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# HADRON SPECTROSCOPY AND THE NEW PARTICLES*

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## I. INTRODUCTION: THE QUARK MODEL

Hadron spectroscopy would be of interest to physicists if only because the manner of organization of matter falls within the definition of the subject of physics. More specifically, with hundreds of hadronic states it behooves us to find some order and degree of understanding of what is known to exist and to be able to predict particles yet to be found.

However, present interest in hadron spectroscopy stems largely from a different source: the large body of evidence, spectroscopic and otherwise, for hadron substructure and in particular for a quark basis of hadronic matter. In many ways the focus of particle physics has shifted down to the quarks and leptons as the primary components of matter and hence of spectroscopy. Even though hadrons are then a secondary spectroscopy, it is only through a study of them that we learn the properties of the quarks (at least in the absence of free quarks). Moreover, the dynamics between quarks can only be studied by the spectroscopy and interactions of hadrons. We still have much to learn about these quark-quark forces: how quark confinement comes about, the nature of the force law, the spin dependent forces etc., etc.

### Quarks

We have already cited the fact that much points to quarks as the building blocks of hadrons. Let us review briefly some of the evidence:

(1) Deep Inelastic eN, $\mu$N, $\nu$N, and $\bar{\nu}$N Scattering.

The magnitude of the cross section, scaling behavior, and the relationship of structure functions observed in deep inelastic scattering indicate that the nucleon has point, spin 1/2 constituents with which the weak or electromagnetic current interacts.[1] Further, the amount of scattering depends on whether the target is a neutron or proton and on the spin orientation of the proton,[2] so that the constituents which are related to the nucleons isospin or spin are also what is "seen" by the weak or electromagnetic currents.

(2) Electron-Positron Annihilation

The ratio R of the cross section for $e^+e^- \rightarrow$ hadrons to that for $e^+e^- \rightarrow \mu^+\mu^-$ is a (different) constant both below and above charm threshold, as it should be if the basic process were production of a pair of point particles, followed by their eventual materialization as hadrons.[3] In fact the part of R due to charmed meson production at SPEAR agrees with what is expected from the basic process of production of a pair of charmed quarks.[4] Furthermore, the observation of back-to-back jets at SPEAR yields the additional information that their angular distribution is that characteristic of production of a pair of spin 1/2 particles.[3]

(3) Hadron Spectroscopy

With a few possible exceptions,[5] the hundreds of hadrons we now know are understood as quark-antiquark bound states (mesons) or three quark bound states (baryons). An enormous simplification has taken place and is part of the standard "lore". Now one often forgets that something as basic as the ordering of spins and parities of states ($0^-$, $1^-$ as lowest mass mesons and $1/2^+$, $3/2^+$ as lowest mass baryons) is trivially understood in the quark model but is otherwise quite mysterious.

(4) Weak and Electromagnetic Current Matrix Elements

The quark model gives us a quantitative understanding of both the magnetic moments and magnetic transition moments between the ground state baryons, as we will see in detail later. When formulated in the general framework of the transformation from current to constitutent quarks,[6] one can discuss the photon transition amplitudes from the nucleon to excited nucleon resonances. When a few reduced matrix elements are fixed in terms of known amplitudes, one gets correct predictions for the signs and magnitudes of a fair number of other amplitudes.[7] Further, if one is willing to use PCAC to relate matrix elements of the axial-vector current to pion amplitudes, then a similar theory of pionic transitions ensues. Again the signs and magnitudes of many amplitudes are correctly given.[7] It would seem very unlikely that all this is an accident.

(5) High Transverse Momentum Phenomena

It seems very likely that high transverse momentum hadron production in hadron-hadron collisions has its origin in "hard scattering" of constitutents of the hadrons.[8] The connection to quarks is much less direct, and certainly not unique, when compared to (1)-(4) above. But the similarities to hadron production in deep inelastic scattering and electron-positron annihilation, especially the production of jets in each case, are quite striking. Although it is much harder to get precision information on quarks in this case, this is an important area of research exactly because it may give us information on quark dynamics in a different setting.[9]

Color

Quarks are thought to carry a strong interaction "charge" called color. There are three such colors, which we take as red, yellow, and blue. Present experimental evidence for the need for color comes from three sources:

(1) The rate for $\pi^0 \rightarrow \gamma\gamma$.

The amplitude for $\pi^0 \rightarrow \gamma\gamma$, when related to that for $\partial_\mu A_\mu \rightarrow \gamma\gamma$ by PCAC, has a magnitude and sign given by the triangle graph (with a closed fermion loop) anomaly[10] in the coupling of two vector currents to an axial-vector current. Without color, one gets the wrong rate. With it, the amplitude is increased by a factor of three and the rate by a factor 9 and then agrees with experiment.[11]

(2) The ratio $R = \sigma(e^8 e^- \to \text{hadrons}) / \sigma(e^+ e^- \to \mu^+ \mu^-)$.

Color increases the predicted cross section (on the basis of the quark model) by a factor of three. This is needed to get even rough agreement with experiment both below and above charm threshold.[3]

(3) The Baryon Wave Function

The wave function for fermions should be totally antisymmetric. If the three quarks in a baryon are a singlet with respect to color (see below), the color part of the wave function is antisymmetric. Thus the remainder (spin, space and quark type or flavor) must be symmetric. This is indeed the case from the experimental spectrum and in particular is true for the ground state, which has a symmetrical spatial wave function combined with one symmetrical in spin and flavor.

Each of these experimental pieces of evidence for color needs some theoretical analysis to deduce the appropriateness of the concept of color, but they only involve "counting" the color quantum numbers. There are other, non-experimental, reasons for color, which have a much less solid basis in concrete facts. They all involve using color as a non-Abelian charge in a gauge field theory context. Nevertheless, they are important and have much to do with the overwhelming acceptance of the idea that colored quarks and gluons are the basis of all strong interactions.

(1) Quantum Chromodynamics (QCD).

The theory of quarks coupled via the color "charge" to gauge vector bosons (gluons) is often referred to as QCD. It is a non-trivial point that QCD is the only known field theory (and a non-Abelian gauge theory at that) which has a chance of being the correct one for strong interactions.

(2) Asymptotic Freedom

A non-Abelian gauge theory like QCD has the property of asymptotic freedom:[12] the effective coupling constant vanishes logarithmically at small distances, i.e.

at large four momentum squared. This allows one to "understand" the scaling behavior[1] (characteristic of free field theory) observed in deep inelastic scattering. Even more, the theory predicts that scaling is not exact and the (small) predicted logarithmic breaking is consistent with what is seen in recent experiments.[1]

(3) Infrared Slavery

The increase in the coupling constant as one goes to larger distances inspires the hope that the color forces become infinite and quarks (and other objects with color) are confined. Up to now this has not been shown rigorously, but there are some suggestive model calculations of how it might come about.[13]

(4) Okubo-Zweig-Iizuka[14] Rule Violation

Certain strong interaction decays where none of the final hadrons contain the quarks of the initial hadron, are very much suppressed in rate. This is particularly well exemplified in the case of the "new" particles. A theory of these processes involving intermediate gluons leads to a systematics of mass and spin-parity dependence of the degree of suppression[15] which we will discuss later in these lectures.

(5) Spin-Dependent Quark-Quark Forces

Such forces result in hadron states with the same quark content but different relative spin orientations being split in mass. From the experimental observations it seems that the force between quark and quark in a baryon must have the same sign as between quark and antiquark in a meson. Exchange of a neutral vector meson without color does not yield such a result, but exchange of gluons coupled to color does if within color singlet mesons and baryons.[16] While single gluon exchange does not have to be the origin of all such forces, it still is to be desired that the lowest order effect have at least the right sign.

(5) Dynamical Gluons

Sum rules for deep inelastic scattering indicate that quarks do not carry all the momentum or energy of the nucleon.[1] If the remainder is assigned to the gluons they should manifest themselves in a variety of ways by interacting with quarks and other gluons to produce hadrons in hadron-hadron collisions, to produce gluon jets in $e^+e^-$ collisions,[17] etc.

