New e^+e^- resonances and classification of hadrons by color

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We discuss the possibility of identifying new e^+e^- resonances with colored hadron states in the case of strongly broken color SU^3 symmetry, and the ensuing classification of the hadrons.

The discovery of new narrow resonances in the e^+e^- system[1] has immediately raised the question of their nature. In this article we consider one of the variants of identifying these resonances with colored hadrons.

If $\Psi(3105)$ and $\Psi'(3695)$ are produced by a photon, then it is necessary to consider first of all the "color structure" of the electromagnetic current. The general form of the current, in which the usual (singlet with respect to color SU^3) particles preserve the correct charges, has the following structure (see, e.g.,[2]):

$$J_{em} = \left(F_3 + \frac{F_8}{\sqrt{3}}\right) I + I\,(xF^3 + yF^8), \tag{1}$$

where the first matrices pertain to the usual SU_3 group and the second to the color SU^3 group, while I is a unit matrix. x and y, generally speaking, are arbitrary numbers which will be chosen by us later on. The second term of (1) leads to a shift of the charges of the quarks for the red (first), yellow (second), and blue (third) colors by respective amounts $\alpha_1 = (1/2)(x + y/\sqrt{3})$, $\alpha_2 = (1/2)(-x + y/\sqrt{3})$, $\alpha_3 = -y/\sqrt{3}$, $\alpha_1 + \alpha_2 + \alpha_3 = 0$.[1)]

The first part of the electromagnetic current (1) is responsible for the transition of the photon into the ordinary vector mesons ρ, ω, and ϕ; the second part corresponds to transition of the photons through colored mesons which, as seen from (1), constitute a singlet in the usual SU_3 group. Since, however, the usual SU_3 invariance is strongly broken by the increased weight of the strange quark (which, as is well known, leads to a mixing between the singlets and octets), the second part of the current (1) actually will produce two combinations of the type ω and ϕ with respect to the indices of the usual SU_3. It is natural to identify the lighter particle $\Psi(3105)$ with ω and the heavier one $\Psi'(3695)$ with ϕ. As to the color structure of these particles, it depends essentially on what we assume concerning the rigor with which the color symmetry is satisfied.

We consider first the case when the color SU^3 symmetry is broken only by an electromagnetic interaction. Then the color state $(xF^3 + yF^8)/(x^2 + y^2)^{1/2}$ generated by the current (1) is not stationary because of the electromagnetic mixing, with coefficients on the order of unity,

Designation	Color isospin	Type of decay	Mass, GeV
M(nonet, ω)	$I=0$	(Principal nonet)	0.9
M(nonet, ϕ)		strong	~1.7
M(nonet, $K^{\pm,0,\bar{0}}$)	$I=1/2$	weak	~2.5
M(nonet, $\rho^{\pm,0}$)	$I=1$	electromagnetic	~3.5
B(octet, S)	$I=0$	(Principal octet)	1.2
B(octet, Λ)		strong	?
B(octet; p,n)	$I=1/2$	weak	?
B(octet; Ξ^-, Ξ^0)			?
B(octet, $\Sigma^{\pm,0}$)	$I=1$	electromagnetic	?

with the state $(-yF^3+xF^8)/(x^2+y^2)^{1/2}$ orthogonal to it. (Although there is no direct transition of the latter state into a photon, it can become mixed with the former, for example, as a result of photon exchange between quarks.) As a result, each of the two resonances Ψ and Ψ' should be split into two peaks, with a spacing on the order of several MeV between them; this seems to contradict the experimental data.

