Diquark color excitation and the narrow resonances

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The new narrow resonances are interpreted in the three-triplet model with integral baryon numbers as diquark color excitations of the $qq \pm \bar{q}\bar{q}$ type. Hadronic decays, γ transitions, and coupling to γ occur through impurity $q\bar{q}$ admixtures. Except for the coupling to γ, all decay rates are suppressed. The enhancements above 4 GeV in hadronic cross sections are attributed to $q\bar{q}$ color octets or still higher diquark levels.

The exciting discovery a year ago of two narrow resonances,[1] J/ψ and ψ', has led to uncovering of many new states which include, up to now, the χ's at 3.5 and 3.4 GeV, a possible pseudoscalar at 2.8 GeV, and broader enhancements around 4.1 and 4.3 GeV. It also has spawned many theoretical attempts involving new hadronic degrees of freedom such as charm and color.[2] In this paper we would like to point out that in the three-triplet model[3] with unconfined color there exists an entirely new family of mesons corresponding to two-body color excitations of the qq type which are color triplets and sextets in addition to the standard $q\bar{q}$ type (color singlets and octets). We will thus interpret the various narrow resonances as bound states of diquarks.

In a model with integrally charged quarks, baryon numbers may be either fractional or integral. With the fractional baryon numbers, the qq configuration is of no use. As we have previously investigated, the case of integral baryon numbers leads to the possibilities of unstable quarks decaying into ordinary baryons, antibaryons, or leptons and of an appreciable mixing between quarks and antiquarks having the same Q, Y, B, and L quantum numbers.[4] With the baryon number assignments (a) $B=(0,0,1)$ or (b) $B=(-1,1,1)$ for the color index 1, 2, 3 (or red, green, blue), the diquark states consisting of red and green quarks have $B=0$ as well as the red-blue combination for the case (b). In general, the baryon numbers will be 0, 1, 2 for the case (a), and 0, −2, 2 for the case (b). Furthermore, the case (a) allows for a simultaneous assignment of lepton numbers to these quarks, say, $L=(1,-1,0)$. The qq states with $B=L=0$ correspond to new types of mesons which we are going to explore below.

According to our mass formula,[5] the two-quark color excitations occur in the order $qq(3)$, $q+\bar{q}$ threshold, $q\bar{q}(8)$, and $qq(\bar{6})$, arranged in increasing order of the Casimir operator of SU(3)′. The color octet and sextet are unbound resonances, but the triplet qq is a bound state which is the lowest, color excitations beginning at the 2–3 GeV region. Higher color excitations begin to set in above 4 GeV, where the cross section $\sigma(e^+e^- \to \text{hadrons})$ rises markedly. The qq meson states will be subjected to a q-$\bar{q}$ mixing, namely a transition $q \leftrightarrow \bar{q}$, which we assume to be induced by a short-range interaction between the quarks, with a characteristic distance small compared to the size of the bound system. (See comments at the end of the paper.) This allows the wave function to have an appreciable $q\bar{q}$ (octet) admixture at the origin, which enables it to couple to the photon. But the outer part of the wave function is purer and the decays to ordinary hadrons (with or without a photon) are strongly suppressed. The narrow resonances are then identified with the states $qq \pm \bar{q}\bar{q}$, depending on whether C (charge conjugation) $=\pm 1$. In this picture any broad resonances above 4 GeV could be interpreted as either a geniune color octet or still higher levels of $qq\pm\bar{q}\bar{q}$. Furthermore, if we assign lepton numbers as well, the anomalous μe events reported from SPEAR[6] could be attributed to a pair of produced free quarks carrying lepton number $L=\pm 1$.

