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THEORY AND PHENOMENOLOGY OF THE QCD VACUUM

6. HADRONIC STRUCTURE AND HADRONIC REACTIONS

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НОВОСИБИРСК

ABSTRACT

This preprint contains discussion of some aspects of hadronic structure relevant for the theory of QCD vacuum. In section 6.1 we discuss the so-called quark effective mass, appearing due to SBCS. We emphasize that it develops at distances, being several times smaller than hadronic dimensions. It is suggested that this observation explains existence of hadronic substructure in form of «additive» constituent quarks. In section 6.2 we discuss quark-quark interactions, with emphasis on the instanton-induced effects at intermediate distances. Sections 6.3 and 6.4 are devoted to comments on the current literature on «hard» and «soft» hadronic reactions.

6. HADRONIC STRUCTURE AND REACTIONS

The title of this chapter sounds very general, so it is probably necessary from the start to emphasize that we are not going to review this vast area of strong interaction physics. In fact it contains some set of comments on recent theoretical ideas and experimental discoveries which have some connection to theory of the QCD vacuum considered above. The central topics to be discussed are connected with the interplay of confinement and SBCS effects, as well as with the dependence on the quark masses.

In section 6.1 we concentrate on the problem of the so-called quark effective mass, using the main qualitative conclusions following from applications of QCD sum rules considered in the preceeding chapter. Many phenomenological facts leading to nonrelativistic (or even quasinuclear) picture of hadrons are not new, but only recently they were connected with observations that nonperturbative effects in vacuum seem to have at least two different scales. In particular, the nonperturbative interaction of light quarks with vacuum takes place at relatively small distances and are connected with the quark condensate, where confinement effects are not still important (in applications of sum rules considered in chapter 5 they were never included). These observations qualitatively suggest formation of relatively small constituent quarks with some effective mass, which mainly determines hadronic masses.

In section 6.2 we discuss current ideas concerning quark interactions. At small distances we know that one-gluon exchange dominates, while at large one confinement forces are believed to produce a kind of the «string» between quarks, leading to famous linear potential. However we are going to emphasize that in addition to these known mechanisms there exists also the third important component in the quark interaction generated by the instanton-induced effects and most effective at some intermediate distances.

In section 6.3 we make remarks on recent progress in the theory of hard hadronic reactions, being a traditional field of application of perturbative QCD for evaluation of the so-called gluon radiative corrections. However, we concentrate on other questions connected with the main characteristics of hard process, the structure functions for inclusive lepton scattering and the «wave functions» for exclusive reactions. These quantities are determined by the nonperturbative physics and are not much discussed in theoretical literature, because methods of their evaluations are not so far developed. However, as we have already mentioned in section 5.4, the moments of the «wave functions» can be evaluated by sum rules. The moments of structure functions can in principle be found by technique similar to that used for the evaluation of baryonic magnetic moments (see section 5.5).

Finally in section 6.4 we discuss related problems connected with soft hadronic reactions, in which «additivity» (or independence) of constituent quarks is most clearly seen even in total cross sections. Recently more convincing arguments came from studies of hadron-nuclei collisions.

Completing this introduction I would like to make the following general remarks. In spite of huge amount of empirical information, hadronic structure and reactions are rather poorly understood. Twenty years ago the quark model have initiated progress in this field, and about ten years ago ideas of perturbative QCD have played similar role. Unfortunately, the available methods of nonperturbative QCD are so far not well suited for their applications in this field. Nevertheless, many parameters of interest can already be evaluated by indirect methods (e.g. the sum rules). And also one can not ignore main qualitative conclusion drown from these studies (e.g. on the very important role of chiral symmetry breaking effects). The new type of interactions (e.g. the instanton-induced ones) should probably be included in development of the phenomenological models. In short, new ideas in nonperturbative physics are now becoming useful, so the experts in this field should probably follow them more closely.

6.1. Effective quark mass and the two-scale hypophesis

The pioneer works by Gell-Mann and Zweig [6.1, 6.2] have suggested that «hadrons consist of quarks». The word «consist» should be specifyed somewhat more definitely. Its first and widely used meaning is that one can easily understand flavour quantum numbers and classify hadrons in SU(3) multiplets. However, in various quark models of hadrons developing since early sixties this word is understood in more straightforward meaning, similar to that in the statement that «nuclei consist of nucleons». In other words, it is assumed that quarks are some meaningful objects present in the fixed number, in terms of which one may formulate dynamics of the system. .

It should be emphasized from the start that there are observations supporting such nonrelativistic approach to hadronic structure. To give a couple of examples let me mention that it is the nonrelativistic classification which explains why hadrons with «natural» parity $P=(-)^{j+1}$ are lighter than those with «unnatural» one: the latter are «orbital excitations». Also magnetic moments of baryons are traditionally described well enough if one assumes that they are connected with only spin part of the wave function, without any references to orbital momentum.

However, if one considers this problem from the theoretical side, at first sight he does not find any reasons for this picture to take place. As we have discussed in the chapter 1, quark masses present in the QCD Lagrangian are very small, about few MeV, and it is unclear why it is so difficult to create extra pair of them or why their motion may be so slow that nonrelativistic considerations make sense.

In order to reconcile these facts it was suggested in Refs [6.3—6.5] to distinguish two types of objects:

1. «Current quarks», being the elementary (and pointlike) objects of field theory, seen explicitely in various hard processes.
2. «Constituent quarks», being some clusters (or «quasiparticles») inside hadrons with complicated internal structure. They are assumed to have some «effective mass» and therefore to move nonrelativistically. This effective mass is estimated to be of the order of $M(meson)/2$ or $M(baryon)/3$.

Existence of such clusters was completely misterious, and in some recent models (like the MIT bag model) this assumption is not made, leaving a lot of questions open.

The interest to this long-standing problem was renewed with the development of the sum rule method. Starting from small distances and «current» quarks we proceed to larger ones in hope to understand hadronic structure, or at least to connect it to that of the QCD vacuum. As we have stressed above, splitting of different parity states takes place if one takes into account the quark condensate effects. It is intriguing that it indeed takes place at distances several times smaller than confinement length.

