Science and Engineering Research Council

Rutherford Appleton Laboratory

Chilton DIDCOT Oxon OX11 0QX

RAL-93-049

$f_0(975)$, $a_0(980)$ as eye-witnesses of Confinement

F E Close Yu L Dokshitzer V N Gribov V A Khoze and M G Ryskin

November 1993

RAL - 93-049
LU TP 93-12

$f_0(975)$, $a_0(980)$ as eye-witnesses of Confinement

F.E. Close [1]

Yu.L. Dokshitzer [2, 3]

V.N. Gribov [4 5]

V.A. Khoze [6, 3]

M.G. Ryskin [3]

Abstract

We investigate some phenomenological consequences of an idea [1,2] that the $f_0(975)$ and $a_0(980)$ play a special role in the dynamics of quark confinement.

[1]Rutherford Appleton Lab, Chilton, Didcot, OX11 0QX, UK
[2]Department of Theoretical Physics, University of Lund, Sölvegatan 14A, S–22362 Lund, Sweden
[3]Permanent address: Nuclear Physics Institute, Gatchina, St. Petersburg 188350, Russia
[4]KFKI Research Institute for Particle and Nuclear Physics, Konkoly Thege ut 29, Budapest XII, Hungary
[5]Permanent address: Landau Institute, Moscow, Russia
[6]Center for Particle Theory, University of Durham, Durham DH1 3LE, UK

1 Super-Critical Confinement and "novel" hadrons

Recently one of us [1] has proposed a theory of confinement in QCD in which light quarks interact strongly enough that the total energy of quark antiquark pairs becomes less than zero. This results in the appearance of a new type of "condensate" consisting of strongly interacting pairs of light flavours $q, \bar{q}$ with positive kinetic energy but negative total energy. In the present paper we suggest some phenomenological tests of the theory (section 2 et seq.). First we briefly summarise the ideas in order to motivate and define terms for the subsequent phenomenology. For details of the theory we refer to Refs [1,2].

It is the existence of quarks with *very small* (current) mass $m \ll \lambda \sim 1$GeV that are essential to the theory. These lead to a radical change of the perturbative vacuum in the region between $1/\lambda$ and $1/m$, the Compton wavelength of the light quarks, analogous to the phenomenon of "super-charged" ions in QED [3].

In QED, when the electric charge of a nucleus exceeds some critical value $Z \gtrsim 180$ ($Z > 137$ for a point-like charge), light fermions in the vacuum start to "fall on the centre" creating stationary states with negative electron energy, $\epsilon < -m$. This causes instability of the perturbative vacuum. One consequence is that nuclei with $Z > Z_{crit}$ cannot survive free, and they decay: $Z \rightarrow (Z-1) + e^{+}$.

In QCD the Coulomb-like attraction between fermions leads to a similar falling on the centre. It is important to notice that this happens not only for a light quark in an external field of a heavy quark (as in the above QED example) but for interaction between light quarks as well.

Any coloured particle in QCD acquires a spatial colour charge distribution due to gluonic vacuum polarisation. The "super-critical" phenomena develop when the size of the volume $r_0 \equiv \lambda^{-1}$ in which the total charge $\alpha_s(\lambda)$ exceeds some critical value $\alpha_{\rm crit}(\sim 0.6)$, is much smaller than the light quark Compton wavelength $m^{-1} \sim (5\text{–}10 \text{ MeV})^{-1}$; *i.e.* the parameter $m/\lambda \ll 1$. Contrary to the QED case where the nuclear charge would decrease by one unit, in the QCD context this results in producing a *colourless* bound state with negative total energy which causes instability of any coloured state.

The existence in the theory of the small parameter $m/\lambda \ll 1$ makes it possible to construct a non-linear equation for the quark Green function [1] that is a relativistic analogue of the gap equations in the theory of super-conductivity and the Nambu-Jona-Lasino model.

Starting from $\frac{\alpha_s}{\pi} > \frac{\alpha_{\rm crit}}{\pi} \sim 0.2$ this equation has two types of solutions. The first solution corresponds to a fast increase of fermion masses and resembles the properties of the well-known spontaneous symmetry breaking solutions (for $m = 0$). The second solution corresponds to a new type of phase transition and has the following features.

In Dirac theory fermions can have both positive or negative energies $q_0 \geq \epsilon \equiv (m_1^2 + \vec{q}^{\,2})^{1/2}$ and $q_0 \leq -\epsilon$; in Dirac's language, the former zone is empty and the latter is occupied. The energy range $-\epsilon \leq q_0 < \epsilon$ may be looked upon, by analogy with the solid state physics, as the forbidden zone: Normal excitations correspond to the creation of $q\bar{q}$ pairs with energy $\geq 2m_1$.

As far as positive energy quarks are concerned, the fact that the lower zone $0 \leq q_0 < \epsilon$ is forbidden and the upper one $q_0 \geq \epsilon$ empty, implies that the mean number of quarks (and antiquarks) in the vacuum state is zero.

In the solution corresponding to the new phase transition, the latter statement is no longer true. In the vacuum, quarks with *positive* kinetic energy are present but are clustered into "super-bound" $q\bar{q}$ pairs with *negative* total energy.

