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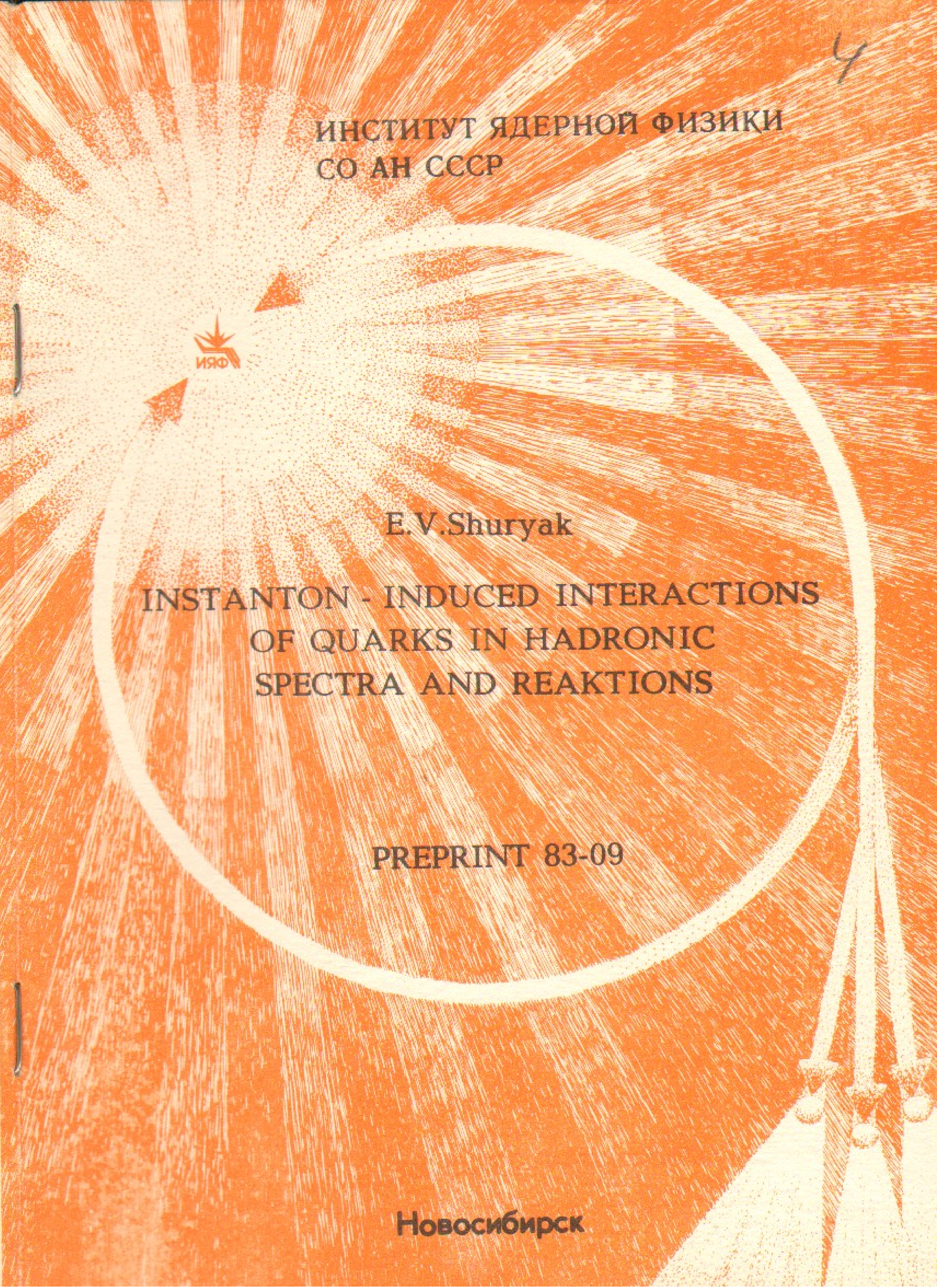

ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ
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E.V.Shuryak

INSTANTON - INDUCED INTERACTIONS OF QUARKS IN HADRONIC SPECTRA AND REAKTIONS

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INSTANTON-INDUCED INTERACTIONS OF QUARKS IN HADRONIC SPECTRA AND REACTIONS

E.V.Shuryak

Institute of Nuclear Physics,
630090, Novosibirsk 90, USSR

Abstract

We consider effective interaction between small scale instantons by the effective Lagrangian in Minkowski space-time. We present estimates of its intensity and give arguments that it is important ingredient of soft hadronic physics. Examples of pseudoscalar meson spectrum and flavour dependence of quark interactions in various hadronic reactions are considered in more details.

The understanding of nonperturbative phenomena in QCD vacuum is now much better than several years ago. Important phenomenological analysis was made in the framework of QCD sum rules [1], while interesting theoretical calculations are done by Monte-Carlo simulations on the lattice. We still do not understand the most famous property of the QCD vacuum, quark confinement, but it is not the only one and, moreover, not even the strongest nonperturbative effect. For example, the total energy density of nonperturbative fluctuations is about one order of magnitude larger than needed for confinement [2]. Respectively, asymptotic freedom breaks down at distances ρ_c several times smaller [1,3] than confinement length ($R_{conf} \simeq \frac{1}{2\Lambda} \simeq 1\, fm$).

