Diquarks as a solution to some difficulties of the quark model

M. I. Pavković

Stanford University School of Medicine, Welch Road 701, Suite C-1, Palo Alto, California 94304

(Received 24 December 1975; revised manuscript received 3 May 1976)

As a reaction to the difficulties of the ordinary quark model we propose the diquark model for hadrons. The number of elementary objects in the diquark model is larger than in the quark model, for aside from the usual three quarks one finds here 18 new objects—diquarks—that can be regarded as two quarks glued together. The spin of quarks is $\frac{1}{2}^+$. The spins of diquarks are 0^+ and 1^+. From the point of view of unitary symmetry the diquarks are the spinors from the irreducible representations $\underline{\bar{3}}$ and $\underline{6}$ in $\underline{3}\times\underline{3}=\underline{\bar{3}}+\underline{6}$. In a larger group-theoretical framework of SU(6) symmetry (that mixes unitary and spin degrees of freedom), the diquarks are spinors from the irreducible representations $\underline{15}$ and $\underline{21}$ in $\underline{6}\times\underline{6}=\underline{15}+\underline{21}$.

DIFFICULTIES WITH THE QUARK MODEL

In the quark model of Gell-Mann and Zweig, one deals with three elementary pointlike objects, characterized by spin-parity $\frac{1}{2}^+$ and fractional charges $\frac{2}{3}$, $-\frac{1}{3}$, and $-\frac{1}{3}$. Mesons are bound states of $q\bar{q}$ type, while the baryons are three-body bound states of qqq type. This model has been remarkably successful in providing an acceptable explanation for almost all aspects of particle phenomenology such as the mass spectra, magnetic moments, electromagnetic and strong decay rates, scaling, etc. Recently, however, several problems have appeared, which call for reexamination of the fundamental assumptions on which the quark model resides. The difficulties with the quark model include the following:

(i) The SU(6) baryonic multiplets $\underline{20}$ which are predicted by the quark model are absent. The absence of $\underline{20}$'s could be explained by the well-known difficulties in observing $\underline{20}$'s experimentally ($\underline{20}$ does not couple to the baryon-meson system $\underline{56}\times\underline{35}$, rendering the formation experiments useless), but if all efforts of the experimentalists remain without reward one sould seek an answer to this puzzle on a more fundamental level.

(ii) Experimentally, the ratio

$$(\nu W_2)_{\text{neutron}}/(\nu W_2)_{\text{proton}}$$

is close to $\frac{1}{4}$ at the threshold $\xi\to 1$. This behavior of the scaling functions of nucleons flatly contradicts the predictions of the usual quark model with the symmetric spatial wave function for quarks. In the symmetric quark model this ratio should be $\frac{2}{3}$.

(iii) In the annihilation channel $e^+e^-\to$ hadrons any quark model dealing exclusively with the point-like spin-$\frac{1}{2}^+$ objects will predict either a constant value for the ratio $R=\sigma(e^+e^-\to\text{hadrons})/\sigma(e^+e^-\to\mu^+\mu^-)$ or a stepwise behavior characteristic for the presence of several channels that have different energy thresholds (quarks with different masses?). The experimental data do not lend an unambiguous support to such a picture in the annihilation channel, but indicate instead a possible rise of R with energy.

All described difficulties can be resolved within the framework of the diquark model apparently without penalty of having to explain embarrassing disagreements with experiment elsewhere.

The diquark model is a natural extension of the quark model.[1] By forming new elementary objects from pairs of spin-$\frac{1}{2}^+$ quarks, one gains additional degrees of freedom reflected in

(i) a larger number of elementary objects that are basic blocks of hadronic matter, and

(ii) a larger variety of elementary spins.

In the diquark model that we propose, the number of elementary objects is $3(\text{quarks})+2\times 3\times 3(\text{diquarks})=21$, and we deal now with spins 0^+ (scalar diquarks), $\frac{1}{2}^+$(quarks), and 1^+ (axial-vector diquarks). The newly acquired degrees of freedom are particularly welcome in the annihilation channel where the need arises for both the larger number of elementary objects as well as the spins higher than $\frac{1}{2}$.

GROUP-THEORETICAL ASPECTS

The quarks are regarded as spinors from the fundamental 6-dimensional representation of the SU(6) group that mixes spin and the unitary spin degrees of freedom. Their quantum numbers are

	$\mathcal{P}$	$\mathfrak{N}$	λ
T_3	$\frac{1}{2}$	$-\frac{1}{2}$	0
electric charge	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
hypercharge	$\frac{1}{3}$	$\frac{1}{3}$	$-\frac{2}{3}$
baryon number	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$.

The diquarks are the spinors from the (reducible) representation $\underline{6\times 6}$ of the SU(6) group. There are, in total, $\overline{36}$ diquark states which fall into the two irreducible representations of the SU(6) group, namely $\underline{15}$ and $\underline{21}$ ($\underline{6\times 6}=\underline{15}+\underline{21}$). The SU(3) content of these irreducible representations is

$$\underline{21}=\{6\}\times 3+\{\overline{3}\}\times 1$$

and

$$\underline{15}=\{\overline{3}\}\times 3+\{6\}\times 1\ ,$$

where the curly brackets enclose the irreducible representations of SU(3), while the numbers outside the brackets count the degrees of freedom associated with the ordinary spin. In other words, in $\underline{21}$ we find an SU(3) sextet of axial-vector diquarks and a triplet of scalar diquarks, while in $\underline{15}$ the situation is reversed, i.e., we have a sextet of scalar diquarks and a triplet of axial-vector diquarks. The SU(3) representation $\{\overline{3}\}$ consists of an isotopic singlet with hypercharge $\frac{2}{3}$ and electric charge $\frac{1}{3}$, and an isotopic doublet with hypercharge $-\frac{1}{3}$ and electric charges $-\frac{2}{3}$ and $\frac{1}{3}$, respectively.

The SU(3) representation $\{6\}$ comprises an isotopic singlet with hypercharge $-\frac{4}{3}$ and electric charge $-\frac{2}{3}$, an isotopic doublet with hypercharge $-\frac{1}{3}$ and electric charges $-\frac{2}{3}$ and $\frac{1}{3}$, and finally an isotopic triplet with hypercharge $\frac{2}{3}$ and electric charges $-\frac{2}{3}$, $\frac{1}{3}$, and $\frac{4}{3}$.

Since the isospin of nucleons is $\frac{1}{2}$, and no λ quarks are present, we expect to find in nucleons only the diquarks with isospins 0 and 1. The isospin-0 diquark in the nucleon comes from the SU(3) representation $\{\overline{3}\}$, while the isospin-1 diquark is supplied by $\{6\}$. There is another isospin-0 diquark from $\{6\}$, but this one does not show its presence in the nucleonic wave function, because it carries hypercharge $-\frac{4}{3}$ which cannot be neutralized by an accompanying quark to yield the required nucleonic hypercharge 1. Consequently, in the case of nucleons we find an accidental match between the ordinary spin and the isotopic spin of the diquarks, a convenient circumstance from the "mnemonic" point of view (scalar diquarks are also isoscalar, and the vector diquarks are also isovector).

