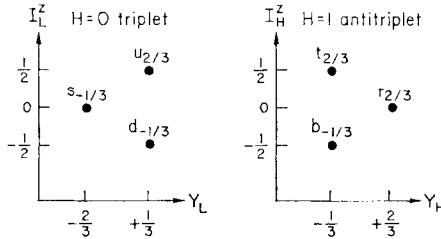


FIG. 5. The ordinary  $u$ (up),  $d$ (down), and  $s$ (singlet) quarks, and the proposed Heavy  $t$ (top),  $b$ (bottom), and  $r$ (right) quarks.

All six mesons come in three colors [14], but all observed mesons and baryons, including the  $\psi$ -particles, are color singlets. We have  $R = 2$  below the Heavy meson threshold and  $R = 5$  above it, in agreement with experiment (Fig. 1).

### 5. THE SYMMETRIES OF THE MODEL

Since we have six quarks and three colors, the full algebra of the model is  $U(6) \times U(3)$  where  $U(6)$  is generated by the  $36\ q\bar{q}$  operators and  $U(3)$  is the color symmetry group. If we construct the usual gauge theory of quarks and colored gluons using our quark assignments, we necessarily end up with such an algebra.

The full  $U(6)$  algebra is obviously a badly broken symmetry. Its most interesting subalgebra, which might be a reasonable approximate symmetry, is  $SU(3)_L \times SU(3)_H \times U(1) \times U(1)$ . This subalgebra is generated by an  $SU(3)_L$ -algebra that acts on the three light quarks, an  $SU(3)_H$ -algebra for the Heavy quarks, and two additional  $U(1)$  symmetries representing Baryon number and Heaviness. Six additive quantum numbers are conserved by the strong and electromagnetic interactions:  $B, H, I_L^z, Y_L, I_H^z, Y_H$ . The isospin and hypercharge of the light quarks as well as those of the Heavy quarks are separately conserved. The electric charge obeys

$$Q = \frac{1}{2}(Y_L + Y_H) + (I_L^z + I_H^z) + \frac{1}{3}H.$$

The separate conservation of  $I_L$  and  $I_H$  implies, for instance, that an isovector  $H = 0$  meson consisting of  $u\bar{d}$  will not be able to mix strongly with an isovector

$H = 0$  meson consisting of  $t\bar{b}$ , since the first has  $I_L = 1, I_H = 0$  while the latter has  $I_L = 0, I_H = 1$ . Similarly,  $\psi''(4100)$  cannot mix with the  $\rho$ -meson, etc. We will refer to the above symmetry as the  $U$ -scheme.

Another alternative is to assume that only the "diagonal"  $SU(3)$  algebra within  $SU(3)_L \times SU(3)_H$  is a good approximate symmetry. In such a scheme,  $I_L$  and  $I_H$  are not separately conserved, but their vector sum  $I$  is conserved. Similarly, only  $Y = Y_L + Y_H$  and  $I^z = I_L^z + I_H^z$  are exactly conserved, but not  $Y_L, Y_H, I_L^z, I_H^z$ . In this case  $\psi''-\rho$  mixing could take place. A  $u\bar{d}$  state and a  $t\bar{b}$  state also could mix. The mixing angles may be very small because of the mass differences between the light and Heavy quarks, but they would be due to the strong interactions.

In this case the hierarchy of algebras might be:

$$U(6) \supset O(6) \supset SU(3) \times U(1)$$

where the six quarks are in the fundamental six-dimensional multiplet of  $O(6)$ . Note that the  $O(6)$  algebra is isomorphic to that of  $SU(4)$ . It has an  $SU(3)$  sub-algebra and a  $U(1)$ , which is orthogonal to it. The six-dimensional multiplet of  $O(6)$  necessarily decomposes into an  $SU(3)$  triplet and an  $SU(3)$  antitriplet with different  $H$ -values. We will refer to this possibility as the  $O$ -scheme.

The  $U$ -scheme is a more attractive theoretical framework. It is the natural symmetry for a theory of quarks and gluons and we will see in Section 8 that it is also better suited for accommodating the weak currents. Therefore, we prefer it at the present time. However, the  $O$ -scheme is also interesting. It leads naturally to a light triplet and a Heavy antitriplet of quarks and it requires the smallest number of new conserved quantum numbers. Therefore, we do not reject it, and we will consider it from time to time as a possible alternative.

## 6. THE MESONS: $H = 0$

For any given value of  $J^P$ , we expect 36 mesons, representing all possible  $q\bar{q}$  combinations. Of these, nine will have  $H = +1$  and nine will have  $H = -1$ . We discuss these Heavy mesons in Section 7. The other 18 mesons have  $H = 0$ . Of these, nine are the usual mesons, which are bound states of the  $u, d, s$  quarks and their antiquarks. Nine others are bound states of a Heavy quarks and a Heavy antiquark. These include the  $\psi$ -particles. The present section is devoted to these particles and their properties.

The lowest lying states are presumably the pseudoscalars and the vector mesons. Of the nine vector mesons, three are neutral and nonstrange. Only these three couple directly to the photon. We identify them as the three  $\psi$ -particles. We have already stated in Section 4 that we assign  $\psi(3100)$  to an  $SU(3)$  singlet,  $\psi'(3700)$

to an  $I = 0$  member of an octet, and  $\psi''(4100)$  to an  $I = 1$  multiplet in an octet. The corresponding quark states are:

$$\psi = \frac{1}{3^{1/2}}(t\bar{i} + b\bar{b} + r\bar{r}); \quad \psi' = \frac{1}{6^{1/2}}(t\bar{i} + b\bar{b} - 2r\bar{r}); \quad \psi^a = \frac{1}{2^{1/2}}(t\bar{i} - b\bar{b}).$$

What are the consequences of these assignments and the predictions of our model?

(i)  $\Gamma(\psi \rightarrow e^+e^-) : \Gamma(\psi' \rightarrow e^+e^-) : \Gamma(\psi'' \rightarrow e^+e^-) = 2 : 1 : 3$ . The corresponding experimental figures are [5, 17, 19]:  $\Gamma(\psi \rightarrow e^+e^-) = 4.8 \pm 0.6$  keV;  $\Gamma(\psi' \rightarrow e^+e^-) = 2.2 \pm 0.5$  keV;  $\Gamma(\psi'' \rightarrow e^+e^-) \sim 4$  keV (with a very large error). The agreement is satisfactory. It is amusing to note that if we ignore the mass differences between  $\rho$ ,  $\omega$ ,  $\phi$  and  $\psi$ ,  $\psi'$ ,  $\psi''$  we also predict:

$$\Gamma(\psi \rightarrow e^+e^-) : \Gamma(\rho \rightarrow e^+e^-) = 2 : 3.$$

Experimentally, this ratio is  $\sim 0.75 \pm 0.15$ .