In contradistinction to the 81 $q\bar{q}$ states which break up into (1, 1), (8, 1), (1, 8), and (8, 8), the 81 qq states consist of 27 color triplets, $(\bar{3}, 3)$ and (6, 3), and 54 color antisextets, $(\bar{3}, \bar{6})$ and $(6, \bar{6})$, under the SU(3)′ × SU(3)″ or $\text{SU}(3)_f \times \text{SU}(3)_c$ (c = color; f = flavor). The color antisextets lie above the $q\bar{q}$ octet threshold and will not be considered here any further. Owing to the overall Pauli principle, the S states of $(\bar{3}, 3)$ have spin 0 while the spin is 1 for the (6, 3) S states. Assuming (6, 3) to lie somewhat higher, we will take the $(\bar{3}, 3)$ states to be the lowest-lying diquarks. The flavor-color parts of the wave functions of the $(\bar{3}, 3)$ nonet consist of the $(\bar{3})$ flavor components, $(2)^{-1/2}(\mathcal{N}\lambda - \lambda\mathcal{N})$, $(2)^{-1/2}(\mathcal{P}\lambda - \lambda\mathcal{P})$, and

$(2)^{-1/2}(\mathcal{P}\mathcal{N}-\mathcal{N}\mathcal{P})$, for each of the 3 color components, $(2)^{-1/2}(\overline{2}\overline{3}-\overline{3}\overline{2})$, $(2)^{-1/2}(\overline{1}\overline{3}-\overline{3}\overline{1})$, and $(2)^{-1/2}(\overline{1}\overline{2}-\overline{2}\overline{1})$. With the baryon-number assignment[7] $B=(0,0,1)$, i.e., $B=\frac{1}{3}A+Y_c$, where A is the quark number ($=\pm1$ for q and $\overline{q}$, respectively), the three states, $\frac{1}{2}[\mathcal{N},\lambda][\overline{1},\overline{2}]$, $\frac{1}{2}[\mathcal{P},\lambda][\overline{1},\overline{2}]$, and $\frac{1}{2}[\mathcal{P},\mathcal{N}][\overline{1},\overline{2}]$ have $B=0$. They all have the color isospin $I_c=0$ and positive intrinsic parity; the quantum numbers for charge Q, hypercharge $Y=Y_f+Y_c$, and flavor isospin I_f are $(-1,-1,\frac{1}{2})$, $(0,-1,\frac{1}{2})$, and $(0,0,0)$, respectively. In this way, only one state, $\frac{1}{2}[\mathcal{P},\mathcal{N}][\overline{1},\overline{2}]$, is singled out as the neutral state with $B=Q=Y=0$; it also has $I_f=I_c=0$.

The l-excited qq states have quite different spectra from those of $q\overline{q}$ states. The difference in intrinsic parity, the connection between l and spin due to statistics, and the presence of both charge-conjugation parities, lead to J^{PC} quantum numbers not available in the $q\overline{q}$ sector and vice versa. As shown in Table I, 1^{+-} and 1^{++} states are totally missing whereas the diquark states with 0^{+-}, 0^{--}, 1^{-+}, and 2^{+-} are now present. We will call these $qq\pm\overline{q}\overline{q}$ states without $q\overline{q}$ analogs "exotic." These exotic states do not couple to an ordinary meson or a photon, but can certainly participate in hadronic transitions between diquark states, and may provide an explanation for the "missing" decay modes of $\psi'(3684)$. In general, these states will be very narrow. The existence of such exotic narrow states is one of the striking features of our model.

For further characterization of the diquark states, it is necessary to specify the pattern of symmetry breaking in strong interactions. We assume that the q-$\overline{q}$ mixing is a main agent of symmetry breaking, but it is of such a nature as to preserve Y, I_f, and I_{c3}. What is specifically violated is A (quark number) and I_c, the latter satisfying $\Delta I_c=0$ and 1. Accordingly we can define a G parity with respect to flavor only, i.e., $G=C\exp(i\pi I_{f2})$, which will be a good quantum number of strong interactions. It is also instructive to define charge reflection $R=\exp[i\pi(I_{c2}+I_{f2})]$, since the electromagnetic current in $Y=0$ sector is odd with respect to R.

The diquark states under consideration have $I_f=I_c=Y=0$, $R=\pm1$, and $C=G=\pm1$ (respectively for $qq\pm\overline{q}\overline{q}$). The γ transitions between $C=\pm1$ levels are forbidden in zeroth order because it requires a change of R. Hadronic transitions allow only emission of mesons in an $I=0$ state. Hadronic decays, γ transition, and coupling to γ can only occur through an impurity $q\overline{q}$ configuration. This impurity is concentrated near the origin of the wave function, and consists of $(I_f,I_c,R)=(0,0,+)$ and $(0,1,-)$ pieces according to our assumption. The former couples exclusively to hadrons, whereas the latter couples exclusively to the photon. The γ transitions between the two pieces mediate those of the host levels. Except for the coupling to γ, all decay rates can be suppressed because of the reduced phase space of the impurity.