## Confinement

As we have already indicated above in our discussion of "infrared slavery," color is central to another aspect of quarks, that of confinement. We will take as a principle, perhaps derivable at a later time from QCD, that color is confined, i.e. only color singlet states can be seen. Then both quarks and gluons are not found among the asymptotic states of the theory. Bound states which are colorless can be and are seen: they are the hadrons.

The form of the effective color confining potential is not known for sure. Some arguments[13] in QCD and the string model suggest that the effective potential is linear, $V(r) = kr$, so that the force, $-dV/dr = -k$ is a constant. It then takes infinite energy to move a quark infinitely far away, as expected for a confining potential. Estimates of the force, k, principally from fitting charmonium spectroscopy[18] suggest that $k \approx 0.2\ \text{GeV}^2$ = 17 metric tons × (the acceleration of gravity).

## Flavor

In addition to carrying color, quarks are distinguished from one another by their "flavor". At present we know of four flavors for quarks: up, down, strange and charm. A fifth flavor (at least) is strongly suspected on the basis of the recently discovered $\Upsilon$ enhancement[19] at $\sim 9.5$ GeV in the muon pair spectrum produced in proton-nucleon collisions. A particle data group type summary of the quark flavors is given in Table I.

TABLE I

Quark Flavors à la the Particle Data Group

| Quark | $J^P$ | Mass (MeV) | Q/e | Baryon No. | Strangeness | Charm |
|---|---|---|---|---|---|---|
| u | $1/2^+$ | ~350 | 2/3 | 1/3 | 0 | 0 |
| d | $1/2^+$ | ~350 | -1/3 | 1/3 | 0 | 0 |
| s | $1/2^+$ | ~500 | -1/3 | 1/3 | -1 | 0 |
| c | $1/2^+$ | ~1650 | 2/3 | 1/3 | 0 | 1 |
| ? | $1/2^+$ | ~5000 | ? | 1/3 | 0 | 0 |

The masses given in Table I of course cannot have the usual meaning since we do not see the quarks as free particles. They are so-called "constituent masses" and occur as parameters with the dimensions of mass in certain equations. They are different from current quark masses which occur in other equations. Any meaning to be attached to them is only within these equations, if then.

The values of Q/e are most easily obtained by noting that baryons contain three quarks. Then the $\Delta^{++}$, $\Delta^+$, $\Delta^o$, $\Delta^-$ charge states of the 3-3 resonance yield the u and d quark charges, while the $\Sigma^{*+}$, $\Sigma^{*o}$, $\Sigma^{*-}$ or $\Omega^-$ tell us the charge on the s quark must be -1/3. In the case of the charmed quark, the best present evidence for Q/e = 2/3 comes from the charges of the $D^o$ and $D^+$, the (non-strange) mesons containing a charmed quark. That it is a charmed quark and not antiquark in the $D^o$ and $D^+$ follows from assuming that $c \rightarrow s$ in weak decays (so that the states with a charmed quark decay into final hadrons with strangeness -1).

There is other confirmatory evidence for all these charge assignments, such as the size of the change in R in $e^+e^-$ annihilation on crossing the appropriate threshold, the size of the electromagnetic coupling of the vector mesons, etc.

## Weak Couplings

We have already touched on the weak couplings of quarks. For the moment, we recall the standard model[20] where the weak-electromagnetic gauge group is SU(2) × U(1) and the left-handed quarks fall into doublet representations:

$$\begin{pmatrix} u \\ d_\theta \end{pmatrix} , \qquad \begin{pmatrix} c \\ s_\theta \end{pmatrix} ,$$

where

$$d_\theta = d \cos\theta + s \sin\theta \tag{1a}$$

$$s_\theta = -d \sin\theta + s \cos\theta \tag{1b}$$

and $\theta$ is the Cabibbo angle ($\sin^2\theta_c \approx 0.05$). Right-handed quarks are singlets. The charged weak current has V-A transitions between u and d and between c and s with amplitude proportional to cos $\theta$, while u and s and c and d have amplitude proportional to sin $\theta$. A very important question, which we will return to later, is the addition of more quarks and the possibility of having right-handed new and/or old quarks in doublet rather than singlet representations. But we note now that experiment prohibits the right-handed u quark from being coupled with more than a few percent of full strength to the d or s quark, nor can the right-handed c quark couple to the d quark with strength comparable to the left-handed c to s quark coupling.[21]

## Hadrons

We now review briefly the states composed of quarks which we do observe, the hadrons. The simplest possible hadrons are made of a quark and an antiquark forming a meson, or three quarks, forming a baryon. All other combinations of one, two, or three quarks and/or antiquarks have a net color (i.e., are not singlets under color SU(3)), and are forbidden by the principle of color confinement.

In the case of mesons it is simple to see that the color wave function

$$\left(\bar{q}_{1R}q_{2R} + \bar{q}_{1B}q_{2B} + \bar{q}_{1Y}q_{2Y}\right)/\sqrt{3}$$

is a normalized color singlet for any antiquark ($\bar{q}_1$) -quark ($q_2$) bound state.

The quark and antiquark spin may be combined to form a total quark spin, S, which is either 0 or 1. When coupled with the relative internal orbital angular momentum, L, we can form a total meson angular momentum, $\vec{J} = \vec{L} + \vec{S}$.

To complete the meson wave function we can choose any of the four (or more ) flavors, u, d, s, c, for the quark and any of the four flavors for the antiquark. Thus there are 16 possible flavor possibilities for each value of L, S, and J. A meson wave function in the quark model then can be written in factorized form as

$$\psi_{\text{color}}\ (\text{singlet}) \times \psi_{\text{flavor}} \times \left[\psi_{\text{spin}}\ (S = 0, 1) \times \psi_{\text{orbital}}\ (L = 0, 1, \ldots)\right]_{\text{total } J}$$

For baryons the situation is a little more complicated. The normalized color singlet state with quarks $q_1q_2q_3$ is

$$\frac{1}{\sqrt{3!}} \begin{vmatrix} q_{1R} & q_{2R} & q_{3R} \\ q_{1B} & q_{2B} & q_{3B} \\ q_{1Y} & q_{2Y} & q_{3Y} \end{vmatrix}$$

as is easily seen by noting that a transformation induced by an element of the color SU(3) group multiplies the matrix above by another matrix of determinant unity.

The total quark spin, S, may be 1/2 or 3/2. This is to be combined with the net internal orbital angular momentum L, to form the total baryon angular momentum, $\vec{J} = \vec{L} + \vec{S}$. The internal orbital angular momentum can be constructed in several ways, but most simply one may take $\vec{\ell}_{12}$ as the orbital angular momentum between quarks 1 and 2 and add to it $\vec{\ell}_3$, the orbital angular momentum of the third quark relative to the center of mass of the first two, to form $\vec{L} = \vec{\ell}_{12} + \vec{\ell}_3$.

The flavor wave function is also a bit more complicated than for mesons because not all flavor states are allowed for a given L and S due to Fermi statistics. With a color singlet wave function which is antisymmetric, the remainder of the baryon wave function must be symmetric. We will discuss the detailed implications of this later.

Exotics

The meson and baryon states we have discussed so far are the conventional ones of the quark model and involve the minimum number of quarks and/or antiquarks which can form a color singlet. We might well define a manifest exotic as any state which cannot be made out of quark-antiquark in the case of a meson and three quarks in the case of a baryon.

Traditionally, one breaks up exotics into two categories. Exotics of the first kind, or "flavor exotics," are states in SU(2), SU(3), . . . representations not found when hadrons are formed as described above. Examples include doubley charged mesons, a baryon with positive strangeness, a meson with two units of charm, etc.

Exotics of the second kind are sometimes called "CP exotics." These are specifically mesons with parity $P = (-1)^J$ which have CP = -1 or a meson with $J^{PC} = 0^{--}$. Neither of these can be formed from a quark and antiquark. A particular example of such an exotic is a vector meson with even charge conjugation.

In models which have a mechanism for forming exotic states, very often there are hadrons which do not have manifestly exotic quantum numbers themselves, but which have a quark content such that they have exotic relatives. These states are sometimes called "crypto-exotics." It is convenient to extend the definition of exotic to include them. Then an exotic is a meson which is not a quark-antiquark state or a baryon which is not three quarks. To use this definition we of course imply that we can tell what quarks are inside a given hadron!

