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# How light may observable color gluons be?*

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In the context of the unconfined-color gauge theory, we study whether the color gluons may be relatively light and yet have escaped experimental detection. We find that photoproduction experiments, which provide the most severe restrictions, are not yet quite sensitive enough to exclude the existence of color gluons with a mass in the region of 1.1 to 1.8 GeV, but a modest increase in sensitivity in such experiments should enable one to settle this question one way or the other. A gluon mass below 1 GeV appears to be difficult to reconcile simultaneously with the observed value of $g-2$ for the muon, experimental upper limits on new-charged-particle lifetimes, and photoproduction experiments. A mass between 2 and 3 GeV appears to be incompatible with data from $e^+e^-$ annihilation and photoproduction. An explicit search for a narrow neutral gluon ($\Gamma\sim 1$ to few MeV) in $e^-e^+$ annihilation in the energy range 1.1 to 1.8 GeV, which (if it exists) will exhibit itself as a prominent peak in $\sigma_{\text{total}}$, should provide a more definitive answer to the question of whether observable gluons exist with such light mass.

## I. INTRODUCTION

The theory of quarks with flavor and color permits two distinct alternatives: (i) Quarks are integer-charged, and the octet of color gluons acquires mass through the Higgs-Kibble mechanism; color is observable and is as physical as flavor quantum numbers.[1,2] (ii) Quarks are fractionally charged and the octet of color gluons is massless; in this second case one must assume that *all* color-carrying objects, including quarks and gluons, are permanently confined.[3]

To facilitate discrimination between these alternatives, it is important to seek out those differences in their predictions that are observable at relatively low energies. In particular, many readily observable phenomena should exist in the scheme (i) if the color gluons are fairly light, say $m \lesssim 2$ GeV. While this scheme does not necessarily require the color gluons to be light, light gluons might be favored over heavy ones in this framework for reasons stated below. Experiments should be able to support or rule out this variant of scheme (i) without much difficulty.

We are led to consider the possibility that the color gluon may be relatively light because of the recent realization[4] that within the color-gauge-theory approach,[2] leptoproduction of color receives contributions from two sources—the photon $A_\mu$ and its orthogonal color-gauge partner $U_\mu$ which cancel each other at large $q^2$ (except for the difference between their propagator functions). When allowance is made for this cancellation effect, the lack of production of color states in leptoproduction experiments becomes consistent with the hypotheses that (a) quarks carry integer charges and yet (b) the color threshold is relatively low.

A theoretical motivation for pursuing this possibility comes from the following consideration: Presumably the exchange of color gluons provides the potential which binds the quarks to form ordinary hadrons. If the range of this potential is very short, corresponding to a large gluon mass, it may be difficult to reconcile such a picture with the known size of hadrons. (Large coupling constants might then also be required, which would be in conflict with estimates obtained from analyses of electroproduction.)[5]

A further independent motivation for examining this possibility arises if one wishes to interpret[6] the $\mu e$ events observed at SPEAR[7] as due to integer-charge-quark decays rather than heavy leptons. Within a unified model[2] of quarks and leptons, this appears to require the existence of colored-octet vector mesons lighter than quarks (in this case $m_V < m_q \approx 1.9$ GeV).

The purpose of this paper is to consider to what extent the existence of light color gluons is compatible with present experimental information and to suggest where further experimental effort might best be focused. In Sec. II we discuss the decay modes of the color gluons and give some formulas for the decay widths. In Sec. III we discuss photoproduction, which at present appears to put the most severe constraints on the allowable gluon masses. In Sec. IV we consider the constraints from various other processes. Our main conclusions are summarized in Sec. V. The Appendix contains a calculation of the gluon self-energy, which is needed for an estimate of the photoproduction cross section.

## II. DECAY MODES AND LIFETIMES

The discussion below assumes that the spin-1 octet of color gluons ($V_\rho^\pm$, $V_{K^*}^\pm$, $V_{K^*}^0$, $\tilde{U}$, and

$\tilde{V}$) are the lightest states transforming as (1, 8) under $SU(3)\times SU(3)'_{col}$. The corresponding physical gauge particles inevitably possess[2] (via spontaneous symmetry breaking and mass diagonalization) small admixtures of flavor-gauge mesons ($W$'s), since in the integer-charged quark theory the photon is an admixture of flavor- and color-gauge mesons. The relative proportions of these small admixtures get essentially determined by the composition of the photon on the one hand and the physical masses of the gauge particles and the gauge-coupling parameters on the other. These small admixtures are crucial to the decays of color gluons since without such admixtures, six members of the octet ($V^{\pm}_{\rho}$, $V^{\pm}_{K*}$, $V^0_{K*}$, $\overline{V}^0_{K*}$) would be stable by conservation of color quantum numbers ($I'_3$ and $Y'$), even though electromagnetism would violate color symmetry. We list below the charged and neutral eigenstates and discuss their decay modes separately.

### A. Decay modes and lifetimes of the charged members

The charged-particle eigenstates [ignoring correction terms of $O(\delta^2)$ with $\delta \lesssim 10^{-4}$] are given by[8]

$$\begin{aligned}\tilde{V}^{\pm}_{\rho} &= \cos\beta \tilde{V}^{\pm}_{\rho} + \sin\beta W^{\pm}_{L},\\ \tilde{V}^{\pm}_{K*} &= \cos\alpha V^{\pm}_{K*} + \sin\alpha W^{\pm}_{L},\\ \tilde{W}^{\pm}_{L} &= W^{\pm}_{L} - V^{\pm}_{\rho}\sin\beta - V^{\pm}_{K*}\sin\alpha,\end{aligned} \tag{1}$$

where

$$\begin{aligned}\sin\alpha &= -\sin(\theta_L+\phi_L)(m_V/m_{W_L})^2(g/f),\\ \sin\beta &= -\cos(\theta_L+\phi_L)(m_V/m_{W_L})^2(g/f).\end{aligned} \tag{2}$$

Here $W^{\pm}_{L}$ are the canonical weak gauge fields coupled to the familiar color-singlet charged $V-A$ currents (of quarks and leptons), while $V^{\pm}_{\rho}$ and $V^{\pm}_{K*}$ are the charged members of the canonical color-octet strong gauge fields, which are coupled to flavor-singlet but color-octet vector currents of quarks and gluons. The low-energy effective gauge-coupling parameters associated with the $W_L$ and ($V^{\pm}_{\rho}$, $V^{\pm}_{K*}$) gauge mesons are denoted by $g$ and $f$ ($g^2 \approx 2e^2$ and $f^2/4\pi \approx 1$ to 10). The masses of the color gluons and $W^{\pm}_{L}$ are denoted by $m_V$ and $m_{W_L}$, respectively. The angles $\theta_L$ and $\phi_L$ denote Cabibbo rotations in $(\mathfrak{N}, \lambda)_L$ and $(\mathcal{P}, c)_L$ spaces, respectively; the observed Cabibbo angle is $\theta_C = \theta_L - \phi_L$. For our estimates of decay rates of $\tilde{V}^{\pm}_{\rho}$ and $\tilde{V}^{\pm}_{K*}$, we shall take $\sin(\theta_L+\phi_L) \approx \cos(\theta_L+\phi_L) \approx 1/\sqrt{2}$.

