RAPID COMMUNICATIONS

PHYSICAL REVIEW D VOLUME 28, NUMBER 1 1 JULY 1983

Rapid Communications

The Rapid Communications section is intended for the accelerated publication of important new results. Manuscripts submitted to this section are given priority in handling in the editorial office and in production. A Rapid Communication may be no longer than 3½ printed pages and must be accompanied by an abstract. Page proofs are sent to authors, but, because of the rapid publication schedule, publication is not delayed for receipt of corrections unless requested by the author.

Baryons from diquarks in e^+e^- annihilation

Svante Ekelin, Sverker Fredriksson, Magnus Jändel, and Tomas I. Larsson
Department of Theoretical Physics, Royal Institute of Technology, S-100 44 Stockholm, Sweden
(Received 18 April 1983)

We find experimental support for the view that diquarks appear only as spin-0 objects. When their production rate in the color field of a quark from e^+e^- annihilation is described by the appropriate Schwinger formula for scalars, it turns out that they must be substantially lighter than earlier believed in order to explain the baryon yield.

Baryon production in e^+e^- annihilation is a sensitive probe of fundamental quark processes. About 10% of all hadrons from such reactions are baryons, and this is most likely too much to be understood in a quark-recombination picture. A recent analysis[1] indeed shows that at least 90% of the baryons must come from other sources, although another opinion has been presented within a more complicated recombination scheme.[2] The most widespread explanation of the rather large baryon yield in high-energy e^+e^- processes is, however, that baryons come from *diquarks,*[3,4] and the aim of this work is to learn about those diquarks from the scarce data.

Diquarks, i.e., tightly bound quark pairs, can in principle appear on two levels in e^+e^- annihilation: *direct* ones from $e^+e^- \rightarrow D\bar{D}$, where the diquarks D and $\bar{D}$ fragment to hadrons, or *indirect* ones from $e^+e^- \rightarrow q\bar{q}$, followed by a quark fragmentation like $q \rightarrow q(D\bar{D})$ before the hadronization stage. We will not consider the complication that diquarks might be created in a collective fashion, and then break up before fragmenting to hadrons.[5] A diquark is therefore assumed always to end up in a baryon (neglecting possible $D\bar{D}$ bound states).

Only the indirect diquarks have so far been analyzed in the literature, since it has been assumed that the direct ones are strongly suppressed by unfavorable electromagnetic form factors. In addition, the direct diquarks would mostly escape in baryons that are too fast to be identified. We still believe that direct diquarks give very interesting signatures in existing data, but since they pose a different problem than the indirect ones, we will return to them in a forthcoming and more detailed work, and concentrate here on the $D\bar{D}$ pairs created in the color field from a directly produced quark-antiquark pair.

Earlier it has been taken for granted that diquarks are SU(6) symmetric and rather heavy, so that the agreement with data is a result of a delicate balance between the number of different diquarks and their best-fit masses.

Here we would like to point out that an orthogonal, and more economical, diquark model fits the data on baryon yields equally well. We assume that only spin-0 pairs can form bound diquark systems, and that these are substantially lighter than earlier anticipated. This rather extreme view on diquarks is a result of our earlier analyses of the nucleon as a bound quark-diquark system. When investigating deep-inelastic structure functions, we found[6,7] that nucleons are nearly always in $q(ud)_0$ configurations, with the $(ud)_0$ being a bound spin-0 diquark. The small fraction of spin-1 diquarks can be explained[7] as "accidental." We argued that a spin-1 system is not bound, but that the photon nevertheless can interact with such an entity whenever the lone quark happens to be so close to one of the quarks in the "true" $(ud)_0$ diquark that the photon cannot dissolve a "false" spin-1 system. Such a picture is consistent with the best-fit values both for the admixture of spin-1 diquarks in the proton wave function and for their form factor, which is much less pointlike than that of the $(ud)_0$.

If our interpretation of data from deep-inelastic scattering is correct, so that only spin-0 diquarks exist as dynamically bound two-quark systems, there is obviously no room whatsoever for spin-1 diquarks in e^+e^- annihilation. Therefore, we expect the lightest diquarks $D_1 \equiv (ud)_0$, $D_2 \equiv (us)_0$, and $D_3 \equiv (ds)_0$ and their antidiquarks to be responsible for the bulk of identified baryons. Heavier $D\bar{D}$ pairs are suppressed in the vacuum, and appear only as directly produced diquarks at high energies. Their influence on data in general will therefore be considered in our forthcoming work.