(ii) If  $\psi$  is an  $SU(3)$  singlet, the following decays are forbidden by  $SU(3)$  [20]:

$$\psi = K\bar{K}, K^*\bar{K}^*, K\bar{K}^*(1420), \text{ etc.}$$

Experimentally, these decays have not been seen. Several branching ratios are predicted, such as:

$$\frac{\Gamma(\psi \rightarrow \pi\gamma)}{\Gamma(\psi \rightarrow \eta\gamma)} = 3; \quad \frac{\Gamma(\psi \rightarrow \omega\pi\pi)}{\Gamma(\psi \rightarrow K^*\bar{K}\pi, \bar{K}^*K\pi)} = \frac{1}{2}; \quad \frac{\Gamma(\psi \rightarrow \rho\pi)}{\Gamma(\psi \rightarrow K^*\bar{K}, \bar{K}^*K)} = \frac{3}{4}.$$

These, as well as numerous similar predictions are based only on the  $SU(3)$ -singlet properties of the  $\psi$ . They are therefore common to our model and to the Charm scheme.

(iii) The decays of  $\psi$ ,  $\psi'$ , and  $\psi''$  into ordinary mesons are suppressed by Zweig's rule [10, 20].

In the case of  $\psi$ , decays into  $H = \pm 1$  mesons are clearly forbidden by energy conservation. The suppressed decays are therefore dominant.

In the case of  $\psi'$  the situation is somewhat confusing. A careful inspection of Fig. 1 ( $R$  versus  $W$ ) indicates that the rise in  $R$  may begin just below the  $\psi'$  mass. If this is the case, we may have a small decay width for  $\psi' \rightarrow (H = 1 \text{ meson}) + (H = -1 \text{ meson})$ . Such a decay, if energetically allowed, will be inhibited strongly by the tiny available phase space. On the other hand, it is equally possible that the threshold for producing the lightest Heavy mesons is just above the  $\psi'$ , in which case such a decay is impossible.

The  $\psi''$  state should decay mostly into a pair of Heavy mesons. Consequently, the isospin of  $\psi''$  cannot be determined by establishing dominant decay modes into even numbers or odd numbers of pions, etc.

(iv) The three  $\psi$ -particles belong to a vector meson nonet. The other predicted states are:

(a)  $\psi''^+$  and  $\psi''^-$  states, degenerate with  $\psi''(\psi''^+ = t\bar{b}, \psi''^- = b\bar{t})$ . These complete the  $\psi''$  isotriplet. They are presumably as wide as  $\psi''$ , and decay mostly into pairs of Heavy mesons.

(b) Four strange  $\psi$ -particles with quantum numbers analogous to those of  $K^{*+}, K^{*0}, \bar{K}^{*0}, K^{*-}$  (quark content:  $t\bar{r}, b\bar{r}, r\bar{b}, r\bar{i}$ ). The mass of these states presumably obeys:

$$m = \frac{1}{4}[3m(\psi') + m(\psi'')] \sim 3800 \text{ MeV.}$$

Since this mass is approximately equal to the combined masses of a Heavy meson pair, it is not clear if these  $S = \pm 1$   $\psi$ -states can decay into such a pair and whether they are wide or narrow.

All states in the  $\psi$ -nonet, except for the three observed states, cannot be formed as resonances in  $e^+e^-$  collisions. They can be produced in pairs in such collisions above  $W = 7.6$  BeV but their detection would be very difficult. The best possibility of discovering these states is presumably offered by neutrino reactions. We will return to this point in Section 10.

(v) Having determined the masses of the vector mesons, we may assume that the mass splittings within the  $SU(3)$  octet are entirely given by the mass differences of the Heavy quarks. Using a linear mass relation, this gives:

$$m(t) \sim m(b) \sim m(r) + 360 \text{ MeV.}$$

Contrary to the situation of the light quarks, we find that the isoscalar Heavy quark  $r$  has a lower mass than the isodoublet  $(t, b)$ . However, in both cases, the mass increases in the direction of decreasing hypercharge (Fig. 5).

The  $SU(3)$ -singlet  $\psi$  is presumably split from the octet by an  $SU(3)$ -invariant interaction. Such a situation is known to exist in the case of the ordinary pseudoscalar mesons where the singlet  $\eta'(960)$  has a significantly different mass from those of the members of the octet. We do not know why the ordinary vectors and pseudoscalar nonets show completely different patterns. We also do not know why the  $\psi$ -particles and ordinary vector mesons show such different patterns. We return to this point in Section 11.

(vi) We expect nine pseudoscalar  $\psi$ -particles, which we denote by  $\psi_\pi, \psi_K, \psi_n, \psi_{\eta'}$ . These will have the same quantum numbers as the ordinary pseudo-

scalar but will contain a Heavy quark and a Heavy antiquark. The  $\psi_n$ - $\psi_{n'}$  mixing pattern is not determined a priori. The masses of the pseudoscalars are probably somewhere in the 3–4 BeV region, and those states that are below the threshold for pairs of Heavy mesons should be very narrow. Each of the neutral vector particles,  $\psi$ ,  $\psi'$ ,  $\psi''$  should have a radiative  $M1$  transition into  $\psi_{\pi 0}$ ,  $\psi_n$ ,  $\psi_{n'}$ . It is likely that at least one of these pseudoscalars is below the  $\psi'$  and the transition  $\psi' \rightarrow \gamma + \psi_n$  should eventually be seen. Radiative decay of  $\psi''$  are much more difficult to detect because of the large  $\psi''$  width. Radiative  $\psi$ -decays may be absent if all three pseudoscalars are above or very near the  $\psi$ -mass.

The pseudoscalar  $\psi$ -particles can be discovered through radiative  $\psi'$ -decay, in photoproduction (via the Primakoff effect), in hadronic collisions (as narrow bumps) or in neutrino reactions.

(vii) Radial and orbital excitations of the  $\psi$ -states are probably well above the threshold for Heavy meson pair productions and above  $\psi''$ . Consequently, they will be wide and may escape detection easily. Since we do not assign any of the three observed  $\psi$ -states to a radial excitation, we do not predict any  $J^{PC} = 0^{++}, 1^{++},$  or  $2^{++}$  states between  $\psi$  and  $\psi'$ . Consequently, the large radiative  $E1$  transitions from  $\psi'$  to these states are not predicted in our model. In this point we clearly differ from the Charm scheme. Present experimental limits [12] on such  $\psi'$ -decays are well below the predicted rates of the Charm model [11].

Up to this point, the entire discussion in this section was independent of whether we assume the  $U$ -scheme or the  $O$ -scheme discussed in Section 5. The following predictions depend on the selected scheme and may serve as experimental tests of the two schemes as well as of the entire model.