Discussing connections between the quark condensate and the quark «effective mass» we may note that even in the pioneer works [1.34] the nonzero effective mass («the gap» in the excitation spectrum) in the asymmetric phase was suggested, driven by the analogy with superconductivity. However, this point becomes obscured due to confinement effects, completely excluding quarks from the physical spectrum.

The idea to start with small distances using the OPE was first suggested by Politzer [1.36] who has considered the contribution to quark proragator generated by the diagram shown at Fig.1 and has obtained the following result:

$$M_{eff}(q) \xrightarrow[q^2\to\infty]{} 16\pi\alpha_s\langle\Psi\Psi\rangle/q^2 \qquad (6.1)$$

Dependence on q and proportionality to the quark condensate looks reasonable, but unfortunately this expression can not have direct physical meaning because it depends explicitely on the gauge used for the virtual gluon. This defect is easily traced to the fact that the propagator itself is gauge dependent, and in order to get rid of it one should consider correlators of gauge invariant operators. (By the way, Vainshtein and Zakharov have told me that it was discussion of this point which has triggered their sum rule programm.)

Another defect of the expression (6.1) is that it is not clear whether the virtual gluon in it is indeed needed. As an example (suggesting the negative answer to this question) let me consider the problem already discussed in section 4.2, namely the mesons consisting of one light («dynamical») quark and one very heavy («static») antiquark, the latter needed in order that gauge invariance be kept intact. We remind that the result for leading power correction to the relevant correlator was obtained very simply, taking into account the regular part of the quark propagator at $x\to 0$, namely:

$$S(x) = -\frac{\hat{x}}{2\pi^2x^4} - i\langle\Psi\Psi\rangle + \dots \qquad (6.2)$$

Now, let us make (somewhat artifitial, though) comparison of this expression with the fermion propagator expansion up to first power of mass:

$$S(x) = -\frac{\hat{x}}{2\pi^2x^4} + \frac{im}{4\pi^2x^2} + O(m^2) \qquad (6.3)$$

obtain the following coordinate-depending «effective mass»:

$$M_{eff}(x) = -4\pi^2x^2\langle\Psi\Psi\rangle \qquad (6.4)$$

In order to gain insight where this effect becomes relevant we may mention that it reaches the phenomenological constituent mass value as early as at x∼ .1 fermi!

Note that existence of this small scale is essentially due to large geometrical factor $4\pi^2$, demonstrating that in 4-dimensional space-time a quark emitted by one current is soon mixed with others in QCD vacuum. Note also, that in cases considered in sections 5.2, 5.3 contribution of the simple term (6.2) is proportional to quark mass and is relatively small, so the quark condensate affects the correlators starting with some four-fermion operators. However, this also happens at small distances mentioned, because large geometrical factor is present in this case as well.

Now we remind ideas underlying the quasinuclear hadronic models: constituent quarks inside hadrons are of relatively small dimensions [6.4] as compared to those of hadrons. This, in turn, allows one to understand why the OPE-type sum rule method may produce the hadronic masses, although it is based on the evaluation of the correlators at distances essentially smaller than hadronic size and the effects taken into account are not directly connected with quark confinement. The proposed explanation is that effective mass is formed already at such distances and that it is the main ingredient of hadronic masses.

In order to complete discussion of hadronic structure let us also consider larger distances between quarks, at which the general OPE analysis does not work. In this case one has to assume something about the vacuum structure. An interesting extreme case emerges if the vacuum contains only the small size fluctuations (say, the instantons of definite size ϱ_c). In this case the intermediate distances x between the quark paths in space time are such that

$$\varrho_c \ll x \ll R\,(confinement)$$

The former inequality suggests that these quarks do not interact with the same instantons but rather with different ones, appearing on their way. In some approximation such interactions may become «additive» (or independent). The latter inequality ensures that such additivity is not much affected by «strings» between quarks, representing confinement forces. Schematic picture of these interactions as a function of quark separation is shown at Fig.2. Although there is not much space for the two inequalities in (6.5) to be fulfilled (ϱ_c and R are different only by the factor 3 in the «instanton liquid» model) it should be stressed that usual separation of quarks in hadrons are indeed in these limits.

At the same time one should not forget that such quark additivity is very approximate at best, and even in the model with only small size instantons in it there appear also correlations of neighbouring instantons, as well as specific quark interactions, to be considered in the next section.

The last point we adress in this section is the flavour dependence of the quark effective mass. Probably the most interesting information on this topic come not from (rather uncertain) mass formulae, but from investigations of quark magnetic moments. The ratio of magnetic moments of strange and nonstrange quarks is very well fixed from several sources, in particular analysis of baryonic magnetic moments [6.18] leads to the value 0.663 ± 0.005 while the recent experiment [6.18] measuring the relative probability of $\varphi\to\eta\gamma$ and $\omega\to\pi\gamma$ decays suggests for it the value 0.66 ± 0.04. Assuming that this ratio is inversely proportional to quark effective masses one may conclude that

$$M_{eff}(nonstrange)/M_{eff}(strange)=0.65\text{—}0.7 \qquad (6.5)$$

We remind that in section 5.7 similar ratio has entered the discussion of SU(3) violating effects for the pseudoscalar current correlator, and with the «instanton liquid» model it was indeed estimated to be close to this number.

6.2. Interaction between quarks

At small distances between quarks the one-gluon exchange dominates. This is most clearly seen for heavy quarkoniums, which are in many respects nearly Coulomb systems [6.20]. Unfortunately, the available c, b quarks are not sufficiently heavy. Probably the best illustration to this statement is the fact that in many potentials successfully applyed to their spectroscopy the Coulomb-type term is omitted completely (see Refs [6.23—6.25] and multiple references therein). Nevertheless, the special analysis (see e.g. [6.30]) may reveal its role and even approximately give estimates for $\Lambda_{\overline{MS}}$ to be 250 ± 100 MeV.

