ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

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THEORY AND PHENOMENOLOGY OF THE QCD VACUUM

8. CONCLUSIONS AND DISCUSSION

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НОВОСИБИРСК

ABSTRACT

This preprint summarises the series of works devoted to discussion of properties of the QCD vacuum, as well as consider perspectives for further investigations. In section 8.1 we have summarised different methods of determination of the gluon condensate, fixing the absolute scale of the gauge field fluctuations in vacuum. The next section 8.2 is devoted to their qualitative features, in particular distribution in space-time. In section 8.3 we discuss the role of virtual quarks in vacuum and dependence of gluon and quark condensates on their masses. Section 8.4 contains comments on the limit of large number of colours, while section 8.5 is a brief resume on the discussions of hadronic structure. Finally in section 8.6 we dicuss whether high energy collisions of heavy ions are really relevant for the problems considered.

8. CONCLUSIONS AND DISCUSSION

8.1. The gluon condensate

In this section we summarize the attempts to evaluate the fundamental quantity

$$\langle 0|(gG^a_{\mu\nu})^2|0\rangle \neq 0 \qquad (8.1)$$

first introduced in Ref. [5.13], which fixes the scale of nonperturbative fluctuations of gauge field in vacuum and, in particular, determins its energy density (see section 1.3).

First, let me enumerate existing sources of its estimates in historical order:

1. Sum rules for the vector current made of charmed quarks [5.45, 5.47—5.53].
2. Sum rules for the vector current made of light quarks [5.13, 5.14, 5.18].
3. Sum rules for the vector current made of b quarks [5.46, 5.50—5.53].
4. Lattice data for the «average plaquette» with explicite subtraction of perturbative component [3.76].
5. Lattice data for relatively small Wilson loop [3.74, 3.75, 3.77—3.79].
6. Joint analysis of different sum rules, e.g. for currents $\bar\Psi\Psi$ and $\bar\Psi G\Psi$ [5.52].

Although discussion of these topics was already made above, it is reasonable to collect discussion of their accuracy at one place. Unfortunately, none of these methods is free from umbiguities and most of them are so far only the preliminary estimates, with the accuracy not better than, say, the factor of two.

The most clear case is probably the second one, connected with high quality experimental data on low enegry e^+e^- annihilation into hadrons. There are two works addressing the question of their comparison with OPE-type formulae derived in Ref. [5.13]. Both conclude that power corrections of the proposed kind can indeed fit data very well (see e.g. Fig.1.) with the following numerical value for the gluon condensate (in GeV^4):

$$0.12 \leqslant \langle (gG)^2\rangle \leqslant 0.83 \qquad [5.14]$$

$$\langle (gG)^2\rangle \simeq 0.49 \pm 0.05 \qquad [5.15] \qquad (8.2)$$

The former work is an example of rather conservative experimental analysis while the latter one is much more optimistic. Although in Ref. [5.15] are used some later data, so spectacular increase of the accuracy claimed is essentially due to inclusion of statistical errors only, disregarding the systematic ones mentioned in experimental works. The nice feature of this analysis is the consideration of logarithmic derivative instead of the correlators by itself, so some uncertainties (like those in general normalization, perturbative corrections etc.) may indeed become less important. It is not easy to make strong statements in so complicated situation, but in any case I think the real accuracy level is somewhere in between of the numbers given in (8.2). One more comment is that error of the condensate is correlated with two other parameters relevant for such analysis, being the vacuum average value of the four-fermion operator and that of lambda parameter. Therefore, with some independent information on them coming from some other experiment, one has the immediate progress in determination of the gluon condensate.

The method number one in our list have produced the «standard» value [5.13]

$$\langle (gG)^2\rangle_{SVZ} \simeq 0.5 \text{ GeV}^4 \qquad (8.3)$$

but the original analysis have included distances 0.5—1 fm and, as it was recently demonstrated [5.49], OPE is not quite reliable here. There are two possible ways for improvement. Reinders et al. in their recent preprint [5.47] have shown that their previous analysis is less sensitive to higher corrections than the original SVZ fit, and insist that the value (8.3) holds with accuracy on the level of 20%. The former conclusion is natural, because their method is connected with somewhat smaller distances. However, going in this direction one comes across problems with uncertainties of the nonresonance continuum, and with its proper account the errors become somewhat larger.

Another alternative is to go to larger distances where data are better. This possibility was studied by myself [5.53], based on the substitution of OPE by direct numerical evaluation of propagators. The conclusion of this work is that quite different vacuum models can indeed desribe data (independent of whether their OPE series are good or bad) with the condensate values in the region 0.5—1. GeV^4.

We have discussed in details in section 5.6 why bottonium sum rules are less useful for the determination of the condensate: it is necessary to go to essentially larger distances, about 1—3 fm in order to see noticeable effect. In addition, one should work hard in order to account very accurately for much more important Coulomb effects. Thus, one

should probably disregard exotic possibilities suggesting in [5.50, 5.51], leading to the condensate larger by orders of magnitude!

Considering two lattice methods let me first comment that the latter one is essentially more precise. At the elementary plaquette level the perturbative component is much larger than the nonperturbative one, while increasing the loop area A one finds that the former decreases and the second strongly increases (according to OPE prediction, as $\langle (gG)^2\rangle \cdot A^2$). Obviously, there exist some optimal loop size in order to measure this effect.