MASS SPECTRA

The known mesons remain the bound states of $q\overline{q}$ (quark-antiquark) type. The diquark model does not have much to say about the mesons. Baryons are the bound states of qd (quark-diquark) type. The well-established SU(6) baryonic multiplets $\underline{56}$ and $\underline{70}$ of the lowest mass are built from the diquarks supplied by the irreducible representation $\underline{21}$, i.e., $\underline{6}\times\underline{21}=\underline{56}+\underline{70}$. In the case of low-lying baryons, the relative orbital angular momentum between the quarks and the diquarks is zero. Nonzero orbital angular momenta are associated with the baryons that lie higher in mass. The other diquark irreducible representation $\underline{15}$ could lead to the baryonic multiplets $\underline{20}$ and another $\underline{70}$ via $\underline{6}\times\underline{15}=\underline{20}\times\underline{70}$. Since the experimental status of $\underline{20}$'s is uncertain at present, it is not clear whether the diquarks from $\underline{15}$ do indeed couple to quarks. If not, the $\underline{20}$'s are absent, together with the $\underline{70}$'s that have their origin in the diquarks from $\underline{15}$. Further reduction in the number of baryonic levels can be accomplished at the expense of additional dynamic assumptions concerning the nature of forces that bind the quarks together, and which are ultimately responsible for the formation of diquarks. In particular, it appears possible[2] to obtain the SU(6) multiplets of only one parity sign, i.e., the $\underline{56}$'s of only even parity, and the $\underline{70}$'s of only odd parity. This results in a much sparser spectrum for baryons—a desirable feature in the light of present experimental evidence.[3]

SCALING

The scaling properties of the diquark model have been discussed at great length in an earlier article on the same subject,[4] and for this reason we give here only a summary of the main points.

The spin-averaged invariant electroproduction structure functions of the nucleon in the scaling region are determined by the form of the nucleonic wave function (in the infinite-momentum Lorentz frame), and by the charges of the elementary constituents.

In the diquark model the proton and the neutron are bound states of the $\mathcal{P}$ and $\mathcal{N}$ quarks with the diquarks from $\{6\}$ and $\{\overline{3}\}$ in

$$\underline{21}=\{6\}\times 3+\{\overline{3}\}\times 1\ .$$

The phenomenological mixing angle α that breaks the SU(6) symmetry and determines the relative weight of $\{6\}$ and $\{\overline{3}\}$ in the nucleonic wave function makes its appearance also in the associated scaling functions.

We have (ξ is the scaling variable $\xi=-q^2/2M\nu$, $0\le\xi\le 1$)

$$\frac{1}{\xi}(\nu W_2)_{\text{proton}}=\tfrac{4}{18}\cos^2\alpha\, f_0^q(\xi)+\tfrac{1}{18}\cos^2\alpha\, f_0^d(\xi)+\tfrac{2}{18}\sin^2\alpha\, f_1^q(\xi)+\tfrac{11}{18}\sin^2\alpha\, f_1^d(\xi)\ ,$$

$$\frac{1}{\xi}(\nu W_2)_{\text{neutron}}=\tfrac{1}{18}\cos^2\alpha\, f_0^q(\xi)+\tfrac{1}{18}\cos^2\alpha\, f_0^d(\xi)+\tfrac{3}{18}\sin^2\alpha\, f_1^q(\xi)+\tfrac{3}{18}\sin^2\alpha\, f_1^d(\xi)\ ,$$

with the normalization conditions

$$\int_0^1 f_{0,1}^{q,d}(\xi)d\xi = 1\,.$$

The scaling components $f_{0,1}^{q,d}$ differ in the isotopic-spin number of the participating diquark, which is either 0 or 1, and in the manner in which the scattering takes place, i.e., whether the quark or the diquark piece of the electromagnetic current is engaged in the scattering process (Fig. 1). All four quantities $f_{0,1}^{q,d}$ are positive-definite, of course.

The obtained representation for the nucleonic scaling functions serve as a starting point for the derivation of a number of interesting sum rules and other predictions of the diquark model in the scaling region.[4] As an illustration we bring the example of the well-known sum rule based on the integral

$$\Delta I = \int_0^1 \frac{1}{\xi}[(\nu W_2)_{\text{proton}} - (\nu W_2)_{\text{neutron}}]d\xi\,.$$

In the quark model of Gell-Mann and Zweig

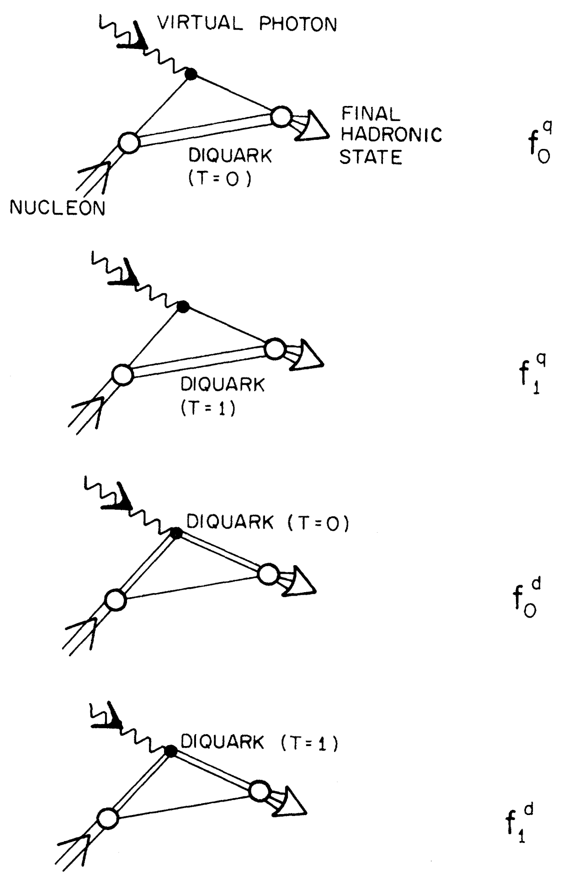

FIG. 1. Graphic representation for the scaling components $f_{0,1}^{q,d}(\xi)$ of the nucleonic structure functions $(1/\xi)(\nu W_2)$ in the diquark model.

$$\Delta I = \tfrac{1}{3}\,,$$

a number that is quite difficult to reconcile with the experimental value $\Delta I_{\text{exp}} = 0.18 \pm (?)$. On the other hand, in the diquark model,

$$\Delta I = \tfrac{3}{18} + \tfrac{4}{18}\sin^2\alpha\,,$$

and a match with experiment can easily be accomplished by placing α in the vicinity of 0.25.

