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Color and the New Particles

A Brief Review

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COLOR AND THE NEW PARTICLES.
A BRIEF REVIEW*.

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Abstract : The possibility of interpreting the new particles as colored ω and ϕ mesons is discussed in the light of the experimental information available on widths and decay modes.

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COLOR AND THE NEW PARTICLES
A BRIEF REVIEW

1. Introduction

The experimental facts on the new particles[1] have been thoroughly reported on by the experimentalists at this meeting. The experimental data on production in hadron interactions, e^+e^- annihilation and photoproduction strongly suggest that the new particles are hadronic vector states. In Table 1 I only show masses and total and leptonic widths Γ and Γ_e of the new particles and refer to the experimental talks[2] for detailed information on the decay modes, which have been observed so far.

	Mass [GeV]	Γ [keV]	Γ_e [keV]
$J(3,1) \equiv \psi(3,1)$	3.095 ±0.004	69 ±15	4.8 ±0.6
$\psi(3,7)$	3.684 ±0.0005	$200 \leq \Gamma \leq 800$	2.2 ±0.5
$\psi(4,1)$	~4.1	~250 to 300 MeV	~4

Table 1

Because of the narrow widths of the new particles an interpretation seems most natural, which somehow introduces a new hadronic degree of freedom. Starting from the SU(3) classification of hadronic states in the language of the quark model, we have the following alternatives:

(1) We can extend the symmetry group according to $SU(3) \rightarrow SU(n)$ $(n \geq 4)$, specifically SU(4)[3], i.e. we add at least one new quark to the p, n, λ, triplet p, n, $\lambda \rightarrow$ p, n, λ, c. The charmed quark (antiquark) c ($\bar{c}$) carries the charm quantum number C = +1 (-1), while the p, n, λ quarks have C = 0. The new particles are interpreted as $c\bar{c}$ states in close analogy to $\phi = \lambda\bar{\lambda}$. The narrow widths are related to a suppression of their decays via Zweig's rule as in the case of $\phi \rightarrow 3\pi$. The charm option is being discussed by other speakers[4] at this meeting, and I will not go into it any further.

(2) We extend the SU(3) symmetry group of the hadrons via $SU(3) \to SU(3) \times G$ with an appropriately chosen group G. In the quark model language this possibility corresponds to attributing to the p, n, λ quarks an additional internal degree of freedom, "color", $p,n,\lambda \to p_i, n_i, \lambda_i$, where the "color index" i runs over e.g. three values $i = 1, 2, 3$. The ordinary hadrons are usually assumed to correspond to the singlet representation of G. The higher dimensional irreducible representations of G are supposed to be filled by particles of higher masses. Each ordinary hadron within an SU(3) multiplet will then have higher mass partners with the same SU(3) quantum numbers, the number of additional multiplets and the number of states within each multiplet being, of course, dependent on the group G and the representation chosen for the fundamental constituents. In order to accommodate the new particles, J(3.1) and ψ(3.7), which couple directly to the photon, the electromagnetic current in such a scheme clearly has to have a piece, which does not transform according to the singlet representation of G. Consequently, the charges assigned to the constituents, e. g. the three quark triplets, in such a scheme will have to depend on the color degree of freedom.

Historically, a color degree of freedom (with three colors) for the basic quarks has first been introduced[5] in order to have an antisymmetric ground state wave function for the baryons classified according to the 56 representation in SU(6) with symmetric SU(6) and space parts of the wave function. For the purpose of obtaining Fermi statistics for the quarks, and also the approximately correct ($s \lesssim 9$ GeV^2) values of

$$R = \sigma_{e^+e^-\to h}/\sigma_{\mu^+\mu^-} \cong 2 \qquad (1)$$

and of the $\pi^0 \to 2\gamma$ width, the color degree of freedom need not be excited. One may thus assume that all observable hadrons are color singlet states, and likewise that the current operator and the charges of the quarks do not contain any additional color non singlet pieces. Such models[5,6] thus clearly work with three triplets of quarks, which have identical third integral charges, and do not allow for additional color non singlet hadrons coupled directly to the photon.

The kind of color model which could be relevant for a description of the new particles, i. e. a model, in which the photon has an additional color non singlet component and the charges of the three triplets of quarks are different, has first been given by Han and Nambu[7]. The group G in this model is identified with an SU(3) group, i. e. the underlying symmetry is $SU(3) \times SU(3)^{color}$. In a model[8] worked out by Govorkov the $SU(3)^{color}$ group is replaced by the discrete permutation group S_3. This model has much in common with the Han Nambu model, but predicts a much smaller number of additional non singlet hadron states; in particular it does not require doubly charged mesons. Tati[9] replaces $SU(3)^c$ by $SO(3)^c$ as color group. In what follows, we will concentrate on models based on $SU(3) \times SU(3)^c$.