If we accept the  $U$ -scheme, i.e., separate exact conservation of  $I_L$ ,  $Y_L$  and  $I_H$ ,  $Y_H$  as well as approximate conservation of  $SU(3)_L$  and  $SU(3)_H$ , we find:

(a) The decays  $\psi' \rightarrow$  ordinary hadrons,  $\psi' \rightarrow \psi\pi\pi$ ,  $\psi' \rightarrow \psi\eta$  are all forbidden by  $SU(3)_H$ . They are allowed by  $I_H$  and  $I_L$  conservation. Consequently, we predict:

$$\Gamma(\psi' \rightarrow \text{ordinary hadrons}) \ll \Gamma(\psi \rightarrow \text{ordinary hadrons}).$$

The decays of  $\psi'$  into ordinary hadrons, which are presumably suppressed both by Zweig's rule and by  $SU(3)_H$  invariance, will mostly proceed into  $SU(3)_L$ -singlet states. Therefore, they will obey the same selection rules and branching ratios as  $\psi$ -decays (see (ii) above). It is hard to compare  $\psi' \rightarrow \psi\pi\pi$  with  $\psi' \rightarrow$  ordinary hadrons since in the two cases Zweig's rule is violated with regard to different quarks. In  $\psi' \rightarrow \psi\pi\pi$  the violation relates to the  $u$  and  $d$  quarks. In  $(\psi' \rightarrow \text{ordinary hadrons})$  it relates to the Heavy quarks. Since empirically Zweig's rule "improves" when the quark mass increases, we know that  $\Gamma(\psi' \rightarrow \psi\pi\pi) > \Gamma(\psi' \rightarrow \text{ordinary hadrons})$ , but we cannot give a quantitative estimate.

The relative strength of  $\Gamma(\psi' \rightarrow \psi\pi\pi)$  and  $\Gamma(\psi' \rightarrow \psi\eta)$  is an interesting problem. In the  $U$ -scheme both processes are suppressed by the Zweig rule, and both violate  $SU(3)_H$  conservation. If  $\eta$  is a pure octet state,  $\psi' \rightarrow \psi\eta$  also violates  $SU(3)_L$ -invariance, while  $\psi' \rightarrow \psi\pi\pi$  does not. The relative magnitude of the matrix elements of the two processes then depends on the dynamics of the breaking of  $SU(3)_H$  and  $SU(3)_L$ , but it is likely that  $\psi' \rightarrow \psi\eta$  will be suppressed relative to  $\psi' \rightarrow \psi\pi\pi$ .

(b) In the  $U$ -scheme, decays such as  $\psi' \rightarrow K + \psi_K$ ,  $\psi' \rightarrow \rho^\pm + \psi_\pi^\mp$ , etc. are forbidden by  $I_L$  and  $I_H$  conservation, even if allowed energetically. Such decays could proceed only via the weak interactions. The decay  $\psi' \rightarrow \rho^0 + \psi_\pi^0$  could be a second-order electromagnetic transition and would be significantly weaker than  $\psi' \rightarrow \gamma + \psi_\pi^0$  (if allowed by energy).

(c) The states  $\psi_\pi$  and  $\psi_K$  cannot decay into ordinary hadrons (even with a Zweig rule suppression) because of  $I_H$  conservation. The leading decay modes of these mesons would then be weak (except for  $\psi_\pi^0 \rightarrow 2\gamma$ ). The details of the weak decays depend on the general properties of the weak currents and we return to them in Section 11.

The production rate of the  $\psi_\pi$  and  $\psi_K$  states in neutrino reactions should be comparable to those of the Heavy ( $H = \pm 1$ ) mesons. Consequently, neutrino reactions may be the best way of searching for them.

If we assume the  $O$ -scheme of Section 5, namely, allow the strong interaction to break  $I_H$  and  $I_L$  while conserving their sum, we find that a  $u\bar{d}$  state may mix with  $t\bar{b}$ , etc. Consequently,  $\pi$ - $\psi_\pi$  mixing is allowed as well as  $\omega$ - $\psi$ ,  $\omega$ - $\psi'$ ,  $\rho$ - $\psi''$ ,  $K$ - $\psi_K$ , etc. If we assume that the mixing is of order  $\epsilon$  in all cases, we find that the following decays are of order  $\epsilon^2$ :  $\psi \rightarrow$  ordinary hadrons,  $\psi' \rightarrow$  ordinary hadrons;  $\psi' \rightarrow \psi\pi\pi$ ;  $\psi' \rightarrow \psi\eta$ ;  $\psi' \rightarrow K\psi_K$ ;  $\psi' \rightarrow \rho\psi_\pi$ ;  $\psi_\pi \rightarrow \pi\pi\pi$ ;  $\psi_K \rightarrow K\pi\pi$ , etc. The order of magnitude of  $\epsilon^2$  will be around  $10^{-3}$ , as given by the ratio of  $\Gamma_{\text{tot}}(\psi)$  to a typical hadronic width. We find that in the  $O$ -scheme:

(a)  $\Gamma(\psi \rightarrow \text{ordinary hadrons}) \sim \Gamma(\psi' \rightarrow \text{ordinary hadrons})$ .

(b) The matrix elements for  $\psi' \rightarrow \psi\pi\pi$ ,  $\psi' \rightarrow \psi\eta$  are comparable (but phase space and angular momentum factors still work against  $\psi' \rightarrow \psi\eta$ ).

(c)  $\Gamma(\psi' \rightarrow K\psi_K, \rho\psi_\pi)$ , etc., could be of the order of a few percent of  $\Gamma_{\text{tot}}(\psi')$ , if they are energetically allowed.

(d) The widths of  $\psi_\pi^\pm$  and  $\psi_K$  are comparable to those of  $\psi(3100)$  or  $\psi'(3700)$ , rather than being due to weak decays.

The predictions of the two schemes are clearly very different, but their experimental resolution seems to be difficult, since it involves mostly rare decays or elusive  $\psi$ -like states.

7. THE HEAVY MESONS:  $H = \pm 1$

For each  $J^P$ -value we expect nine  $H = 1$  mesons and nine  $H = -1$  mesons. The lowest lying Heavy mesons are presumably the pseudoscalar and/or the vector mesons. The rise in  $R$  begins somewhere around  $W = 3.6-3.8$  GeV. Therefore, we conclude the lowest mass Heavy meson is somewhere around 1800-1900 MeV.