The basis of the parton model is the observation that the electroproduction structure functions for free pointlike spin-0 or spin-$\frac{1}{2}$ objects scale. This important property of spins 0 and $\frac{1}{2}$ is not shared by the particles of higher spin. Since the diquark model deals with elementary objects of spin 1, in addition to spins 0 and $\frac{1}{2}$, the issue of scaling must be approached with care. It turns out that under the assumption of a "minimal" violation of scaling, the scaling component f_1^d in the nucleonic scaling structure functions acquires a scale-violating factor $1 - q^2/6M_V^2$ (M_V is the mass of the axial-vector diquark; remember that in the nucleon the isovector diquark has spin 1, and the isoscalar diquark is of spin 0), i.e.,

$$f_1^d(\xi) \to \left(1 - \frac{q^2}{6M_V{}^2}\right) f_1^d(\xi)\,.$$

The other three components $f_{0,1}^q$ and f_0^d remain unaffected, since they describe the scattering on elementary pointlike objects of spins $\frac{1}{2}$ and 0, respectively, and hence lead to perfect scaling. We note that the deviations from scaling due to the spin-1 character of (axial-) vector diquarks are in the opposite direction from the deviations of scaling that one would expect from an internal quark or the diquark form factor.[5]

The described spin-induced kinematical violations of scaling (that are a natural feature of the diquark picture) can be of some interest as a part of a possible mechanism that could explain the pattern oı recently observed small violations of scaling for larger values of the momentum transfer $-q^2$.[6] What is observed cannot be understood in a satisfactory manner within the framework of the ordinary quark model, even when the quarks are supplied with a small internal form factor. The crucial point is that the deviations from scaling obtained through the quark form factor are characterized by the uniformly downward shift of data points for $(\nu W_2)_{\text{nucleon}}(\xi, q^2)$ when $-q^2$ becomes large, while, in fact, for small values of the scaling variable ξ, $\xi \lesssim 0.25$, the trend of data seems to be in the opposite direction, namely, pointing upwards. Working under the hypothesis that the component $f_1^d(\xi)$ is large and dominates for small values of ξ, the observed trend of scaling data for the proton target can be satisfactorily explained within the framework of the diquark model; the upward shift of data points in the interval $\xi \lesssim 0.25$ is assigned to the spin-induced violations of scaling due to the spin-1 character of vector diquarks, while in the rest of the interval $0 \leq \xi \leq 1$ a small internal form factor of quarks and scalar diquarks can take care of the observed downward shift of data points for $(\nu W_2)_{\text{proton}}$.

It is significant that the hypothesis about the dominance of the axial-vector diquarks for small values of ξ (and the corresponding depletion for $\xi \to 1$) is not an isolated, stand-alone hypothesis, but is also required if one wants to understand the observed behavior of the ratio

$$(\nu W_2)_{\text{neutron}}/(\nu W_2)_{\text{proton}}$$

at the threshold $\xi \to 1$.[4]

ANNIHILATION CHANNEL

We are considering only processes mediated by one virtual photon, i.e., the processes of the type

$$e^+e^- \to \gamma^* \to X\overline{X},$$

where $X\overline{X}$ represents either a pair of quarks, or a pair of scalar diquarks, or a pair of (axial-) vector diquarks, or a pair in which one object is the scalar diquark while the other one is the vector diquark.

The integrated cross sections for these four different types of processes are (α is here the fine-structure coupling constant, E is the beam energy in the center-of-mass system of the e^+e^- pair) as follows.

quarks (spin $\frac{1}{2}$): $\sigma(e^+e^- \to q\overline{q}) = \dfrac{\pi\alpha^2}{3E^2}\left(\dfrac{M_q^2}{E^2}\right)^{1/2}\left(1+\dfrac{M_q^2}{2E^2}\right),$

scalar diquarks (spin 0): $\sigma(e^+e^- \to S\overline{S}) = \dfrac{\pi\alpha^2}{12E^2}\left(1-\dfrac{M_S^2}{E^2}\right)^{3/2},$

(axial-) vector diquarks (spin 1, zero anomalous magnetic moment):

$$\sigma(e^+e^- \to V\overline{V}) = \frac{\pi\alpha^2}{3M_V^2}\left(1-\frac{M_V^2}{E^2}\right)^{1/2}\left(1-\frac{M_V^2}{4E^2}-\frac{3M_V^4}{4E^4}\right),$$

scalar diquark–(axial-) vector diquark combination (spins 0 and 1):

$$\sigma(e^+e^- \to S\overline{V}, \overline{S}V) = \frac{\pi\alpha^2}{6M_V^2}\left(1-\frac{M_V^2+M_S^2}{2E^2}+\frac{(M_V^2-M_S^2)^2}{16E^4}\right)^{3/2}C \quad (C \text{ is a constant}).$$

To obtain $\sigma(e^+e^- \to \text{hadrons})$ we follow the usual parton-model philosophy of summing all individual contributions $\sigma(e^+e^- \to X\overline{X})$, multiplied by the appropriate squares of charges of the quarks and the diquarks, respectively:

$$\begin{aligned}\sigma(e^+e^- \to \text{hadrons}) = &\sum_{\text{quarks}} (\text{charge of quark})^2\sigma(e^+e^- \to q\overline{q}) \\ &+ \sum_{\substack{\text{scalar}\\ \text{diquarks}}} (\text{charge of scalar diquark})^2\sigma(e^+e^- \to S\overline{S}) \\ &+ \sum_{\substack{\text{vector}\\ \text{diquarks}}} (\text{charge of vector diquark})^2\sigma(e^+e^- \to V\overline{V}) \\ &+ \sum_{\substack{\text{scalar diquark-}\\ \text{vector diquark}\\ \text{combinations}}} (\text{charge of scalar or vector diquark})^2\sigma(e^+e^- \to S\overline{V}, \overline{S}V).\end{aligned}$$

The sum of (charges)^2 for quarks is the well-known number $(\frac{1}{3})^2+(\frac{1}{3})^2+(\frac{2}{3})^2=\frac{2}{3}$. When we evaluate the analogous sums of (charges)^2 for the scalar diquarks, vector diquarks, and the combinations of scalar and vector diquarks, we take into account *all* combinations allowed by the known conservation laws of quantum electrodynamics, including the case when one diquark belongs to $\underline{15}$ and its partner comes from $\underline{21}$, or when the isospin is violated by the amount $\Delta T = 1$. Under the described conditions we obtain

sum of (charges)^2 for scalar diquarks = sum of (charges)^2 for vector diquarks $=\frac{16}{3}$,

sum of (charges)^2 for the mixed case of scalar diquarks–vector diquarks $=\frac{32}{3}$.

