NEW RESULTS FROM THE DIQUARK MODEL *

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The diquark model for exclusive reactions at moderately large momentum transfer is reviewed. This model is a modification of the Brodsky–Lepage picture in which diquarks are considered as quasi-elementary constituents of baryons. Recent applications of this model are discussed: weak and electromagnetic formfactors of baryons, Compton scattering, photoproduction of mesons and $p\bar{p}$ annihilations into pairs of heavy flavour hadrons.

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1. Introduction

Exclusive processes at large momentum transfer are described in terms of hard scattering among elementary constituents, in the framework of perturbative QCD [1]. This so-called hard scattering picture (HSP) in which a hadronic amplitude is described as a convolution of universal process independent distribution amplitudes (DA) with subprocess amplitudes, has two characteristic properties. In a reaction $AB \to CD$ the fixed angle cross-section behaves as

$$\frac{d\sigma}{dt}(AB \to CD) = f(\vartheta)s^{2-n_A-n_B-n_C-n_D}\,, \tag{1.1}$$

where n_I is the minimum number of constituents in particle I. Eq. (1.1) applies analogously to formfactors. These power laws are founded on a very

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general basis, namely dimensional counting [2]. QCD modifies them by powers on $\ln s$ arising from the running coupling strength α_s and from the evolution of the wave functions. The power laws seem to be in fair agreement with data although in detail deviations from (1.1) are to be observed. As an example the situation in elastic proton-proton scattering for which reaction the fixed angle cross-section should behave as s^{-10}, is displayed in Fig. 1. The actual power seems to be slightly smaller than 10.

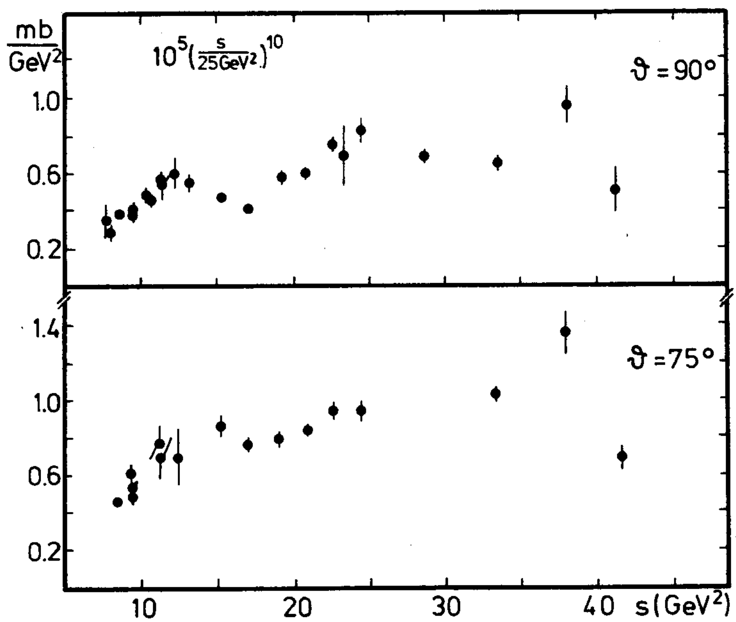

Fig. 1. The pp→pp differential cross-section at fixed cms scattering angle ϑ *vs.* s. Data are taken from [3].

The second property of the HSP is the conservation of hadronic helicity

$$\lambda_A + \lambda_B = \lambda_C + \lambda_D . \tag{1.2}$$

It appears as a consequence of dealing with (almost) massless quarks which conserve their helicities when interacting with gluons. The helicity sum rule is violated to about 20–30% by all experimental data. The large analysis power in elastic proton-proton scattering measured at Brookhaven [4] is a particularly striking example of such violations.

In explicit applications of the HSP one encounters the difficulty that the data are available only at moderately large momentum transfer, a region in which nonperturbative dynamics may still play a crucial role. A general feature of such applications is the extreme sensitivity to the DA's chosen for the hadrons involved. Only very asymmetric DA's like the one proposed by Chernyak et al. [5, 6] provide results which are at least for the electromagnetic formfactor of the nucleon in fair agreement with the data. This apparent success of the HSP is only achieved at the expense of strong contributions from soft regions where one of the constituents carries only a tiny fraction of its parent hadron momentum. This is a very problematic situation for a perturbative calculation. It should be stressed that none of the DA's used in actual applications leads to a common successful description of all the large $p_\perp$ processes investigated so far, namely nucleon formfactors, N–Δ transition formfactors, Compton scattering and photoproduction of mesons.

