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# Possible new species of quarks and hadrons*

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Assuming that the strong interactions are mediated by a color-SU(3) gauge theory, we consider unusual possibilities for the constituents. The simplest possibility, "shiny" quarks, is that some new quarks are not triplets under color. We analyze the production and signatures for this possibility. Special attention is drawn to the spectroscopy of hadrons containing shiny quarks, some of which are absolutely stable. A more complicated (and possibly deeper dynamically) idea is that of "echo" quarks. These result when the unbroken color SU(3) arises from the breakdown of a larger SU(3) × SU(3) gauge symmetry. The dynamical motivations for this speculation and the distinctive phenomena that follow from it are analyzed. We find that there is no evidence against echo quarks of quite low mass ($\gtrsim$ 2 GeV), which might be produced at present-day accelerators.

## I. INTRODUCTION

The last few years have witnessed the emergence of a fundamental theory of strong interaction, a theory which appears to have the potentialities, at least, of explaining all of hadron physics. This theory, now commonly referred to as quantum chromodynamics, endows the quarks with an internal color-SU(3) symmetry which is then gauged in the manner of Yang and Mills. The strong interaction at the fundamental level is then generated by an octet of colored gluons interacting with colored and flavored quarks while the observed strong force between hadrons is supposed to be a pale reflection of this underlying force, in much the same way as the force between molecules is a pale reflection of the underlying Coulombic force. Whether or not this theory will prove to be ultimately correct we do not know, but there certainly are a number of encouraging signs.

For the sake of rendering our speculations more definite we will subscribe to the conjecture that quantum chromodynamics is such that it confines all color-nonsinglet states while releasing all color-singlet states as observable hadrons. In spite of the amount of work that has been expended on proving this conjecture, it remains unproven at the moment and may conceivably even be false. Much of our discussion, however, need be modified only slightly should the confinement of color-nonsinglet states turn out to be only temporary and to break down at some higher energy scale.

Also, when we have occasion to speak of electromagnetic and weak interactions we will assume the standard framework of a gauge theory of these interactions, with the gauge group of strong interaction commuting with the gauge group of the nonstrong interactions.

One of the assumptions of quantum chromodynamics is that the quarks so far observed, for every specific flavor, belong to the $\underline{3}$ representation of color SU(3). We remind the reader that this assumption is motivated[1] by (a) the spin-statistics theorem applied to baryons, (b) the decay rate of the neutral pion, and (c) the value of $R$ in $e^+e^-$ annihilation.

We would like to propose that there may be quarks belonging to representations other than $\underline{3}$. To the reader's inevitable dynamical question "Why?" the best answer is probably "Why not?" We know of no dynamical principle or even evidence of any kind which would suggest the nonexistence of quarks belonging to the representation $\underline{6}$, say. Indeed, if we envision the unbroken strong-interaction SU(3) gauge group as the relic of a larger broken gauge symmetry involving possibly the weak, electromagnetic, or other interactions, it would be surprising if fermions came only in color-SU(3) singlets or triplets. We will later consider in detail this dynamical motivation for wishing to have this type of "exotic" quarks. (We note that the proliferation of quarks discussed in this paper is to be distinguished from the proliferation of flavors often indulged in discussing weak interaction.)

Emboldened by the thought that in the history of physics everything not known to be forbidden occurs we assume our conjecture to be true and go on to explore the myriad phenomenological consequences.

Our discussion will be divided into two parts. We first consider the consequences of simply adding to the present theory quarks belonging to representations $\neq \underline{3}$ without reference to any possible dynamical motivation. We christen this type of quark as "shiny quark." We than move on to a much bolder dynamical conjecture: The basic theory of strong interaction is a gauge theory with a group $G$ which contains color SU(3) as a subgroup. Spontaneous symmetry breaking then breaks $G$ to SU(3), giving us the known strong interaction.

In this view, there are not only quarks not belonging to $\underline{3}$ but there are also additional (massive) gluons. We will refer to the extension of strong interaction in the fashion as "covering strong interaction" and the quarks which appear as "echo quarks." (This is not to be confused with schemes which unify the strong and the weak and electromagnetic interactions and which have unresolved difficulties of their own.)

These two steps in our discussion, hierarchical in the level of speculation involved, lead to rather different phonomenological consequences and will be discussed in Secs. II and III in turn.

The most striking phenomenological consequence in the shiny-quark scheme is the existence of absolutely stable hadrons. There may be one or more of these hadrons. If there is only one, it may be electrically neutral. If there are more than one, we expect some of these hadrons to be charged.

It turns out that in the echo-quark scheme the situation is quite different. In the examples we have studied either all new hadrons are unstable or there is one electrically neutral stable hadrons. The notion of quarks belonging to color representation other than the triplet has also been independently suggested by Ma[2] in a different context. However, the present discussion differs crucially from Ma's. Ma proposed that the charmed quark is exotic in this sense. This leads to phenomenological consequences which are at variance with observations[3] and to grave theoretical difficulties. This point will be discussed below in Sec. II. (See Ref. 10).

