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Classification of new particles*

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A classification of the new particles is proposed. Hadrons are constructed from quarks corresponding to several different representations of an SU_3 color group, with confined color. The new family of resonances, related to ψ/J, is assigned to color-antisextet quarks Q. These new quarks Q do not form mixed mesons $\bar{q}Q$ with old antiquarks but can form mixed baryons Qqq. We speculate on the relation between color and mass. High-mass recurrences of the ψ/J family are expected to have associated large changes in the cross section for electron-positron annihilation ($\Delta R > 4$). A conjectured mass formula, which relates the masses of ψ/J and ω, predicts the masses of possible recurrences of the ψ/J particle. Other experimental implications at presently available energies are discussed, especially the necessity for an isovector partner for ψ/J, and for pseudoscalar mesons at 1.8–2.2 GeV, some of which can decay into two photons.

I. INTRODUCTION

The new,[1] narrow resonances $\psi/J, \psi', \ldots$ have provoked a great deal of speculation, especially on the question of their relation to the older and more established particles. The remarkable prediction[2] of a new fermionic degree of freedom, based on a weak-interaction puzzle, has led immediately[3] to the interpretation of ψ/J as the ^3S bound state of a charmed-quark-antiquark pair. However, as learned from the cross section of electron-positron annihilation, more than one new charged fermion is excited. This has led to interpretations which call for several new quarks,[4] or one new quark and one new heavy lepton,[5] or several new heavy leptons.[6] Most of these proposals are either experimentally motivated or are concerned with theories of the weak interaction, which can offer little guidance on spectroscopic issues such as the simultaneous emergence in a narrow mass range of several new degrees of freedom. As a result many proposals are not particularly sensible from a spectral point of view, for instance by grouping together in the same pseudoscalar multiplet states as disparate in mass as the kaon at 490 MeV (not to mention the pion) and a hypothetical "paracharmonium" state at 2.8 GeV (and possibly higher states).

The present article speculates, primarily from a spectral point of view, about the classification of the new particles. We want to guarantee that the right number of new charged fermions (constituents) appear in the same mass range, as we know is the case. We attempt to group in multiplets only states of similar mass. A related purpose of our model is to give a quantitative form to our vague expectation for further narrow states and associated thresholds in electron-positron annihilation. In this sense, our model elaborates earlier and more amorphous speculations by Cabibbo and Karl[7] who conjectured that the spectrum of quarks is unbounded as the energy grows.

Quite apart from the preference for an unbounded spectrum of vector-meson states (and corresponding constituent fermions) it seems very wasteful to invent a new conserved quantum number (flavor) for every new constituent quark which has to be introduced. Cabibbo and Karl[7] conjectured that new quarks come in threes and that a new quark triplet Q carries a hypothetical quantum number h, somehow related to the mass, to distinguish it from the old quark triplet q. This quantum number is over and above the flavor quantum numbers that distinguish the low-mass quarks u, d, and s from each other. The proposal of this article is to identify this supplementary quantum number h with the color multiplet of the new quarks under the usual SU_3 color group. With this identification it is then natural to speculate about the dependence of mass on color and, *a fortiori*, about the masses of the present ψ/J particles and future narrow resonances.

It is interesting that several authors[8] have discussed the possibility that diquarks play a role in forming the resonances at $\sqrt{s} \simeq 4$ GeV, and in particular Iizuka[9] and Nambu and Han[9] have constructed the ψ/J and ψ' from such diquarks. These models also lead to a sensible spectroscopy. Our proposal is loosely connected with these models, since the quarks we use have diquark colors. There is an important distinction, however: Diquarks have integral spin whereas quarks have spin $\frac{1}{2}$. The experimental indication of a triplet of positive charge conjugation (P-wave) states at 3.4–3.5 GeV seems to favor models of the ψ/J family constructed from two spin-$\frac{1}{2}$ particles. A model containing a quark having antisextet color *and* charm was considered by Ma.[10] *A priori* it seems more complicated and somewhat redundant to introduce both a new flavor and new colors to be carried by a new quark.

II. ASSUMPTIONS

We are concerned primarily with the relationship between the new hadrons and the old hadrons. Let us consider right away the best-known case: the vector mesons. Is the relation of the set of new vector mesons, $\psi/J, \psi', \psi'', \ldots$ to the set of old vector mesons ρ, ω, ϕ of the same kind as the relation of the ϕ to the ρ and ω? A mere glance at the mass spectrum suggests that the answer to this question is "no." There is an enormous mass splitting between even the lowest-mass state of the ψ family and the old vector mesons, when compared with the mass splitting between the ρ and the ϕ. In fact, the mass splitting between the old vector mesons and the new vector mesons is also larger than the "internal" splitting between the new vector mesons. This suggests that the set of new vector mesons does not belong in the same "split" multiplet with the old vector mesons but forms a new multiplet on its own. We formulate this conclusion in terms of constituent quarks[11] which allows us to draw the full implications of the statement.