2. Models Based on $SU(3) \times SU(3)^c$

2.1. The Spectrum of States and the Electromagnetic Current in the $SU(3) \times SU(3)^c$ Model

The fundamental building blocks of hadronic matter, the quarks p_i, n_i, λ_i $(i = 1, 2, 3)$, are described[7,10] by the (3,3) or $(3,3^*)$ representation of $SU(3) \times SU(3)^c$. The group SU(3) transforms p, n and λ, while $SU(3)^c$ acts on the color index $i = 1, 2, 3$. The ordinary hadrons are usually classified[11] as singlets with respect to $SU(3)^c$, i. e. we have e. g. for vector mesons

$$\begin{aligned} \rho^+ &= \frac{1}{\sqrt{3}} (p_1 \bar{n}_1 + p_2 \bar{n}_2 + p_3 \bar{n}_3) \equiv (\rho^+, \omega_1), \\ \phi &= \frac{1}{\sqrt{3}} (\lambda_1 \bar{\lambda}_1 + \lambda_2 \bar{\lambda}_2 + \lambda_3 \bar{\lambda}_3) \equiv (\phi, \omega_1) \quad \text{etc}. \end{aligned} \tag{2}$$

Here we have introduced the notation $(\rho^+,\omega_1) \equiv (\rho^+, 1^c)$ to be used subsequently. ω_1 specifies the $SU(3)^c$ singlet character of the vector meson ρ^+ in distinction to the color octet states to be discussed subsequently. The usual particle names are thus used to indicate the color quantum numbers (e. g. color isospin and color hypercharge) of the particle in question. Instead of writing down the $q\bar{q}$ decomposition (2) of the states explicitly we will equivalently use a matrix notation in the $SU(3) \times SU(3)^c$ space by writing for e. g. the ϕ meson

$$(\phi,\omega_1) \equiv \begin{pmatrix} 0 & & \\ & 0 & \\ & & 1 \end{pmatrix} \times \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} . \tag{3}$$

In addition to the color singlet (1^c) mesons the model predicts color octet (8^c) states. Each ordinary (1^c) meson with fixed $SU(3)$ quantum numbers thus has an octet of colored partners with the same $SU(3)$ (isospin and hypercharge), but different color quantum numbers. In particular, one will have the additional vector mesons

$$(\phi,8^c), \quad (\rho,8^c), \quad (\omega,8^c), \quad (K^*,8^c),$$

where 8^c runs through the $SU(3)^c$ octet. With ideal singlet octet mixing in ordinary $SU(3)$ (i.e. $\phi = \lambda\bar{\lambda}$), which mixing will be assumed later on, we have e. g. for the ϕ meson the color neutral 8^c states

$$\begin{aligned} (\phi,\omega_8) &= -\frac{1}{\sqrt{6}} (\lambda_1 \bar{\lambda}_1 + \lambda_2 \bar{\lambda}_2 - 2 \lambda_3 \bar{\lambda}_3) \\ (\phi,\rho^0) &= -\frac{1}{\sqrt{2}} (\lambda_1 \bar{\lambda}_1 - \lambda_2 \bar{\lambda}_2) \end{aligned} \tag{4}$$

and six more, which correspond to the six other members of the color octet.

The electric charge of the quarks in the Han Nambu model is additively composed of a color independent part Q^{GMZ} identical with the Gell-Mann Zweig charges of the usual quarks, and a color dependent part Q^c, the color charge

$$Q = Q^{GMZ} + Q^{c}$$
$$Q^{GMZ} = \begin{pmatrix} 2/3 & & \\ & -1/3 & \\ & & -1/3 \end{pmatrix} \times \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} . \tag{5}$$

Q^c is restricted[7,12] by the obvious requirement that the charges of the ordinary (1^c) mesons and baryons come out correctly. Indeed, the charge of e. g. the $\rho^+ \equiv (\rho^+, \omega_1)$,

$$(\rho^+, \omega_1) = \frac{1}{\sqrt{3}} (p_1 \bar{n}_1 + p_2 \bar{n}_2 + p_3 \bar{n}_3) \tag{6}$$

is given by

$$Q^{\rho^+} = Q^{GMZ}(p_i) - Q^{GMZ}(n_i) + Q^c(p_i) - Q^c(n_i) \tag{7}$$
$$= 1 + Q^c(p_i) - Q^c(n_i),$$

and thus Q^c has to fulfill the condition

$$Q^c(p_i) = Q^c(n_i) = Q^c(\lambda_i), \quad i = 1, 2, 3, \tag{8}$$

where the generalisation to the λ quark is obtained by also looking at the charge of the $K^{*+} = \frac{1}{\sqrt{3}} (p_1 \bar{\lambda}_1 + p_2 \bar{\lambda}_2 + p_3 \bar{\lambda}_3)$. The color charge from (8) thus has to be a singlet in ordinary SU(3).

The charges of the ordinary (1^c) baryons yield an additional restriction on Q^c. In fact, in order to obtain the correct charge for the proton $p \sim \sum \epsilon_{ijk} p_i p_j n_k$ we must have

$$Q^c(p_1) + Q^c(p_2) + Q^c(n_3) = 0 . \tag{9}$$

With (8), p and n in (9) may be replaced by arbitrary combinations of p, n, λ and thus we have

$$Q^c = \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} \times \begin{pmatrix} a_1 & & \\ & a_2 & \\ & & a_3 \end{pmatrix} \quad \text{with} \quad \sum a_i = 0, \tag{10}$$

i. e. the matrix acting on the color indices has to be traceless.

