A NEW QUARK MODEL FOR HADRONS ☆

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We propose a new quark model for the hadron spectrum. It consists of six quarks — the usual triplet and a new antitriplet of heavy quarks, with electric charges $+2/3$, $+2/3$, $-1/3$. The ψ particles are bound states of heavy $q\bar{q}$ pairs. Among many other predictions we find that $R = 5$ in e^+e^- scattering and $\Gamma(\psi \to e^+e^-) : \Gamma(\psi' \to e^+e^-) = 2 : 1$. The model naturally forbids neutral $|\Delta S| = 1$ weak currents and predicts a spectrum of heavy mesons and baryons.

The discovery of the new particles [1] ψ and ψ' and the realization [2] that the quantity $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ goes through an apparent new threshold around $\sqrt{s} \sim 4$ GeV necessitate a reevaluation of our ideas of hadron spectroscopy. The charm scheme [3] accommodates some features of the new observations, while many of its predicted states remain undiscovered. Various other ideas including several models involving color [4] as an unconfined quantum number, are already in some difficulty [5].

In this paper we propose a new model for the spectrum of hadrons. Our model differs from all previous schemes known to us, but it incorporates some of the ideas of the charm and color schemes. It does not lead to any conflict with present data and it yields a large number of testable predictions.

We propose that the building blocks of hadronic states are six quarks: the usual SU(3) triplet (u, d, s) and new SU(3) *antitriplet* of heavy quarks. The antitriplet includes an isodoublet (t, b) with electric charges $(2/3, -1/3)$ and an isosinglet r with charge $+2/3$ (fig. 1). Note that of the six quarks, three (u, t, r) have $Q = +2/3$ and three (d, s, b) have $Q = -1/3$. The heavy quarks possess a new additive quantum number which we name *heaviness*. They have $H = 1$, while the usual quarks have $H = 0$. The six antiquarks clearly form an $H = 0$ SU(3) antitriplet and an $H = -1$ SU(3) triplet. We further assume that all six quarks come in the usual three "colors" [6], but no "colored" hadrons exist.

The first immediate result of this scheme is that below the threshold for the production of heavy mesons, $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-) = 2$, *while above this threshold* $R = 5$. This is clearly in good agreement with the data [2], provided that heavy mesons are produced above $\sqrt{s} \sim 4$ GeV.

The meson spectrum involves 36 states for each J^P-value: (i) the usual octet and singlet of ordinary $H = 0$ mesons; (ii) nine $H = 1$ heavy mesons (in $\bar{6}$ and 3 multiplets of SU(3); fig. 2) and nine $H = -1$ mesons (in 6 and $\bar{3}$); (iii) an octet and singlet of $H = 0$ mesons which are bound states of a heavy quark and a heavy antiquark. Among these last states, only three are predicted to couple directly to the photon — the three neutral, nonstrange, vector mesons. We will identify $\psi(3100)$ as the SU(3) singlet, $\psi'(3700)$ as the $I = 0$ member of an octet, and the wide bump [2] at 4100 MeV (which we denote by ψ'') as the $I = 1$ member of the same octet. Hence:
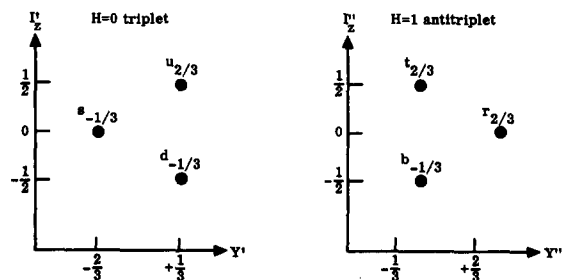