It seems clear from the above remarks that the HSP although likely to be the true asymptotic picture for exclusive reactions, needs modifications at moderately large momentum transfer. In a series of papers [7–14] such a modification has been proposed by us in which baryons are viewed as made of quarks and diquarks, the latter being treated as quasi-elementary constituents which partly survived medium hard collisions. Their composite nature is taken into account by diquark formfactors (vertex functions). Diquarks are an effective description of correlations in the wave functions and constitute a particular model of nonperturbative effects. The diquark model may be viewed as a generalization of the HSP appropriate for moderately large momentum transfer and is designed such that it turns into the pure quark model asymptotically. The existence of diquarks inside baryons is a hypothesis. However, from many experimental and theoretical approaches there have been indications suggesting its presence. A long time ago diquarks were introduced in baryon spectroscopy, see for instance Ref. [15]. Recently, they have been used in nuclear physics [16], in astrophysics [17] and in weak interactions to explain the $\Delta I = {}^1\!/_2$ rule [18]. The quark-diquark configuration is favoured by minimum energy arguments [19]. Diquarks also provide a natural explanation of the equal slopes of meson and baryon Regge trajectories.

Even more important for our aim, diquarks have also been found to play a role in inclusive hard scattering reactions. The most obvious place to signal their presence is deep inelastic lepton-hadron scattering. Indeed the combined SLAC and EMC structure function data demonstrate the need for higher twist terms; QCD evolution alone cannot account for the observed scaling violations at $x \geq 0.4$ [20]. This higher twist term may be modelled as lepton diquark elastic scattering. Fits provide a diquark formfactor parameter Q_S^2 =3.22 GeV^2 (see below). Baryon production in inclusive pp collisions also reveals the need for diquarks scattered elastically in the hard interaction [21].

In this article, I am going to discuss the rules of the diquark model (Section 2) and to present applications of the model to a number of reactions such as electromagnetic formfactors, Compton scattering or photoproduction of mesons, carried out recently by us (Section 3). The role of diquarks in the physics of heavy baryons is also briefly mentioned.

2 The diquark model

As in the HSP the helicity amplitude for a reaction $AB \to CD$ is expressed by a convolution of universal DA's with amplitudes $\hat{T}$ representing the scattering off constituents. The DA's specify the distribution of the longitudinal momentum fractions the constituents carry inside their parent hadrons. They are wave functions of constituent Fock states integrated over intrinsic transverse momenta. The convolution manifestly factorizes long (DA's) and short distance physics (constituent scattering). Explicitly, a helicity amplitude reads

$$M_{CDAB}(s,t) = \int dx_A dx_B dx_C dx_D \Phi_C^*(x_C)\Phi_D^*(x_D) \times \hat{T}(x_A, x_B, x_C, x_D, s, t)\Phi_A(x_A)\Phi_B(x_B), \qquad (2.1)$$

where helicity labels are omitted for convenience. Implicitly, it has been assumed in (2.1) that the valence Fock state consist of only two constituents, namely quark and diquark. In so far the specification of the quark momentum fraction x_i suffices; the diquark carries $1 - x_i$. Because of the QCD evolution the DA's depend logarithmically on $p_\perp$. This fact is of minor importance in the limited range of $p_\perp$ in which data are available and is as usual ignored. In case that one of the particles A, B, C or D is pointlike the accompanying DA is to be replaced by a δ function. As in the HSP contributions from higher Fock states are neglected. This is justified by the fact that such contributions are suppressed by powers of $\alpha_s/p_\perp^2$ as compared to those from the valence Fock state.

In the diquark model spin 0 (S) and spin 1 (V) diquarks are considered. Within flavour SU(3) the S diquarks form a$\{\bar{3}\}$ multiplet, the V diquarks a $\{6\}$. In terms of colour the diquarks may be either $\{6\}$ or $\{\bar{3}\}$ states. Only the latter ones can form ordinary baryons together with a quark. Therefore, the colour $\{6\}$ diquarks if they exist after all, are of no interest here.