The old quarks q carry two sets of quantum numbers. One set, now called flavors, consists of isotopic spin, its third component, and strangeness. These quantum numbers distinguish the three quarks u, d, and s from each other. The second set, now called colors[12] are quantum numbers of a different kind. To start with, colors are quantum numbers which are almost perfectly hidden. Nonetheless, these quantum numbers probably exist, as can be argued from the several distinct functions they perform: Colors provide a necessary degeneracy factor when computing the contribution of quarks to the electron-positron annihilation rate, or the radiative decay rate of the neutral pion.[13] The color degeneracy also allows Fermi-Dirac statistics to apply when quarks are bound in baryons.[12] Finally, colors play the role of "charges" in Yang-Mills–type field theories,[14] which allow the rational discussion of quark binding and offer the hope[15] of proving, (rather than guessing) quark confinement and the hope of understanding hadronic masses.[16] Optimists have conjectured that the basic rule of quark confinement is color confinement, and we shall follow this optimistic conjecture. From the rule that only color-singlet states are physical, it follows that free quarks and diquarks do not exist, and only $q\bar{q}$ mesons and qqq baryons are physical. To summarize, old quarks q transform as $(3, 3^c)$ under $(\mathrm{SU}_3, \mathrm{SU}_3^{\mathrm{color}})$.

We assume that the new quarks Q do not belong in the same "badly broken" multiplet of quarks with the old quarks q, but form a new multiplet of their own. The assumed relation between the new quarks Q and the old quarks q is similar to the relation between the new vector mesons and the old vector mesons discussed at the beginning of this section. We distinguish the new quarks Q from the old quarks q only by their behavior under the SU_3 color group. This is done both for economy reasons (we do not want to introduce new quantum numbers) and for empirical reasons—there is a clear association between color and mass. The main assumption of this article, therefore, is that the new quarks Q responsible for the ψ/J family and the attendant threshold in the well-known ratio R transform as $(3, \bar{6}^c)$ under the $(\mathrm{SU}_3, \mathrm{SU}_3^c)$ groups. In other words, the new quarks Q are color-excited analogs of the old quarks q. It immediately follows from this assumption that there must be three kinds of new quarks U, D, and S, as there are three kinds of old quarks u, d, and s. There are no new flavors at all. We also assume that the conjectured rules of color confinement, as set up for the old quarks q, continue to apply for the new quarks Q.

Each of the new quarks U, D, and S comes in six color combinations rr, rw, rb, ww, wb, bb, but the physical states are colorless. The new quark U has the same isospin $(\frac{1}{2})$, its third component $(+\frac{1}{2})$ and strangeness (0) as the old quark u. The new quark D has the same isospin $(\frac{1}{2})$, its third component $(-\frac{1}{2})$, and strangeness (0) as the old quark d, and the results are similar for the new quark S which is the color image of s. More-complicated assignments can no doubt be found, and might even be useful, but we wish to restrict attention to the simplest logical possibility.

We focus right away on the intuitive connection between color and mass. Just as ordinary mesons composed of color-triplet quarks are heavier than positronium or muonium, composed of leptons, which are colorless, mesons composed of color-antisextet quarks will be heavier than the mesons composed of color-triplet quarks. Any simple relation between color charge and mass will guarantee our first goal, that states composed of the new quarks U, D, S will show up in the same mass range. An example of the kind of mass relation that may well hold true will be discussed later. It is also apparent right away that we have a framework into which we can welcome any further narrow resonance to be found at higher energies. Once we have opened the door for the $\bar{6}$

representation of SU_3 color, we will be able to allow higher-dimensional representations of SU_3 color. Therefore we have a simple model of the type mentioned in the Introduction. Other models of this type can be constructed, for instance by taking a different color group. The present model is pursued mainly for simplicity.

We shall also assume that the new quarks Q have the same baryon number $\frac{1}{3}$ as the old quarks. This assumption can be checked if and when baryons containing some new quarks Q are found. The reason for the assignment $\overline{6}^c$ rather than 6 for the new quarks is connected with baryonic states to be mentioned in the next section: With $B=\frac{1}{3}$ the representation $\overline{6}^c$ avoids fractional baryon number.

