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Spin effects and vector diquarks: η_c decay into baryon-antibaryon

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Abstract: Experimental evidence for diquarks is briefly reviewed. The decay rate for $\eta_c \to p\bar{p}$ is computed, modeling the proton with a quark-diquark system. Satisfactory agreement with the data is obtained. The importance of vector diquarks as nucleon components to explain several spin effects is stressed.

Diquarks as fundamental constituents of baryons have received considerable attention since the advent of $SU(3)$ symmetry and the quark-parton model.[1] Recently, many experiments have supported the idea of diquarks as constituents inside nucleons.

Large transverse momentum protons produced in pp collisions at the ISR can only be explained in terms of hard scatterings between diquarks and their successive fragmentation:[2] a careful analysis of the charge and nature of the resulting jets indicates the presence, inside protons, of both scalar and vector diquarks.[3]

The EHS-RCBC collaboration[4] has made precise measurements of the Feynman z distribution for the inclusive reaction $pp \to \text{hadron}+X$ at 360 GeV. The data are analyzed by assuming the proton to be composed either of a quark and a diquark or of three independent quarks, and indeed it is found that the model with diquarks provides a better description.

A study of diquark fragmentation in νn and νp interactions[5] shows some evidence of a coherent fragmentation, thus suggesting the existence of diquarks as basic subunits of a nucleon. Also, in K^+p interactions[6] at 70 GeV, the fragmentation of the proton is seen to occur predominantly from a quark-diquark configuration.

It thus seems that diquarks play indeed a role as baryon constituents in several hadronic interactions. This should be particularly evident in the intermediate energy region $Q^2 \leq 10\ (\text{GeV})^2$ where diquarks behave as quasi-elementary objects. At higher energies, instead, we expect a diquark to look like a two-free-quark state, thus leading back to the usual quark-parton model.

It is precisely in the intermediate energy range that a variety of spin effects in exclusive hadronic reactions have been observed experimentally, which the pure-quark models cannot explain. In Ref. [7] it has been shown (in the framework of the end-point model) that spin effects in nucleon-nucleon elastic scattering might be understood if vector diquarks are taken among the active constituents of the nucleon. Also proton-antiproton annihilation into hyperon-antihyperon has been consider within the same scheme.[8]

A more accurate description of exclusive reactions with diquarks is obtained by suitably modifying the pure-quark Brodsky-Farrar-Lepage (BFL) scheme.[9] This has been accomplished and used in a series of papers.[10,11]

Here, we review the simplest process which presents a crucial and clean spin effect, the η_c decay into baryon-antibaryon, and its description in the quark-diquark scheme.[11]

A perturbative QCD description of exclusive decays of charmed mesons is justified by the observation that these processes should be mediated by relatively hard gluons (as suggested by the presence of the OZI suppression). This is usually done in the framework of the BFL scheme[9,12] via the factorization of the amplitude in a hard, perturbative part, describing the dynamics of the given process, and a process-independent wave function which contains the non perturbative information on the hadronization.

Whereas the $J/\psi \to p\bar{p}$ decay is described rather well in this approach[12,13] (although with some inconsistencies, see below), the decay of another charmed meson, namely $\eta_c \to p\bar{p}$ is forbidden,[14] while being experimentally observed. Moreover, the experimental branching ratio of the last decay is of the same order of magnitude as that of the first one.

Indeed, in the BFL scheme, due to the masslessness of quarks, only helicity-conserving couplings are present. As a consequence, in the above decays the final state should have $S = 1$, while parity and angular momentum conservation force it to have $S = 0$; hence the process – a spin effect – is forbidden.

Introducing diquarks as active constituents while maintaining the general picture of a factorized amplitude provides the helicity-flipping couplings which allow the decay. A possible alternative would be to stick to the pure-quark picture, including quark-mass corrections which are discarded in the BFL scheme. This leads to helicity flipping couplings proportional to the ratio of the light quark to the heavy meson masses. We shall compare our results with this approach in the sequel.

