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Multiquark Exotics in a Stringlike Model with Diquarks (*) (**).

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Summary. — The multiquark exotic resonance states q^2-$\bar{q}^2$, q^3-$\bar{q}^3$ and q^6 are discussed as systems composed of the few color clusters and in particular of diquarks. Special attention is devoted to the problem of narrow dibaryon resonances (with strangeness $S = 0$, -1 and -2).

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PACS 14.20.Gk - Baryon resonances with $S = 0$.
PACS 14.80.Dq - Quarks.

1. – Is it possible to find narrow exotic states?

The existence of a new (color) degree of freedom in QCD leads to the prediction that the spectrum of multiquark system should apparently contain unusual mesons, baryons and nuclei—the so-called states with hidden color. The first candidates for such states were spherical $q^2\bar{q}^2$ and q^6 bags (1). However these states have strong coupling to hadronic channels and can easily fall apart. P-matrix analysis of these states shows that they may be wide ($\Gamma \sim (300 \div 500)$ MeV) or may even disappear as poles of S-matrix (2).

An exceptional state in the q^6 spherical bag spectrum is the H-dihyperon or dilambda. There exists however controversy concerning its mass. Originally in the MIT bag model the H-particle was predicted about 80 MeV below the $\Lambda\Lambda$

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(1) R. L. JAFFE: *Phys. Rev. D*, 15, 267 (1977).
(2) YU. A. SIMONOV: *Sov. J. Nucl. Phys.*, 36, 722 (1982).

threshold ($M_H = 2.15$ GeV) and therefore long lived. It was shown in ref. ([3]) that because of the nonuniversality of the bag constant B (*i.e.* due to the different properties of the QCD vacuum in hadrons with different number of quarks) the H-dihyperon becomes heavier by $(250 \div 300)$ MeV. In this case the hadronic shift ([4]) may not be large enough to restore a stable (with respect to strong interactions) H-particle. The experimental status of dilambda is not yet clear. The existence of double hypernuclei tells us ([5]) that $M_H > 2.219$ GeV. However it would be important to confirm these results because the authors of ref. ([6]) claim that they have found one event which can be interpreted as the production and Σ^- decay of H-dihyperon with the mass (2173 ± 15) MeV.

The main decay channels of multiquark exotic resonances contain usually many ($n \geqslant 3$) particles in final states. If such resonances were wide this would complicate very much their separation from the background. That is why the search for narrow exotic resonances is very desirable. In fact recently there have been reports on narrow ($\Gamma \leqslant (5 \div 20)$ MeV) dibaryon resonances below and near 2 GeV and of rather narrow (unusual) meson states around 3.1 GeV in the channels $\Lambda\bar{p}$ + pions. What quark dynamics could be responsible for their existence and for the rather strong suppression of their decays? One of the most popular theoretical ideas is that they consist of separated color quark clusters which interact via the confining gluon field. Such clustering can be caused by orbital motion of clusters and by interaction with nonperturbative QCD vacuum and with themselves. Here are some aspects discussed by different authors:

i) the formation of color quark clusters may lead to decrease of the bag volume energy $4/3\pi \cdot B \cdot R^3$ and colormagnetic energy of spin-spin interaction (see, for example, ([7]));

ii) the interaction with instantons may produce rather stable color triplet diquark D_{00} with $I = 0$ and $S = 0$ ([8]);

([3]) L. A. KONDRATYUK, M. I. KRIVORUCHENKO and M. G. SCHEPKIN: *JETP Lett.*, **45**, 10 (1986); *Sov. J. Nucl. Phys.*, **45**, 514 (1987).

([4]) A. M. BADALYAN and YU. A. SIMONOV: *Sov. J. Nucl. Phys.*, **36**, 1479 (1982); B. O. KERBIKOV: *Sov. J. Nucl. Phys.*, **39**, 816 (1984).

([5]) M. DANYSZ, K. GARBOWSKA, J. PNIEWSKI, T. PNIEWSKI, J. ZAKRZEWSKI, E. P. FETCHER, J. LEMONNE, P. RENARD, J. SACTON, W. T. TOUER, D. O'SULLIVAN, T. P. SHAH, A. THOMPSON, P. ALLEN, SR. M. HEERAN, A. MONTWILL, J. E. ALLEN, M. J. BENISTON, D. H. DAVIS, D. A. GARBUTT, V. A. BULL, R. C. KUMAR and P. V. MARCH: *Nucl. Phys.*, **49**, 121 (1963), D. PROWSE: *Phys. Rev. Lett.*, **17**, 782 (1966).

([6]) B. A. SHAKHBAZYAN, A. O. KECHECHYAN and A. M. TARASOV: preprint JINS P1-86-626 (Dubna, 1986).

([7]) L. A. KONDRATYUK: in *Few-Body Systems, Suppl.*, 2, 242 (1987).

([8]) S. EKELIN and S. FREDRIKSSON: *Phys. Lett. B*, **162**, 373 (1985); P. S. BETMAN and L. V. LAPERASHVILI: *Sov. J. Nucl. Phys.*, **41**, 463 (1985); A. E. DOROKHOV and N. I. KOCHELEV: JNR Preprint E2-86-224 (Dubna, 1986).

iii) the short-range gluon interaction (see [9]) may lead to attraction of color-triplet quarks with any spin.