We shall therefore discuss a second variant, in which the color SU^3 symmetry is strongly violated, but in such a way that its subgroup, the color SU^2 symmetry, is conserved (accurate to within the electromagnetic interactions). This variant can explain the small width of the decay of Ψ or Ψ' into hadrons as being due to conservation of the color isospin I in strong interactions. The simplest method of introducing such a violation is to assume a great increase of the weight of the the third (blue) color-in analogy with the increased weight of the strange quark. Assuming, just as in the usual SU_3, that the increase in the weight of the blue color is greater than the splitting between the color octet and singlet, we arrive at a mixing of these multiplets, so that definite mass will be possessed by states of the type ω and ϕ with respect to their color. Then, in particular, the usual mesons cease to be pure singlets, but being the lightest, they do not contain the blue (third) color, i.e., they are sources of the type ω with respect to color. Thus, the usual ρ^0 meson is $1/2[(\bar{p}^1p^1-\bar{n}^1n^1)+(\bar{p}^2p^2-\bar{n}^2n^2)]$, which we shall designate as $M(\rho^0,\omega)$ (the first argument pertains to the usual SU_3 structure of the particle and the second to its color structure), while the usual K^{*+} meson is $M(K^+,\omega)$ $=1/\sqrt{2}\,(\bar{\lambda}^1p^1+\bar{\lambda}^2p^2)$, etc.

We thus arrive at the following classification of the mesic states (see the table). Usual mesons are now no longer singlets in terms of color SU^3, but remain singlets ($I=0$) in the SU^2 group connected with the first two colors. It is precisely this circumstance which enables us to determine x and y uniquely in expression (1) for the electromagnetic current. Since we wish to retain all the usual SU_3 relations for the electromagnetic processes in the principal meson nonets (for example, the $V\to p+\gamma$ decays or the $V\to\gamma$ transitions), we must require that the trace of the color matrix over the first two colors be equal to zero, i.e., $y=0$. The minimum value x that leads in this case to integer charges of the colored mesons and baryons is $x=2$. This choice of the colored part of the electromagnetic current corresponds to the fact that the charges of the red quarks are shifted by $+1$, those of the yellow quarks by -1, and the blue (heavy) have the usual quark charges. The sum of the squares of the charges of all quarks R, which determines the total cross section of the e^+e^- annihilation, is equal to 8.

By its construction, the color increment to the usual electromagnetic current is not contained in the first-order term. It can come into play, however, when two-current matrix elements are considered. It is easily seen, incidentally, that the electromagnetic mass differences and the electromagnetic meson mixings remain the same as before. The amplitude of the $\pi^0\to 2\gamma$ decay likewise remains unchanged, but its ratio to the amplitude of the $\eta\to 2\gamma$ decay changes and is equal to $\sqrt{3}(\cos\theta+11\sqrt{2}\sin\theta)^{-1}$, where $\sin\theta$ characterizes the admixture of the ordinary SU_3 singlet in η.

In addition to the principal meson nonet, a singlet with respect to color isospin is the nonet M(nonet, ϕ) (henceforth the "ϕ nonet"), which can strongly decay into ordinary particles. There is the possibility of identifying a particle from this nonet $M(\rho^0,\varphi)$ with the well-known resonance $\rho'(1600)$, and $M(\omega,\phi)$ with $\omega(1675)$. We note that in the region 1.7–1.8 GeV there are also candidates for the role of $M(K^*,\phi)$ and $M(\phi,\phi)$. Particles belonging to the ϕ nonet consist of the blue and antiblue quarks; from the mass difference of the ϕ and ω nonets we can estimate the increase in the weight of the blue color, namely ~0.5 GeV.

There are three nonets with $I=1$, which can decay into ordinary hadrons only electromagnetically. They are produced either as a result of electromagnetic interaction or in pairs. Two neutral mesons $M(\omega,\rho^0)$ and $M(\phi,\rho^0)$ can go over directly into a photon; we identify them with $\Psi(3105)$ and $\Psi'(3695)$. Thus,

$$\begin{aligned}\Psi(3105) &= M(\omega,\rho^0) = {}^1/_2[\bar{p}^1p^1+\bar{n}^1n^1)-(\bar{p}^2p^2+\bar{n}^2n^2)],\\ \Psi'(3695) &= M(\phi,\rho^0) = 1/\sqrt{2}\,(\bar{\lambda}^1\lambda^1-\bar{\lambda}^2\lambda^2)_{\gamma}\end{aligned} \qquad (2)$$

