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ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ
СО АН СССР

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# TWO SCALES AND PHASE TRANSITIONS IN QUANTUM CHROMODYNAMICS

ПРЕПРИНТ 81-83

Новосибирск

# TWO SCALES AND PHASE TRANSITIONS IN QUANTUM CHROMODYNAMICS

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## Abstract

Several phenomenological and theoretical arguments are given for existence of the second scale in QCD, besides the confinement length, and the second phase transition connected with chiral symmetry breaking and instanton-induced effects.

It is well known that quark masses are relatively inessential ingredients of the QCD Lagrangian and in fact the only relevent dimensional parameter of this theory is $\Lambda$ which enters the famous asimptotic freedom expression for the coupling constant at distance $1/K$ namely $\alpha_s(K^2)=4\pi/(11-\frac{2}{3}N_F)\ln\frac{K^2}{\Lambda^2}$ ( $N_F$ is the number of flavours ). It is known now that $\Lambda$ is of the order of 100 Mev ( in $\overline{MS}$ scheem ).

However, the world of strong interaction is complicated enough to include some numerical factors leading to new scales. To give an example one may remind the well known discussion of the number of colors $N_c$ as large parameter.

In this paper we discuss several phenomenological and theoretical observations which we consider as arguments in favor of real existence of at least two scales and phase transitions in QCD, affecting the structure of ordinary hadrons made of light quarks. Of course, numerically these two scales are not very different, their ratio is 3-5, but even such parameter is of importance in so complicated problem.

The main and so far unexplained phemomenon in QCD is color confinement. It happens when the coupling constant becomes strong enough, and determines the so called confinement length

$$R_{conf} \sim 1/2\Lambda \sim 1/200 \text{ Mev} = 1 \text{ fermi} \qquad (1)$$

As experiment shows, this is also the scale of hadronic dimentions.

The instructive way of looking at QCD vacuum structure is to discuss not only its elementary excitations ( hadrons ), but macroscopic excitations, say by the nonzero temperature. In this case one is able to speak about qualitatively different phases, separated by phase transitions. In particular, in works [1] the so called deconfinement transition was predicted at some temperature $T_{conf}$ above which the confining strings " are melted". Interesting, that quite different estimates of $T_{conf}$ based on the instanton suppression [2] lattice numerical calculations [3] , analysis of data on hadronic collisions [4] all give very close values 200-250 Mev. More details on this transition can be found in reviews [5,6].

The second scale we are going to discuss in this work is the dimension of the constituent quark $R_{c.q.}$ , which is several times smaller than the confinement length

$$R_{c.q.} \sim 1/(0.5 \div 1 \text{ Gev}) \qquad (2)$$

Probably the most convincing argument in favor of this suggestion is given in recent work [9] where power scaling violation in deep-inelastic lepton-hadron scattering is discussed. It follows from this analysis that average values of certain four-fermion operators over the nucleon are very large. In order to explain them the cloud of virtual pairs surrounding the valence quark should have the dimensions (2).

Earlier works include the idea of constituent quark as the meaningful dynamical objects in multiple models devoted to description of hadronic spectroscopy. The smallness of $R_{c.q.}/R_{conf}$ naturally explains this idea, for the interaction between constituents quarks is in such case relatively small.

This idea is also in agreement with data on hadronic interactions, as seen from total cross sections [7] and interaction with heavy nuclei [8]. The value of quark-quark cross section $\sigma_{qq} \simeq \frac{1}{9}\sigma_{NN}$ used in these works is also in agreement with (2). And it also corresponds to rather high "intrincic" transverse momentum of the order of 1 Gev seen in high mass dileptons and high $p_t$ hadrons.