Since $\tilde{V}^{\pm}_{\rho}$ and $\tilde{V}^{\pm}_{K*}$ decay only because of their $W^{\pm}_{L}$ component, some of their allowed and forbidden decay modes are

$$\begin{aligned}(\tilde{V}^{\pm}_{\rho} \text{ and } \tilde{V}^{\pm}_{K*}) &\to e^+\nu_e,\ \mu^+\nu_\mu\\ &\to \pi\pi e\nu,\ K\overline{K}e\nu,\ \eta\eta e\nu \quad (\text{hadrons in } I=0,\ C=+1 \text{ state})\\ &\to \pi\pi,\ \pi\pi\pi,\ K\overline{K},\ 5\pi, \text{ etc.}\\ &\to \pi e\nu,\ Ke\nu,\ \eta e\nu.\end{aligned} \tag{3}$$

Note that the semileptonic decay modes of $\tilde{V}^{\pm}_{\rho}$ must necessarily involve emission of hadrons via strong interactions through transitions of the form $V^{\pm}_{\rho} \to (V^{\pm}_{\rho})_{\text{virtual}} + (\text{pions})$, etc. Thus, by conservation of isospin, strangeness, and $C$ invariance, the semileptonic decay modes can involve *two* pions or *two* kaons in the final state with $I=0$, $C=+1$; but single-pion, single-kaon, single-$\rho$, or single-$\omega$ emission (i.e., $V^+_{\rho} \to \pi e\nu$ or $Ke\nu$, etc.) is forbidden [at least to $O(\alpha)$ in the matrix element]. Single-$\eta$ emission is forbidden by SU(3) *and* SU(3)'.

Using Eqs. (1) and (2), and setting $(g^2/2m_{W_L}{}^2) = G_F/\sqrt{2}$, we find that the decay rates for some of the typical modes are given by

$$\begin{aligned}\Gamma(\tilde{V}^+_{\rho} \to \mu^+\nu) &\simeq \Gamma(\tilde{V}^+_{\rho} \to e^+\nu)\\ &\simeq \frac{1}{12\pi}(G_F m_V{}^2)^2\left(\frac{m_V}{f^2}\right),\\ \Gamma(\tilde{V}^+_{\rho} \to \pi^+\pi^0) &\simeq \frac{1}{48\pi}(G_F m_V{}^2)^2\left(\frac{m_V}{f^2}\right)\ F_\rho(m_V{}^2)|^2\\ &\quad\times\left(1-\frac{4m_\pi{}^2}{m_V{}^2}\right)^{3/2},\end{aligned} \tag{4}$$

where, assuming a $\rho$-dominant form factor for the transition $V^+_{\rho} \to W^+ \to \pi^+\pi^0$,

$$F_\rho(m_V{}^2) = \frac{m_\rho{}^2}{m_V{}^2 - m_\rho{}^2 + i m_\rho\Gamma_\rho}.$$

Note that the partial width for the pure leptonic mode is proportional to the *fifth power* of the gluon mass and is inversely proportional to the strong gauge-coupling parameter $f^2$ [this is because the sine of the mixing angle $\beta$ is proportional to $(m_V{}^2/f)$, while the phase space for the leptonic mode is proportional to $m_V$]. We give below the numerical values of the leptonic rates multiplied by $f^2/4\pi$ for some typical value of $m_V$:

$$\begin{aligned}\left(\frac{f^2}{4\pi}\right)\Gamma(\tilde{V}^+_{\rho} \to \mu^+\nu) &\simeq \tfrac{1}{6}\times 10^{12}\ \text{sec}^{-1} \quad (m_V \simeq 500 \text{ MeV}),\\ &\simeq 5\times 10^{12}\ \text{sec}^{-1} \quad (m_V \simeq 1000 \text{ MeV}),\\ &\simeq 4\times 10^{13}\ \text{sec}^{-1} \quad (m_V \simeq 1500 \text{ MeV}).\end{aligned}$$

We have made a rough estimate of the semileptonic $\pi\pi e\nu$ mode assuming $\epsilon$ dominance and find its rate to be suppressed by at least an order of magnitude compared with the $e\nu$ mode. We obtain $\Gamma(\tilde{V}_\rho^+ \to \pi\pi e\nu) \approx (\frac{1}{40}$ to $\frac{1}{10})\,\Gamma(\tilde{V}_\rho^+ \to e\nu)$ for $m_V \approx 1500$ MeV.

For the hadronic modes, following asymptotic freedom or light-cone analysis, we expect the inclusive hadronic versus leptonic ($e\nu$ or $\mu\nu$) branching ratio to be 3 : 1 for a sufficiently heavy gluon ($m_V > 3$ GeV),[6] the number 3 arising from the three quark colors. However, for a light gluon, we expect this ratio to be less than 3 (perhaps of order unity if $m_V \sim 1$ to 2 GeV and less than unity if $m_V < 1$ GeV) owing to limited phase space, which restricts the number of hadronic decay modes. Thus we typically expect the following branching ratios for a light gluon:

$$\begin{aligned} \tilde{V}_\rho^+ &\to e^+\nu_e \quad (30\pm5)\% \\ &\to \mu^+\nu_\mu \quad (30\pm5)\% \\ &\to \pi\pi, 3\pi, 4\pi, K\bar{K}, \ldots \quad (30\mp10)\% \\ &\to \pi\pi e\nu, K\bar{K}e\nu, \eta\eta e\nu \quad (\text{few})\%. \end{aligned} \tag{5}$$

Using these, the total decay rate of the charged gluons is found to be

$$\begin{aligned} \left(\frac{f^2}{4\pi}\right)\Gamma(\tilde{V}_\rho^+)_{\text{total}} &\approx 5\times10^{11}\ \text{sec}^{-1} \quad (m_V = 500\ \text{MeV}) \\ &\approx 1.5\times10^{13}\ \text{sec}^{-1} \quad (m_V = 1000\ \text{MeV}) \\ &\approx 1.2\times10^{14}\ \text{sec}^{-1} \quad (m_V = 1500\ \text{MeV}). \end{aligned} \tag{6}$$

If $\sin(\theta_L + \varphi_L) \approx \cos(\theta_L + \varphi_L)$, the rate of $\tilde{V}_{K^*}^+$ decay would be similar to that of $\tilde{V}_\rho^+$ decay.

