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Abstract

The new particles J(3.1) and ψ(3.7) are interpreted as colored ω and ϕ mesons, respectively. By relating the radiative decay $J(3.1) \rightarrow \eta\gamma$ to 2γ decays of the color singlet mesons π^0, η, X^0, we find that the radiative decay $J(3.1) \rightarrow \eta\gamma$ is suppressed (in contrast to simple expectations from $\omega \rightarrow \pi^0\gamma$). Via "strong new duality" we predict the recurrences $J'(4.18 \pm 0.08)$, $J''(5.03 \pm 0.13)$, ••• and $\psi'(4.63 \pm 0.08)$, $\psi''(5.41 \pm 0.13)$, $\cdots$.

+) A preliminary version of this paper has been circulated in a limited number of XEROX copies. It should be replaced by this final one.

1. Introduction

There are various theoretical schemes, which enlarge the traditional I-B-Y degrees of freedom of hadronic matter by new ones, like charm or color. The particles $J(3.1)$ [1] and $\psi(3.7)$ [2] can be the milestones (Stolpersteine?) for them. The difference between the charm [3] and the color [4] interpretation of the new particles is that in the first case the new degree of freedom is "hidden", while in the second it is "manifest". In group theoretical language one has to discriminate between the two main possibilities of extending SU(3): Charm corresponds to SU(3)$\rightarrow$ SU(n), specifically SU(4) [3], whereas color extends SU(3) to SU(3) x $\mathcal{G}$, where $\mathcal{G}$ may again be identified [4] with SU(3).

The mentioned theoretical alternatives have certain similarities, but also very characteristic differences. In both cases, when identifying the new particles with either hidden charm or color octet vector mesons, decays into normal hadrons are forbidden. In the charm identification this prohibition of the decay is obtained via the Zweig or duality diagram selection rule [5] in close analogy to the case of $\phi(1019)$. In the color case, transitions to normal hadrons are forbidden, as they would correspond to SU(3) color ($\equiv$ SU(3)^c) octet $\rightarrow$ singlet transitions. Differences become important as soon as transitions of the new states into photons plus hadrons are considered: The hidden charm particle cannot lose its hidden charm by photon emission; the colored (color octet) vector meson, however, can turn into a normal (color singlet) hadron just by radiating away its color via a color octet photon (Fig. 1). While available phase space for photon emission may thus be small in the charm case ($m(\eta_{c\bar{c}}) \cong$ 3 GeV has been suggested [3]), phase space is enormous in the color case, where the final hadron state may be as light as 550 MeV (η(549)).

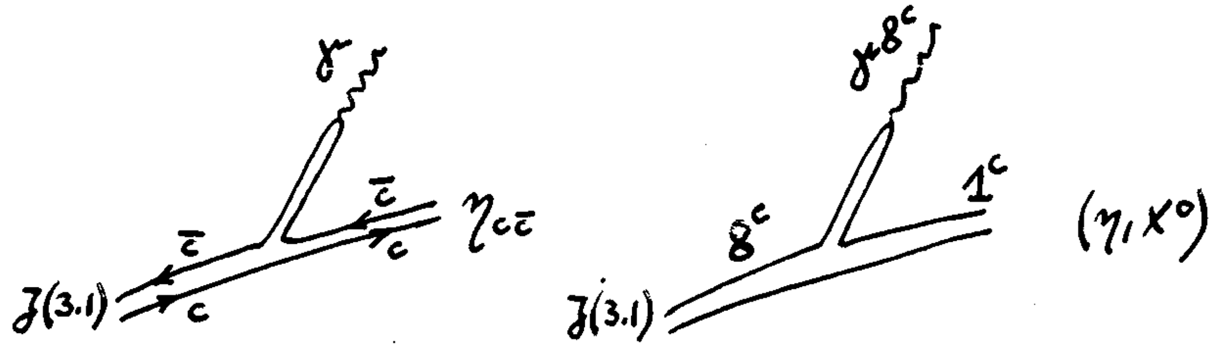

Fig. 1. Photon emission in the charm and color cases

Radiative decay widths in the hidden charm case may thus be of the usual magnitude of first order electromagnetic transitions (i.e. $<$ 1 MeV). In the color case, simple estimates from $\omega \to \pi^0 \gamma$ lead to widths of the order of magnitude of 15 MeV (from phase space), and an identification of the new extremely narrow states with colored states seems to face severe problems right from the beginning [6].

On the other hand the SU(3) x SU(3)^c Han Nambu model [4] has attractive features, as e.g. integral charges of the basic quark triplets, no spin statistics problem for baryons, and it also yields an asymptotic value of $R \equiv \sigma_{e^+e^- \to h} / \sigma_{\mu^+\mu^-} = 4$ quite consistent with data for $\sqrt{s} \cong 4$ to 5 GeV. A more detailed discussion of the vector meson phenomenology and of the width problem in particular thus seems clearly worthwhile. Subsequently we will show that <u>the radiative decays of colored vector mesons may be estimated more convincingly by relating them to experimentally known 2γ decays of ordinary (color singlet) mesons, i.e. $\pi^0, \eta, X^0 \to 2\gamma$</u>. From our analysis of these decays we conclude that a <u>strong suppression of the radiative decays of the new particles should in fact be expected</u> in contrast to the above mentioned estimate. Considerations of different $1^c 8^c 8^c$ hadronic couplings show that such a suppression of $1^c 8^c 8^c$ couplings cannot be universally valid, however.

