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Are the D Mesons Diquarks?

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The newly discovered mesons with mass near 1.87 GeV are speculatively identified with diquark states of integrally charged Han-Nambu quarks. The weak decays of diquarks are found to be similar but not identical to the decays of charmed mesons.

The SU(3) color forces in quantum chromodynamics are such that the lowest energy states are color singlets. If colored states exist at all, their mass scale is set by the mass of free quarks or by the mass of the lowest colored composite state. In the present Letter I will speculatively identify the newly discovered charged and neutral mesons[1] of mass around 1.87 GeV with the color triplet diquark states $(qq)_3$ formed by integer-charged Han-Nambu quarks.[2] These color-triplet states are the lowest bound colored states to be expected.[2] I will also assume that quarks and diquarks have roughly the same mass. With this input, Nambu's mass formula[2,3] leads to small masses for color-singlet mesons and baryons, and gives for the mass of color octet mesons

$$m((q\bar{q})_8) \approx \tfrac{9}{4} m((qq)_3) \approx 4 \text{ GeV}.$$

Hence, in this picture one may identify the J/ψ family and in particular the states around 4 GeV seen in e^+e^- annihilation with $(q\bar{q})_8$ states as was done with some success in previous work.[4] If energetically allowed, these color-octet states will now partly decay into pairs of quarks and diquarks, and partly—via color-octet symmetry breaking—directly into usual hadrons.

The assumed existence of mesonic diquarks requires special assignments for the baryon numbers of quarks or the violation of baryon number in diquark decays. An interesting possibility is the baryon number assignment[2] $B=0,\ 0,$ and 1 for the three colors red, white, and blue, denoted here by 1, 2, and 3. In the following this case shall serve as an illustrative example. It gives special significance to the SU(2)(color) subgroup (the color isospin group) which affects red and white quarks only. These quarks will eventually decay into an odd number of leptons and thus must carry lepton number. The choice $L=-1,\ 1,$ and 0 gives zero lepton number to usual baryons and allows for the existence of mesonic diquarks with lepton number zero, a case discussed already by Nambu and Han[5] for a somewhat different purpose. With the strangeness quantum number $S=0,\ 0,$ and -1 for u, d, and s quarks, the Gell-Mann–Nishijima formula may be written as

$$Q=(I_3+\tfrac{1}{2}S)_{\text{flavor}}+\tfrac{1}{2}(B+L). \qquad (1)$$

According to the Pauli principle the color-triplet diquarks of spin zero and orbital angular momentum zero form a $(\underline{3}^*, \underline{3})$ multiplet of particles.[5] Out of these nine states six have simultaneously baryon and lepton numbers different from zero and $I(\text{color})=\frac{1}{2}$. The remaining $\underline{3}^*$ SU(3) flavor multiplet has $I(\text{color})=0$. It consists of the mesons

$$F^0=d^1u^2-d^2u^1,$$
$$D^0=u^1s^2-u^2s^1, \qquad (2)$$
$$D^-=d^1s^2-d^2s^1.$$

The isospin-singlet meson F^0 has zero charge and is expected to be lighter than the isospin doublet $D^{0,-}$, both in contrast to the case of the charmed F meson.[6,7] Another difference with the charm picture appears for the spin-1 mesons with orbital angular momentum zero: The spin-1 diquarks are in a $\underline{6}$ representation of SU(3) flavor containing the isospin states 1, $\frac{1}{2}$, and 0. At this place a number of predictions about the diquark spectroscopy could be made which follow from their spin, parity, and SU(3) properties. In view of the speculative character of the present proposal this appears premature. It is, however, important to discuss the weak decay processes in order to see whether or not the diquarks have charmlike properties.