### B. Decay modes of the neutral members ($\tilde{U}, \tilde{V}, V_{K^*}^0, \bar{V}_{K^*}^0$)

Two of these, $\tilde{U}$ and $\tilde{V}$, are primarily mixtures[9] of the canonical color-gluon fields $U^0 = \frac{1}{2}(\sqrt{3}\,V_3 + V_8)$ and $V^0 \equiv \frac{1}{2}(V_3 - \sqrt{3}\,V_8)$ with small admixtures of flavor-gauge mesons. The canonical $U^0$ field is a component of the photon field as well (for the case of integer-charge quarks under consideration). The allowed decay modes[9] of $\tilde{U}$ and $\tilde{V}$ are listed below together with the magnitude of the corresponding decay amplitudes:

$$\begin{aligned} (\tilde{U}, \tilde{V}) &\to e^+e^-, \mu^+\mu^- \quad [2/\sqrt{3}\,(e^2/f)(\cos\xi, \sin\xi)] \\ &\to \pi\pi\gamma, 4\pi\gamma, 6\pi\gamma, \eta'\gamma \quad [O(e)] \\ &\to \pi\pi, 4\pi, 6\pi\pi, KK, \eta\pi\pi \quad [O(\alpha)] \\ &\to 3\pi, 5\pi, KK, \rho\pi, \pi\pi\omega \quad [O(\alpha)\pm O(\epsilon_8')]. \end{aligned}$$

Here $\cos\xi$ and $\sin\xi$ denote the magnitude of the $U^0$ component in $\tilde{U}$ and $\tilde{V}$, respectively, while $\epsilon_8'$ denotes the strength of the *nonelectromagnetic* SU(3)$'$-breaking term ($H_8'$) in the Hamiltonian. We assume that $H_8'$ is an SU(3) scalar. Note that subject to this assumption, *$H_8'$ contributes to odd-pion modes but not to even-pion modes*. For the leptonic $e^-e^+$ and $\mu^-\mu^+$ modes, we thus obtain

$$\begin{aligned} \Gamma(\tilde{U}, \tilde{V} \to e^+e^-) &= \left(\frac{2}{\sqrt{3}}\,\frac{e^2}{f}\right)^2 \left(\frac{m_U}{12\pi}\right)(\cos^2\xi, \sin^2\xi) \\ &\approx (f^2/4\pi)^{-1}(18\ \text{keV})(2\cos^2\xi, 2\sin^2\xi) \\ &\qquad (m_U = 1.5\ \text{GeV}). \end{aligned} \tag{7}$$

To avoid an awkward notation we have denoted the mass of $\tilde{U}$ by $m_U$. Thus for $(f^2/4\pi) \approx 2$ to 5, gluon mass $m_U \approx 1.5$ GeV, and $\cos^2\xi \sim \sin^2\xi \sim \frac{1}{2}$, we expect $\Gamma(\tilde{U} \to e^+e^-) \sim \Gamma(\tilde{V} \to e^+e^-) \sim (3$ to $10)$ keV.

The widths of the radiative modes as well as those of the hadronic modes are harder to estimate accurately. Using a dimensional mass scale of 1 GeV ( to the appropriate power) for defining the invariant amplitudes and strength parameters $e$, $\alpha$, and $\epsilon_8'$ for the respective decay mode as indicated above, we obtain[10] (for $m_U \approx 1.5$ GeV)

$$\begin{aligned} &\Gamma(\tilde{U} \to \text{hadrons} + \gamma) \approx 1 \text{ to } 3\ \text{MeV}, \\ &\Gamma(\tilde{U} \to \text{even number of pions}) \approx (1 \text{ to } 20)\ \text{keV}, \\ &\Gamma(\tilde{U} \to \text{odd number of pions}) \approx \left|\left(\frac{\epsilon_8'}{\alpha}\right) \pm 1\right|^2 (5 \text{ to } 50)\ \text{keV}, \\ &\Gamma(\tilde{U} \to \pi^+\pi^-) \approx (\tfrac{1}{10} \text{ to } \tfrac{1}{3})\ \text{keV}. \end{aligned} \tag{8}$$

Among the odd-pion modes $\omega\pi\pi$ and $\rho\pi$ are dominant channels, while among the even-pion modes $4\pi$ and $\eta\pi\pi$ are dominant. The partial width of the odd-pion modes depends on the effective strength $\epsilon_8'$ of the nonelectromagnetic SU(3)$'$-color-symmetry-breaking term. If $\epsilon_8'$ is of the same order as the strength of the (presumably) nonelectromagnetic isospin breaking exhibited by $\eta \to 3\pi$ decay, which is $\approx 10\alpha$, we would expect[11] $\Gamma(U \to \text{odd number of pions}) \approx \frac{1}{2}$ to 5 MeV, whereas if $\epsilon_8'$ is of order $\alpha$ this partial width could be much smaller. Also, as will be seen in Sec. III, the coupling of $\tilde{U}$ to the photon may be greatly suppressed, and hence the radiative decay width may be smaller than the above estimate.

Combining the radiative and the hadronic decay modes, we obtain (for a light gluon)

$$\begin{aligned} &1\ \text{MeV} \lesssim \Gamma(\tilde{U})_{\text{total}} \lesssim (5 \text{ to } 10\ \text{MeV}), \\ &\frac{\Gamma(\tilde{U} \to e^+e^-)}{\Gamma(\tilde{U} \to \text{all})} \approx (1 \text{ to } 10)\times10^{-3}, \\ &\frac{\Gamma(\tilde{U} \to \pi^+\pi^-)}{\Gamma(\tilde{U} \to \text{all})} \approx 10^{-4}. \end{aligned} \tag{9}$$

Similar estimates apply to $\tilde{V}$ decays. We have

$\Gamma(\tilde{U}\to e^+e^-)=\Gamma(\tilde{U}\to\mu^+\mu^-)$. Note that $\tilde{U}$ and $\tilde{V}$ would be produced in $e^-e^+$ annihilation in the proportion $\cos^2\xi:\sin^2\xi$. [If $\sin^2\xi=0$, only one of the gluons (i.e., $\tilde{U}$) would be produced by $e^-e^+$ annihilation and photoproduction; the $\tilde{V}$ meson may still be produced in pairs in $NN$ collisions and would decay into hadrons through the nonelectromagnetic SU(3)$'$ -breaking term $H'_{8'}$.]

