et al., *ibid.* 33, 1408 (1974).

[2]A. K. Mann, D. B. Cline, and D. D. Reeder, SLAC Proposal No. SP-7 (unpublished).

[3]Other tests involving polarized beams are described by the author (to be published). See also the review paper by L. Wolfenstein, in *Particles and Fields—1974*, edited by C. E. Carlson, AIP Conference Proceedings No. 23 (American Institute of Physics, New York, 1975).

[4]R. W. Brown, L. B. Gordon, and K. O. Mikaelian, Phys. Rev. Lett. 33, 1119 (1974).

[5]R. F. Cahalan, Phys. Rev. D 9, 257 (1974); R. F. Cahalan and K. O. Mikaelian, Phys. Rev. D 10, 3769 (1974).

[6]The cross section is proportional to $(g_V^l \sec\alpha_l)^2$.

Are the New Particles Color Gluons?

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We explore the possibility that the new particles ψ and ψ' are color gluons and propose characteristic tests of such a possibility.

The discovery[1] that there exist massive particles (at 3105 and 3695 MeV) with extremely narrow widths suggests that new quantum numbers provide selection rules for the decays of these objects to normal hadrons. Examples of such new quantum numbers are charm[2] and color.[3-5] We proposed a unified theory[4,5] of the weak, electromagnetic, and strong interactions, in which the presence of *both* charm and color were found essential. From the point of view of this scheme, the discovered particles might indeed be charm-anticharm–quark composites φ_c's with $J^P = 1^-$ or, alternatively, colored gauge bosons. The φ_c hypothesis has been explored by several authors. We explore in this note to what extent these particles could be related to the two neutral members of the color octet of gauge particles (V_3 and V_8 or their linear combinations U and V), which were suggested by us in the context of our unification scheme. It was proposed in Ref. 5 that if quarks are integer-charged, the U and V should be produced *singly* as resonant particles in e^-e^+ annihilation and $\gamma + p$ reactions with expected masses[4] around 3 to 5 BeV, and if they are the lightest color-nonsinglet states, they would decay into hadrons + photon and into hadrons only via color-symmetry breaking with secondary decays to lepton pairs; they would thus possess narrow widths.

We examine here the expected decay modes of U and V in some detail and remark that the fact that a significant fraction of their decays should involve hadrons in association with a single photon and that their decays possess characteristic selection rules should provide some clear tests for the color hypothesis for the new particles. We also remark that the "rapid" decay[6] of the upper one into the lower one might be a difficulty, if either or both are charm composites, but this fact can be explained naturally in the color scheme. The extreme narrowness of the new particles is related to damping due to heavy-mass color-octet states and the fact that their decay amplitudes are $\lesssim e$.

To make our arguments, we recall that in the scheme of Ref. 5 there are five neutral gauge fields $W_{L,R}^3$, V_3, V_8, and S^0 coupled to the diagonal generators of the local symmetry group $G = SU(2)_L \otimes SU(2)_R \otimes SU(4')_{L+R}$. The physical particles are linear combinations of them. We list below only the three "light" particles (for the simplest case of spontaneous symmetry breaking), the two remaining ones (Z^0 and $\tilde{S}$) being too heavy to be relevant here:

$$A = (e/fg)[fW + (2/\sqrt{3})gU^0], \quad V^0 = \tfrac{1}{2}(\sqrt{3}V_8 - V_3),$$
$$\tilde{U} \simeq (3f^2 + 2g^2)^{-1/2}[\sqrt{3}fU^0 - gW], \tag{1}$$

where $U^0 \equiv \frac{1}{2}(\sqrt{3}V_3 + V_8)$, $W \equiv W_L^3 + W_R^3 - (\frac{2}{3})^{1/2}(g/f)S^0$, $2e^2 = g^2f^2/(f^2+g^2)$, and the masses[4] are $M_A = 0$, $m_{\tilde{U}} \simeq m_{V^0} \simeq 3$–$5$ BeV. For ease of writing, we have set $g_L = g_R = g$, where g_L, g_R, and f denote renormalized effective coupling constants at *low energies* (of the order of BeV or less) for the gauge particles W_L, W_R, and V, respectively, with $g_{L,R}/4\pi^2 \simeq 2\alpha$ and $f^2/4\pi \simeq 1$–10. The coupling of the physical gauge particles to the fermions is given by