The general defect of the nowdays lattice calculations is that in most of them no account for virtual quarks is made, therefore the results obtained so far refer only to pure gluonic worlds. As discussed in chapter 3, the situation with the value of lambda parameter is rather uncertain and therefore it is difficult to put lattice results into physical units. But anyway the condensates evaluated on the lattice seem to be one order (or even more) larger than in real world! Fortunately, virtual quark effects make vacuum more dilute (see more on this in section 8.3), so presumably with their proper account we will find more agreable values.

The last method recently was suggested by Novikov et al. [5.52], its idea is to consider the following current

$$a_\mu = \frac{g}{2}\bar{d}\gamma_\alpha \tilde{G}^a_{\alpha\mu} t^a u \qquad (8.4)$$

in combination with purely quark one $j_\mu = \bar{u}\gamma_\mu\gamma_5 d$. At first sight it is not reasonable because there appears new unknown coupling constant

$$\langle 0| a_\mu| \pi(p)\rangle = \text{const}\cdot p_\mu \qquad (8.5)$$

but in fact there are two new sum rules, for diagonal and nondiagonal correlators $\langle a_\mu j_\nu\rangle$, $\langle a_\mu a_\nu\rangle$, therefore new information (e.g. for the condensate evaluation) can be extracted.

(Considering their results it is interesting to mention the following fact: the constant (8.5) was earlier evaluated by other method in Ref. [5.42], and both completely independent numbers agree within 10%! So, one may obtain reliable information on this way, and also with general increase of the field of applications the confidence to the method is growing. Similar investigations in other directions are therefore wellcomed.)

The final remark is that our list of methods is far from being complete. To give an example of more physical determination of the nonperturbative energy density one may mention the «energy shift» between the asymptotically dense quark-gluon plasma and the vacuum state. In the combination

$$(\varepsilon-3p)\underset{\varepsilon\to\infty}{\longrightarrow}4|\varepsilon_{vac}| \qquad (8.6)$$

(ε is the energy density and p is the pressure) the contribution of massless quarks and gluons cancel, so it should be asymptotically some fundamental constant (related to vacuum energy density, or the condensate). In section 7.3 we have shown that lattice numerical experiments provide spectacular support for this statement. One may also hope that in some future this idea may even be tested by real experiments!

8.2. «Homogeneous» versus «twinkling» vacuum

Having fixed the general normalization of the nonperturbative fields in vacuum let us now consider their distribution in space-time. The question in the title of this section was in fact first posed in section 1.3 and it was systematically discussed above. In short, the alternatives considered are as follows.

The former implies that the QCD vacuum posess the dimensional parameter $\Lambda\sim200$ MeV~1 fm^{-1} and all quantities are just its powers without large coefficients. The latter picture corresponds to very inhomogeneous field distributions with much larger fields and their derivatives at one place, compensated by their small values at another one.

Historically the first possibility was suggested by Shifman et al. in [5.13], driven by their first estimates of the typical instanton dimensions. However, as it was discussed in chapter 2, this estimate is not well grounded, because (as noted later by the same authors) t'Hooft results for the instanton density is valid only for very small instantons.

Nevertheless, such a possibility is the simplest one and naturally it is systematically used for the evaluation of different vacuum expectation values. It is known as «hypothesis of vacuum dominance» (or «factorization hypothesis»), and it states that if some operator may be split into the product of two scalars, its average is dominated by the vacuum intermediate state. For example, the following ratio

$$R_G\equiv\langle(gG)^4\rangle/\langle(gG)^2\rangle^2 \qquad (8.7)$$

is assumed to be close to unity (we disregard here numerically small contributions of the cross channels).

In sections 5.7 and 5.8 it was discussed that in some cases strong

vacuum fields show up most clearly, and these considerations have triggered the idea that rather strong instanton-like fluctuations are important [5.57]. The corresponding «instanton liquid» model leads to very inhomogeneous vacuum. In particular, it suggests that the ratio (8.7) is not unity but rather

$$R_G\simeq\frac{3}{7}(\pi^2 n_+\rho_c^4)^{-1}\simeq5\div10 \qquad (8.8)$$

Unfortunately, as it was demonstrated in section 5.6, much efforts made in order to observe clearly the higher corrections and evaluate this parameter from data have so far failed. Most promising line of investigations here is connected with further studies of spectral densities of gluonic correlators by means of charmonium and upsilon decays into photon plus hadrons. More accurate data on e^+e^- annihilation into c, b quarks may also be useful.

Another qualitative aspect of the vacuum gluonic fields is whether they are «locally selfdual» or not. As it was discussed in section 5.8 in more details, an answer to this question can in short be summarized by the value of the following dimensionless parameter

$$\begin{aligned}
R_{sd}&=-P(0)/S(0)=\frac{8\pi^2}{b}(A/\langle(gG)^2\rangle)\\
P(0)&=i\int dx\,\langle T[\alpha_s G\tilde G(x),\alpha_s G\tilde G(0)]\rangle \qquad (8.9)\\
S(0)&=i\int dx\,\langle T[\alpha_s G^2(x),\alpha_s G^2(0)]\rangle
\end{aligned}$$

where A is the topological susceptibility. If the fields are locally selfdual it is equal to unity, and available phenomenological information really suggest it to be of this order. As far as I could understand, results of the lattice calculations indicate much smaller values of this parameter.