Without going into the detail of the bound-state problem, a possible spectrum is shown in Fig. 1. We have assumed a sizable spin-orbit splitting, but each pair of levels with $C=\pm1$ is nearly degenerate because the splitting is a second-order effect through the $q\overline{q}$ impurity. With $^3P_0$ and $^3P_1(\psi)$ being identified with $P_c(2750)$ and $\psi(3095)$, respectively, the $^3P_2$ will be at ~3.8 GeV and is not shown in the figure. The $\psi'(3685)$ is identified with the first radial recurrence of $^3P_1$ and is denoted by $1^{--\prime}$; similarly, the first radial recurrence of $^3P_0(0^{-+\prime})$ is located in the 3.4–3.5 GeV region which contains the $^1S_0(0^{++})$ and $^1D_2(2^{++})$ levels as well. These three states in the 3.4–3.5 GeV region may be interpreted as the three χ states, $\chi(3530)$, $\chi(3410)$, and P_c or $\chi(3500)$.[8] The $^3P_0$ ground state is a natural candidate for $P_c(2750)$.[9,10] As for exotic levels, they are indicated by dashed lines in Fig. 1. They can be reached from higher nonexotic levels by hadronic transition. For example, $\psi'\to0^{--}(2.8?)+\eta$ followed by $0^{--}\to\rho+\pi,\ \omega+\eta$. This results in $2\pi^+2\pi^-2\pi^0$ (G-parity violating) and $3\pi^+3\pi^-3\pi^0$ decay modes of ψ'. In the case of 1^{-+}, we have $\psi'\to1^{-+}(3.1?)+\pi^+\pi^-\pi^0$ followed by $1^{-+}\to\sigma+2\pi,\ \rho+\rho$, etc., which will ap-

TABLE I. Quantum numbers of some low-lying $qq\pm\overline{q}\,\overline{q}$ states with corresponding $q\overline{q}$ analog states.

L	S	qq	J^{PC} of $qq-\overline{q}\,\overline{q}$	$q\overline{q}$ analog	J^{PC} of $qq+\overline{q}\,\overline{q}$	$q\overline{q}$ analog
0	0	$^1S_0$	0^{+-}	···	0^{++}	$^3P_0$
		$^3P_0$	0^{--}	···	0^{-+}	$^1S_0$
1	1	$^3P_1$	1^{--}	$^3S_1, {}^3D_1$	1^{-+}	···
		$^3P_2$	2^{--}	$^3D_2$	2^{-+}	$^1D_2$
2	0	$^1D_2$	2^{+-}	···	2^{++}	$^3P_2$

pear as $\psi' \to 3\pi^+3\pi^-\pi^0$, $2\pi^+2\pi^-3\pi^0$, $\pi^+\pi^-5\pi^0$, etc.

More quantitative estimates of the decay rates are difficult to make without a precise dynamical theory. We will make a working assumption that before applying any special suppression mechanism, the zeroth-order theory roughly scales with the mass of a particle considered in comparison with a typical ordinary hadron. This means that we compare the coupling strength to γ, the electric and magnetic dipole moments, etc., of the diquark state against those known for ordinary mesons (0^- and 1^-) by applying appropriate dimensional factors. This is consistent with the nonrelativistic picture of diquarks consisting of weakly bound heavy quarks. Any extra suppression factors one finds after such zeroth-order estimates will then be attributed to the special suppression mechanism. In this way we conclude that the special suppression factors are $F_\gamma \simeq 1-10^{-1}$ for coupling to γ, $F_{\text{trans}} \simeq 10^{-1}-10^{-2}$ for transitions, and $F_h \simeq 10^{-3}$ for coupling to hadrons. Pitted against them are essentially two impurity $\bar{q}\bar{q}$ amplitude concentration factors $f_1(r)$ and $f_0(r)$ for $I_{c3}=1$ and 0, respectively, which are functions of the interquark distance. Then $f_1(0)^2 = F_\gamma$, $|\langle f_1 f_0\rangle|^2 = F_{\text{trans}}$, and $|\langle f_0\rangle|^2 = F_h$, where the averages are over appropriate transition operators. It seems reasonable to simplify them as $f_1^{\,2}(0) = F_\gamma$, $f_1^{\,2}(0)f_0^{\,2}(0)\epsilon = F_{\text{trans}}$, $f_0^{\,2}(0)\epsilon' = F_h$, where ϵ and ϵ' are effective fractions of the volume over which the $\bar{q}\bar{q}$ impurity is appreciable. ϵ' will be smaller than ϵ if hadrons are larger: $\epsilon'/\epsilon \simeq 10^{-1}$, say. Thus we find $f_1^{\,2}(0) \simeq 1-10^{-1}$ and $f_0^{\,2}(0)\epsilon \simeq 10^{-1}-10^{-2}$ as a possible solution.