We assume that the masses of quarks and the scalar diquarks are small, say, less than 0.3 GeV, while the mass of vector diquarks is large, say, greater than 1.7 GeV.

For small energies of the beam ($M_q, M_S \ll E \ll M_V$) the vector diquarks are not contributing because the channels with vector diquarks are not opened as yet. Without the contribution of the vector diquarks, we have

$$\frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \frac{\frac{2}{3}\sigma(e^+e^- \to q\bar{q}) + \frac{16}{3}\sigma(e^+e^- \to S\bar{S})}{\sigma(e^+e^- \to \mu^+\mu^-)} = 2 \, .$$

On the other end of the energy axis, it is the channels with vector diquarks that dominate, and we have ($M_V \ll E$)

$$\begin{aligned}\sigma(e^+e^- \to \text{hadrons}) &= \tfrac{16}{3}\sigma(e^+e^- \to V\bar{V}) + \tfrac{32}{3}\sigma(e^+e^- \to S\bar{V}, \bar{S}V) \\ &= (\tfrac{16}{3})(\pi\alpha^2/3M_V{}^2)(1+C) \, .\end{aligned}$$

We see that the vector diquarks lead to a constant cross section for $E \to \infty$. This behavior of spin-1 pointlike objects should be contrasted to the behavior of the spin-0 or spin-$\frac{1}{2}$ pointlike objects that give a decreasing ($\propto 1/E^2$) cross section for $E \to \infty$. It is in this sense that the presence of elementary spins 1 is desirable in the annihilation channel, for the data on the ratio

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

give indications about the presence of a constant component in the total cross section. More precisely, the situation is the following: In the energy region $E \lesssim 3$GeV the data on R are consistent with $R = 2$, in excellent agreement with the prediction of the diquark model in this energy range. Beyond 3 GeV, R suddenly rises into a broad peak located at 4.1 GeV and with the approximate width of 0.25 GeV. There may be another smaller peak at 4.4 GeV. After 5.5 GeV R continues with a moderate growth until the end of the explored energy range, $E \lesssim 7.4$ GeV. In this energy interval R varies between $R \simeq 5$ and $R \simeq 6$. The observed behavior of R is not consistent with the picture of pointlike diquarks (which predict a smooth quadratic growth with energy, $R \propto E^2$ as $E \to \infty$), but can be easily explained in terms of diquarks with structure.[7] The strange behavior of R in the interval $3.5 \lesssim E \lesssim 5.5$ GeV could signal the point where the internal gears of diquarks become visible. Beyond that point, the observed behavior of R could be interpreted as an interplay between two competing mechanisms, namely the quadratic growth with energy due to the spin-1 character of diquarks and the dampening effect of the internal form factor of diquarks. A victory of one component over another would mean either a continued growth of R with energy or a decrease of R with energy. Such a clear-cut situation would obviously be welcomed by the diquark model. A constant or a "stepwise" behavior of R would certainly diminish the credibility of the diquark model while enhancing the chances of the quark models that use a larger number of quarks.[8]

ANGULAR DEPENDENCE

It is commonly assumed that the hadrons originating from the fragmentation of quarks (partons) will display the jetlike structure aligned along the momentum of the quark (parton). By measuring the angular distribution of final hadron momenta, one can infer the underlying angular distribution of parent partons and hence discriminate against various quark-parton models that may predict different angular distributions. In the e^+e^- annihilation channel the angular distribution of produced objects in $e^+e^- \to \gamma^* \to X\bar{X}$ is dependent upon the spins of these objects. We have shown this relationship in Table I.

For small energies of the beam ($M_q, M_S \ll E \ll M_V$) the angular distribution in the diquark model will be

$$1 + \epsilon\cos^2\theta \, , \quad -1 \le \epsilon \le 1 \, ,$$

where the magnitude and the sign of the asymmetry parameter ϵ will depend upon the relative importance of the spin-0 diquark component and the spin-$\frac{1}{2}$ quark component in this energy range and θ is the angle between the e^+e^- collision axis and the momentum of X. This covers the case of isotropic distribution ($\epsilon = 0$) as well.

For large values of the beam energy ($M_V \ll E$), it is the vector diquarks that dominate, and we expect the angular distribution to be fairly well represented by

$$1 + \cos^2\theta \, .$$

ψ's

Two narrow resonances recently discovered[9] at 3.1 and 3.7 GeV cannot find a place in the quark model of Gell-Mann and Zweig. Within the framework of the diquark model these objects are interpreted as the bound states of $d\bar{d}$ (diquark-antidiquark) type. Since the scalar diquarks are of small mass, by assumption, the diquarks that are involved in the formation of ψ's must be the axial-vector diquarks. Now, two 1^+ objects in an s wave can combine only in the spins 0^+, 1^+, and 2^+. They

TABLE I. Angular distribution of produced objects in $e^+e^- \to \gamma^* \to X\bar{X}$ (θ is the angle between the e^+e^- collision axis and the momentum of X).

Spins of X and $\bar{X}$	Angular distribution
Spin $\frac{1}{2}$	$1+\cos^2\theta$
Spin 0	$1-\cos^2\theta$
Spin 0–spin 1 combination (zero anomalous magnetic moment of spin-1 object)	$1+\cos^2\theta$
Spin 1 (zero anomalous magnetic moment)	$1+\frac{1-\frac{3}{3}(M_V{}^2/E^2)}{1+\frac{3}{2}(M_V{}^2/E^2)}\cos^2\theta$

cannot yield 1^-. Consequently, the well-established spin-parity assignment $J^P=1^-$ for ψ's forces us to place the $d\bar{d}$ pair in a p-wave configuration. Using the usual spectroscopic notation, we are led to consider the states ${}^1P_1$, ${}^3P_1$, and ${}^5P_1$ as possible candidates for ψ's. The triplet states ${}^3P_1$, however, are characterized by an even charge-conjugation quantum number $C=+1$, and hence cannot participate in the formation of ψ's that have the well-established $C=-1$. Thus, in the final analysis, ψ's are either ${}^1P_1$, ${}^5P_1$, or a combination of the two.

From the point of view of the SU(3) classification scheme, ψ's must come from the irreducible representations $\underline{1}$, $\underline{8}$, $\overline{\underline{10}}$, and $\underline{27}$ in $\underline{3}\times\overline{\underline{3}}=\underline{1}+\underline{8}$, $\underline{3}\times\overline{\underline{6}}=\overline{\underline{10}}+\underline{8}$, $\overline{\underline{3}}\times\underline{6}=\underline{10}+\underline{8}$, and $\underline{6}\times\overline{\underline{6}}=\underline{1}+\underline{8}+\underline{27}$. Since the quantum numbers of ψ's are, by assumption, the same as that of the photon, only the particles that fall into the centers of the associated Cartan eigenvalue diagrams need be considered. Taking the multiplicities properly into account, we count in total $2\times 1+4\times 2+2\times 1+1\times 3=15$ possible neutral candidates for ψ's. The two possible values of the total spin of d and $\bar{d}$ (without orbital part) multiply this number by 2. Hence $2\times 15=30$. It remains a mystery why only two, or possible three, of these 30 objects have been discovered thus far. Perhaps only two of them are genuine bound states, while the rest belong to the continuum.