The two remaining neutral color gluons ($V^0_{K^*}$ and $\overline{V}^0_{K^*}$) may decay[8] (for example) by first converting to a virtual $U$ through convergent loop diagrams which involve $V^-_\rho$-$W^-$ as well as $V^-_{K^*}$-$W^-$ mixings. Thus $V^0_{K^*}$ and $\overline{V}^0_{K^*}$ would decay via the same decay channels as $\tilde{U}$. Their lifetime (calculated on the basis of such loop diagrams) is $\ll 10^{-15}$ sec [if $(m_{V_{K^*}}{}^2-m_U{}^2)\ll m_U{}^2$] for $m_V\approx 1.5$ GeV. These two members ($V^0_{K^*}$ and $\overline{V}^0_{K^*}$) would not be produced by $e^-e^+$ annihilation or photoproduction. However, they could be produced in pairs in $NN$ collisions.

### C. Constraints from lifetimes and $g-2$ of the muon

We see that a very light gluon would lead to relatively long-lived charged gluons. However, objects with lifetimes $\gtrsim 10^{-11}$ sec would probably have been observed in bubble-chamber searches. Since none have been seen, we infer

$$m_V > 400 \text{ MeV (for } f^2/4\pi=1), \qquad m_V > 700 \text{ MeV (for } f^2/4\pi=10). \tag{10}$$

An independent constraint on the mass of the gluon arises from consideration of $g-2$ for the muon. If a light neutral color gluon $\tilde{U}$ exists, there will be an additional contribution to the muon $(g-2)$ factor arising from the $\tilde{U}$-exchange[12] vertex correction. One finds that $\delta(g-2)=(e^2/f)^2(m/m_U)^2(1/9\pi^2)$. The agreement between the theoretical and experimental values[13] of $g-2$ at the present time requires that $\delta(g-2)\lesssim 6\times10^{-8}$. This in turn implies that

$$\frac{f^2}{4\pi}m_U{}^2 \gtrsim 2\ (\text{GeV})^2. \tag{11}$$

Thus, for example,[14] with $(f^2/4\pi)\approx 2$, $m_U\gtrsim 1$ GeV.

## III. PHOTOPRODUCTION

The neutral $\tilde{U}$ can be photoproduced with a subsequent decay into lepton pairs. Many photoproduction experiments sensitive to the existence of narrow vector-meson resonances decaying into lepton pairs have been carried out. In the vector-meson mass range 500–2600 MeV these experiments[15] set an upper limit for production cross section times leptonic branching ratio of the order of $10^{-34}$ cm$^2$.

The leptonic branching ratio for $\tilde{U}$, from our calculations, may be expected to be from $10^{-3}$ to $10^{-2}$. Hence the data put an upper limit on the photoproduction cross section of the order $10^{-32}$ cm$^2$ to $10^{-31}$ cm$^2$. The corresponding production cross section for $\rho^0$ is $10^{-28}$ cm$^2$. If the $\tilde{U}$ photoproduction is not greatly suppressed in comparison with $\rho^0$ photoproduction, then the above limits could already be used to rule out the existence of light color gluons. However, in general there is a large degree of uncertainty in theoretical predictions of vector-meson photoproduction. There is at least one argument for a severe suppression in the specific case of $\tilde{U}$ photoproduction: In the gauge theory[2] of unconfined color the photon and $\tilde{U}$ are orthogonal linear combinations of the same two neutral gauge mesons $W_3$ and $U_0$. Consequently the color piece of the photon source is proportional to that of the $\tilde{U}$ source ($J^\mu_{\tilde{U}}$), except for a (finite) mass counterterm $\delta m_U{}^2$ in the $\tilde{U}$ source. Therefore

$$\langle 0|J^\mu_{\text{em}}|\tilde{U}\rangle=\frac{e}{f}\langle 0|J^\mu_{\tilde{U}}-\delta m_U{}^2\tilde{U}^\mu|\tilde{U}\rangle = -\frac{e}{f}\delta m_U{}^2\epsilon^\mu .$$

The corresponding matrix element for $\rho$ photoproduction is $\langle 0|J^\mu_{\text{em}}|\rho\rangle=(em_\rho{}^2/\gamma_\rho)\epsilon_\mu$. Using vector-meson dominance based on dispersing in the photon-mass variable we then get

$$\frac{\sigma(\gamma N\to\tilde{U}N)}{\sigma(\gamma N\to\rho N)}=\eta\,\frac{\sigma(\tilde{U}N\to\tilde{U}N)}{\sigma(\rho N\to\rho N)}\,,\quad \eta=\left(\frac{\delta m_U{}^2/fm_U{}^2}{m_\rho{}^2/\gamma_\rho m_\rho{}^2}\right)^2, \tag{12}$$

To proceed further we need to evaluate $\delta m_U{}^2$. This quantity is directly related to the color part of the photon vacuum-polarization tensor,

$$\pi^{\mu\nu}_{\text{col}}(k^2)=(g^{\mu\nu}k^2-k^\mu k^\nu)\pi_{\text{col}}(k^2),$$

via (13)

$$\frac{\delta m_U{}^2}{m_U{}^2}=\pi_{\text{col}}(m_U{}^2).$$

In the Appendix we estimate $\pi_{\text{col}}(m_U{}^2)$, using a once-subtracted dispersion relation for $\pi_{\text{col}}$. As shown in Sec. II, values of $m_U$ less than 1 GeV are difficult to reconcile with a variety of other experimental observations. Limiting ourselves to 1 GeV $\lesssim m_U\lesssim$ 2 GeV, we find that

$$\pi_{\text{col}}(m_U{}^2)\approx(1\text{ to }2)(f^2/48\pi^2). \tag{14}$$

If we take $f^2/4\pi\sim0.5$, corresponding to the running coupling constant for timelike $s\sim1$ to 2 GeV, we get

$$\eta\sim\tfrac{1}{1500}\times(1\text{ to }4). \tag{15}$$

One sees that a suppression of three orders of magnitude of the $\tilde{U}$ versus $\rho^0$-photoproduction cross section (from the factor $\eta$ alone) is not out of the question. Taking $\eta \approx 10^{-3}$ and the leptonic ($e^-e^+$)-branching ratios of $\tilde{U}$ and $\rho^0$ to be (1 to 10) $\times 10^{-3}$ [see Eq. (8)] and $5\times 10^{-5}$, respectively, we obtain

$$\frac{\sigma(\gamma+N\to\tilde{U}+X\to e^-e^+ +X)}{\sigma(\gamma+N\to\rho^0+X\to e^-e^+ +X)} \approx (\tfrac{1}{50})(1 \text{ to } 10)\frac{\sigma(\tilde{U}N)}{\sigma(\rho^0 N)}\,. \quad (16)$$