Now we pass to consideration of various operators containing quark fields. It is natural to start with questions similar to those mentioned above, whether quark fields are distributed homogeneously or not. For example, the straightforward analog of (8.7) is the following parameter

$$R_\Psi=\langle(\bar\Psi\Psi)^2\rangle/\langle\bar\Psi\Psi\rangle^2$$

However, even for the «instanton liquid» it turns out to be close to unity [5.57], so it does not allow to separate these cases. It is not also easy to «measure» the ratio (8.9) for usually four-fermion operators appear from the gluon exchange diagrams, so they contain colour matrixes. Let us therefore consider the following dimensionless ratios:

$$R_A = \frac{\langle(\bar{u}\Gamma t^a d)(\bar{d}\Gamma t^a u)\rangle}{\langle\bar{u}u\rangle\langle\bar{d}d\rangle} \tag{8.10}$$

$(A = S, P, V, A, T$ for $\Gamma = 1, \gamma_5, \gamma_\mu\gamma_5, \sigma_{\mu\nu})$

Factorization hypothesis predicts the following values: $R_S = 4/9$, $R_V = -16/9$, $R_T = 16/3$ etc. Investigations made by A.R. Zhitnitsky [5.23] using specially designed sum rules and also considering approach from the heavy quark end lead to the following estimates: $R_S \sim 0.1$, $R_V \sim -2$, $R_T \sim 20$, so according to this work factorization is valid only for vector (and axial) case. This conclusion is in correlation with the observation that instanton zero modes are not important in this case, but strong correlation between the neighbouring instantons in the «instanton liquid» model does not so far allow for reliable determination of such detailed information on the vacuum parameters.

Another information on the four-fermion operators came from analysis of ω—φ mixing and ϱ—ω splitting [5.13], leading to

$$\langle(\bar{d}\gamma_\alpha\gamma_5 t^a d)(\bar{u}\gamma_\alpha\gamma_5 t^a u)\rangle / \langle(\bar{u}\gamma_\alpha\gamma_5 t^a u)^2\rangle \sim 0.06 \ll 1$$

also suggesting that for axial case factorization indeed works.

At the end of this section let me call upon experts in lattice calculation. It is not reasonable now to evaluate, say, the proton mass with high numerical accuracy. It is much more important to understand first the qualitative features of the vacuum fields, in particular, to «measure» a set of dimensionless ratios mentioned above. Another important aspect of the problem is their dependence on the the quark masses, on which we concentrate in the next section.

8.3. The role of virtual quarks

One of the most attractive features of QCD is the fact that it does not contains many free parameters, in fact the only adjustable ones are the quark masses and the number of colours (the latter to be discussed in the next section). However, for some time it was widely believed that the former parameters are not really relevant because the virtual quarks in general are unimportant. This point of view was especially popular among people making lattice calculations, for «quenching» the quarks one gets rid off many complications connected with them. However, recent studies (including those made on the lattice) have shown

that it is not so and the understanding of virtual quark effects have become the most urgent problem of the theory. This statement was repeatedly emphasized above, but in this section we are going to outline the known facts on this point in more systematic way.

Let us start with heavy quarks posessing the mass m being much larger than the characteristic hadronic scale. In this case the effective action (in Minkowsky notations)

$$S_{eff}^{(M)} = -\ln\det(i\hat{D} - m)$$

(which appears when quark fields are «integrated away») can be expanded in powers of $1/m$. The general calculation made by Novikov et al. [4.22] up to operators of dimension 8 have produced the following result:

$$S_{eff}^{(M)} = \frac{1}{2}\int dx \, \mathrm{Tr}\left\{-\frac{1}{4}G_{\mu\nu}^2\left(\frac{g^2}{24\pi^2}\right)\ln\frac{K_{max}^2}{m^2} + \right.$$
$$+ \frac{ig^3 G_{\mu\nu}G_{\nu\sigma}G_{\sigma\mu}}{180m^2(16\pi^2)} + \frac{g^4}{288m^4(16\pi^2)}\Big[-(G_{\mu\nu}G_{\mu\nu})^2 +$$
$$\left. + \frac{7}{10}\{G_{\mu\sigma}G_{\sigma\nu}\}_+^2 + \frac{29}{70}[G_{\mu\gamma}G_{\gamma\nu}]_-^2 - \frac{8}{35}[G_{\mu\nu}G_{\gamma\delta}]_-^2\Big]\right\} \tag{8.11}$$

Note that first term contains the ultraviolet cut off, for this term is connected with charge renormalization. In principle, one may obtain these results by evaluation of perturbative loop diagrams, but the background field method considered in chapter 4 is much more convenient.

Now we are going to use this general result in order to see up to which mass values the quark-induced corrections are small. The $O(G^3)$ effect is numerically small, so we start directly with the $O(G^4)$ one. As we have noted in the last section, «homogeneous» and «twinkling» vacuum models suggest an estimates which differ by several times. However, in power 1/4 predictions are more close, and one may observed that at mass values about

$$m \lesssim m_c = 500 \div 800 \text{ MeV} \tag{8.12}$$

these corrections become noticable and expansion in $1/m$ breaks down. This fact was independently noticed in lattice calculations (see chapters 3 and 7), in particular inclusion of so heavy quarks was shown to reduce the transition energy density and the qualitative behaviour of the deconfinement transition!