$$L_I \simeq eA_\mu[(J_\mu{}^W - J_\mu{}^{S^0}) + (2\sqrt{3})J_\mu{}^{U^0}] + fV_\mu{}^0 J_\mu{}^{V^0} + f\tilde{U}_\mu[J_\mu{}^{U^0} - (1/\sqrt{3})(g^2/f^2)(J_\mu{}^W - J_\mu{}^{S^0})], \quad (2)$$

where

$$J_\mu{}^W = \tfrac{1}{2}[\sum_{i=a,b,c} (\bar{q}_i\tau_3{}^W q_i) + \bar{l}\tau_3{}^W l]_{L+R},$$
$$J_\mu{}^{S^0} = \tfrac{1}{6}[\sum_{i=a,b,c} (\bar{q}_i\tau_0{}^W q_i) - 3\bar{l}l]_{L+R},$$
$$J_\mu{}^{U^0} = \sqrt{\tfrac{3}{4}}[\sum_{\alpha=\mathcal{P},\mathfrak{N},\lambda,\chi} q^{-\alpha}(\lambda_3{}' + \lambda_8{}'/\sqrt{3})q^\alpha]_{L+R}, \quad (3)$$
$$J_\mu{}^{V^0} = \sqrt{\tfrac{1}{4}}[\sum_{\alpha=\mathcal{P},\mathfrak{N},\lambda,\chi} \bar{q}^\alpha(\sqrt{3}\lambda_8{}' - \lambda_3{}')q^\alpha]_{L+R}.$$

Here l denotes the lepton quartet $(\nu_e, e^-, \mu^-, \nu_\mu)$, $\tau_3{}^W$ and $\tau_0{}^W$ $(=1)$ act on the valency indices $\alpha = (\mathcal{P}, \mathfrak{N}) + (\lambda, \chi)$, while $\lambda_{3,8}{}'$ act on the color indices $i = a, b, c$. Note that the *photon "contains" the color gluon* U^0 *and is orthogonal to* V^0.

As stressed in Ref. 5, in a general case[7] the eigenstates of the mass matrix are expected to be orthogonal linear combinations of $\tilde{U}$ and V^0:

$$U = \cos\xi\tilde{U} + \sin\xi V^0; \quad V = -\sin\xi\tilde{U} + \cos\xi V^0. \quad (4)$$

Since $\tilde{U}$ is directly coupled to (e^-e^+) through its $W_{L,R}{}^3$ and S^0 components [see Eqs. (1) and (3)], but not V^0, we expect both U and V to be produced in e^-e^+ collisions through their $\tilde{U}$ *component only,* and therefore in the ratio $\cos^2\xi : \sin^2\xi$. Similarly they would both decay to (e^-e^+), $(\mu^-\mu^+)$, and (hadrons + photon) only through the $\tilde{U}$ component; thus these partial widths of U and V should also be in the same ratio. On the other hand their decays to hadrons *without* a photon will in general involve both $\tilde{U}$ and V^0 (see later).