Fig. 1. The ordinary u(up), d(down), s(singlet) quarks and the proposed heavy t(top), b(bottom), r(right) quarks.
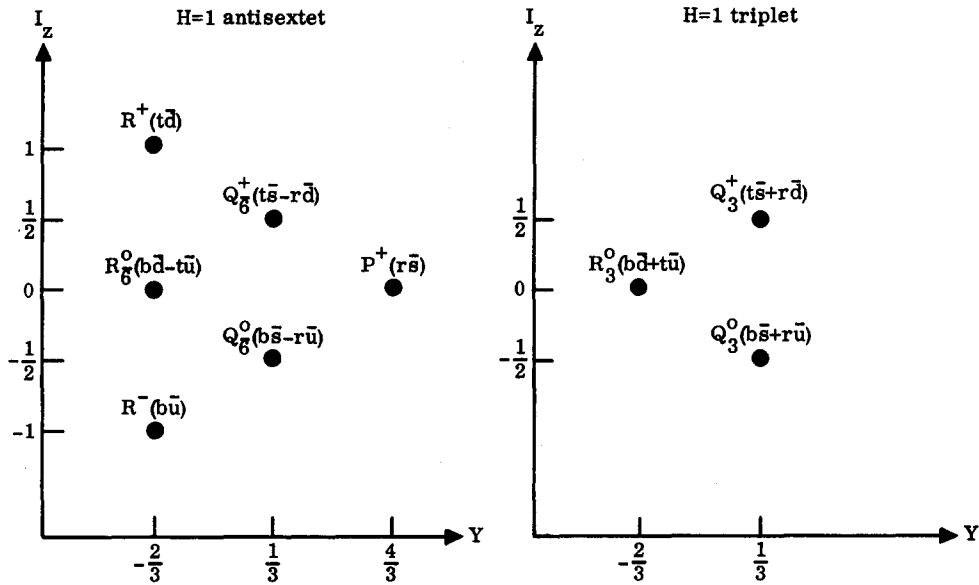
Fig. 2. The predicted $H = 1$ heavy mesons and their quark content.

$$\psi = \frac{1}{\sqrt{3}}(t\bar{t} + b\bar{b} + r\bar{r}); \quad \psi' = \frac{1}{\sqrt{6}}(t\bar{t} + b\bar{b} - 2r\bar{r});$$

$$\psi'' = \frac{1}{\sqrt{2}}(t\bar{t} - b\bar{b}).$$

This identification immediately leads to the following predictions:

(i) $\Gamma(\psi \to e^+e^-) : \Gamma(\psi' \to e^+e^-) : \Gamma(\psi'' \to e^+e^-) = 2 : 1 : 3$. The corresponding experimental values for ψ and ψ' are respectively [7] 5.2 and 2.2 keV. The $\psi'' \to e^+e^-$ width is estimated [2] to be 4 keV, but it will be accurately known only when the precise shape of the ψ'' bump is studied experimentally.

(ii) The $K\bar{K}$, $K^*\bar{K}^*$ decays of ψ (but not ψ') are SU(3)-forbidden [5].

(iii) The decay $\psi' \to \psi \eta$ is allowed (it is SU(3)-forbidden in the charm scheme). $\psi' \to \psi \pi^+ \pi^-$ is, of course, also allowed.

The relative masses of ψ' and ψ'', who reside in the *same* octet, enable us to estimate the mass differences among the heavy quarks. Isospin conservation gives $m(t) = m(b)$. Using a linear mass relation between meson and quark masses we find:

$$m(t) - m(r) = \frac{3}{4}\left[m(\psi'') - m(\psi')\right] \sim 350 \text{ MeV}.$$

Hence, the isosinglet quark r is the lightest of the three

heavy quarks! This is consistent with the empirical fact that larger hypercharge always corresponds to lower mass, for quarks (or baryons).

