INFN - Laboratori Nazionali di Frascati
Servizio Documentazione

LNF-91/018 (R)
3 Maggio 1991

QCD, QUARK MODEL AND DAΦNE

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ABSTRACT

A short introduction into new nonperturbative QCD methods is given, together with a new quark model, deduced from QCD. Implications for DAΦNE experiments are discussed.

1. - INTRODUCTION

Most of the physics to be studied at DAΦNE directly involves long-distance QCD interactions, as it is shown in Fig. 1.

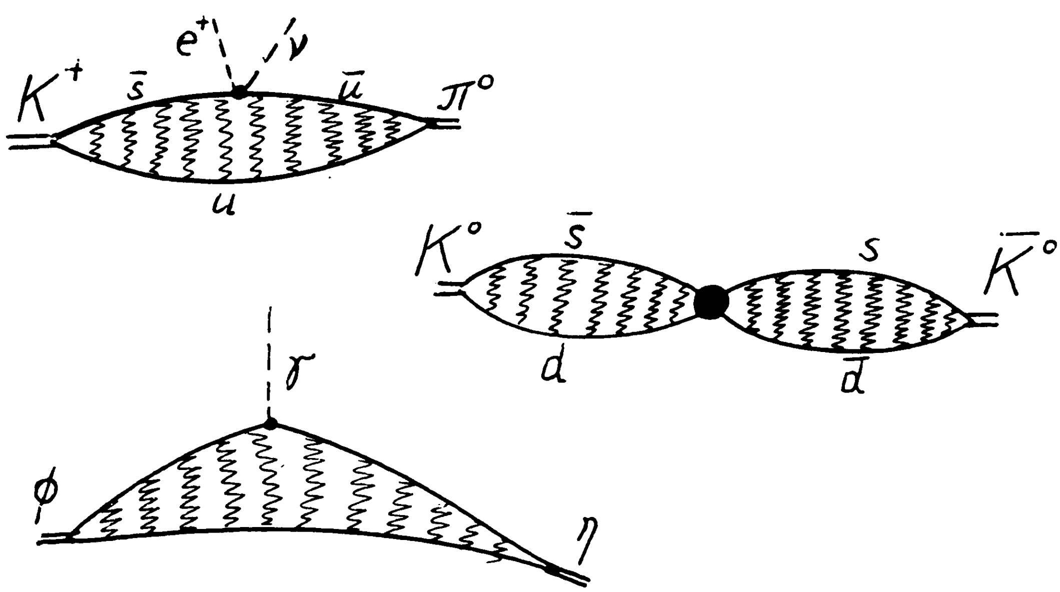

FIG. 1 - Three types of processes to be studied at DAΦNE: Ke3 decay, $K\bar{K}$ transition and $\phi\to\eta\gamma$.

Therefore one can say that DAΦNE is also a machine for the long-distance QCD, which may clarify main aspects of non-perturbative QCD. Those can be conveniently grouped into three topics:

1) confinement,
2) chiral symmetry breaking (CSB),
3) quark pair creation, OZI etc.

Historically, CSB has been the first to study[1] and a practical tool to implement CSB is the chiral perturbation theory[2] which enables one to compute soft pion and kaon amplitudes without looking into the mechanisms of CSB. We shall shortly discuss in Sect. 4 chiral dynamics.

Confinement is incorporated in the quark potential model QPM[3], where linear potential is introduced by hand, with rather good phenomenological consequences for the spectrum[4]. Unfortunately till recently the connection of QPM with QCD was not understood. Recently a new powerful method has appeared[5,6] which incorporates naturally all non-perturbative QCD effects, e.g. confinement and CSB. This method, called the Vacuum Correlator Method (VCM), is a natural extension of the QCD sum rules[7] and contains those as a limiting case. In the next Sect. we give elements of 'VCM' and then derive a new quark model (Sect. 3), compare it to the old one (QPM) and to the experiment.

In Sect. 4 we discuss the CSB and connect this phenomenon to quark zero modes. We argue that the latter bring a new dynamics, which e.g. incorporated in chiral Lagrangians.

Sect. 5 is devoted to possible links between the new theoretical method, VCM, and low energy experiments like DAΦNE.