III. SIMPLE CONSEQUENCES

The first consequence which follows from our assignment of the ψ/J family to antisextet quarks is the contribution of these quarks to the total cross section of electron-positron annihilation into hadrons. Following the rule that the ratio R is the sum of the squares of the electric charges of all the quarks, we can compute the step in R contributed by the new quarks. The old quarks contribute $3\times\frac{2}{3}=2$ (where 3 is the color degeneracy of the old quarks), while the new quarks contribute $6\times\frac{2}{3}=4$, raising the total value of R to $2+4=6$ after the threshold for production of new quarks. This value is in rough agreement with experiment. Although this value of R can easily be obtained in many other ways, we stress that the new quarks have the virtue of predicting this rise in R in *a small energy range by necessity rather than accident, because of the relation between color and mass.*

From the rule of color confinement we can find the hadronic states expected in this model. Since only color-singlet states are allowed and $Q\in(3,\overline{6}^c)$, we expect a nonet of new mesons $Q\overline{Q}\in(1+8,1^c)$. Keeping to states with no orbital angular momentum these mesons can be pseudoscalar ($J^P=0^-$) or vector ($J^P=1^-$) mesons. Of the nine new vector mesons $Q\overline{Q}$, only three states can couple into the electron-positron-annihilation channel since the remaining six carry electric charge, or strangeness, or both. The new $Q\overline{Q}$ vector mesons are in one-to-one correspondence with the old vector mesons $\omega,\phi,\rho^0,\rho^+,\rho^-,K^{*+}$, $K^{*0},\overline{K}^{*0},K^{*-}$. We shall discuss in the next section a specific proposal for the assignment of the vector states which have been observed so far. Of the three states which can couple into the electron-positron-annihilation channel, two states have $I=0$ and one has $I=1$. So far no resonance with $I=1$ has been found in the ψ/J family, and until one is found the model we discuss is in trouble.

The color-confinement rule implies immediately that there are no mixed mesons, composed of new quarks Q and old antiquarks $\overline{q}$, since $\overline{6}\times\overline{3}=8+\overline{10}$ does not contain a color singlet. This is the main difference between the new quarks in our model and new flavored quarks.

In "ordinary" quark models, the mixed mesons $\overline{q}Q$ explain the threshold in R, namely the increase from $R\simeq 2.5$ to $R\simeq 5.5$ in the neighborhood of $\sqrt{s}\simeq 4$ GeV. It is also fairly well established experimentally that resonances above this threshold have widths of the order of 20–100 MeV, much larger than the narrow resonances $\psi/J,\psi'$ below 4 GeV. There are two logical possibilities for an explanation of this threshold in the model contemplated here. The threshold corresponds either to the production of pairs of Qqq baryons or the production of pairs of $Q\overline{Q}$ mesons. If (Qqq) baryon-antibaryon pairs are responsible for the threshold, then by baryon-number conservation these states would eventually decay into proton-antiproton pairs. This mechanism predicts a huge increase in the number of protons (or antiprotons) produced at $\sqrt{s}>4$ GeV, which is in fact not observed.[17] Therefore, one is forced to assign the threshold in electron-positron annihilation to the production of pairs of $Q\overline{Q}$ pseudoscalars which, therefore, must have a lowest-mass state of 1.8–2 GeV. At first this proposal sounds surprising, since it is generally believed that these states, called "paracharmonium," have masses much closer to the mass of ψ/J. In fact, our speculations about the masses of mesons composed of the new quarks which will be discussed in the next section also indicate that the mass of the pseudoscalar nonet of $Q\overline{Q}$ states is in the region of 2 GeV, so that even if we are wrong, we are at least consistent. How can we tell the difference between low-mass $Q\overline{Q}$ pseudoscalars and mixed mesons $Q\overline{q}$? One specific difference is that the pseudoscalar nonet of $Q\overline{Q}$ states contains three states which can decay into two photons, the analogs of π^0,η,η' composed of the new quarks. The two-photon decay mode of $\pi^0_{\overline{6}}$ may be its principal decay mode, if the Appelquist-Politzer mechanism[18] is the only strong decay mode of new mesons into old mesons—as will be discussed later, in Sec. 6. I am not certain about the mass splitting of the pseudoscalar nonet, in particular whether the $\pi^0_{\overline{6}}$ is the lowest-mass state in that multiplet, but in any case one would expect one of the three $I_3=0$ states, which can decay into two photons, to lie as low as about 2 GeV. Such a state would be very hard to accommodate in a model with new flavored quarks, while it is required in a model with new colored quarks.

From the rule of color confinement it follows that mixed baryons of type Qqq are allowed, but, on the other hand, QQq are forbidden. It is surprising that the same rule, which prohibits mixed mesons $Q\bar{q}$ tolerates some mixed baryons Qqq. The baryons Qqq belong to the multiplets $\{10, 2\}$, $\{8, 2\}$ or $\{1, 4\}$, $\{8, 4\}$, $\{1, 2\}$ in the notation $\{\mathrm{SU}_3, 2S+1\}$. This classification follows from the requirement of antisymmetry under exchange of the two quarks qq and color confinement. The states Qqq provide the rationale for choosing $\bar{6}^c$ rather than 6^c for the color representation of the new quarks Q. The choice 6^c would lead to states with fractional baryon number. As noted already by Ma,[10] the general rule is to have color representations for quarks of the same triality as the ordinary quarks 3^c.