## II. SHINY QUARKS

Suppose there is a quark $\mathcal{S}$ which belongs to the representation $\underline{6}$ of color SU(3). We pick the representation $\underline{6}$ for the sake of definiteness and will return to consider other representations $\neq \underline{3}$. We will also first consider the existence of only one flavor $\mathcal{S}$. We refer to the new additive quantum number associated with $\mathcal{S}$ and absolutely conserved by strong interaction as "shininess." The baryon number $B$ of $\mathcal{S}$ can be taken to be 0 (by convention). With the triality of $\underline{3}$ defined to be $+1$, the triality of $\underline{6}$ is $+2$.

### Spectroscopy and stability

Armed with our dynamical assumption that only color-singlet states can be unconfined hadrons[4] we can easily, with a bit of tensor analysis, work out the hadron spectroscopy. Some hadrons with nonzero shininess (written in terms of their color contents and baryon number) are

$B=-\frac{2}{3}$ $(6\bar{3}\bar{3})$

$B=\frac{1}{3}$ $(6\bar{3}33)$ $[(6\bar{6}63)]$

$B=\frac{2}{3}$ $(6633)$

$B=\frac{4}{3}$ $(63333)$

$B=0$ $(666)$

Each of these levels [except for (666)] correspond, of course, to many hadrons depending on the flavor of the nonshiny quark $=\mathcal{P}, \mathcal{N}, \lambda, c$ and so forth, and also on the spin-parity assignemtns. These assignments can be easily worked out using the standard rules. For example, the ground state of $(6\bar{3}\bar{3})$ presumably will have the pair $\underline{\bar{3}\bar{3}}$ in a relative $S$ wave and the $\underline{6}$ in an $S$ wave relative to the pair. The pair $\underline{\bar{3}\bar{3}}$ is in a color $\underline{\bar{6}}$ wave function; its flavor SU(3) (disregarding charm for the moment) could be $\underline{3}$ or $\underline{\bar{6}}$ and its spin could be $S=0$ or $S=1$. Applying Pauli's principle we find that this particular state actually consists of a $\underline{\bar{6}}$ under flavor SU(3) with $J^P=\frac{1}{2}^+$ and two triplets $\underline{3}$ under flavor SU(3) with $J^P=\frac{1}{2}^+$ and $\frac{3}{2}^+$. In other words, there are 12 hadrons altogether for this state.

There are also hadrons with spin but whose antiparticles do not belong to the same flavor-SU(3) multiplets. One would perhaps hesitate to call them mesons. For example, the state (6633) consists of an antitriplet $\underline{3}$ under flavor SU(3) with $J^P=1^+$, and one sextet $\underline{6}$ under flavor SU(3) with $J^P=0^+$.

Depending on their masses some of these hadrons may suffer strong decay. (As a first guess one might perhaps suppose the mass of a hadron to be roughly the sum of the effective masses of the shiny quark and ordinary quarks inside that hadron.) The following are some strong decays not forbidden by baryon and shininess conservation:

(a) $(6\bar{6}63) \rightarrow (6\bar{3}33)+$ (ordinary hadrons with $B=0$),

(b) $(63333) \rightarrow (6\bar{3}33)+$ (ordinary hadrons with $B=1$),

(c) $(6\bar{3}33) \rightarrow (6\bar{3}\bar{3})+$ (ordinary hadrons with $B=1$),

(d) $(666) \rightarrow (6633)+(6\bar{3}33)+$ (ordinary hadrons with $B=-1$).

Of these, (b), (c), and (d) are forbidden by our most naive mass estimates. Depending on the masses, some of these strong decays may, of course, be forbidden or reversed. Different hadrons corresponding to the same color content may, of course, decay strongly into each other if the mass separation is sufficiently large, for example, $(6\bar{3}\bar{3}) \rightarrow (6\bar{3}\bar{3})+\pi$.

There are also hadrons with zero shininess. The most interesting is $B=0$ $(6\bar{6})$, the $J^{PC}=1^{--}$ member of which should be seen in $e^+e^-$ annihilation. No quantum number forbids it to decay strongly; however, the as yet poorly understood Zweig-Iizuka-Okubo[5] rule which operates in the case of $J/\psi(3100)$ may also render this state quite narrow to the point that the leptonic modes $(6\bar{6}) \rightarrow e^+e^-$, $\mu^+\mu^-$ may have substantial branching ratio. There are other states such as $(63\bar{6}\bar{3})$, however, which should decay readily into $(6\bar{6}) + (3\bar{3})$.

We should also mention the possible existence of hadrons composed of quarks and gluons such as

$$B = \tfrac{1}{3} \quad (63;\ 8 \text{ gluon}),$$

which may decay, for example, into $(6\bar{3}33)$ + (ordinary hadrons with $B = 0$).

We have considered only strong decay so far. However, in cases where the appropriate strong decay is blocked because of insufficient mass separation, the hadron may still decay via electromagnetic and weak interaction. For example, members of $(6\bar{3}\bar{3})$ may decay via

$$(6\bar{3}\bar{3}) \rightarrow (6\bar{3}\bar{3}) + e\nu .$$

[The exception is the hadron (666) which, if blocked from strong decay, will be absolutely stable.]

To summarize the above we have sketched in Fig. 1 what a spectroscopic chart of shiny hadrons may look like.