The p-wave configuration for ψ's that was forced upon us by the clearly established 1^- spin-parity assignment of ψ's may, at first, appear somewhat unusual, but in fact this spatial arrangement for the constituents of ψ's is helpful in explaining at least one remarkable feature of ψ's, namely, their exceptionally narrow width.

It is our contention that this striking phenomenon does not have a single explanation, but is a cummulative effect of at least two factors. First, it is not surprising that the exotic quark configurations of the $d\bar{d}=qq\bar{q}\bar{q}$ type have longer life than the "normal" $q\bar{q}$ modes. This is a consequence of the selection rules based on the duality diagrams.[10] Still, the reduction of the decay width of ψ's due to this cause cannot be greater than two orders of magnitude, at most. An additional suppression factor of 10^{-1} or 10^{-2} is needed, and it comes in a natural way from the spatial p-wave configuration of diquarks in the ψ's. Objects in a p-wave state are pushed apart by the centrifugal barrier, and thus have the difficulty of interacting or annihilating each other. By conducting the considerations within the framework of a nonrelativistic potential model, it is not difficult to verify that the required factor of 10^{-1} or 10^{-2} can easily be obtained by this mechanism.

The cnly problem is how to explain the absence of the same effect in the annihilation of d and $\bar{d}$ into a lepton pair, for the measured decay rate of ψ's into the e^+e^- pair is approximately the same as the corresponding decay rate of known vector mesons ρ, ω, and ϕ. An answer to that puzzle may very well lie in the peculiarities of the diquark model itself, i.e., in the large charges of some of the diquarks that will enhance their interaction of electromagnetic origin, and in their larger spins. (For example, the electric charge of the d_{11} diquark is 4 times larger than the electric charge of either the $\mathfrak{N}$ or λ quark. When squared, this brings in the factor of 16.)

A distinct virtue of the diquark model for ψ's is that there is no need to look for new quantum numbers such as charm or color in the debris of ψ's. Despite considerable experimental efforts in that direction, no such new quantum numbers have been found so far.

A weakness of the model is in the lack of clear understanding why so few of a sizeable number of possible bound states with spin 1^- appear in the annihilation channel.

The idea of ψ's as the bound states of $d\bar{d}$ type would receive a substantial boost from a discovery of other exotic mesons. These whose decay is not hampered by the p-wave centrifugal barrier (exotic mesons with spins 0^+, 1^+, and 2^+, which can be explained as $d\bar{d}$ pairs in an s-wave state) should have a decay width of several MeV and should therefore be easier to observe. A natural place to look for them is in the $\bar{p}p$ scattering experiments and/or in the radiative decays of ψ's such as $\psi' \to X+\gamma$. Possible bound states of the baryon-antibaryon type are the most likely candidates to be mistaken for the described exotic states.

NEW-MESON SPECTROSCOPY

The diquark model is characterized by an avalanche of new meson states of the $d\bar{d} = qq\overline{qq}$ type that should show their presence already in the mass range between 2 and 4 GeV. From the SU(3) group-theoretical point of view, we expect the multiplets $\underline{1}$, $\underline{8}$, $\underline{10}$, $\overline{\underline{10}}$, and $\underline{27}$. Even if it turns out that the scalar diquarks do not participate in the formation of bound states, the multiplicity of the spin-parity options for the new meson states is large. Combining two axial-vector objects in an s-wave state will give us the spin-parities 0^+, 1^+, and 2^+. The p-wave spatial arrangement leads to spin-parities $1^- \times 0^+ = 1^-$, $1^- \times 1^+ = 0^-, 1^-, 2^-$, and $1^- \times 2^+ = 1^-, 2^-, 3^-$. The contribution of higher orbital angular momenta will result in even larger multiplicities.

A discovery of rich spectral patterns among mesons above $M = 2$ GeV, say, would substantially enhance the credibility of the diquark model.

VARIATIONS ON THE THEME: COLORED DIQUARK MODEL

The described diquark model for hadrons is unsatisfactory from at least two aspects: The predicted spectra of new meson states is too dense, and in order to explain the SPEAR data on R we have been forced to abandon early the idea of pointlike diquarks, clearly an unhappy solution for the objects that were introduced as "fundamental." These two flaws of the model, and perhaps some others, can be corrected at the expense of introducing new degrees of freedom expressed in color.[11] Briefly, our assumptions are the following:

There are three triplets of quarks with the usual fractional charges. No charm quark is postulated. In fact, its presence would make the calculated value of R too big and in disagreement with the experimental data. All hadron states are color singlets, *ψ's included*. For reasons that will remain unexplained in this article, the quarks form pairs. These are the diquarks, of course, but now they come in colors. Applying the Pauli exclusion principle to the hilt we form the diquarks only from the quarks that differ in color. Accordingly, we end up with only three classes of diquarks corresponding to three color combinations. (If the quark colors are red, white, and blue, the combinations are red-white, white-blue, and blue-red. No red-red, white-white, or blue-blue diquarks exist.)

We require that the wave function of diquarks be antisymmetric in the color indices, so that the baryons can be made totally antisymmetric in color, as appropriate for the color singlets. How many diquark states do we have in the colored diquark model? First, there are again the scalar diquarks and the (axial-) vector diquarks. Each variety contains three SU(3) (anti-) triplets and three SU(3) sextets, differing in color combination. In total, $2 \times 3 \times (3+6) = 54$ states.

The baryons are the bound states of the quark-diquark type, or, symbolically,

$$\text{baryons} = d_{ij}q_k + d_{ki}q_j + d_{jk}q_i \qquad (i,j,k = \text{red, white, blue}).$$

The known mesons are the bound states of the quark-antiquark type, with all colors entering on the same footing. In other words, symbolically,

$$\text{mesons} = \sum_i q_i\bar{q}_i \quad (i = \text{red, white, blue}).$$

The newly discovered narrow resonances at SPEAR are the bound states of the diquark-antidiquark type, or

$$\text{new mesons} = \sum_{i,j} d_{ij}\bar{d}_{ij} \quad (i,j = \text{red, white, blue}).$$

In the diquark model without color, the ψ's are the bound states of the (axial-) vector diquarks. Here, *in the colored diquark model the ψ's are the bound states of the scalar diquarks*.