Thus a picture emerges of the vacuum as a conductor (instead of that of "Dirac's insulator"); there is also a new mass scale $\mu_F \sim \lambda$ which reflects the position of the "Fermi surface" separating the occupied and empty zones. The former parameter m_1 now describes the effective mass of quark excitations in the upper zone and becomes complex (in a conductor single electron excitations decay with time). The specific relation between $\mathrm{Re}\, m_1 > \mu_F$ and the corresponding complex effective quark mass in the lower zone, $\mathrm{Re}\, m_2 \lesssim \mu_F$, depends crucially on the dynamics near the Fermi surface and on current quark masses (if any): this must be studied quantitatively but lies beyond the present work.

This form of the quark spectrum suggests the possibility of new types of vacuum excitations which correspond to pair creation in the new zones *below* the Fermi surface (see Fig. 1) and manifested as $I = 0, 1$ nonstrange mesons.

These excitations correspond to quarks and antiquarks with negative kinetic energy that are interacting repulsively leading to positive total energy. (We shall denote these quark states by $q_{(-)}$ in contrast to the conventional positive energy states, $q_{(+)}$). It is the existence of the $q_{(-)}$ modes that causes instability of isolated quarks and results in colour "neutralisation" through "decay" into hadrons; $q_{(\pm)} \rightarrow M_{(+)} + q_{(-)}$.

Normal excitations corresponding to creation of $q\bar{q}$ pairs with mass-scale m_1 also have to exist, of course. Thus in the theory there are two types of hadrons ("normal" and "novel") and since the new condensate consists only of u,d quark flavours, SU(3) flavour symmetry will be badly broken for these novel states. In reality the normal hadrons will have some admixture of the "novel" (negative kinetic energy) quark states and vice versa. For baryons one expects the superposition of the two types of state corresponding to three quarks with large mass, m_1 which could be described by the non relativistic quark model and another state which corresponds to three negative energy quarks with repulsion. The latter is essentially an excitation of the condensate that has a chance to be described in terms of self-consistent pion field as in the Skyrmion model.

A notable feature of the new states is that as their constituents have negative kinetic energy and the interaction that elevates the meson mass to a positive value must be repulsive, one expects that the system's mass is large for small systems and small for spatially extended systems. Here "large" and "small" are with respect to $\mathcal{O}(\lambda \sim 1\mathrm{GeV})$ where $\alpha(\lambda) = \alpha_{\mathrm{crit}} = \mathcal{O}(1)$. The lowest mass strongly interacting states of the new type are expected to be scalars and pseudoscalars [2].

The purpose of this paper is to abstract some phenomenological consequences of the above "axioms" [1,2].

2 $f_0(975)$ and $a_0(980)$ as "Vacuum Scalars"

Given the above qualitative features, it is tempting to identify the $f_0(975)$ and $a_0(980)$ as compact nearly degenerate systems of (negative kinetic energy) u and d flavours

$$f_0 = \left(u\bar{u} + d\bar{d}\right)/\sqrt{2}$$
$$a_0 = \left(u\bar{u} - d\bar{d}\right)/\sqrt{2}\,.$$

As we shall discuss below, it is possible that the corresponding pseudoscalar pair consists of $\pi(1300)$ and one of the nearby η states. The *light* pseudoscalars, π and η, are expected to be mainly normal states; any admixture of negative energy u and d pairs in the *light* pseudoscalars will presumably be at *long* range.

We expect that the "vacuum scalars" (VS) $f_0(975)$ and $a_0(980)$ are compact states with a size

$$r_{\mathrm{VS}}^{-1} \gtrsim \lambda \sim 1\mathrm{GeV} \gg m_1\,,\, m_s \,>\, m_2$$

(where m_1, m_s are respectively the masses of the constituent positive energy u,d, and s flavours). In such circumstances, decays of f_0 which require the creation of pairs of light flavours (m_1) or strange quarks (m_s) have a good chance to be free from any "strangeness suppression". Empirically the coupling to KK and $\pi\pi$ for the f_0 appear to be comparable [4,5]. The hadronic couplings of the a_0 are currently unclear, see *e.g.* Ref. [6].

2.1 Coupling to "normal" hadrons

$f_0(975)$ decay width. The suppressed widths of the f_0 and a_0 have been a long-standing problem for the $^3P_0$ $q\bar{q}$ interpretation of these states in the quark model. For S-wave decays of $^3P_0$ $\bar{q}q$ into $\pi\pi$ one would expect [7] a width of 500–1000 MeV in contrast to that of the $f_0(975)$, for example, whose width is ≈ 50 MeV.

A recent analysis of $\pi\pi$ and $K\bar{K}$ processes [4] finds that the $f_0(1400)$ of the PDG [8] is better described as "a very broad $f_0(1000)$ of width around 700 MeV", which is thereby a good candidate for the conventional $^3P_0$ state; in addition this state is strongly decoupled from the narrow $f_0(975)$ even though they have superficially the same quantum numbers**. The $\gamma\gamma$ width of the $f(1000/1400)$ state is consistent with it being the $^3P_0$ [9,5].

Both the suppressed width of the $f_0(975)$ and the negligible coupling to the $f(1000/1400)$ arise rather naturally in our picture of these states.

The decay $f_0(975) \to \pi\pi$ occurs either by the "direct" transition from the compact $f_0[q_{(-)}]$ system to the long range $q_{(-)}$ component in the π wavefunction, or by "tunnelling" to the dominant $q_{(+)}$ component of the π. Each of these dynamically causes a suppressed width and nugatory mixing with the $f(1000/1400)$ $^3P_0$ state.