We predict ψ''^+ and ψ''^- states around 4100 MeV, completing the $I = 1$ ψ'' multiplet. We also predict four strange ψ-particles around 3800 MeV with quantum numbers identical to those of K^* and $\bar{K}^*$. We predict a nonet of pseudoscalar bound states of heavy quarks and antiquarks somewhere near the 3–4 GeV region. The electromagnetic transitions between ψ, ψ' and the three $I_Z = Y = 0$ pseudoscalars are allowed, and *should eventually be seen if one or more of these pseudoscalars are below the ψ'-mass.*

All p-wave ψ-like $q\bar{q}$ states are presumably above 4100 MeV. Consequently, *we predict that the 0^{++}, 1^{++} and 2^{++} narrow mesons, predicted by the charm scheme [3] to lie between ψ and ψ', are not there.* Note that in our model, ψ, ψ' and ψ'' are 1^3S states. Radially excited mesons are much higher, and are very wide.

The lowest lying heavy mesons ($H = \pm 1$) are presumably the 0^- or 1^- states. Using $m(t) - m(r) \sim 350$ MeV, $m(s) - m(u) \sim 130$ MeV (from the ρ, ω and ϕ masses) we *guess* that the lowest lying heavy meson is the $r\bar{s}$, $I = 0$ state P^+ (fig. 2). The mass differences

within the SU(3) sextet or triplet of heavy mesons should then be around 100–150 MeV per unit of hypercharge. An inspection of the experimental values of R as a function of energy [2] indicates that the rise in R may actually begin somewhat below the ψ' mass. It is then possible that $m(P^+) \sim 1800$ MeV and R begins to rise at the P^+P^- threshold. In this case, ψ' may have an ordinary strong decay mode $\psi' \to P^+P^-$. The width for this decay is severely inhibited by the tiny phase space volume which is extremely sensitive to the precise value of $[m(\psi') - 2m(P^+)]$. If $m(P^+)$ is indeed around 1800 MeV, it is entirely possible that all nine heavy mesons are below 2050 MeV, in which case the ψ'' is above threshold for many different strong decay modes into pairs of heavy mesons (+ pions, etc.). The above speculations are somewhat modified if we use quadratic mass relations.

The *lowest lying* heavy ($H = \pm 1$) mesons are presumably stable against strong and electromagnetic decays. They would have only weak decays, the nature of which depends on the properties of the weak currents in our scheme. We therefore now turn to the weak currents.

We first construct the charged weak current. We assume that it has the usual space-time properties (V-A). Its most general dependence on the quark quantum numbers can be expressed as:

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

Note that u, t, r have $Q = +2/3$, while d, s, b have $Q = -1/3$. We now *postulate* that the matrix A is an *orthogonal* matrix. *This immediately leads to the absence of $|\Delta S|$ and $|\Delta H| = 1$ neutral currents.* The proof is a simple extension of the ideas of the charm scheme [3]. We define:

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

Consequently, $J^+ = u\,\overline{d}' + t\overline{s}' + r\overline{b}'$. Assuming that the neutral weak current forms a vector of the "weak isospin" together with J^+ and J^-, we find: $J^0 = (u\overline{u} + t\overline{t} + r\overline{r}) - (d'\overline{d}' + s'\overline{s}' + b'\overline{b}')$. However, the orthogonality of A guarantees: $(d'\overline{d}' + s'\overline{s}' + b'\overline{b}') =$

$(d\overline{d} + s\overline{s} + b\overline{b})$ and all $|\Delta S| = 1$, $|\Delta H| = 1$ *neutral* currents are absent. At this stage we still have complete freedom in our choice of the orthogonal matrix A. Since it can be characterized by three rotation angles, we have three parameters — one of which is the Cabibbo angle. *It is possible that some additional symmetry assumption may lead to a determination of one or more of these angles,* but regardless of the choice, the neutral currents have the desired form.

One possible choice of the matrix A which we find attractive (but by no means compulsory) is to assume that the weak mixing of heavy and light quarks is negligible. The only mixing will therefore be between d and s (for $Q = -1/3$) and between t and r (for $Q = +2/3$). If we denote the mixing angles by θ (the Cabibbo angle) and ϕ, respectively, we find:

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

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

This particular form of the matrix A automatically leads to a $\Delta H = \Delta Q$ rule for semileptonic heaviness-changing decays. The single vanishing matrix element in A is the $\Delta H = -\Delta Q$ term.