Now let us attack the problem from another side, considering expansion over powers of the light masses (the so-called chiral perturbation theory). Such discussion was in particular made in the work of Novikov et al. [5.58], where it was noted that the condensate derivative over quark mass is known on general ground

$$\frac{d}{dm}\langle (gG)^2\rangle \Big|_{m=0} = -\frac{96\pi^2}{b}\langle \bar{\Psi}\Psi\rangle \tag{8.13}$$

Again the effect is surprisingly strong: $O(m)$ correction becomes noticeable already for quarks as light as the strange one, with «current» mass of about 150 MeV. In other terms, the SU (3) symmetric case with three massless flavours posess the gluon condensate about twice smaller!

Summarizing all this, the dependence of the gluon condensate on the quark mass seems to be monotoneous at both limits, with more «dilute» vacuum containing lighter quarks. Unfortunately, intermediate mass region .2—.8 GeV is not under control, therefore no simple «light-to-heavy quark matching» (originally suggested in [5.13]) is in fact possible. Now, what is the mechanism of so strong suppression of vacuum fields by the virtual quarks?

We do not know the answer, unless for the particular kind of fluctuations, the instantons, and for the very specific vacuum parameters. The explanation goes in two main steps. First, it is connected with t'Hooft zero modes leading to the factor in the instanton density $(M_{eff}\cdot\varrho_c)^{N_f}\ll 1$. The second step is the observation of numerical «trace» of the chiral symmetry in the chirally asymmetric QCD vacuum, due to which M_{eff} is numerically small.

Unfortunately, this explanation probably does not work for the lattice calculations, for which instantons seems to be practically absent. However, existence of fermionic quasi-zero modes is probably more general phenomenon, which is not so far well understood. It is desirable to study this point in lattice calculations, considering the distribution over eigenvalues of the fermionic matrix. (We remind that the gauge field weight function is proportional to its determinant or the product of these eigenvalues.) The obvious two alternatives are their homogeneous distribution versus that peaked at small values (as in the «instanton liquid»). In more physical terms this question means an «ordinary» strong field screening by the production of quark pairs versus more specific phenomena connected with the topological charge.

The last topic discussed in this section is the flavour dependence of quark condensates. For heavy quarks the situation is rather simple, their pairs are present in vacuum for short time only, therefore this process is sensitive to local vacuum properties. The calculation in background field formalism is rather simple and the first term of the expansion in $1/m$ was found by Shifman et al. already in the work [5.13]:

$$\langle \bar{\Psi}\Psi\rangle = -\frac{1}{48\pi^2 m}\langle (gG)^2\rangle + O(m^{-3}) \tag{8.14}$$

The situation is more complicated for light quarks, and special investigations were made (based on the sum rules) in order to find effects of violation of SU (3) and isotopic SU (2) in vacuum. The results are collected in the Table 1, they suggest that the condensates decrease monotonously with m, starting from very small masses of the u, d quarks. Note that different authors and methods lead to similar results, so they seem to be relible. As a spectacular example we show at Fig.2 the results on the hyperon masses due to Reinders et al. [5.30].

Table 1

SU(3) and SU(2) asymmetry parameters of the quark condensates

$1-\langle\bar{s}s\rangle/\langle\bar{u}u\rangle$	$1-\langle\bar{d}d\rangle/\langle\bar{u}u\rangle$	Authors and references
0.2	—	Ioffe [5.24] (corrected according to erratum)
0.5	—	Narison and de Rafael [5.16]
0.19±0.02	—	Reinders et al. [5.30]
0.2	—	Malik [5.29]
0.1	—	Belyaev and Ioffe [5.28]
0.5	.006	Pascual and Tarrach [5.32]
0.2	.008	Chernyak et al. [5.42]
0.2	—	Ioffe and Smilga [5.72]

I have estimated this dependence in the «instanton liquid» model [6.8] and obtained the following results

$$1-\frac{\langle\bar{s}s\rangle}{\langle\bar{u}u\rangle}\simeq 1-(1+m_s^2/4M_{eff}^2)^{1/2}+m_s/2M_{eff}\simeq 0.2\div 0.3$$

$$1-\frac{\langle\bar{d}d\rangle}{\langle\bar{u}u\rangle}\simeq -\frac{m_u-m_d}{4M_{eff}}=(6\div 10)\cdot 10^{-3} \tag{8.15}$$

which agree well with data given in Table 1. However, it seems natural that (8.15) is more general than this model and it is interesting to see whether lattice calculations lead to similar results.

Finally, let me emphasize once more that the understanding of light quark effect in the vacuum parameters is now the key problem of the theory. It is especially true for lattice calculations, where evaluation of the fermionic determinant is extremely time-consuming. I think that qualitative understanding, leading even to very crude estimates of such determinant, may trigger fast progress in this field.

8.4. Large number of colours

The pioneer works [1.40] have raized the very interesting question concerning the properties of gauge theories at large number of colours. Another aspect of this problem is whether with the real number of colours $N=3$ we are close to this limit or not.