The assignments of the Heavy mesons depend on whether we consider the  $U$ -scheme or the  $O$ -scheme. In the  $U$ -scheme we expect all nine  $H = 1$  mesons to be in a  $(\bar{3}, \bar{3})$  representation of  $SU(3)_L \times SU(3)_H$ . Their isospin assignments and masses are predicted in Table I. Using a linear mass formula we find (see Section 6) that the mass splitting among the Heavy quarks is:

$$\Delta = m(t) - m(r) \sim 350 \text{ MeV.}$$

A similar calculation using the  $\rho, K^*$  masses yields:

$$\delta = m(s) - m(u) \sim 130 \text{ MeV.}$$

If the masses of the lowest  $H = \pm 1$  mesons (the  $r\bar{u}, r\bar{d}$  isodoublet) are around, say, 1850 MeV, we expect the entire nonet of Table I to lie between 1850 and 2350 MeV. All nine mesons in the lowest lying  $H = 1$  nonet should be stable against strong and electromagnetic decays. Their leading decay modes are weak, and their details depend on the structure of the weak currents (Section 8).

TABLE I  
Heavy Mesons in the  $U$ -Scheme

$SU(3)_L \times SU(3)_H$	$SU(2)_L \times SU(2)_H$	Quark content	Mass
	$(\frac{1}{2}, 0)$	$(r\bar{d})^+, (r\bar{u})$	$M$
	$(0, 0)$	$(r\bar{s})^+$	$M + \delta$
$(\bar{3}, \bar{3})$	$(\frac{1}{2}, \frac{1}{2})$	$(t\bar{d})^+(t\bar{u})^0(b\bar{d})^0(b\bar{u})^-$	$M + \Delta$
	$(0, \frac{1}{2})$	$(t\bar{s})^+, (b\bar{s})^0$	$M + \Delta + \delta$

In the  $O$ -scheme, the Heavy mesons are expected to be in pure states of  $I = I_L + I_H$ , and in approximate eigenstates of the "diagonal"  $SU(3)$  algebra. The nine  $H = 1$  mesons are in an antisextet and a triplet of  $SU(3)$ . The mass splittings within the  $SU(3)$  multiplets are presumably smaller in this case. Using the same values of  $\delta, \Delta$  we find that only 200 MeV separate the lowest and highest mass states in the sextet. Three of the nine  $H = 1$  mesons of the  $O$ -scheme can undergo radiative decays. The radiative transitions  $R_0^0 \leftrightarrow R_1^0, Q_6^+ \leftrightarrow Q_3^+,$

$Q_6^0 \leftrightarrow Q_3^0$  are allowed by isospin and hypercharge conservation. Two of them ( $R^0, Q^0$ ) are allowed by  $SU(3)$  while the  $Q_6^+ \leftrightarrow Q_3^+$  transition is forbidden by  $U$ -spin. These radiative decays are predicted to be the dominant decays of three of the nine  $H = 1$  mesons (except if these are pseudoscalar mesons, in which case radiative decays are forbidden by angular momentum considerations and the emission of  $e^+e^-$  pairs is the leading decay mode).

The dominant decay modes of the six other Heavy mesons in the  $O$ -scheme are weak decays. Their details depend, again, on the structure of the weak currents to which we now turn.

### 8. THE WEAK CURRENTS

Our model contains three quarks ( $u, t, r$ ) with electric charge  $Q = \frac{2}{3}$  and three quarks ( $d, s, b$ ) with  $Q = -\frac{1}{3}$ . The most general quark content of the positively charged hadronic weak current will therefore be:

$$J^+ = (u, t, r) \begin{pmatrix} A_{11}A_{12}A_{13} \\ A_{21}A_{22}A_{23} \\ A_{31}A_{32}A_{33} \end{pmatrix} \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}.$$

The space-time properties of  $J^+$  are presumably given by the usual  $V-A$  structure. The negatively charged current  $J^-$  is obviously the conjugate of  $J^+$ . We will assume that the neutral current  $J^0$  forms a "weak isospin"  $SU(2)$  algebra together with  $J$  and  $J^-$ . This is the usual structure expected in the simplest gauge theory of the weak currents.

Within such a framework it is natural to expect that the  $3 \times 3$  matrix  $A$  is a real orthogonal matrix. We will now show that if  $A$  is orthogonal, the neutral current  $J^0$  does not contain any  $|\Delta S| = 1$  or  $|\Delta H| = 1$  components.

The simplest way to see this is to define:

$$\begin{pmatrix} \bar{d}' \\ \bar{s}' \\ \bar{b}' \end{pmatrix} = A \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}.$$

This would mean that  $(u, d')$ ,  $(t, s')$ ,  $(r, b')$  are three doublets of our weak isospin and that:

$$\begin{aligned} J^+ &= u\bar{d}' + t\bar{s}' + r\bar{b}' \\ J^- &= d'\bar{u} + s'\bar{t} + b'\bar{r} \\ J^0 &= (u\bar{u} + t\bar{t} + r\bar{r}) - (d'\bar{d}' + s'\bar{s}' + b'\bar{b}'). \end{aligned}$$



However, the orthogonality of  $A$  assures us that:

$$d\bar{d} + s\bar{s} + b\bar{b} = d'\bar{d}' + s'\bar{s}' + b'\bar{b}'.$$

Hence,

$$J^0 = (u\bar{u} + t\bar{t} + r\bar{r}) - (d\bar{d} + s\bar{s} + b\bar{b}).$$

and the neutral current is diagonal, with no  $|\Delta S| = 1$  or  $|\Delta H| = 1$  components.

We have achieved the goal of eliminating the unwanted neutral currents using a simple generalization of the method of the Charm model [7]. We could do this only because of our specific charge assignments, which gave us a triplet and an antitriplet of quarks. The same method could not have worked with two triplets (i.e., the  $z = \frac{2}{3}$  solution [16] that we discarded in Section 4).

The matrix elements of  $A$  can be expressed in general in terms of three angles. One of these angles is the Cabibbo angle. We know experimentally that the coefficients of  $u\bar{d}$  and  $u\bar{s}$  in  $J^+$  are approximately given by  $\cos \theta$  and  $\sin \theta$ . Hence,

$$A_{11} = 0.97, \quad A_{12} = 0.23, \quad A_{13} \lesssim 0.1.$$

The value of  $A_{11}$  is determined from the comparison of nucleon and muon beta decay with proper radiative corrections [21];  $A_{12}$  is determined from  $K$ -decays and hyperon decays [22]. The upper bound on  $A_{13}$  is determined on the basis of comparing the values of the Cabibbo angle which are obtained from  $A_{11}$  and  $A_{12}$  and requiring  $A_{11}^2 + A_{12}^2 + A_{13}^2 = 1$ . The value of  $A_{13}$  is consistent with zero, and is significantly smaller than  $A_{11}$  and  $A_{12}$ .

At this point we could leave the determination of all other elements of the  $A$ -matrix to experiment. However, the smallness of  $A_{13}$  encourages us to consider a particularly simple form of  $A$ . If we assume that  $A_{13} = 0$ , we immediately obtain several interesting consequences:

(i) The only  $\Delta Q = -\Delta H$  term in the matrix  $A$  vanishes. This is analogous to the absence of  $\Delta Q = -\Delta S$  transitions, and is esthetic, if nothing else.