From this we can readily find that the ratio of the lepton widths of the decay of Ψ and Ψ' is ≈ 2. The third neutral meson with $I=1$, $M(\rho^0,\rho^0)$, which is close in mass to $\Psi(3105)$, does not go over into a photon, since it also has isospin $T=1$, and therefore should not yield a resonant peak in e^+e^- annihilation. The ρ^+ and ρ^- nonets have charges that are shifted by ± 2 units in comparison with the ordinary nonet; we note that all their decays proceed with photon emission, and their production cross section is small, so that they are difficult to register.

Obviously, in the proposed scheme the main decays of the Ψ and Ψ' mesons are decays into a photon and hadrons. The decays $\Psi'\to\Psi+2\pi$ observed in 30% of the cases should be due to strong interaction, which incidentally is somewhat suppressed because the λ quarks are converted in this decay into p and n quarks.

Assuming that mass splitting between multiplets with different values of the color isospin I is determined by the quantity $m_1I(I+1)$, we obtain, from a comparison of the masses of the ρ^0 and ω nonets, that $m_1\sim 1.3$ GeV. It follows therefore, with allowance for the increased mass of the blue color, that the masses of the four K nonets having $I=1/2$ lie in the region ~2.5 GeV. Mesons from these nonets can decay only in weak fashion; their lifetime is therefore ~10^{-10} sec (incidentally, the heaviest terms of these nonets can in principle decay rapidly into lighter ones and into ordinary mesons). The charges of the $K^+(K^-)$ and $K^0(\overline{K}^0)$ nonets are shifted in comparison with the ordinary ones by +1 (−1). The general formula for the charge of any color state is

$$Q = T_3 + Y/2 + 2I_3, \tag{3}$$

where Y is the usual hypercharge, and T_3 and I_3 are the third projections of the usual and colored isospin. Since both T and I are violated only by electrodynamics, particles that differ only in the values of T_3 and I_3 have close masses, which are grouped within the limits of the normal electromagnetic splitting; the multiplicity of such groups is $(2T+1)(2I+1)$.

Let us dwell briefly on baryon classification, confining ourselves only to octets according to the usual SU_3 group (see the table). We identify the usual baryon octet with B (octet,S), where S denotes a singlet according to the SU^3 group; it corresponds, obviously, to $I=0$.$^{2)}$ Another octet with $I=0$ is the Λ octet, which has in accordance with the color indices the structure (12−21)3; it should decay strongly into the principal octet. Three octets (Σ^+, Σ^0, and Σ^{-1}) have color isospin $I=1$; they decay electromagnetically. Four octets (p, n, Ξ^0, Ξ^-) have $I=1/2$ and decay only as a result of weak interaction.

Thus, the principal prediction of the described scheme is the existence of a large number of stable mesons and baryons (with lifetime ~10^{-10} sec), which can be produced either in pairs or (in meson-baryon collisions) a colored meson together with a colored baryon.

In conclusion we note that regardless of whether the identification of the particles and the previously known resonance with color states is correct, we considered it of independent interest to investigate the consequences of the classification of particles within the framework of strongly broken color SU^3 symmetry.

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$^{1)}$The Han-Nambu model[3] corresponds to $x=0$ and $y=2/\sqrt{3}$.

$^{2)}$We call attention to the fact that the principal multiplet of the baryons, unlike the mesons, contains the blue color. Baryons containing no blue quarks have instead $I=1/2$, and we assume that the splitting in I is larger than the increased mass of the heavy color.

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[1] Aubert *et al.*, Preprint MIT, 1974; J.I. Augustin *et al.*, SLAC Preprint.
[2] L.B. Okun', Adrony i kvarki, Konspekt lektsii (Hadrons and Quarks, Lecture Outline), MIFI, 1974.
[3] M.Y. Han and Y. Nambu, Phys. Rev. **139**, B1006 (1965).