In the "direct" transitions to the $q_{(-)}$ component, the small width is due to the small overlap between the $f_0(975)$ compact $\mathcal{O}\left(1\mathrm{GeV}^{-1}\right)$ wavefunction and that of the more extended pseudoscalar π. The alternative dynamics is that the transition is from the $q_{(-)}$ initial state

**hereafter we denote this state as $f(1000/1400)$

to the $q_{(+)}$ component of the final state pions. This "tunnelling" or "annihilation" from the initial compact system is also expected to be suppressed but the theory is not yet developed enough to give a definite prediction. As an educated guess one might attempt to look upon this transition as an "annihilation" of $q_{(-)}$'s into $q_{(+)}$'s. Then as far as the $q\bar{q} \to$ any number of gluons is helicity violating, the rate can be estimated parametrically as

$$\Gamma(f_0(975) \to \pi\pi) \sim \left(\frac{\alpha_s^2 m_2}{\mu}\right)^2 \Gamma(a_1 \to \rho\pi) \approx \frac{1}{10}\,\Gamma(a_1 \to \rho\pi) \tag{1}$$

where we have made a measure of the ratio of widths of the "novel" and "normal" states by a comparison of $f_0(975) \to \pi\pi$ and the similar S wave decay of the "normal" P-state meson $a_1 \to \rho\pi$; the power of α_s has been taken from the leading two-gluon channel, μ is some hadronic reference mass scale on dimensional grounds, and we have used the empirical values for the widths in the final equation. If the $f(1000/1400)$ were established as the "normal" $^3P_0$ state, then the $f_0(1000/1400) \to \pi\pi$ would be a more direct comparison; note that this would give essentially the same result as eq.(1).

$f_0(975)$ production in decays of "normal" hadrons. At leading order the $f_0(975)$, $f(1000/1400)$ are $q_{(-)}$ and $q_{(+)}$ excitations respectively, and hence are orthogonal states. Wavefunction mixing contains the helicity suppression factor m_2/m_1 and an extra power of small $\alpha_s(\lambda)$ in tunnelling and thus should be smaller than would be expected were the $f_0(975)$ a glueball, for example. Hence, extreme decoupling may be more natural in the present picture.

However, VS do decay (*e.g.* $f_0(975) \to \pi\pi$) with width of order tens of MeV. Taking this number as a quantitative estimate for the phenomenological magnitude of the "normal"/"novel" (ad)mixture, we anticipate that such a width should be typical for the VS "appearance" in the decays of "normal" $q_{(+)}$ states: the tunnelling between $q_{(-)}$ and $q_{(+)}$ states that suppresses the $f_0(975)$ width will also suppress its production in decays of conventional $q_{(+)}$ hadrons.

If A,B are such hadrons, then by analogy with eq.(1) we expect that (apart from phase space effects)

$$\Gamma(A \to B + f_0(975)) \approx \frac{1}{10}\,\Gamma(A \to B + f_0(1000/1400))\,.$$

Thus we would expect qualitatively that $f_0(975)$ and $a_0(980)$ will be suppressed relative to $f(1000/1400)$ say in processes where the decaying hadron has a "normal" hadronic width (of order 150 MeV or more). At the same time, in processes where selection rules and/or phase space suppress the total width to be of order tens of MeV or less, the $a_0(980)$ and $f_0(975)$ may show up (the "normal competition" has been removed).

A survey of the Particle Data Tables shows consistency with this picture (though this may be due to lack of search as much as lack of signal for the $f_0(975)$).

As a first example we note the conventional quark model state, $\pi_2(1670)$, whose width is 250 MeV: the $\pi + f_0(1000/1400)$ channel†† is seen with a branching ratio at the level of

††recall that the PDG call it 1400 but we use the new Morgan-Pennington numbers

ten percent whereas there is no reported sighting of $\pi + f_0(975)$. To test this we suggest systematic study of

$$f_0(975)/f_0(1000/1400) + \text{meson(s)}$$

in the decay products of "conventional" $q_{(+)}$ states with large widths (we expect the ratio to be small).

The vacuum scalars may be anticipated to be significant in the decays of hadrons of suppressed widths. An example is the $f_1(1285)$ whose width of 25 MeV is due to G-parity suppressing the "dominant" two body decays. In this latter case the $a_0(980)$ (at least) is a prominent two-body channel. An extreme case is the ψ (where the small width is due to short distance physics and this will make the a_0 or f_0 production particularly favourable). This is discussed later.

A systematic study of the ratio of "novel" and "conventional" states in the decays of various hadrons is encouraged.

Comment on the $a_0(980)$ decay width. The uncertainties on the $q_{(-)}$ content of the π and η make it hard to relate the relative size of $\Gamma(f_0(975) \to \pi\pi)$ and $\Gamma(a_0(980) \to \eta\pi)$. However,we expect that $\Gamma(a_0(980) \to \eta\pi) \geq \Gamma(f_0(975) \to \pi\pi)$ (even after allowing for the reduced phase space). First, the smaller momentum transferred to the final state in the a_0 case causes less dramatic overlap suppression between the $q_{(-)}$ components of the initial and final states. Furthermore, any $q_{(-)}$ in the $\eta(550)$ are likely to be at shorter distance than in those in the light π and hence will aid the $(a_0(980) \to \eta\pi)$ decay. A relatively "broad" width of the a_0 may be necessary in our picture both for the above qualitative reasons and in order that the branching ratio for $a_0(980) \to \eta\pi$ be large enough for the $\gamma\gamma$ width to be small (as required by eq.(9), see below).