Thus from the requirement that the charges of the ordinary mesons and baryons (classified as singlets under $SU(3)^c$) come out correctly, the <u>color piece of the electromagnetic current has to transform as a singlet under SU(3) and an octet under $SU(3)^c$</u>,

$$J_\mu = J_\mu^{GMZ}(8,1^c) + J_\mu^c(1,8^c). \tag{11}$$

Assuming moreover that the photon conserves color, i. e. forbidding transitions such as $\gamma p_1 \to p_2$, the 8^c part must transform as the color neutral member of the octet; the matrix in (10) must be diagonal (and traceless). Requiring also integral charges for the quarks, we finally obtain

$$Q^c = 1 \times \frac{1}{3}\begin{pmatrix} -2 & & \\ & 1 & \\ & & 1 \end{pmatrix}, \tag{12}$$

or permutations thereof

$$Q^c = 1 \times \frac{1}{3}\begin{pmatrix} 1 & & \\ & 1 & \\ & & -2 \end{pmatrix}, \quad Q^c = 1 \times \frac{1}{3}\begin{pmatrix} 1 & & \\ & -2 & \\ & & 1 \end{pmatrix}, \tag{13}$$

which choices are equivalent, as long as no direction in color space is a preferred one. Clearly, as soon as color symmetry is broken by medium strong interactions, which then define a preferred direction in color, the choices (12) and (13) correspond to different physics. As only the relative directions of the photon and a possible symmetry breaking by medium stronginteractions are important, we will use[13] (12) in what follows without loss of generality, and will consider different choices of breaking color symmetry by medium strong interactions. The basic quarks then correspond to the $(3,3^*)$ representation, and the color charge is described by the U^c spin scalar U^c,

$$Q = \frac{1}{3}\left\{\begin{pmatrix} 2 & & \\ & -1 & \\ & & -1 \end{pmatrix}\times\begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}+\begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}\times\begin{pmatrix} -2 & & \\ & 1 & \\ & & 1 \end{pmatrix}\right\} \tag{14}$$

$$= U \times 1 + 1 \times U^c .$$

The modified Gell-Mann Nishijima formula reads

$$Q = I_3 + \frac{1}{2} Y + I_3^c + \frac{1}{2} Y^c, \qquad (15)$$

and clearly implies the existence of doubly charged meson states. The quantum numbers of the (integrally charged) Han Nambu quarks are given in Table 2.

	I_3	Y	I_3^c	Y^c	Q^{GMZ}	Q^c	Q
p_1	1/2	1/3	-1/2	-1/3	2/3	-2/3	0
n_1	-1/2	1/3	-1/2	-1/3	-1/3	-2/3	-1
λ_1	0	-2/3	-1/2	-2/3	-1/3	-2/3	-1
p_2	1/2	1/3	1/2	-1/3	2/3	1/3	1
n_2	-1/2	1/3	1/2	-1/3	-1/3	1/3	0
λ_2	0	-2/3	1/2	-1/3	-1/3	1/3	0
p_3	1/2	1/3	0	2/3	2/3	1/3	1
n_3	-1/2	1/3	0	2/3	-1/3	1/3	0
λ_3	0	-2/3	0	2/3	-1/3	1/3	0

Table 2

The peculiar third integral Gell-Mann Zweig charges in such a scheme appear as average charges of the quarks and antiquarks, respectively, in the color singlet states. The ρ^+ for example,

$$(\rho^+, \omega_1) = \frac{1}{\sqrt{3}} (p_1 \bar{n}_1 + p_2 \bar{n}_2 + p_3 \bar{n}_3),$$

spends one third of the time in the color 1, 2, and 3 states, the average quark and antiquark charges being 2/3 and -1/3 respectively.

2.2. Number of Vector Mesons Coupled to the Photon.

Assignment of the New Particles

From the form of the electromagnetic current (11) and (14), we now can discuss the number of vector mesons coupled directly to the photon and their coupling strengths, turning to an assignment of the new particles to colored vector mesons subsequently. In my discussion I will largely follow the work by M. Krammer, F. Steiner and myself[14]. Surveys of possible interpretations of the J and ψ including the color interpretation have been given in reference 15. Color interpretations have also been discussed in the papers listed in references 16,17.

As the color singlet (1^c) part of the electromagnetic current transforms as the U spin scalar component of an SU(3) octet, with no breaking of SU(3) by strong interactions we would have one 1^c vector meson only (the U spin = 0 component of the octet) coupled to the photon. Actually, because of symmetry breaking by the medium strong interaction, we expect two, and due to singlet octet mixing there are even three 1^c vector mesons coupled to the photon, the well known ρ^o, ω and ϕ. Schematically the situation for the 1^c states may be presented as follows:

$$1^c : \; (\omega_8^{U=0}, \omega_1) < \begin{matrix} (\rho^o, \omega_1) \\ (\omega_8, \omega_1) < \begin{matrix} (\omega, \omega_1) \\ (\phi, \omega_1) \end{matrix} \end{matrix} \qquad (16)$$

Next, let us look at the color octet (8^c) part of the electromagnetic current . As this part transforms as a singlet under SU(3), a priori, colored versions of the SU(3) singlet state, ω_1, only should be coupled directly to the photon. Within the quark model it seems natural, however, to assume ideal singlet octet mixing in SU(3) also for the color octet vector mesons. Then colored versions of ω and ϕ, consisting of non-strange and strange quarks respectively, should couple to the photon. (Colored ρ^o mesons cannot couple directly.) As the color octet part of the electromagnetic current has been assumed to transform as a color U spin scalar, a maximum number of two additional colored ω and ϕ mesons may be expected. They correspond to the two $I_3^c = 0$, $Y^c = 0$ members of the color octet:

$$8^c \quad : \quad (\omega_1, \rho^o_\omega) \begin{cases} (\omega, \rho^o_\omega) \\ (\phi, \rho^o_\omega) \end{cases} \tag{17}$$

Whether there are actually two colored ω and two colored ϕ mesons coupled to the photon, or whether the two states are degenerate, depends upon symmetry breaking in $SU(3)^c$.