IV. SPECULATIONS ABOUT MASS AND ASSIGNMENTS OF STATES

The spectrum of new $Q\bar{Q}$ mesons, in our model, is a repetition of the spectrum of the old $q\bar{q}$ meson. *Ignoring differences in flavor mixing* there is a one-to-one correspondence between old mesons and new mesons. The question therefore arises immediately: What is the relation between masses of states which are images of each other under change of quark color? We speculate here about this relation.

In view of the "charge" meaning of color it is natural to assume that the mass of physical particles depends on the color charge of quarks. Furthermore, it is also natural to expect that higher-dimensional representations of the color group correspond to higher masses: This rule agrees with the mass relation between leptons and ordinary hadrons. Since physical states are color singlets, the mass of a physical state can only depend on color-singlet operators constructed from quark color charge. The simplest possibility, consistent with these prejudices, is for mass to scale with quark color charge. I assume that the mass relation for a sequence of corresponding meson states is

$$M = A(F_c^2)^{3/2}, \tag{1}$$

where M is the mass of a meson in the sequence, A is a constant for the whole sequence of mesons, and F_c^2 is the color charge squared appropriate to the quarks composing the meson in question. The exponent $\frac{3}{2}$ is chosen for empirical reasons mentioned later.

The mass formula (1) makes sense in the MIT bag model[16] for hadronic masses although it is not required by this model. In the MIT bag model only hadrons composed of color-triplet quarks have been discussed so far. One can demand, nevertheless, that the bag mass formula scales under change of quark color. Then every single term in the bag mass formula should scale the same way. The easiest term to consider is the contribution for color magnetic interaction which, ignoring spin, looks like F_c^2/R. This term scales as shown in formula (1), provided R, the radius of the bag, scales like $(F_c^2)^{-1/2}$, under increase of color charge. It is not unreasonable to expect the bag to shrink if the quarks are more "charged", although the definite power does not follow from these considerations. To summarize, the conjectured formula (1) is based on some prejudices we subscribe to and on an empirical fact to be mentioned.

Given a sequence of representations of SU_3 color, formula (1) relates the masses of corresponding states in the sequence. For a triplet[19] $F_c^2 = \frac{4}{3}$, while for a sextet (or antisextet) $F_c^2 = \frac{10}{3}$ so that we can write

$$M_3 = (\tfrac{4}{3})^{3/2} A, \tag{2}$$

$$M_{\bar{6}} = (\tfrac{10}{3})^{3/2} A. \tag{3}$$

We now assume that the vector mesons composed of color-antisextet quarks have identical flavor mixings to the vector mesons composed of color-triplet quarks, in which case taking as input the mass of the ω meson, formulas (2) and (3) predict an isoscalar, vector meson of mass $M(\omega_{\bar{6}})$:

$$M(\omega_{\bar{6}}) = (\tfrac{5}{2})^{3/2} M(\omega). \tag{4}$$

From the mass of the ω, listed in the Particle Data Tables[20] as 782.7 MeV, formula (4) predicts a mass for the color image of ω of 3093.9 MeV. This is rather close to the mass of ψ/J of 3095 ± 4 MeV, so that we shall assume that the ψ/J is the $\omega_{\bar{6}}$ particle.

The reason for choosing the exponent $(\frac{3}{2})$ in the Eq. (1) is the resulting consequence (4). Therefore it is quite possible that Eq. (1) is wrong and Eq. (4) is an accident. The conjectured mass formula (1) has other consequences from (4) which we shall try to describe. The evidence available so far is insufficient to rule out (1) in my opinion.

If we take as input the mass of the ϕ vector meson, formulas (2) and (3) would predict an isoscalar vector meson of mass $M(\phi_{\bar{6}})$

$$M(\phi_{\bar{6}}) = (\tfrac{5}{2})^{3/2} M(\phi). \tag{5}$$

From the mass of ϕ, given in the Particle Data Tables,[20] formula (5) predicts a mass for the color image of ϕ of 4031 MeV. There is apparently[21] a state at 4.03 GeV, probably a vector particle, although its isospin is not known yet. We shall therefore assume that the state at 4.03 GeV is the color image of the ϕ.