2.2 The $f_0 - a_0$ mass splitting

The $f_0 - a_0$ mass splitting due to (helicity violating) $q\bar{q} \to gg$ annihilation can be estimated as

$$M(a_0) - M(f_0) \sim \frac{(\alpha_s^2(M)\, m_2)^2}{2M} . \tag{2}$$

The suppression of $q_{(-)} \to q_{(+)}$ transitions expressed in eq.(1) implies that

$$\left(\alpha_s^2(M)\, m_2\right)^2 \sim \mu^2 \cdot \frac{\Gamma(f_0(975) \to \pi\pi)}{\Gamma(f_0(1000/1400) \to \pi\pi)} \tag{3}$$

If the parameter μ is naturally associated with the constituent mass scale $m_1 \sim \frac{1}{3}$GeV then we would have

$$M(a_0) - M(f_0) \approx \mathcal{O}(5\text{MeV}) \tag{4}$$

in accord with the data [8]. However, one should exercise some caution here as numerical factors in a detailed modelling could change these conclusions by an order of magnitude in either direction. The actual mass difference for $a_0 - f_0$ is rather poorly determined empirically. At this stage we note only that the picture appears to have some consistency.

2.3 Coupling to photons

The $\gamma\gamma$ couplings to f_0, a_0 promise to be rather sharp probes of the mesons' substructure. Their $\gamma\gamma$ widths are up to an order of magnitude smaller than expected for conventional $^3P_0(q\bar{q})$ states [10,9].

The $\gamma\gamma$ branching ratio is similar to that expected for the $^3P_0$ states, suggesting that a common suppression is at work for the $\gamma\gamma$ and total widths of the $f_0(975)$. This is natural in the present picture.

In the quark model these decays violate helicity conservation in the zero mass limit. If we extract the "nonstrange" component of the η' width into $\gamma\gamma$ (approximately 8/9 of the total) then the suppression of the helicity violating $\Gamma(0^+ \rightarrow \gamma\gamma)$ decay can be used to estimate the (smaller) "novel" mass m_2:

$$\Gamma_{\gamma\gamma}(\eta'_n) \approx 4\text{keV} \; ; \qquad \Gamma_{\gamma\gamma}(f_0) \lesssim 670\text{eV} \; ; \tag{5a}$$

$$\left(\frac{m_2}{m_1}\right)^2 \approx \frac{\Gamma_{\gamma\gamma}(f_0)}{\Gamma_{\gamma\gamma}(\eta')} \lesssim \frac{1}{6} \, . \tag{5b}$$

Note that the essential dynamics here is exactly as for the case of the $f_0(975) \rightarrow \pi\pi$ suppression discussed above. A detailed comparison is clearly rather naive as there are S and P-wave factors that will influence the $\gamma\gamma$ example in contrast to the S-wave dominated hadronic decays eq.(1). Note that this implies the welcome result that $m_2 < m_1$; in particular, if we identify $m_1 \approx 350$MeV as the scale of constituent quark masses then $m_2 \lesssim 150$MeV. However, at this stage we emphasize that more detailed modelling is required before too strong conclusions are drawn.

The most immediate test of the entire hypothesis and one that is free from detailed dynamical assumptions (such as mass scales) comes from the ratio of the f_0 and a_0 amplitudes to $\gamma\gamma$ as this probes primarily the squared charges of the mesons' constituents as well as their relative phases. In the present theory where the f_0, a_0 are compact, the $\gamma\gamma$ decays are short distance dominated and the relevant couplings are directly to the u, d flavoured quarks; thus one expects

$$\frac{\Gamma(f_0 \rightarrow \gamma\gamma)}{\Gamma(a_0 \rightarrow \gamma\gamma)} = \frac{25}{9} \, . \tag{6}$$

This is to be contrasted with the hypothesis [11] that the f_0, a_0 are diffuse $K\bar{K}$ molecular states in which case the $\gamma\gamma$ coupling will be dominated by the $K\bar{K}$ loop [12] and the widths be equal. The values quoted by the Particle Data Group [8] have large uncertainties and do not discriminate among models,

$$\begin{aligned} \Gamma(f_0 \rightarrow \gamma\gamma) &= 0.30 \pm 0.10 \text{ keV} \, , \\ \Gamma(a_0 \rightarrow \gamma\gamma) &= 0.19 \pm {}^{0.17}_{0.14} \text{ keV} \, . \end{aligned} \tag{7}$$

However, a recent analysis by Morgan and Pennington [4] has modified these numbers. The current world average is [8]

$$\begin{aligned} \Gamma(a_0 \rightarrow \gamma\gamma)B(a_0 \rightarrow \eta\pi) &= 0.24 \pm 0.08 \text{ keV} \; ; \\ \Gamma(f_0 \rightarrow \gamma\gamma) &= 0.56 \pm 0.11 \text{ keV} \, , \end{aligned} \tag{8}$$

and the absolute magnitude of the a_0 width and the ratio of the two depends on the poorly determined $B(a_0 \to \eta\pi)$. This has often been approximated by unity (as in the numbers cited above in eq.(7)) whereas the value could be below 50 percent. Given that $B(a_0 \to \eta\pi) \leq 1$ we can only limit the ratio (6)

$$\frac{\Gamma(f_0 \to \gamma\gamma)}{\Gamma(a_0 \to \gamma\gamma)} \leq \frac{21 \pm 4}{9 \pm 3}\,. \tag{9}$$

Information on the $a_0 \to \eta\pi$ couplings from LEAR [13], Fermilab [14] and from the impending $\phi \to \gamma a_0 \to \gamma\eta\pi$ at DAFNE [15,12] will be important in helping to clarify this important datum.