One point is inescapably true: The lowest-mass shiny hadron will be *absolutely stable* (in the same sense that the proton is absolutely stable). We will refer to this absolutely stable hadron as $X_{\mathcal{S}}$ (and in case there exist more than one, generically as $X_{\mathcal{S}}$).

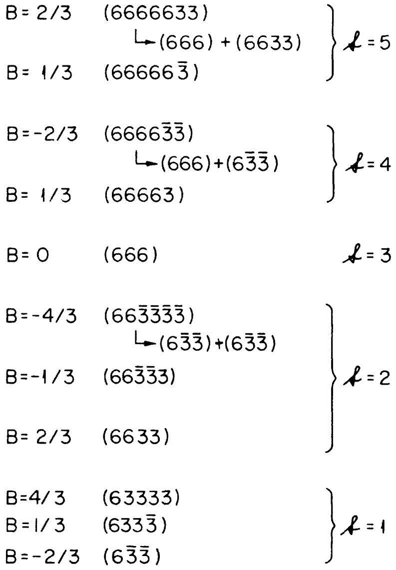

FIG. 1. Low-lying shiny states formed of quarks only. Stability is estimated by naive quark-mass counting. There are eight different types of stable particles in this scheme, with different shininess and baryon number. The figure indicates only the color quantum numbers; for each entry we would have various possible flavors, spins, etc., with weak and electromagnetic transitions within the entry. Possible mixed gluon-quark states are ignored.

This naturally furnishes a striking signal for possible experimental searches for $X_{\mathcal{S}}$. We will briefly comment on the evidence at present. There have been numerous unsuccessful searches for fractionally charged stable particles using a variety of techniques. In addition there are high-energy accelerator experiments[6] searching for charged stable particles. For example, the experiment of Leipuner *et al.*[6] at Fermilab established an upper limit on production cross section of about $10^{-1}$ $\mu$b in hadron-hadron collision for an integral charged particle with lifetime greater than $2 \times 10^{-7}$ sec. The upper limits for charged $e/3$ and $2e/3$ particles are about four orders of magnitude better. Another experiment is that of Appel *et al.*,[6] who saw with a 300-GeV beam production of $\pi^\pm, p, \bar{p}, d, \bar{d}$ but not ${}_2{}^3$He and ${}_2{}^4$He and set an upper limit for the ratio of production of exotic charged stable particles to that of pions and protons in the neighborhood of $10^{-7\pm1}$ depending on the mass. We must caution the reader, however, that hadron-hadron collision is expected to offer a rather inefficient production mechanism for shiny hadrons since they will have to be pair produced—witness the recent searches for charmed hadrons. In particular the upper limits quoted above should be compared with the present upper limits for charmed-hadron production in hadron-hadron collision.[7]

The evidence against a stable neutral hadron is much weaker and, for a sufficiently massive hadron, say $\gtrsim 3$ GeV, is practically nonexistent. One would have to do a rather delicate time-of-flight experiment after sweeping away all charged particles at high energies.

We should also emphasize that some of the hadrons which are unstable only against weak decay may be rather long lived and so also readily detectable. For example $(6\mathcal{P}\mathcal{N})$ may only $\beta$ decay into $(6\mathcal{P}\mathcal{P})$ and may have a lifetime comparable to that of the neutron. We cannot be completely definite in the absence of a dynamical knowledge about the exact mass separations. But naively we could expect a number of stable and quasistable hadrons.

### Electromagnetic interaction and production

So far we have not assigned a value to $Q_{\mathcal{S}}$, the electric charge of $\mathcal{S}$. *A priori*, $Q_{\mathcal{S}}$ can be an arbitrary real number (unless the electromagnetic gauge group is embedded in a larger compact group). However, given the empirical fact that numerous searches for fractionally charged stable particles have failed we should probably assign $Q_\mathcal{S}$ so that $X_\mathcal{S}$ has integral charge. It is easy to see that, with $Q_\mathcal{S} = \frac{1}{3} \pm \text{integer} = \ldots, -\frac{2}{3}, \frac{1}{3}, \frac{4}{3}, \ldots$, *all* new hadronic states (i.e., with zero triality) will have integral charge. Indeed, we may always pick $Q_\mathcal{S}$ so as to make the lowest absolutely stable shiny hadron $X_\mathcal{S}$ electrically neutral. For example, suppose the lowest $X_\mathcal{S}$ is ($6\bar{3}33$; flavor $\mathcal{S}\bar{\mathcal{N}}\mathcal{N}\mathcal{N}$); then $Q_\mathcal{S} = \frac{1}{3}$ will make $X_\mathcal{S}$ neutral.

If, as remarked above, there exist more than one $X_\mathcal{S}$, and if, as naive expectations would suggest, that the stable hadrons include ($6\bar{\mathcal{P}}\mathcal{P}\mathcal{P}$) and ($6\bar{\mathcal{P}}\bar{\mathcal{P}}$) and perhaps also ($6\mathcal{P}\mathcal{P}\mathcal{P}\mathcal{P}$), then at least one stable hadron will be charged no matter what choice we take for $Q_\mathcal{S}$. This hadron could then be searched for and a lower limit set on its mass.