We outline here our calculation, and refer to Ref. [11] for the details. The amplitude for the decay is

$$\begin{aligned} M_{\lambda_p\lambda_{\bar p}}(\eta_c \to p\bar p) &= \sum \int \mathrm{d}x\mathrm{d}y\mathrm{d}z\, \psi^*_{p,\lambda_p}(x)\psi^*_{\bar p,\lambda_{\bar p}}(y) \\ &\times\ T_{\lambda_q,\lambda_Q,\lambda_{\bar q},\lambda_{\bar Q};\lambda_c\lambda_{\bar c}}(c\bar c \to qQ\bar q\bar Q; x,y,z)\psi_{\eta_c}(z) \end{aligned} \quad (1)$$

where the ψ's are the wave functions of the hadrons, T is the elementary helicity amplitude for the constituent process $c\bar c \to qQ\bar q\bar Q$ (in our scheme where a nucleon is made up of a quark q and a diquark Q) and the sum goes over all allowed quantum numbers of the constituents (colour, helicities and flavours). The quark (antiquark) four-momentum is related to the momentum of the proton (antiproton) by $q = xp$ ($\bar q = y\bar p$) and all masses are consistently taken into account.

The only non zero elementary amplitudes turn out to be those with vector diquarks $T_{\lambda_q,\lambda_Q\neq 0,\lambda_{\bar q}=-\lambda_q,\lambda_{\bar Q}=0;\lambda_c\lambda_{\bar c}=-\lambda_c}$ and $T_{\lambda_q,\lambda_Q=0,\lambda_{\bar q}=-\lambda_q,\lambda_{\bar Q}\neq 0;\lambda_c\lambda_{\bar c}=-\lambda_c}$ which both flip the diquark helicity; all other elementary amplitudes are zero, including those with scalar diquarks. We obtain for the decay rate of $\eta_c \to p\bar p$:

$$\Gamma(\eta_c \to p\bar p) = \frac{2^{17}\pi^3 M^4}{3^5 m_p^2}(M^2 - m_p^2)^{5/2}|F_{\eta_c}|^2|F_N|^4 I^2 \quad (2)$$

where m_p and M are, respectively, the proton and charmed quark masses and

$$I = \int \mathrm{d}x\mathrm{d}y\, \frac{\phi_2(x)\phi_3(y)\alpha_s^2(1-x)(y-x)}{g_1^2 g_2^2(k^2 - M^2)} G_2(g_2^2) \quad (3)$$

with

$$\begin{aligned} g_1^2 &= (x-y)^2 m_p^2 + 4xyM^2 \\ g_2^2 &= (x-y)^2 m_p^2 + 4(1-x)(1-y)M^2 \\ k^2 - M^2 &= (x-y)^2 m_p^2 + 2(2xy - x - y)M^2 \end{aligned} \quad (4)$$

Here, $G_2(g_2^2)$ indicates the vector diquark form factor, which approximately equals 1 in our energy range, while $\phi_2(x)$ and $\phi_3(x)$ are probability distributions for the vector diquark to carry the momentum fraction x, that appear in the definition of the proton wave function (see Refs. [10, 11] for details).

F_{η_c}, and F_N are dimensional ([F] = [mass]) constants, which appear in the definition of the meson and nucleon wave functions, respectively, and are related to the probability of the constituents to hadronize into the pertinent meson or baryon with the proper quantum numbers. These are non perturbative quantities analogous to the pion decay constant F_π. Thus, they ought to be treated as phenomenological parameters and determined by comparison with the experimental data.

The value of F_{η_c} may be fixed in two independent ways. First we computed the decay rate $\Gamma(\eta_c \to \gamma\gamma)$ and compared with the existing experimental data.[15]

Alternatively, we assumed $\Gamma(\eta_c \to \text{all}) \simeq \Gamma(\eta_c \to gg)$, and compared the result for $\Gamma(\eta_c \to gg)$ with the experimental value of the total hadronic decay rate of η_c. The values obtained (with large errors) are in fair agreement with each other.