The main idea underlying this activity is that at large N the field is «less fluctuating» and exact or approximate solution of this problem will become possible. In particular, it was emphasized by Migdal [1.45] and Witten [1.41] that this limit is similar to the semiclassical one in the sense that there exists some particular («classical») field configuration (the «master field»), with relatively small fluctuations around it. As an example, for the parameters like R_G (8.7) it can be proven that

$$R_G \xrightarrow[N\to\infty]{} 1+O(N^{-2}) \tag{8.16}$$

which (using terminology of section 8.3) means that vacuum is of «homogeneous» type. This statement was strengthened by Eguchi and Kawai [3.40], who have shown that at large N one may consider only A_μ^a independent on coordinates!

It seems evident that at large N there is no place for short-range fluctuations. An example of instantons was studied in more details and Witten [1.41] have formulated some dilemma which, in rough presentation, sounds as follows: «either instantons or large N limit have nothing to do with reality». In order to explain this conclusion more clearly let us present here expression for the instanton density at large N (including the two-loop effect in the Gell-Mann—Low function, which is important here):

$$\frac{dn}{d\varrho} \sim \exp\left[N\left(2.91+\frac{5}{11}\ln\ln\frac{1}{\varrho\Lambda_{PV}}-\frac{11}{3}\ln\frac{1}{\varrho\Lambda_{PV}}\right)\right] \tag{8.17}$$

At infinitely large N instantons with small radius (for which the bracket is negative) drop away, while at some critical point ϱ_c there is some

qualitative phenomenon. In order to see whether semiclassical analysis have chances to be meaningful let us check whether the coupling constant at such radius is large or small. Unfortunately, $\varrho_c=(2\Lambda_{PV})^{-1}$ and we are in strong coupling domain, therefore instantons are indeed most probably «melted» completely!

By the way, rather strange phenomena may happen on the way toward large N. In particular, in the variational approach to the «instanton liquid» [2.22] it was found that at N around 20 it seems to be «frozen» into some dense «instanton crystall», so Lorents and colour symmetries may be spontaneously broken! (There are people looking for such phenomena in Grand Unification framework, say there are ideas that graviton is a tensor Goldstone particle developed due to spontaneous creation of the tensor condensate.)

Thus, observations of instanton-induced effects imply that we are not in fact close to the large N limit. To give an example, let us mention the famous η' meson: its mass is suppressed at large N (as all mixing phenomena [1.41]) unlike that of other lowest mesons, but in real world it is surprisingly heavy! Another well known consequence of the large N limit is the fact [1.41] that all quark loops are also $1/N$ effects and are inessential, in contrast to what was concluded in the preceeding section.

Finally, if this limit is not close to real case, is it so interesting at all?

I think that it is still very important part of the nowdays activity in QCD. In particular, it allows to study the long-range component of the vacuum field more clearly, without the short-range ones. One may hope that it will shed some light on the mechanism of colour confinement. And after all, we do not have many parameters in our disposal in QCD!

8.5. The hadrons: drops of the new phase or collective excitations in vacuum?

In this section we are going to compare two different trends in the approach to the problem of hadronic structure, which may be called macro- and microscopical ones. The first one implies that physical conditions inside hadrons and in the surrounding vacuum are completely different. In other terms, one considers the hadrons as some drops of completely new phase. The classical model of such type is the MIT bag model: energy difference of two phases is the volume effect (surface effects etc. are neglected).

The second approach is most spectacular in the sum rule and the lattice frameworks: one introduces weak «probes» in vacuum and study how the perturbations caused by them propagate in space-time.

Obviously, it is not clear beforehand which approach is more close to reality for very different situations are known in similar problems of the traditional physics. Rather similar to «bags» are the excitations in liquid helium connected with electrons: due to repulsion from atomic electrons and relatively large compressibility of this liquid there appear «bubbles» with effective mass of the order of 250 atomic mass, being therefore really macroscopic objects! Therefore «pressure balance» and other similar considerations are in this case completely justified. The standard example of the excitations of collective type are phonons in solids.

It is also important to note that sometimes confrontation of these two trends is caused just by different terminology used. For example, in the former case one introduces quarks into some region of space and discuss their influence on the vacuum properties (on the nonperturbative energy density etc.). In the latter case the vacuum fields are considered as some external ensemble and their influence on quark propagators is calculated. However, looking at this problem more closely we find that it is nothing but different order of integration over gauge fields and quark paths in the same functional integral!

However, in order that macroscopic approach makes sence, at least semi-quantitatively, certain conditions should be fulfilled. It is most likely that for ordinary lowest hadronic states they do not take place in real world.

The classical example in hadronic physics (which always was a problem for the composite models) is the pion. Being massless in the chiral limit, it can not even be stopped in some reference frame and can hardly be well localised. Quite on the contrary, the fact that extra quark-antiquark pair may be completely «lost» among multiple quarks of the vacuum condensate is crucial, that is why no extra energy is needed for them. Evidently, such Goldstone modes are much more similar to the phonons!

Considering other hadrons made of light quarks by the sum rules we again find that effects of SBCS (the quark condensate etc.) are the dominant ones in all cases. As it was discussed in chapter 6, in some approximation it presumably can be considered as appearance of the nonzero effective mass and «constituent» quarks. It is extremely important, that these objects seem to have relatively small dimensions compared to hadronic size, so the energy distribution inside hadrons is rather inhomogeneous. Connections between these observations and

recent suggestions that the vacuum is very inhomogeneous by itself are quite natural.