1. - VCM AND DERIVATION OF THE QUARK MODEL

The essence of VCM is that the amplitude of any physical process, like the correlators G(x,y) (the Green function of a $q\bar{q}$ pair) can be written as in a form, where all dependence on gluon fields (perturbative and nonperturbative) is contained in one (or more) Wilson loops[5,6]

$$G(x\,,y) \sim \langle W(c) \rangle \tag{1}$$

For the latter one can use the formalism of cluster expansion[8] which was suggested for W(c) in[5,6]

$$\begin{aligned}\langle W(c)\rangle &= \langle P \exp ig \int_c A_\mu \, dz_\mu \rangle = \\ &= \exp\left\{-\frac{g^2}{2}\int_S d\sigma(1)\int_S d\sigma(2) \langle F(1)\, F(2)\rangle + O(\text{« FFFF », etc.})\right\}\end{aligned} \tag{2}$$

Therefore dynamics in the $q\bar{q}$ system can be defined by the set of lowest correlator, e.g.

$$<F_{\mu\nu}(x)\, F_{\lambda\rho}(y)> = \left(\delta_{\nu\lambda}\ \delta_{\nu\rho} - \text{perm.}\right) D\left(x-y\right) + O\left(\partial_\mu\, ,\left(x-y\right)_\nu\right) D_1 \qquad (3)$$

The string tension is connected to D:

$$\sigma \sim \int d^2x\ \ D(x) + \int d^2x\, d^2y\, d^2z < F\,F\,F\,F > + \ldots \qquad (4)$$

The simplest choice of $\mathcal{D}$, $\mathcal{D}_1$ was used in[10] to describe the properties of charmonium and bottomonium with good phenomenological results.

This is appropriate for small systems, for of the size comparable or less than the vacuum correlation time T_g, which enters $\mathcal{D}$ correlators, e.g.

$$< F(x)\, F(g) > \sim \exp\left(\frac{-|x-y|}{T_g}\right) \qquad (5)$$

On the lattice T_g was found to be[11]

$$T_g \sim 0.2\ \div 0.3\ \text{fm} \qquad (6)$$

For large systems, made of light quarks, it is more appropriate to use the asymptotics of the Wilson loop which follows both from the cluster expansion[5] and from the Monte Carlo data

$$< W(c) > = \exp\left(-\sigma\, S_{min} - c\, L - \Delta_c\right) \qquad (7)$$

where L is the perimeter term (including quark mass renormalization), Δ_c incorporates perturbative gluon exchanges (PGE). Thus the input for light quark systems is: current quark masses m_1, m_2, string tension σ and α_s. The perimeter term contributes to the overall constant C_0 in the mass formula.

Using the proper-time representation and quark path integrals we rewrite G, (1) as

$$G = \int ds\ \ d\bar{s}\ \ \mathcal{D}z\, \mathcal{D}\bar{z}\ \ \exp\left(-B\right) \qquad (8)$$

with the "effective action" B equal to[12]

$$B = m_1^2\, s + m_2^2\ \bar{s} + \ \text{kin. part} + \sigma\, S_{min} \qquad (9)$$

We can introduce now "dynamical mass" variable μ_1, μ_2 as the ratio of the proper time(s) over the center-of-mass time, $T = |x-y|$.

$$\frac{s}{T} = \frac{1}{2\mu_1} \quad , \quad \frac{\bar{s}}{T} = \frac{1}{2\mu_2} \qquad (10)$$

To get rid of path integrals one can formally introduce Hamiltonian H (which is actually a proper-time Hamiltonian) and obtains

$$G \sim \int d\mu_1\, d\mu_2 < x \mid e^{-HT} \mid y > \tag{11}$$

where H is (12)

$$H = \frac{m_1^2}{2\mu_1} + \frac{m_2^2}{2\mu_2} + \frac{\mu_1 + \mu_2}{2} + h + H_4\,(r_4\,,\dot{r}_4) \tag{12}$$

and h is

$$h\,\varphi \equiv \left(-\frac{1}{2\tilde{\mu}}\,\frac{\partial^2}{\partial\, r_i^2} + \sigma\, r \right) \varphi = \varepsilon\left(\tilde{\mu}\right)\, \varphi\,,\, \tilde{\mu} = \frac{\mu_1\, \mu_2}{\mu_1 + \mu_2} \tag{13}$$