In any case the shiny quark $\mathcal{S}$ is probably not electrically neutral and so will have a dramatic impact on $e^+e^-$ annihilation. The fact that a bump corresponding to ($6\bar{6}$) has not yet been seen suggests that the mass of $\mathcal{S}$ must be at least $\gtrsim 2$ or 3 GeV. On the other hand, there is no dynamical reason why the masses of shiny hadrons cannot be such that they are detectable by the next round of experiments. Above threshold $e^+e^-$ will annihilate into a pair of shiny and antishiny hadrons, each of which will cascade-decay strongly, presumably by meson emission, into $X_\mathcal{S}$ (or $\bar{X}_\mathcal{S}$). If $X_\mathcal{S}$ is neutral, it will be lumped into the "missing neutrals" and the energy it carries will account for part of the "missing energy." If $X_\mathcal{S}$ is charged, its signature should be unmistakable. Should the production of shiny states be mistakenly accounted into the ordinary hadronic cross section which defines $R$, there will be a dramatic rise in $R$ inasmuch as the shiny quark contributes to $R$ the amount $6{Q_\mathcal{S}}^2$, twice as much as a nonshiny quark of the same charge. If $Q_\mathcal{S} = \frac{1}{3}$ then $6{Q_\mathcal{S}}^2 = \frac{2}{3}$, which when added to $3\sum_{i=\mathcal{P},\mathcal{N},\lambda,c} {Q_i}^2 = \frac{13}{3}$ brings $R$ to exactly 5. Of course, if $Q_\mathcal{S} = -\frac{2}{3}$ (or $\frac{4}{3}$) there will be a truly dramatic rise in $R$ and profuse production of shiny hadrons and their decay debris.

We also expect substantial shiny-hadron production in photoproduction and in electroproduction, in the diffractive region. The cross section should not be much less than the corresponding cross section for charm production; the suppression factor from the presumably higher mass may be partially compensated by the factor $6{Q_\mathcal{S}}^2/3(\frac{2}{3})^2$ depending on the value of $Q_\mathcal{S}$. Pair production outside the diffractive region is expected to be quite small as it is empirically small for charm pair production.

### Effects on strong interaction and nonleptonic weak interaction

The renormalization-group function $\beta(g) = -bg^3 + \cdots$ relevant for the strong interaction will be affected in a calculable way. The addition of a single shiny quark in the $\underline{6}$ representation has roughly the same effect on renormalization-group parameters as the addition of five triplets [precisely, in the notation of Ref. 8, $T(6) = 5T(3)$, $C_2(6) = \frac{5}{2}C_2(3)$]. The scaling property of deep-inelastic production will be affected as the relevant mass scale is approached. More importantly, the increased value of $b$ may have an important effect on nonleptonic weak interaction of *ordinary* hadrons even though $\mathcal{S}$ may very well not participate in charged weak interaction at all. In particular, this will enhance $\Delta I = \frac{1}{2}$ transitions further.[9]

### Weak interaction

We probably do not wish to have transitions between the shiny quark $\mathcal{S}$ and ordinary antiquark (antiquark if charge is to change by one or zero unit); otherwise we wreak havoc[10] on the present framework of strong and weak interaction alluded to in the Introduction. And thus $\mathcal{S}$ can only be a singlet under the weak gauge group and couples to the neutral current. This still contributes to $\Delta S = 0$ nonleptonic weak interaction a term like $(\bar{\mathcal{P}}\mathcal{P})(\bar{\mathcal{S}}\mathcal{S})$ which is expected to have negligible matrix elements between nucleons.

To the extent that there is no reason why shiny quarks cannot exist there is also no known reason why there should not be more than one quark with shininess quantum number +1. Any number of flavors are allowed; one can assign the quarks to various multiplets under the weak gauge group in the usual way. We insist only that the weak current transforms shiny quarks only into shiny quarks. There will still be at least one absolutely stable shiny hadron $X_\mathcal{S}$. All shiny hadrons built with other shiny quarks will eventually decay weakly into $X_\mathcal{S}$, either nonleptonically into ordinary hadrons or semileptonically into leptons.

Our earlier remarks about pair production by photoproduction and electroproduction carry over essentially unchanged into neutrino production. Also, the branching ratio of the $W$ boson into leptons should be suppressed due to the relative ratio[11] of 6:3:1 for decay into shiny hadrons, ordinary hadrons, and leptons, respectively.

However, the most interesting effect on weak interactions is probably the indirect one on the $\Delta I = \frac{1}{2}$ rule which was mentioned earlier. Finally, we may also speculate on the cosmological consequences[12] of the existence of stable shiny hadrons.

We have concentrated our discussion on the case where the shiny quarks transform as a $\underline{6}$ under color SU(3). This case is typical of any representation ($\neq \underline{3}$) with nonzero triality; we would expect several species of stable or nearly stable particles (some of which will be charged and copiously produced in electromagnetic processes, etc.).