This is one of the essential differences between the two versions of the diquark model. In the diquark model without color the masses of scalar diquarks are small and comparable to the masses of quarks. This is dictated by the observed behavior of R. In the colored diquark model the same data lead to a different constraint on the masses of elementary objects, namely

$$m_q \lesssim 0.6 \text{ GeV},$$

$$m_S \gtrsim 1.7 \text{ GeV},$$

and

$$m_V > 3.7 \text{ GeV}.$$

The choice of the estimated upper limit on the masses of quarks will be left unexplained. It is sufficient to remark that it does not contradict any aspect of the presently available particle data.

The lower limit for the masses of scalar diquarks corresponds roughly to the beginning of what appears to be a threshold for the production of new elementary objects in $e^+e^- \to$ hadrons. Finally, the opening of the channel with the pointlike (axial-) vector diquarks would result in a sudden upswing of R with energy, $R \propto E^2$. Since nothing of this sort has been observed in the covered energy range $E \lesssim 7.4$ GeV, we place the lower limit for m_V at 3.7 GeV.

What is the behavior of R in the colored diquark model? For the energies above the resonance region and below the threshold for the production of scalar diquarks, $1 \lesssim E \lesssim 3.4$ GeV,

$$R = \sum_{\text{colors}} \sum_{\text{quarks}} e_q^{\,2} = 3 \times (\tfrac{4}{9} + \tfrac{1}{9} + \tfrac{1}{9}) = 3 \times \tfrac{2}{3} = 2\,.$$

Above the threshold for the production of scalar diquarks, $5 \lesssim E \lesssim ?$ GeV,

$$R = \sum_{\text{colors}} \sum_{\text{quarks}} e_q^{\,2} + \tfrac{1}{4} \sum_{\substack{\text{color}\\ \text{combinations}}} \sum_{\substack{\text{scalar}\\ \text{diquarks}}} e_S^{\,2} = 3 \times \tfrac{2}{3} + 3 \times \tfrac{1}{4} \times \tfrac{16}{3} = 2 + 4 = 6\,.$$

The energy interval $3.4 \lesssim E \lesssim 5$ GeV is the most interesting from the physical point of view. This is where the channels with scalar diquarks open up. Unfortunately, without specific assumptions about the pattern of mass differences between diquark states and the nature of forces between the diquarks and antidiquarks, we are not able to explain the observed behavior of R in this energy range. However, we do have an explanation for ψ's, and we are able to make rough predictions concerning the spectroscopy of the new meson states.

Because of the spinless constituents, the spectra of the new meson states in the colored diquark model are much sparser than in the diquark model without color. Two spin-0^+ objects in a bound state can give rise only to the "natural" $0^+, 1^-, 2^+, \ldots$ sequence of levels. The absence of the complementary "unnatural" sequence $0^-, 1^+, 2^-, \ldots$ is one of the most prominent characteristics of the colored diquark model.

The ψ's are, again, the p-wave bound states of diquarks-antidiquarks. The explanation for their exceptionally narrow decay width is the same as before, i.e., the combination of the selection rules based on the duality diagrams and the depletion of the wave function at the origin due to the centrifugal barrier that slows down the interaction and the eventual annihilation of constituents. Note that this argument works under the tacit assumption that the volume where the annihilation process $d\bar{d} \to$ hadrons takes place is small in comparison with the size of the $d\bar{d}$ bound-state system.

From the point of view of unitary symmetry the new meson states should come from irreducible representations that appear in the Clebsch-Gordon decomposition of the tensor products $\underline{3} \times \underline{\bar{3}}$, $\underline{3} \times \underline{\bar{6}}$, $\underline{3} \times \underline{6}$, and $\underline{6} \times \underline{\bar{6}}$. It is likely, however, that the sextets do not participate in the formation of a genuine bound state, making $\underline{1}$ and $\underline{8}$ from $\underline{3} \times \underline{\bar{3}} = \underline{1} + \underline{8}$ the only SU(3) multiplets which can be found among the new meson states of spin-parity 1^-.

Although the sextets presumably do not participate in the formation of genuine bound states, they may form metastable resonant states that lie higher in mass. Indeed, the data seem to indicate the presence of several broad resonant states above 4 GeV. The sextets may also participate in the formation of s-wave bound states where the forces between the constituents are stronger because of the larger overlap between their wave functions.

In the light of present experimental evidence on the behavior of R and the spectroscopy of newly discovered meson states the colored version of the diquark model enjoys definite advantages over the version without color. The spectrum of new meson states is sparce (because the constituents do not carry the spin), and the observed behavior of R is consistent with the prediction of the model. We stress that this prediction was made without the necessity of fitting the data with a hypothetical internal form factor of diquarks (partons).

A major test of the model should consist of the search for the "unnatural" spin-parity states $0^-, 1^+, 2^-, \ldots$ in the radiative decays of ψ's. Such states are predicted by many quark models, including the charm model. They are absent in our model. A discovery of these states would bring an early end to the colored variant of the diquark model. A spectacular confirmation of the basic validity of the assumptions on which the colored diquark model rests would come from a discovery of a sudden upswing of R with energy, $R \propto E^2$. Such rapid growth of R points to a presence of elementary (axial-) vector objects, and can hardly be explained by any other means. The absence of the described change in the trend of data on R, on the other hand, does not constitute, as yet, evidence against the diquark model. It merely asserts that the (axial-) vector diquarks are heavy and beyond the reach of presently available energies.

CONCLUSIONS

In search for the possible inconsistencies in the proposed diquark model for hadrons we have made a rough calculation of the magnetic moments for the well-known $\frac{1}{2}^+$ octet of baryons, and evaluated the $|g_A/g_V|$ ratio for the neutron. Both types of calculation favor a small value for the parameter α, in consistency with each other and the rest of the calculations presented in an earlier article.[4] Furthermore, in all cases the data-fitting was easier than in the quark model. A good example of this type of situation is provided by the already discussed case of the sum rule for

$$\int_0^1 \frac{1}{\xi}[(\nu W_2)_{\text{proton}} - (\nu W_2)_{\text{neutron}}]d\xi,$$

which is difficult to satisfy in the quark model, but is quite easy to accommodate in the diquark model. Taking all evidence into account, the diquark model emerges as a viable alternative to the quark model as a theoretical tool for understanding and parametrizing particle data.