The integral over $d\mu_i$ can be taken using the steepest descent method, exact in the limit $T \to \infty$; the relative time (r_4) excitations can be disregarded (they enter additatively), and we end up with the mass formula for the $q\bar{q}$ bound states[12,6]

$$M = \frac{m_1^2}{2\mu_1} + \frac{m_2^2}{2\mu_2} + \frac{\mu_1 + \mu_2}{2} + \varepsilon\left(\tilde{\mu}\right) - C_o \tag{14}$$

where μ_1, μ_2 are to be found from the steepest descent condition

$$\frac{\partial M}{\partial \mu_1} = \frac{\partial M}{\partial \mu_2} = 0 \tag{15}$$

Eq. (15) defines $\mu_i = \mu_i^{(o)}$ which can be identified with the constituent mass of the quark (we shall omit subscript zero in what follows).

3. - THE NEW QUARK MODEL

We now can compare our new quark model (12-14) with the old quark model[4] characterized by the Hamiltonian:

$$H_{old} = \sqrt{p^2 + m_{10}^2} + \sqrt{p^2 + m_{20}^2} + V(r) + V_{spin} - C_o \tag{16}$$

$$V_r = \sum_{ij} \vec{\lambda}_i\, \vec{\lambda}_j \left(C\,\frac{\alpha_s}{r_{ij}} + \sigma\, r_{ij} \right) \tag{17}$$

First of all, we remark that for $q\bar{q}$ the square root terms in (16) can be obtained from (12) if one applies there the steepest descend condition directly to the operator H, neglecting the noncommutativity of $p^2/2\tilde{\mu}$ and σr in h. This brings about 5-7% error for M (in addition to other approximations which are done in obtaining (12), and which can be corrected in VCM).

Another feature of QPM is more dangerous - the assumed form of pairwise confining forces (17). For 3 and more quarks this form is invalid and should be replaced by configuration ensuring the minimal surface S_{min}, as in (9). For baryons one obtains the string junction[13] and for $q^2\bar{q}^2$ a more sophisticated configuration appears, which is discussed in the talk of A.M. Badalyan[14]. This brings a net decrease in the mass of $q^2\bar{q}^2$ of several hundred MeV as compared to QPM.

A very important feature of the new quark model[14] derived from QCD via VCM is the appearance of the constituent mass $\mu_i = \mu_i^{(o)}$, which depends on the state. Physically μ_i is due to the inertia of the string, connecting q and $\bar{q}$ (or q to the string junction in the baryon). The values of μ_i computed from (15) with PGE (with $\alpha_s = 0{,}39$) are for m_u, m_d =4 and 7 MeV μ ($L = n_r = 0$) = 0.393 GeV; μ ($L = 1, n_r = 0$) = 0.481 GeV; $\mu(L = 0,\ n_r = 1) = 0.560$ GeV.

For the $s\bar{s}$ system with $m_s = 0.2$ GeV one obtains μ_{ss} ($L = n_r = 0$) = 0.468 GeV, μ_{ss} ($L = 1,\ n_r = 0$) = 0.540 GeV, μ_{ss} ($L = 0,\ n_r = 1$) = 0.611 GeV.

We note in passing that in QPM (16) one should have current quark masses for m_{10}, m_{20}, if one deduces (16) approximately from QCD via VCM. Instead in[4] m_{10}, $m_{20} \sim 0{,}22$ GeV are used, which are neither current non constituent mass values.

Meson masses and Regge trajectories have been computed from (14), see[12,6,15] for more details. One obtains linear Regge trajectories with the slope $\alpha' = 1/8\sigma$, the experimental slope of ~0.8 GeV^{-2} corresponds to $\sigma = 0.17$ GeV^2. This value allows to predict meson masses in reasonable agreement with experiment[12,6,15]. Heavy-light mesons and coupling constants f_B, f_D have been computed recently[15] together with electronic widths Γ_{el} of vector mesons sor the same parameters m_i, σ, α_s.

The agreement with experiment of Γ_{el} and hf splittings $M_{D*} - M_D$, $M_{D_S^*} - M_{D_S}$ is within 10%.

Preliminary calculation of baryon Regge trajectories are done in[12,16]. One obtains two types of Regge trajectories, persisting also for multiquark systems, where the third quark is: i) at the center of the string or ii) at the end (the quark-diquark type).

Glueballs have been considered in[17]. Since the adjoint string does not break up to large distances[18] and its tension σ_{adj} is 9/4 times the fundamental quark tension σ, all glueball spectrum has the scale of $\sqrt{9/4} = 3/2$ that of $q\bar{q}$ spectrum.