Specifically, in section 2, we will briefly discuss different possibilities for the $SU(3)^c$ structure of the electromagnetic current and their consequences concerning number and photon coupling strengths of the new states. We will tentatively identify the states at 3.1 and 3.7 GeV with colored ω and ϕ vector mesons respectively. In section 3, our arguments on the widths of the new vector mesons are presented. Further consequences of the color interpretation for the value of R via q^2 duality and the spectrum of vector mesons to be expected will be pointed out in section 4. A few concluding remarks are collected in section 5.

2. Color Structure of the Electromagnetic Current, Tentative Assignment and Coupling Strengths of the New Particles.

In the Han Nambu $SU(3) \times SU(3)^c$ model [4], mesons and baryons are built up from three basic triplets $(p, n, \lambda)_i$, where the color index i runs over red, green, blue or rather i = 1,2,3. The charges of the nine basic states take integral values 1,0,-1(2,5 and 2 times respectively), and ordinary hadrons are supposed to be $SU(3)^c$ singlet states. The electromagnetic current contains two pieces

$$J_\mu = J_\mu(8, 1^c) + J_\mu(1, 8^c). \qquad (1)$$

The first term is well known from ordinary SU(3) symmetry. It transforms as the U spin scalar component of the SU(3) octet and is a singlet in $SU(3)^c$. The second term in (1) supplements the Gell-Mann Zweig third integral charges due to the first term in (1) in such a way that the final charges of the basic triplets take the mentioned integral values. The $(1,8^c)$ structure of the second term in (1) follows rather uniquely from the requirement [7] that the charges of the ordinary (color singlet) hadrons come out correctly. There is freedom, however, as to which octet operator is actually chosen in color space. Physical properties of the color octet hadron spectrum of states, e.g. the number of vector mesons coupled to the photon and their coupling strengths, sensitively depend upon the choice taken, which choice may thus eventually be confronted with experiment.

In the following, let us restrict ourselves in (1) to operators from the color octet which are diagonal in color space. Physically this restriction corresponds to assuming that the photon is a color neutral and thus cannot change the color of a particle (i.e. it cannot convert e.g. a type 1 (red) into a type 2 (green) quark). Excluding thus off-diagonal terms, the number of possibilities for the 8^c current operator is rather limited.

In fact, if the three basic triplets are chosen to be in the $(3,3^*)$ representation of $SU(3) \times SU(3)^c$, only one possibility remains, namely the U spin scalar in color space, U^c. The current with respect to $SU(3)^c$ then looks just the same (apart from a sign from $3 \rightarrow 3^*$), as with respect to ordinary SU(3). For subsequent use let us note the explicit expression of the charge operator, which is then given by

$$Q = \mathcal{U} \times 1^c + 1 \times \mathcal{U}^c$$
$$= \frac{1}{3}\left[\begin{pmatrix} 2 & & \\ & -1 & \\ & & -1 \end{pmatrix} \times \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} + \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} \times \begin{pmatrix} -2 & & \\ & 1 & \\ & & 1 \end{pmatrix}\right], \qquad (2)$$

where in each term the matrix on the left hand side acts in ordinary SU(3), while the matrix on the right hand side transforms in color space. U equals $U = I_3 + Y\frac{1}{2}$ ($U^c = I_3^c + \frac{1}{2}Y^c$) and I_3 and Y denote the third component of isospin (color isospin) and hypercharge (color hypercharge), respectively.

If the basic triplets are chosen to transform according to the (3,3) representation of SU(3) x $SU(3)^c$, two different choices are possible for the 8^c piece of $\mathcal{J}_\mu$. These correspond to a color I spin and a color V spin scalar, i.e. color hypercharge, Y^c, and color V spin, V^c, respectively. Explicitly, U^c in (2) has to be replaced by either

$$Y^c = \frac{1}{3}\begin{pmatrix} 1 & & \\ & 1 & \\ & & -2 \end{pmatrix} \quad (3)$$

or

$$V^c = \frac{1}{3}\begin{pmatrix} 1 & & \\ & -2 & \\ & & 1 \end{pmatrix}. \quad (4)$$

Both, the U^c and Y^c choices are discussed in ref.9. The V^c choice does not seem to appear in the literature. The different choices of $\mathcal{J}_\mu$ reflect themselves in the charge assignment within the spectrum of states and especially in the number of vector mesons coupled to the photon and in the magnitude of the coupling constants to which properties we will turn next.

As the <u>color singlet piece of the current</u> (1) is a pure octet operator with respect to ordinary SU(3), the $SU(3)^c$ singlet states coupled to the photon must be neutral octet states with respect to ordinary SU(3) (ω_8 and ρ^0). As is well known, due to singlet octet (ω_1, ω_8) mixing

$$\underbrace{(1,1^c) + (8,1^c)}_{\text{mixing}},$$

there are actually three ordinary vector mesons coupled to the photon, ρ^0, ω and ϕ. In order to distinguish them from possible color octet states, these well known vector mesons may conveniently be denoted by (ρ^0, ω_1^c), (ω, ω_1^c) and (ϕ, ω_1^c) respectively. (The conventional notation is thus used also within

$SU(3)^c$ multiplets, in order to denote the color quantum numbers of the particles.) Explicitly, the $SU(3) \times SU(3)^c$ wave function of these particles may be written as

$$(\rho^0, \omega_1^c) = \frac{1}{\sqrt{6}} \begin{pmatrix} 1 & & \\ & -1 & \\ & & 0 \end{pmatrix} \times \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix},$$
$$(\omega, \omega_1^c) = \frac{1}{\sqrt{6}} \begin{pmatrix} 1 & & \\ & 1 & \\ & & 0 \end{pmatrix} \times \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}, \qquad (5)$$
$$(\phi, \omega_1^c) = \frac{1}{\sqrt{3}} \begin{pmatrix} 0 & & \\ & 0 & \\ & & -1 \end{pmatrix} \times \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix},$$

where ideal mixing (i.e. ϕ contains λ quarks only) has been assumed.