There are many examples of predictions of such exotic states:

(1) $q\bar{q}q\bar{q}$ mesons and qqq $q\bar{q}$ baryons as in bag model calculations;[22]

(2) $(c\bar{q})$ $(\bar{c}q)$ bound states of two charmed mesons to form "molecular" charmonium;[23]

(3) Baryonium;[24]

(4) Mesons composed of $\bar{q}q$ in a color octet state coupled to a gluon;[25]

(5) Quarkless states composed of gluons alone or "glueballs;"[26]

(6) States where the energy-momentum and perhaps spin are carried by fields other than the quarks, such as a neutral "soul;"[27]

(7) String excitations in a model of quark binding through a field theoretic string. String excitations may also be coupled to the quark orbital angular momentum to produce a fairly complicated spectroscopy.[28]

In fact, it is difficult to avoid exotic states with any real dynamics in a field theoretic framework. For no matter whether we confine quarks with gluons, with strings, or with some other fields, in a true field theory the binding field will have dynamical degrees of freedom of its own. Then, in addition to the quarks, there will be other fields which carry energy and momentum—which have their own spectrum of excitations and can "slosh" around inside the hadron relative to the quarks. The coupling of these excitations to the quark excitations in general gives rise to extra, sometimes manifestly exotic, states in the hadronic spectrum in addition to the ones usually expected. It is thus not a question so much of whether exotic states exist at all: almost any theory of hadrons worthy of the name predicts them at some mass. The important question is quantitative: at what mass and with what quantum numbers do they occur?

## II. MESONS

We now consider in more detail the spectroscopy of mesons. Their flavor quantum numbers can be read off directly from their quark content, while their parity $P = (-1)^{L+1}$ and, for charge self-conjugate states ($\bar{u}u$, $\bar{d}d$, $\bar{s}s$, $\bar{c}c$), their charge conjugation $C = (-1)^{L+S}$.

The flavor states in the case of four quarks (u, d, s, and c) are:

| | | | |
|---|---|---|---|
| $\bar{u}u$ | $\bar{u}d$ | $\bar{u}s$ | $\bar{u}c$ |
| $\bar{d}u$ | $\bar{d}d$ | $\bar{d}s$ | $\bar{d}c$ |
| $\bar{s}u$ | $\bar{s}d$ | $\bar{s}s$ | $\bar{s}c$ |
| $\bar{c}u$ | $\bar{c}d$ | $\bar{c}s$ | $\bar{c}c$ |

To the extent that the u and d quarks are degenerate in mass and have the same strong interactions, one has a strong interaction SU(2) symmetry (called isotopic spin). Similarly, to the extent that u, d, and s are degenerate and have the same strong interactions, one has an SU(3) symmetry. The grouping of mesons composed of u, d, s, and c quarks into multiplets which are irreducible representations of these symmetries is given in Table II.

For the L = 0 ground state mesons we have quark spin 0 or 1 and hence $J^P = 0^-$ or $1^-$. The approximate assignment of observed pseudoscalar and vector mesons to the flavor states composed of u, d, s and c quarks is indicated in Table III.

With the discovery of $D^o$, $D^+$ and $D^{*o}$, $D^{*+}$ last year,[29] the additional evidence[30] for the X(2830), and the new indications[31] from the DASP group for the F and $F^*$, we have a known particle for every one of the 16 pseudoscalar and 16 vector mesons expected for the mesonic ground states with four quarks. If we take the $\Upsilon(9.5)$ to be the ground state vector meson composed of a fifth quark and its antiquark then we still have 25-16 = 9 pseudoscalar and 8 vector mesons yet to

TABLE II

SU(2) and SU(3) Multiplets for Mesons

| | Quark Flavor State | | Isospin (SU(2) Representation) | SU(3) Representation |
|---|---|---|---|---|
| $\bar{d}u$ | $(\bar{u}u - \bar{d}d)/\sqrt{2}$ | $\bar{u}d$ | 1 | 8 |
| $\bar{s}u$ | $\bar{s}d$ | | 1/2 | |
| | $\bar{d}s$ | $\bar{u}s$ | 1/2 | |
| | $(\bar{u}u + \bar{d}d - 2\bar{s}s)/\sqrt{6}$ | | 0 | |
| $\bar{d}c$ | $\bar{u}c$ | | 1/2 | $\bar{3}$ |
| $\bar{s}c$ | | | 0 | |
| | $\bar{c}u$ | $\bar{c}d$ | 1/2 | 3 |
| | | $\bar{c}s$ | 0 | |
| | $(\bar{u}u + \bar{d}d + \bar{s}s)/\sqrt{3}$ | | 0 | 1 |
| | $\bar{c}c$ | | 0 | 1 |

be found! But given the existence of the 32 ground state mesons composed of four quarks, we have no doubt they all will eventually be found. For in fact, we do not have 32 unaffiliated particles, but really 32 examples of the same thing—the ground state of a quark-antiquark system—obtained by putting in different flavors for the quark and antiquark and changing their spin orientation.

The ground state, by implication of its name, is not the only level found in the quark-antiquark spectrum. There are (at least) radial and orbital excitations. We define a radial excitation as a state which has all the same quantum numbers, including internal quark L and S, as another $\bar{q}_1q_2$ state at lower mass. The idea as well as the name for such states is borrowed from non-relativistic potential

TABLE III

Ground State Mesons[34]

| Quark Flavor State | | | Observed $J^P = 0^-$ Meson[11, 29, 30, 31] | Observed $J^P = 1^-$ Meson[11, 30, 31] |
|---|---|---|---|---|
| $\bar{d}u$ | $(\bar{u}u - \bar{d}d)/\sqrt{2}$ | $\bar{u}d$ | $\pi^{+,0,-}$ (140) | $\rho^{+,0,-}$ (770) |
| $\bar{s}u$ | $\bar{s}d$ | | $K^{+,0}$ (495) | $K^{*+,0}$ (890) |
| | $\bar{d}s$ | $\bar{u}s$ | $\bar{K}^{0,-}$ (495) | $\bar{K}^{*0,-}$ (890) |
| | $(\bar{u}u + \bar{d}d)/\sqrt{2}$ | | $\eta$(550) ← mixture | $\omega$ (783) |
| | $\bar{s}s$ | | $\eta'$(958) ← mixture | $\phi$(1020) |
| $\bar{d}c$ | $\bar{u}c$ | | $D^{+,0}$ (1865) | $D^{*+,0}$ (2010) |
| $\bar{s}c$ | | | $F^{+}$ (2030) | $F^{**}$ (2140) |
| | $\bar{c}u$ | $\bar{c}d$ | $\bar{D}^{0,-}$ (1865) | $\bar{D}^{*0,-}$ (2010) |
| | | $\bar{c}s$ | $\bar{F}^{-}$ (2030) | $\bar{F}^{*-}$ (2140) |
| | $\bar{c}c$ | | X (2830) | $\psi$(3095) |

theory. There, in a potential of sufficient strength, one finds a series of such levels, each successive radial excitation having another node in its radial wave function. Familiar examples of such a situation occur for the Coulomb, harmonic oscillator and linear potentials.

Suppose such a higher mass pseudoscalar or vector meson is discovered; is it necessarily a radial excitation of the ground state? For a $J^P = 0^-$ state the answer is yes; one can only make a pseudoscalar out of a quark and antiquark if $L = S = 0$. Thus all quantum numbers including L and S are the same as that for the ground state pseudoscalar. For a $J^P = 1^-$ state, this is not necessarily so. Both internal $L = 0$, $S = 1$ and $L = 2$, $S = 1$ can result in $J^P = 1^-$ states and only the first case meets our definition of a radial excitation of the ground state. Furthermore, the closeness in mass of L = 0 radial excitations and L = 2 states in linear and harmonic potentials makes mixing between the corresponding $J^P = 1^-$ states very likely.