The 3g glueballs have been treated in[19]. The summary of spectra is given in Fig. 2.

We close this Section by considering magnetic momens and transitions. The quark magnetic momentum (q.m.m.) is computed adding magnetic field to color fields in Wilson loop and is $e_i / 2\mu_i$. This justifies the notion of constituent mass for μ_i and yelds the familiar ratio for nucleon magnetic momentum $\mu_p/\mu_n = -3/2$. The q.m.m. enter also magnetic transitions $V \to P + \gamma$ which are planned to measure at DAΦNE. The existing experimental widths Γ_{exp} are shown in the Table. They do not agree with naive theoretical estimates Γ_{th}[20], obtained with q.m.m. fitted to neutron and proton moments.Estimates show that q.m.m. obtained in VCM are in better agreement with experiment however a better experimental accuracy is needed to establish the details of the process and the quark contents of ϕ, η, η'(see the talk of F. Close at this Workshop[21]).

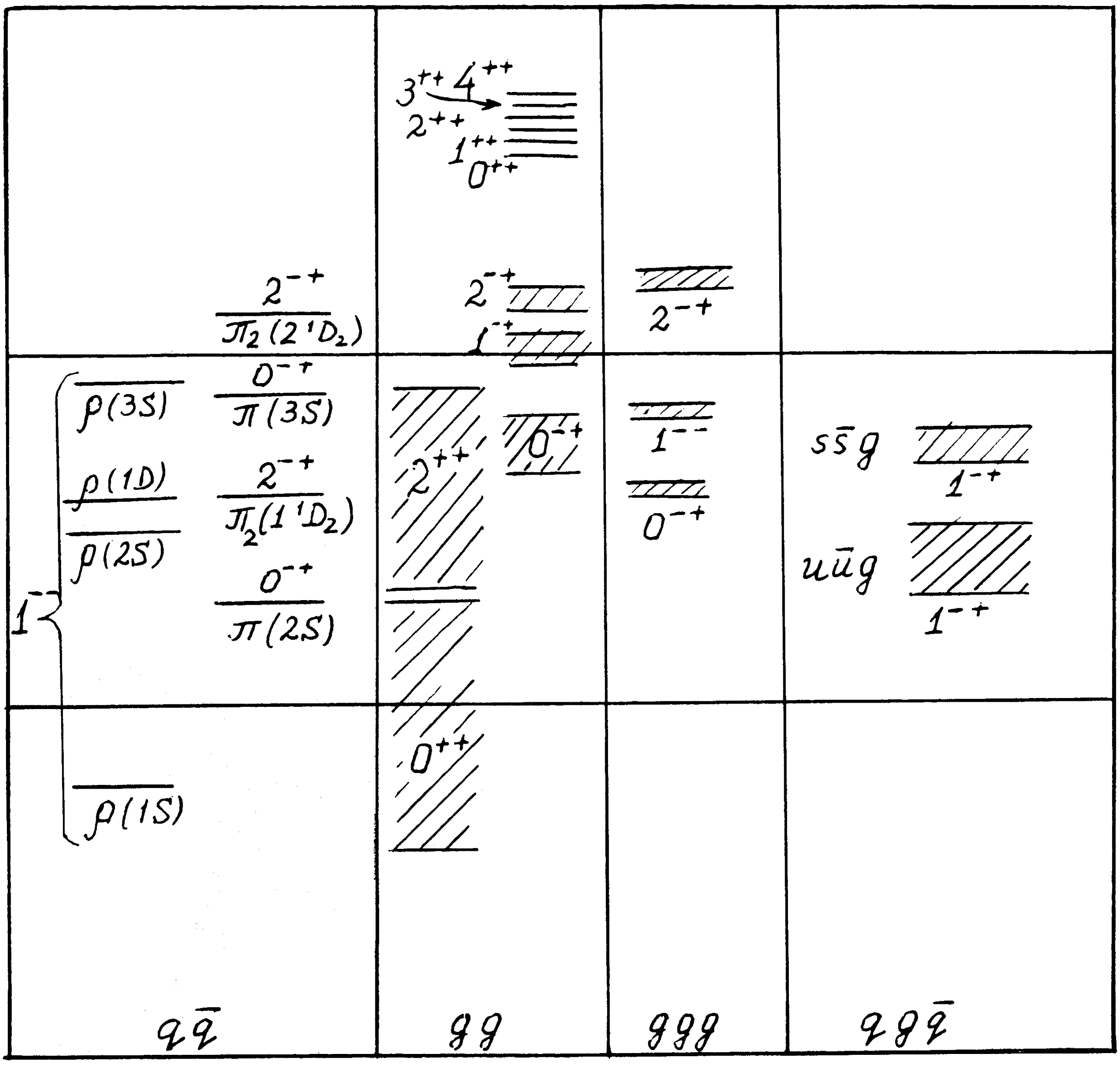

FIG. 2 - Spectrum of mesons computed in VCM by A.M. Badalyan , glueballs and hybrids computed in VCM in(17,19) (not all states shown).

TABLE

Process	$\Gamma_{theor.}$MeV	Γ_{exp} MeV
$\omega \rightarrow \pi^o\gamma$	1.2	0.716 ± 0.04
$\rho^- \rightarrow \pi^-\gamma$	0.11	0.068 ± 0.0075
$K^{*-} \rightarrow K^-\gamma$	0.11	0.050 ± 0.005
$\varphi \rightarrow \eta\gamma$	0.105	0.057 ± 0.003
$\rho^o \rightarrow \eta\gamma$	0.1	0.057 ± 0.012
$K^{*o} \rightarrow K^o\gamma$	0.2	0.115 ± 0.010

4. - CHIRAL SYMMETRY BREAKING IN QCD

For the fundamental understanding of pions, kaons and to judge the applicability of chiral Lagrangians, one needs to take into account a new dynamics, which can be called dynamics of zero quark modes (ZQM). The phenomenon of CSB is closely connected to ZQM. Indeed, using the spectral representation of the quark Green function

$$S(x, y) = \sum_n \frac{w_n(x)\, w_n^+(y)}{\Lambda_n - im} \tag{18}$$

where Λ_n is an eigenvalue of the equation

$$\left(-i\hat{D}(A)\right) w_n = \Lambda_n w_n \tag{19}$$