From (1), (2), <u>the color octet part of the current</u> is a singlet in ordinary SU(3), and thus a color octet version of the ordinary ρ^0 , and likewise of ω_8 , does not couple to the photon. Depending on the color octet structure of J_μ , there can be two ω_1 color octet states (with color isospin $I_c = 0$ and $I_c = 1$ respectively) coupled to the photon, the states (ω_1, ω_8^c) and (ω_1, ρ^{0c}). We conjecture ω_1-ω_8 mixing to be present also for color octet states,

$$\underbrace{(1,8^c) + (8,8^c)}_{\text{mixing}} .$$

If we moreover assume also this mixing to be ideal, then ω and ϕ will have color octet recurrences, which are coupled to the photon (ω_8^c and ρ^{0c}) and which predominantly consist of nonstrange and strange quarks respectively. The <u>vector mesons thus allowed to couple to the photon</u> according to the $(8,1^c)+(1,8^c)$

structure of the electromagnetic current are collected in table 1. There is a maximum number of four additional (colored) vector mesons with direct electromagnetic coupling.

SU_3^c \ SU_3	ω_1^c	ω_8^c $(I^c=0,\ Y^c=0)$	ρ^{oc} $(I^c=1, I_3^c=0, Y^c=0)$
ω_1	x	$(\omega_1,\omega_8^c) \to (\omega,\omega_8^c),\ (\phi,\omega_8^c)$	$(\omega_1,\rho^{oc}) \to (\omega,\rho^{oc}),\ (\phi,\rho^{oc})$
ω_8	$\omega_8 \to \omega \equiv (\omega,\omega_1^c),\ \phi \equiv (\phi,\omega_1^c)$	x	x
ρ^o	$\rho^o \equiv (\rho^o,\omega_1^c)$	x	x

Table 1: SU(3) x SU(3)^c selection rules for vector meson-photon couplings.

The vector meson photon couplings γ_V^{-2} are defined by the current matrix element

$$\langle 0 | J_\mu(0) | V \rangle = \frac{m_V^2}{2\gamma_V} \cdot \varepsilon_\mu \tag{6a}$$

and are related to the width by

$$\Gamma_{V\to e^+e^-} = \frac{\alpha^2}{12}\left(\frac{\gamma_V^2}{4\pi}\right)^{-1} \cdot m_V \tag{6b}$$

For a local current, $J_\mu(x) = Z[\bar{\psi}(x), \gamma_\mu Q \psi(x)]$ and in a bound state model for the vector mesons, this matrix element is expressed by [10)]

$$\frac{m_V^2}{2\gamma_V}\varepsilon_\mu = (2\pi)^{-4}\, tr\left(Z\gamma_\mu \cdot \int \chi(k,P)\, d^4k \cdot Q \cdot V_{SU(3)\times SU(3)^c}\right)$$

and consists of a product of two terms:

(a) The SU(3) x $SU(3)^c$ internal symmetry structure of the vector meson V (Eq. (5) and Table 1) and the electromagnetic current (Eq. (2),(3) or (4));

(b) The configuration space wave function at zero distance, $tr\left(\gamma_\mu \int \chi(k,P)\,d^4k\right)$

The first term is simply calculated from

$$\langle Q_V \rangle \equiv tr\left(Q \cdot V_{SU(3)\times SU(3)^c} \right) \tag{7}$$

and the results thus obtained for the different models are collected in Table 2. These numbers give the relative coupling strengths of vector mesons, if the dynamical term (b) is assumed to be SU(3) x $SU(3)^c$ invariant. Empirically this holds in good approximation for the well known 9:1:2 ratio of $\gamma_\rho^{-2} : \gamma_\omega^{-2} : \gamma_\phi^{-2}$. We may thus conjecture that the relative couplings of the colored states, as given in table 2, are correct, while the absolute magnitude may be different for the color octet mesons because of symmetry breaking in the dynamical part.

Let us try next to tentatively assign the observed states J(3.1) and ψ (3.7) to colored vector mesons. Since colored ρ^0 mesons do not couple to the photon, both J and ψ have to be isospin 0 states. Only two narrow states have been found up to now, and table 2 thus suggests the I^c spin scalar model (3), leading to only two additional new ground state vector mesons coupled to the photon. If we associate the lower mass state, J, with (ω, ω_8^c) and the higher one, ψ(3.7), with (ϕ, ω_8^c) i.e. $J(3.1) \equiv (\omega, \omega_8^c)$, $\psi(3.7) \equiv (\phi, \omega_8^c)$, the leptonic decay widths of these particles should be in the ratio of $2m_J/m_\psi \cong 1.7$ (see Table 2 and eq. (6b)), which indeed seems in agreement with experiment[1,2,11)]

$$\Gamma_{e^+e^-}(J) \cong 5.5 \pm 0.5\ keV, \quad \Gamma_{e^+e^-}(\psi) \cong 3\ keV$$
$$\gamma_J \cong 5.6 \pm 0.3, \qquad \gamma_\psi \cong 8.3$$