To obtain the weak-interaction current one has to group the nine quark fields into multiplets and singlets of a weak-interaction $SU(2)\otimes U(1)$ symmetry.[8] With the special baryon- and lepton-number assignment used here, only SU(2)(weak) doublets and singlets can occur (the weak current should not change lepton or baryon number). To the usual doublets

$$\begin{pmatrix} u^1 \\ d^1 \end{pmatrix}_L, \begin{pmatrix} u^2 \\ d^2 \end{pmatrix}_L, \begin{pmatrix} u^3 \\ d^3 \end{pmatrix}_L, \begin{pmatrix} \nu^e \\ e^- \end{pmatrix}_L, \begin{pmatrix} \nu^\mu \\ \mu^- \end{pmatrix}_L, \quad (3)$$

one has to add new doublets which let the diquarks decay to conventional mesons. The resulting additional piece of the charged weak current should be a member of a color SU(3) triplet which is at the same time a singlet with respect to color isospin and—in analogy to the color-octet part of the electromagnetic current—also a singlet with respect to flavor isospin. These requirements insure that the group

$$[SU(2)\otimes U(1)]\otimes[SU(2)\otimes U(1)]_{\rm color} \quad (4)$$

can be used as a gauge group in a way similar to that of Pati and Salam.[9] These authors use SU(4) $\otimes$SU(4)(color) as a spontaneously broken gauge group. In the present paper SU(3) flavor and SU(3) color are, however, only taken as (broken) global symmetries, and the connection to a full SU(9) gauge symmetry is not explored. One finds the two SU(2) (weak) doublets

$$\begin{pmatrix} s^{2C} \\ -s^1 \end{pmatrix}_L, \begin{pmatrix} s^{1C} \\ s^2 \end{pmatrix}_L, \quad (5)$$

where C denotes charge conjugation and the minus sign in one of the doublets causes the charged current to be a color-triplet component. The left-handed fields $d_L^{\,1}$, $s_L^{\,1}$ and $d_L^{\,2}$, $s_L^{\,2}$ will now be rotated with Cabibbo-type angles ϑ_1 and ϑ_2. Automatically, a Glashow-Iliopoulos-Maiani mechanism[10] results, in which $s_L^{\,2C}$ and $s_L^{\,1C}$ (containing the unrotated right-handed s fields) play the role of charmed quarks. As a result of color-isospin symmetry the two Cabibbo-type angles for red and white quarks should be equal: $\vartheta_1=\vartheta_2=\vartheta$. Then the effective Cabibbo angle between color-singlet states is[11]

$$\sin\theta_{\rm Cabibbo}=\tfrac{2}{3}\sin\vartheta, \quad \sin\vartheta\simeq\tfrac{1}{3},$$
$$\text{“}\cos\theta_{\rm Cabibbo}\text{”}=\tfrac{1}{3}+\tfrac{2}{3}\cos\vartheta. \quad (6)$$

The neutral current obtained from the weak doublets changes neither strangeness nor color isospin, and is—in the sector involving the strange quarks—a pure vector current. It can, however, excite color-octet states with $I(\text{color})=0$.

From the form of the weak current the decay properties of the mesonic diquarks are now evident. In transitions to usual particles one has $\Delta S=2$ in nonleptonic, and $\Delta S=2\Delta Q$ in leptonic and semileptonic processes in first order of the Fermi constant. The $\Delta S=1$ nonleptonic and $\Delta S=\Delta Q$ semileptonic transitions are suppressed by the factor $\sin^2\vartheta\simeq\frac{1}{9}$. Examples for the nonsuppressed decay modes are

$$F^0\to K^+K^0\pi^-, \quad F^0\to K^+K^0e^-\bar\nu^e,$$
$$D^0\to K^+\pi^-, \quad D^0\to K^+e^-\bar\nu^e, \quad (7)$$
$$D^-\to K^+\pi^-\pi^-, \quad D^-\to K^0e^-\bar\nu^e.$$

Except for the F decays, these transitions have the same characteristics as the charmed-meson decays.[12] The charm hypothesis is, therefore, not unique in predicting D^--meson decays to exotic channels! Only the properties of the F meson allow a distinction. Also the neutrino production of diquarks is similar to the weak production of charmed particles. In the diffractive process a D meson will always be produced together with a strange particle. On the other hand, two strange particles are expected in the diffractive production of the F^0 meson. This last effect will be welcome in case the high K-meson multiplicity seen in μ^-e^+ events[13] is substantiated by further measurements.