In fact, if $SU(3)^c$ symmetry is exact except for electromagnetism, then the eigenstates of the mass matrix are Q^c, U^c multiplets within the color octet. The photon couples to the $Q^c = 0$, $U^c = 0$ member of the octet only:

$$8^c \quad : \quad (\omega_1, \omega_8(U^c = 0)) \begin{cases} (\omega, \omega_8(U^c = 0)) \\ (\phi, \omega_8(U^c = 0)) \end{cases}$$

The relative vector meson photon couplings $1/\gamma_V$ appearing in the matrix element

$$\langle 0 | J_\mu(0) | V \rangle = \frac{m_V}{2\gamma_V} \varepsilon_\mu \qquad \text{are then obtained} \tag{18}$$

from the $SU(3) \times SU(3)^c$ wave functions of the particles and the quark charges in Table 2. From

$$(\omega, \omega_8(U^c{=}0)) = \frac{1}{\sqrt{12}} (-2\, p_1 \bar{p}_1 + p_2 \bar{p}_2 + p_3 \bar{p}_3 - 2\, n_1 \bar{n}_1 + n_2 \bar{n}_2 + n_3 \bar{n}_3), \tag{19}$$

and

$$(\phi,\omega_8(U^c=0)) = \frac{1}{\sqrt{6}}(-2\lambda_1\overline{\lambda}_1 + \lambda_2\overline{\lambda}_2 + \lambda_3\overline{\lambda}_3) ,$$

we obtain

$$\gamma^{-2}_{(\omega,\omega_8)} : \gamma^{-2}_{(\phi,\omega_8)} = 2 : 1 . \quad (20)$$

Combined with the well known relation for color singlets we have

$$\gamma_\rho^{-2} : \gamma_\omega^{-2} : \gamma_\phi^{-2} : \gamma^{-2}_{(\omega,\omega_8)} : \gamma^{-2}_{(\phi,\omega_8)} = 9 : 1 : 2 : 8 : 4 . \quad (21)$$

The coupling of the $U^c = 1$ states may clearly be explicitly checked to be zero from the decomposition

$$(\omega,\rho(U^c=1)) = \frac{1}{2}(p_2\overline{p}_2 - p_3\overline{p}_3 + n_2\overline{n}_2 - n_3\overline{n}_3),$$
$$(\phi,\rho(U^c=1)) = \frac{1}{2}(\lambda_2\overline{\lambda}_2 - \lambda_3\overline{\lambda}_3) . \quad (22)$$

When deriving the ratios for the photon couplings, $SU(3) \times SU(3)^c$ symmetry of the dynamical part (the configuration space wave function in a quark model approach) of the matrix element (18) has of course been assumed. The $9 : 1 : 2$ ratio for $\gamma_\rho^{-2} : \gamma_\omega^{-2} : \gamma_\phi^{-2}$ is empirically valid within experimental errors. There may be stronger symmetry breaking, however, when comparing color singlet with color octet couplings. The conclusions on the ratios (21) of the coupling constants and on the number of states coupled to the photon directly remains unchanged, if there is breaking of color symmetry by medium strong interactions, as long as the breaking is in the direction of the photon.

If $SU(3)^c$ is broken by medium strong interactions in a direction different from the photon direction, i. e. if the color octet breaks up into Y^c, I^c multiplets (whereas the photon transforms as a U^c spin scalar), then diagonalisation of the mass matrix leads to $\omega_8^c(I^c=0)$ and $\rho_o^c(I^c=1)$ states both coupled to the photon. The states

$$(\omega,\omega_8(I^c=0)), \quad (\omega,\rho^o(I^c=1)) \quad (23)$$

and

$$(\phi,\omega_8(I^c=0)), \quad (\phi,\rho^o(I^c=1)) \tag{24}$$

are simply obtained by cyclic permutation $123 \rightarrow 312$ from the $U^c = 0,1$ states given in (19) and (22). The relative couplings for the four vector mesons are given in Table 3 (case B) together with the couplings (21) obtained for the case discussed before.

	ω_1^c	Case A $\omega_8^c(U^c=0)$	Case A $\rho^c(U^c=1)$	Case B $\omega_8^c(I^c=0)$	Case B $\rho^c(I^c=1)$
ρ^o	$\frac{3}{\sqrt{6}}$	0	0	0	0
ω	$\frac{1}{\sqrt{6}}$	$\frac{2\sqrt{2}}{\sqrt{6}}$	0	$\frac{-\sqrt{2}}{\sqrt{6}}$	$\frac{-\sqrt{6}}{\sqrt{6}}$
ϕ	$\frac{\sqrt{2}}{\sqrt{6}}$	$\frac{-2}{\sqrt{6}}$	0	$\frac{1}{\sqrt{6}}$	$\frac{\sqrt{3}}{\sqrt{6}}$

Table 3

The experimental observation of only two narrow states then suggests case A to be realized in nature and to make the assignment (Krammer, Schildknecht, Steiner[14] and Bars and Peccei[16])

$$\begin{aligned} J(3.1) &\equiv (\omega,\omega_8(U^c=0)), \\ \psi(3.7) &\equiv (\phi,\omega_8(U^c=0)) . \end{aligned} \tag{25}$$

The broader state at 4.1 GeV is then interpreted[14] as a recurrence (radial excitation) of the one at 3.1 GeV.