one obtains the quark condensate

$$\langle \bar{q} q \rangle = \frac{1}{V_4} \left\langle \sum_n \frac{1}{\Lambda_n - i m} \right\rangle = -\frac{2m}{V_4} \int_o^\infty \frac{\nu(\Lambda)\, d\Lambda}{\Lambda^2 + m^2} \to -\frac{\pi}{V_4} \nu(o) \tag{20}$$

where $\nu_{(\Lambda)}$ is the density of eigenvalues, V_4 is the total 4d volume. From (20) one can see that CSB is due to the density of quasi zero modes, $|\Lambda| \sim m \to 0$.

Similarly, the $q\bar{q}$ Green function at zero momentum p is expressed through $\nu(\Lambda)$, e.g. in the scalar channel[22]

$$G_S(p=0) \approx \left. \frac{d\nu(\Lambda)}{d\Lambda} \right|_{\Lambda = o}, \text{ is finite at } m \to 0 \tag{21}$$

while for pseudoscalars one has

$$G_{ps}(p=0) \sim \frac{\nu(o)}{m} \quad , \quad m \to 0 \tag{22}$$

From (22) and definition of f_π one easily deduces well-known relations

$$f_\pi^2 m_\pi^2 = -(m_u + m_d) < \bar{u}u + \bar{d}d > + O(m^2) \tag{23}$$

$$f_k^2 m_k^2 = -(m_u + m_s) < \bar{u}u + \bar{s}s > + O(m^2) \tag{24}$$

Those are the only relations one obtains without model assumptions about $W_n(p)$. One can tell more of one used the picture of disordered QCD vacuum for CSB as in[23]. In this case one can see the appearance of the so-called zero-mode zone (ZMZ) of the width $\Delta\Lambda \sim 10 \div 30$ MeV, with eigenfunctions $W_n(p)$ of large range, $r_o \sim m_\pi^{-1}$. This ZMZ participates in the formation at all chiral properties, i.e. pion amplitudes, pion structure and pion-pion interaction at energies less than m_π. However for larger energies and/or for nonpseudoscalar channels also other eigenmodes contribute outside of ZMZ. In particular, for vector and scalar mesons ZMZ contributes only a correction. Therefore the study of meson decays using chiral Lagrangians (which do not contain any confinement dynamics and e.g. do not depend on the string tension) is of limited value and should be supplemented by the confinement dynamics, as in the Hamiltonian(15).