Finally, one expects an isovector, vector meson $\rho_{\bar{6}}$, with a mass

$$M(\rho_{\bar{6}}) = (\tfrac{5}{2})^{3/2} M(\rho) . \tag{6}$$

Equation (6) predicts the color image of the ρ to be in mass near the ψ/J. There is no such state near 3100 MeV as far as is known, and one concludes either that the mass formula (1) is incorrect, or that the mass of the ρ meson is shifted relative to the prediction of formula (1). Here we shall follow this second alternative and comment only that (as opposed to the ω and ϕ) the ρ meson has a width which is not negligible compared to its mass. This fact could perhaps account for a shift towards lower values of the mass of the ρ by an amount of the order of its width. We shall assume that the $I = 1$ partner of the ω_6 and ϕ_6, which must exist if our model is viable, is one of the many states of mass near 4 GeV, or is yet to be found.

The isovector, vector meson $\rho_{\bar{6}}$ has probably a mass larger than 3.5 GeV, otherwise the decay $\psi' \to \pi^+ \rho_{\bar{6}}^-$ would have been noticed experimentally. If the $\rho_{\bar{6}}$ is below the threshold at 3.9–4 GeV, it presumably has a hadronic width only due to virtual-photon coupling, i.e., of the order three times its leptonic decay width. This statement assumes that the direct decay of $\rho_{\bar{6}}$ into hadrons cannot proceed through the Appelquist-Politzer[18] mechanism, since gluons cannot carry isospin. At first it would seem that if $\omega_{\bar{6}}$ is split from $\rho_{\bar{6}}$ by more than 400 MeV they should have quark compositions $U\bar{U}$ and $D\bar{D}$, respectively, rather than $U\bar{U} \pm D\bar{D}$ as assumed when applying formula (1). This argument is fallacious if the quarks U, D carry isospin and isospin is conserved as we assume.[22] The state with $I = 1$ is obliged to have the composition $U\bar{U} - D\bar{D}$ while the state with $I = 0$, if it contains no $S\bar{S}$, is the orthogonal combination.

We take the ψ' to be a radial excitation of ψ. This makes sense in any fermion-antifermion model, given the known (in fact predicted[3]) existence of positive-charge-conjugation states at 3.4–3.5 GeV. Note that there is no reason why formula (1) should work for radial excitations. This is rather analogous to the situation in molecular spectroscopy, where the vibrational ("radial" excitations of a molecule) frequencies of two different electronic states of a molecule are quite often very different and the frequency of an electronic transition between corresponding vibrational states is not a constant.

Given that ψ' is a radial excitation of ψ/J, one can compute the positions of other radially excited states. Tryon[23] has computed numerically from a relativistic wave equation the positions of further S-wave radial excitations, namely 4.13 GeV, 4.48 GeV, and 4.79 GeV. As far as we are concerned, it is interesting that this calculation does not conflict with our assignment of the state at 4.03 GeV with a mirror image of the ϕ.

There is one bad consequence of these assignments and, *a fortiori*, of formula (1). The leptonic decay widths of ρ, ω, and ϕ are in the well-known and understood ratio of 9:1:2. If the quarks U, D, and S have the same electric charges as the quarks u, d, and s (as we have tacitly assumed in our computation of R) and if the vector mesons $\rho_{\bar{6}}$, $\omega_{\bar{6}}$, and $\phi_{\bar{6}}$ have the same quark-flavor composition as ρ, ω, and ϕ [as we have assumed when stating that formula (1) is relevant], we would expect the same 9:1:2 ratio for the leptonic widths of the heavy vector mesons. In fact, $\psi/J\ (\equiv \omega_{\bar{6}})$ seems to have a much larger leptonic width than the $\phi_{\bar{6}}$ candidate at 4.03 GeV, and surely if $\rho_{\bar{6}}$ were to have a leptonic width 9 times that of ψ/J, it would have been found a year ago. I do not know the solution of this problem. In any case, until an isovector partner for ψ/J is found in the mass range 4 ± 0.5 GeV the model described here is in difficulty.[24]

We now turn to pseudoscalar mesons. As mentioned in the previous section, the threshold in R demands that the mass of pseudoscalars $Q\bar{Q}$ lies in the range of 1.8–2.2 GeV. This is consistent, in an average sense, with mass formula (1). The average mass of the old pseudoscalar nonet is about 450 MeV, so that $4 \times 450 \simeq 1.8$ GeV. To apply formula (1) to individual pseudoscalars we require that the mixing of U, D, S quarks in $Q\bar{Q}$ mesons be identical to the mixing of $q\bar{q}$ mesons. The mixing of old pseudoscalars is just beginning to be understood,[25] and it is not clear whether the mixing of all pseudoscalars will be the same. For the K mesons, because we claim strangeness is the same for Q and q quarks, there has to be identical mixing in the $Q\bar{Q}$ and $q\bar{q}$ sectors and formula (1) would predict the analog $K_{\bar{6}}$ states at 1.937 GeV. For $I = 1$ states $\pi_{\bar{6}}$ formula (1) predicts a mass much too low to be believed, so that one is left with little predictive power about the $\pi_{\bar{6}}$ state. This also makes the masses of $\eta_{\bar{6}}, \eta_{\bar{6}}'$ uncertain.