Alternatively, one may assume case B, strong breaking of $SU(3)^c$ symmetry in a direction different from the photon direction. In such a case it is tempting to identify (e. g. Stech[16])

$$J(3.1) \equiv (\omega, \rho^o(I_c=1)),$$
$$\psi(3.7) \equiv (\phi, \rho^o(I_c=1)), \qquad (26)$$
$$J(4.1) \quad (\omega, \omega_8(I_c=0)),$$

while evidence for the fourth state to be expected around 4.8 GeV is still missing. The above assignment seems to be preferable to (e. g. Sanda and Terazawa[16])

$$J(3.1) \equiv (\omega, \rho^o(I_c=1)),$$
$$\psi(3.7) \equiv (\omega, \omega_8(I_c=0)), \qquad (27)$$
$$J(4.1) \equiv (\phi, \rho^o(I_c=1)),$$

as a strong color isospin breaking must be invoked in (27) to allow for the observed cascade decay $\psi(3.7) \to J(3.1) + \pi\pi$, while otherweise $SU(3)^c$ should not be too badly broken, because of the narrow width of $J(3.1)$.

3. Experimental Consequences, Difficulties of the Color Interpretation

Let us now come to a discussion of consequences and experimental tests of the interpretation of the new particles as color excitations. We will concentrate on the assignment (25) corresponding to unbroken color symmetry or breaking of color symmetry in the photon direction. The main features of the color interpretation may be seen within this assignment[14].

3.1. $J(3.1)$ and $\psi(3.7)$ as Colored ω and ϕ

Photon Couplings: With the assignment (25)

$$J(3.1) \equiv (\omega, \omega_8(U^c=0))$$
$$\psi(3.7) \equiv (\phi, \omega_8(U^c=0))$$

the photon couplings should be in the ratio 2 : 1. Experimentally we have from Table 1 $(\Gamma_e = \alpha^2\ \pi\ m_V/3\ \gamma_V^2)$

$$\gamma_J^{-2} : \gamma_\psi^{-2} = 2.6 \pm 0.6 , \tag{28}$$

which is compatible with the prediction.

Additional States Predicted. Within the quark model, from the assignment (25) we may immediately obtain a naive estimate of the masses of the colored partners of ω and ϕ, namely $(\rho, \omega_8(U^c=0))$ and $(K^*, \omega_8(U^c=0))$. If the mass differences between the particles within the vector meson nonet are attributed to mass differences between nonstrange and strange quarks ($m_n = m_p \equiv m;\ m_\lambda = m + \Delta$), with ideal mixing we have

$$m_\rho^2 = m_\omega^2 , \tag{29}$$

and from

$$\begin{aligned} m_\phi^2 &= (m_\omega + 2\Delta)^2 \cong m_\omega^2 + 4\, m_\omega \Delta , \\ m_{K^*}^2 &= (m_\omega + \Delta)^2 \cong m_\omega^2 + 2\, m_\omega \Delta , \end{aligned} \tag{30}$$

also the relation

$$2\, m_{K^*}^2 = m_\phi^2 + m_\rho^2 . \tag{31}$$

Both, (29) and (31), as is well known, are fulfilled within a few percent for ordinary (1^c) vector mesons. Relations (29) and (31) should likewise hold for the color octet, and one predicts from the masses of J(3.1) and $\psi(3.7)$ the masses of the colored ρ and K^* mesons to be

$$\begin{aligned} m[(\rho, \omega_8(U^c=0))] &= 3.1 \text{ GeV}, \\ m[(K^*, \omega_8(U^c=0))] &= 3.4 \text{ GeV}. \end{aligned} \tag{32}$$

As Δ is fixed by the masses of the color singlet states, consistency of the scheme requires the mass splittings of 1^c and 8^c mesons to be related by

$$m^2_{(\phi,\omega_8)} - m^2_{(\omega,\omega_8)} = (m^2_\phi - m^2_\omega) \frac{m_{(\omega,\omega_8)}}{m_\omega} \qquad (33)$$

which yields $m(\phi,\omega_8) = 3.41$ GeV instead of the experimental válue of 3.7 GeV, if the mass of J(3.1) is used as input. These naive estimates of the masses are thus not quantitatively consistent. Nevertheless, (32) may still be used as a reasonable guide; with the colored ϕ lying at 3.4 GeV, instead of at 3.7 GeV, the K^* mass would have shifted to about 3.3 GeV.

Each one of the color neutral vector mesons should be accompanied by other partners from the color octet. With no symmetry breaking in a direction different from the photon direction, there will be degeneracy between states of equal color charge. If mass splitting is due to electromagnetism only, it may be on the 1 % or 2 % level, i. e. 30 or 60 MeV. Non-neutral members of color octets would be weakly decaying long living states, some of them with ordinary and color electromagnetic charge, i. e. doubly charged.

Besides colored vector mesons, the color interpretation would require colored pseudoscalars in roughly the same mass range, and many further meson states[17] besides colored baryons, etc. We are not going into further discussions of the complete spectroscopy.