We now turn our attention to broader aspects of the model. First of all, the enhancements above 4 GeV in hadronic cross sections can be attributed to other $q\bar{q}$- and qq-type excitations which are above the free-quark threshold. The threshold must then be slightly above ψ', say 3.8 GeV. These other excitations are color triplet, octet, and sextet. The octet excitations have been extensively discussed in the literature.[11] The triplet and sextet diquark states are similar to the narrow states we have already discussed, but with I_c and I_f both being 0 or 1. Their hadronic widths are still suppressed compared to those for the octet, but γ transitions with ΔI_c or $\Delta I_f \neq 0$ will not be suppressed.

The well-known ratio R characterizing the size of hadronic cross section $\sigma(e^+e^- \to h)$ is equal to 4 in the asymptotic sense, and this poses an obvious, if not necessarily fatal, problem. There will also be contributions expected from charged gluons, with an unknown threshold. A much more serious question is in the baryonic color spectrum. So far, no threshold effects have been observed in

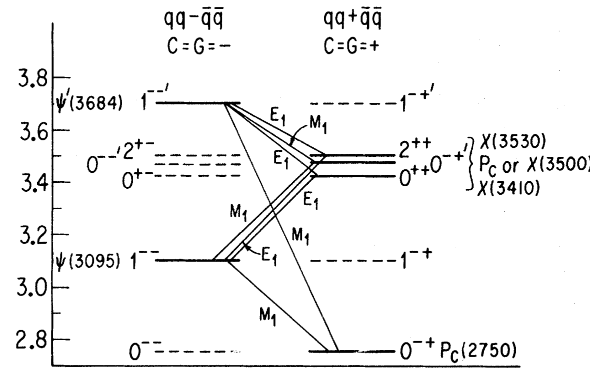

FIG. 1. A schematic diagram of $qq \pm \bar{q}\bar{q}$ (diquark) states anchored at the $I_f = I_c = 0$ state of $(\bar{3}, 3)$. The "exotic" states are shown in dashed lines. The connecting lines indicate γ transitions (E_1 and M_1 for electric and magnetic dipole, respectively).

electromagnetic, weak, or hadronic excitation of nucleons, whereas we expect, for example, an increase by a factor of about 2 in the inclusive ep cross section above the color threshold. We do not attempt here to offer a solution out of this difficulty.[12]

Restricted to the e^+e^- reactions, however, the present model has a few more intriguing possibilities. As we have mentioned at the beginning, the reported heavy leptons might actually be free quarks carrying lepton numbers and decaying into three leptons or a lepton plus hadrons.[13] This must be due to a new type of weak interactions, and how to deal with electron and muon number assignments also remains an open question. A less drastic possibility is, of course, to assign only baryon numbers to the quarks, say $B=(-1, 1, 1)$. In any case, there will be a tendency for formation of a pair of jets, initiated by free quarks, when available energy is sufficiently high.

In hadronic reactions, creation of colored states are to be expected. There will be a host of them having various combinations of Q, B, Y, etc. In particular, the eighteen narrow states belonging to $qq(\bar{3}_f, 3_c)$ and $\bar{q}\bar{q}(3_f, \bar{3}_c)$ may be produced in pairs.