Another result of Refs. 6 and 7 is that the $(ud)_0$ is surprisingly pointlike, with a mean radius being around one third that of the proton. The $(ud)_0$ is therefore confined to about 3% of the nucleon's volume. Since it, in addition, has a momentum distribution in the proton that is only a bit more extended towards high momenta than the distribution of the lone u quark, we suspect the $(ud)_0$ to be very light. It is, however, impossible to get a more quantitative estimate of the $(ud)_0$ mass from deep-inelastic scattering data. One can, on the other hand, derive a more model-dependent value from the MIT bag model, by assuming that the proton is a u quark and a $(ud)_0$ diquark moving freely within the MIT bag. With the normal values of other model parameters, and assuming that the color-magnetic contribution is absorbed in the diquark mass, we need a $(ud)_0$ mass of 225 MeV to reproduce the proton mass of

938 MeV. Since the production rate of $D\bar{D}$ pairs from the color field in e^+e^- annihilation is very sensitive to the D mass, the internal consistency of the model hence requires a best-fit value of 200 − 300 MeV for the $(ud)_0$ mass.

The standard way of estimating the number of fermion-antifermion pairs created in a strong color field is to apply the celebrated Schwinger formula,[8] as borrowed from quantum electrodynamics:

$$W_F = \frac{\alpha E^2}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left[-\frac{n\pi m^2}{eE}\right] \quad . \tag{1}$$

W_F is the probability of pair creation per unit time and volume, α is the fine-structure constant, eE the strength of the field, and m the mass of the fermion.

It seems to have been overlooked in the current diquark literature, however, that *Eq. (1) is not valid for spin-0 diquark pairs.* For such bosons the correct Schwinger formula[8] reads

$$W_B = \frac{1}{2}\frac{\alpha E^2}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2}(-1)^{n-1} \exp\left[-\frac{n\pi m^2}{eE}\right] \quad . \tag{2}$$

The crucial difference between (1) and (2) is the trivial spin factor $\frac{1}{2}$ in (2), a feature that would remain in any reasonable QCD modification of (1) and (2). A questionable, but widespread, simplification is to use only the first term in (1) for the massless u and d quarks. This gives an error of about 40%, and is not in line with the interpretation in the original literature,[8] where it is pointed out that the nth term in the sum is *not* equal to the probability to produce n simultaneous $q\bar{q}$ pairs.

An obvious effect of using (2) instead of (1) for scalar diquarks is that considerably lower masses are needed to fit the baryon yields.

In order to estimate the production rates of quarks and diquarks, we assume that the pair creation is mediated by low enough momentum transfers, so that the D_1, D_2, and D_3 form factors can be safely set equal to unity. The parameters in (1) and (2) that we need to fix are therefore the field energy eE per unit length in the color flux tube and the quark and diquark masses m_u, m_d, m_s, m_{D_1}, m_{D_2}, and m_{D_3}. We assume first that

$$m_u = m_d = 0 \tag{3}$$

for simplicity, and that

$$m_{D_2} = m_{D_3} \tag{4}$$

from isospin symmetry. The field strength $F = eE$ can be related to the universal Regge slope α' through[9]

$$F \equiv eE = \frac{1}{\pi\alpha'} \quad . \tag{5}$$

With the standard value $\alpha' = 0.90\ \mathrm{GeV}^{-2}$,[10] one gets the alternative

$$F_1 = 0.35\ \mathrm{GeV}^2 \quad . \tag{6}$$

After a more detailed analysis of the bulk of e^+e^- hadron data, the Lund group argued,[3] however, that the smaller value

$$F_2 = 0.20\ \mathrm{GeV}^2 \tag{7}$$

is needed for a good fit to data. We will test both options.

The mass m_s can be related to the mean number of K^0's per event, which leads to the following ratios for the rates of $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$ pairs at the energy $\sqrt{s} = 34$ GeV (Ref. 11):

$$W(u\bar{u}):W(d\bar{d}):W(s\bar{s}) = 1:1:(0.3 \pm 0.1) \quad . \tag{8}$$

Disregarding the experimental uncertainty in (8), we get from Eq. (1) that

$$m_s \approx \begin{cases} 300\ \mathrm{MeV\ for}\ F_1\ \mathrm{in}\ (6) \ , \\ 225\ \mathrm{MeV\ for}\ F_2\ \mathrm{in}\ (7) \ . \end{cases} \tag{9}$$

Next we assume for simplicity that

$$m_{D_2} = m_{D_3} = m_{D_1} + m_s \ , \tag{10}$$

so that the mass excess in the strange diquarks D_2 and D_3 is caused entirely by the nonzero mass of the strange s quark.

The only remaining parameter is the $(ud)_0$ mass. It can be fixed to reproduce the ratio B/M of baryon to meson yields. At PETRA energies it is known[11] that this ratio grows somewhat with increasing hadron momentum, but stays at about 8% at momenta that are low enough to ensure that the outgoing hadron does not contain a directly produced quark or diquark.