Let us also repeat once more, that there are good reasons to consider confinement as some relatively weak effect. In particular, in order to confine quarks inside hadrons it is sufficient to modify the vacuum energy density by only few percent!

Considering all this one can see that there is not much hope to find even «small bag» inside hadrons in which simple perturbative picture holds. Thus, ideas popular some time ago and suggesting that the problem of hadronic structure is simpler than (and not so directly connected with) the problem of vacuum structure are not confirmed. It is essentially the same problem!

However, the general philosophy of the macroscopic approach has rather deep roots and have survived, changing the object of its application. We come to these topics in the next section.

8.6. Can the macroscopic excitations of the QCD vacuum be studied in real experiments?

Many physicists just smile listening that such investigations of heavy ion collisions at high energies are announced to be relevant for the fundamental physics. (The typical joke of one well-known physicist is known, commenting that according to his observations the vacuum chamber of most accelerators allow for acceleration of boots up to 42-nd size.) It is true, such collisions are rather complicated phenomena. However, they are not more complicated than collisions of two protons (studied for a long time), but are much more effective in «vacuum excitation». Therefore many people believe that this activity will be among the most important experimental programms of the coming decade.

We have already mentioned in chapter 7 that macroscopically large excited system is very attractive from the theoretical point of view because it is the simplest imaginable problem. In addition, the methods for its investigation are well developed and they have been tested before many times in more traditional physics. We would also like to mention that macroscopically large system, if produced, is also more convenient for experiments: it is not a subject of so strong fluctuations as those known for *pp* collisions analysed event-par-event. However, can some macroscopic system be really created in experiments?

Starting with the most trivial question we may ask whether the necessary energy is available. Obviously, there is no problem here for, say, CERN SPS collider produce $p\bar{p}$ pair with the total energy 540 GeV. Assuming it to «dissipate» into vacuum excitations up to the energy densities of interest about 1 GeV/fm^3 we conclude that some «fireball» can be produced being as large as 540 fm^3! Such object is large compared to mean free path, being in excited matter only some fraction of fermi.

Unfortunately, this process has negligible probability because protons are too transparant. In the typical event half of the energy just «goes through» and form the so-called «leading nucleons». Another half is spent on pion production, but unfortunately it is shered among them in very specific way. In any reference frame (between two extremes, «lab» and «antilab» ones) one may observe about the same picture: only few secondaries have low energies and are produced «promptly» after collision, all others being the ultrarelativistic ones, coming from two «jets» in forward and backward directions and being formed at large distances. As a result, only about 1% of the total energy is spent to the «fireball» we are going to study!

In other words, trying to convert energy into the enthropy we come across problems with too low efficiency of this process. Similar situation takes place in thermonuclear studies (it is interesting that in this field heavy ion beems also look very promising).

Now, the next obvious question concerns the probability to create much larger «fireballs» in pp collisions. It was not so far studied systematically (although special experiments are now in preparation), but I may mention that in the UA5 experiment at SPS collider have seen events with compact clusters in rapidity of about 15 charged particles (which is about 5 times larger than the average density per such rapidity interval) on the probability level of few events per thousand. Not being an expert in such questions, I am still quite sure that with special trigger one may study events on the probability level orders of magnitude lower. It is probably useful to look in this direction analysing already existing data of different groups, for example it is easy to imagine that UA1 experiment have in fact seen events with «fireballs» containing up to hundred of pions!

Nevertheless, it is more reasonable to study this problem with heavy ion beams. The first obvious point is that energy in the individual collision is increased as atomic number A. The second observation is that this energy is used much more effectively. Let me comment on this point in more details.

The «additive» quark model (much advocated above and, in particular, explaining data on hadron-nuclear collisions well enough) suggests that the mean free path of constituent quark is about 5 fermi,

compatible with dimensions of even heaviest nuclei. This observation mean that nuclei are rather transparant as well, and more than half of the energy still may «go trough» them without interaction in typical events. Another difficulty is that instead of one common «fireball» one may find in fact just a series of independent collision centers at different positions in transverse plane (this is what would happen with «accelerated boots» etc. because they are not dense enough).

However, mean free path in excited matter is much shorter than in ordinary nuclei, only some fraction of fermi. As a result one may predict the «snow plow» effect, the rapid growth of excited areas under the flow of incoming matter. It is difficult to evaluate its effect numerically, but after all this is rather technical problem which can much better be studied experimentally. What is important, there are already evidences that the «tail» of the multiplicity distribution for nuclear-nuclear collisions do not drop fast toward the large multiplicity end. For example, JACEE experiment [7.90] have seen collisions of mediate and even light nuclei at energies of about 1 TeV/N, and with few percent probability the total multiplicity is of the order of one thousand charged tracks! (As it was already mentioned in chapter 7 these events have many unusual features, in particular larger $\langle p_\perp \rangle$.) So, with ISR-like collider and U beams the systematic studies of «fireballs» containing 10^4 particles is quite feasible!

Realization that such perspectives are practically feasible have recetnly created much excitement among experimentalists, and several specialized meetings were devoted to this subject. In section 7.5 different ideas were summarized presumably to be useful for such experiments.