On the theoretical side, some interesting questions remain regarding the symmetry breaking. For example, we may postulate that the q-$\bar{q}$ mixing is induced by a heavy neutral boson coupled to a Pauli-Gürsey current. Such a current can be constructed from combinations like $\bar{q}_\alpha\gamma_\mu q_\alpha + \bar{q}_\beta\gamma_\mu q_\beta$, where $q_\alpha = \mathcal{P}_1\cos\theta + \gamma_5\mathcal{N}_2^c\sin\theta$, $q_\beta = \mathcal{N}_1\cos\theta - \gamma_5\mathcal{P}_2^c\sin\theta$ (c stands for charge conjugate). This will produce the mixing not only in the quark self-energy but also as an interaction effect.

Even though our discussion of the color-excited diquark states is restricted in this paper only to the case involving three flavors, it should be remarked that the existence of $qq\pm\overline{q}\overline{q}$ diquark meson states, with their characteristic narrow widths, q-$\overline{q}$ mixing, and J^{PC} properties, is a natrual consequence of an unconfined quark model with integer charges, and integer baryon and lepton numbers, independent of the number of flavors. With more than three flavors, the number of diquark states will, of course, proliferate.

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[1]J. J. Aubert *et al*., Phys. Rev. Lett. 33, 1404 (1974); J.-E. Augustin *et al*., *ibid*. 33, 1406 (1974); G. S. Abrams *et al*., *ibid*. 33, 1453 (1974).

[2]The overall experimental and theoretical situation up to August, 1975 has been reviewed by many invited talks (R. Schwitters, G. Abrams, G. Feldman, B. Wiik, F. Gilman, H. Harari, etc.) in *the Proceedings of the 1975 International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California,* edited by W. T. Kirk (SLAC Stanford, 1976).

[3]M.-Y. Han and Y. Nambu, Phys. Rev. 139B, 1006 (1965); Y. Nambu, in *Preludes in Theoretical Physics,* edited by A. de-Shalit, H. Feshbach, and L. van Hove (North-Holland, Amsterdam, 1966), p. 133.

[4]Y. Nambu and M.-Y. Han, Phys. Rev. D 10, 674 (1974), Sec. III, Eqs. (23)–(25). See also J. Pati and A. Salam, Phys. Rev. Lett. 31, 661 (1973); they discuss the possibility of quarks decaying into leptons.

[5]Y. Nambu and M.-Y. Han (Ref. 4), Eq. (26) and Table II.

[6]M. L. Perl *et al.*, Phys. Rev. Lett. 35, 1489 (1975).

[7]Assignments other than this will be discussed elsewhere.

[8]W. Braunschweig *et al.*, Phys. Lett. 57B, 407 (1975); G. J. Feldman *et al.*, Phys. Rev. Lett. 35, 821 (1975); W. Tanenbaum *et al*., *ibid*. 35, 1323 (1975).

[9]B. Wiik, in *Proceedings of the 1975 International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California,* edited by W. T. Kirk (SLAC, Stanford, 1976).

[10]Theoretically one might suggest that $\chi(3410)$ is actually a radial excitation of $^1S_0(0^{++})$, in which case there should be two states, 0^{++} and 0^{-+}, below $\psi(3095)$. $P_c(2750)$ could be identified with either of the two. For possible experimental evidence, see F. Winkelman, LRL Phys. Notes TG-254, Berkeley, 1975 (unpublished).

[11]For example, I. Bars and R. D. Peccei, Phys. Rev. Lett. 34, 985 (1975); Phys. Rev. D 12, 823 (1975); M. Krammer *et al., ibid*. 12, 139 (1975); A. I. Sanda and H. Terazawa, Phys. Rev. Lett. 34, 1403; G. Feldman and P. Matthews, *ibid*. 35, 344 (1975).

[12]An answer to this question has been proposed by J. Pati and A. Salam within their framework of broken gauge theory of color (Ref. 4) [J. Pati and A. Salam, Phys. Rev. Lett. 36, 11 (1976)].

[13]The Pati-Salam theory (Ref. 4) also envisages similar processes as ocurring. In their theory, even the proton would be unstable because baryon-number contribution is spontaneously broken. For the moment, we leave this as an open question.