The hadronic decay products of the lower mass state should then be ω-like, while the upper state should give rise to a large fraction of strange particles. The cascade decay

SU_3 \ SU_3^c	ω_1^c	$I^c=0$: ω_8^c	$I^c=0$: ρ^{oc}	$U^c=0$: ω_8^c	$U^c=0$: ρ^{oc}	$V^c=0$: ω_8^c	$V^c=0$: ρ^{oc}
ρ^o	$\frac{3}{\sqrt{6}}$	0	0	0	0	0	0
ω	$\frac{1}{\sqrt{6}}$	$\frac{2\sqrt{2}}{\sqrt{6}}$	0	$\frac{-\sqrt{2}}{\sqrt{6}}$	$\frac{-\sqrt{6}}{\sqrt{6}}$	$\frac{-\sqrt{2}}{\sqrt{6}}$	$\frac{\sqrt{6}}{\sqrt{6}}$
ϕ	$\frac{\sqrt{2}}{\sqrt{6}}$	$\frac{-2}{\sqrt{6}}$	0	$\frac{1}{\sqrt{6}}$	$\frac{\sqrt{3}}{\sqrt{6}}$	$\frac{1}{\sqrt{6}}$	$\frac{-\sqrt{3}}{\sqrt{6}}$

Table 2: Photon vector meson couplings $\langle Q_V \rangle$ in various SU(3) x SU(3)^c models.

$\psi(3.7) \rightarrow J(3.1)$ + hadrons, is strongly suppressed by Zweig's rule, because $\psi(3.7)$ thus consists of strange quarks while J contains nonstrange ones only. Cascading is present in so far, as the $\omega_1-\omega_8$ (ordinary SU(3)) mixing differs from the ideal one.

The ratio of photon couplings and the suppression of strong cascading remains unchanged, if J and ψ are assigned to colored ω and ϕ with $I^c = 1$ (ρ^{0c}), in the <u>U^c spin scalar model:</u> $J(3.1) \equiv (\omega, \rho^{0c})$; $\psi(3.7) \equiv (\phi, \rho^{0c})$.
The two additional colored vector mesons required in this model have not been seen so far. They could be broader states, if we would allow for color octet-singlet $\omega_8^c-\omega_1^c$ mixing. The observed $I^c=1$ states, however, would clearly have a small width if I^c is assumed conserved in strong interactions, much in analogy to ordinary isospin.

3. Are the Radiative Decays Suppressed?

Having thus concluded that the interpretation of J(3.1) and $\psi(3.7)$ as colored ω and ϕ is reasonable as regards the ratios of their photon couplings and the suppression of cascading, let us next turn to what seems to be a central problem for the color interpretation, the question of the magnitude of the radiative decay widths. Because of the general selection rules for decays of color octet states (8^c)

$$\begin{aligned} &8^c \not\rightarrow 1^c + 1^c \ , \\ &8^c \rightarrow 1^c + 8^c \ , \\ &8^c \rightarrow 8^c + 8^c \ , \end{aligned} \tag{8}$$

we may have the radiative transitions

$$8^c \rightarrow 1^c + \gamma, \tag{9a}$$
$$8^c \rightarrow 8^c + \gamma, \tag{9b}$$

where γ now stands for a color octet photon and 1^c, 8^c denote color singlet, octet hadrons respectively. (A 2γ decay is forbidden for 1^{--} vector mesons.) Since the 8^c photon as well as J(3.1) and ψ(3.7) have zero isospin in the color scheme, typical radiative decays are

$$J(3.1), \psi(3.7) \rightarrow \begin{matrix} \eta + \gamma, \\ X^0 + \gamma, \end{matrix} \tag{10}$$

while the $\pi^0\gamma$ decay is forbidden.

Phase space is small for (9b), if the 8^c pseudoscalars are assumed to have masses comparable to the masses of the new particles, and radiative widths may therefore be sufficiently small to be consistent with experiment. Simple estimates [12] for reactions (9a), however, as mentioned in the introduction, yield widths, which are larger by roughly two orders of magnitude than the observed extremely narrow widths of the new particles. Indeed, from

$$\Gamma(V \rightarrow PS + \gamma) = \alpha g^2 \frac{P^3_{c.m.}}{3}, \tag{11}$$

one obtains a width for $J(3.1) \rightarrow \eta\gamma$ of the order of 15 MeV, if one simply inserts for the coupling g the value obtained from the $\omega \rightarrow \pi^0\gamma$ decay ($\Gamma_{\omega\pi^0\gamma} \cong 0.9$ MeV) corrected by a Clebsch Gordan coefficient. Such a large width would obviously exclude the color interpretation. Evidence will be presented, however, in what follows, which shows that the above estimate may in fact be misleading. By analyzing the <u>decay of the η(549)</u> meson (which can decay into 8^c photons) we will see that there is empirical support for the hypothesis that the coupling between two color octet vector mesons and a color singlet pseudoscalar meson is much smaller than suggested by the above reasoning based on the coupling between three color singlet states (ω, π^o, γ).