Now a few words are in order on the main goals of these investigations. It is repeatedly said that its primary aim is to observe the new form of matter, the quark-gluon plasma. However, sceptics comment that such observations can not add much to our understanding of Nature since relatively weak interaction among quarks at small distances was demonstrating 15 years ago in deep inelastic scattering experiments.

Therefore it is reasonable to emphasize once more: our main goal is to understand the QCD vacuum structure. Observation of asymptotic (and thus rather simple) quark-gluon plasma is a step toward systematic investigation of the transition region, accurate tests of theoretical calculations etc. In particular, transition parameters provide direct information on the fundamental quantity, the so-called nonperturbative vacuum energy.

The situation here much resembles that with atmospheric pressure.

For centures people never pay attention to its reality, which have become completely obvious only when it was technically possible to pump the air out of some volume. Since the nonperturbative phenomena makes the physical vacuum to be lower in energy than the «empty» (perturbative) one, in order to «pump them away» one has to «pump in» sufficient amount of excitation energy. That is why heavy ion accelerators are needed!

Parting remarks

The strong interaction physics is at present at the stage of rapid development. Powerful theoretical methods have appeared recently, in particular semiclassical ones and lattice formulation, but it has become so far quite evident that their achievements are far reaching, qualitatively changing the quantum field theory in general.

Strong interaction phenomenology have now obtained some «new dimension»: it is considered as a potential source of more fundamental «phenomenology of the QCD vacuum», being the main object of the present work.

Finally; priorities in experimental programm have changed. There is not much progress in theoretical understanding of the traditional questions (like how the *pp* cross section depends on collision energy, etc.), but some completely different questions have obtained much attention (e.g. those considered in the last section) because there are hopes that their results will be much easier to connect with the underlying theory.

However, one should not forget that (as it is typical for any rapidly developing field) any new achievement leads to more new questions than provide answers. This tendency is clearly seen in the present work, leaving a lot of question open. Only well organized collaboration of multiple theorists and experimentalists will clarify answers to them. Among the main motivations of this review were their formulation in the most clear way, and if it will somewhat initiate their discussion its aim is fulfilled.

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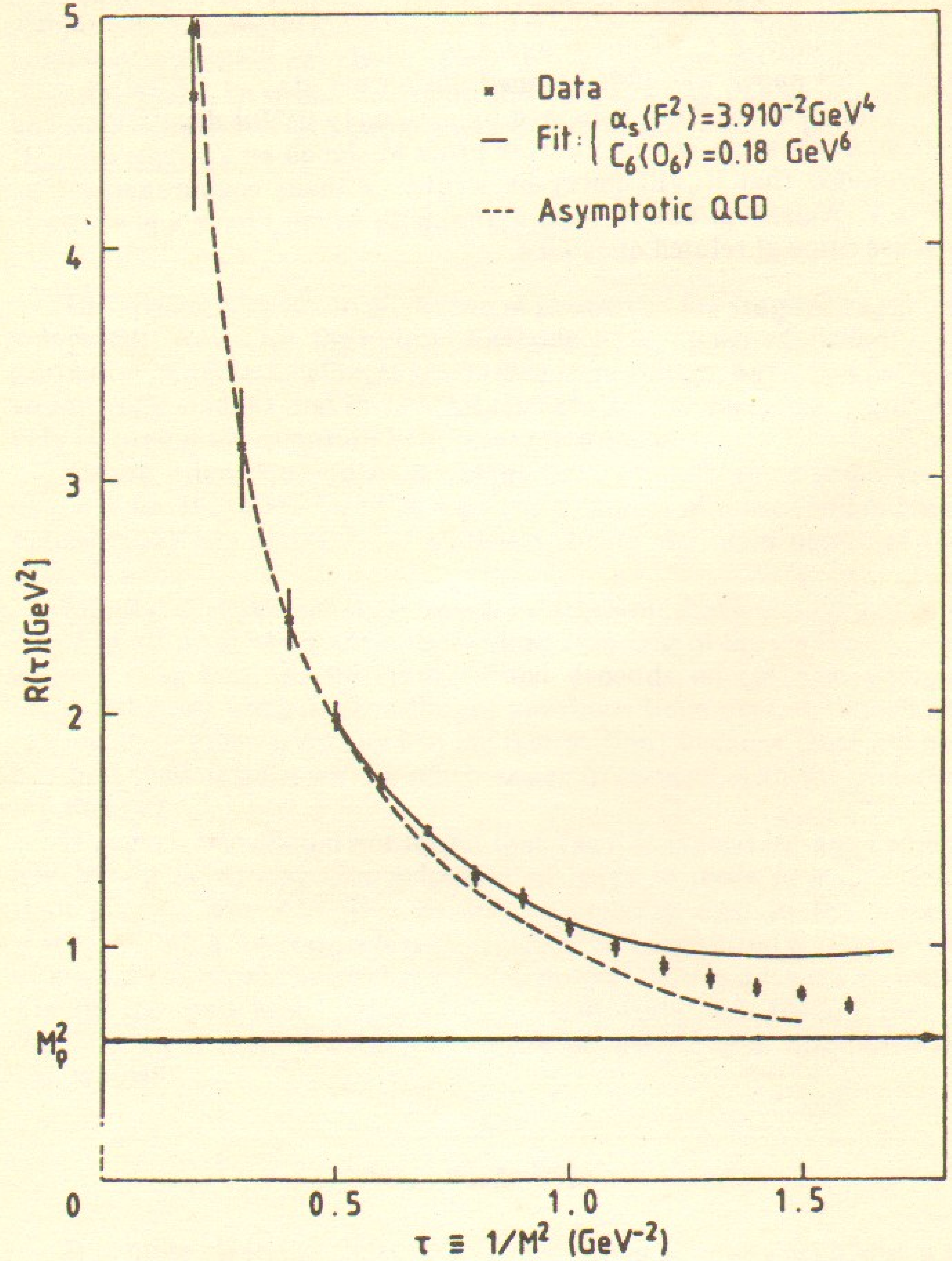