The situation is different if the shiny quarks transform as a representation with zero triality, say an 8. In this case one quarantees that color-singlet bound states have integral charge by assigning the octet shiny quark integral electric charge $Q_{\mathcal{S}} = 0, \pm 1, \ldots$. If $Q_{\mathcal{S}} \neq 0$, the shiny quark has, needless to say, a spectacular signature in $e^+e^-$ annihilation (for $|Q| = 1$ we get $\Delta R \cong 8$ as threshold is crossed). The expected spectrum of stable particles associated with an octet shiny quark depends markedly on the dynamical question of whether the color-singlet state formed of one shiny quark and one color gluon is lighter or heavier than that formed from one shiny quark and an ordinary quark-antiquark pair. If the gluon-quark state is lighter we expect $(\mathcal{S}q\bar{q})$ states to decay into it electromagnetically or by meson emission. If the $\mathcal{S}q\bar{q}$ states are lighter we expect some charged particles of this type which are stable or have only $\beta$ decays and might live as long as a neutron. In any case, we might expect a family of $(\mathcal{S}\mathcal{S})$, $(\mathcal{S}\mathcal{S}\mathcal{S}), \ldots$ stable particles.

If $Q_{\mathcal{S}} = 0$ and the $\mathcal{S}$-gluon $(\mathcal{S}G)$ state is the lowest shiny state, the shiny quark is quite elusive experimentally. The most promising signature for this seems to be the existence of the stable neutral $(\mathcal{S}G)$ particle. This particle could be produced as a decay product of charged $(\mathcal{S}q\bar{q})$ particles, which in turn would be photoproduced. Neutral octet quarks are suggested by attempts to promote the local color-SU(3) symmetry of the strong interactions to a local supersymmetry.

## III. ECHO QUARKS

In the preceeding section we explored the phenomenological consequences of introducing shiny quarks without referring to possible reasons for wishing to do so. In this section we would like to present a possible theory which would provide some motivation for introducing shiny quarks.

Suppose that at very short distances the theory of strong interaction is actually a gauge theory based on a group $G$ which contains color SU(3) as a subgroup. We envisage this theory to suffer some symmetry breaking which breaks the group $G$ down to color SU(3) and thus to the strong theory we presently know something about. (We will refer to the gauge theory based on the group $G$ as the "covering theory" of strong interaction.)

In order to be specific and in order to illustrate what we have in mind we take as a possible example the group $G = \mathrm{SU}(3) \times \mathrm{SU}(3)$. We assign the quarks to the representation (3, 3). (Note this is to be done flavor by flavor.) It is not unnatural for gauge groups of this type to break down to the "diagonal" SU(3) subgroup of $G = \mathrm{SU}(3) \times \mathrm{SU}(3)$. Identifying the diagonal SU(3) as color SU(3) we find that the quarks decompose into a $\bar{3}$ and a 6 of color. Note that in this type of theory we not only introduce new quarks but also new (massive) gluons. This particular theory will be discussed in more detail below. We name these new type of quarks as echo quarks to distinguish them from the shiny quarks of the previous section. As we will show below, the phenomenology of echo quarks is quite different from that of shiny quarks and thus it is useful to distinguish between the two possible schemes by name. We refer to the type of theory to be discussed here as the echo theory of quarks and gluons.

We emphasize that the present discussion is *not* to be confused with attempted unification of strong, weak, and electromagnetic interactions into one supergauge theory with a gauge group $\mathcal{G}$. These so-called superunified theories[13] have unusual features and/or difficulties peculiar to them. In particular, leptons and quarks belong to the same multiplet and some gauge bosons carry both quark and lepton number. Furthermore, the mass scale at which symmetry breaking occurs in these superunified theories is necessarily enormous; the breaking of a covering theory could in principle occur at relatively modest mass scales. An interesting possibility is that a covering theory could emerge as an intermediate step in the breakdown of a superunified theory. In general, it may not be so easy to arrange matters so that the group $\mathcal{G}$ can be broken to color SU(3) in one step. Indeed, in view of the hierarchies of mass scales that one has in a superunified theory, it is not unreasonable to suppose that the breaking of $\mathcal{G}$ occurs in several steps. In any case, there is no need to specify how a covering theory comes about for the purpose of the present discussion.

We will restrict $G$ to unitary groups as these naturally occur in gauge theories of quarks and gluons. Let us first consider SU($n$); in particular, for the sake of definiteness take SU(4). If quarks fields are assigned to the fundamental quartet representation 4 then upon symmetry breaking quarks decompose into a color triplet and a color singlet while the gluons decompose into an octet, a singlet, a triplet, and an antitriplet. The color-singlet quark would be unconfined and fractionally charged. A color-antitriplet gluon and a triplet (ordinary) quark would form an unconfined (color-singlet) fractionally charged state. The lowest such state would of course be stable. With the present evidence against fractionally charged stable particles this type of theory is viable only if the mass scale of symmetry breakdown is rather high.