Expected decay modes of U and V.—In the integer-charge quark model, which is the case of relevance here, SU(3′) color as a global symmetry[8] is broken by electromagnetism. In general, it is also broken by the quartic terms in the scalar potential. We denote such a nonelectromagnetic color-symmetry breaking term by $H_8{}'$ and assume[8] that $H_8{}'$-generated *amplitudes* are of order $(1–10)\alpha$ (see later) and that $H_8{}'$ has a dominant piece transforming as $(\underline{1}, \underline{8})_{I_3{}'=Y'=0}$ under SU(3)⊗SU(3′). Thus, for our considerations, color as a global symmetry is at least as good as SU(3) symmetry and may even hold to the same extent as isospin symmetry. With this picture, if the octet of gluons $V(\underline{8})$ are the lowest-lying color-octet states, then their strong decays to normal hadrons, assumed to be singlets under SU(3′), are forbidden. They may decay only electromagnetically, or via $H_8{}'$, or via their small components[5] (for example $W_{L,R}{}^3$ and S^0 in U and V). These lead to three varieties of decay modes:

(1) *U and V → hadrons + one photon.*—Since the electromagnetic current contains color $(J_\mu{}^{U^0})$, these decays are, in general, expected to have amplitudes of order e, given by $e\langle\text{hadrons}|J_\mu{}^{\text{em}} \times |U\rangle\epsilon_\mu = e\langle\text{hadrons}|J_\mu{}^{U^0}|U\rangle\epsilon_\mu$ [see Eqs. (2) and (3)]. Noting, however, that $J_\mu{}^{U^0}$ is a singlet under isospin as well as SU(3) symmetry, we see that the hadrons must be in an $I=0$ state and (approximately) in an SU(3)-singlet state. *This forbids* $U \to \pi^0 + \gamma$ *as well as*[9] $U \to$ *(odd number of pions + photon)* and suppresses $U \to \eta + \gamma$ decay. Some of the allowed decay modes are $U \to \eta' + \gamma$, $2\pi + \gamma$, $(4\pi + \gamma)(K\bar{K} + \gamma)$, and $2\eta + \gamma$. The $\eta' + \gamma$ mode shown above should be replaced by the $E^0 + \gamma$ mode, if E^0 is the 0^- SU(3) singlet instead of η'. Below we estimate the partial widths of two typical decay modes $\eta' + \gamma$ and $2\pi + \gamma$.

Denoting the amplitude of $U \to \eta'(p) + \gamma(k)$ by $(g_{U\eta'\gamma}/M_{\text{eff}})\cos\xi\epsilon_{\alpha\beta\gamma\delta}e_\alpha{}^U e_\beta{}^\gamma p_\gamma k_\delta$, where M_{eff} denotes an effective mass, we find that $\Gamma(U \to \eta' + \gamma) = (g_{U\eta'\gamma}{}^2/e^2)\cos^2\xi[(1\text{ BeV})/M_{\text{eff}}]^2(6.8\text{ MeV})$, where, for the sake of *illustration only,* we have substituted $M_U = 3105$ MeV. While, we expect $g_{U\eta'\gamma}$ to be of order e, M_{eff} is expected to be of order $(3\text{ BeV})^2/(1\text{ BeV}) \approx 10$ BeV, assuming that all color-octet *hadronic* states are heavier than about 3 BeV. This is suggested by a dispersion-theoretic approach[10] based on the picture $U \to \eta' + |m\rangle$ followed by $|m\rangle \to \gamma$ in which any intermediate state $|m\rangle$ occurring in the saturation of the T-product $\langle\eta'|T(J_U(x')J_{em}(x))|0\rangle$ *must correspond to a color-octet state with* $m^2 \gtrsim (3\text{ BeV})^2$; this circumstance damps the corresponding amplitudes in comparison to those of the familiar transitions of color-singlet states such as $\rho \to \pi + \gamma$. Taking this into account, one can expect these particles (U and similarly V) to be extremely narrow; for example, with $M_{\text{eff}} \simeq 10$ BeV, we have $\Gamma(U \to \eta' + \gamma) \approx (50–100\text{ keV})\cos^2\xi$ if $g_{U\eta'\gamma} \sim e$. Estimating similarly, we find[11] that $\Gamma(U \to \pi\pi\gamma) \approx (2\text{ keV})\cos^2\xi$.