Barring such complete mixing, how can we tell the L = 0 from L = 2 vector mesons? First, if a pseudoscalar partner is found nearby in mass, we know it must be a radial excitation, and hence also the vector meson. Second, if we have enough confidence in our knowledge of the potential binding the quark and antiquark together, then we can calculate the mass expected for a given state and expect experiment to agree. Along the same lines, if we know experimentally the mass of expected nearby states, it may be possible to associate a new state with L = 0 or L = 2 depending on its mass. Third, in a nonrelativistic picture $\Gamma(V^0 \rightarrow e^+e^-) \propto |f(r = 0)|^2$, the square of the spatial wave function at the origin. This vanishes for L = 2 in the nonrelativistic approximation. For charmed quarks at least, even after relativistic corrections, the L = 2 vector mesons should have a very much smaller leptonic width than those with L = 0. Last, in a theory of pionic decays based on the quark model, the relative signs of various vector meson decay amplitudes are different depending on whether L = 0 or 2. For example, the amplitudes for $\rho' \rightarrow \pi\omega$ vs. $\rho' \rightarrow \pi\pi$ have a different relative sign[32] if the $\rho'$ is a quark-antiquark state with L = 2 rather than L = 0. Similar considerations led to the establishment[33] of a $J^P = 3/2$, I = 3/2 pion-nucleon resonance at ~1700 MeV as a radial excitation of the $\Delta(1232)$ rather than an L = 2 baryon state.

The most persuasive evidence for a sequence of mesonic radial excitations comes from charmonium. There we have[34] the $\psi \equiv \psi(3095)$ and its radial excitation $\psi' \equiv \psi(3684)$. The new state,[35] $\psi(3772)$, on the basis of its leptonic width and agreement with potential model calculations is most likely an L = 2 state, though with some mixture of the L = 0 radial excitation, $\psi'$. The mass region between $\sim$4 and $\sim$4.2 GeV contains several bumps, with one very likely another radial excitation of the $\psi$. The $\psi$(4414) fits fairly well as yet a third radial excitation. There is every reason to expect still higher mass radially excited states but they become very difficult to distinguish from background because of the increasing total width and smaller coupling to $e^+e^-$.

At the moment, with some recent additions to the list of known states, the evidence for radial excitations in the "old" meson spectrum is fairly convincing by itself. The only established mesonic radial excitation[11] for quite some time was the $\rho'$ (1600). In the last year or so it has been joined by a K' (1400) which was found[36] in an isobar model analysis of the $K\pi\pi$ final state produced in $K^{\pm}p$ collisions at 13 GeV/c. It is a $J^P = 0^-$ state decaying to $K(\pi\pi)$ and as noted before, must be a radial excitation of the ground state K(495). It has a possible $K^{*'}$ (1650) vector meson partner found in some $K\pi$ phase shift analysis solutions of the same experiment.[37]

The last few months have seen a population explosion among vector mesons composed of "old" quarks. The initial result from Orsay[38] was an indication of a bump in $e^+e^- \rightarrow 5\pi$ near 1780 MeV. This has been followed by evidence for a relatively narrow bump at $\sim$1820 MeV from Frascati.[39] Even more recent data indicates that the region from 1500 to 2000 MeV may be quite complicated with as many as half a dozen (or even more!) vector meson states found in that region.[40] Inasmuch as we do expect both L = 0 radial excitations and L = 2 vector mesons, all composed of $\bar{u}u$, $\bar{d}d$, and $\bar{s}s$ in that mass region, such a complicated situation is not totally unexpected. In any case, although much remains to be sorted out, both charmonium and the old mesons emphatically indicate that <u>radial excitations of mesons do exist.</u>

The other clear set of excitations in the meson spectrum is that corresponding to non-zero orbital angular momentum between the quarks. We recall from the first section that in the quark model when L = 1 each quark flavor combination occurs in an S = 0 state with $J^{PC} = 1^{+-}$ and three S = 1 states with $J^{PC} = 0^{++}$, $1^{++}$, and $2^{++}$.

The most spectacular examples of the L = 1, S = 1 states are the $\chi(3414)$, $\chi(3508)$, and $\chi(3552)$ charmonium ($\bar{c}c$) levels[4] which very likely have $J^{PC} = 0^{++}$, $1^{++}$, and $2^{++}$ respectively. For u, d, and s quarks, only the $J^P = 2^+$ states are completely found (see Table IV).

The $J^P = 1^+$ states of u, d, and s quarks are a traditional area of experimental confusion. However, in the last year or so the situation is beginning to clarify. The biggest single advance has been the evidence[41, 42, 43] for two Q mesons, $Q_1(\sim 1300)$ and $Q_2(\sim 1400)$, which are axial-vector states containing a strange quark and a u or d quark. The observed states are actually mixtures[42] of the S = 0 and S = 1 quark model states. The B(1235) meson is an established[11] candidate for the isospin one axial-vector state composed of u and d quarks with quark spin S = 0. The D(1285) (not to be confused with the charmed mesons) is the only established[11] isospin zero meson which likely has $J^P = 1^+$ (and from its positive charge conjugation would correspond to S = 1).

Along with the Q mesons, the traditional problem child of the axial-vector mesons is the $A_1$. Even here some real progress is being made. Although earlier analyses of diffractive three pion production were never able to show evidence for a real resonance at the peak mass of ~1100 MeV, more recent theoretical work[44] with multichannel analyses do indicate resonance behavior, although perhaps at a higher mass (even possibly 1400 to 1500 MeV). At the same time, more direct experimental indications of a resonance decaying to $\pi\rho$ at ~1100 MeV come from

TABLE IV

$J^P = 2^+$ Mesons Composed of u, d, and s Quarks

| Quark Flavor State | | | Observed Meson[11] |
|---|---|---|---|
| $\bar{d}u$ | $(\bar{u}u - \bar{d}d)/\sqrt{2}$ | $\bar{u}d$ | $A_2(1310)$ |
| | $(\bar{u}u + \bar{d}d)/\sqrt{2}$ | | f(1270) |
| $\bar{s}u$ | $\bar{s}d$ | | $K^*(1420)$ |
| ds | $\bar{d}s$ | $\bar{u}s$ | $\bar{K}^*(1420)$ |
| | $\bar{s}s$ | | f'(1515) |

several different experiments performed at CERN.[43] It seems unlikely that the uncertainty with regard to the $A_1$ will persist very much longer. With, in addition, the new evidence[45] for the heavy lepton decay $\tau \rightarrow A_1 \nu_\tau$, the establishment of a suitable isospin one meson to match the L = 1, S = 1 axial-vector meson composed of u and d quarks seems finally to be within sight.

With the situation for $1^+$ states composed of u, d and s quarks straightening out, that for the $J^P = 0^+$ states is still confusing. Several of these states, like the $\delta$(970), which would be the I = 1 scalar meson composed of u and d quarks, are established.[11] But the confusion surrounding the isoscalar $J^P = 0^+$ states (of which there may be too many, and at the wrong masses) prevents one from being very optimistic at the moment.[46] There are in fact various proposals assigning some or all these scalar mesons to what we would call exotic multiplets.[22,26,47]

At the next level of orbital excitation, L = 2, only a few states are pinned down for sure. We have already noted the $\psi$(3772), which is very likely L = 2 and S = 1 combined to form $J^P = 1^-$. The g(1690), $\omega^*$(1675) and $K^*$(1780) all are now established[11] to have $J^P = 3^-$ and hence correspond to L = 2 and S = 1 combined to form $J^P = 3^-$ for states with u, d, and s quarks. While many states, particularly with $J^P = 2^-$, remain to be established experimentally, enough has been found to give us assurance that all the L = 2 levels must exist for all possible quark flavors.

When we get to L = 3, the only established state[11] is the h(2040) which fits well as the L = 3, S = 1 isoscalar state composed of u and d quarks with $J^P = 4^+$. Although most specific quantum number assignments are unknown above ~2 GeV for mesons, there is no indication that the sequence of orbital (or radial) excitations stops here. On the contrary, there are clear signals[11,48] for meson resonances extending above 2.5 GeV and we have every reason to expect that broad, difficult to isolate states exist at masses much higher than that.