The DA of an octet baryon B with helicity λ which is written as (omitting colour indices for convenience)

$$|B,\lambda\rangle = f_V\phi_V(x)\sum_{ij\nu} C_{\lambda\nu\sigma}^{Bij}|q_i\nu;\, V_j\sigma\rangle + f_S\phi_S(x)\sum_{ij} C_{\lambda\lambda 0}^{Bij}|q_i\lambda;\, S_j\rangle\,, \qquad (2.2)$$

where $\sigma = \lambda - \nu$ and the C's are appropriate Clebsch-Gordan coefficients. The two functions ϕ_S and ϕ_V for scalar and vector diquarks, respectively, denoted simply as the DA, are conventionally defined such that

$$\int_0^1 dx \phi_{S(V)}(x) = 1 . \qquad (2.3)$$

The constant f_S and f_V which may be interpreted as baryon decay constants, are in principle determined by the probability of the corresponding Fock state, either $|qS\rangle$ or $|qV\rangle$ and the k_T dependence of the wave functions belonging to it. Since for these constants only very rough estimates can be given they are in practice considered as free parameters to be adjusted when the model is confronted with experiment. The explicit form of a proton DA reads

$$\begin{aligned} |p, \pm\rangle = & \pm \tfrac{1}{3} f_V \phi_V(x) \big[|u\pm;\, V(ud)\, 0\rangle - \sqrt{2} |d\pm;\, V(uu)\, 0\rangle \\ & - \sqrt{2} |u \mp;\, V(ud) \pm 1\rangle + 2 |d \mp;\, V(uu) \pm 1\rangle \big] \\ & + f_S \phi_S(x) |u \pm;\, S\rangle . \end{aligned} \qquad (2.4)$$

Since we are treating diquarks as elementary objects, no attempt is made to antisymmetrize the wave function under the interchange of any two quarks in the system. Interference terms resulting from antisymmetrization are often not important [15]. If $\Phi_V = \Phi_S$ and $f_V = f_S$ and if the diquarks are replaced by the quarks they are made of Eq. (2.3) represents the usual SU(6) wave functions of baryons.

The DA's controlled by long-distance physics, cannot reliably be calculated from QCD although a few attempts have been performed [22, 23]. It is still necessary to make educated guesses for the DA's and to compare with experiment. Hence, both the models, the HSP as well as the diquark model, only get predictive power when a number of reactions involving the same hadrons, are investigated. In the diquark model the following DA has been proven to work satisfactorily well in many applications

$$\phi_S(x) = \phi_V(x) = Ax(1-x)^3 \exp\Big[-b^2 \Big(\frac{m_q^2}{x} + \frac{m_D^2}{(1-x)} \Big) \Big] . \qquad (2.5)$$

This DA is a suitable adaptation of a meson DA obtained by transforming the harmonic oscillator wave function to the light cone [24]. The DA exhibits a flavour dependence *via* the exponential which also guarantees a strong suppression of the end-point regions. The masses in Eq. (2.5) are constituent masses since they enter through a rest frame wave function. For u and d quarks we take 330 MeV whereas for the diquarks 580 MeV is used [15]. Strange quarks and diquarks are assumed to be 150 MeV heavier than the non-strange ones.

The full wave function has a k_T dependence

$$\sim \exp\left[-b^2\frac{k_T^2}{x(1-x)}\right], \tag{2.6}$$

which allows to fix the oscillator parameter b such that $\sqrt{\langle k_T^2\rangle} = 600$ MeV as found for instance by the EMC [25] in a study of the transverse momentum distribution in semi-inclusive deep inelastic μp scattering. Actually b is taken to be 0.498 GeV^{-1}.

To demonstrate the influence of the DA chosen alternatives to (2.5) have also been utilized. With the rather poor quality and quantity of the large $p_\perp$ data at our disposal the DA's, even that of the nucleon, cannot be regarded as being well determined. The DA (2.5) works sufficiently well. With more and better data it may turn out that a more refined DA is needed. Polarization data are most efficient for that purpose. The elementary amplitudes $\hat{T}$ determined by short-distance physics, are calculated for a given process from a set of Feynman diagrams. Diquark–gluon vertices appear which, following standard prescriptions, are defined by

$$\mathrm{S}g\mathrm{S}: \; -ig_s\frac{\Lambda^a}{2}(q_1+q_2)_\mu\,, \tag{2.7}$$

$$\begin{aligned}\mathrm{V}g\mathrm{V}: \; & -ig_s\frac{\Lambda^a}{2}\{(q_1+q_2)_\mu g_{\lambda\nu} - ((1+\kappa_{\mathrm{V}})q_{2\lambda} - \kappa_V q_{1\lambda})g_{\mu\nu} \\ & - ((1+\kappa_{\mathrm{V}})q_{1\nu} - \kappa_{\mathrm{V}} q_{2\nu})g_{\lambda\mu}\}\,,\end{aligned} \tag{2.8}$$

where $g_s = \sqrt{4\pi\alpha_s}$ is the coupling constant of QCD. κ_{V} is the magnetic moment of the V diquark and Λ the Gell-Mann colour matrix. Other notations should be obvious. The generalization to photons instead of gluons is also obvious. Gauge invariance requires contact terms which have also to be taken into consideration.