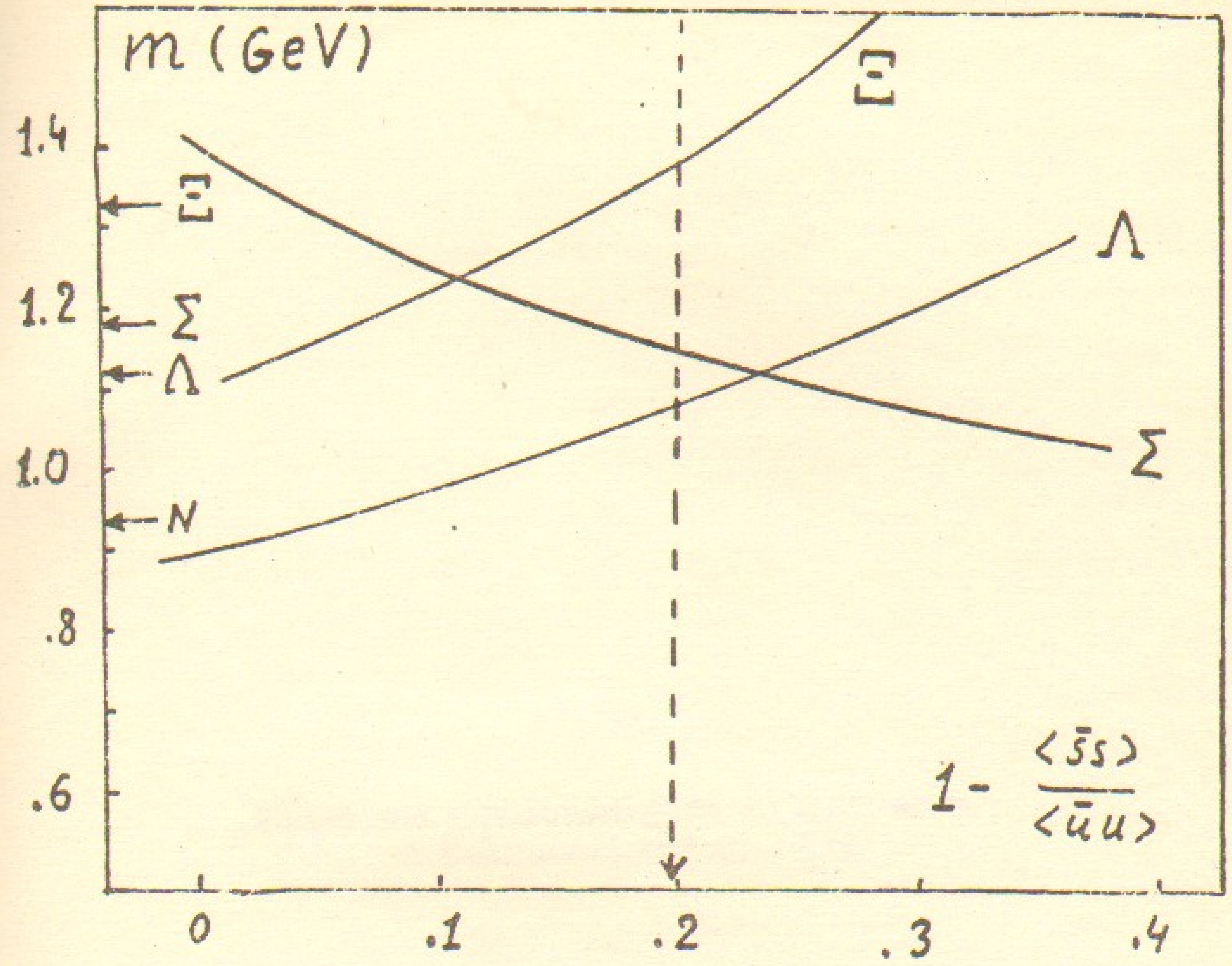

Fig.2. Dependence of hyperon masses on the quark condensate SU(3) asymmetry according to Ref. [5.30]. Arrows at the left show experimental values, the dashed line is the preferable value for the asymmetry parameter used in the text.

Fig.1. Logarithmic derivative

$$R(\tau) \equiv -\frac{d}{d\tau}\log \int ds \exp(-s\tau)\,\mathrm{Im}\,\Pi(s)$$

versus Borel parameter $\tau = 1/m^2$ (GeV^{-2}) according to work [5.15]. The points correspond to experimental data, the solid line is its fit with OPE formulae and parameters, indicated on the Figure. The dashed line corresponds to perturbative contribution only, it is shown for comparison.

E.V. Shuryak

Theory and phenomenology of the QCD vacuum
8. Conclusions and discussion

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