We know that $\theta \sim 15°$. Assuming that ϕ is also small, we find that the three diagonal matrix elements are close to one, while all other matrix elements are much smaller. The *leading* charged weak transitions are therefore: u ↔ d, t ↔ s, r ↔ b.

Having decided on the form of the weak currents, we may now proceed to study the decay modes of the heavy mesons. A detailed study of these decays involves many possible alternatives and will be discussed elsewhere. However, assuming the current-current interaction for nonleptonic decays, and neglecting all branching fractions which are inhibited by $\tan^2\theta$ or $\tan^2\phi$ factors, we find the following major decay modes for the nine heavy mesons:

(i) *P^+ decays:* Leptonic $-\ell^+\nu$; semileptonic $-\phi\ell^+\nu$, $K^+K^-\ell^+\nu$, $K^0\overline{K}^0\ell^+\nu$, etc.; nonleptonic $-\pi^+\eta$, $K^+\overline{K}^0$, $\pi^+\pi^+\pi^-$, $\pi^+\pi^0\pi^0$, $\pi^+\pi^0\eta$, etc. All of these rates include a factor of $\sin^2\phi$.

(ii) *Q^+ decays:* For each of the *two* Q^+ particles

(in the $\bar{6}$ and 3 multiplets), the list of leading weak decay modes is identical to the above list for P^+. In this case, none of the rates contain $\sin^2\theta$ or $\sin^2\phi$ factors, but their *relative* strengths may be similar to those of P^+. The heavier Q^+ can decay into the lighter Q^+ by emitting a photon. This would presumably be its dominant decay mode. This radiative decay is forbidden by U-spin, if the Q particles are pure SU(3) states, but any SU(3) mixing will allow it.

(iii) Q^0 *decays:* For each of the two Q^0 particles, we have the following leading modes: semileptonic — $K^-\ell^+\nu$, $K^-\pi^0\ell^+\nu$, $\bar{K}^0\pi^-\ell^+\nu$, etc.; nonleptonic — $\bar{K}^0\pi^0$, $K^-\pi^+$, $K^0\eta$, $K^-\pi^+\pi^0$, $K^-\pi^+\eta$, $\bar{K}^0\pi^+\pi^-$, $\bar{K}^0\pi^0\pi^0$, etc. All rates contain $\sin^2\theta$ or $\sin^2\phi$ factors. Again, the heavier Q^0 can decay radiatively into the lighter Q^0.

Both Q^+ and Q^0 may decay nonleptonically into $P^+ + \pi$, provided that $m(Q) > m(P) + m(\pi)$.

(iv) R^+ *decays:* Semileptonic — $\bar{K}^0\ell^+\nu$, $\bar{K}^0\pi^0\ell^+\nu$, $K^-\pi^+\ell^+\nu$, etc.; nonleptonic — $\bar{K}^0\pi^+$, $K^-\pi^+\pi^+$, $\bar{K}^0\pi^+\pi^0$, $\bar{K}^0\pi^+\eta$, etc. These decays do not contain $\sin^2\theta$ or $\sin^2\phi$ factors.

(v) R^0 *decays:* For each of the two R^0 particles we have the same decays as for the two Q^0 particles, including the radiative transition between the two R^0 states. All weak R^0-decays contain $\sin^2\theta$ or $\sin^2\phi$ factors, but the branching ratios should not depend on these overall factors.

(vi) R^- *cannot decay* into $H = 0$ mesons. Its leading decays would be into $R^0 + \ell^- + \bar{\nu}$ (inhibited by $\sin^2\phi$ or $\sin^2\theta$). R^- is likely to have the longest lifetime among the heavy mesons.

All R-mesons can decay nonleptonically into $Q + \pi$ or $P + \bar{K}$, provided that such decays are energetically possible. The R^--meson may live long enough to leave a detectable track in a bubble chamber.