More interesting are theories based on direct product of unitary groups. Take $G = \mathrm{SU}(3) \times \mathrm{SU}(3) \times \mathrm{U}(1)$. In other words, we proposed to gauge the $\mathrm{SU}(3) \times \mathrm{SU}(3) \times \mathrm{U}(1)$ subgroup of $\mathrm{U}(3) \times \mathrm{U}(3)$. The "diagonal" U(1) subgroup of $\mathrm{U}(3) \times \mathrm{U}(3)$ corresponds to baryon number and is not gauged. Let us also impose a discrete symmetry interchanging the two SU(3) subgroups of $G$. We assign quarks to $(3,1)+(1,3)$. Denote the gauge bosons corresponding to the two SU(3) subgroups as $A_\mu$ and $B_\mu$, respectively, and the gauge boson corresponding to the U(1) subgroup of $G$ as $V_\mu$. When $G$ is broken down to the "diagonal" SU(3) subgroup the linear combination $G_-^\mu \equiv (A^\mu - B^\mu)/\sqrt{2}$ form a color octet of massive vector bosons while the orthogonal combinations $G_+^\mu \equiv (A^\mu + B^\mu)/\sqrt{2}$ emerge as the color gluons of quantum chromodynamics. We also have, in addition to $G_+$ and $G_-$, a color-singlet vector meson $V$. Since it is a color singlet, $V$ may emerge as a "hadron."

When speculating about the eventual structure of strong interaction, one is inevitably faced with our total ignorance of how symmetry breaking comes about. Most people, naturally, prefer to see dynamical symmetry breaking[14] rather than symmetry breaking by elementary Higgs scalars. Such people may disregard the next remark. In spite of our present ignorance, it behooves us to say a few words about the possible scalar-meson structure of the theory. In this way we can at least check that our speculations can be realized in a sensible field theory. We can imagine that symmetry breaking is caused by Higgs fields $\Phi$ belonging to $(3,\bar{3})+(\bar{3},3)$ under $G$. These may or may not be composite fields formed out of $\bar{\Psi}\Psi$. It would be foolhardy at this stage of our knowledge to discuss the Higgs potential. In particular, we feel that it is probably an unwarranted assumption to allow only terms quartic in $\Phi$. In any case, after symmetry breaking a number of Higgs fields emerge as scalar mesons. For example, with the representation $(3,\bar{3})+(\bar{3},3)$ we will have a color singlet and a color octet.

Given all these uncertainties the only thing definite we can say about these scalar mesons and the hadrons they may or may not form is that all these particles are electrically neutral and so quite difficult to detect. One might argue that they are quite massive if one thinks of them as bound states of quarks; however, such statements amount to mere guesses. The color-singlet scalar meson may be an exception to this statement. However, it is expected to be very broad, since it is able to decay directly into ordinary hadrons, and thus may even have been produced already.

Let us denote the fermion fields belonging to $(3,1)$ and $(1,3)$ as $\psi_0$ and $\chi_0$, respectively. Then $G_+$ couples to $\bar{\psi}_0\gamma_\mu\psi_0 + \bar{\chi}_0\gamma_\mu\chi_0$ while $G_-$ and $V$ couple to $\bar{\psi}_0\gamma_\mu\psi_0 - \bar{\chi}_0\gamma_\mu\chi_0$. In the Lagrangian there may be a mass term $m(\bar{\psi}_0\psi_0 + \bar{\chi}_0\chi_0)$ in addition to the Higgs coupling $(\bar{\psi}_0\Phi\chi_0 + \mathrm{H.c.})$. This implies that after the symmetry breaking the physical fermion fields $\psi$ and $\chi$ are some linear combination of $\psi_0$ and $\chi_0$. We identify the field with lower mass, say $\psi$, with the "ordinary" quark and the more massive field $\chi$ as the associated echo quark. They are both color triplets, of course. $G_+$ couples to $(\bar{\psi}\gamma_\mu\psi + \bar{\chi}\gamma_\mu\chi)$; as to be expected, the color-octet massless gluons do not couple ordinary quarks to echo quarks. In contrast $G_-$ and $V$ do couple the ordinary world to the echo world; they couple to $(c^2 - s^2)(\bar{\psi}\gamma_\mu\psi - \bar{\chi}\gamma_\mu\chi) + 2cs(\bar{\psi}\gamma_\mu\chi + \bar{\chi}\gamma_\mu\psi)$. Here $c \equiv \cos\theta$ and $s \equiv \sin\theta$; $\theta$ is the angle characterizing the rotation connecting $\{\psi_0, \chi_0\}$ and $\{\psi, \chi\}$.

## Spectroscopy and decay

The spectroscopy in this theory, with all quarks as color triplets, is simpler than our previous discussion with exotic quarks in color $\underline{6}$ representation. The new hadrons are $(3'\bar{3})$, $(3'\bar{3}')$, $(3'33)$, $(3'3'3)$, and $(3'3'3')$. (The symbols 3 and 3′ may denote quarks of any desired flavor of course.)

These hadrons are all unstable owing to the fact that $G_-$ (and $V$) have diagonal couplings ($\psi \to \psi$, $\chi \to \chi$) as well as cross couplings ($\psi \to \chi$, $\chi \to \psi$). For example the baryons $(3'33)$ decay via $(3'33) \to (333) + \text{virtual } G_- \to (333) + (3\bar{3})$, i.e., into an ordinary baryon and ordinary mesons. All the hadrons listed above can decay into this fashion. The meson $(3'\bar{3}')$, however, can decay via semistrong interaction involving $G_-$ into $(3\bar{3})$ and is thus expected to be broad unless, of course, the effective $G_-$ mass is large. The decay rates of these other echo hadrons would depend on the masses involved, particularly that of $G_-$ (and $V$). We would expect the strength of the interaction to be less than the usual strong-decay interaction, perhaps even weaker than the electromagnetic interaction. However, the abundant phase space available may still make these hadrons very short lived.