In applications of the diquark model at moderately large momentum transfer Feynman diagrams are evaluated with these rules for point-like particles. In order to take care of the composite nature of the diquarks phenomenological vertex functions have to be introduced. Advice for the parametrization of the 3-point functions, ordinary diquark formfactors, is obtained from the requirement that asymptotically the diquark model evolves into the HSP of Brodsky–Lepage. Bearing this in mind the formfactors are actually parametrized as

$$F_{\mathrm{S}}(Q^2) = \delta\frac{Q_{\mathrm{S}}^2}{Q_{\mathrm{S}}^2+Q^2}\,, \tag{2.9}$$

$$F_{\mathrm{V}}(Q^2) = \delta\Big(\frac{Q_{\mathrm{V}}^2}{Q_{\mathrm{V}}^2 + Q^2}\Big)^2, \tag{2.10}$$

with $\delta \simeq 1$. Besides the simple DgD vertices four- and in some cases five-point functions also appear in applications of the diquark model. The corresponding phenomenological vertex functions are parametrized in accordance with the required asymptotic behaviour, as ($n = 4$, 5)

$$F_{\mathrm{S}}^{(n)}(Q^2) = a_{\mathrm{S}} F_{\mathrm{S}}(Q^2), \tag{2.11}$$

$$F_{\mathrm{V}}^{(n)}(Q^2) = a_{\mathrm{V}}\delta\Big(\frac{Q_{\mathrm{V}}^2}{Q_{\mathrm{V}}^2 + Q^2}\Big)^{n-1}. \tag{2.12}$$

The $a_{\mathrm{S,V}}$ are strength parameters. There is no reason why they should be 1. Indeed, since the diquarks in the intermediate states are rather far off-shell one has to consider the possibility of diquark excitation and break-up. Both these cases would likely lead to particle production and, therefore, do not have to be considered explicitly. But excitation and break-up lead to a certain amount of absorption which is taken into account by the strength parameters.

3. Applications

The diquark hypothesis has striking consequences. It reduces the effective number of constituents inside baryons and, hence, alters the power law, Eq. (1.1). In a baryon–baryon reaction, for instance, the usual power s^{-10} becomes

$$\frac{d\sigma}{dt} \sim s^{-6} F(s), \tag{3.1}$$

where F is generic for the effect of diquark formfactors. Asymptotically, F provides the missing 4 powers of s. In the region of moderately large momentum transfer ($p_\perp^2 \geq 4$ GeV^2) in which the diquark model can be applied, the diquark model can be applied, the diquark formfactors are already active, *i.e.*they supply a substantial s-dependence. The diquark model predictions, therefore, lie somewhere between the powers 10 and 6. This is consistent with the data for pp scattering, see Fig. 1. Another example is the magnetic formfactor of the proton for which quite clearly the transition from $G_M^{\mathrm{p}} \sim Q^{-2}$ (diquark model) to $G_M^{\mathrm{p}} \sim Q^{-4}$ (HSP) is to be observed.

The hadronic helicity is not conserved at finite momentum transfer since vector diquarks may flip their helicities when interacting with gluons. Thus, in principle, spin-flip dependent quantities like the polarization in elastic pp scattering or the electric nucleon formfactors can be calculated.

In explicit applications of the diquark model hadronic amplitudes (or form factors) are to be calculated from the convolution (2.1), the elementary ones from diagrams such as shown in Fig. 2. The blobs appearing at the diquark vertices represent n-point functions (n=3, 4, 5). In the region of moderately large momentum transfer the blobs are evaluated in lowest order for point-like diquarks according to the couplings (2.7), (2.8) and multiplied by the appropriate phenomenological vertex functions (2.9)–(2.12).

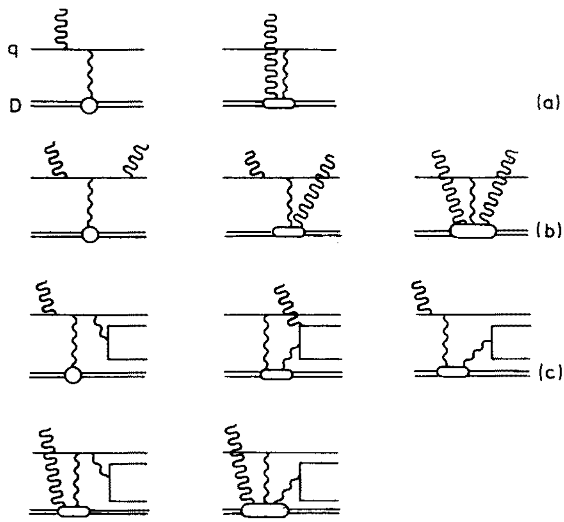

Fig. 2. Representative diagrams contributing to electromagnetic formfactors (a), Compton scattering (b) and photoproduction of mesons (c).