Relativistic effects are somewhat more concentrated at smaller distances, so it is reasonable to look at spin-dependent forces [6.6]. For one-gluon exchange they have the following structure

$$V_{spin-spin}\sim(\sigma_1^m\sigma_2^m)\,(t_1^at_2^a) \qquad (6.6)$$

and it surprisingly well describes spin splittings even for hadrons made of light quarks, see e.g. MIT bag model calculations [6.12] and also more general analysis [6.7].

Coming to nonperturbative interactions between quarks inside hadrons we remark that the framework used in this section is quite different from that considered in chapters 4 and 5. There are no currents which may single out space-time scale of interest, so there is no place for OPE-type analysis. Even if spatial dimensions of the system are small (as it takes place for very heavy quarkonia), one has infinite duration over the time axis. However, Voloshin and Leutwyler [6.29] have applied in the latter case the ordinary multipole expansion, using the fact that vacuum fields are in this case relatively weak. As an example of their results let me mention the mass shift

$$m_n=2m_Q-\frac{K_n^2}{m_Q}\left[1-\frac{m_Q^2}{72K_n^6}n^2a_n\langle(gG)^2\rangle\right]$$

$$K_n\equiv\frac{m_Q}{n}\cdot\frac{2}{3}\alpha_s(K_n)\,,\qquad a_1=1.65\,,\qquad a_2=1.78\ \ldots \qquad (6.7)$$

which is expressed in terms of the gluon condensate. Only local (in time) vacuum parameter is present here, because for superheavy quarkonia the dipole moment fluctuates with frequency being much larger than those typical for vacuum fields.

For ordinary hadrons so general approach can not be used, so one should include some models. Let us now consider predictions on the quark interactions which follow from the instanton-based models. In Ref. [6.8] it was noted that for the intermediate distances (6.5) typical for ordinary hadrons one may neglect the instanton dimensions ϱ_c and consider t'Hooft interaction between quarks as being generated by the local Lagrangian (2.41). It is emphasized in [6.8] that in principle it can be used not only in Euclidean formulation, where it was derived, but also extrapolated to Minkowski space and incorporated in various hadronic models. The difficult problem here is to modify this Lagrangian in order to include in it the effect of chiral symmetry breaking. Approximately it can be made just by its averaging over vacuum state, accounting for nonzero quark condensate. As a result, it includes not only some vertex with $2N_f$ quark lines, but there appear also vertexes with 2, 4, ... lines. The former effect is just the «effective mass» term

$$L_2=M_{eff}\cdot\bar{\Psi}\Psi\,,\qquad M_{eff}\simeq-\frac{2n_+}{\langle\Psi\Psi\rangle}\sim200\ \text{MeV} \qquad (6.8)$$

while the four-fermion one is the quark interaction under consideration (where $q_{R,L}=(1\pm\gamma_5)/2q$):

$$L_4=\lambda_{ud}(\bar{u}_R u_L)(\bar{d}_R d_L)+\lambda_{su}(\bar{s}_R s_L)(\bar{u}_R u_L)+\lambda_{sd}(\bar{s}_R s_L)(\bar{d}_R d_L)+(L\leftrightarrow R)$$

$$\lambda_{ud}\simeq 2n_+/\langle\Psi\Psi\rangle^2 \tag{6.9}$$

$$\lambda_{su}=\lambda_{sd}\simeq\lambda_{ud}[\langle\bar{u}u\rangle/(\langle\bar{s}s\rangle-3m_s/2\pi^2\varrho_c^2)]$$

Note, that estimates of the couplings are given in very rough approximation, valid only by the order of magnitude.

We have already discussed this interaction in section 5.7 in the sum rule context, but it is probably useful to repeat the main conclusions in simpler terms here. This interaction is attractive for the pion, strong enough to compensate $2M_{eff}$ and to make it massless. The same interaction is essentially weaker for the kaons and eta, making them «more normal». It is strongly repulsive in the η' case, making it to be very heavy.

Instanton-induced interaction of heavy quarks can be studied more qualitatively because here there are no complications connected with SBCS. Its theory was given by Callan et al. [6.26] up to terms $O(v^2)$ where v stands for velocity. Qualitatively, the picture is similar to that displayed at Fig.2: strongly growing at small x and than tending to finite mass renormalization at large ones:

$$V(x)=\begin{cases} 11.2x^2\int dn^+(\varrho)\varrho & (x\to 0) \\ 37\int dn^+(\varrho)\varrho^3 & (x\to\infty) \end{cases} \tag{6.10}$$

In order to apply it one should know how many instantons are there in vacuum. With «instanton liquid» model one finds rather modest effect, approximately explaining deviations of «constituent» quark masses used in potential models from those used in sum rule analysis. In Ref. [6.26] (where the instanton density was taken to be one order of magnitude larger than even the limit suggested by «standard» gluon condensate value) much stronger potential is found, imitating partly the linear «string» effect. However, as noted in sections 5.6, 8.1 such value of parameters strongly contradicts to conclusions drown from much more reliable analysis.

Now we come to largest distances among quarks, of the order of 1 fermi or more, relevant for hadronic physics. Here confinement effects clearly dominate. There are two related models for its

phenomenological account, related to «strings» and «bags», based on the idea that colour field is in vacuum under some constant pressure B_{bag}.

The most clear manifestation of «strings» is now provided by quarkonium spectroscopy, in which linearly rizing potential is well seen. But is the potential approach indeed justified in these cases?

The usual argument here is that «heavy quarks move slowly». It is indeed so in respect to velocity, but frequences of their rotation ω are parametrically large, exceeding at $M_Q\to\infty$ those of vacuum fields. Evidently, this situation is «antipotential», as it was strongly emphasized by Voloshin. Quite different situation takes place for real Ψ, Υ mesons and especially for their excited states. In this case rotation periods

$$T\simeq 2\pi/\omega_{mn}\gtrsim 2\ \text{fm/c} \tag{6.11}$$

may indeed be large enough in order to justify the potential approach!