It is notable that the semistrong decay (via $G_-$) of a given echo quark always involves the associated flavor of ordinary quark. This feature provides a signature for the echo scheme—we get flavor selection rules for decay much as for weak interactions, but no parity violation and no semileptonic decays.

Note that $G_-$ and $V$ will produce a short-ranged force between quarks and thus affect the spectroscopy of ordinary (nonecho) hadrons. Perhaps a short-ranged force of this type should be included in potential-model calculation of bound states of heavy quarks.

Let us next turn to the theory based on $G = \mathrm{SU}(3) \times \mathrm{SU}(3)$ already mentioned in the beginning of this section. We again impose the discrete symmetry interchanging the two SU(3) subgroups of $G$.

Quarks belong to (3, 3). Writing the quark field $\Psi_{i\alpha}$ [with $i$ and $\alpha$ referring to the two SU(3)'s, respectively] as a $3 \times 3$ matrix we have the transformation

$$\Psi \to U \Psi V^T . \tag{3.1}$$

Here $U, V$ are $3 \times 3$ simple unitary matrices belonging to the two SU(3)'s, respectively, and the superscript $T$ means transpose. Denoting the gauge bosons corresponding to the two SU(3)'s by $A^a_\mu$ and $B^a_\mu$, respectively, we have the gauge interaction

$$\mathrm{Tr}\bar{\Psi}^T \gamma_\mu (A^\mu_a \lambda_a \Psi + \Psi \lambda^T_b B^\mu_b) . \tag{3.2}$$

Just as before when $G$ is broken down to the diagonal SU(3) subgroup (i.e., $U = V$) the linear combinations $G^\mu_- \equiv (A^\mu - B^\mu)/\sqrt{2}$ form a color octet of massive vector bosons while the orthogonal combinations $G^\mu_+ \equiv (A^\mu + B^\mu)/\sqrt{2}$ emerge as the color octet of massless gauge bosons of quantum chromodynamics. The quarks decompose into a color $\bar{3}$ and a color 6. Thus, for example, the usual color-triplet $\mathcal{P}$ quark will have "associated" with it an echo $\mathcal{P}$ quark belonging to a color antisextuplet. The same goes for any other given flavor $\mathfrak{N}, \lambda, c, \ldots$, of course. Notice that the electric charges of echo quarks are determined in this theory—3 and $\bar{6}$ have the same electric charge. (We are assuming, as always, in this paper that the weak and electromagnetic gauge group commutes with the strong-interaction gauge group).

We can now write out the gluon coupling to quarks [Eq. (3.2)] in detail in terms of $\underline{3}$ and $\underline{\bar{6}}$ and $G_+, G_-$ gluons. One finds that $G_+$ couples $\underline{3}$ to $\underline{3}$ and $\underline{\bar{6}}$ to $\underline{\bar{6}}$ while $G_-$ couples $\underline{3}$ to $\underline{\bar{6}}$ and $\underline{\bar{6}}$ to $\underline{3}$. It is also easy to see that, if one writes out the Yang-Mills couplings of the gauge bosons, the couplings always involve an even number of $G_-$ fields. Thus, for instance, there is a three-point coupling of the type $G_-G_-G_+$ but not of $G_-G_+G_+$, nor of $G_-G_-G_-$. These observations merely reflect the discrete symmetry interacting the two SU(3) subgroups which we have imposed and which is not broken. Under this "internal parity" $\Psi \to \Psi^T$ and $A \to B$. Thus color-triplet $\underline{3}$ quarks are even while color-sectet $\underline{6}$ quarks are odd.

With all the caveats mentioned earlier we proceed to say a few words about the Higgs system. To be definite let us assign the Higgs fields $\Phi$ to (8, 8). [Other Higgs representations such as $(8, 1) \times (1, 8)$ can also certainly occur in general.] In any case, after symmetry breaking, a number of Higgs fields appear as physical scalar mesons. (Presumably, some number of pseudo-Goldstone bosons[15] may also be present, depending on the precise details of the Higgs potential. However, it is not possible to say how massive they actually are; strong interaction is involved, and these scalar mesons could well end up quite massive as well.) Under internal parity $\Phi \to \Phi^T$. After symmetry breaking we have under color SU(3) scalars transforming as $\underline{1}, 8_S, \underline{10}, \underline{\overline{10}}, \underline{27}$. (The antisymmetric $8_A$ has been absorbed by the gauge boson $G_-$.)

The spectroscopy in the echo scheme is much richer than in the shiny scheme. Firstly, there is now one $\underline{\bar{6}}$ of echo quark for *each* flavor. Notice the weak interaction of color $\underline{\bar{6}}$ quarks among themselves merely "echoes" the weak interaction of their associated color $\underline{3}$ quarks. Secondly, new hadrons can be formed by having the massive vector bosons $G_-$ as constituents. For instance, there will be gluon bound states $(G_-G_-)$ and $(G_-G_+)$. People have already speculated on the existence of gluon bound states formed of the massless color-octet gluons [in our notation $(G_+G_+)$]; $G_-$, being massive, perhaps will bind more readily. Also, $(G_+G_+)$ and $(G_-G_-)$ are expected to be rather broad, decaying rapidly into pions. However, $(G_+G_-)$ may be much longer lived or even stable (depending on its mass). This point will be discussed further below.