(2) *U and V → (e^-e^+) and $(\mu^-\mu^+)$.*—U and V are directly coupled to e^-e^+ and $\mu^-\mu^+$ with equal strengths. Using Eqs. (1)–(4), we obtain

$$\Gamma(U \to e^+e^-) = \left(\frac{2}{\sqrt{3}}\frac{e^2}{f}\right)^2 \frac{M_U}{12\pi}\cos^2\xi \simeq \left(\frac{f^2}{4\pi}\right)^{-1}(77\text{ keV})\cos^2\xi.$$

A determination of the leptonic partial widths of *both*[12] U and V would thus provide an *unambiguous determination of the fundamental effective strong-coupling* constant f (without the uncertainty of form factor effects). Assuming that $\cos^2\xi \approx \frac{1}{2}$ to 1, the observed partial width $\Gamma(\psi \to e^+e^-) \approx 5$ keV yields $f^2/4\pi \simeq 7-14$, which is a reasonable value for f [assuming that $\psi(3105) = U$].

(3) *U and V → hadrons.*—These decays can occur (a) via the small components of $\tilde{U}$, (b) via photon loop,[13] and (c) via H_8', leading to amplitudes of order e^2/f, $O(\alpha)$, and $O(H_8')$, respectively. Because H_8' is an SU(3)-singlet operator, it cannot lead to decays of U into $(\pi^+\pi^-)$, $(K\bar{K})$, and (even number of pions). Note also that these hadronic decay modes can receive contributions from *both* $\tilde{U}$ and V^0 components via H_8'. We list below some of the typical hadronic modes with the expected orders of magnitude for their amplitudes based on the selection rules mentioned above:

$$U \to 3\pi,\ \pi\pi\omega,\ \rho\pi,\ K^*\bar{K},\ B\pi\ [O(H_8'),\ O(\alpha)]$$
$$\to \pi^+\pi^-,\ 4\pi,\ K\bar{K},\ \eta\pi\pi,\ \eta'\pi\pi,\ \rho\rho\ [O(\alpha)].$$

Simple estimates with amplitudes of order (1 to 10)α and effective[13] mass ≈1 BeV lead to partial widths for two- and three-body decays shown above of order (1–100)×(few keV). For example, $\Gamma(U \to \rho\pi) \approx 10$ keV, if $g_{U\rho\pi} \simeq \alpha/(1\,\text{BeV})$. [This then suggests that if $U = \psi$ or ψ', $O(H_8')$ should not be much bigger than α.] The $\omega\pi\pi$ mode has a small phase space, but is expected to be enhanced due to two-body channels (ωS^0, $B\pi$, and virtual $\rho\pi$); this leads to partial width $\Gamma(U \to \omega\pi\pi) \sim 2$ to 5 keV. Thus, adding other channels, the hadronic modes may possess a partial width ~50 to several hundred keV comparable to that of the hadrons $+\gamma$ modes.

In summary, we conclude that a distinct characteristic of the color-gluon explanation in contrast to the φ_c possibility[14] is that hadrons + one-photon modes should constitute a significant fraction (20 to 50%) of all decay modes. Among these the two-body mode $\eta' + \gamma$ (or $E^0 + \gamma$) should be an appreciable fraction. We therefore urge a search for γ-ray–associated decays and monoenergetic γ rays in the peak regions. The high degree of forbiddeness of $U \to$ (odd number of pions + γ) compared to $U \to$ (even number of pions + γ) provides a *crucial test* for the color explanation. We expect[15] that $R \equiv \Gamma(U \to (2n+1)\pi + \gamma)/\Gamma(U \to 2n\pi + \gamma) \approx O(\alpha^2)$.

In addition to the color octet of gluons $V(\underline{8})$, we do expect to see the color octet of $(q\bar{q})$ composites (the analogs of π, η, ρ, ω, ... in color space) transforming as $(\underline{1},\underline{8})$ under SU(3)⊗SU(3′) with masses in the range of 2 to 5 BeV and $J^P = 0^-$, 1^-, etc. The 1^- multiplet $C(\underline{8})$ of this kind will have quantum numbers identical to those of the $V(\underline{8})$. While transitions of the type $V_3 \to V_8 + \pi + \pi$ and $C_3 \to C_8 + \pi + \pi$ are forbidden by color-symmetry, those of the type $C_{3,8} \to V_{3,8} + \pi + \pi$ are allowed strong processes.