From the SU(3) x SU(3)^c structure of π^o, η_8 and η_1 and the electromagnetic current (1), one obtains for the couplings

$$
\begin{aligned}
g_{\pi^o \gamma\gamma} &= \frac{1}{\sqrt{6}}\, g^{1^c}, \\
g_{\eta_8 \gamma\gamma} &= \frac{1}{\sqrt{6\cdot 3}}\, g^{1^c}, \\
g_{\eta_1 \gamma\gamma} &= \frac{2\sqrt{2}}{\sqrt{6\cdot 3}} \left(g^{1^c} + g^{8^c} \right),
\end{aligned}
\qquad (12)
$$

where g^{1^c} and g^{8^c} denote the reduced couplings of a color singlet hadron to two color singlet and two color octet photons respectively. Because of mixing the η and X^o couplings are related to the couplings (12) by

$$
\begin{aligned}
g_{\eta\gamma\gamma} &= g_{\eta_8\gamma\gamma} \cos 10^o + g_{\eta_1\gamma\gamma} \sin 10^o, \\
g_{X^o\gamma\gamma} &= - g_{\eta_8\gamma\gamma} \sin 10^o + g_{\eta_1\gamma\gamma} \cos 10^o,
\end{aligned}
\qquad (13)
$$

and the η and X^o decay widths are given by

$$
\Gamma(PS \to \gamma\gamma) = \frac{\alpha^2 \pi}{4}\, m_{PS}^3\, g_{PS\gamma\gamma}^2 \qquad (14)
$$

From the experimental π^o, η, X^o widths according to (12), (13), (14) one may thus (at least in principle) derive a bound on the coupling g^{8^c} between a color singlet hadron and two color octet photons.

In table 3, two extreme alternatives for this coupling are compared with experiment, namely the assumptions $g^{8^c} \equiv 0$ and $g^{8^c} \equiv g^{1^c}$. One observes that $g^{8^c} \equiv g^{1^c}$ is incompatible with the experimental value [13)] of the η width, whereas $g^{8^c} \ll g^{1^c}$ is in good agreement with the data. Thus the coupling of a 1^c pseudoscalar hadron to two color octet photons (8^c) seems suppressed. This result may suggest the $8^c \rightarrow 1^c + \gamma(8^c)$ transition (10) to be

	π^0	η	X^0
$\Gamma^{exp.}_{\gamma\gamma}$	7.8 ± 0.9 eV	324 ± 46 eV	<22 keV
$g^{exp.}$ [GeV^{-1}]	0.275 ± 0.016	0.216 ± 0.015	<0.78
g^{th} [GeV^{-1}] ($g^{8^c} \equiv 0$)	input	0.234 ± 0.014	0.415 ± 0.024
g^{th} [GeV^{-1}] ($g^{8^c} \equiv g^{1^c}$)	input	0.312 ± 0.018	0.857 ± 0.05

Table 3: Comparison with experiment [13,14)] of the $\gamma\gamma$ couplings for two extreme alternatives for g^{8^c}.

strongly suppressed also relative to what one estimates from the $1^c \rightarrow 1^c + \gamma(1^c)$ type transition, $\omega \rightarrow \pi^0\gamma$.

This latter conclusion may be more explicitly arrived at, if the $\eta\gamma\gamma$ decay is related to the J(3.1)$\to\eta\gamma^{v}$ decay via J(3.1) dominance à la Gell-Mann Sharp Wagner [15] (Fig. 2).

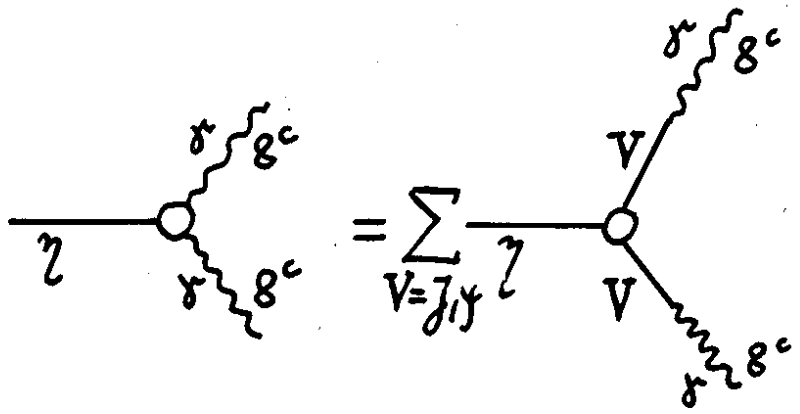

Fig. 2: J,ψ dominance of the $\eta\to\gamma^{8^c}\gamma^{8^c}$ amplitude.

From

$$g^{8^c}_{\eta\gamma\gamma}=\sum_{V=J,\psi}\frac{1}{2\gamma_V}\,g_{V\eta\gamma}=\sum_{V=J,\psi}\frac{1}{4\gamma_V^2}\,g_{V\eta V} \qquad (15)$$

we infer that the smallness of $g^{8^c}_{\eta\gamma\gamma}$ should in fact also yield a suppression of $g_{J\eta\gamma}$, which coupling is responsible for the J(3.1)$\to\eta\gamma$ decay. Putting experimental errors aside for the moment, we may be bold enough to conclude: <u>If the colored triplet model is correct at all, then from the above analysis of the η-decay a suppression of the decay of the colored vector mesons does not seem so surprising after all and could have been anticipated (at least qualitatively) prior to the experimental data.</u>