The value of F_N, instead, characterizes the hadronization of a quark-diquark pair, and therefore may be determined only by computing, in our quark-diquark scheme, other physical quantities which are experimentally measured. Since only few such data are presently available, both theoretically and experimentally, we prefer to express our result as a determination of F_N (with error bounds) and verify the consistency of this value with that obtained from other processes.

We find, with many different choices of the proton wave function,[11]

$$F_N \simeq (300 \pm 100)\ \text{MeV}. \qquad (5)$$

It should be noted that the result is rather stable and depends very little on the wave function chosen.

This is to be compared with the value of F_N obtained from the description of $\gamma\gamma \to p\bar{p}$ within the same scheme:[10]

$$F_N \simeq 100\ \text{MeV}. \qquad (6)$$

The latter value, however, is obtained by taking $\alpha_s(Q^2)$ to be a running coupling, and neglecting all quark masses, whereas the former is derived by taking masses into account and keeping $\alpha_s = \alpha_s(m^2_{\eta_c}) = 0.28$ fixed.

If the value (5) is calculated again with running coupling and without quark masses we get

$$F_N \simeq (150 \pm 50)\ \text{MeV}. \qquad (7)$$

in good agreement with (6). Although this is enough to assess consistency, we believe that it is more appropriate to our intermediate energy region to take all masses into account and keep α_s fixed.

It should be remarked that since only vector diquarks contribute to $\eta_c \to p\bar{p}$, while only scalar diquarks are used in the calculation of $\gamma\gamma \to p\bar{p}$,[10] strict equality of the two determinations of F_N should be violated by several effects as, for instance, mass differences between scalar and vector diquarks. In Ref. [10] a heuristic argument was presented to roughly evaluate the values of F_N from integrating explicit examples of hadronic wave functions over intrinsic transverse momenta. Estimating the mean transverse momentum of the constituents to be of the order of 300 MeV, one would find $F_N \sim 40$ MeV, a value much smaller than the ones suitable to describe both the $\gamma\gamma \to p\bar{p}$ and the $\eta_c \to p\bar{p}$ data. It is not clear, however, whether such an argument, based on pure quark light cone perturbation theory,[9] is to be taken too seriously in our energy range, where masses and non perturbative effects (like diquarks) still play a crucial role.

We may now compare the quark-diquark picture of these decays with the (massive) pure-quark approach. First, let us observe that determinations of F_N from the description of $J/\psi \to p\bar{p}$ with pure quarks[13] vary of up to 5 orders of magnitude, according to the wave functions used. If one tries alternatively to use sum rules to fix F_N, a simple argument[11] suggest that the result for the decay rate is suppressed by a factor 0.05 as compared to ours, thus making the agreement with the data rather troublesome.

All this leads us to the conclusion that vector diquarks are essential to provide the helicity-flip amplitudes which are required to account for the experimental data on the $\eta_c \to p\bar{p}$ decay.

In addition to this, we have been able to give predictions for the decay rates of η_c, and η_b into various kinds of baryon-antibaryon pairs, as the ratios $\Gamma(\eta_c \to B\bar{B})/\Gamma(\eta_c \to p\bar{p})$ and $\Gamma(\eta_b \to B\bar{B})/\Gamma(\eta_c \to B\bar{B})$. While the former is again rather insensitive to the choice of hadronic wave function, the latter strongly depends on it. This may provide a good testing ground for a comparative study of quark-diquark hadronic wave functions.

Many more decays of the charmoniurn, bottomonium and toponium families may be described with the quark-diquark approach. Work is in progress towards a systematic treatment of all these processes within our scheme.[16]

Let us conclude by noting that the pure-quark model has severe difficulties when trying to describe other simple meson decays, like $\eta_c \to \phi\phi$. The width for this is strictly zero (at the tree level), even when quark masses are taken into account, because the elementary amplitude which describes this decay is completely antisymmetric in the interchange of the momentum fractions carried by the quarks of each ϕ-meson, whereas the product of the two wave functions is completely symmetric. However, once again, the decay has been observed with a fairly large branching ratio. Clearly, diquarks cannot help when only mesons

are involved. Does this mean that other nonperturbative effects, as *e.g.* glueballs, should come into play?

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