(ii) The weak rotation "mixes" the two light quarks  $d$  and  $s$ , but it does not "mix" the Heavy quark  $b$  with the light quarks.

(iii) The most general form of the matrix  $A$ , consistent with  $A_{13} = 0$  is

$$A = \begin{pmatrix} \cos \theta & -\sin \theta & 0 \\ \cos \phi \sin \theta & \cos \phi \cos \theta & -\sin \phi \\ \sin \phi \sin \theta & \sin \phi \cos \theta & \cos \phi \end{pmatrix}$$

where  $\theta$  and  $\phi$  are two weak rotation angles. This form of  $A$  can be factorized into:

$$A = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi & \cos \phi \end{pmatrix} \begin{pmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

Hence, the new weak rotation angle  $\phi$  mixes the Heavy quarks  $t$  and  $r$  but leaves  $u$  unmixed. This is analogous to the  $d$ - $s$  mixing introduced by the  $\theta$ -angle which leaves  $b$  unmixed.

We, therefore, see that the single choice  $A_{13} = 0$ , which is almost dictated by experiment, forces several consequences that are theoretically very appealing. It is, of course, possible that  $A_{13}$  is very small but does not exactly vanish. In such a case, statements (i), (ii), and (iii) above will be only approximately true. This could be the case if the weak mixing between the light and Heavy quarks is small (but nonvanishing) because of their large mass differences.

Assuming that the angles  $\theta$ ,  $\phi$  do not vanish, our matrix  $A$  is inconsistent with the  $O$ -scheme of Section 5. The  $O$ -scheme requires  $A_{13} = A_{21} = A_{32} = 0$  since these matrix elements do not correspond to generators of  $O(6)$ . It is clear that this is consistent only with  $\sin \theta = \sin \phi = 0$  or with  $\cos \theta = \cos \phi = 0$ . Both possibilities are experimentally unacceptable. However, in the limit of  $\theta, \phi \rightarrow 0$  our favorite solution for  $A$  is actually consistent with the  $O$ -scheme.

The  $U$ -scheme is clearly perfectly consistent with any choice of  $A$ , and we have already remarked that we prefer it.

In order to determine the leading weak transition we have to know the value of  $\phi$ . If  $\phi$  is small, the leading transitions are:

$$u \leftrightarrow d; \quad t \leftrightarrow s; \quad r \leftrightarrow b.$$

If  $\cos \phi < \sin \phi$ , the leading transitions are:

$$u \leftrightarrow d; \quad r \leftrightarrow s; \quad t \leftrightarrow b.$$

In both cases the only leading transition from a Heavy quark to a light quark produces an  $s$ -quark. This is, of course, qualitatively similar to the situation in the Charm scheme.

Note that if  $A_{13} = 0$ , the Heavy  $b$ -quark can decay weakly only to other Heavy quarks. Consequently, any meson or baryon containing a  $b$ -quark will have to decay first via a  $\Delta H = 0$  transition into another Heavy particle, which will then decay via  $\Delta H = \pm 1$  transitions into ordinary  $H = 0$  particles. This result does not hold if  $A_{13}$  is very small but nonvanishing. In that case, a  $\Delta H = \pm 1$  transition with a very small matrix element may be favored when compared with a  $\Delta H = 0$  transition that has a larger matrix element but significantly smaller phase space volume.

In order to discuss nonleptonic weak decays we have to make additional assumptions concerning the decay mechanism. In the absence of better alternative we will assume the conventional current-current interactions. It has been shown [23] that in the Charm scheme the current-current term has no component in the 15-dimensional adjoint representation of  $SU(4)$ . A similar situation occurs in our model. Our current-current Hamiltonian does not have a component in the

35-dimensional adjoint representation of  $SU(6)$ . In both cases, it is not clear how to implement the idea of  $SU(3)$ -octet enhancement, and we will not attempt to do so in the present paper. However, we will make full use of the current-current picture.

We are now ready to discuss the weak decays of the Heavy mesons and baryons. We devote the next two sections to these decays.

### 9. WEAK DECAYS AND EXPERIMENTAL SEARCHES OF HEAVY MESONS

The quark content of each nonet of  $H = 1$  mesons in the  $U$ -scheme is listed in Table I. We have already remarked that the lowest lying Heavy mesons are probably the vector or pseudoscalar states and that the dominant decays of each meson in the lowest lying nonet proceed via the weak interaction. Our choice of the weak currents in Section 8, as well as our assumption on the current-current nature of the nonleptonic decays, enables us to list the dominant decay modes of each of the nine mesons.

We find the following results:

- (i)  $(r\bar{d})^+$ : leptonic —  $l^+\nu(\Gamma \propto \sin^2 \theta \sin^2 \phi)$   
 semileptonic —  $\bar{K}^0 l^+\nu, (\bar{K}\pi)^0 l^+\nu, \bar{K}^0 \eta l^+\nu(\Gamma \propto \cos^2 \theta \sin^2 \phi)$   
 nonleptonic —  $\bar{K}^0 \pi^+, (\bar{K}\pi\pi)^+, \bar{K}^0 \pi^+ \eta, \bar{K}^0 \bar{K}^0 K^+(\Gamma \propto \cos^4 \theta \sin^2 \phi)$
- (ii)  $(r\bar{u})^0$ : semileptonic —  $K^- l^+\nu, (\bar{K}\pi)^- l^+\nu, K^- \eta l^+\nu(\Gamma \propto \cos^2 \theta \sin^2 \phi)$   
 nonleptonic —  $(\bar{K}\pi)^0, \bar{K}^0 \eta, (\bar{K}\pi\pi)^0, (\bar{K}\pi\eta)^0(\Gamma \propto \cos^4 \theta \sin^2 \phi)$
- (iii)  $(r\bar{s})^+$ : leptonic —  $l^+\nu(\Gamma \propto \cos^2 \theta \sin^2 \phi)$   
 semileptonic —  $(K\bar{K})^0 l^+\nu, \phi l^+\nu, \eta l^+\nu(\Gamma \propto \cos^2 \theta \sin^2 \phi)$   
 nonleptonic —  $\phi \pi^+, \eta \pi^+, \bar{K}^0 K^+, (\bar{K}K\pi)^+, \eta \pi^+ \pi^0(\Gamma \propto \cos^4 \theta \sin^2 \phi)$
- (iv)  $(t\bar{d})^+$ : same as  $(r\bar{d})^+$  — with  $\sin^2 \phi$  replaced by  $\cos^2 \phi$ .
- (v)  $(t\bar{u})^1$ : same as  $(r\bar{u})^0$  — with  $\sin^2 \phi$  replaced by  $\cos^2 \phi$ .
- (vi)  $(b\bar{d})^0$ : semileptonic —  $(r\bar{d})^+ + l^-\nu(\Gamma \propto \cos^2 \phi)$   
 $(t\bar{d})^+ + l^-\nu(\Gamma \propto \sin^2 \phi)$   
 nonleptonic —  $(r\bar{u})^0 + \pi^0, (r\bar{d})^+ + \pi^-(\Gamma \propto \cos^2 \theta \cos^2 \phi)$
- (vii)  $(b\bar{u})^-$ : semileptonic —  $(r\bar{u})^0 + l^-\nu(\Gamma \propto \cos^2 \phi)$   
 $(t\bar{u})^0 + l^-\nu(\Gamma \propto \sin^2 \phi)$   
 nonleptonic —  $(r\bar{u})^0 + \pi^-(\Gamma \propto \cos^2 \theta \cos^2 \phi)$
- (viii)  $(t\bar{s})^+$ : same as  $(r\bar{s})^+$ , with  $\sin^2 \phi$  replaced by  $\cos^2 \phi$ .
- (ix)  $(b\bar{s})^0$ : semileptonic —  $(r\bar{s})^+ + l^-\nu(\Gamma \propto \cos^2 \phi)$   
 $(t\bar{s})^+ + l^-\nu(\Gamma \propto \sin^2 \phi)$   
 nonleptonic —  $(r\bar{s})^+ + \pi^-(\Gamma \propto \cos^2 \theta \cos^2 \phi)$   
 $(r\bar{u})^0 + \pi^0, (r\bar{d})^+ + \pi^-(\Gamma \propto \sin^2 \theta \cos^2 \phi)$ .