Let us add at this point a quantitative estimate of the $1^c8^c8^c$ couplings $g_{J\eta\gamma}$ and $g_{J\eta J}$. While a quantitative statement on $g^{8^c}_{\eta\gamma\gamma}$ from the η decay beyond the above conclusion, $g^{8^c} \ll g^{1^c}$, seems not feasible, we may at least check the consistency of the $\eta, \chi^o \to \gamma\gamma$ and $J(3.1) \to \eta\gamma, \chi^o\gamma$ decays. From the total width $\Gamma_{tot}(J) \cong 100$ keV, one estimates (with $\Gamma(J \to \chi^o\gamma) \cong$ $\cong 2\Gamma(J \to \eta\gamma)$) $g_{J\chi^o\gamma} < 0.1$ GeV^{-1} and (with $\gamma_J = 5.6$) $g^{8^c}_{\chi^o\gamma\gamma} < 0.015$ GeV^{-1}. From this value we obtain with the help of the eqs. (12), (13) $g^{8^c} < 0.02$ GeV^{-1}, which has to be compared with the corresponding color singlet coupling, $g^{1^c} = 0.68$ GeV^{-1}. One concludes that the ratio of the color octet to singlet couplings must be less than 3 % in consistency with our earlier conclusion (from $\eta \to \gamma\gamma$) that $g^{8^c} \ll g^{1^c}$. Likewise from (15) we infer $\sqrt{3}\, g_{J\eta J} < 1.2$ GeV^{-1}, to be compared with the $\rho^o\omega\pi^o$ coupling, $g_{\rho^o\omega\pi^o} \cong 14$ GeV^{-1}. From our analysis of the η and the J(3.1) decays one may thus be led to conjecture a strong suppression of the hadronic couplings, $g_{PS^{1^c}V^{8^c}V^{8^c}}/g_{PS^{1^c}V^{1^c}V^{1^c}} < 9\%$, as the dynamical origin for the strongly suppressed radiative decays of the new particles.

From the above analysis it may be tempting to quite generally postulate a suppression of the $1^c8^c8^c$ relative to the $1^c1^c1^c$ couplings. One immediately convinces oneself, however, that at least some of the $1^c8^c8^c$ couplings have to be large, provided simple vector meson dominance arguments are again assumed to hold. In fact, for a color neutral π^+ meson, $(\pi^+, \pi^{cc}) = \frac{1}{\sqrt{2}}(\bar{n}_1 p_1 - \bar{n}_2 p_2)$ the color octet charge vanishes and the color singlet photon only couples. Simple $\rho^o(770)$ dominance combined with universality of the electric charge requires

$$g_{\rho\pi^c\pi^c}/2\gamma_\rho = 1.$$

The $V^{1^c} - PS^{8^c} - PS^{8^c}$ coupling would thus be expected to be of the same magnitude as the $V^{1^c} - PS^{1^c} - PS^{1^c}$ type $\rho\pi\pi$-coupling. If the three triplet model is correct at all, we have to conclude at this stage that the underlying dynamics is complicated.

4. The Value of R and the Recurrences of J(3.1) and ψ(3.7)

Recently it has been suggested by two of us [16] that the new particles J and ψ set the scale for e^+e^- annihilation into hadrons of a new hadronic degree of freedom quite independently of the color or charm interpretation. In what follows, we wish to supplement recent considerations by a detailed discussion of the ratio R in the light of the color interpretation as presented in the previous sections.

With "new duality" [17], R is given by [16,18]

$$R = \sum_V R_V = \frac{3\pi}{4} \sum_V \frac{1}{(\gamma_V^2/4\pi)} \frac{m_V^2}{\Delta m_V^2} \Theta\left(s - \left(m_V^2 - \frac{\Delta m_V^2}{2}\right)\right), \tag{16}$$

where the sum over V runs over ρ^0, ω, ϕ and over additional (ground state) vector mesons corresponding to the coupling of the photon to new types of hadronic matter, i.e. J(3.1) and ψ(3.7) in the color scheme.

Below the color threshold, determined by the mass of J(3.1), the ratio R from (16) is given by the couplings of the photon to $\rho^0 \omega, \phi$. With a Veneziano type mass spectrum, $m_n^2 = m_\rho^2(1+2n)$, n=0,1,2,... , we have $\Delta m_V^2 \equiv \alpha'^{-1} = 2 m_\rho^2 \cong$ 1.2 GeV^2, and consequently (with $\gamma_\rho^2/4\pi \cong 0.64$) $R_{\rho^0,\omega,\phi} \cong 2.5$. This value for R agrees surprisingly well with the value determined from the sum of the squared quark charges [4)19)], $R^{(1^c)} = \sum_i \left(Q_i^{(8,1^c)}\right)^2 = 2$, where below the color threshold only color singlet states are produced.