There is an important difference between the echo scheme and the shiny scheme. For the shiny scheme we have seen that there must be at least one, and probably more, absolutely stable particles. Furthermore, some of these stable particles may be charged. This is not necessarily so in the echo scheme. (We have already seen one theory in which all the new hadrons decay.) In the theory being discussed here, since $G_-$ couples $\underline{6}$ to $\underline{\bar{3}}$, hadrons formed out of color $\underline{6}$ quarks can decay via strong interaction by emitting $G_-$. For example, the hadrons (63333) can decay strongly via

$$(63333) \to (\bar{3}3) + (333) + (G_-G_+)$$

provided that the hadron $(G_-G_+$ is light enough.

The question arises: Is $(G_-G_+)$ itself stable? To put it in another way, can $(G_-G_+)$ decay into hadrons made up only of ordinary color 3 quarks and $G_+$? The answer is no because $(G_-G_+)$ is odd under the internal parity discussed above. If it is massive enough it could decay into hadrons made of scalar mesons; for instance

$$(G_-G_+) \to (\phi_{10} G_+ G_+) + (\phi_{8S} G_+) ,$$

where $\phi_8$ and $\phi_{10}$ denote the color $\underline{8}_S$ and $\underline{10}$ scalar mesons, respectively. In any case there will be one hadron, odd under internal parity which cannot decay into ordinary hadrons. Notice this contrasts with the shiny scheme. This stable hadron, and there is only one, is electrically neutral and a boson.

Of course, if we had not imposed internal parity on our theory then no absolutely stable hadrons remain.

Since the rise in $e^+e^-$ annihilation as each threshold is crossed need not be accompanied by very narrow resonances, it is even conceivable that echo hadrons are being produced at present energies. To distinguish this possibility would require a careful search for broad resonances, although it might be suggested simply by the rise in the total cross section.

The examples given in this section are meant to illustrate the typical sort of theories which can emerge if strong interaction is covered. Let us stress again that if we want the unbroken strong SU(3)-color gauge group to arise from the breakdown of a larger gauge group at a moderate mass scale, then we must have an echo scheme.

## IV. CONCLUSION

We have worked out the phenomenological consequences of introducing quarks which transform as higher representations of color SU(3). This type of quark proliferation is to be distinguished from the flavor proliferation often suggested in discussions of weak interaction. We distinguish two schemes which are rather different in the number of stable hadrons they contain.

Our speculations are neither required nor forbidden by dynamical principles as we presently understand them. Nature may well choose not to utilize this dynamical possibility. On the other hand she might. In any case experimenters should look out for stable and/or very long-lived hadrons—there may be surprises in the next higher energy scale.

*Note added.* After this manuscript was completed two very relevant papers came to our attention. Karl[16] has discussed a scheme related to our echo quarks. His assumptions concerning the weak interactions of these quarks are, however, quite different from ours. An experiment searching for strongly interacting stable neutral particles has been reported by Gustafson *et al.*[17] The limits set in this paper are comparable or perhaps smaller than $\psi$ production cross sections. Thus stable or quasistable strongly interacting particles of $\lesssim 5$ GeV seem implausible.

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[10] The gauge groups of strong and weak interactions would not commute. The weak currents will have pieces transforming as color singlets and as color nonsinglets. It is at this point that we differ crucially from Ma's analysis of exotic quarks (Ref. 2).

[11] As expected from asymptotic-freedom or naive-parton-model arguments.

[12] As long as we are speculating we can entertain the notion that shiny quarks $\mathcal{S}$ were also present in the beginning of the universe, perhaps in comparable abundance to nonshiny quarks. We can then raise the question of whether there are any conceivable mechanisms, as the universe cools and expands and as quarks combine into hadrons, which would segregate the shiny quarks from the nonshiny quarks. With our scarce knowledge about the infancy of the universe we cannot give certain answers to any questions of this type. Nevertheless, the larger masses of shiny hadrons suggest that gravity could conceivably condense shiny hadrons into aggregates. If the absolutely stable shiny hadron $X_{\mathcal{S}}$ is charged, these $X_{\mathcal{S}}$ could capture electrons to form atoms, molecules, and astrophysical objects. In any case, there is ample evidence that terrestrial matter does not contain a substantial fraction of shiny matter (although a minute contamination is certainly not ruled out). However, is it possible that a fraction of the matter in the universe resides in shiny worlds floating far from us? (We can rule out nearby astrophysical objects from being shiny since

their spectral lines would have betrayed them.) Physicists in this shiny world, unlike those in our world, could readily discover the existence of color-triplet quarks by annihilating $e^+$ and $e^-$ at low energies. If $X_S$ is neutral then there will not be atoms and molecules, as we know it, but only aggregate $X_S$ nuclear matter.

[13] For example, H. Georgi and S. Glashow, Phys. Rev. Lett. 32, 438 (1974); J. Pati and A. Salam, Phys. Rev. D 8, 1240 (1973).

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