In the quantitative sense, even better results can be obtained if the standard qqq configuration for baryons is retained on the probabilistic basis, namely, if we assume that the baryons still spend a fraction of their time in the qqq configuration and the rest of the time in the quark-diquark configuration. By introducing the relative probabilities P_{qqq} and P_{dq}, $P_{qqq}+P_{dq}=1$, we can compute the quantities of physical interest according to the following phenomenological rule of averaging:

$$A = P_{qqq}\langle A\rangle_{qqq} + P_{dq}\langle A\rangle_{dq}.$$

In particular, in this extended picture the scaling functions of nucleons are determined by 6 independent components $f_{\mathcal{P}}(\xi)$, $f_{\mathfrak{N}}(\xi)$, and $f_{0,1}^{q,d}(\xi)$, and the 3 real parameters P_{qqq}, P_{dq}, and α. We will have [all $f(\xi)$ functions are normalized to unity]

$$\left(\frac{1}{\xi}\nu W_2\right)_{\text{nucleon}} = P_{qqq}\left\langle\left(\frac{1}{\xi}\nu W_2\right)_{\text{nucleon}}\right\rangle_{qqq} + P_{dq}\left\langle\left(\frac{1}{\xi}\nu W_2\right)_{\text{nucleon}}\right\rangle_{dq},$$

$$\left\langle\left(\frac{1}{\xi}\nu W_2\right)_{\text{proton}}\right\rangle_{qqq} = \tfrac{8}{9}f_{\mathcal{P}}(\xi) + \tfrac{1}{9}f_{\mathfrak{N}}(\xi),$$

$$\left\langle\left(\frac{1}{\xi}\nu W_2\right)_{\text{neutron}}\right\rangle_{qqq} = \tfrac{2}{9}f_{\mathcal{P}}(\xi) + \tfrac{4}{9}f_{\mathfrak{N}}(\xi),$$

$$\left\langle\left(\frac{1}{\xi}\nu W_2\right)_{\text{proton}}\right\rangle_{dq} = \tfrac{4}{18}\cos^2\alpha f_0^q(\xi) + \tfrac{1}{18}\cos^2\alpha f_0^d(\xi) + \tfrac{2}{18}\sin^2\alpha f_1^q(\xi) + \tfrac{11}{18}\sin^2\alpha f_1^d(\xi),$$

$$\left\langle\left(\frac{1}{\xi}\nu W_2\right)_{\text{neutron}}\right\rangle_{dq} = \tfrac{1}{18}\cos^2\alpha f_0^q(\xi) + \tfrac{1}{18}\cos^2\alpha f_0^d(\xi) + \tfrac{3}{18}\sin^2\alpha f_1^q(\xi) + \tfrac{3}{18}\sin^2\alpha f_1^d(\xi).$$

As a first rough guess for P_{qqq} and P_{dq}, we may suggest $P_{qqq}=P_{dq}=\frac{1}{2}$.

Evidently, the diquark model does not experience a shortage in the new degrees of freedom. This may raise the worry that very little predictive power will be left over after all these numerous degrees of freedom are satisfied.

The steady stream of data coming from various sources such as deep-inelastic neutrino-nucleon scattering, the physics of high-$p_\perp$ events, the Drell-Yan process $p+p\to(\mu^+\mu^-)+\text{hadrons}$, deep-inelastic scattering of electrons on polarized targets, etc., should serve to reassure us that such worries are unfounded. Once the wave function of the nucleon is determined, the results from a large variety of experiments can be correlated and interpreted from the presented new point of view.

NOTE ADDED: MOST RECENT DEVELOPMENTS

Since this article was written, there has been rapid development of new physics at SPEAR and elsewhere. The accumulated data are of direct relevance to the diquark picture, and for this reason it seems appropriate to comment here upon some of the issues that has been raised by these data.

First and foremost, no evidence of charm or color or a similar new quantum number in the final states products of $e^+e^-\to$ hadrons has been found thus far. This is significant since there is very little room in the diquark model for an additional quark bearing a new quantum number. Charm, if found, will cause difficulties to the diquark model, and, in particular, to the predictions related to the magnitude of the total cross section $\sigma(e^+e^-\to\text{hadrons})$.

The most interesting new development of very recent vintage appears to be the growing awareness about the presence of the whole new families of 1^{--} narrow resonances around 4.1 GeV and perhaps at some other places, higher in mass,[12] as well. These resonances have so far escaped detection since they couple to the e^+e^- system with considerably smaller strength than ψ's. As much as they are welcomed in the diquark model, the newly discovered resonances are a cause of anxiety for those theoreticians who rely exclusively on additional quarks for the new degrees of freedom. Already the charm model has difficulties explaining the possible "ministructure" underneath the bump at 4.1 GeV, and if the proliferation of the resonances continues, any reasonable quark model utilizing only spin-$\frac{1}{2}$ constituents may soon find itself running out of the much needed degrees of freedom.

Aside from the indications about the new narrow resonances, further support to the diquark picture comes from the data on the behavior of the final-state products in $e^+e^- \rightarrow$ hadrons as a function of energy. In particular, good data exist on the behavior of the average charged-particle multiplicity[13] and on the particle ratios $\pi:K:$protons.[14] Significantly, these quantities fail to exhibit a dramatic change when the threshold of the "new" physics at around 4 GeV is crossed. Such smooth continuation from "old" physics to "new" physics is to be expected in the diquark model (where the new degrees of freedom are associated to the different quark configurations, not to the new quark species), but it is quite surprising in the charm model where one would expect much stronger impact of the new quantum number on the composition of the final-state products.

An interesting situation that has good chances of developing into a major testing ground for various theoretical models is shaping up at the low-energy end of the annihilation of e^+e^- pairs into hadrons.[15] On the energy interval $1 \lesssim E \lesssim 3$ GeV R does not appear to be constant, as complacent theorists would like it to be, but seems to be rising with energy. The data points (from SPEAR and Frascati) in this energy range are scarce, so that even a surprise discovery of new ψ-like narrow structures in this energy range is by no means ruled out. Should the events indeed take this turn, the significance for the diquark picture would be great, for the diquark model (in its noncolored version) does anticipate a complicated cross section at the point where the channels with the scalar diquarks open up. We recall that the contribution of the scalar diquarks to R is $(\Delta R)_{\text{scalar diquarks}} = \frac{4}{3}$, an increase that should be reflected in a sudden jump from $R = \frac{2}{3}$ to $R = 2$ at the energies $E \sim 2M_S$. As a first approximation we have tacitly assumed that $M_S = M_q$. However, for $M_q < M_S$ the described jump should be noticeable. If the forces between the scalar diquarks and its antiparticles are strong enough to form the bound states, the jump should be preceded by a number of narrow ψ-like structures. The mechanism that prevents a rapid disintegration of ψ's, and is responsible for their narrow decay width, is also in effect here (with the scalar diquarks taking place of the axial-vector diquarks), and we could very well witness a replay of the drama that accompanied the exploration of the $3 \lesssim E \lesssim 5$ GeV energy range. The upcoming more extensive data from Frascati should soon give us the answers to these important questions.