It is thus tempting to require consistency between the value of R obtained via "new duality" and the value of R obtained from the sum of the squared charges of the constituents to also hold for the contribution due to the production of colored states. From [4] $R = R^{(1^c)} + R^{(8^c)} = \sum_i Q_i^2 = 4$ we thus have

$$R^{(8^c)} = R_J + R_\psi = 2,$$

which equation may be used to calculate the a priori unknown level spacing $\Delta m_V^2(8^c)$ for the recurrences of the color octet states. From the experimental e^+e^- width [11], $\Gamma^J_{e^+e^-} = 5.5 \pm 0.5$ keV, one obtains the photon coupling $\gamma_J^2/4\pi = 2.5 \pm 0.25$ which yields

$$\Delta m_V^2(8^c) = \frac{3\pi}{8}\frac{1}{(\gamma_J^2/4\pi)}\left(m_J^2 + \frac{1}{2}m_\psi^2\right) = $$
$$= 7.8 \pm 0.7 \ \mathrm{GeV}^2,$$

where the predicted ratio $\gamma_J^{-2} : \gamma_\psi^{-2} = 2:1$ from Table 2 has been used in addition. With the calculated value for the level spacing [20] the ratios R_J and R_ψ are found to be $R_J = 1.2 \pm 0.2$ and $R_\psi = 0.8 \pm 0.1$, in nice agreement with experiment (see Figure 3).

If the above value for $\Delta m_V^2(8^c)$ is taken literally as the level spacing of a spectrum of daughters of J and ψ, or of radially excited quark antiquark bound states, one predicts two series of colored vector mesons $(m_n^2 = m_{J,\psi}^2 + \Delta m_V^2(8^c)\cdot n, \ n = 0,1,2,\cdots)$ with the masses given in table 3.

n	SU(3) x SU(3)^c structure	mass [GeV]	e^+e^- width [keV]
0	$(\omega, \omega_8^c) \equiv J$	3.105 (input)	5.5 ± 0.5 (input)
1	$(\omega, \omega_8^c)' \equiv J'$	4.18 ± 0.08	4.0 ± 0.5
2	$(\omega, \omega_8^c)'' \equiv J''$	5.03 ± 0.13	3.4 ± 0.4
⋮	⋮	⋮	⋮
0	$(\phi, \omega_8^c) \equiv \psi$	3.695 (input)	3.3 ± 0.3
1	$(\phi, \omega_8^c)' \equiv \psi'$	4.63 ± 0.08	2.6 ± 0.3
2	$(\phi, \omega_8^c)'' \equiv \psi''$	5.41 ± 0.13	2.3 ± 0.2
⋮	⋮	⋮	⋮

Table 3: Recurrences of J(3.1) and ψ(3.7) in the color scheme.

It is quite clear from the table that the predicted levels involve experimental errors as well as a theoretical uncertainty as regards the exact validity of the "strong new duality" requirement, which says that the magnitude of R determined by the prominent low lying vector mesons coincides [22] with the value of R determined from the squares of the constituent quark charges. Nevertheless, the level spectrum may serve as a guide for further experimental searches. Due to the huge number of predicted colored meson states in the three triplet model, narrow widths should not be expected, however, for the higher mass recurrences, as many decay channels open up.

5. Summarizing and Concluding Remarks

Let us thus briefly summarize the main points, which have been made, and at the same time add a few comments on topics not discussed in the previous sections.

From section 2, within the three triplet model, one expects (table 1) either two (I^c-scalar model) or four (U^c-scalar model) additional (color octet) vector mesons with direct photon couplings. These are colored versions (color neutral members of the color octet) of the ordinary ω- and ϕ-meson. Their relative couplings (table 2) fulfil $\gamma^{-2}_{(\omega,8^c)} : \gamma^{-2}_{(\phi,8^c)} = 2:1$. The new particles J(3.1) and ψ(3.7) have been tentatively identified [25] with colored ω and colored ϕ, respectively. The relative photon couplings (leptonic widths $\Gamma_{e^+e^-}$) of these two states are thus correctly predicted from SU(3)xSU(3)^c symmetry; the absolute values, relative to the ρ^0 (1^c) photon coupling, show an SU(3) x SU(3)^c symmetry breaking effect, the magnitude of which depends upon the SU(3)^c structure chosen for the electromagnetic current.

As regards the analysis of the $\eta\to\gamma\gamma$ decay in section 3, a pessimist (as regards the relevance of the three triplet model) may stress that the η decay width just shows that there is no color octet current contribution, and that the new particles have thus quite obviously nothing to do with the Han Nambu model. He may add that the suppression of certain couplings ($PS^{1^c} V^{8^c} V^{8^c}$, as inferred from $\eta\to\gamma\gamma$), while others seem to be required to have normal strength ($V^{1^c} PS^{8^c} PS^{8^c}$), looks artificial to him. An optimist may answer at this point that the consistency between the η decay and the narrow widths of the new particles is encouraging to him, and that nothing prevents the dynamics behind the couplings to be more complicated. The realist may wish to wait for further crucial experiments. An answer to the question, whether the missing neutral energy around 4 GeV is due to (color octet) photons, may be decisive already.

Requiring "strong new duality", i.e. consistency between the value of R calculated from the quark charges and the value obtained from the photon couplings to the prominent low lying vector mesons, in section 4, we have predicted a level spacing $\Delta m_V^2(8^c) \cong 8\ \mathrm{GeV}^2$, dramatically different from the well known level spacing of 1^c states $\Delta m_V^2(1^c) \cong 1.2\ \mathrm{GeV}^2$. The spectrum of daughter states to be expected from $\Delta m_V^2(8^c) \cong 8\ \mathrm{GeV}^2$ has been listed in table 3.