3.1. Electromagnetic formfactors of the nucleon [11]

This is the simplest application of the diquark model. Representative diagrams for the elementary subprocesses γ^*qD→qD are shown in Fig. 2a. All together one has to compute 5 diagrams for each of the two diquarks, S and V. For the DA the harmonic oscillator one (2.5) is used. The data on the 4 quantities, the magnetic and electric formfactors of the proton and neutron, respectively, are fitted with this ansatz for $Q^2 \geq 4$ GeV^2 and the parameters of the diquark model are determined. The following set of parameters

$$\begin{aligned} Q_S^2 &= 3.22\,\mathrm{GeV}^2\,, & Q_V^2 &= 1.58\,\mathrm{GeV}^2\,, \\ f_S &= 66.1\,\mathrm{MeV} & f_V &= 120.2\,\mathrm{MeV}\,, \\ a_S &= a_V = 0.286\,, & \kappa_V &= 1.16 \end{aligned} \qquad (3.2)$$

provides good fits to the data. G_M^p is perfectly reproduced, the ratio G_M^n/G_M^p is about -0.3. Interesting predictions for the electric form factors are obtained. It would be of utmost importance to have at disposal some accurate data for them in the Q^2 region of interest in order to examine these predictions. It should be stressed that in the HSP no prediction for the electric formfactors can be given because these formfactors require helicity flips of the nucleon.

Making use of Eq. (2.2) the formfactors of hyperons can be calculated free of parameters [13].

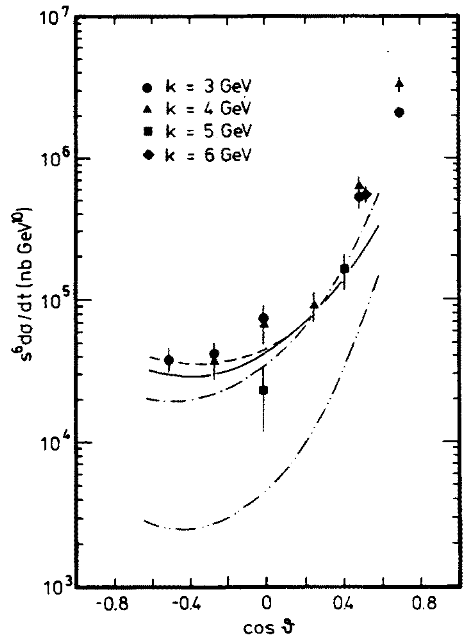

Fig. 3. The Compton cross-section *vs.* $\cos\vartheta$ for various photon energies. Data taken from Ref. [28]. Solid (dash-dotted) line: predictions of the diquark model using the DA (2.5) and the parameters listed in (3.2) at 4 (10.2) GeV. Dashed line: results obtained with another DA. Dash-dot-dotted line: predictions of Ref. [27].

3.2. Compton scattering [10]

The reaction $\gamma p \to \gamma p$ (as well as $\gamma\gamma \to p\bar{p}$ by crossing) can now be predicted, no freedom is left. $2\times$ 32 diagrams contribute to the lengthy and complicated calculation. Still fairly simple expressions are found for the Compton helicity amplitudes. They exhibit an interesting behaviour: The nucleon flip amplitudes $M_{-1-\frac{1}{2},1+\frac{1}{2}}$, $M_{+1-\frac{1}{2},1+\frac{1}{2}}$ and $M_{-1+\frac{1}{2},1-\frac{1}{2}}$

are non-zero; they are fed by subprocesses involving V diquarks. At fixed angle and large s the helicity amplitudes behave as

$$M_{+1+\frac{1}{2},1+\frac{1}{2}} \quad M_{+1-\frac{1}{2},1-\frac{1}{2}} \sim s^{-2},$$
$$M_{-1+\frac{1}{2},1+\frac{1}{2}} \sim s^{-3},$$
$$M_{-1-\frac{1}{2},1+\frac{1}{2}}, \quad M_{+1-\frac{1}{2},1+\frac{1}{2}}, \quad M_{-1+\frac{1}{2},1-\frac{1}{2}} \sim s^{-5/2}. \tag{3.3}$$