Now we return to ordinary hadrons and to «bag» models. Recently they were much criticized [6.15—6.19] for the following defect: the chiral symmetry is explicitely violated at the bag boundary and also the SBCS effects are completely ignored. There were suggested «small» or «chiral bag» models [6.15—6.17] in which the axial current is conserved because hadrons are surrounded by the pion cloud. This criticism correlates with our conclusions based on the sum rules, also pointed toward great importance of SBCS effects, but it should still be checked whether these models can pass severe test by confrontation to existing data, in particular on hadron-nuclei collisions to be discussed in section 6.4. It seems more likely that they favor the «additive quark» model, in which each of constituent quark is a kind of a «small bag».

What is most important, applications of the bag models have shown that confinement forces are in some sense small effect. Using as a reference point the MIT model fit [6.12] in its initial variant with massless quarks, one obtains the value for the «vacuum pressure» confining quarks in hadrons

$$B_{bag}\simeq(146\ \text{MeV})^4\simeq .06\ \text{GeV/fm}^3 \tag{6.12}$$

Note now, that it is one order of magnitude smaller than total vacuum energy density ε_{vac} (1.25). Including effective quark mass one finds even smaller pressure (6.12), and the discrepancy becomes even larger. It means that hadronic interior is very far from being «empty» perturbative vacuum, as assumed by this model. On the contrary, vacuum fields are only slightly modified inside hadrons. We have already mentioned in section 1.4 about the idea [6.11] that the bag constant is due to partial suppression of the instanton-type fluctuations by quarks and colour fields. Attempt made by Callan et al. [2.13] do not quantitatively corresspond to our present knowledge of the instanton parameters, and in any case this effect is much more modest. However, we do not in fact need so strong effect! Only future will show whether this qualitative idea to explain confinement contains some truth or not.

6.3. Hard hadronic reactions

Hard hadronic reactions, involving momentum transfer Q large compared to 1 GeV (the typical hadronic scale) are the traditional method of investigations of hadronic structure. Two particular cases are studied in great details: inclusive lepton-hadron scattering and hard exclusive processes (say, measurements of hadronic formfactors). In this section we comment on recent experimental observations and theoretical ideas, connected to these processes.

Considering deep inelastic lepton-hadron scattering we discuss briefly three poins: (I) flavour composition of the «sea» quarks, (II) recent works on scaling violation and (III) the EMC effect.

There appeared first data [6.39] demonstrating that «sea» quark pairs are strongly SU(3) asymmetric, the ratio of strange to nonstrange quarks in it is not unity but

$$R_s=\frac{2\bar{s}(x)}{\bar{u}(x)+\bar{d}(x)}\simeq .52\pm .09 \tag{6.13}$$

with very weak dependence on x. This fact shed some light on the origin of the «sea» in general, for in usually considered perturbative framework it was assumed to be caused entirely by bremsstrahlung-type processes, accompanying all hard processes. However, this mechanism is strongly connected with large virtuality (comparable to Q) therefore it should be completely insensitive to small strange quark mass. Thus, the observation (6.13) implies that the «sea» is the so-called «intrinsic» one and that it is related to «soft» nonperturbative effects.

In Ref. [6.8] I have suggested that the flavour composition of the QCD vacuum and the «sea» are connected as follows:

$$\begin{aligned} &R_s\simeq|\langle\bar{s}s\rangle/\langle\bar{u}u\rangle|^2=0.5-0.6\\ &R_c\simeq|\langle\bar{c}c\rangle/\langle\bar{u}u\rangle|^2\sim 10^{-2} \end{aligned} \tag{6.14}$$

Here numbers come from data on the condensates to be discussed in section 8.3. For strange quarks it seems to work, while for charmed ones there are only limits [6.40] $R_c< .5R_s$. However, there are other data for proton fragmentation into charmed particles which indeed show that «intrinsic charm of hadrons» (using terminology of Brodsky et al. [6.74]) is indeed present at the one-per-cent level.

Another interesting speculation concerning flavour properties of structure functions was made by R. Hwa [6.37]: they can be considered as a sum of some «additive» clusters, constituent quarks or «valons».

Now we come to scaling violation in deep inelastic scattering, being the traditional place for «QCD tests». Since the pioneer paper by Politzer [1.17] a lot of work have been done on «radiative corrections», see more recent review [6.31]. Experimentalists also made impressive work during last decade, and now we have not only the famous SLAC data but also those for νN and μN scattering at essentially larger Q^2 up to hundreds of GeV^2, see e.g. [6.32]. Unfortunately, the original goal of this work (being the convincing test of the perturbative QCD and measurement of fundamental parameter Λ) was not reached so far, because at mediate $Q^2=1-10$ GeV^2 these effects are masked by the nonperturbative or the so-called higher-twist effects. The Fig.3 (borrowed from recent review [6.32]) shows at what accuracy level they are seen in present data.

Our main point is that these irritating «higher-twist» effects are in fact very interesting and potentially important for better understanding of the hadronic structure. It is probably necessary first to explain the terminology. As mentioned in section 4.1, deep inelastic data provide an amplitude for nucleon transition to all other states under the influence of (electromagnetic or weak) current. Via dispersion relations they can be translated into the language of the two-current correlator averaged over the nucleon state. The OPE of such correlator is similar to that considered in sum rules, with one evident modification: not only scalar operators contributes, but those with arbitrary number of Lorentz indexes. By definition, twist T is the difference between the Lorentz spin and dimension d of the operator. The leading $T=2$ operators have the structure $\bar{\Psi}\Psi$ (with arbitrary number of derivatives), their physics corresponds to parton model times the calculatable logarithmic factors due to radiative corrections.

The $T=4$ effects make $1/Q^2$ corrections and so on. Because of technical complexity, the theory of such effects was discussed in literature only recently, see Refs [6.33—6.35]. Not going into details we try to present here the main physical points.