These observations lead to the idea of two scales of nonperturbative phenomena [3], being due to strong fluctuations of size ρ_c of instanton nature. Although this small parameter is not so far explained, its applications in [3] give very reasonable results. Recently, two phase transitions suggested in [3] were discovered [4], also in [5] it was shown that instantons are suppressed at energy density one order of magnitude larger than that of the deconfinement transition.

In view of such promising results it is reasonable to consider effects of small instantons in wider context. In this letter we discuss how one can estimate them, and also give some phenomenological arguments that this kind of quark interaction is really important.

As far as instantons are assumed to be small in hadronic scale their effects can be considered by means of local effective Lagrangian, which can be used not only in Euclidean, but Minkowsky space as well. Roughly speaking, external momenta each component of which tends to zero equally belongs to both formulation of the theory. Formally, taking t'Hooft zero mode ψ_0 [6] in singular gauge one has in this limit $p_\mu \to 0$

$$\psi_0(p) \equiv \int dx\, e^{ipx}\, \psi_0(x) \longrightarrow \frac{1}{\hat{p}}\, 2i\sqrt{2}\, \rho\pi\, \chi_0 \qquad (1)$$

which up to constant spinor coincides with the ordinary propagator. It allows to "amputate" the legs of Green functions and to write down the effective Lagrangian[7]. We do not present here the arizing rather long expression, giving only the simplest term relevant for what follows 1)

$$\mathcal{L}_{eff} = \int dn(\rho) \Big\{ \prod_{i=u,d,s} \Big(m_i \rho - \frac{4\pi^2}{3}\rho^3 \bar{q}_{iR}\, q_{iL}\Big) \qquad (2)$$

Here the subscript L (R) means left (right) handed quarks and $dn(\rho)$ is the instanton density of radius ρ.

Such Lagrangian can be used for a number of problems. In ref. [7] its vacuum average was used in order to estimate the influence of nonperturbative quark fields in vacuum on a given instanton. In [3] it was used in the context in which all quark but one pair are due to vacuum fluctuations, producing an estimate for the quark effective mass. The key parameter here is the instanton density, taken from empirical value of the gluon condensate. As a result, the simple estimate follows

$$\Delta \mathcal{L}_{eff} = M_{eff}\, \bar{\psi}\psi , \quad M_{eff} \simeq \frac{\langle (g G^a_{\mu\nu})^2 \rangle}{32\pi^2 \langle \bar{\psi}\psi \rangle} \qquad (3)$$

Similarly, the four (and six) quark effective interactions follow from (2), for example there are terms such as

$$\Delta \mathcal{L}_{eff} = \lambda_{ud}\, \bar{u}_R u_L \bar{d}_R d_L + \lambda_{su}\, \bar{s}_R s_L \bar{u}_R u_L + \lambda_{sd}\, \bar{s}_R s_L \bar{d}_R d_L + \ldots$$

$$\lambda_{ud} \simeq \frac{\langle (g G^a_{\mu\nu})^2 \rangle}{16\pi^2 \langle \bar{u}u \rangle \langle \bar{d}d \rangle} ; \quad \lambda_{su} = \lambda_{sd} \simeq \lambda_{ud} \frac{\langle \bar{u}u \rangle}{\langle \bar{s}s \rangle - 3 m_s / 2\pi^2 \rho_c^2} \qquad (4)$$

As shown in [3], this interaction is sufficiently strong to produce chiral symmetry breaking, the reasonalble value of quark condensate and it is very important for correlators of pseudoscalar currents, explaining even details of SU(3) breaking.

But now let us look at (4) in more simple way, in the framework of quark models of hadrons. For the pion it is strong local attraction between quark and antiquark, producing the energy shift -(400÷600) MeV. So, it can presumably compensate the constituent quark masses and bring together the two pictures of a pion, as made of two constituent quarks and as a Goldstone massless spin wave in vacuum.

Such attraction is weaker for K, η, as seen from (4), and they are indeed heavier, by the amount much larger than just $m_s \simeq 150$ MeV. Finally, (4) is repulsive in η' case, making it heavier 2) than "normal" mesons (such as ρ) by similar amount. We think that more wide investigation of the role of such interactions in hadronic spectroscopy should be made.

One should not forget, of course, that the couplings given above are only some crude estimates. They are based on the assumption that elimination of a small instanton or the additional quark fields do not significantly change the local vacuum properties such as $\langle \bar{\psi}\psi \rangle$. As discussed in [3], its accuracy is not better than up to factor $2^{\pm 1}$. The polarization of a vacuum by the additional quark produce a "bubble" around it, identified with constituent quark [3], but at present we are not able to consider these effects quantitatively.