Hadronic Decays. Invariance of the interaction under the color group requires color conservation,

$$8^c \not\rightarrow 1^c + 1^c,$$

i. e. the decay of the colored vector mesons into ordinary hadrons is forbidden. This is the color interpretation of the narrow widths of J(3.1) and $\psi(3.7)$. The transition

$$8^c \rightarrow 8^c + 8^c$$

is allowed by color symmetry, but forbidden by sphase space, if 8^c states are assumed to be in the vicinity of 3 GeV. The transition

$$8^c \rightarrow 8^c + 1^c$$

requires closer inspection. For <u>$J(3.1) \equiv (\omega,\omega_8)$</u>, the decays corresponding to $\omega \rightarrow 3\pi$, namely

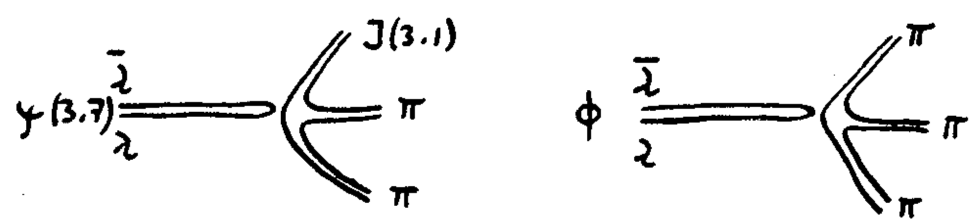
$$\begin{aligned} J(3.1) \rightarrow\ & (\pi^o,\omega_8)\ \pi^+\ \pi^-, \\ & (\pi,\omega_8)\ \rho, \\ & (\rho,\omega_8)\ \pi, \end{aligned} \qquad (34)$$

are again prohibited because of lack of phase space. The narrow width of $J(3.1)$ yields lower limits for the colored pseudoscalars.

For the <u>$\psi(3.7) \equiv (\phi,\omega_8)$</u>, we expect the decays

$$\begin{aligned} \psi(3.7) \equiv (\phi,\omega_8) \rightarrow (\omega,\omega_8) + & \begin{cases} \pi^+\ \pi^- \\ \pi^o\ \pi^o \\ \eta \end{cases} \\ \equiv J(3.1) + & \begin{cases} \pi^+\ \pi^- \\ \pi^o\ \pi^o \\ \eta \end{cases} \end{aligned} \qquad (35)$$

which are the observed cascade decays, the evidence for which has been thoroughly discussed in the experimental talks[2]. These decays are suppressed by Zweig's rule[18], much in analogy to $\phi \rightarrow \rho^o\ \pi$.



The decay

$$\psi(3.7) \equiv (\phi,\omega_8) \rightarrow (\rho^{\pm},\omega_8)\ \pi^{\mp} \tag{36}$$

is also suppressed by Zweig's rule, but from the above estimate (32) of the mass of the colored ρ is a rather crucial test of the model, as it seems hard to shift the (ρ,ω_8) mass to beyond the threshold of about 3.5 GeV. If (32) is correct, the decay should give a clean monoenergetic pion signal, as the colored ρ should be a narrow state. If its mass lies above 3.1 GeV, the colored ρ is expected to be broader, however, since cascade decay according to $(\rho,\omega_8) \rightarrow (\omega,\omega_8)\ \pi \equiv J(3.1)\ \pi$ becomes possible. The process would then contribute to the cascade $\psi(3.7) \rightarrow J(3.1) + \pi^+\ \pi^-$. To my knowledge, definite upper limits on reaction (36) have not been given as yet. Also by Zweig's rule suppressed are the modes

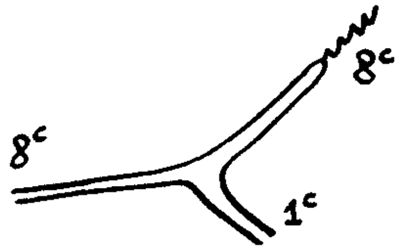
$$\begin{aligned} \psi(3.7) \rightarrow\ & (\pi^o,\omega_8)\ \rho, \\ & (\pi^o,\omega_8)\ \pi^+\ \pi^-, \end{aligned} \tag{37}$$

which, if nonexistent, put a lower limit on masses of colored pseudoscalars. The decays

$$\begin{aligned} \psi(3.7) \rightarrow\ & (K^{\pm},\omega_8)\ K^{\mp} \\ & (\eta,\omega_8)\ \omega \rightarrow (\eta,\omega_8)\ \pi^+\ \pi^-\ \pi^o \end{aligned} \tag{38}$$

are neither forbidden by color conservation nor inhibited by Zweig's rule and thus yield definite lower limits for the colored pseudoscalars, namely $m(K,\omega_8) \gtrsim 3.2$ GeV and $m(\eta,\omega_8) \gtrsim 3.2$ GeV.

Radiative Decays. Among the transitions $8^c \rightarrow 8^c + 1^c$ are the radiative decays, in which the 8^c vector mesons lose their color by radiating off a 8^c photon. These decays constitute the



big problem of the color interpretation, as naive estimates indicate a width of these decays, which is orders of magnitude larger than the measured one. In fact, by simply starting from the measured width of $\omega \to \pi^o\gamma$, $\Gamma_{\omega\pi^o\gamma} = 0.9$ MeV and taking into account the enormous phase space available for $J(3.1) \to \eta\gamma$ according to

$$\Gamma = \alpha\, g^2\, p^3_{C.M.}/3, \tag{39}$$

one obtains $\Gamma_{J\to\eta\gamma} \sim 15$ MeV. Implicitly it has been assumed in this argument that the coupling $g_{8^c 8^c 1^c}$ between two 8^c and a 1^c state appearing in the J(3.1) decay is of the same magnitude as the color singlet coupling, $g_{1^c 1^c 1^c}$, of relevance for the ω decay. In the paper[14] by Krammer, Steiner and myself it has been argued that there may be a strong suppression $g_{8^c 8^c 1^c} << g_{1^c 1^c 1^c}$. Evidence for such a suppression effect has been given[14] by analysing the 8^c photon contribution to the $\eta \to \gamma\gamma$ decay within a vector dominance framework. From the measured $\eta \to \gamma\gamma$ and $\pi^o \to \gamma\gamma$ width, we concluded that in fact a strong suppression of the $V(8^c)V(8^c)PS(1^c)$ couplings compared with the $V(1^c)V(1^c)PS(1^c)$ couplings should be expected.