One might ask why the proposed F^0 particle, which is presumably lighter[7] than the D mesons, has so far escaped detection in e^+e^- processes. The answer is that the rate for F^0 pair production by single virtual photons will be small because the F^0 form factor is expected to be very small at all q^2. (The d^1 and u^2 constituent quarks have similar masses but opposite charges and point couplings.) For the D^0 meson, on the other hand, the difference in mass between strange and nonstrange quarks prevents a corresponding cancellation of amplitudes.

If the D mesons are diquarks, quarks with a mass of the order of 2 GeV should exist. Their production rate is presumably less energy-dependent than the production rate for D mesons which has a peak near 4.03 GeV. They can be misidentified as heavy leptons.

The weak current obtained from (3) and (5) will cause the decay of the blue quarks to baryons. For instance, the decays $u^3 \to \Xi^0\pi^+$, $u^3 \to \Xi^0 e^+\nu_e$, and—less frequently—$u^3 \to \Lambda\pi^+$ are predicted.

Beside the Cabibbo rotation of the quark fields in the weak current, further mixing effects are possible. In particular, a small mixing of $\nu_L{}^e$ with $u_L{}^1$ and of $\nu_L{}^\mu$ with $s_L{}^{2C}$ appears likely (in the convention used here, ν^e, e^- and ν^μ, μ^- carry lepton number -1):

$$\nu_L{}^e \to \nu_L{}^e + \epsilon_1 u_L{}^1, \quad u_L{}^1 \to u_L{}^1 - \epsilon_1 \nu_L{}^e,$$
$$\nu_L{}^\mu \to \nu_L{}^\mu + \epsilon_2 s_L{}^{2C}, \quad s_L{}^{2C} \to s_L{}^{2C} - \epsilon_2 \nu_L{}^\mu, \qquad (8)$$
$$\epsilon_{1,2} \ll 1.$$

If such a mixing occurs, the charged weak current obtained from (3) and (5) will also be responsible for the decays of red and white quarks: $s^1 \to \nu^\mu e^- \bar{\nu}^e$, $s^1 \to \nu^\mu \mu^+ \bar{\nu}^\mu$, $s^2 \to \mu^+ +$ hadrons, $d^1 \to \nu^e +$ hadrons, $d^1 \to e^- +$ hadrons, etc. These decays are similar to the ones expected for heavy leptons but with different transition rates and hadron multiplicities. The same mechanism will then also cause the decays of those diquark states which are simultaneously baryons and leptons leading, for example, to the unusual $\Xi\mu$ final states. The values of the mixing parameters ϵ are restricted. An upper limit may be obtained by considering the process $K^+ \to \pi^+ \nu_e \bar{\nu}_\mu$ which is of order ϵ^4. With the experimental number[14] $R(K^+ \to \pi^+ 2\nu) \lesssim 0.6 \times 10^{-6}$ one finds $\epsilon \lesssim 0.05$.[15]

The existence of quarks and diquarks would lead to remarkable effects. Perhaps it is worthwhile to look for them, if for no other reason than to be sure that they are not there.

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[15]Such small values of the mixing parameters ϵ could give quark lifetimes too long to be compatible with experiment. However, matrix elements of operators like $(\bar{\nu}^e d_9{}^1)(\bar{d}_9{}^1 u^1) - (\bar{\nu}^e e^-)(\bar{e}^- u^1)$ have a good chance to be considerably enhanced by a mechanism similar to octet dominance. An alternative possibility for the decay of red and white quarks is obtained by adding new doublets to the weak current, for instance the right-handed doublet $(u^1, e^-)_R$.

Asymptotic Estimates in Scalar Electrodynamics

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Lipatov's estimates for large orders of perturbation theory are extended to scalar electrodynamics.

Lipatov has recently obtained estimates for large orders of the renormalized perturbation series in scalar field theories using semiclassical methods.[1-3] He has beautifully extended the pioneering work done on the quantum-mechanical harmonic oscillator by Bender and Wu[4] and by Loeffel *et al.*[5] We pres-