We anticipate [12] that the branching ratio for production of $\phi \to \gamma a_0$ in the present picture will be of order 10^{-6} due to the quark line disconnected production process. It is possible that the $\phi \to \gamma f_0$ could be somewhat larger due to its spatially compact nature which may enable enhanced production from the vacuum (see also the subsection on "Onium decays"). In any event, the branching ratios and the ratio of the branching ratios for $\phi \to \gamma f_0/\phi \to \gamma a_0$ should distinguish the present picture from a $K\bar{K}$ molecule interpretation [11,12].

2.4 Looking for partnership

The light pseudoscalar states appear to be more complex structures than their scalar analogues (*e.g.*, containing both $q_{(+)}$ and $q_{(-)}$ components [2]) and so we are not able to say anything about the $\pi - \eta$ mass splittings at this stage.

We expect that there will also be compact pseudoscalars made of $q_{(-)}$ modes and existing around 1GeV in mass. The large ratio

$$\Gamma(\eta'(960) \to \gamma\gamma)/\,\Gamma(f_0 \to \gamma\gamma)$$

(see eq.(5)) suggests that the $\eta'(960)$ is not dominantly a compact $q_{(-)}$ state. Therefore it is to the $\pi(1300) - \eta(1440)$ region that we look for pseudoscalar analogues of the $a_0(980) - f_0(975)$ states.

It is possible that there are two nearly degenerate η states in the 1440 region, the "normal" one decaying dominantly to K^*K and the other being the "novel" state decaying via π emission to its scalar "partner"

$$\eta(1440) \to \pi a_0(980)$$

with a moderate width and feeding both the $K\bar{K}\pi$ and $\eta\pi\pi$ final states (see the "Note on the $\eta(1440)$" on page VII.42 of Ref. [8].) As for the photon width, we expect that (*cf.* eq.(5))

$$\Gamma(\eta(1440) \to \gamma\gamma) \leq 1\text{keV} \approx \Gamma(f_0(975) \to \gamma\gamma)$$

which is consistent with the present experimental limit.

If the $\pi(1300)$ is the isovector partner there is the problem of explaining its broad width. By analogy with the $f_0(1000/1400) - f_0(975)$ and possibly also the $\eta(1440)$ system we suggest therefore that the broad illdefined structure called $\pi(1300)$ may in fact be a combination of a conventional $q_{(+)}$ state and a "novel" $q_{(-)}$ state which are strongly decoupled from one another. We expect that this latter state decays in a manner analogous to the $\eta(1440)$, namely by the chain $\pi(1300) \to \pi f_0(975)$ and with a comparable width (some 50 MeV). Isolating a πf_0 contribution from the $\pi\pi\pi$ continuum or in $KK\pi$ is a challenge.

3 Search for Scalars in Hard Interactions

This picture of the f_0, a_0 as compact "vacuum scalars" suggests conditions where their production and isolation may be favourable.

The spatial separation of coloured objects produced in a hard interaction causes a collective negative-energy quark current built up from consecutive decays

$$q_{(+)} \to M_{(+)} + q_{(-)}\,, \tag{10a}$$
$$q_{(-)} \to M_{(+)} + q_{(-)}q_{(-)}\bar{q}_{(-)}\,. \tag{10b}$$

It is the existence of the $q_{(-)}$ quark modes in the theory of [1] that causes instability of isolated quarks and results in colour neutralisation (or "confinement"). Within the sequence of the (10b) decays one could expect "vacuum scalars" to show up.

To illustrate the idea here, consider the $q\bar{q}$ produced in e^+e^- annihilation. As the coloured $q\bar{q}$ move apart from one another, a colour "neutralisation" current flows between them. Initially this is due to (perturbative) gluons, then at larger distances as the force increases a negative-energy quark current develops. For inclusive production at high energy the final state is dominated by soft production of many particles for which traditional ideas apply; it is in the (near-)exclusive processes, which are relatively improbable at high energies and where abnormal energy goes into the production of relatively few particles, that the negative energy quark current flows and consequent production of the "vacuum scalars" f_0, a_0 is expected to become more important. The essential sequence is that the $q_{(-)}$ and $\bar{q}_{(-)}$ produced in colour neutralisation via eq.(10) bind to form a "vacuum scalar" that is phase-space displaced from the leading hadron(s) $M_{(+)}$. One may attempt to enhance the signal by studying hadroproduction with *finite* but *larger than typical* separation between "neighbouring" hadrons.