A comparison of the known charmonium ($\bar{c}c$) spectroscopy with that expected from a linear potential is shown in Table VI. The match between the $\bar{c}c$ states expected and the experimental observations is rather convincing evidence, even taken by itself, that we are dealing with the bound states of a fermion-antifermion system.

However, the knowledge of strange mesons acquired over the years, or of isospin one mesons, is fairly impressive also (see Table VII). Even more important, where gaps exist in the established charmonium states, they are often filled in the case of strange or I = 1 mesons, and vice versa. On the one hand, this gives us great confidence that all the $J^P$ states corresponding to a given L level do in fact exist. On the other hand, from the ground state mesons and some of the excited levels where most of the different flavor states have been found, we also have great confidence that each level comes in all possible quark-antiquark flavor states. Sooner or later they will all be found. The most important question is whether other, non-$\bar{q}q$ levels exist in the meson spectrum.

TABLE VI

$J^{PC}$ Levels of $\bar{c}c$ in a Linear Potential (not to scale)

| Quark Model Level | | Observed Meson[4,11] |
|---|---|---|
| 1D | $3^{--}$ | ? |
| | $2^{--}$ | ? |
| | $2^{-+}$ | ? |
| | $1^{--}$ | ψ(3772) |
| 2S | $1^{--}$ | ψ(3684) |
| | $0^{-+}$ | χ(3455) ? |
| 1P | $2^{++}$ | χ(3552) |
| | $1^{++}$ | χ(3508) |
| | $1^{+-}$ | ? |
| | $0^{++}$ | χ(3414) |
| 1S | $1^{--}$ | ψ(3095) |
| | $0^{-+}$ | X(2830) |

TABLE VII

$J^{PC}$ Levels of $\bar{q}_1 q_2$ in a Linear Potential

| Quark Model Level | | Observed Strange Meson[11] | Observed I = 1 Meson[11] |
|---|---|---|---|
| 1D | $3^{--}$ | $K^*(1780)$ | g(1690) |
| | $2^{--}$ | ? | ? |
| | $2^{-+}$ | L(1770) ? | $A_3(1640)$ ? |
| | $1^{--}$ | ? | ? |
| 2S | $1^{--}$ | $K^{*\prime}(1650)$ | $\rho'(1600)$ |
| | $0^{-+}$ | $K'(1400)$ | ? |
| 1P | $2^{++}$ | $K^*(1420)$ | $A_2(1310)$ |
| | $1^{++}$ | $Q_2(1400)$ ↖ mix | $A_1$ ? |
| | $1^{+-}$ | $Q_1(1300)$ ↙ | B(1235) |
| | $0^{++}$ | $\kappa$ (1250) ? | $\delta(970)$ ? |
| 1S | $1^{--}$ | $K^*(890)$ | $\rho(770)$ |
| | $0^{-+}$ | K(495) | $\pi(140)$ |

## III. BARYONS

The baryon ground state has all three quarks in relative s-states and therefore overall L = 0. If the total quark spin S = 3/2, the spin wave function is completely symmetric. Since the space wave function is also symmetric for the ground state, the quark flavor wave function must also be symmetric. Then in combination with the antisymmetric color singlet wave function, one has an overall antisymmetric three quark wave function, in accord with Fermi-Dirac statistics. With four quark flavors from which to choose, there are 20 possible symmetric three quark flavor states. These are shown in Table VIII, together with the corresponding observed baryon, if known.

TABLE VIII

S = 3/2 Baryon Ground States

| Quark Flavor States | | | | Observed States[11,49] |
|---|---|---|---|---|
| uuu | uud | udd | ddd | $\Delta^{++,+,0,-}$(1232) |
| | uus | uds | dds | $\Sigma^{*+,o,-}$ (1385) |
| | | uss | dss | $\Xi^{*o,-}$(1530) |
| | | | sss | $\Omega^-$ (1670) |
| uuc | udc | ddc | | $\Sigma_c^*$ or $C_1^{*++,+,o}$(2500 ?)[50] |
| | usc | dsc | | $S^{*+,o}$(?) |
| | | ssc | | $T^{*o}$ (?) |
| ucc | dcc | | | $X_u^{*++}$, $X_d^{*++}$(?) |
| | scc | | | $X_s^{*+}$ (?) |
| ccc | | | | $\theta^{++}$ (?) |

In the case of total quark spin S = 1/2, it may be shown that the spin wave function is of "mixed symmetry." With a symmetric ground state spatial wave function, Fermi-Dirac statistics now demands a mixed symmetry flavor wave function. With four quarks, it turns out there are again 20 such quark flavor states. It is purely an accident that the number of flavor states is the same as for a symmetric flavor wave function, and, as we will see below, is not true when there are other than four quark flavors. The appropriate mixed symmetry states composed of u, d, s, and c quarks, together with their experimental counterparts, are shown in Table IX.

TABLE IX

S = 1/2 Baryon Ground States

| Quark Flavor States | | | | Observed States[11,49] |
|---|---|---|---|---|
| | uud | udd | | $N^{+,o}$ (940) |
| | uus | {ud} c | dds | $\Sigma^{+,o,-}$ (1190) |
| | | [ud]s | | $\Lambda$ (1115) |
| | | uss | dss | $\Xi^{o,-}$ (1320) |
| uuc | {ud} c | ddc | | $\Sigma_c$ or $C_1^{++,+,o}$ (2426 ?)[51] |
| | {us} c | {ds} c | | $S^{+,o}$ (?) |
| | | ssc | | $T^o$ (?) |
| | [us] c | [ds] c | | $A^{+,o}$ (?) |
| | [ud]c | | | $\Lambda_c$ or $C_o^+$ (2260)[50] |
| ucc | dcc | | | $X_u^{++}$, $X_d^+$ (?) |
| | scc | | | $X_s^+$ (?) |
| | { } ≡ symmetrized, in flavor | | | [ ] ≡ antisymmetrized in flavor |

Radial excitations of the baryon ground state, as for meson radial excitations, differ only in having a different radial wave function and should have the same spin and flavor states available as the ground state. For S = 3/2 we then have a symmetric flavor wave function, while for S = 1/2 one of mixed symmetry. The number of possible baryon (three quark) flavor states as a function of the number of different quark flavors is given in Table X. Also shown is the number of flavor states times the number of $S_z$ states available for the entire ground state or its radial excitation. We often refer to the set of these states by their total spin ($S_z$) and flavor multiplicity, e.g. for three quarks (u, d, s) it is the "56", made up of an SU(3) octet with S = 1/2 and a decuplet with S = 3/2.

TABLE X

Multiplicity of the Baryon Ground State or its Radial Excitations

| N = No. of Quark Flavors | No. of Baryon Flavor States S = 1/2 | S = 3/2 | No. of Spin Times Flavor States |
|---|---|---|---|
| 1 | 0 | 1 | 4 |
| 2 | 2 | 4 | 20 |
| 3 | 8 | 10 | 56 |
| 4 | 20 | 20 | 120 |
| 5 | 40 | 35 | 220 |
| 6 | 70 | 56 | 364 |

Besides the ground state or its radial excitations, we will of course have the same accounting of baryon spin and flavor states whenever the quark spatial wave function is symmetric. For then the flavor times spin wave function is required to be symmetric, and we have exactly the same arguments on the available spin and flavor states that led us to Table X for the ground state.

For baryon orbital excitations one can in principle have quark spatial wave functions which are symmetrical, antisymmetrical, or of mixed symmetry. The lowest orbital excitation, that with L = 1, turns out to have a spatial wave function with mixed symmetry among the three quarks. For the case of quark spin S = 3/2 (a symmetric spin wave function), this forces a mixed symmetry flavor wave function. However, when S = 1/2 (mixed symmetry spin wave function) the overall Fermi-Dirac statistics can be satisfied with either a symmetrical, mixed symmetry, or antisymmetrical flavor wave function. The situation with regard to the multiplicity of baryon flavor states in this case is shown in Table XI.