We have not attempted in this paper to give complete systematics and production characteristics of all the additional 72 colored spin 0, spin 1 etc. states to be expected in the Han Nambu model. Let us, however, add a few rather obvious comments. Since we have assumed the $\omega_1 - \omega_8$ mixing (in ordinary SU_3) to be the same for the 8^c versions of $\omega(783)$ and $\phi(1019)$, we can use the mass formulas valid for ideal mixing

$$\begin{aligned} m_\rho^2 &= m_\omega^2 , \\ 2 m_{K^*}^2 &= m_\omega^2 + m_\phi^2 \end{aligned} \tag{19}$$

to predict the masses of the color neutral partners of $J(3.1) \equiv (\omega, \rho^{oc}$ or $\omega_8^c)$ and $\psi(3.7) \equiv (\phi, \rho^{oc}$ or $\omega_8^c)$, namely $m[(\rho, \rho^{oc}$ or $\omega_8^c)] = 3.1$ GeV and $m[(K^*, \rho^{oc}$ or $\omega_8^c)] = 3.41$ GeV. The masses of e.g. (ω, K^{*c}) are probably not degenerate with the (ω, ρ^{oc}) because of the a priori unknown symmetry breaking in color space.

Finally, let us add a brief remark on the decays of especially the recurrences J' and ψ' of the colored ω and ϕ mesons. Typical decay modes are e.g.

$$J'(4.18) \rightarrow (\rho^0, 8^c) + \pi^0$$
$$\hookrightarrow \pi^0 + \gamma^c$$

$$J'(4.18) \rightarrow (\rho^+, 8^c) + \pi^-$$
$$\hookrightarrow \pi^+ + \gamma^c$$

$$\psi'(4.6) \rightarrow (K^{*+}, 8^c) + K^-$$
$$\hookrightarrow K^+ + \gamma^c$$

and thus involve lots of direct photons, which would have to be responsible for the missing neutral energy [24], if the color option is correct.

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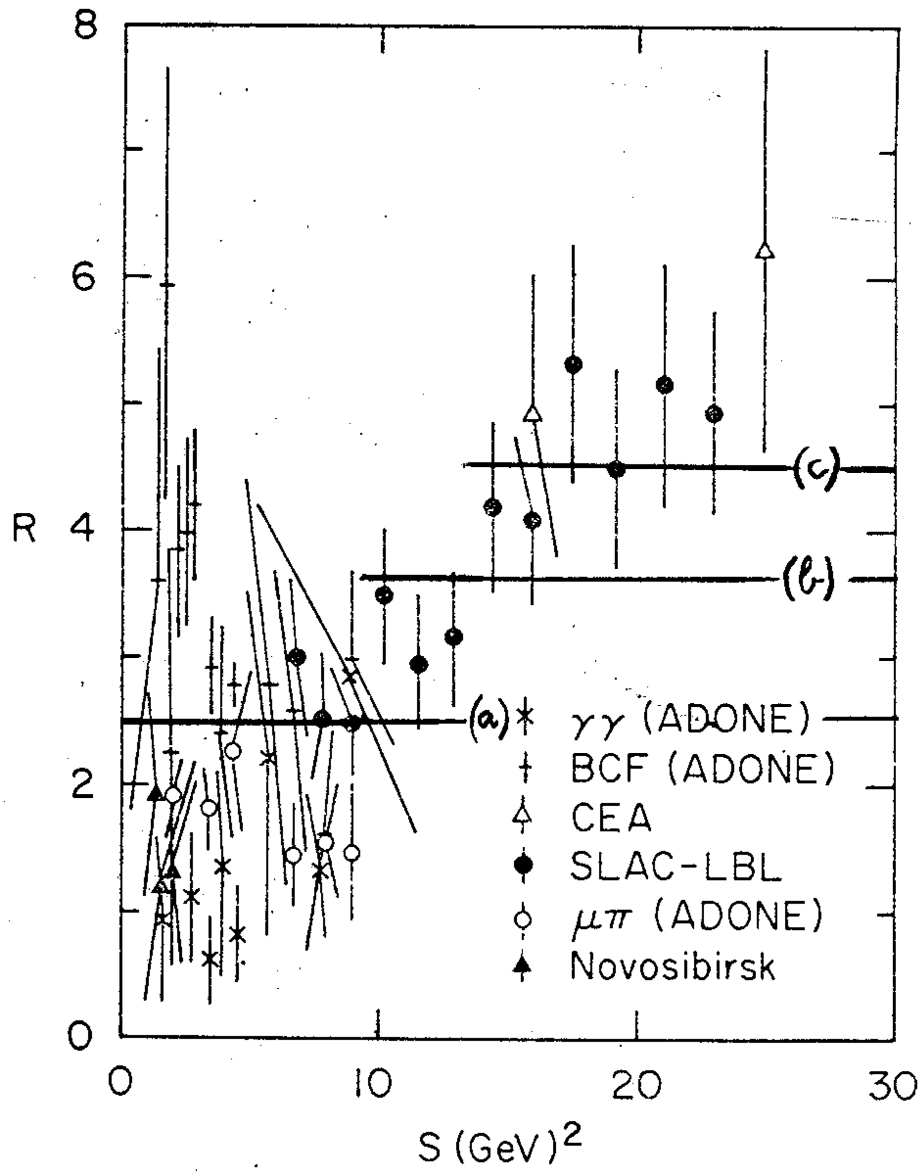

Fig. 3. R from "new duality", showing the contributions to R dual to ρ^0, ω, ϕ (curve a) and the effect of adding the contributions dual to J(3.1) (curve b) and to ψ(3.7) (curve c). Figure from ref. 24)