Finally, it is worth pointing out the striking similarity in the energy dependence between the e^+e^- annihilation into hadrons and the $p\bar{p}$ annihilation into hadrons. In particular, by employing a suitable overall scaling factor one can bring to a very good match the data on $\sigma(e^+e^- \rightarrow \text{hadrons})$ with the data on $\sigma(p\bar{p} \rightarrow \text{pions})$, and also the data on the respective charge multiplicities, and the data on the exclusive processes $\sigma(e^+e^-, p\bar{p} \rightarrow 2\pi^+2\pi^-)$.[16]

Since the $qq\bar{q}\bar{q}$ system strongly couples to the baryon-antibaryon system,[17] the similarity in the energy dependence between the two annihilation processes is expected and can be easily understood within the framework of the diquark model. The same does not apply to the charm model nor to any other quark model that I know of.

The described new experimental results from SPEAR and elsewhere have given the idea of diquarks a new degree of credibility. If the present trend of data continues, i.e., new high-mass meson resonances continue to be discovered, and no charm is found, one should perhaps start to contemplate a departure from this purely qualitative level of description and think about a more detailed elaboration of the diquark model, as it applies to the new spectroscopy. In particular, one could introduce the forces between the diquarks and the antidiquarks and attempt to make predictions concerning the mass spectra and the decay rates.

ACKNOWLEDGMENTS

Most of the work presented in this article was done during the author's stay at SLAC. I would like to thank Professor Bjorken for the hospitality extended at SLAC, and for the numerous discussions on the subject of diquarks. In fact, the concept of diquarks as partons is due to Professor Bjorken, and many ideas expressed in the article were simply borrowed from him. It goes without saying that it is entirely my own fault if I have misunderstood them.

[1]The basic idea of the diquark model, i.e., that two of the three quarks inside the baryon are glued together, has been suggested before: M. Ida, and R. Kobayashi, Prog. Theor. Phys. 36, 846 (1966); D. B. Lichtenberg, L. J. Tassie, and P. C. Kelemen, Phys. Rev. 167, 1535 (1968); J. Carroll, D. B. Lichtenberg, and J. Franklin, *ibid.* 174, 1681 (1968); S. Ono, Prog. Theor. Phys. 48, 964 (1972). As far as we know, the scaling properties of the diquark model (diquarks in the role of partons) have not as yet been investigated. Recently there have been several attempts to explain the earlier SPEAR data in terms of spin-1 partons. See, for example, S. G. Matinyan and S. V. Esaibegyan, Zh. Eksp. Teor. Fiz. Pis'ma Red. 19, 418 (1974) [JETP Lett. 19, 227 (1974)]; J. Cleymans and G. J. Komen, Nucl. Phys. B78, 396 (1974). An early suggestion to consider the possibility of spin-1 partons is due to J. D. Bjorken, in *Proceedings of the Sixth International Symposium on Electron and Photon Interactions at High Energies, Bonn, Germany, 1973,* edited by H. Rollnik and W. Pfeil (North-Holland, Amsterdam, 1974), p. 25.

[2]D. B. Lichtenberg, Phys. Rev. 178, 2197 (1968); R. H. Capps, Phys. Rev. Lett. 33, 1637 (1974).

[3]P. J. Litchfield, in *Proceedings of the XVII International Conference on High Energy Physics, London, 1974,* edited by J. R. Smith (Rutherford Laboratory, Chilton, Didcot, Berkshire, England, 1974), p. II-65.

[4]M. I. Pavković, Phys. Rev. D 13, 2128 (1976).

[5]The possibility of quarks with structure has been explored in M. S. Chanowitz and S. D. Drell, Phys. Rev. Lett. 30, 807 (1973); Phys. Rev. D 9, 2078 (1974); K. Matumoto, Prog. Theor. Phys. 47, 1795 (1972).

[6]E. M. Riordan *et al.*, Contributed paper to the 1975 International Symposium on Lepton and Photon Interactions at High Energies, Stanford, 1975 [SLAC Report No. SLAC-PUB-1634 (unpublished)].

[7]As is well known, the total description of an (axial-) vector object requires not one but three form factors. The simplest way to introduce structure is to assume only a small spread in charge, while keeping the static anomalous magnetic moment and the static anomalous electric quadruple moment equal to zero. With this assumption only one form factor is required. We will have

$$\sigma(e^+e^- \to V\bar{V}) = \sigma(e^+e^- \to V\bar{V})_{\text{pointlike}} f_1(E^2),$$

where the *same* positive-definite function f_1 will also make its appearance in the direct channel, i.e.,

$$\left(1-\frac{q^2}{6M_V^2}\right)f_1^q(\xi) \to \left(1-\frac{q^2}{6\,M_V^2}\right)f_1(q^2)f_1^q(\xi)\,.$$

Note that $f_1(0)=1$. For $-q^2 \to \infty$ or $E^2 \to \infty$ f_1 decreases toward zero.

[8]An example is the 6-triplet models of H. Harari, Phys. Lett. 57B, 265 (1975).

[9]J.-E. Augustin *et al.*, Phys. Rev. Lett. 33, 1406 (1974); J. J. Aubert *et al.*, *ibid.* 33, 1404 (1974); C. Bacci *et al.*, *ibid.* 33, 1408 (1974); G. S. Abrams *et al.*, *ibid.* 33, 1453 (1974).

[10]P. G. O. Freund, R. Waltz, and J. Rosner, Nucl. Phys. B13, 237 (1969).

[11]Color was first proposed under a different name by O. Greenberg, Phys. Rev. Lett. 13, 598 (1964). The recent emphasis on its importance and relevance, and the name "color," were proposed in various papers by W. Bardeen, H. Fritzsch, F. Gell-Mann and H. Leutwyler. See, for example, H. Fritzsch *et al.*, Phys. Rev. Lett. 47B, 365 (1973).

[12]F. J. Gilman, invited talk presented at the Third Orbis Scientiae, Univ. of Miami, 1976 [SLAC Report No. SLAC-PUB-1720 (unpublished)].

[13]R. Schwitters, in *Proceedings of the 1975 International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California,* edited by W. T. Kirk (SLAC, Stanford, 1976), p. 5.

[14]C. Morehouse, Talk given at the 1975 SLAC Summer Institute on Particle Physics, July 1975 (unpublished); T. L. Atwood *et al.*, Phys. Rev. Lett. 35, 704 (1975); B. Wiik, in *Proceedings of the 1975 International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California* (Ref. 13), p. 69.

[15]J. Bjorken, in *Proceedings of the 1975 International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California* (Ref. 13), p. 987.

[16]B. Margolis, in *Proceedings of the IV International Symposium on $N\bar{N}$ Interactions, Syracuse,* 1975, edited by T. E. Kalogeropoulos and K. C. Wali (Syracuse Univ., Syracuse, 1975).

[17]J. L. Rosner, Phys. Rep. 11C, 189 (1974). This review paper contains an exhaustive list of earlier references.