Note that all Heavy mesons that contain a  $b$ -quark decay only into other Heavy mesons. This follows from our assumption in Section 7 concerning the vanishing of the  $\Delta Q = -\Delta H$  term  $A_{13}$ . However, if we assume that this term is small but nonvanishing, the  $b \rightarrow u$  transition will be allowed. In that case, we will have the additional decays:

$$\begin{aligned}
 (b\bar{d})^0 &\rightarrow \pi^+ l^- \nu, \pi^+ \pi^0 l^- \nu (\Gamma \propto \zeta^2) \\
 &\quad \pi^+ \pi^-, \pi^0 \pi^0, \pi^0 \eta, \pi^+ \pi^- \pi^0 (\Gamma \propto \zeta^2 \cos^2 \theta) \\
 (b\bar{u})^- &\rightarrow l^- \nu (\Gamma \propto \zeta^2) \\
 &\quad \pi^0 l^- \nu, (\pi\pi)^0 l^- \nu, \pi^0 \eta l^- \nu (\Gamma \propto \zeta^2) \\
 &\quad \pi^- \pi^0, (\pi\pi\pi)^-, (\pi\pi\eta)^- (\Gamma \propto \zeta^2 \cos^2 \theta) \\
 (b\bar{s})^0 &\rightarrow K^+ l^- \nu, (K\pi)^+ l^- \nu (\Gamma \propto \zeta^2) \\
 &\quad (K\pi)^0, (K\pi\pi)^0, (K\pi\eta)^0 (\Gamma \propto \zeta^2 \cos^2 \theta),
 \end{aligned}$$

where  $A_{13} = \zeta$ . These additional decay modes have smaller matrix elements but much larger phase space factors than the decay modes of the same states into Heavy mesons. For certain values of  $\zeta$  (say  $\zeta \sim 0.1$ ) they may be able to compete with the other decays.

At this point we must emphasize that our list of dominant nonleptonic decays is very strongly based on the assumed current-current form of these transitions. Any dynamical enhancement (similar to the  $SU(3)$ -octet enhancement) could turn otherwise inhibited decays into playing a dominant role. We have no real handle on this question.

The lifetimes of the lowest lying mesons can be estimated using the methods used in the Charm scheme [7]. For Heavy mesons containing  $t$  or  $r$  quarks, we expect  $\tau \sim 10^{-13}$  sec (within one order of magnitude). The Heavy mesons containing a  $b$ -quark will have a longer lifetime. Their lifetimes depend quite sensitively on the mass splittings  $\Delta$  within the Heavy quark triplet and on the values of  $\phi$  and  $A_{13} = \zeta$ . For  $\zeta = 0$ ,  $\Delta = 350$  MeV and small  $\phi$  we estimate  $\tau \sim 5 \times 10^{-12}$  sec for Heavy mesons containing a  $b$ -quark. Larger values of  $\epsilon$  and  $\Delta$  would give a shorter lifetime, while values of  $\phi$  near  $90^\circ$  would significantly increase  $\tau$ . One or more of these mesons may live long enough to leave a short detectable track in a bubble chamber.

The leading weak decay modes of the Heavy mesons in the  $O$ -scheme (Table II) can be found easily in a similar way. Since we have listed them previously [8] we do not repeat them here.

The  $H = 0$   $\psi$ -like mesons such as the four strange  $J^P = 1^- \psi$ -states at 3800 MeV and the pseudoscalar states  $\psi_\pi$  and  $\psi_\kappa$  will have only weak decays if they are below the threshold for two Heavy mesons. Their list of leptonic, semileptonic, and

TABLE II  
Heavy Mesons in the *O*-Scheme

Name	<i>SU</i> (3)	<i>I, Y</i>	Quark content	Mass
<i>P</i> <sup>-</sup>		(0, $\frac{4}{3}$ )	( <i>r</i> $\bar{s}$ ) <sup>+</sup>	<i>M</i> <sub>6</sub> + δ
<i>Q</i> <sub>6</sub> <sup>+</sup> , <i>Q</i> <sub>6</sub> <sup>0</sup>	$\bar{6}$	( $\frac{1}{2}$ , $\frac{1}{3}$ )	( <i>t</i> $\bar{s}$ - <i>r</i> $\bar{d}$ ) <sup>+</sup> , ( <i>b</i> $\bar{s}$ - <i>r</i> $\bar{u}$ ) <sup>0</sup>	<i>M</i> <sub>6</sub> + $\frac{1}{2}(\delta + \Delta)$
<i>R</i> <sub>1</sub> <sup>+</sup> , <i>R</i> <sub>1</sub> <sup>0</sup> , <i>R</i> <sub>1</sub> <sup>-</sup>		(1, - $\frac{2}{3}$ )	( <i>t</i> $\bar{d}$ ) <sup>+</sup> , ( <i>b</i> $\bar{d}$ - <i>t</i> $\bar{u}$ ) <sup>0</sup> , ( <i>b</i> $\bar{u}$ ) <sup>-</sup>	<i>M</i> <sub>6</sub> + Δ
<i>Q</i> <sub>3</sub> <sup>+</sup> , <i>Q</i> <sub>3</sub> <sup>0</sup>		( $\frac{1}{2}$ , $\frac{1}{3}$ )	( <i>t</i> $\bar{s}$ + <i>r</i> $\bar{d}$ ) <sup>+</sup> , ( <i>b</i> $\bar{s}$ + <i>r</i> $\bar{u}$ ) <sup>0</sup>	<i>M</i> <sub>3</sub> + $\frac{1}{2}(\delta + \Delta)$
<i>R</i> <sub>0</sub> <sup>0</sup>	3	(0, - $\frac{2}{3}$ )	( <i>b</i> $\bar{d}$ + <i>t</i> $\bar{u}$ ) <sup>0</sup>	<i>M</i> <sub>3</sub> + Δ

nonleptonic decay can be constructed easily. The semileptonic decays are into a Heavy meson, a lepton, and a neutrino. The nonleptonic decays are partly into one Heavy and one ordinary meson and partly only into ordinary mesons. The neutral, nonstrange  $\psi$ -like objects are the only ones who can have a (Zweig-rule suppressed) strong decay or an electromagnetic decay, below the threshold for Heavy meson pairs.