The characteristic feature of the t'Hooft interaction considered is that it is present mainly for light quarks, while for heavy ones it is suppressed. We note below that such trend is consistent with what is really observed in various hadronic processes.

We start with the discussion of the role of quark masses in the QCD vacuum. If the chiral breaking is caused by instantons, one has for each flavour $(M^{(i)}_{eff} + m_i)\langle \bar{\psi}_i \psi_i \rangle = const.$ Using the approximation $M^{(i)}_{eff} \sim \langle \bar{\psi}_i \psi_i \rangle$ one can estimate the magnitude of SU(3) and SU(2) violation for quark condensates

$$\langle \bar{s}s \rangle / \langle \bar{u}u \rangle = (1 + m_s^2 / 4M_{eff}^2)^{1/2} - m_s / 2M_{eff} = 0.7 - 0.8 \quad (0.8)$$

$$\frac{\langle \bar{u}u \rangle - \langle \bar{d}d \rangle}{\langle \bar{u}u \rangle + \langle \bar{d}d \rangle} = - \frac{m_u - m_d}{4 M_{eff}} \simeq 3 \div 5 \cdot 10^{-3} \qquad (4 \cdot 10^{-3}) \qquad (5)$$

Our estimates use M_{eff} = 200-300 MeV, the numbers in brackets are taken from QCD sum rule analysis [8], so there is good agreement with empirical information. We also mention the expression [1]

$$\langle \bar{\psi}_q \psi_q \rangle \xrightarrow[m_q \to \infty]{} - \frac{\langle (g G^a_{\mu\nu})^2 \rangle}{48\pi^2 m_q} + O\Big(\frac{1}{m_q^3}\Big) \qquad (6)$$

which in particular implies $\langle cc\rangle / \langle uu\rangle \simeq 1/10$.

Now, we suggest that the 4,6-quark instanton-induced interaction is responsible for the cloud of virtual "see" quarks in hadrons, which become real in hadronic reactions. An argument for it is the strong dependence on quark masses seen in data. Using $\langle\bar\psi\psi\rangle$ as a measure of coupling to instantons, one can estimate the relative production rates of s,c quarks to be about $(\langle ss\rangle/\langle uu\rangle)^2 \simeq 1/2$ and $(\langle cc\rangle/\langle uu\rangle)^2 \simeq 1/100$, which is roughly consistent with data on soft and hard hadronic reactions$^{3)}$.

The suppression of the contribution of heavier quarks is usually considered in perturbative context, as a simple kinematic effect. However, in some cases this viewpoint is difficult to support. For example, the "see" strange quarks in deep inelastic lepton-hadron collisions are similarly suppressed, while m_s is much smaller than the typical parton transverse momentum, 1-2 GeV.

One more example is given by the cross sections of constituent quarks in high energy collisions:

$$\sigma_{uN} \simeq \frac{1}{3}\sigma_{NN} \simeq 13\,mb\,,\quad \sigma_{SN} \simeq \sigma_{KN} - \frac{1}{2}\sigma_{\pi N} \simeq \frac{1}{2}\sigma_{\varphi N} \simeq 7\,mb \qquad (7)$$

$$\sigma_{cN} \simeq \frac{1}{2}\sigma_{\psi N} \simeq 1.7\,mb$$

Again, such trend is natural if heavier quarks affect the surrounding vacuum weaker than the light ones. It is difficult to to explain (7) in the framework of gluon exchange mechanism suggested in [9], as well as the quark additive relations like [10]:

$$\sigma_{NN} / \sigma_{\pi N} = 3/2 \qquad (8)$$

Our last comment is connected with corrections to this relation. Experimentally this ratio is about 1.7, while all estimates of shadowing (see e.g. [11]) give the negative sign of the correction to (8). However we note, that the interaction (4) is much more important for pion than for nucleon (e.g. it plays quite different role in their mass values) and it is strongly attractive. We suggest that in pion it leads to clustering of quarks at small distances, diminishing pion cross section. If the cross section of such cluster is about σ_{qq}, its probability in pion should be as large as 1/3.

In conclusion, we propose to apply the effective Lagrangian (2) and the factorization estimates (3,4) to quark models of hadrons and hadronic reactions. We demonstrate its utility for understanding of pseudoscalar meson spectrum, as well as flavour dependence of quark fluctuation in vacuum and of quarks produced in various hard and soft processes.

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Footnotes

1) These terms have the same flavour and chiral structure, (which is the only one important below) but vanish in the factorization-type estimates.

2) Note, that it is exactly the solution of Weinberg $U(1)$ problem as it was suggested by t'Hooft [6].

3) We remind that the so called "intrinsic charm" of hadrons is indeed at 1% level, see e.g. [12].

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Э.В.Шуряк

ВЗАИМОДЕЙСТВИЕ КВАРКОВ, ГЕНЕРИРОВАННОЕ ИНСТАНТОНАМИ, В АДРОННЫХ СПЕКТРАХ И РЕАКЦИЯХ

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