With these ideas in mind we suggest the following event configurations as worthy of investigation:

- **"Next-to-the-leader"** topology:
  1. e^+e^- annihilation:
     (a) Measure the relative yield of (2π) resonances (*e.g.*, ρ, f_0, f_2) next to the leading particle in jets as a function of relative rapidity $\Delta\eta$ with respect to, say, thrust axis;
     (b) *ibid.* with respect to leading D, B triggered in heavy quark jets in the Z^0 peak.

     With $\Delta\eta$ increasing one could expect an increase of the ratios

$$f_0/\rho\,, \quad f_0/f_2\,, \quad etc.$$

2. large-p_t hadron-hadron interactions:
   Measure the relative amount of f_0 production as a function of p_t of the leading hadron.

- **"Isolated Meson"** topology:

  In e^+e^- annihilation, $\gamma\gamma \rightarrow$ jets, $p\bar{p}$ annihilation and Onium decays measure the relative production of vacuum-scalar mesons that are

  1. isolated in rapidity from other hadrons, (*e.g.* central production) as a function of the size of "rapidity window". We note the recent report of f_0, f_2, ρ production in Z^0 decays at LEP [16] and the first f_0 seen at DESY [17] and urge that these events be analysed as a function of the rapidity window.
  2. as a function of total event multiplicity (less particles $\rightarrow$ larger "isolation" $\rightarrow$ larger yield of VS).
  3. as a function of total energy (*e.g.*, s of $p\bar{p}$ annihilation at LEAR [13] or Fermilab [14]).
  4. in e^+e^- annihilation immediately above flavour threshold at a τ-Charm-Factory or a B-factory. As s increases we expect that $D\bar{D}f_0$, $D\bar{D}a_0$ and $B\bar{B}f_0$, $B\bar{B}a_0$ final states will be significant among low multiplicity events. Measure the relative importance of heavy hadrons accompanied by a_0, f_0, f_2, ρ in such experiments.

- **Proton Antiproton annihilation at rest**

  It is reasonable to expect that the proton will have a component containing three quarks with negative kinetic energy[2]. If this is true, then $p\bar{p}$ annihilation at rest can contain three quarks and three antiquarks with negative energy. But these correspond to the excitation of the new condensate and in such circumstances it will be natural that the products are $\pi\eta$ **and also** the scalar states f_0, a_0. We note that these states are rather clearly seen in the LEAR $p\bar{p}$ final states [13]. It will be interesting to study their production rate as a function of energy and, at higher energies, rapidity.

- **Short distance annihilation: Onium decays**

  As the vacuum scalars are expected to be spatially compact relative to "normal" hadrons, their production may be relatively enhanced in processes that are short distance dominated, such as ψ and Υ decays. The $f_0(975)$ was seen in ψ decay as a resonance peak recoiling against the ω and ϕ in $\psi \rightarrow \omega f_0(975)$ and $\psi \rightarrow \phi f_0(975)$. ARGUS reported recently [17] the first measurement of $f_0(975)$ production in the Υ energy range: a significant inclusive production rate has been found, namely,

$$\frac{f_0(975)}{\rho^0(770)} = \begin{cases} (7.2 \pm 1.8)\% & \text{continuum}\,, \\ (11.7 \pm 3.0)\% & \Upsilon\,. \end{cases}$$

  At the Z^0 the corresponding ratio measured by DELPHI in the $x_p > 0.05$ momentum range [16], is

$$\frac{f_0(975)}{\rho^0(770)} = \frac{0.10 \pm 0.04}{0.83 \pm 0.14}\,.$$

We urge study of this ratio as a function of rapidity and the separation from other hadrons in phase space.

It is noticeable that the $\eta(1440)$ system is prominent in $\psi \to \gamma + X$ (which is why we were attracted to this as a possible novel candidate). If these ideas are right, then we anticipate that the S-wave decay of the η_c into a pair of novel states

$$\eta_c \to f_0(975) + \eta(1440) \tag{11a}$$

may be significant. The rate for this should dominate, for example, that for

$$\eta_c \to f_0(1000/{\scriptstyle 1400}) + \eta(1440)\,. \tag{11b}$$

Interesting combinations of novel states might be anticipated in the decays of the χ states and should be searched for at BEBC or at future τ-Charm Factories. S-wave decays of $\chi(0^+)$ should be examined for the presence of $f_0(975) + f_0(975)$ and for $\eta(1440) + \eta(1440)$. In general, $\chi(J^+) \to f_0(975) + X_J$ is a promising pathway to studying the nature of light spectroscopy with spin$_J$ and can be used to test the flavour content of the $f_0(975)$. For example, this may be probed in the relative strengths of

$$\chi \to f_0 f_2(1270) : a_0 a_2(1320) : f_0 f_2(1525) \tag{12}$$

We anticipate that the first pair are similar in rate and the latter is relatively supressed[‡‡].

4 Other Dynamical Implications

- In the usual approach to hadronization, gluons from QCD cascades are highly virtual - of $\mathcal{O}\left(1\mathrm{GeV}^2\right)$ - due to the sequence $g \to q\bar{q} \to hadrons$. This is especially true for the production of heavy particles such as baryons. This causes a conceptual problem for understanding, from "first principles", the yield of massive hadrons and the structure of their inclusive momentum spectra. In the present picture, by contrast, there is no need for extreme gluon virtuality due to the existence of the $q_{(-)}$ modes: $g \to M_{(+)} q_{(-)} \bar{q}_{(-)}$. As a result it is rather natural to have a direct correspondence between the distribution of partons and hadrons and thereby give a theoretical basis for the phenomenologically successful "local parton hadron duality" [19].