Quite apart from the (as yet not convincingly solved) problem[19] of the absolute magnitude of the (radiative) widths, it is a firm prediction of the color scheme that the radiative decays $J, \psi \to \gamma$ + hadrons should be dominant. At this meeting we have heard that the DASP group at DESY has identified events for the reaction $J(3.1) \to \eta\,\gamma$ giving limits of $0.1 \text{ keV} < \Gamma_{\eta\gamma} < 2.0$ keV. The decay width for this transition is quite small, but it may be considered a positive point for color that it does exist. The prominent radiative decays may actually be multibody decays, such as

$$J \to \pi^+ \pi^- \gamma, \quad \pi^+ \pi^- \pi^+ \pi^- \gamma, \quad \pi^+ \pi^- \pi^+ \pi^- \pi^+ \pi^- \gamma. \tag{41}$$

As we have heard from the SPEAR group[2], there is actually a considerable fraction of events of the type

$$J(3.1) \to \pi^+ \pi^- \pi^+ \pi^- X_{neutral} \quad \pi^+ \pi^- \pi^+ \pi^- \pi^+ \pi^- X_{neutral}, \tag{42}$$

where the system X has not been directly observed, its mass being consistent with zero (i. e. the photon mass) and the π^o mass. Assuming that X is a π^o, a peak at the ω mass has been found, which shows that the missing neutral system X cannot always be a photon. Further conclusions cannot be drawn at the moment, except for the rather obvious remark: If the major decay mode of the J(3.1) is an odd number of pions (i. e. of the type of the color forbidden decay $8^c \to 1^c + 1^c$), while the color allowed decay into γ + hadrons constitutes a negligible fraction, then there is no reason to keep the color interpretation any longer. Conversely, if the radiative decays are dominant after all, the color interpretation may well be on the right track, and we may look for an explanation of the small absolute value of the total (radiative) width with increased confidence in the model. Let me also remind you of the fact that the so called "energy crisis" i. e. an appreciable increase[20] of the neutral to charged energy ratio in the region around 3.8 GeV, where R seems to rise, is still present, and colored photons would still be an attractive resolution.

Recurrences of J(3.1), ψ(3.7). Via "new duality"[21], recurrences of J(3.1) and ψ(3.7), i.e. of the colored ω and ϕ respectively, may be predicted as follows. First of all, for color singlet vector mesons, by requiring scaling of $\sigma_{e^+e^- \to hadrons}$ (i.e. constancy of R) with the scale being set by the low lying leading vector mesons, we simply have[21,22]

$$R(1^c) = \sum_{\rho^o,\omega,\phi} R_V = \frac{3\pi}{4} \sum_V \frac{1}{(\gamma_V^2/4\pi)} \cdot \frac{m_V^2}{\Delta m_V^2} \,\Theta\left(s - (m_V^2 - \frac{\Delta m_V^2}{2})\right) . \tag{43}$$

With a Veneziano type mass spectrum[23], $m_n^2 = m_\rho^2(1 + 2n)$, $n = 0, 1, \ldots$, and the measured values of the ρ^o, ω, ϕ photon couplings, one obtains $R \cong 2.5$ from (43) which is in agreement with experiment below about 3 GeV, where effects due to the production of J and ψ start to set in. This value of $R \cong 2.5$ roughly coincides with the value obtained from the squares of the color singlet parts of the quark charges, $R = \sum(Q^{GMZ})^2 = 2$. Thus in ref. 14, we have speculated that consistency between R obtained via "new duality" and the squares of the quark charges should also hold for the production of colored vector states, i. e.

$$R(8^c) = R_J + R_\psi = 2.$$

Inserting masses and photon couplings for J and ψ, a level spacing $\Delta m_V^2(8^c) = 6.8 \ \text{GeV}^2$ is obtained, which is dramatically different from the level spacing of ordinary vector mesons. The masses of the recurrences and the leptonic widths thus predicted are listed in Table 4. The state at about 4.1 GeV and its leptonic width nicely fit into the scheme and have actually been predicted[14] prior to the confirming data. If our conjecture of the 4.1 GeV state being a recurrence of the one at 3.1 GeV is correct, we expect a strong cascade decay of $J'(4.1) \rightarrow J(3.1)$. No evidence for the required recurrence of the colored ϕ has been reported so far. Figure 1 shows how the asymptotic value of R interpolates the low lying resonances which separately set the scale for each particular kind of hadronic matter coupled to the photon.

n		mass [GeV]	e^+e^- width [keV]
0	$J(3.1) \equiv (\omega, \omega_8^c)$	3.105 (input)	4.8 ±0.6 (input)
1	J'	4.05	3.7
2	J"	4.8	3.1
0	$\psi(3.7) \equiv (\phi, \omega_8^c)$	3.7 (input)	2.2 ±0.5 (input)
1	ψ'	4.5	1.8
2	ψ"	5.2	1.6