There are arguments given in [6.34] suggesting that here (as in the sum rules) the main corrections are also given by four-fermion operators. Roughly speaking, effect is proportional to the probability to find two quarks in certain spin-colour state at the same point in the transverse plane (remember that in the infinite momentum frame the nucleon is infinitely contracted disc). Naive picture of hadrons as being made of valence only quarks suggests it to be about $1/r^2$ (where r is a hadronic radius), but such estimates [6.34, 6.35] predict extremely small effect, at least one order of magnitude smaller than needed in order to explane data. Fortunately, there are also «sea» quarks around the valence ones (which we know from structure functions of the leading twist). The new information is however needed here: it becomes essential how close the «sea» quarks follow the positions of valence quarks in space. In order to explane data rather small «clusters» (constituent quarks?) seem to be needed [6.34].

However, most of the recent works on higher twist physics concentrate on attempts to formulate this theory in parton-like way. The general difficulty here is that simple probabilistic language do not apply here because effects are in principle of interference type. (By the way, the «scattering on diquark» models [6.37] ignore this point, therefore they consider $1/Q^4$ rather than leading $1/Q^2$ corrections.)

It is true that the OPE formalism is rather cumbersome and inconvenient, so some simplified models are badly needed in this field. However, they should be based on physical rather than formal arguments.

Our final comments on inclusive deep-inelastic processes deels with the so-called EMC effect [6.41], or deviations of the nuclear and nucleon structure functions. This discovery, made in traditional field of experimentation so late, is a good lesson for experimentalists: once again it is demonstrated that one should check everything! There is vast current literature on the subject, full of quite different «explanations». To name a few, it is «percollation» of quarks between the nucleons, some increase of the nucleon's dimensions in nucleons due to the reduced vacuum pressure, admixture of 6 or even 12 quark bags, enhanced pion cloud in nuclei etc. (see e.g. [6.42]). No doubt, this set of ideas will stimulate many new experiments, and many of them will be excluded quite soon. I do not think that theory can immediately produce any reliable predictions here: even the proton structure function is not in fact understood, and obviously it is not possible to go round this main problem.

Now we proceed to another vast field of investigations, namely exclusive reactions. Perturbative QCD have lead to quark counting rules [6.43] and other considerations [6.44—6.48] which allow one to estimate the power asymptotics of any exclusive reactions. The next step [6.49—6.52] was connected with OPE-type analysis, in which the coefficients for different powers of Q were expressed via some «wave functions», containing all large distance physics. Assuming some shape of this function, one may evaluate the amplitudes for different exclusive reactions including this particular hadron. Some surprises came from such investigations: in particular it turns very nontrivial to obtain even correct sign of the proton and neutron formfactors at large Q [6.54, 6.55]! The latest activity in this field concentrates on attempts to evaluate parameters of the wave functions, which we have discussed in section 5.4. Summary of all this is contained in recent review [6.59].

We have already demonstrated in section 5.4 that these «wave functions» are very asymmetric in momentum space and therefore are very different from those expected, e.g. in nonrelativistic quark models. However, such wave functions refer only to very specific sector of hadronic states in which, say, the pion is made exactly of one quark-antiquark pair. It is natural that this sector is dominant in exclusive reactions at large momentum transfer (and the asymmetry mentioned increase the probability further). there are also other «wave functions» related to «higher twist» corrections. Unfortunately, they are just matrix elements of some operators and no natural normalization conditions is available. Therefore, it is difficult to answer questions like «What is the relative probability of such configurations?» etc. The strongly fluctuating, «multifaced» nature of hadrons is well known, being for example the origin of diffractive dissociation, «penetrating component» in hadron-nuclei collisions and many other phenomena (see the next section).

In current literature on exclusive reaction theory debates are concentrated on the applicability region of asymptotic formulae. At one hand, predictions of the quark counting rules (say, those for meson and baryon formfactors

$$F(meson)\sim 1/Q^2;\qquad F(baryon)\sim 1/Q^4 \tag{6.15}$$

and large angle scattering) are in reasonable agreement with data. On the other hand, attempts to make explicite evaluation of «higher twist» corrections (in particular for the $1/Q^4$ effects in pion formfactor) produce rather large effects which are, however, rather uncertain. The three-point correlators discussed in section 5.5 can reasonably well reproduce pion formfactor up to rather large Q, but the gluon-exchange diagramm on which (6.15) is based is far from being the dominant effect! In addition, there are multiple attempts to reproduce formfactor in all measured region of Q in phenomenological quark models, which also do not use the one-gluon exchange at all. In view of all this there appear doubts whether agreement between data and (6.15) is really so convincing.

The situation resembles that for charmonium sum rules and opinions of different people drastically differ. Of course, experiment will decide. A number of interesting exclusive decays of charmonium states have given a lot, but the crucial test will probably be provided by (much more difficult!) experiments with upsilon exclusive decays.

6.4. «Additive» quarks in soft processes

Studies of soft hadronic processes have produced a lot of empirical information, therefore discussion in this section is especially fragmentary. Its main point is that there are rather interesting arguments supporting the «additive» quark picture of hadrons.

Historically the first was the well known observation [6.60] that the pion-proton and proton-proton cross sections are such that

$$\sigma_{\pi N}/\sigma_{NN}\simeq 2/3 \tag{6.16}$$

which can be explained in the picture of independent quark-quark interaction. Other similar arguments were soon presented in [6.61], see also recent discussion of related phenomenology in [6.62]. The natural consequence of this picture and $\sigma_{qq}\simeq(1/9)\sigma_{NN}$ is that quark dimension is rather small $r_q\simeq(1/3)R_N$ [6.5]. For some time this model was generally considered as interesting but very questionable possibility.

Rather interesting argument against this model was suggested rather unexpectedly on the basis of discussion of diffractive dissociation. We remind that according to pioneer works [6.68] this phenomenon is due to the fact that different components of hadronic wave functions have different ability to interact, so the through-going wave is not identical to the incoming one and has some admixture of other (multihadronic) states. If nucleon is made of three quarks, the only fluctuating parameters are their positions in transverse plane and one may estimate features of the diffractive dissociation. It turns out [6.69] that on general grounds the d.d. cross section at zero angle becomes zero, in evident contradiction to experiment! Thus, it was concluded in [6.69] that the proton is made of many «partons» with their number strongly fluctuating.