The predicted large mass splitting between pseudoscalar and vector states makes sense also from the point of view of the bag model—if the quarks are antisextet in color. The splitting between $S = 0$ and $S = 1$ states is due to color magnetic interaction, which is larger in a $\bar{6}^c 6^c$ state both on account of the higher color charge and the smaller size of the system, when compared to a $3^c \bar{3}^c$ state. In summary, I do not know if formula (1) works exactly for pseudoscalars, but roughly its predictions are of the correct order of magnitude to explain the threshold in R.

The physical picture corresponding to formula (1) is one in which quarks are massless objects and the mass of a physical particle resides entirely in the interaction between quarks. This is consistent with viewing quarks as fictitious objects which are useful to label the states in the model. The view that mass arises entirely from interactions is ancient prejudice: Formula (1) is a particularly simple way of expressing that prejudice.

V. SPECULATIONS ABOUT HIGHER ENERGIES

In the classification scheme proposed here, one would order known $J=1$ states as follows:

(a) orthopositronium and orthomuonium, states of zero mass on the scale discussed here, composed of unconfined leptons which are colorless;

(b) old vector mesons (ρ, ω, ϕ), states of about 0.7–1 GeV in mass, composed of confined, color-triplet quarks;

(c) new vector mesons $(\psi/J, \psi', \ldots)$, states of about 3–4 GeV in mass, composed of confined, color-antisextet quarks.

There is an abvious correspondence between the mass of vector mesons and the color of their constituents, more color charge leading to higher mass.

A priori, there is nothing to prevent the existence of even heavier vector mesons, and I presume this is one reason why larger storage-ring machines are being built. If further narrow resonances will be found, we would classify them as being composed of quarks corresponding to higher representations of the color group. Associated with such narrow resonances there should be thresholds in the cross section of electron-positron annihilation. If hadronic mass indeed has its origin entirely in the color interaction of constituents, as we suppose, the higher-mass narrow resonances *must* correspond to higher representations of SU_3 color. *Therefore, the change in R corresponding to higher-mass resonances is larger the higher the mass of the resonance.* This rough quantitative conclusion holds in other models for color, or with different mass formulas provided mass increases with color charge.

More precisely, the conjectured formula (1) predicts the masses of an infinite number of vector mesons (provided they exist) and correlates them to the contribution of the respective quarks to the rate of electron-positron annihilation. If we consider representations of SU_3 color of the same triality as 3 and $\overline{6}$, the next few representations are 15′, 15, and $\overline{21}$. For these representations, formula (1) predicts the following masses:

$$M(\omega_{15'}) = (4)^{3/2} M(\omega) \simeq 6.26 \text{ GeV},$$

$$M(\omega_{15}) = (7)^{3/2} M(\omega) \simeq 14.49 \text{ GeV},$$

$$M(\omega_{\overline{21}}) = (10)^{3/2} M(\omega) \simeq 24.75 \text{ GeV}.$$

For the 15 and 15′ representations the associated rise in R is 10 units, while for the $\overline{21}$ representation it is 14 units. There is no sign[26] of a resonance at 6.26 GeV in electron-positron annihilation at SPEAR, nor an associated rise of R of 10 units, so that we conclude either that there is no 15′-plet or that the mass formula (1) is false. The other two possibilities ω_{15} and $\omega_{\overline{21}}$ are in the energy range covered by the new storage rings PETRA and PEP so that we should perhaps reserve judgement for a while until we can discard formula (1) for good.[27]

There is one other prediction we can make if we believe formula (1) holds roughly for pseudoscalar as well as vector mesons. In that case, we can forecast the position of the thresholds associated with the new colors: Roughly, they correspond to the recurrences of the ϕ resonance, which experimentally is quite close to the threshold at 4 GeV, if we believe formula (5). Therefore, the energy spacing between higher resonances and the associated thresholds is larger, which will leave room for more narrow radially excited states, when compared with the $\psi/J, \psi'$.

The discussion in this section reveals a particular weakness of our considerations: We can either claim to understand the mass or claim to understand which representations of SU_3 color will show up, but not both. Of course, it may also turn out that we do not understand either of these subjects.

VI. INTERACTIONS OF NEW QUARKS

The primary task of this investigation was to discuss the spectroscopy of the new particles with minimal prejudices about the interactions of their constituents. As a result, the following considerations about these interactions are much more tentative, unsatisfactory, and incomplete. We outline simple logical possibilities which were arrived at from the requirement of consistency with the assumptions discussed so far.