In this context, the observation that $\psi'(3695)$ decays into $\psi(3105) + \pi^+ + \pi^-$ with estimated partial width ≳100 keV is significant. Writing the effective coupling as $h\psi_\mu'\psi_\mu\varphi_\pi^+\varphi_\pi$, we obtain $h^2/4\pi \gtrsim 8$, which suggests[16] that *it is a strong decay.* We now note the following: (1) If ψ and ψ' are charm composites φ_c and φ_c', we may expect $h^2/4\pi$ to be small[17] on the basis of the familiar Zweig rule. (2) With the color-hypothesis, on the other hand, the strong decay is allowed, but then *one must identify one of them* (ψ *and* ψ') *with an elementary gluon* (U *or* V) *and the other with a composite* (C_3 or C_8, or C_U or C_V) with overlapping quantum numbers. Being produced by a strong decay, the two pions should be in the $I = 0$ state; $\psi' \to \psi$ + (odd number of pions) is forbidden and $\psi' \to \psi + \eta$ is suppressed by SU(3).

With this identification, we are led to predict two more particles (one out of U and V and one out of C_U and C_V) related to ψ and ψ'. They ought to exist within at most 50 to 100 MeV of ψ and ψ'; we urge a search for them. In the event that they do not show up in (e^-e^+) experiments, we would consider two possible explanations: (i) Their production in e^-e^+ experiments is suppressed by $\sin^2\xi$ (implying that the states are almost pure $\tilde{U}$ and V^0 and similarly the C's); these two missing particles can then be produced in associated production and singly (via H_8') in hadronic collisions; they would decay almost entirely into hadrons (also via H_8'). (ii) Alternatively, we would be tempted to suggest that each one of the resonances ψ and ψ' is a *superposition* of two resonant particles. This would be the case if color symmetry is so good in "practice" that U and V are close in mass within a few hundred keV, and similarly the C's.

To conclude, if the color identification for ψ and ψ' turns out to be correct (in this case, one will have to abandon the familiar fractional-charge hypothesis for the quarks), it would be in order to search[5,18] for the remaining members of the gluon octet ($V_{\tilde{\rho}}$, V_{K^*}) and the composites ($C_{\tilde{\rho}}$, C_{K^*}) in addition to the whole panorama of color composites and, in particular, unstable[5] integer-charge quarks decaying into leptons + pions.

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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); C. Bacci *et al.*, *ibid.* 33, 1408 (1974).

[2]S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 3, 1285 (1970).

[3]M. Y. Han and Y. Nambu, Phys. Rev. 139, B1006 (1965).

[4]J. C. Pati and A. Salam, cited by J. D. Bjorken, in *Proceedings of the Sixteenth International Conference on High Energy Physics, The University of Chicago and National Accelerator Laboratory, Batavia, Illinois, 1972,* edited by J. D. Jackson and A. Roberts (National Accelerator Laboratory, Batavia, Ill., 1973), Vol. 2, p. 304; J. C. Pati and A. Salam, Phys. Rev. D 8, 1240 (1973).

[5]J. C. Pati and A. Salam, Phys. Rev. D 10, 275, 703(E) (1974).

[6]G. S. Abrams, private communication.

[7]See footnotes 23 and 30 of Ref. 5.

[8]Maintenance of SU(3′) color as a global symmetry is discussed in a forthcoming preprint by R. N. Mohapatra, J. C. Pati, and A. Salam.

[9]This is by using isospin and charge-conjugation selection rules.