Now, what is the physical origin of such substructure inside ordinary hadrons and what interaction determins the scale (2) ? First, it should be connected with breakdown of chiral symmetry for constituent quarks ( unlike "current" ones from the Lagrangian ) have mass of the order of 0.3 Gev. Possible mechanism of this phenomenon, connected with the instanton-induced multi-fermion interaction is discussed in the works [10]. Although the general defect of the instanton calculus - - the strong divergency for large scale instantons - - does not allow for the real solution of the problem, it is observed that rather small instantons with $\rho \leq 1/0.5$ Gev can give the needed effect. This statement can also be demonstrated with the result of the work [11] where the effective mass of quark due to its interaction with quark condensate has been found*):

$$m_{eff} = \frac{2\pi^2}{3}\langle 0|\bar{\Psi}\Psi|0\rangle \rho^2 \simeq 0.1\,\text{Gev}^3\,\rho^2 \qquad (3)$$

where $\rho$ is the scale at which it is measured ( in fact, by size- $\rho$ instantons ). Again, the needed mass is reached at rather small $\rho$ , of the order of (2).

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*) The earlier result [14] obtained by OPE of the quark propagator is not gauge invariant, so its meaning is unclear.

There are other indications that instanton-induced effects are connected with rather large scale, although we are still unable to calculate their effect consistently. In particular, such effects are known to be important for $J^P=0^{\pm}$ mesons. For gluonium $0^-$ the prediction of the QCD sum rules[13] is that it has mass 2÷3 Gev. For ordinary pion the chiral symmetry demands small mass proportional to that of quarks. However, if one devides by it as follows

$$M \equiv m_\pi^2/(m_u + m_d) \qquad (4)$$

in order to get finite result in exact chiral limit, he also finds the result as large as 1.8 Gev.

So large effects are not seen for other hadrons, for which the mass is more or less close to the sum of constituent quar masses. Arguments given in papers[12, 13] show that it is also true for gluoniums with constituent qluon mass of the order of 700 Mev. However for hadrons made of heavy quarks the effects under consideration seem to be small.

Now we are going to put these observations on the languag of finite temperature theory. As far as instantons are suppr sed at high enough T, the chiral symmetry is restored. Let the temperature of corresponding phase transition be $T_{chir}$. What is the relation between $T_{chir}$ and $T_{conf}$ ?

First, they are not equal because they depend on quark ma ses in different way: for $m_q$ going to infinity $T_{conf}$ remai fixed while $T_{chir}$ disappears. The proposed picture of small instanton-induced constituent quarks being much smaller than hadrons naturally suggests that $T_{conf} < T_{chir}$. In this case there exists at least three phases as follows: (1) $T < T_{conf}$ being the gas of hadrons, (2) $T_{conf} < T < T_{chir}$ where hadrons are melted but the constituent quarks and quark condensate is present, and (3) $T < T_{chir}$, the plasma of nearly massless "current" quarks and gluons.

It is difficult at present to estimate reliably $T_{chir}$. The obvious idea is that constituent quarks are melted when they strongly overlap in space. More quantitative way is the studies of instantons at finite temperatures ( see e.g.[5,6] and references therein ) which are suppressed if $\rho \lesssim 1/T$, and so the interaction producing chiral symmetry breaking becomes weaker with higher T till it disappears. For orientation, $T_{chir}$ is of the order of 300 Mev. The corresponding barion charge density ( at T=0 ) is of the order of 100 $n_o$, where $n_o$ is ordinary nuclear density.

In conclusion, many observations point toward the existence of the substructure inside ordinary hadrons, the constituent quarks with dimensions (2). Presumably, two scales are due to two different phenomena: confinement and chiral symmetry breaking due to instantons. The most transparant it becomes with the macroscopic treatment which suggest two independent phase transitions.

The author acknowledge discussions with A.I.Vainshtein, V.I.Zakharov and V.F.Dmitriev on the subject of this work.

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Работа поступила - 22 июня 1981 г.

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Ответственный за выпуск - С.Г.Попов
Подписано к печати 22.07-1981 г. МН 03274
Усл. 0,4 печ.л., 0,3 учетно-изд.л.
Тираж 200 экз. Бесплатно
Заказ № 83.

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Отпечатано на ротапринте ИЯФ СО АН СССР