Since the strong-interaction cross sections $\sigma(\phi N)$ and $\sigma(\psi n)$ (at high energies) are nearly a factor of 3 and a factor of 27 lower than $\sigma(\rho^0 N)$ respectively, it is not implausible that $\sigma(\tilde{U}N)$ might be as much as an order of magnitude lower than $\sigma(\rho^0 N)$. As a plausible estimate, we may thus infer

$$\frac{\sigma(\gamma+N\to\tilde{U}+X\to e^-e^+ +X)}{\sigma(\gamma+N\to\rho^0+X\to e^-e^+ +X)} \approx (10^{-2})(\tfrac{1}{5} \text{ to } 5). \quad (17)$$

Therefore the accuracy of photoproduction experiments needs to be further improved, *particularly near the lower-energy range* ($\simeq 1$ GeV), before the existence of $\tilde{U}$ can be definitely disproved by means of this process. Because of this, it seems to us that $e^+e^-$ annihilation, discussed below, offers a more direct check on the question of a light $\tilde{U}$.

We should note that if there exists a composite particle with the quantum numbers of the $\tilde{U}$, call it $U'$, say, 2 to 3 or above 4 GeV, there is no analogous suppression mechanism. Indeed, on comparison with the photoproduction of $\rho$, one expects

$$\frac{\sigma(U')}{\sigma(\rho)} \simeq \left(\frac{m_\rho{}^2}{m_{U'}{}^2}\right)^2 \left[\left(\frac{g_{\gamma\to U'}}{g_{\gamma\to\rho}}\right)^2 \frac{\sigma(U'N\to U'N)}{\sigma(\rho N\to\rho N)}\right]^2 . \quad (18)$$

If the quantity in the square brackets is of order unity, we will get

$$\sigma(U')/\sigma(\rho) \sim 10^{-2} \text{ to } 10^{-3}. \quad (19)$$

We expect $U'$ to have, in general, the following set of decay modes:

$$\begin{aligned} U' &\to \tilde{U}+2\pi \quad \text{(strong)}\\ &\to \tilde{V}_\rho^+ + \tilde{V}_\rho^- \quad \text{(strong)}\\ &\to \pi\pi\gamma, \eta'\gamma \quad [O(\alpha)]\\ &\to e^+e^-, \mu^+\mu^- \quad [O(\alpha)]. \end{aligned} \quad (20)$$

The branching ratio for $U'\to e^+e^-$ is expected to be negligible. If $m_{U'} \lesssim 2m_U$, its dominant decay mode would be $U'\to\tilde{U}+2\pi$. The resulting effective $\tilde{U}$-production cross section arising via $U'$ decay would in this case be in the range of $10^{-2}$ to $10^{-3}$ relative to $\rho$ production, if the square bracket in (18) is of order unity.

If $m_U' > 2m_U$, the decay $U'\to\tilde{V}_\rho^+ + \tilde{V}_\rho^-$ would dominate and our conclusions would remain essentially unchanged.

Also, if $U'$ exists, there would be a contribution to direct photoproduction of $\tilde{U}$, via the process $\gamma\to U'$ (in the dispersion-theoretic sense), followed by a diffractive process $U'+N\to\tilde{U}+N$. In addition to the mass-denominator damping one expects that such "off-diagonal" processes will be smaller than the diagonal process $U'+N\to U'+N$, so that our estimate of the range of values for the lepton signal remains unchanged.

Finally, we mention that the hadronic signals in the photoproduction of $\tilde{U}$ would stand out less clearly than the leptonic signals, because no one particular final state is dominant in the set shown in the preceding section. In view of the possible suppression of photoproduction as a whole, discussed above, and the greater uncertainties in the branching ratios of such hadronic modes, we will not enter into a detailed comparison with experiment for the hadronic signals.

## IV. CONSTRAINTS FROM OTHER PROCESSES

### A. $e^-e^+\to\tilde{U}\to$ leptons and/or hadrons

If $\tilde{U}$ exists it will be formed at $E_{\text{c.m.}} \simeq m_U$ in $e^+e^-$ annihilation. The coupling strength of $\tilde{U}$ to $e^+e^-$ is $[(e^2/f)-(e^2\delta m_U{}^2/f m_U{}^2)](2/\sqrt{3})$. If our estimate of $\delta m_U{}^2$ is correct, the second term is negligible relative to the first term. In this case, since the area under the resonance peak in the $e^+e^-$ total cross section is proportional to the partial width of $\tilde{U}\to e^+e^-$ [see Eq. (7)], *the $\tilde{U}$ will show up at least as prominently as $\psi'(3700)$ in any sweeping search with a good resolution.* But even if our estimate of $\delta m_U{}^2$ is totally wrong in magnitude, and even if there is a cancellation between the two terms in the bracket which makes the $\tilde{U}\to e^+e^-$ coupling much smaller than $e^2/f$, the suppression mechanism in photoproduction discussed in Sec. III will then no longer operate, and the $\tilde{U}$ should have been seen there, at least in the hadronic channels. So, in conjunction with photoproduction, the $e^+e^-$ experiment can settle this question without any ambiguities. Narrow resonances ($\Gamma\approx 1$ to few MeV) in $e^+e^-$ annihilation should be searched for by sweeping the energy region 1–3 GeV. While this has been done partially,[16] there appear to be significant gaps. This search deserves urgent attention.