- The present picture also may offer the promise of explaining the observed similarity of K and Λ inclusive $\log x_p$ distributions [18].

  The negative-energy "strange" vacuum current is absent. Because of that we would expect the double-strange ϕ and Ξ production to be **strongly** suppressed (stronger than the "single strangeness suppression squared") and their momentum spectra to be stiffened as compared to K, Λ.

‡‡Note that the $f_2(1525)$ is a "normal" ($s\bar{s}$) tensor meson

- Nuclear targets may help identify the dynamical structure of the scalars. A loosely bound $K\bar{K}$ "molecular" a_0, f_0 will propagate very differently in nuclei compared to a compact vacuum scalar. A compact state has a good probability to propagate and depart the nucleus intact with the result that equal numbers of K^+, K^- will be observed from the decay $f_0 \to K^+K^-$. For a loosely bound $K\bar{K}$ molecule, by contrast, the K^- has a high chance of disappearance through $K^-p \to \pi\Lambda$ whereas the K^+ continues to propagate in essentially the same direction as the initial scalar. The A dependence and other kinematic dependences of scalar production on nuclei should be able to distinguish between dynamical structures rather clearly [20,21].

  For example, it would be interesting to study energy and atomic number dependence of the effective width of a_0, f_0 mesons produced on nuclear targets. As is well known in atomic spectroscopy and has been discussed by D.V. Bugg in a particle physics context [22], the lifetime of a particle resonance propagating through a nucleus is reduced by collisions, and, consequently, its width increases.

  Indeed, interactions between the resonance and the nucleons inside nuclear matter leads to absorption of the resonance and diminishes its lifetime. If the absorptive cross section is denoted by σ and the nucleon density ρ, then the inverse lifetime inside a nucleus (neglecting the natural width of a resonance, *i.e.*, in the $\Gamma \to 0$ approximation) would be $1/\tau_N = \Delta\Gamma_N = \sigma\rho \cdot c$. In the vacuum the inverse lifetime of a fast hadron is $1/\tau = \Gamma/\gamma$, with $\gamma = E/m_{res}$ the Lorentz factor. So the effective width of a resonance produced on a heavy nuclear target should be

  $$\Gamma_{eff} = \Gamma + \Delta\Gamma_N \cdot \gamma = \Gamma + \frac{E}{m_{res}}\,\sigma\rho c\,.$$

  If a_0 and f_0 mesons are $K\bar{K}$ "molecules", the absorptive cross section would be ≥ 30 mb and at initial energy $E \approx 5$ GeV one would expect a huge effective width ~ 500 MeV ; at higher energies the Γ_{eff} will be even bigger.

  In practice, the effect will be not so strongly pronounced because a part of the resonance production occurs on the periphery of the nucleus where the nucleon density ρ is much smaller. Only when the resonance is produced in this way will it actually be observed as a peak in the mass distribution. The A-dependence of the cross section in this peak will be rather weak: $A^{1/3}$ instead of the conventional $A^{2/3}$ for asymptotically large nuclei $(A \to \infty)$.
  On the other hand, if a_0 and f_0 as VS are small size objects, their cross sections should be of the order of 1-4 mb ($\sigma = 2\pi(1\text{GeV})^{-2}$). In such a case one would observe normal nuclear dependence and only a small increase of VS-width with energy.

- The present picture could provide a clue for understanding the phenomenological success of the so called "frozen couplant" approach, based on the idea that the effective QCD interaction strength (strong coupling) "freezes" at low energies (for a recent review see [23]). It is interesting to note that the optimized low energy value $\alpha_s/\pi = 0.26$ (below 300 MeV) found within the framework of this approach is in accord with $\alpha_{\rm crit}/\pi$.

5 Outlook

We have limited ourselves to a first survey of phenomenological consequences of the idea [1,2] that the $f_0(975)$ and $a_0(980)$ play a special role in the dynamics of confinement. At this stage we have restricted attention to the more well defined tests (*e.g.* $\gamma\gamma$ widths and ratios) and currently active experiments (such as Z^0 decays and $p\bar{p}$ at LEAR). The advent of τ-Charm or B factories would open up new possibilities for developing and testing these primitive ideas both above the heavy flavour threshold and in the ψ or Υ decays.

Acknowledgement

This work was supported in part by European Economic Community contract number CHRX-CT92-0026.

References

[1] V.N. Gribov, Lund preprint LU-TP 91–7, March 1991.

[2] V.N. Gribov, in preparation.

[3] I. Pomeranchuk and Ya. Smorodinsky, Journ. Fiz. USSR 9 (1945) 97; W. Pieper and W. Greiner, Z. Phys. 218 (1969) 327; Ya.B. Zeldovich and V.S. Popov, Uspekhi Fiz. Nauk 105 (1971) 4.

[4] D. Morgan and M.R. Pennington, Rutherford Lab report RAL-92-070 (Phys Rev D, in press).

[5] D. Morgan and M.R. Pennington, Z. Phys. C48 (1990) 623.

[6] R.N. Cahn and P.V. Landshoff, Nucl. Phys. B266 (1986) 451.

[7] S. Godfrey and N. Isgur, Phys. Rev. D32 (1985) 189.