Old quarks interact with a color octet of vector gluons, believed to be responsible for quark confinement. This gluon octet can couple just as well to antisextet quarks, and therefore if the confinement of color-triplet quarks is proven, that proof will carry over to antisextet quarks. The same coupling allows the annihilation of a quark-antiquark pair into gluons. This process has been investigated carefully by Appelquist and Politzer[18] who predicted the narrow width of the ψ/J particles. I shall assume that their reasoning holds also for antisextet quarks. There is one interesting consequence which arises from the assumption that gluons do not carry flavors like electric charge, isospin, or strangeness. As a result, meson states which carry a flavor will be stable against strong decay into states composed of old quarks. If there are no other strong-decay mechanisms available, these mesons are obliged to decay weakly, (or electromagnetically, as in $\pi^0_{\bar{6}} \to \gamma\gamma$), by the weak annihilation of $Q\overline{Q}$ pairs into leptons, or leptons plus old hadrons, or old hadrons. Therefore the mere observation of a meson which decays weakly, say leptonically, does not imply automatically that a new extra flavor has been discovered. This implication can only be drawn if any other degrees of freedom apart from new flavors are ruled out from the beginning. The present model by allowing new colors does, therefore, get by without new flavors, and can *in principle* explain the so-called "dimuon events" and other neutrino-induced interactions leading to weak decays. However, the explanation we just described relies entirely on flavorless gluons as the only strong communication channel between new and old quarks. This mechanism can be a candidate for explaining, say, "dimuon" events, provided neutrinos can produce $Q\overline{Q}$ mesons off ordinary hadrons.

The electromagnetic interactions of the new quarks Q are fairly straightforward—they only depend on the electric charges and magnetic moments one associates with these quarks. The magnetic moments have to be fairly small so as not to lead to any difficulties with the enormous mass splitting we predict between the vector and the pseudoscalar states by giving too large radiative decay rates $V \to P\gamma$.

The weak interactions appear to be rather difficult to discuss in a consistent manner. The main requirement is consistency with color confinement, and we shall forbid any process which violates color confinement in the actual final physical states. This still allows many interactions some of which will be discussed in the next section on the Glashow-Iliopoulos-Maiani (GIM) mechanism.[2]

One particular difficulty, which probably prevented many people from seriously considering the classification discussed here, is the decay of baryons of type Qqq, whose existence is allowed by the color-confinement rules, but whose decay is forbidden in some models for weak interactions. Therefore some states Qqq appear to be absolutely stable in some weak decay schemes. While I share the prejudice against absolutely stable baryons heavier than the proton, I do not see any general principle to rule them out. Atomic spectroscopy abounds with examples of excited states of atoms (so called metastable states) which are stable against radiative decay by single-photon emission into any lower-energy state. These atomic states usually decay by very slow two-photon emission or by collisions with other atoms. While this is not an argument in favor of the existence of such baryons, it shows that we should not attach too much weight to their emergence. The example also suggests that there may well be rare decay mechanisms normally not seen, which make these states metastable rather than truly stable.

If one insists, a particular way to prevent the stability of Qqq states is to allow the process $Q \to q$ + gluon, for instance, at semiweak strength. Then $Qq \to qq$ at a strength comparable to weak interactions. There are at least two objections to this proposal: The first is that it leads to the process $Q\overline{Q} \to q\overline{Q}$, which is forbidden by color confinement. However, one can allow $Q \to q$ + gluon while forbidding $Q\overline{Q} \to q\overline{Q}$. This is not as arbitrary as it seems at first. We can think of colored states having a very high mass and then $Q\overline{Q} \to q\overline{Q}$ is not really forbidden, just not energetically possible. The second objection against the process $Q \to q$ + gluon is that it apparently violates gauge invariance, since the quarks Q and q have different masses. As discussed in Sec. IV the quarks Q and q really have zero mass and the mass of physical states resides in the interaction between the quarks. Therefore this objection presumably need not rule out the process $Q \to q$ + gluon. The reason I would like to allow this process is not in order to make heavy-baryon decay possible, but because it removes all arbitrariness in assigning flavor quantum numbers to the new quarks. Needless to say, this is not a physical argument in favor of the existence of such a process.

VII. WEAK INTERACTIONS AND STRANGENESS-CHANGING NEUTRAL CURRENTS

The argument of Glashow, Iliopoulos, and Maiani[2] on the role of an additional ("charmed") quark in cancelling $\Delta S = \pm 1$ hadronic neutral currents is too well known to be repeated here. One of the questions which arises immediately from their argument is whether the new charged quark is obliged to form bound states with the old quarks. In a color-confinement model this question translates to: Is the new quark(s) responsible for the

GIM mechanism a color triplet, or could this quark perhaps belong to some other representation of the color group? It turns out that there is a choice and therefore the GIM (Ref. 2) solution to the question of strangeness-changing neutral currents is not the only possibility.