### B. $e^-e^+ \to (\tilde{V}_\rho^+ \tilde{V}_\rho^-, \tilde{V}_{K^*}^+ \tilde{V}_{K^*}^-) \to \mu e$ or $\mu + X$

In the spirit of the parton model, the two pairs of charged gluon partons ($V_\rho^\pm$ and $V_{K^*}^\pm$) asymptotically contribute[4] an amount ($\frac{1}{8}$) to $R$. However, in the nonasymptotic region (e.g., for $E_{\text{c.m.}} \approx 5$ GeV and $m_V \approx 1$ to 2 GeV), this contribution ($R_{V\overline{V}}$) may be as large as[17] $\frac{1}{4}$. In the model of unconfined color, the *parton pairs* ($V^+V^-$) may in part survive as a pair of real charged gluons, while in part they may recombine to form colored states plus known hadrons. These alternatives may be symbolized by three different channels:

$$e^-e^+ \xrightarrow[(V^+V^-)_{\text{partons}}]{} \tilde{V}^+\tilde{V}^- \tag{21a}$$

$$\longrightarrow \text{single colored state (e.g., } \tilde{U}) + \text{mesons } (\pi\pi, K\overline{K}, \eta\eta) \tag{21b}$$

$$\longrightarrow \tilde{V}^+ + \tilde{V}^- + \text{mesons } (\pi\pi, K\overline{K}, \eta\eta). \tag{21c}$$

The amount of real ($\tilde{V}^+\tilde{V}^-$) production (*without* accompanying mesons) would depend upon the square of the electromagnetic form factor of the charged gluons $[\rho_V(s) \equiv |f_{VV\gamma}(s)|^2]$. Thus asymptotically (i.e., setting the threshold kinematic factor equal to unity)

$$\begin{aligned}\sigma(\tilde{V}^+\tilde{V}^-) &= R_{V\overline{V}}\,\rho_V(s)\sigma(\mu^+\mu^-),\\ \sigma(21\text{b}) + \sigma(21\text{c}) &= R_{V\overline{V}}[1-\rho_V(s)]\sigma(\mu^+\mu^-).\end{aligned} \tag{22}$$

Since the leptonic ($e\nu$ or $\mu\nu$) branching ratio of light charged gluons $\approx$(25 to 35)% [see Eq. (5)], we would expect a contribution to a pure leptonic $\mu^\pm e^\mp$ signal (without accompanying hadrons) from pair production of $\tilde{V}^+\tilde{V}^-$ [i.e., $e^-e^+ \to \tilde{V}^+ + \tilde{V}^- \to (\mu\nu) + (e\nu)$] given by an effective $R$ parameter:

$$\begin{aligned} R(\mu^+e^-)_{V\overline{V}} &= R(\mu^-e^+)_{V\overline{V}}\\ &= (\tfrac{1}{8} \text{ to } \tfrac{1}{4})(0.25 \text{ to } 0.35)^2\rho_V(s)\\ &= \rho_V(s)(1 \text{ to } 4)\times 10^{-2}.\end{aligned} \tag{23}$$

The true leptonic $\mu e$ signal[7] (allowing for angular and momentum cuts and threshold kinematic factor for production of massive pairs) corresponds to $R(\mu^+e^-) = R(\mu^-e^+) \approx$ (2 to 4)% [the upper value corresponding to the assumption that the $\mu e$ signal originates entirely from parents with three-body leptonic decays]. The observed lepton momentum spectrum tells us that sources with three-body (or effective three-body[6]) leptonic decay contribute *at least* a significant fraction [$\approx$(50 to 60)%] of the net observed $\mu e$ events, which leaves a balance of at most $\approx$1% for $R(\mu^+e^-) = R(\mu^-e^+)$, that can be attributed to two-body-decay sources (e.g., the charged gluons). Such a balance is compatible with the estimate for $R_{V\overline{V}}(\mu^+e^-)$ given by Eq. (23), if the square of the gluon electromagnetic form factor $\rho_V(s)$ $\approx\frac{1}{2}$ to 1 at SPEAR energies and is slowly varying. [As regards three-body-decay sources, it has been argued[6] that such sources can be provided by quarks themselves in a model with unconfined unstable integer-charge quarks if the quarks have a mass $\approx$1.8 to 2 GeV *and* if the gluons are lighter than the quarks—see Ref. 6 for this suggestion and more details for the combined contributions from quarks and gluons to leptonic signals. Alternatively, three-body-decay sources may be provided by heavy leptons; however, in this case, if we accept the leptonic branching ratio of heavy leptons[18] to be $\approx$0.17 for the $e$ (or $\mu$) mode, the contribution from a gluon pair can at most be 10% of the signature events.]

The charged-gluon pairs ($\tilde{V}^+\tilde{V}^-$) produced via channel (21a) would contribute to semileptonic signals $[e^+e^- \to \tilde{V}^+\tilde{V}^- \to (\mu^+ + \nu) + (e^- + \overline{\nu}_e + \pi^+ + \pi^-)]$ through semileptonic decay of one of the gluons. Using the estimate of $\Gamma(\tilde{V}_\rho^+ \to \pi\pi e\nu) \approx (2\%$ to $10\%) \times \Gamma(\tilde{V}_\rho^+ \to l^+\nu)$, one may expect a semileptonic $\mu e$ signal of nearly (2 to 10)% compared with the leptonic $\mu e$ from charged-gluon pair production. The present indicated experimental limit (<10%) is compatible with this estimate.

Pair production of charged gluons ($\tilde{V}^+\tilde{V}^-$) in association with charged mesons [channel (21c)] would also contribute to semileptonic signals. However, the strength of such signals is proportional in the first place to $[1-\rho_V(s)]$, where $\rho_V(s)$ is the square of the gluon form factor, and in the second place it depends upon the relative branching between the channels (21b) and (21c), their *sum* being determined by $[1-\rho_V(s)]$. [Note that channel (21b) would contribute very little to signature lepton events, since the leptonic decay branching ratio of $\tilde{U}$ is only (1 to 10)$\times 10^{-3}$. Thus the semileptonic signal expected from channel (21c) is harder to estimate. All we may say (given the uncertainties) is that it need not be any larger than 10% compared with the leptonic $\mu e$ signal.]

The inclusive muon experiment ($e^-e^+ \to \mu + X$) carried out by the Maryland, Pavia, Princeton collaboration[19] observes a two-particle signal, which is not incompatible with that of the SLAC-LBL collaboration. As stressed by Snow,[20] this experiment sets a limit: $[\Gamma(M \to n_{\text{ch}} \geq 3)/\Gamma(M \to n_{\text{ch}} = 1)] < 0.33$, where $M$ denotes the source particle for the signature muon. For the charged gluons $\tilde{V}^+$, since the *inclusive hadronic branching* ratio for light gluons is $\approx$30% and since not all of the hadronic modes contain 3 or more *charged* particles, we estimate

$$\frac{\Gamma(\tilde{V}^+ \to n_{ch} \geq 3)}{\Gamma(\tilde{V}^+ \to n_{ch} = 1)} \lesssim 0.2, \qquad (24)$$

which is fully compatible with the experimental limit as stated above. (Note that in the model of Ref. 6, quark decays contributing to the charged-lepton signal would also satisfy the above limit, since they decay into leptons through the intermediary of charged gluons.)