The by-pass was still found for three-quark picture, one have only to account for complicated structure of constituent quarks. The simplest model [6.70] consider two states of the quark: the «active» one with probability P and the «passive» one with $(1-P)$. With P about 0.6 all data on d.d. in hadron-hadron and hadron-nuclei collisions are described reasonably well [6.71, 6.72]. I think this piece of information is also rather important for the understanding of quark interaction with vacuum. Another set of data, providing unexpectedly good support for «additive» quark model, came from hadron-nuclei collisions [6.63—6.67]. It was repeatedly emphasized that nuclei are «nothing but very dense bubble chamber», but of course a lot of heavy numerical work was needed in order to make it really work. We refer to original works for quantitative discussion and only present few qualitative examples. Multiplicity and spectra of secondaries in pp and πp interactions are very similar—in terms of this model it just means that in both cases only one pair of quarks interact. However, they are changed in nuclei in different way! The limiting case of thick nuclei with dimensions of the order of quark free path suggest that all quarks interact once. If so, spectra and multiplicities should be for meson and baryon beams such as

$$\langle n\rangle_{\pi A}/\langle n\rangle_{NA}\xrightarrow[A\to\infty]{} 2/3 \tag{6.17}$$

Of course, one may account for such trivial effect as independent quark interaction more accurately, and the result correlate with data.

Another aspect of the same process is seen in the fragmentation region. It is believed that the so-called leading hadrons contain quarks which have passed without interaction. In the additive quark model attenuation of this effect by nuclei can be evaluated accurately, again with spectacular success [6.63, 6.64].

Finally, an example [6.67] based on more complicated (correlation) data. It is known that the ratio N/D (N and D are average multiplicity and multiplicity dispersion) is remarkably stable as a function of energy and collision type (it was first noticed by Malhotra in 1963). Selecting events in nuclei with small number of knocked-out nucleons one finds the same numbers, while in those with large number there is spectacular increase in N/D which is different for incoming pion and proton (see Fig.4). In the former case it is close to the factor $\sqrt{2}$ while in the latter one it is substituted by $\sqrt{3}$. So, statistical picture is such as if indeed there are two or three independent and identical stochastic processes!

Recently there was some activity connecting with rescattering in hadron-hadron collisions at superhigh energy [6.71, 6.72], motivated by noticable increase in hadronic cross sections. In principle, at large enough energy the «addivity» of quarks should inevitably be lost!

Our final point is connected with flavour dependence of quark interactions. Data on strange hadrons suggest

$$\sigma_{sN} \simeq \sigma_{KN} - \frac{1}{2}\sigma_{\pi N} \simeq \frac{1}{2}\sigma_{\varphi N} \simeq 7 \text{ mb} \tag{6.18}$$

which is about twice smaller than that for nonstrange quarks. Again we come across the suppression factor connected with strange quark, similar to that for the parton «sea» in the preceeding section. Note however, that now it is not the virtual strange pairs in vacuum (which may in principle be suppressed by larger mass), but the probability to interact with vacuum of the external quark. However, there may be similarity between these problems since this interaction is of «exchange» type. The situation here is also similar to kaon sum rules considered in section 5.7, where the somewhat suppressed instanton-induced interaction of strange quark was used.

On the other hand, I do not see easy explanation of this suppression in perturbative type picture [6.73] where the cross section is due to one-gluon exchange process when quark pass each other at high speed. The cut-off is provided by hadronic dimensions, so «additivity» looks rather artificially in this picture. Evidently, the quark mass is not relevant here, unless strange hadrons are somewhat more compact. However, there are estimates for psion cross section, which turns to be extremely small:

$$\sigma_{cN} \simeq \frac{1}{2}\sigma_{\psi N} \simeq 1.7 \text{ mb} \tag{6.19}$$

(It is not quite accurate, being extracted from photoproduction on nuclei.) However, these number also suggests than the heavier is quark, the more «transparant» it becomes! Further data on this point will be very important for the understanding of mechanisms of soft hadronic processes.

The last point in this section refers to the so-called «formation length» of hadrons in hadron-nuclei interactions. It is well known that simple cascading describe data well in the nonrelativistic region, but for high energy collisions it predicts too large multiplicity of secondaries. Natural explanation is that due to relativistic time slowening in (E/M) times (E and M are the particle energy and mass) it is formed at distances exceeding the nuclear dimensions. References and detailed discussion can be found in Refs [6.64—6.66], and now we make the following comment on the interpretation of their results.

The usual form of «formation length» is as follows

$$l_{form} = E/m^2 \tag{6.20}$$

where m is some «typical hadronic mass» (the fit to data gives numbers around rho-meson mass). However, since the constituents considered are implied to be constituent quarks, it is more natural to write it as

$$l_{form} = (E/M_{eff})\tau_{form} \tag{6.21}$$

where M_{eff} is its effective mass and τ_{form} is the formation time at rest. It is important, that these two parameters are rather different: due to «trace» of the chiral symmetry M_{eff} is rather small, around 200 MeV. If so, the formation time τ_{form} becomes very short as well, about 0.1 fermi! So, these data can be considered as one more argument that constituent quarks are very compact objects, as it was repeatedly stressed in this chapter.

(We have mentioned this consideration because in literature it is often refered as suggesting much larger «formation time», about 1 fm.)

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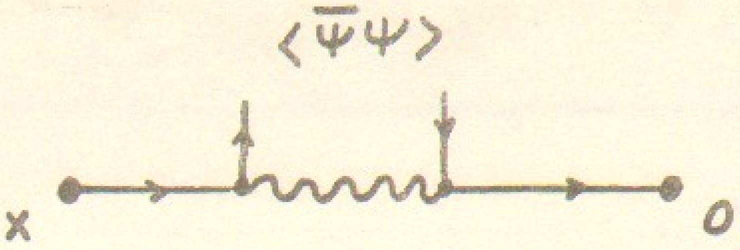

Fig.1. Exchange interaction with vacuum quark, which produces its effective mass at small distances according to Politzer [1.36].