The standard solution[2] *assumes* that the weak vector bosons $W^\pm$ are color singlets. Then there is no other choice since at the vertex qWQ only a color-triplet quark Q can couple—and thus the charmed quark—which is then obliged to bind to the old quarks since it can form color-singlet states.

However, if one wants to, one can allow $W^\pm$ bosons which are linear combinations of color singlet and color octet. This is similar to the situation of the photon with respect to isospin. As a result weak interactions are allowed to break color. Then, at the vertex qWQ the new quark Q can be a color-antisextet quark since 3×8 contains $\overline{6}$. Therefore, the cancellation of strangeness-changing neutral currents could be due to antisextet quarks rather than charmed quarks. One can check that the commutator of two color-octet charged currents, e.g., $[s\overline{U}, U\overline{d}]$, where I dropped the color indices, does contain a color-singlet term $s\overline{d}$. To conclude, the observed suppression of strangeness-changing neutral currents does not distinguish between charmed quarks and color-antisextet quarks. It is the assumption that the W boson is a color singlet which renders the GIM solution unique.

It should be emphasized that the hypothesis of color confinement does not force one to take color-singlet W's, although color-singlet W's are the simplest logical possibility. It would appear at first that one cannot take color-breaking W's without violating color confinement, for instance, that $Q\overline{Q}\to q\overline{Q}\mu\nu$ is allowed by a W which is color breaking. This argument is fallacious, as may be seen from considering the $q\overline{Q}$ state as being not forbidden but just very heavy. In that case $Q\overline{Q}\to q\overline{Q}\mu\nu$ is not allowed because of energy conservation. We can summarize the message of this example as follows: *W's can change the color of quarks but overall color confinement has precedence.*

Strictly speaking, if the number of quarks diverges, as was assumed by Cabibbo *et al.*,[7] there is no need for W bosons, as weak processes became damped by the large number of final states, at high energies. This was discussed for the weak annihilation of an antineutrino on an electron by Kabir *et al.*[28] However, the language of W bosons is convenient, and in any case, conclusions reached in a language with W bosons have a close translation into a language without W bosons, as was emphasized recently by Bjorken.[29]

VIII. SUMMARY OF EXPERIMENTAL EXPECTATIONS AND CONCLUSIONS

The classification proposed here for the family of ψ/J particles makes two predictions at presently available energies which are crucial if this classification is to be believed:

(a) There should be an $I=1$ partner for the ψ/J and $\psi''(4.03)$ in the same mass region. This prediction tests that the new quarks Q form indeed an SU_3 flavor triplet as conjectured.

(b) There should be pseudoscalar partners of ψ/J in the 1.8–2.2 GeV energy region some of which can decay into two photons. These "paracharmonium" states test that the spin-spin coupling in a new $Q\overline{Q}$ state is much stronger than in an old $q\overline{q}$ state, and therefore that the new quarks carry higher color charge than the old quarks.

As regards higher energies which will be available at the new storage-ring machines, our classification of the ψ/J provides a framework for higher-mass vector states and predicts the following:

(c) If higher-mass vector mesons exist, the change in the electron-positron annihilation rate at the threshold associated with these higher mesons is greater ($\Delta R \gtrsim 4$) than that observed near the ψ/J ($\sqrt{s}\sim 4$ GeV). This prediction tests the validity of our assumption about the relation between color and mass.

Finally, if the color group of quarks is indeed SU_3, and our conjectured mass formula for vector mesons correct, we have favored energies, mentioned in Sec. V, at which to find the new vector mesons.

The classification scheme proposed here is extremely attractive, *a priori*, in several respects. In the first place this is an economical scheme, since no new symmetry or conserved flavor has been introduced. We only use the old SU_3 flavor group of Gell-Mann and Ne'eman and the SU_3 color group. Secondly, this classification offers the hope of understanding the mass of hadronic states by correlating it to the color charge. Thirdly, a sensible spectroscopic classification results, with particles of widely different masses belonging in different multiplets, as they should. There are also some *a posteriori* advantages. For example, in many recent attempts to understand CP violation, models with six quarks appear natural, as was noted by Pakvasa and Sugawara and by Maiani.[30] With color excitation the number of quarks grows from three to six in a natural way.

The main advantage of a scheme with color excitation for quarks in my opinion is that of providing a simple framework for further narrow resonances and changes in R. Energies as large as 30 GeV in the center-of-mass system for electron-positron annihilation will be available in a few years time. All interpretations of the new particles will be tested by their predictive power at these higher energies.

Quite apart from these advantages, our proposal as elaborated here is very incomplete in many respects, for instance, as regards

(a) the weak interactions of new quarks,

(b) the arbitrariness in the distinction between physical and unphysical representations of SU_3 color, and

(c) the question of flavor mixing of mesons composed of new quarks.

Much more work is required to deal with these and other obvious questions which are introduced by this proposal.

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