The experimental search for Heavy mesons, in principle, can be pursued in hadronic collisions as well as neutrino, photon, and electron initiated reactions. However, the best chance is offered by  $e^+e^-$  collisions where we believe that 60% of the cross section around  $W \gtrsim 5$  BeV are due to Heavy particles. The predicted inclusive properties such as the  $K/\pi$ ,  $e/\pi$ , or  $\mu/\pi$  ratios are predicted to be similar to those expected in the Charm scheme [7] and should be subject to the same ambiguities and doubts. This follows from the similarity between the lists of Heavy meson and Charm meson decay modes. The search for Heavy mesons as narrow peaks in invariant mass plots of particles in the final state of  $e^+e^-$  collisions is however, more difficult in the case of our model. The cross section  $\sigma(e^+e^- \rightarrow \text{Heavy mesons})$  is expected to be of the order of 10 nb at  $W = 4.8$  BeV. If we neglect baryon-antibaryon pairs, we find that each final state in these 10 nb must include a pair of mesons belonging to the lowest lying Heavy meson nonet. Approximately  $\frac{4}{9}$  of these ( $\sim 4.5$  nb) should include  $r\bar{r}$  pairs. A similar number should have a  $t\bar{t}$  pair and  $\frac{1}{9}$  of the events ( $\sim 1$  nb) should have a  $b\bar{b}$  pair. Thus, the *inclusive* cross section for producing any single Heavy meson (or its antiparticle) in the lowest lying nonet is at most around 3 nb, compared with 7 nb in the Charm case. In other words, the same number of events are divided among nine narrow Heavy states rather than three narrow Charmed states in the Charm case. For instance, the present upper limits [13] on the branching ratios of a Heavy meson decay into  $\bar{K}^0\pi^+$  or  $K^-\pi^+\pi^+$  are then of the order of 16-18% as compared with 7-8% for the Charm scheme.

The search for the charged  $\psi$ -like  $H = 0$  states could be conducted again in various different reactions. However, we believe that neutrino reactions offer the best possibility for these particles because of couplings such as  $\psi_\pi \rightarrow l\nu$ ,  $\psi_K \rightarrow l\nu$  which lead to the possibility of diffractive  $\psi_\pi$ ,  $\psi_K$  production in neutrino reactions.

At this point we cannot resist the temptation to comment that according to our model the dimuon events seen in the Fermilab neutrino experiment [24] could be due to the production of a Heavy meson (the same  $H = \pm 1$  states which are allegedly produced in  $e^+e^-$  collisions) or to the production of charged  $H = 0$   $\psi$ -like states that can also decay leptonically or semileptonically. The latter possibility does not exist in the Charm scheme.

## 10. THE HEAVY BARYONS

The lowest lying Heavy baryons presumably consist of one Heavy quark and two light quarks. They have  $H = +1$  and belong in the  $U$ -scheme to  $(6, \bar{3})$  and  $(\bar{3}, \bar{3})$  multiplets of  $SU(3)_L \otimes SU(3)_H$ . The quark content of the specific states can be worked out easily and their weak decays can be predicted using the same approach we applied to the Heavy mesons in the previous section.

For the sake of brevity we do not present here a detailed list of the low-lying Heavy baryons and their decays. Instead, we will make a few general remarks concerning these states.

(i) All  $H = 1$  Heavy baryons containing an  $r$  or a  $t$  quark presumably will decay mostly into  $H = 0$  baryons containing at least one  $s$ -quark. This follows from our form of the weak currents (Section 7) and the current-current interactions.

(ii) All Heavy baryons containing  $b$ -quarks can decay only into other Heavy baryons, if the coefficient of  $u\bar{b}$  in the charged weak current vanishes ( $A_{13} \equiv \zeta = 0$ ). The lifetimes of such baryons are expected to be around  $10^{-11} - 10^{-12}$  sec, and it may happen that one or more of them will live long enough to leave a detectable short track in a bubble chamber.

(iii) The lightest  $H = 1$  baryons will be an isotriplet  $(uur)^{++}$ ,  $((1/2^{1/2})[udr + dur])^+$ ,  $(ddr)^0$  and an isosinglet  $((1/2^{1/2})[udr - dur])^+$ . Their leading nonleptonic decays are expected to be:

$$\begin{aligned} (uur)^{++} &\rightarrow \Sigma^+ \pi^+, \Lambda \pi^+ \pi^+, (\Sigma \pi \pi)^{++}, \text{ etc.} \\ (udr \pm dur)^+ &\rightarrow (\Sigma \pi)^+, \Lambda \pi^+, (\Lambda \pi \pi)^+, \text{ etc.} \\ (ddr)^0 &\rightarrow (\Sigma \pi)^0, \Lambda \pi^0, \Lambda(\pi \pi)^0, \text{ etc.} \end{aligned}$$

The mysterious event found in the Brookhaven neutrino experiment [25] can be interpreted in our model in the same way as in the Charm scheme.

(iv) The masses of the lowest lying Heavy baryons are expected to be somewhere around 2–2.5 BeV. This estimate is based on the mass difference between Heavy and light quarks as deduced from the meson mass pattern. Note that  $e^+e^-$  collisions around 4.5–5 BeV are likely to produce pairs of Heavy baryons. Consequently, the inclusive cross section for  $e^+e^- \rightarrow (H = \pm 1 \text{ meson}) + \text{anything}$  may be smaller than our estimate in Section 9.

The baryon spectrum in the  $O$ -scheme is somewhat different than in the  $U$ -scheme but we will not discuss it here in detail.

## 11. SUMMARY AND COMPARISON WITH THE CHARM SCHEME

Theoretical studies and experimental tests of our model should always make a clear distinction between predictions and consequences that are common to all models involving additional quarks and results that are specific to our own model.