We hence have

$$\frac{W(D_1\bar{D}_1) + W(D_2\bar{D}_2) + W(D_3\bar{D}_3)}{W(u\bar{u}) + W(d\bar{d}) + W(s\bar{s})} \approx 8\% \quad , \tag{11}$$

and (1) and (2) therefore give

$$m_{D_1} \approx \begin{cases} 300\ \mathrm{MeV\ for}\ F_1 \ , \\ 225\ \mathrm{MeV\ for}\ F_2 \ , \end{cases} \tag{12}$$

and, consequently,

$$m_{D_2} = m_{D_3} \approx \begin{cases} 600\ \mathrm{MeV\ for}\ F_1 \ , \\ 450\ \mathrm{MeV\ for}\ F_2 \ . \end{cases} \tag{13}$$

The relative frequencies of quarks and diquarks become

$$W(u\bar{u}):W(d\bar{d}):W(s\bar{s}):W(D_1\bar{D}_1):W(D_2\bar{D}_2):W(D_3\bar{D}_3)$$

$$\approx 1:1:0.3:0.14: \begin{cases} 0.02:0.02\ \mathrm{for}\ F_1 \ , \\ 0.01:0.01\ \mathrm{for}\ F_2 \ . \end{cases} \tag{14}$$

The existing data on the mean number of baryons in e^+e^- annihilation are therefore in line with our diquark model with maximal SU(6) breaking, i.e., no spin-1 diquarks, and with a very low $(ud)_0$ mass. In order to make more detailed comparisons with data we would also need to make much more specific assumptions, and the basic features of the model would not be as clearly probed. An example is given by the rate of Λ's and their momentum distribution. Here we would need to take into account not only all the different ways to form a Λ from indirect diquarks, but also the "leakage" from both direct diquarks and decaying heavier baryons like the Λ_c. The latter problem has been studied in Ref. 12.

The most crucial prediction for testing our model is naturally that there can be *no spin-$\frac{3}{2}$ baryons* from diquarks. All decuplet baryons must therefore come from recombination of quarks or from the creation of heavier spin-$\frac{1}{2}$ resonances that decay to spin-$\frac{3}{2}$ baryons. Both alternatives are rather improbable, and we hence expect the yields of spin-$\frac{3}{2}$

baryons to be an order of magnitude lower that those of spin-$\frac{1}{2}$ baryons. The clearest case should be the $\Sigma(1385)$, since it is comparatively simple to detect. We predict, for instance, that

$$\sigma(e^+e^- \to \Sigma(1385)) << \sigma(e^+e^- \to \Lambda(1115)) ,$$

while SU(6) symmetry would lead to about three times as many $\Sigma(1385)$ as directly produced $\Lambda(1115)$.

We would like to thank Gösta Gustafson for inspiring discussions. One of us (S.F.) is grateful to the Swedish Natural Science Research Council for financial support.

[1]G. Eilam and M. S. Zahir, Phys. Rev. D 26, 2991 (1982).

[2]R. Migneron, L. M. Jones, and K. E. Lassila, Phys. Lett. 114B, 189 (1982).

[3]B. Andersson, G. Gustafson, and T. Sjöstrand, Nucl. Phys. B197, 45 (1982).

[4]E. M. Ilgenfritz, J. Kripfganz, and A. Schiller, Acta Phys. Pol. B9, 881 (1978).

[5]U. P. Sukhatme, K. E. Lassila, and R. Orava, Phys. Rev. D 25, 2975 (1982); A. Bartl, H. Fraas, and W. Majerotto, *ibid.* 26, 1061 (1982); see also S. Fredriksson and T. I. Larsson, *ibid.* 28, 255 (1983) (this issue).

[6]S. Fredriksson, M. Jändel, and T. Larsson, Z. Phys. C 14, 35 (1982).

[7]S. Fredriksson, M. Jändel, and T. Larsson, Z. Phys. C (to be published).

[8]E. Brezin and C. Itzykson, Phys. Rev. D 2, 1191 (1970); J. Schwinger, Phys. Rev. 82, 664 (1951); *ibid.* 93, 615 (1954).

[9]A. Casher, H. Neuberger, and S. Nussinov, Phys. Rev. D 20, 179 (1979).

[10]A. C. Irving and R. P. Worden, Phys. Rep. 34, 117 (1977).

[11]See, for instance, G. Wolf, DESY Report No. 82-077, 1982 (unpublished).

[12]T. A. DeGrand, Phys. Rev. D 26, 3298 (1982).