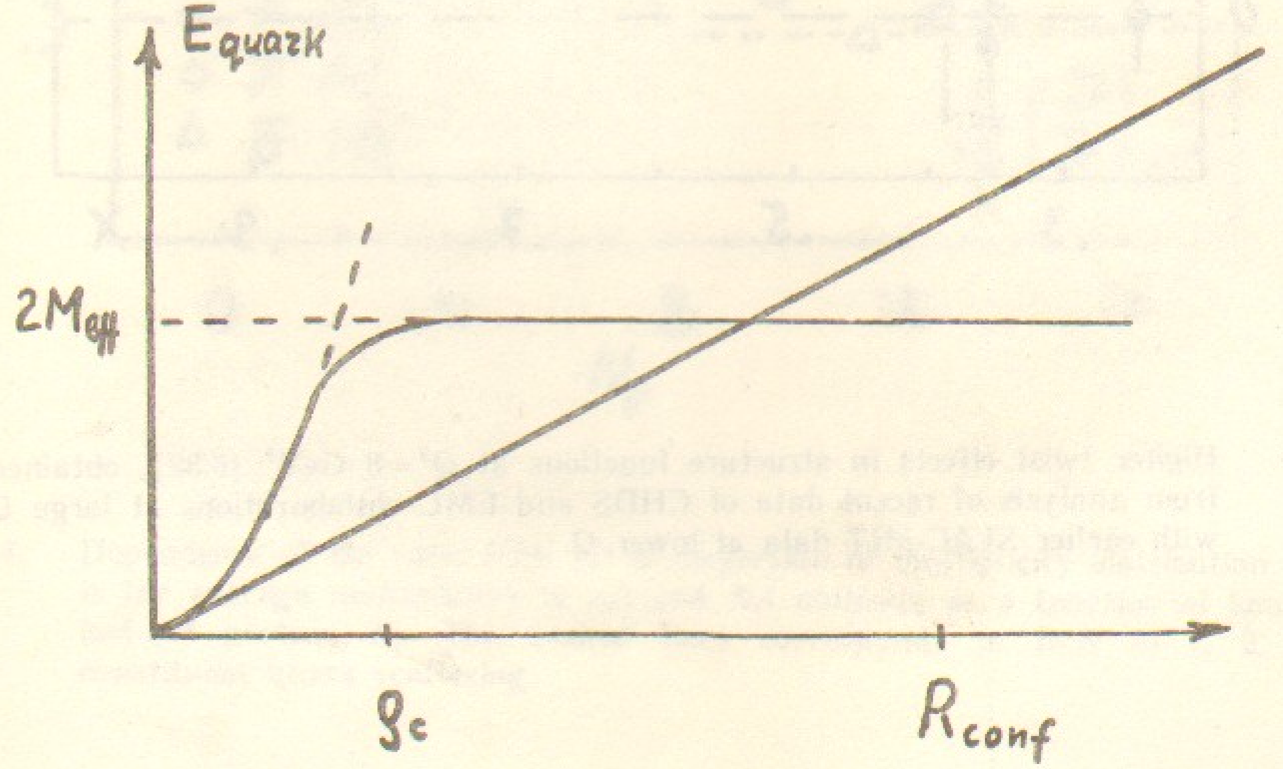

Fig.2. Schematic dependence of quark-antiquark energy as a function of their separation. The quadratic growth at small distances corresponds to OPE (6.4), instanton effect at intermediate distances produce constant effective mass and at large distances motion is restricted by confinement effects.