Thus an interesting spin dependence of Compton scattering is predicted. Of particular interest is that a sizeable (order of 10%) transverse polarization of the proton is found. Two ingredients are needed for a non-vanishing polarization, helicity flips and phase differences between flip and non-flip amplitudes. The first one is obtained from V diquarks as has been mentioned before. In the HSP the flip amplitudes are zero. The second ingredient, the phases, are generated from diagrams where the 2 photons are attached to different constituent lines. This holds true for both the models, the diquark model and the HSP [26, 27]. In such diagrams propagator poles appear within the range of integration. The accompanying singularities are regulated in the usual way by employing the prescription

$$\frac{1}{z \pm i\epsilon} = P\left(\frac{1}{z}\right) \mp i\pi\delta(z). \tag{3.4}$$

It turns out that, not surprisingly, the predictions for the polarization are very sensitive to the DA used. For that reason one should not take the exact values of the polarization literally; we do not know that well the DA. Rather one should understand this prediction as an example that the diquark model combining perturbative and nonperturbative physics, seems to constitute a promising method to describe transverse polarizations. No other model based on constituent scattering is in position to do that. In Fig. 3 predictions for the unpolarized Compton cross-section are compared to the data. Fair agreement between both is to be observed.

3.3. Photoproduction of mesons

This is a large class of reactions and once the new pieces entering here, namely the DA's of the mesons are fixed severe tests of the diquark model can be carried out. Due to SU(6) only one DA for the octet of pseudoscalar mesons, and perhaps another one for the vector mesons, should appear. The DA of the pseudoscalar mesons is fairly well known from studies of the pion formfactor. Many diagrams contribute (*cf.* Fig. 2c), in fact 2×63. The investigation of that class of reactions has just started, it is not yet finished.

Schürmann has computed the amplitudes for scalar diquarks [29]. Fortunately, this already suffices to compare with data. The process $\gamma p \to K\Lambda$ can only proceed through S diquarks, since the p and the Λ have in common only the S(ud) one. Using for the K the simple DA

$$\Phi_K \sim x(1-x) \tag{3.5}$$

eventually modified by exponentials like that one given in Eq. (2.5) and applying [30]

$$f_K = 1.2 \frac{f_{\rm dec}^{\pi}}{2\sqrt{3}}, \tag{3.6}$$

where $f_{\rm dec}^{\pi}(= 92.8\ \mathrm{MeV})$ is the π decay constant, he finds a cross-section which nicely agrees with the data (see Fig. 4). This may be regarded as a big success of the diquark model. The HSP does not lead to similarly good results [32].

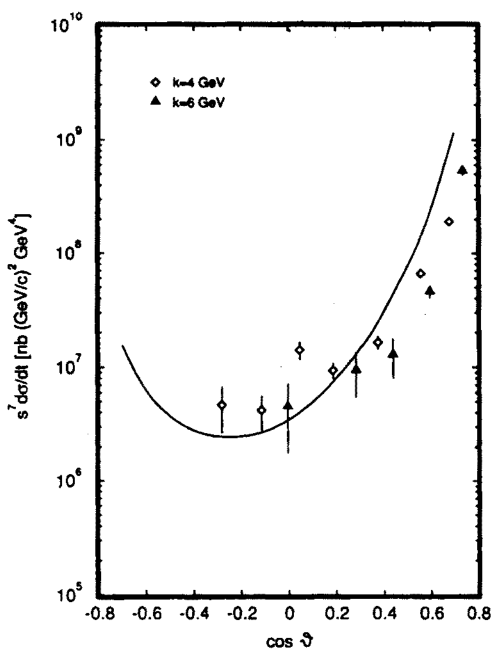

Fig. 4. Predictions of the diquark model for the reaction $\gamma p \to K\Lambda$. Data taken from Ref. [31].

As in Compton scattering phase differences between flip and non-flip amplitudes appear. Nevertheless, since to $\gamma p \to K\Lambda$ only S diquarks contribute the flip amplitudes and consequently the polarizations of the proton and of the Λ are zero. This has to be contrasted with the reaction $\gamma p \to K\Sigma^0$

which proceeds through V diquarks. In this case the helicity flip amplitudes are not necessarily zero and the p and the Σ^0 are expected to be polarized.