[8] Particle Data Group, Phys. Rev. D45 (1992) S1.

[9] Z.P. Li, F.E. Close and T. Barnes, Phys. Rev. D43 (1991) 2161; F.E. Close and Z.P. Li, Z. Phys. C54 (1992) 147.

[10] T. Barnes, Phys. Lett. 165B (1985) 434.

[11] J. Weinstein and N. Isgur, Phys. Rev. D27 (1983) 588; *ibid.* D41 (1990) 2236.

[12] F.E. Close, N. Isgur and S. Kumano, Nucl. Phys. B389 (1993) 513.

[13] Crystal Barrel Collaboration at LEAR, Phys. Lett. 291B (1992) 347; 294B (1992) 451.

[14] G. Smith, Proc. of Dallas HEP Conference (1992).

[15] F.E. Close, in: Proc. of Workshop on Physics and Detectors for DAFNE, Frascati, April 1991, ed G.Pancheri, p. 310

[16] DELPHI Collaboration, CERN-PPE/92–183, October 1992.

[17] ARGUS Collaboration, DESY 92 174, December 1992.

[18] OPAL Collaboration, CERN-PPE/92–118, July 1992.

[19] Yu.L. Dokshitzer, V.A. Khoze, A.H. Mueller and S.I. Troyan, Basics of Perturbative QCD, Editions Frontiéres, Gif-sur-Yvette, 1991, p. 175 ; Yu.L. Dokshitzer, S.I. Troyan and V.A. Khoze, Z. Phys. C55 (1992) 107.

[20] W.R. Gibbs and W.B. Kaufmann, Proc. of "Physics with Light Mesons", Los Alamos report LA-11184-C (1987) 28 ; C. Alexander and T. Sato, Phys. Rev. C36 (1987) 1732.

[21] H. Lipkin, Phys. Lett. 124B (1983) 509.

[22] D.V. Bugg, Nucl. Phys. B88 (1975) 381.

[23] A.C. Mattingly and P.M. Stevenson, preprint DE-FG05-92ER40717-7

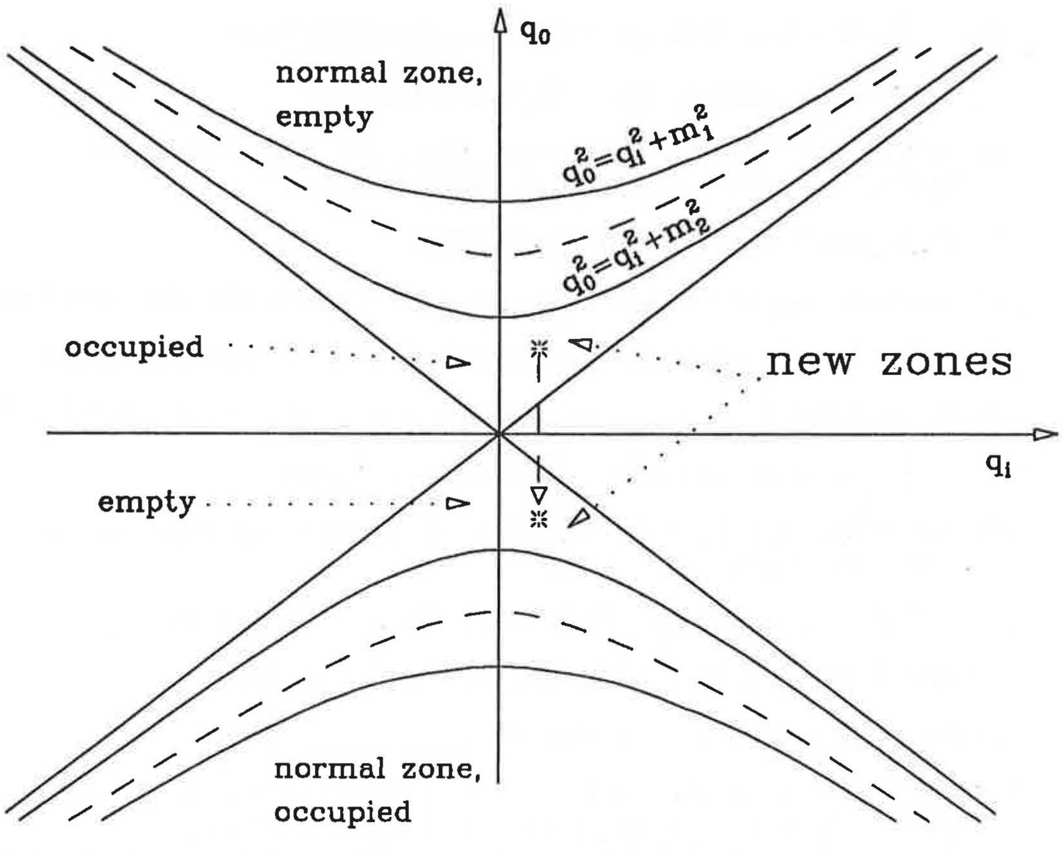

Figure 1: Structure of the quark vacuum in the light quark confinement theory of [1,2]. Upper new zone is filled up with positive kinetic energy quarks bound into colourless pairs with negative total energy. Excitation of such a pair corresponds to creation of a VS meson state. Dashed lines show the "Fermi surface" that separates the zones with standard and inverse population.