TABLE XI

Multiplicity of the Baryon Orbital Excitations with Mixed Symmetry Spatial Wave Functions

| | No. of Baryon Flavor States | | | | No. of Spin |
|---|---|---|---|---|---|
| | S = 3/2 | S = 1/2 | | | Times |
| N = No. of Quark Flavors | Mixed | Antisym. | Mixed | Sym. | Flavor States |
| 1 | 0 | 0 | 0 | 1 | 2 |
| 2 | 2 | 0 | 2 | 4 | 20 |
| 3 | 8 | 1 | 8 | 10 | 70 |
| 4 | 20 | 4 | 20 | 20 | 168 |
| 5 | 40 | 10 | 40 | 35 | 330 |
| 6 | 70 | 20 | 70 | 56 | 572 |

Again, such an array of spin and flavor states will arise any time the three quark spatial wave function is of mixed symmetry. The set of these spin and flavor states is then often referred to by their total spin times flavor multiplicity, e.g. for three quarks one has the "70", composed of an S = 3/2 SU(3) octet and an S = 1/2 SU(3) singlet, octet, and decuplet.

Aside from the observed charmed baryons, which are candidates for being members of the L = 0 ground state, only states composed of u, d and s quarks are known for baryons. Therefore, in discussing the observations of radially and orbitally excited baryonic levels,[52] we consider only states composed of three quarks. As indicated above, we refer to the multiplets of given L by their spin ($S_z$) times flavor multiplicity.

The first excited baryon level above the ground state is a 56, L = 0 multiplet, i.e. a radial excitation of the 56, L = 0 ground state. Its most familiar non-strange member is the Roper resonance, $N^*(1470)$. The radially excited counterpart of the 3-3 resonance is the $\Delta^*(1690)$.

At slightly higher mass, on average, is a set of negative parity states which form a 70, L = 1 orbital excitation. All seven of the non-strange resonances needed to fill this multiplet are known to exist with the right spins and isospins—no more and no less than the expected states.

Above the 70, L = 1 there is another possible radial excitation of the ground state 56, L = 0. However, most of the evidence for this is based on the $N^*(1780)$ with $J^P = \frac{1}{2}^+$ and confirmation of the whole multiplet awaits evidence for some of the other states.

In the same mass range there is a further established multiplet, a 56, L = 2. Most, if not all of the six non-strange states sitting in this multiplet are found experimentally, including the long established $N^*(1688)$ with $J^P = \frac{5}{2}^+$ and the $\Delta^*(1950)$ with $J^P = \frac{7}{2}^+$.

In the 2 GeV mass region there is fairly good evidence for a 70, L = 3 set of states. In particular the established $N^*(2190)$ and $N^*(2140)$ with $J^P = \frac{7}{2}^-$ and $\frac{9}{2}^-$ respectively, rather uniquely fit into just such a multiplet.

At still higher mass there are the established $J^P = \frac{9+}{2}$ $N^*(2220)$ and the $\frac{11+}{2}$ $\Delta^*(2420)$. Even though essentially all the other states remain to be found, these two levels are very likely the first members of a 56, L = 4 multiplet.

Thus we see a fairly extensive sequence of radial and orbital excitations in the baryon spectrum, just as in the case of the meson spectrum. A few more multiplets are quite possible in the mass range discussed up to now (e.g. a 56, L = 2 radial excitation and a 70, L = 1 radial excitation).

The established multiplets so far all have the property that L even corresponds to a flavor times spin multiplicity of 56 while those with L odd have a multiplicity of 70. While this is trivial for the ground state, or first orbital excitation, it is entirely non-trivial that we do not see, say, 70, L = 0 and 70, L = 2 multiplets below 2 GeV. (These are expected in a harmonic oscillator potential to be degenerate with the 56, L = 2). The full significance of this for the quark-quark force remains to be seen. In fact, there are recent suggestions that the empirical connection of 56's and 70's with L even and odd, respectively, may break down: this is based on a $5/2^-$ $\Delta^*$ near 1960 MeV which would seem to fit best in a 56, L = 1 multiplet.[53]

In any case, there are further $N^*$ and $\Delta^*$ bumps (with unknown $J^P$) extending well into the 3 GeV region.[11] We have no reason to doubt that the baryon spectrum continues to much higher masses, albeit with broader, low elasticity, states making it almost impossible to isolate individuals levels and their quantum numbers.

## IV. DECAY PROCESSES

Higher mass hadronic states are unstable with respect to the strong interactions. They generally decay to the lowest mass states with the same (net) flavor and other quantum numbers conserved in the strong interaction, typically by pion emission. Examples are

$$A_2 \xrightarrow{\pi} \rho \xrightarrow{\pi} \pi, \quad K^*(1420) \xrightarrow{\pi} K^*(890) \xrightarrow{\pi} K, \text{ and } N^*(1670) \xrightarrow{\pi} \Delta(1232) \xrightarrow{\pi} N \quad .$$

Occasionally a hadron will have a prominent electromagnetic decay into another hadron (or hadrons) with the same net flavor, when strong interaction quantum numbers and/or phase space inhibit a strong decay mode. $D^{*o} \xrightarrow{\gamma} D^o$, $F^* \xrightarrow{\gamma} F$, and $\omega \xrightarrow{\gamma} \pi^o$ are some outstanding examples of these electromagnetic decays.

A given hadron will then cascade down in mass by strong and/or electromagnetic decays until eventually it drops down to the lowest mass state(s) with baryon number and net flavor the same as the parent hadron. The state of lowest mass, characterized by a combination of quark flavors, then decays weakly except for the lowest mass (pseudoscalar) mesons composed of a quark and its antiquark, which decay electromagnetically, or if massive enough, by strong interactions. We shall now discuss these three types of decays—weak, electromagnetic, and strong—in more detail. We start with the weak decays.

### A. Weak Decays

We view all weak decays of hadrons in terms of what is happening at the quark level. The various amplitudes and their strengths can be read off easily for the u, d, s and c quarks from the doublet structure discussed in Section I for the standard $SU(2) \times U(1)$ model[20] of the weak and electromagnetic interactions.

For example, the usual strangeness non-changing semi-leptonic hadron decays arise at the quark level as $d \rightarrow u + W^- \rightarrow u + e^- \bar{\nu}_e$. They have an amplitude proportional to $\cos\theta_c$ ("Cabibbo allowed") and are clearly characterized by $\Delta I = 1$. On the other hand the semileptonic decay of the strange quark, $s \rightarrow u + W^- \rightarrow u + e^- \bar{\nu}_e$ or $u + \mu^- \bar{\nu}_\mu$, is the quark process responsible for all strange particle semi-leptonic decays. Its amplitude is proportional to $\sin\theta_c$ ("Cabibbo suppressed") and is characterized by the well known selection rules $\Delta S = \Delta Q = \pm 1$ and $\Delta I = 1/2$. There are also non-leptonic strange particle decays. These presumably arise at the quark level as $s \rightarrow u + W^- \rightarrow u + d\bar{u}$. A priori this could be either $\Delta I = 1/2$ or $3/2$, but should always be "Cabibbo suppressed."

For charmed particles, the "Cabibbo allowed" decays at the quark level are $c \rightarrow s + W^+ \rightarrow s + e^+ \nu_e$ or $s + \mu^+ \nu_\mu$ for semileptonic decays and $c \rightarrow s + W^+ \rightarrow s + u\bar{d}$ for non-leptonic decays, respectively. The former are then characterized by the selection rules $\Delta C = \Delta S = \pm 1$, $\Delta I = 0$, while the latter also have $\Delta C = \Delta S = \pm 1$, but $\Delta I = 1$. The corresponding Cabibbo suppressed modes of charmed particles are generated at the quark level by $c \rightarrow d + e^+ \nu_e$ or $d + \mu^+ \nu_\mu$ and $c \rightarrow d + u\bar{d}$.