[10]This is similar to the approach of M. Gell-Mann, D. Sharp, and W. G. Wagner [Phys. Rev. Lett. 8, 261 (1962)], but we would advocate using subtracted dispersion relations for the diagonal transitions (leading to *charge* form factors) and unsubtracted ones for nondiagonal transitions ($U \rightarrow \eta' + \gamma$, $\rho \rightarrow \pi + \gamma$, etc.). This does not alter much the applications of vector-meson dominance to $\rho \rightarrow \pi + \gamma$, $\omega \rightarrow \pi + \gamma$, etc., since $m_{\rho,\omega} \sim 1$ BeV [thus $(1\ \text{BeV})^2/m_\rho^2 \sim O(1)$]; but for color-octet transitions, we do not expect the dispersion denominator damping to be compensated by the numerator; thus $(1\ \text{BeV})^2/m_U^2 \sim 10^{-1}$.

[11]U being heavy, $(S^0+\gamma)$, $(\epsilon^0+\gamma)$, and (many pions $+\gamma$) modes may also be *relatively* significant.

[12]Note that $\Gamma_e(U)+\Gamma_e(V)$ is independent of ξ.

[13]The corresponding matrix element $\langle \text{hadrons} | T(J_\mu^{\text{em}} \times J_\mu^{U^0}) | U \rangle$ can be dominated by low-mass states and hence should not suffer any suppression.

[14]With φ_c, one expects $\Gamma(\varphi_c \rightarrow \text{hadrons} + \gamma)/\Gamma(\varphi_c \rightarrow \text{hadrons}) \approx \alpha$.

[15]Allowing for heavy mass damping of order-e amplitudes we still find $R \lesssim \alpha$.

[16]We have examined whether the large enhancement of a somewhat similiar decay $\rho' \rightarrow \rho + \pi + \pi$ ($h_{\rho'}^2/4\pi \gtrsim 400$) may be relevant to enhance $\psi' \rightarrow \psi + \pi + \pi$ decay to the extent needed (if it were a forbidden decay) and find that this is unlikely.

[17]The familiar Zweig-rule suppression of φ_c and φ_c' $\rightarrow$ hadrons by about 10^{-3} in the amplitude also applies to $\varphi_c' \rightarrow \varphi_c + \pi + \pi$. With the ρ'-decay enhancement factor (Ref. 16), we may then expect $h^2/4\pi \approx 10^{-6} \times 400 = 4 \times 10^{-4}$. The situation will, of course, alter if exceptions to the Zweig rule for $\varphi_c' \rightarrow \varphi_c + \pi + \pi$-type decays may be understood consistently.

[18]The gluons $V_{\rho^\pm}$, V_{K^*} (carrying I_3' or $Y' \neq 0$) will be produced primarily in an associated manner in hadronic collisions and in e^-e^+ annihilation and singly in charged-current neutrino interactions (see Refs. 4 and 5). They would decay solely via their small components into lepton pairs and known hadrons, if there are no lighter mass color-octet states with similar quantum numbers.

Are There Narrow D-Wave Baryon-Antibaryon Resonances?

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The conjecture of a possible narrow D-wave resonance of the $\Omega\bar{\Omega}$ system is extended to general baryon-antibaryon systems. On the basis of the well-known NN forces one finds that $B\bar{B}$ systems bound by pion forces are more likely to produce narrow resonances. In particular one may expect narrow resonances below the $N\bar{N}$, $\Lambda\bar{\Lambda}$, and perhaps even the $\Xi\bar{\Xi}$ thresholds. A narrow $B\bar{B}$ resonance may serve in a second step (similar to the α particle) to explain the narrow ψ and ψ'.

In a recent Letter[1] an interpretation of the $\psi(3100)$ as a $^7D_1$ compound (in the notation $^{2S+1}l_j$) of the $\Omega\bar{\Omega}$ system was suggested. It was argued that an angular momentum $l=2$ may keep the constituents sufficiently apart to substantially reduce their annihilation probability and therefore improve their stability. This mechanism only works if there is no strong leakage into S waves. To suppress this leakage it was assumed that the spin-changing forces are weak. In the present