To summarize, the data at present on single and dilepton production by $e^-e^+$ annihilation are not incompatible with a *part* of the signal (≈30 to 40)% arising from pair production of charged light colored gluons contributing to signature leptons. We would therefore urge: (i) a search for semileptonic $\mu e$ signals at the (2 to 10)% level compared with the leptonic $\mu e$ signal, as stressed also in Ref. 6, (ii) a study of the threshold for the $\mu e$ events, in particular whether it lies much lower than 3.8 GeV and whether in such region the lepton momentum spectrum corresponds to two-body-decay source [such a study would be especially warranted if three-body-decay sources necessary for $E_{\text{c.m.}} > 3.8$ GeV are attributed to quarks,[6] since in this case gluons (or some colored vector mesons) must be quite a bit lighter than 1.9 GeV], and finally of course (iii) a high-statistics study of the kinematics of the $\mu e$ events as well as of inclusive muon production events in $e^-e^+$ annihilation.

### C. $p+p \to \tilde{V}^+\tilde{V}^- + X_{\text{had}} \to$ direct leptons $+ X$

The observed direct lepton production[21] is compatible with the possibility that the leptons are the decay products of $\tilde{V}^+\tilde{V}^-$ produced in hadronic interactions with a cross section of $10^{-3}$ of pion production. The approximate equality of $e$ to $\mu$ is compatible with the vector nature. According to the calculations of Lederman and White,[22] the rise for small $p_\perp$ is better understood if $m_V$ is relatively low in mass (near 700 MeV). Since we have seen that this mass range is probably ruled out for the color gluons, the presently allowed lower value of $m_V \sim 1.1$ GeV would be preferred over $m_V \sim 1.8$ GeV from this viewpoint, provided that the rise at small $p_\perp$ is more firmly established. However, we should note that explanations of the direct-lepton data in terms of more familiar processes have been suggested by several authors.[23]

## V. CONCLUSION

Although there have been several searches for new, relatively narrow vector mesons in the 1–3 GeV range with negative results, their significance can be made clear only by comparison with the nature and the strength of theoretically expected signals. In this paper we have tried to supply the latter information within a definite framework of color-gauge theory, with the conclusion that the experimental limits are close to the expected signal strength, especially in photoproduction experiments, but not yet stringent enough to settle the question one way or another for the existence of color gluons in the (1.1–1.8)-GeV range. Therefore, a further improvement in the sensitivity of photoproduction experiments ($\gamma + N \to e^-e^+ + X$) and a fine scan for narrow resonances ($\Gamma \sim 1$ to a few MeV) in $e^-e^+$ annihilation in the 1- to 1.8-GeV region would be most desirable.

The neutral color gluon $\tilde{U}$ should also be visible in the mass spectrum of $e^-e^+$ and $\mu^-\mu^+$ pairs produced in hadronic (for example $pp$, $\pi N$, $\bar{p}p$) collisions, if either the pair production[24] of $\tilde{U}$ (through strong interactions) or single production of $\tilde{U}$ (through color-symmetry-breaking terms) at high energies has a cross section $\gtrsim 10^{-31}$ cm$^2$; this would correspond to a leptonic signal $= \sigma \times$ (branching ratio) $\gtrsim 10^{-34}$ cm$^2$. *A priori* such a pair-production cross section ($\sim 10^{-31}$ cm$^2$) for a relatively light gluon would appear to be reasonable. It should be noted that although the data of a recent experiment[25] on $\mu^+\mu^-$ production in $np$ collisions show the $\rho^0$ peak in the $\mu^+\mu^-$ mass spectrum, there is no clear signal for the $\phi$ meson. This is despite the fact that one is looking at *inclusive* production of $\phi$ (followed by $\phi \to \mu^+\mu^-$), which includes final states not suppressed by the Zweig rule. The strong-interaction production of $\tilde{U}$ requires either a $\tilde{U}$ pair or a single $\tilde{U}$ with other colored matter. If the $\tilde{U}$-production cross section is comparable to that for the $\phi$ or somewhat lower because of the higher masses of colored matter relative to strange matter, the $\tilde{U}$ peak would not necessarily be more prominent since the leptonic branching ratio for $\tilde{U}$ is only about 10 times bigger than the corresponding ratio for $\phi$. But with better resolution than that of Ref. 25, the $\tilde{U}$ peak might become visible. Thus a good resolution search for possible narrow peaks in the low-mass region (1–2 GeV) in $e^-e^+$ and $\mu^-\mu^+$ systems produced by high-energy hadronic collisions would also be very useful. Table I summarizes the expected properties of $\tilde{U}$.

In Table II we summarize the allowed and forbidden mass regions for a narrow neutral-color gluon, according to our analysis. The $e^+e^-$ annihilation data referred to in the last two entries are based on experiments at Frascati and SLAC.[26]

*Added note.* At the 18th International High Energy Physics Conference, Tbilisi, USSR, 1976, two new pieces of data were reported which are relevant to our considerations.[27] On the one hand, a Frascati group working at DESY has found a possible new narrow resonance at 1.1 GeV in photoproduction, with a width less than the resolution ~30 MeV. The detection was by interference with the Bethe-Heitler background in $\gamma N \to e^+e^-X$. On the other hand, a Novosibirsk group[27,28] has found no evidence for the production of any new resonance in $e^+e^- \to \pi^+\pi^-X$ in the region of 0.74 GeV $\lesssim E_{\text{c.m.}} \lesssim$ 1.34 GeV. With the assumption that the branching ratio into pionic modes is comparable to that of the $\phi$ meson, they conclude that the leptonic partial width of such a new meson is less than 200 eV. Thus the situation remains unresolved, and further experimental study is needed.