For strange particle decays the magnitude of observed semileptonic amplitudes agrees with that expected from the quark weak decay amplitudes. Just looking at the quark level processes, one might expect the nonleptonic and semileptonic decay rates to be comparable. In fact $s \rightarrow u + \bar{d}u$ should very naively occur at three times the rate (because of color) that $s \rightarrow u + e^- \bar{\nu}_e$ does. This is not true, as evidenced by the fact the strange baryons decay about a thousand times more frequently in non-leptonic modes than in semileptonic ones.[11]

The amplitude for $\Delta S =$ 1 non-leptonic decays thus appears to be enhanced compared to the semi-leptonic amplitude.[54] Furthermore, it is the $\Delta I = 1/2$ (octet in SU(3)) part of the overall non-leptonic interaction that is enhanced. While there are explanations of this enhancement, none gives a completely satisfactory quantitative description of the effect. It is particularly damaging to some explanations that no similar enhancement occurs for charm: the semi-leptonic (semi-muonic plus semi-electronic) branching ratio of the D's is ~20 percent.[4] This is not so far from the 40 percent expected in the most naive quark level calculation where the decay rates for $c \rightarrow s + e^+ \nu_e$, $c \rightarrow s + \mu^+ \nu_\mu$ and $c \rightarrow s + u\bar{d}$ are in the ratio 1:1:3.

Up to this time all D decays which have been seen[4] are in accord with the standard model, with the non-leptonic Cabibbo allowed selection rules (particularly $\Delta C = \Delta S = \pm 1$) being spectacularly verified in decays like $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D^o \rightarrow K^- \pi^+$, $K^- \pi^+ \pi^+ \pi^-$, and $D^o \rightarrow K^- \pi^+ \pi^o$. Cabibbo suppressed modes like $\pi^+ \pi^-$, $\pi^+ \pi^+ \pi^-$, etc. are not seen down to levels of ~10 percent of corresponding Cabibbo allowed modes.[4] This is entirely consistent with the relative rate of $\tan^2\theta_c \approx 0.05$ expected in the standard model.

With the discovery[19] of the $\Upsilon$ it has become fairly clear that there is a fifth quark, and the question immediately arises of how it behaves with respect to the electromagnetic and weak interactions. The possibilities are essentially limitless if we do not restrict the discussion to particular weak gauge groups and particular representations of those groups. In the following we only consider the gauge group[20] SU(2) × U(1), with fermions in either doublet or singlet representations.[55]

With only four quarks, the most general classification of the left-handed u, d, s and c quarks into doublets is just

$$\begin{pmatrix} u \\ d_\theta \end{pmatrix}_L \quad , \quad \begin{pmatrix} c \\ s_\theta \end{pmatrix}_L \quad ,$$

the standard model with $\theta$ the Cabibbo angle, as discussed in Section I. All angles except for one which is involved in going from the "bare" quark doublets to a representation in which the quark mass matrix is diagonal can be absorbed in the definition of the quark fields. The single remaining angle can be chosen to be that defining an orthogonal transformation among the d and s quarks: it is just what is called the Cabibbo angle.

For the right-handed quarks, we could also contemplate putting the quarks in right-handed doublets (with, in general, another angle, $\theta'$, characterizing the rotation between right-handed quarks). However, experiment tells us that the transitions $u_R \overset{W^\pm}{\longleftrightarrow} d_R$, $u_R \overset{W^\pm}{\longleftrightarrow} s_R$ and $c_R \overset{W^\pm}{\longleftrightarrow} d_R$ can only have a few percent[21] of full strength (characterized by putting the corresponding quarks unmixed in right-handed doublets). The restrictions on the strength of the first two pairs comes from neutron beta decay, strange particle decays, and the y distributions at moderate energies in deep inelastic scattering. The third pair is restricted by the lack of observation of decays of the D mesons which involve no net strangeness in the final state (e.g. all pionic modes). There is even preliminary evidence that the only remaining pairing, $c_R \overset{W^\pm}{\longleftrightarrow} s_R$, cannot have full strength. This follows from the y distribution of dimuon events in $\nu$ deep inelastic scattering (presumably due to charm production off $\bar{s}$ quarks and subsequent semi-muonic decay) as observed in the CDHS experiment[56] at the SPS.

Thus, if we had only u, d, s and c quarks, they cannot be assigned to right-handed doublets, as no pairing of u or c to d or s, or combination, has the full charged current strength required for such a doublet. Therefore with four quarks we would assign them to be right-handed singlets under $SU(2) \times U(1)$. This is just the so-called standard model.[20]

Now let us assume that $\Upsilon$ involves a fifth quark and its corresponding antiquark. We do not want it to be a left-handed singlet, for this would generally mean[57] that there would be flavor changing neutral currents—something on which there are stringent limits in the case of strangeness and charm.[4] So our fifth quark needs a partner, in order that it can be put in a left-handed doublet. We call these two new quarks t and b, with the $\Upsilon$ being either a $\bar{b}b$ or $\bar{t}t$ vector meson. There are now basically two alternatives: the six quarks are all in left-handed doublets and right-handed singlets, or in left-handed doublets and right-handed doublets. Assuming there are exactly six (and no more) quarks, we consider these possibilities in turn.

First, if the right-handed quarks are all singlets, then only the left-handed quarks are non-trivial. They are to be in doublets which can be written

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L , \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L , \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L ,$$

where d', s', and b' are orthogonal mixtures of d, s, and b. The mixing can be parametrized by three real angles in this case[21] (neglecting a complex angle[58] which leads to CP violation), and their values will completely fix how the quarks decay weakly.

There are again some important restrictions coming from experiment. The combination of muon decay (strength of the weak interaction), neutron decay (strength of $u \overset{W^\pm}{\longleftrightarrow} d$), and strange particle decays (strength of $u \overset{W^\pm}{\longleftrightarrow} s$) tells us that d' must be rather close to the $d \cos\theta_c + s \sin\theta_c$ of Cabibbo. The square of the coefficient of b (in d') is thereby limited[21] to be $\lesssim 0.004$. Furthermore, charm decays into strange particles imply that s' contains a non-trivial s component. There is also a more theoretical argument[59] which tightly restricts the amount of d and s which can be together in b' by demanding that the $K_1^0 - K_2^0$ mass difference turn out to be of the right magnitude.

Altogether, these arguments indicate that d', s' and b' are dominantly d, s, and b respectively, as the names would indicate. In fact, at the moment nothing rules out d' and s' being very close to the Cabibbo mixtures and b' being almost entirely b. In the limit of b' = b, particles containing the lighter of t and b become stable with respect to their weak decay!

The more likely scenario,[21,59] however, is that there is some b mixed into s', and only a tiny bit in d'. Then if $m_t > m_b$, the t quark decays weakly mostly to the b quark, which then decays to the c quark. On the other hand, if $m_t < m_b$, we would have the b quark decaying weakly mostly to the t quark, which then decays weakly mostly to s. Either way, hadrons containing a b quark undergo <u>two</u> successive weak decays before the resulting hadrons contain only "old" quarks (u, d, and s). This might well provide a very characteristic two lepton decay signature for such hadrons, which would help greatly in their discovery. When produced in neutrino induced reactions this leads to various multilepton ($\geq 3$) final states, but the detailed rates depend crucially on the various mixing angles.[21,59]

Second, if the six quarks are in both left- and right-handed doublets, they must have the following form:

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L , \begin{pmatrix} c \\ s' \end{pmatrix}_L , \begin{pmatrix} t \\ b' \end{pmatrix}_L$$

and

$$\begin{pmatrix} u \\ b'' \end{pmatrix}_R , \begin{pmatrix} c \\ s'' \end{pmatrix}_R , \begin{pmatrix} t \\ d'' \end{pmatrix}_R$$

Here the Cabibbo-like mixing angles for both the left- and right-handed quarks must be small. The situation leading to this for the left-handed quarks was just discussed. For the right-handed ones it follows from the limits on the strengths of $u_R \longleftrightarrow d_R$, $u_R \longleftrightarrow s_R$ and, less restrictively, $c_R \longleftrightarrow d_R$ discussed in the case of four quarks. This forces u to be paired cominantly with b, and thence, c with s, leaving t and d, which by process of elimination form the third doublet.