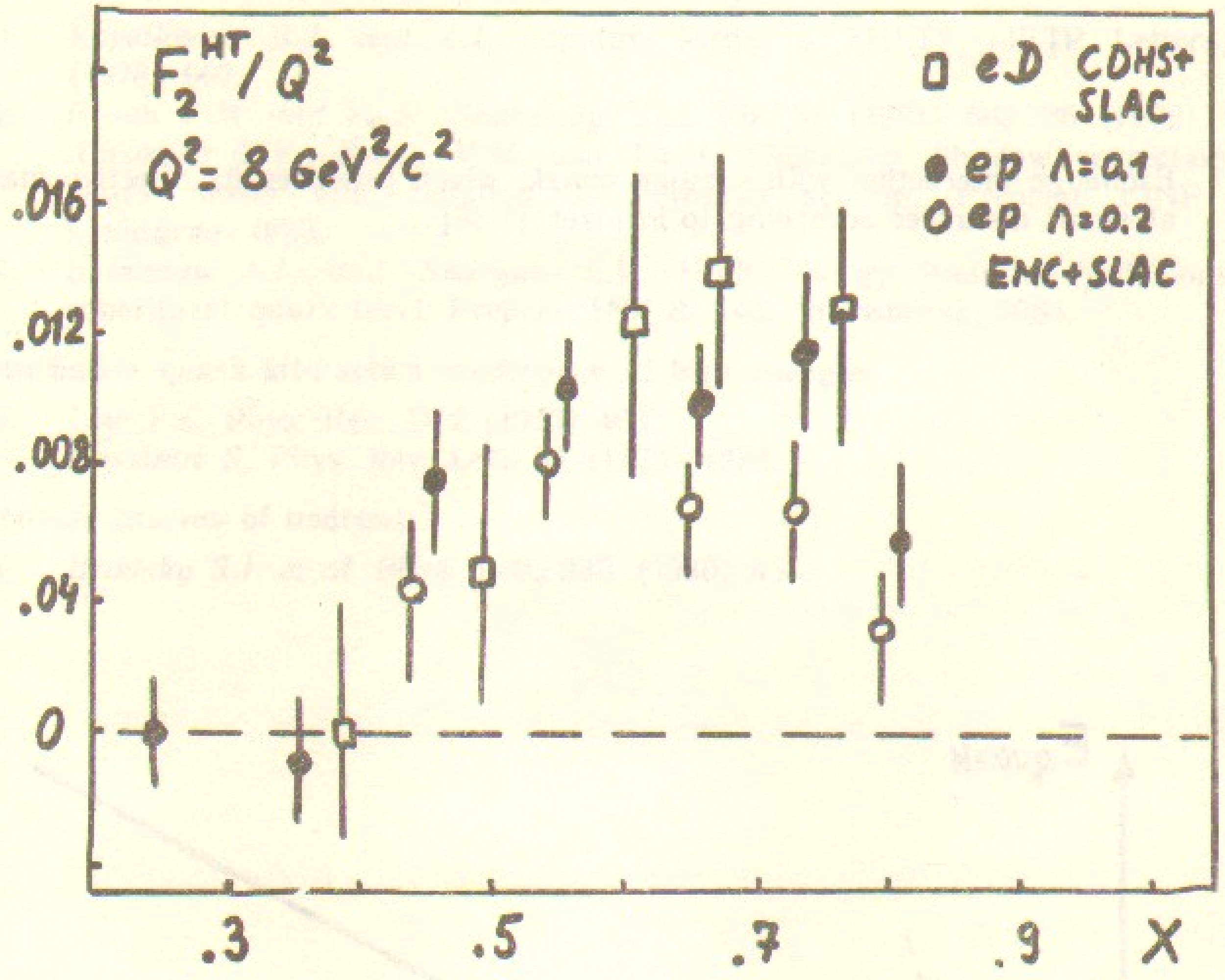

Fig.3. Higher twist effects in structure functions at $Q^2=8$ GeV^2 [6.32], obtained from analysis of recent data of CHDS and EMC collaborations at large Q with earlier SLAC-MIT data at lower Q.

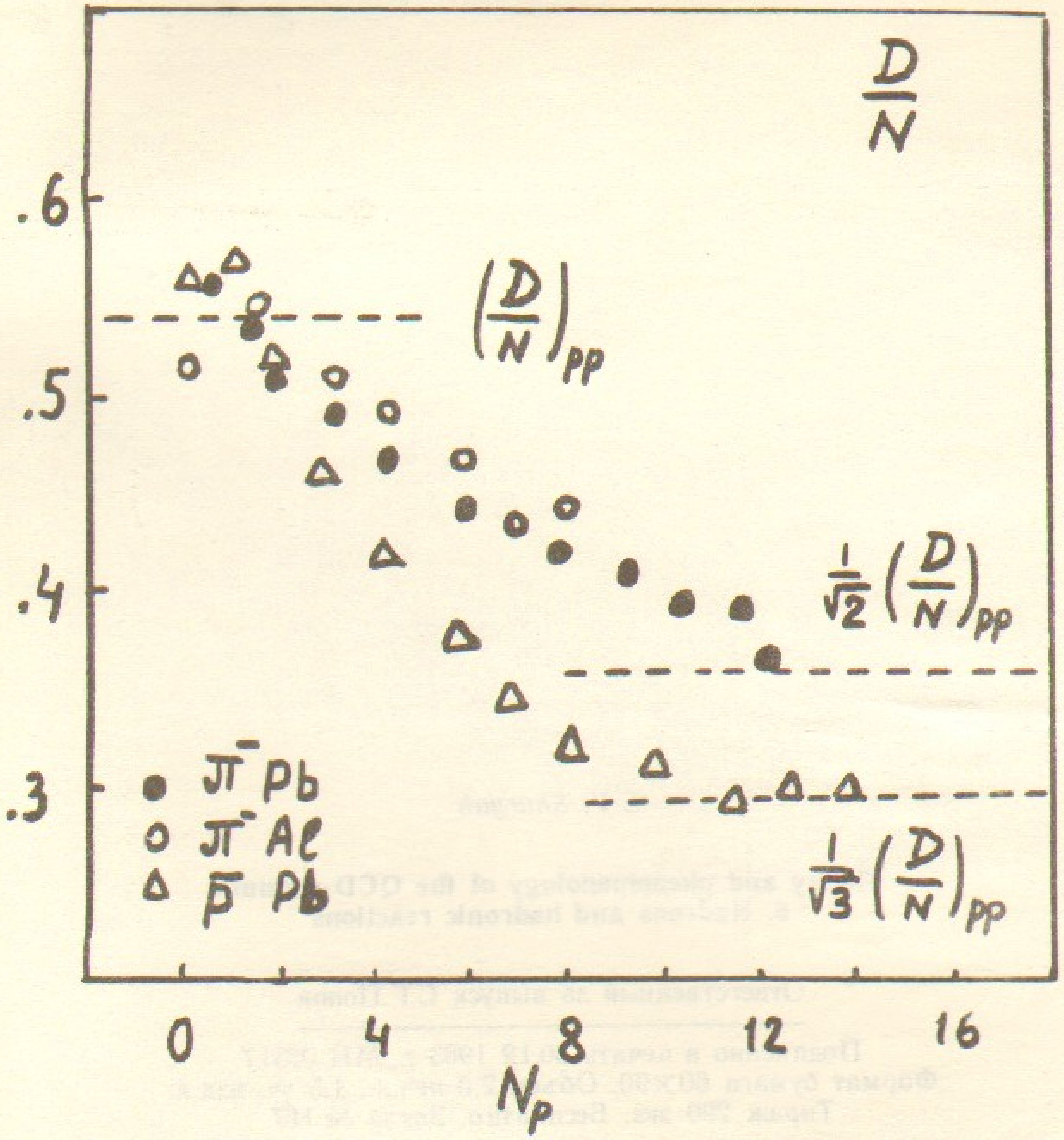

Fig.4. Dependence of the ratio D/N (D is dispersion of multiplicity distribution N is the average multiplicity) in πA and NA collision as a function of knocked-out protons N_p. The dashed lines corresponds to D/N in 1, 2, 3 constituent quark scattering.

E.V. Shuryak

Theory and phenomenology of the QCD vacuum
***6.* Hadrons and hadronic reactions**

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