The existence of new mesons and baryons around or above a mass of 2 BeV, the abundant production of such mesons in  $e^+e^-$  collisions above  $W \sim 4$  BeV, the Zweig rule “explanation” of the narrow widths of  $\psi$  and  $\psi'$ , the prediction that  $\psi'$  decays strongly into pairs of new mesons and is therefore wide, the predicted pseudoscalar  $\psi$ -like mesons, the predicted radiative transition between the  $J^P = 1^-$  and  $J^P = 0^-$   $\psi$ -like states—all of these are common qualitative features of the general class of models involving new quarks in addition to the “conventional”  $u, d, s$ .

The present major difficulties of this class of models are shared by the Charm scheme, by our model and by any other model involving new quarks. The two most important difficulties deserve special considerations:

(i) Searches for new Charmed or Heavy mesons have failed so far. The failure is particularly disturbing in  $e^+e^-$  collisions where a large fraction of the total hadronic final states must include such mesons if the new theories are correct. The absence of a clear change in the  $K/\pi$  ratio in the final states below and above the new threshold [6, 9] is equally embarrassing to us and to the Charm model. The only way out of this difficulty in both models is to reconsider the simple assumptions concerning the current–current interaction for nonleptonic decays. The absence of peaks in the invariant mass plots of  $K^0\pi^\pm$ ,  $K^\mp\pi^\pm\pi^\pm$ ,  $K^\mp\pi^\pm$ , etc. is a grave difficulty to the Charm scheme. In our model such peaks are expected to be significantly smaller, and any reasonable estimate is perfectly consistent with the present upper limits (see Section 9). Should the absence of such peaks persist with much improved statistics (say, five times the present number of events), our model would run into difficulties similar to those faced today by the Charm scheme.

(ii) The absence of an observed radiative transition  $\psi' \rightarrow \gamma + \psi_{0-}$  is difficult to understand in all models involving new quarks. In that respect, however, the Charm scheme enjoys an advantage over our model. Since the  $\psi'$  is a radially excited  $c\bar{c}$  state in the Charm model, its wave function may be such that the transition  $2^3S \rightarrow 1^1S$  is suppressed [11]. Our model does not enjoy such a suppression.

It is extremely important to try to improve the reliability of the various theoretical estimates on the absolute rates of the various radiative transitions among the  $\psi$ -like particles, since these transitions are becoming a crucial issue in various models.

We consider the absence of the decay  $\psi' \rightarrow \gamma + \psi_{0-}$  to be the one and only serious difficulty of our model at the present time.

We now proceed to discuss tests that directly confront our model with the Charm model. It is clear that the detailed spectroscopies of the two models are completely different. They provide us with numerous tests, many of which would be sufficient to distinguish between the two models. However, since no Charmed or Heavy mesons have been discovered so far, it is pointless to repeat here the many predictions made in Sections 7, 9, and 10.

At least two major difficulties of the Charm scheme are not shared by our model:

(i) We have  $R = 5$  while Charm predicts  $R = 3\frac{1}{3}$ . We consider this to be an extremely important point, in view of the constancy or, possibly, slight rise of  $R$  up to  $W = 6.8$  BeV [6].

(ii) The Charm scheme predicts the  $J^{PC} = 0^{++}, 1^{++}, 2^{++}$  levels between  $\psi$  and  $\psi'$  and the relatively strong radiative decays of  $\psi'$  into these levels. We do not predict any such states below 4 BeV, since we do not invoke radial excitations for the  $\psi'$  and  $\psi''$ . The present upper limits [12] on these radiative decays are sufficiently low to cause grave doubts on the validity of the Charm idea.

Other points of comparison between our model and the Charm model are related to matters of elegance and taste rather than to experimental facts. They include the following:

(a) Both schemes naturally eliminate  $|\Delta S| = 1$  neutral currents. Charm does it in the most economic way possible using two pairs of quarks. Our model presumably uses the second most economic way, using three pairs.

(b) We have a natural explanation for the existence of three neutral  $\psi$ -particles. The Charm scheme has to invoke radial excitations which could yield any number of such states. We also predict the relative decay widths of the  $\psi$ -states into lepton pairs.

(c) The Charm scheme has four quarks and four leptons. We have six quarks. We may achieve a similar quark-lepton symmetry by proposing a new



charged heavy lepton and its neutrino. In fact, such a six-lepton scheme is necessary if we wish to preserve the condition

$$\sum_{\text{quarks}} Q_i + \sum_{\text{leptons}} Q_i = 0.$$

This condition is required [26] in a unified theory of quarks and leptons if we want to eliminate the asymptotic contribution of the triangular anomaly diagrams which occur in triple-current vertices (such as two vectors and an axial vector).

If these additional heavy leptons exist, we will eventually have  $R = 6$ . Experimentally, it is entirely possible that pairs of leptons are produced somewhere above  $W \sim 3.5\text{--}4.5$  BeV, and are partly responsible for the rise in  $R$ . We do not feel, however, that our new quark model necessarily implies such additional leptons.

(d) If we take seriously the asymptotically free gauge theory of quarks and colored gluons, we might be able to compute the octet-singlet mixing of the two isoscalar  $\psi$ -particles. The simplest calculation would predict  $\psi$ -states that are "pure"  $q\bar{q}$  states (like  $\phi$ ,  $\omega$ ) rather than "pure"  $SU(3)$  states (like our assignment of  $\psi$ ,  $\psi'$ ). However, both the dominant  $\psi' \rightarrow \psi\pi\pi$  decay and the  $e^+e^-$  widths preclude such a choice (see Section 4). This point deserves further theoretical investigation.

Our overall feeling is that the present model is capable of describing the new phenomena at least as well as any other existing model, including the Charm scheme. However, several important questions remain. Most important among them is the failure to observe the Heavy meson pairs in  $e^+e^-$  collisions and the pseudoscalar  $\psi$ -like state around 3 BeV. Whether these particles exist only time will tell.

*Note added in proof.* In July and August 1975 two important discoveries have changed the experimental and theoretical situation. The first is the discovery of  $C = \pm 1$  intermediate states between  $\psi$  and  $\psi'$ . The second is the discovery of  $e^\pm\mu^\pm$  events at SPEAR, which may reflect the existence of a heavy lepton. The  $C = +1$  states seem to favour the assignment of  $\psi'$  as a radially excited state, as in the Charm scheme. However, the possible new lepton and its associated neutrino provide us with a total of six leptons. Simple quark-lepton analogy as well as the absence of anomalies then lead to a six-quark scheme of the type presented in this paper, with the weak interactions and the meson spectrum discussed here, but with different assignments for the  $\psi$ -particles. For a more complete discussion see H. Harari, Rapporteur talk at the International Symposium on Lepton and Photon Interactions at High Energies, Stanford, 1975 (Weizmann Institute preprint WIS-75/40 Ph).

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