But given that either b or t is to have a mass of ~5 GeV (from the ϒ mass), the assignment to right-handed doublets given above leads to spectacular predictions for inelastic neutrino or antineutrino scattering at presently available energies. For, depending on which quark is in the ϒ, there should be a threshold above which there is large production of t(b) quarks by $\nu(\bar{\nu})$ on valence d (u) quarks in the nucleon. This will give:[60]

(1) A rise in $\sigma_T(\nu N)/E_\nu$ $(\sigma_T(\bar{\nu}N)/E_{\bar{\nu}})$, or correspondingly, a rise in $\sigma_T(\nu N)/\sigma_T(\bar{\nu}N)$ $(\sigma_T(\bar{\nu}N)/\sigma_T(\nu N))$;

(2) An "anomalous y distribution," behaving like $(1-y)^2$ for $\nu d_R \rightarrow \mu^- t_R$ and flat for $\bar{\nu} u_R \rightarrow \mu^+ b_R$;

(3) A rise in dilepton events in $\nu(\bar{\nu})$ induced reactions[61] if hadrons involving t(b) have semileptonic branching ratios anything like those containing the c quark.

All these phenomena must happen together. While there is some experimental controversy[62] on (1) and (2) in the case of anti-neutrinos, there is no disagreement on (3), where there is no indication of anything besides the production and decay of charm.[62]

It would seem that the second possibility of the six quarks in right-handed doublets is ruled out by experiment. Of course, one can avoid (1), (2) and (3) at present energies by simply pushing the b and t quarks to an unaccessible mass, but then neither has anything to do with the $\Upsilon$. The other, easier, way out is to allow more than six quarks. Then the right-handed $u \leftrightarrow b$ and/or $d \leftrightarrow t$ pairings are no longer forced. The $u_R$, $d_R$, $b_R$ and $t_R$ could then be coupled mostly to still heavier quarks, and hence there would be no large neutrino or antineutrino production of the t or b off valence quarks. Whether nature chooses this rather peculiar pairing, seems unlikely, but we will have to wait and see.

B. Electromagnetic Decays

As with the weak interactions, we view the electromagnetic interactions of hadrons at the quark level. The current due to a quark with flavor index i is proportional to $Q_i \bar{u}_i \gamma_\mu u_i$, simply the Dirac current in space-time which is also diagonal in flavor. At the hadronic level such a current is capable of generating the variety of both electric and magnetic multipole transitions that are observed.

Between hadronic states that have internal quark angular momentum $L = 0$, the electromagnetic current, taken as a sum of quark currents, has matrix elements which correspond to magnetic dipole transitions between the hadron states. These magnetic transitions include:

(1) The static magnetic moments of the "stable" baryons;

(2) The transition moments for $\Sigma \to \Lambda\gamma$ and $\Delta \to N\gamma$;

(3) The transition moments for the decays of vector mesons to a pseudoscalar plus photon, e.g. $\omega \to \pi\gamma$, $\phi \to \eta\gamma$, $D^* \to D\gamma$.

We have a reasonable quantitative understanding of (1), (2), and (3) based on the quark level description of electromagnetic properties.[63] Among the "new" particles, rather dramatic exceptions to this are the decays $\psi \to X\gamma$ and $\psi' \to \chi(3455)\gamma$ if X(2830) and $\chi$(3455) are identified as $\eta_c$ and $\eta_c'$ respectively. For then the observed magnetic dipole transitions from the vectors to corresponding pseudoscalars of the charmonium system are an order of magnitude too small when compared to predicted rates.[64]

For transitions from hadrons with internal $L' \neq 0$ to those with $L = 0$ (e.g. $N^*(1520) \rightarrow N\gamma$, $\Delta^*(1950) \rightarrow N\gamma$), one has both electric and magnetic multipole transitions generated by the quark current. The structure of these amplitudes is understood in explicit quark models and in the more general framework of the transformation from constituent to current quarks, or Melosh transformation.[6,7] Both the signs and magnitudes of many amplitudes for $N^* \rightarrow \gamma N$ or $\Delta^* \rightarrow \gamma N$ are predicted correctly. For mesons, the best known transitions of this type are $\psi' \rightarrow \chi_J + \nu$. With heavy quarks and a non-relativistic situation these should be (related) electric dipole transitions for which $\Gamma(\psi' \rightarrow \chi_J\gamma) \propto (2J + 1)\, k_\gamma^3$. Experiment is consistent with this, as well as giving absolute rates which agree with theory within a factor of two or better.[64]

C. Strong Decays

As is now widely recognized, strong interactions decays are of two rather distinct types, depending on whether the corresponding quark diagram is topologically connected ("Zeig allowed") or disconnected (Zweig forbidden").[14] For meson decays, the requirement of having a connected quark diagram is equivalent to demanding that each quark line flow between two different mesons.

Processes corresponding to connected quark diagrams occur with typical strong interaction couplings and widths. Most of the hadron decays that one usually associates with the strong interactions, such as $\Delta \rightarrow \pi N$, $K^* \rightarrow \pi K$, and $\Sigma^* \rightarrow \bar{K}N$, are of this type.

Decays corresponding to disconnected quark diagrams do still occur, but with widths which are greatly suppressed. Among the old mesons we have $\phi \rightarrow \pi\rho$, suppressed in rate by a factor of order $10^2$, while in the charmonium spectrum $\psi$ decays are down a factor of $10^4$ or more.

Considerable effort has gone into trying to understand the actual rates of "Zweig forbidden" decays quantitatively in terms of quantum chromodynamics, where one views the sum of these decays of a given state as occuring via annihilation of a quark and antiquark into gluons.[15] The quark and antiquark in a meson state with even charge conjugation can annihilate into a minimum of two gluons, whereas odd charge conjugation states result in a minimum of three (one is forbidden by color conservation). These gluons then dress themselves as hadronic matter in all possible ways with unit probability. The gluon couplings to the quarks are evaluated at a value of $q^2$ corresponding to the mass squared of the quark-antiquark hadronic state.[15]

This picture leads to a very clear systematics in the properties of "Zweig forbidden" decays:[15]

(1) Widths should decrease with increasing mass, everything else being the same, since the square of the gluon coupling decreases (as $1/\log q^2$);

(2) Odd charge conjugation states should have smaller widths than even charge conjugation ones because they decay via annihilation into more gluons, and hence the width involves another power of $\alpha_s(q^2)$ (the square of the gluon coupling divided by $4\pi$) which is less than unity (at least for $q^2 \gtrsim 1\ \mathrm{GeV}^2$);

(3) The absolute value of the widths can be used to compute $\alpha_s(q^2)$, provided we know the remaining factors in the decay rate, and compared with values extracted from knowledge of the quark-quark forces due to single gluon exchange and from asymptotic freedom corrections to deep inelastic scattering.

This systematics has had some success in the case of charmonium. Item (3) may be turned around and used to compute $\psi \rightarrow$ hadrons or $\psi' \rightarrow$ hadrons via "Zweig violating" processes. (Since the $\psi$ is below $D\bar{D}$ threshold, it decays into "old" hadrons—hence the c and $\bar{c}$ quarks in the $\psi$ must annihilate, yielding a disconnected quark diagram.) The resulting widths are comparable, considering the uncertainties in the parameters, with the experimentally measured ones.[15,64] Again, the apparently much larger decay widths into hadrons of the $\chi_0(3414)$ and $\chi_2(3552)$, with even charge conjugation, compared to the $\psi(3095)$, is explained by item (2). The $\chi_1(3508)$, although it has even charge conjugation, cannot annihilate into two massless gluons, so that its hadronic width, which is likely smaller than that of its L = 1 companions $\chi_0$ and $\chi_2$, is understood.[64,65]

Unfortunately, there are also some major problems,[65] which revolve around the $\chi(2830)$ and $\chi(3455)$, if these are $\eta_c$ and $\eta'_c$, respectively. For then the branching ratio for $\eta_c \rightarrow \gamma\gamma$ is $\gtrsim 0.5 \times 10^{-2}$, and that for $\eta'_c \rightarrow \gamma\psi$ is $\gtrsim 1/4$. This suggests total widths which are less than a few hundred keV for both $\eta_c$ and $\eta'_c$ and perhaps much smaller than that for $\eta'_c$. On the other hand, annihilation through two gluons fairly unambiguously predicts widths of several MeV for such even charge conjugation states. It remains to be seen whether this disagreement of theory and experiment represents a major flaw in the whole idea of explaining "Zeig forbidden" decays quantitatively in terms of QCD. Time, and probably the $\Upsilon$ system, will tell.

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