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TABLE I. Summary of the expected properties of the neutral vector colored gluon $\tilde{U}$ (mass 1.1–1.8 GeV). See text for details. The estimate of the partial width for odd-pion modes depends on the strength of the nonelectromagnetic color-symmetry-breaking term.

| Decay modes | Partial width |
|---|---|
| $\tilde{U} \to e^+e^-$ | 2 to 10 keV |
| $\to \mu^+\mu^-$ | 2 to 10 keV |
| $\to \pi\pi\gamma,\ 4\pi\gamma,\ \eta'\gamma$ | ~1 to 3 MeV |
| $\to 3\pi,\ 5\pi,\ \rho\pi,\ \omega\pi\pi,\ K\bar{K}$ | ~$\frac{1}{2}$ to 5 MeV |
| $\to 2\pi,\ 4\pi,\ 6\pi$ | ~1 to 20 keV |

Thus,

$$1\ \text{MeV} \lesssim \Gamma(U)_{\text{total}} \lesssim 10\ \text{MeV}$$

$$\text{BR}\,(\tilde{U} \to e^+e^-) \approx (1-10)\times 10^{-3}$$

Photoproduction

$$\frac{\sigma(\gamma + N \to \tilde{U} + X \to e^-e^+ + X)}{\sigma(\gamma + N \to \rho^0 + X \to e^-e^+ + X)} \approx 10^{-2}\ (\tfrac{1}{5}\text{ to }5)$$

## APPENDIX: CALCULATION OF $\delta m_U^2$

We use a once-subtracted dispersion relation for the renormalized vacuum-polarization tensor $\pi_{\text{col}}(s')$:

$$\pi_{\text{col}}(s) = \frac{(s)}{\pi} \int_{s_0}^{\infty} ds' \, \frac{\text{Im}\pi_{\text{col}}(s')}{(s'-s)s'}\,.$$

Then

$$\delta m_U^2 = m_U^2 \pi_{\text{col}}(m_U^2).$$

$\text{Im}\pi_{\text{col}}(s)$ receives contributions from quarks as well as gluon components in the current. We estimate below the contribution to $\delta m_U^2$ from the quark component only. Asymptotically, this contribution is given by

$$\text{Im}\pi_{\text{col}}(s') = \sum [Q^{\text{col}}(\text{quark})]^2 \times (f^2/12\pi)$$
$$= (2 + \tfrac{2}{3})(f^2/12\pi),$$

where 2 comes from the *color charge* of $(\mathcal{P}, \mathfrak{N}, \lambda)$ quarks while $\frac{2}{3}$ is from the *color charge* of $c$ quarks.

The intermediate states $|m\rangle$ which would contribute to $\text{Im}\pi(s')$ are $(\tilde{U} + 2\pi)$, $(\tilde{U} + 4\pi)$, $(\tilde{U} + K\bar{K})$, $(\tilde{U} + \eta')$, $(\tilde{V}_\rho^+ \tilde{V}_\rho^-)$, $(q\bar{q})_{\text{color}}$, etc. It is possible to show[9] that unless $\sqrt{s'}$ is about 2 GeV higher than $m_U$, there are strong kinematic suppressions for contributions from $(\tilde{U} + 2\pi)$ and $(\tilde{U} + 4\pi)$ states, etc. If we note that the color-octet quark-antiquark vector-meson composites might be expected to be about 1 to 2 GeV heavier than the gluon (if the gluon is light, which is the case under consideration), it appears reasonable to assume (i) that the effective color threshold $s_1$, starting at which $\text{Im}\pi_{\text{col}}(s')$ begins to receive significant contribution, is about $(m_U + 1\text{ to }2\text{ GeV})^2$ and (ii) that this contribution acquires its asymptotic value (at least for $\mathcal{P}, \mathfrak{N}, \lambda$ flavors) at $s_2 \simeq (m_U + 3\text{ GeV})^2$.

TABLE II. Summary of allowed and forbidden mass regions for a narrow neutral color gluon. (The last entry has excluded $\psi$ and $\psi'$ from consideration. Although a 1-MeV-wide color gluon would have shown up prominently in the SLAC experiment, one that is 10 MeV wide would be less prominent and might still be compatible with the data in the high-mass region.)

| Mass (GeV) | Allowed | Reason |
|---|---|---|
| <1.1 | No | Photoproduction; $g-2$ of muon |
| 1.1–1.8 | Yes | |
| 1.8–3.0 | No | Photoproduction, $e^+e^-$ annihilation, $\mu^+\mu^-$ production in hadron collisions. |
| 3.0–7.6 | No (?) | $e^+e^-$ annihilation |

Assuming a linear rise of $\mathrm{Im}\,\pi(s')$ with a zero value at $s' = s_1$ and the asymptotic value for $s' \geq s_2$, we estimate

$$\frac{\delta m_U{}^2}{m_U{}^2} \approx \frac{f^2}{48\pi^2}\,(1 \text{ to } 2),$$

where the larger value corresponds to $m_U$ near 2 GeV.

The calculation of the asymptotic contribution from the gluon component of the currents to the self-energy of the gluon is more involved; however, judging from the smallness of the asymptotic value of the gluon contribution to the $R$ parameter, it would appear that its inclusion will not change the above estimate drastically.

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[9]See J. C. Pati and A. Salam, Phys. Rev. Lett. 34, 613 (1975) and Ref. 2 for notations and details.

[10]Note that the dispersion-relation-denominator damping for the radiative modes used in Ref. 9 for the case of a heavy gluon is not as important for a light gluon, which is being considered here.

[11]Note that *a priori*, simply from the point of view of the role of color as a good classification symmetry, one cannot perhaps exclude even a somewhat bigger (so-called "medium-strong") color-symmetry breaking; on the other hand, the theory does not require color-symmetry breaking to be any bigger than $O(\alpha)$.

[12]We ignore without loss of generality $V$ exchange; the sum of $U$ and $V$ contributions is constant since $\sin^2\xi + \cos^2\xi = 1$.

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[14]Since the anomalous magnetic moment is a low-energy effect, it appears reasonable to use an effective $(f^2/4\pi) > 1$ for the $g-2$ calculation.

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[24]Note that similar remarks apply to the search for $V^0_{K^*}$ and $\bar{V}^0_{K^*}$ (which should also be pair-produced in hadronic collisions), since they decay into various channels with branching ratios similar to that of $\tilde{U}$. They, of course, need not be degenerate with $\tilde{U}$.

[25]See T. O'Halloran, in *Proceedings of the 1975 International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California*, edited by W. T. Kirk (SLAC, Stanford, California, 1976), p. 189.

[26]See C. Bemporad, in *Proceedings of the 1975 International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California*, edited by W. T. Kirk (SLAC, Stanford, California, 1976), p. 113; and R. F. Schwitters, *ibid.* p. 5.

[27]See rapporteur report of R. F. Schwitters, in Proceedings of the 18th International Conference on High Energy Physics, Tbilisi, U.S.S.R. (unpublished).

[28]One of us (J.S.) thanks V. A. Siderov for a discussion of the work of the Novisibirsk group.