3.4 Electromagnetic transition formfactors [12]

This investigation parallels that of the nucleon formfactors. The same elementary diagrams contribute (Fig. 2a). The new elements needed here are the DA's of the nucleon resonances. The transition formfactors cannot, therefore, be predicted. Rather their analysis serves the purpose of determining these DA's. Other processes like $\gamma p \to \pi\Delta$ may thereafter be investigated without any arbitrariness. Nevertheless, the analysis of transition formfactors is by no means trivial. DA's should look reasonable and not be too different from that of the nucleon. The corresponding constants f should be of the order of f_S, f_V.

Indeed, for the N$\to S_{11}(1535)$ formfactor for which some data at moderately large Q^2 are available [33], this concept works very well. For the N $\to \Delta$ transition on the other hand there seems to exist a little problem. The data [33, 34] in the 3–10 GeV^2 region seem to suggest a drastic decrease of $Q^4 G_{N\Delta}$ with Q^2 of the quantity

$$Q^4|G_{N\Delta}| = Q^4\left(G_M^{N\Delta 2} + 3G_E^{N\Delta 2} + \frac{Q^2}{m^2}\epsilon G_C^{N\Delta 2}\right)^{1/2} \qquad (3.7)$$

(G_M, G_E and G_C are the magnetic, electric and Coulomb formfactors, respectively; ϵ is a kinematical expression with a value $\ll 1$ at large Q^2) in sharp contrast to the behaviour of, say, $Q^4 G_M^p$. Does this indicate the existence of strong nonperturbative contributions to the N $\to \Delta$ formfactors? However, a word of caution is advisable: analyses based on old and new SLAC ep$\to$ eX data lead to different results [33]. The decrease of $Q^4 G_{N\Delta}$ is much less dramatic in the old SLAC data, it is almost compatible with a constant behaviour. Moreover, Stoler claims that in his analysis only the contributions of transversal photons (*i.e.*, G_M, G_E) to $G_{N\Delta}$ are considered. But it is not clear what happens to eventual contributions from the Coulomb formfactor. They may perhaps contaminate $G_{N\Delta}$, a fact that makes the phenomenological analysis of the N $\to \Delta$ formfactors difficult. It turns out that the magnitude of $G_{N\Delta}$ causes no problem for the diquark model (with $f_\Delta = \sqrt{2f V}$). A constant or even slightly dropping behaviour of $Q^4 G_{N\Delta}$ is easily obtained with reasonable DA's. A strong decrease, on the other hand, as the analysis of Stoler seems to indicate, is possible but at the expense of a Φ_Δ being very different from that of the nucleon. In this case G_C is rather large contrary to common believe. More and better data are needed before this issue can be regarded as being settled. Separate information on the three formfactors would be highly welcomed.

3.5. Weak transition formfactors of heavy baryons [14]

Recently, the properties of QCD in the heavy quark limit are subject of much interest see for instance Refs [35, 36]. In this limit which precisely means that the mass and the momentum of a heavy quark (c, b and eventually t) are let go to infinity such that their ratio, namely the velocity v^μ, is kept fixed, QCD experiences great simplifications. In fact, it leads to a new SU(2)×SU(2) spin flavour symmetry for the heavy quark degrees of freedom. This symmetry has a lot of implications: it may lead to a better determination of the Kobayashi–Maskawa matrix, it may be relevant in the analysis of CP violations and so on.

The diquark model can be used to calculate the tail of such formfactors at moderately large Q^2. The simplest example is the process

$$\Lambda_{\rm b} \to \Lambda_{\rm c} e^- \bar{\nu}_e \,. \tag{3.8}$$

The $\Lambda_{\rm f}$ is regarded as a bound state of a heavy quark with flavour f and a S(ud) diquark

$$|\Lambda_{\rm f}, \lambda\rangle = f_{\rm f} \Phi_{\rm S}(x_1, {\rm f}) |{\rm f}, \lambda; {\rm S}\rangle \,. \tag{3.9}$$

Charmed or bottomed diquarks are not assumed to exist contrary to strange diquarks (see Eq. (2.2)). For the DA of a $\Lambda_{\rm f}$ one may again use the harmonic oscillator function (2.5) or a similar one proposed by Wirbel et al. [37] which has some theoretical advantages for the purpose considered here. The elementary amplitudes have to be computed from the diagrams shown in Fig. 2a with the photon replaced by the W. Obviously, only those diagrams contribute where the W is attached to the heavy quark line. Quark masses have to be taken into account properly.