We emphasize that the above list of decay modes is based on assumptions which are not *necessary* consequences of our model. Such assumptions include the current-current picture of nonleptonic decays and our special selection of the matrix A. Several other variations are possible, and will be discussed elsewhere together with an analysis of the heavy baryons and their decays.

The heavy mesons are most likely to be discovered in e^+e^- collisions or in neutrino reactions. Their overall inclusive properties (K/π ratios, μ/π ratios) are similar to those of the predicted new mesons in the charm

scheme. However, their discovery as peaks in invariant mass plots of final charged particles in e^+e^- collisions may be more difficult than in the case of charm, largely because of the smaller production cross section of *each* such peak. (The same σ_{tot} is shared among nine heavy mesons rather than three charmed mesons.) A detailed analysis of this point will be presented elsewhere.

The overall symmetry of our model is a U(6) algebra whose operators correspond to the 36 $q\bar{q}$ combinations. A subalgebra of this is
SU(3)$_L$ $\otimes$ SU(3)$_H$ $\otimes$ U(1) $\otimes$ U(1) where SU(3)$_L$ and SU(3)$_H$ are, respectively, the algebras of operators connecting the light quarks to each other and the heavy quarks to each other. The two U(1) groups represent baryon number and heaviness. The electric charge obeys: $Q = \frac{1}{2}(Y_L + Y_H) + (I_L^Z + I_H^Z) + \frac{1}{3}H$. The usual SU(3) is the diagonal SU(3) algebra of SU(3)$_L$ $\otimes$ SU(3)$_H$. At this point we have two possible variations:

(i) SU(3)$_L$ and SU(3)$_H$, as well as their subsymmetries (e.g., I_L, I_H) are broken. In this case a u$\bar{d}$ state and a t$\bar{b}$ state can mix, since they have the same quantum numbers (except for I_L, I_H). The $H = 0$ physical states would then be mixtures of u$\bar{d}$ and t$\bar{b}$. Thus π^+ will contain a tiny mixture of t$\bar{b}$ while ψ will have a tiny (u$\bar{u}$ + d$\bar{d}$ + s$\bar{s}$) piece. If the typical mixing is of order ϵ, decay amplitudes such as $\psi \to$ hadrons, $\psi' \to$ hadrons, $\psi' \to \psi\pi\pi$, $\psi' \to \psi\eta$ are of order ϵ. Other decay modes of the same order (if they are energetically allowed) will be $\psi' \to K\psi_K$, $\psi' \to \rho\psi_\pi$, etc. where ψ_K, ψ_π are bound states of heavy quarks and antiquarks with K, π quantum numbers. Each such decay could account for a few percent of the ψ' decays. The decays $\psi_\pi \to \pi\pi\pi$, $\psi_K \to K\pi\pi$ will also be of order ϵ.

(ii) Alternatively, we may assume that mixing of different $q\bar{q}$ combinations can take place only through the colored gluons which presumably have $I_L = I_H = 0$. In such a case, we are forced into an exact I_L and I_H conservation in strong interactions. The decay $\psi \to$ hadron will proceed through the three-gluon state. The decays $\psi' \to$ hadron, $\psi' \to \psi\pi\pi$, $\psi' \to \psi\eta$ will proceed through the component of the three-gluons or two-gluon state which is in SU(3)-octet (such a component presumably exists since SU(3) is only an approximate symmetry). The mixing of u$\bar{d}$ and t$\bar{b}$, as well as the decay rates $\psi' \to K\psi_K$,

$\psi' \to \rho\psi_\pi$, $\psi_\pi \to \pi\pi\pi$, $\psi_K \to K\pi\pi$, will then originate from the weak interactions and will be much smaller than in our first alternative.

These two possibilities are equally interesting, and they are experimentally distinguishable.

We believe that our model is sufficiently attractive to justify further experimental and theoretical studies of its features. Whether it will survive future experimental tests, only time will tell.

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