Table 4

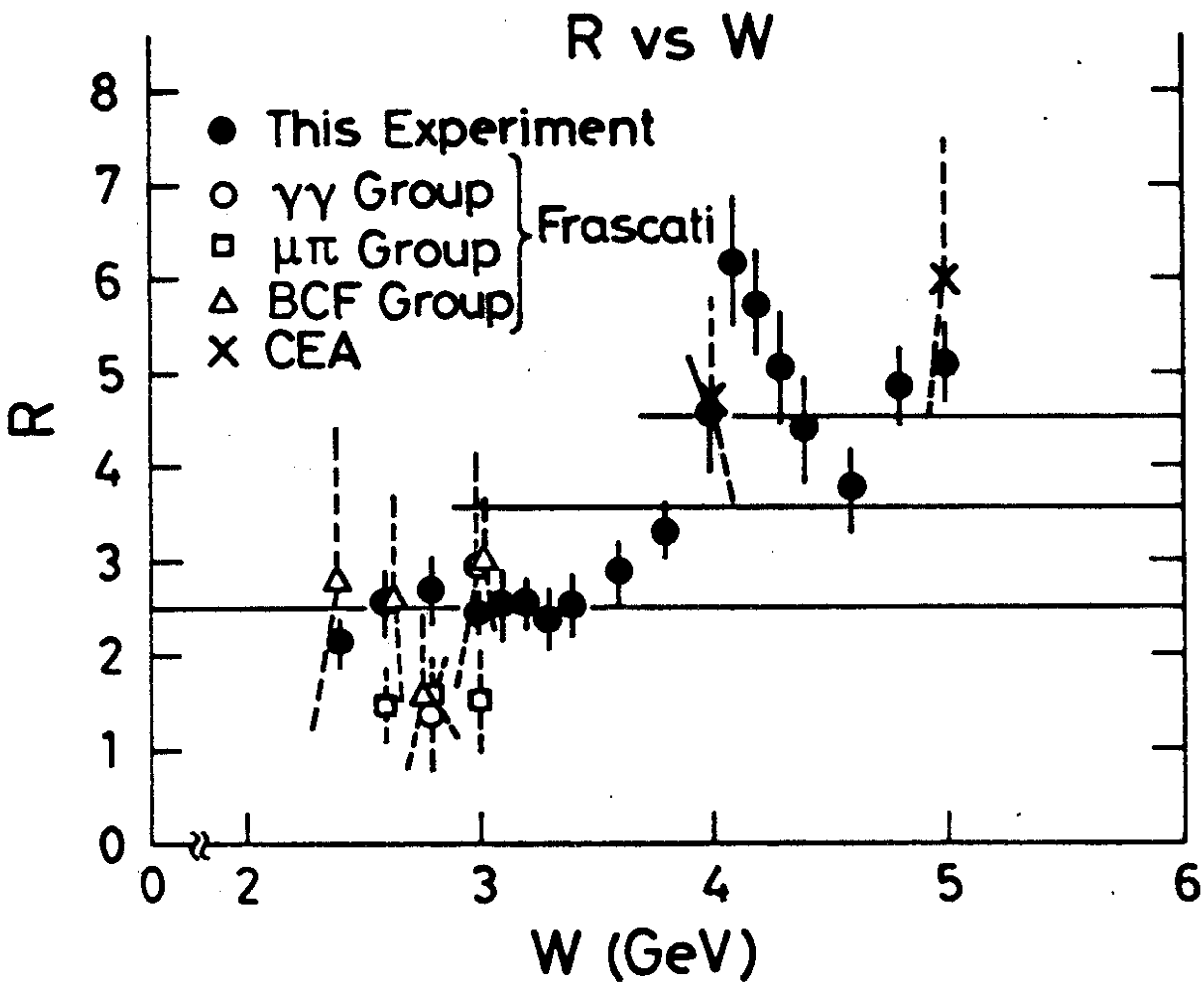


Fig. 1 The contributions to R dual to ρ, ω, ϕ and to J(3.1) and ψ(3.7). Compare ref. 2 for data.

4. Summarizing Conclusions

I have concentrated on color and the new particles and could not comment on deep inelastic scattering and weak interactions in this brief review[24]. Let me summarize the main points, which have been made. The ratios of the leptonic widths of the new particles (including the 4.1 GeV state) can be nicely accommodated within the color scheme, and likewise, suppressing the hadronic widths via color conservation and the cascade decay via Zweig's rule, does not pose serious problems. The extreme narrowness of the total widths, i. e. the strong suppression of the radiative decays (assuming the color interpretation to be correct) constitutes a big problem. Nevertheless, I think it would be premature to give up the color model as long as the most firm prediction of the model, dominance of the radiative decay modes, does not seem to be ruled out. It is satisfying that the color scheme may be readily disproved by just looking at the J(3.1) decays: If the color forbidden ($J(3.1) \rightarrow$ hadron, e. g. many pions) turns out to be allowed in nature, while the color allowed ($J(3.1) \rightarrow$ hadrons + γ) is forbidden, there will be no reason to keep the scheme any longer.

Acknowledgement

I would like to thank my collegues in Hamburg for extensive useful discussions, especially M. Krammer and F. Steiner.

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24) While the written version of this talk was completed, I obtained the recent excellent review by O.W. Greenberg on the color scheme (University of Maryland, report No. 75-064), to which I refer for additional information.