Detailed studies reveal the surprising result that the transition formfactors divided by $f_{\rm b} f_{\rm c}$ have all the properties of the heavy quark theory: In the limit of $M_{\rm b}$, $M_{\rm c} \to \infty$ only one independent universal (*i.e.*heavy quark mass independent) function determines the six weak transition formfactors. In contrast to the general considerations made by Isgur and Wise [36] this function is specified in the diquark model. Corrections for finite quark masses obtained in the diquark model are in agreement with those found by Georgi et al. with the aid of the effective theory [38]. Similar results have been obtained for the transitions $\Sigma_{\rm b} \to \Sigma_{\rm c}(\Sigma_{\rm c}^*)$. With the diquark model one may also calculate weak transitions involving light quarks such as the process $\Lambda_{\rm c} \to \Lambda_{\rm s}$.

3.6. Proton–antiproton annihilation into pairs of heavy flavour baryons and mesons [8, 9]

These are purely hadronic reactions and in principle as complicated as, say, elastic pp scattering. However, they require an annihilation of a light $q\bar{q}$ pair and a subsequent creation of a heavy $f\bar{f}$ pair. It is reasonable, at least for c and b quarks, to assume this annihilation process to be dominant even at small momentum transfer. The hard scale is set by s, instead of $p_\perp$. For kinematical reasons s is larger than $4m_f^2$ ($\gg \Lambda_{QCD}^2$). The model is basically described by the diagram shown in Fig. 5. It is a generalization of the Drell–Yan model for formfactors [39, 40]. To an acceptable approximation a helicity amplitude for the hadronic process can be written as a product of an elementary amplitude — to be calculated from the annihilation diagram — and the square of an overlap integral ($\vec{\Delta}^2 = -t$)

$$F(s,t) = \int d^2k_\perp dx \Theta(xp - m_f) \Psi^*_{bf}(x, \vec{k}_\perp + (1-x)\vec{\Delta}) \Psi_p(x, \vec{k}_\perp) \,. \quad (3.10)$$

Contrary to the applications discussed above the full wave functions are needed, for instance the harmonic oscillator DA (2.5) multiplied by the $k_\perp$ dependence (2.6) (or simply by $\exp(-b^2k_\perp^2)$ [37]). On the basis of that model realistic predictions for the cross-sections of the reactions $p\bar{p} \to \Lambda_c\bar{\Lambda}_c, \Lambda_b\bar{\Lambda}_b, \Sigma_c\bar{\Sigma}_c \ldots$ have been given, assuming a heavy baryon state to be represented by (3.9). Allowing for diquark–antiquark annihilation and subsequent creation of a $f\bar{f}$ pair, cross-sections for $p\bar{p} \to D\bar{D}, B\bar{B}$ can also be calculated. These predictions may be tested by experiments performed at future accelerators like the SUPERLEAR.

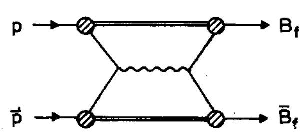

Fig. 5. The basic diagram for the annihilation processes.

4. Concluding remarks

Extending the model to s quarks although in this case the basic assumption is on less sound grounds but perhaps still reasonable, one may also calculate cross-sections for the production of hyperon–antihyperon pairs. Essential is that both the superprocesses, $q\bar{q} \to s\bar{s}$ and $D\bar{D} \to D_s\bar{D}_s$, have to be taken into account. Single (*e.g.*$p\bar{p} \to \Lambda\bar{\Lambda}$) and double (*e.g.*$p\bar{p} \to \Sigma^-\bar{\Sigma}^-$)

annihilation reactions have been calculated and found to be in reasonable agreement with the data.

A modification of the HSP for exclusive reactions is presented in some detail for which guided by many experimental results and theoretical investigations, the presences of diquarks among the constituents of baryons is assumed to hold at moderately large momentum transfer. Asymptotically, *i.e.*for very large momentum transfer, diquarks are resolved into quarks and the usual HSP emerges. Diquarks may be viewed as an effective description of correlations in the baryon wave function and constitute in so far a model for nonperturbative effects which are known to play a role at moderately large momentum transfer.

The diquark model has been applied to a number of photon-proton reactions and to a few other processes like semi-leptonic decays of heavy baryons. With a common set of parameters and common DA's a successful description of this quite large number of reactions has been accomplished.

The investigation of purely hadronic reactions like elastic proton-proton scattering would be very interesting. However, the calculation of such reactions is extremely time-consuming. Moreover, one has to face a complication for purely hadronic reactions, namely the occurrence of multiple scatterings, *i.e.*, the possibility that pairs of constituents scatter independently in contrast to the amplitude (2.1) in which all constituents collide in a small region of space time.

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