This combination of two dynamics, dynamics of ZQM and dynamics of confinement is now under study(22).

CONCLUSIONS

The purpose of this talk was to outline our present understanding of nonperturbative QCD and quark model. We start to understand quark model, confinement and CSB from QCD, and this gives foundation e.g. for calculations of mesons, hybrids, glueballs and four-quark states, reported here in Fig. 2 and in the talk by Badalyan(14).

These states, especially 1^{--}, can be seen at DAΦNE, and work is going on to determine electronic widths, coupling of ρ', ω'(14), as it was already done for ρ, ω, η in(15). Concerning chiral Lagrangians and CSB more work is needed and planned to calulate nonchiral contributions to kaon decays (and e.g. η decay).

Theoretically the question of mixing and OZI is poorely studied and the most important development from the point of view of hadron spectroscopy would be the nonperturbative calculation of such processes. This work is now in progress at ITEP.

ACKNOWLEDGEMENTS

The author is grateful to the experimental group of Prof. C. Guaraldo for financial support, which made this talks possible, and to all staff of National Laboratories of Frascati for kind hospitality.

REFERENCES

(1) Y. Nambu and G. Jona-Lasinio, Phys. Rev. **122**, 345 (1961), S. Weinberg Phys. Rev. Lett. **17**, 616 (1966), ibid **18**, 188 (1967).

(2) J. Gasser and H. Leutwyler, Ann. Phys. **158**, 142 (1984), Nucl. Phys. **B250**, 465 (1985), ibid. **B307**, 763 (1988).

(3) D.R. Stanley and D. Robson, Phys. Rev. Lett. **45**, 235 (1980), J Carlson, J. Kogut and V.R. Pandharàpande, Phys. Rev. **D27**, 233 (1983).

(4) N. Isgur and S. Godfrey, Phys. Rev. **D32**, 189 (1985), J.L. Basdevant and S. Boukraa, Z. Phys. **C28**, 413 (1985).

(5) H.G. Dosch and Yu.A. Simonov, Phys. Lett. **B205**, 339 (1988), H.G. Dosch, Phys. Lett. **B190**, 177 (1987), Yu.A. Simonov, Nucl. Phys. **B307**, 512 (1988) for a review see.

(6) Yu.A. Simonov, TPI - Minn - 90/10 - T (to be published).

(7) M. Shifman, A. Vainshtein and V. Zakharov, Nucl. Phys. **B147**, 335, 448 (1979).

(8) N.G. Van Kampen, Phys. Rep. **C24**, 171 (1976); Physica **74**, 215,239 (1974).

(9) Yu.A. Simonov, Yad. Fiz. **48**, 1381 (1988), ibid. **50**, 213,500 (1989).

(10) A.U. Badalyan and V.P. Yurov, Yad. Fiz. (1990).

(11) M. Campostrini, A. Di Giacomo and G. Mussardo, Z. Phys. **C25**, 173 (1984).

(12) Yu.A. Simonov, Phys. Lett. **B226**, 151 (1989).

(13) Yu.A. Simonov, Phys. Lett. **B228**, 413 (1989).

(14) A.U. Badalyan, this volume.

(15) Yu.A. Simonov, preprint Heidelberg Univ. subm. to Z. Phys.**C.**

(16) M. Fabre and Yu.A. Simonov, Orsay preprint subm. to Ann. Phys.

(17) Yu.A. Simonov, TIP - MiNN - 90/19 - T, to be subm. to Zeit. Phys. **C.**

(18) J. Greensite and M.B. Halpern, Phys. Rev. **D27**, 2545 (1983). I.J. Ford, R.H. Dalitz and J. Hoek, Phys. Lett. **B208**, 286 (1988).

(19) Yu.A. Simonov, A talk at QCD-90 conference, Montpellier, France, Journal de Physique (in press).

(20) B.L. Ioffe, V.A. Khoze and L.N. Lipatov, Hard processes,V.1, North Holland, Amsterdam, 1984.

(21) F. Close, this volume.

(22) H.G. Dosch and Yu.A. Simonov, in preparation.

(23) Yu.A. Simonov, Phys. Rev. **D** (to appear), preprint ITEP 19-91, subm. to Nucl. Phys. **B**.