The role of instantons in low-energy QCD seems to be controversial (see, for example, the discussion in [10]). The short-range gluon attraction and the spin-spin interaction are more reliable. As is shown in ref. [10], the gluon condensate in QCD vacuum leads to oscillatorlike potential between quarks at short distance $r < d$, where d is the correlation length. At long distances the potential becomes the linear one. So we can suppose that the effective potential between the quarks has two minima, one at $r \to 0$ and other (like a cavity) at $r \geqslant d$ with a hump between them at $r \sim d$. The existence of such a hump might lead to the formation of diquarks with the size $r \sim d \sim (0.3 \div 0.4)$ fm for spin zero (D_{00}) and for triplet state as well (D_{11}). Spin-spin interaction would lead to additional stability of quarks with spin zero. As far as the triplet state is concerned, where the spin-spin interaction is repulsive, the diquark correlations could either disappear or survive for some flavours only. Evidently the diquark radius should be less than the baryon radius. Various authors estimate the diquarks radius to be $\langle r_D^2 \rangle^{\frac{1}{2}} \approx (0.3 \div 0.4)$ fm (see, *e.g.*, [8]).

From the fit of the baryon orbital q^2-q excitations in the framework of relativistic QCD string model with spin-orbit coupling [11] $M(D_{00}) = 220$ MeV which should be compared with the mass of the constituent quark $M(q) = 340$ MeV or of heavy triplet $I = S = 1$ diquark $M(D_{11}) = (530 \div 550)$ MeV. The analysis of strange baryon spectra in ref. [12] determines the masses of strange diquarks $M(D^s_{\frac{1}{2}0}) = 360$ MeV ($I = 1/2$; $J = 0$) and $M(D^s_{\frac{1}{2}1}) = 840$ MeV ($I = 1/2$; $J = 1$). A description of the model is given in appendix.

So the diquarks D_{00} and $D^s_{\frac{1}{2}0}$ are expected to be comparatively light. The diquark D_{11} may also be lighter than two nonstrange quarks. As for the $D^s_{\frac{1}{2}1}$ diquark it is most probably unstable with respect to the fission $D^s_{\frac{1}{2}1} \to sq$.

2. – The T-baryonium problem.

Different quark models predicted a very rich spectrum of broad $(q^2)_3$-$(\bar{q}^2)_3$ resonances around $(1.3 \div 2.3)$ GeV. In table I we present the predictions of different models: dual resonance model (DRM) [13], stretched rotating bags

[9] V. V. Anisovich and B. V. Gerasyta: LNPI preprint No. 1274 (Leningrad, 1987).
[10] Yu. A. Simonov: preprint ITEP-68-88 (Atominform, Moscow, 1988).
[11] I. Yu. Kobzarev, L. A. Kondratyuk, B. V. Martemyanov and M. G. Schepkin: *Sov. J. Nucl. Phys.*, **45**, 526 (1987).
[12] L. A. Kondratyuk, Yu. V. Ralchenko and A. V. Vasilets: preprint ITEP-158 (Atominform, Moscow, 1987).
[13] Chan Hong-Mo and H. Hogaasen: *Nucl. Phys. B*, **136**, 401 (1978).

TABLE I. – *The spectra of* T-*baryonium in different models* ($D_{00} = (q^2)_{I=J=0}$, $D_{11} = (q^2)_{I=J=1}$) (*masses in* GeV).

L^P	$I^G(J^P)$	DRM	SRB	QGM	RSM
a) D_{00}-$\overline{D}_{00}$					
0^+	$0^+(0^+)$	—	—	1.26	—
1^-	$0^-(1^-)$	1.68	1.50	1.63	1.28
2^+	$0^+(2^+)$	1.92	1.76	1.93	1.70
3^-	$0^-(3^-)$	2.13	2.05	2.19	2.02
4^+	$0^+(4^-)$	2.33	2.29	2.42	2.30
5^-	$0^-(5^-)$	2.51	2.51	2.63	2.54

b) D_{00}-$\overline{D}_{11} \pm \overline{D}_{00}$-$D_{11}\,(I=1)$

L^P	I^G	J^P	DRM	SRB	QGM	RSM
0^+	1^+	1^+	—	—	1.46	—
1^-	$1^\pm$	0^-	—	1.72	—	1.72
		1^-	—	1.72	—	1.64
		2^-	1.89	1.72	1.79	1.46
2^+	$1^\pm$	2^+	—	2.01	—	2.08
		3^+	—	2.01	—	2.00
		2^-	2.13	2.01	2.06	1.84
3^-	$1^\pm$	2^-	—	2.28	—	2.39
		3^-	—	2.28	—	2.31
		4^-	2.34	2.28	2.31	2.15

c) D_{11}-$\overline{D}_{11}\,(I=0,\,1,\,2)$

L^P	S_{12}	J^P	DRM	SRB	QGM	RSM
0^+	0	0^+	—	—	0.705	—
	1	1^+	—	—	1.26	—
	2	2^+	—	—	1.63	—
1^-	0	1^-	—	1.86	—	1.66
	1	0^-	—	1.90	—	1.90
		1^-	—	1.90	—	1.81
		2^-	—	1.90	—	1.64
	2	1^-	—	1.94	—	2.11
		2^-	—	1.94	—	1.94
		3^-	2.11	1.94	1.93	1.68

(SRB) [14], quark-gluon model (QGM) [15] and rotating relativistic string with spin-orbit interaction (RSM) [16]. The widths of such states are expected to be of the same order of magnitude as the widths of usual q-$\overline{q}$ mesons ($\Gamma = 100$ MeV) [15]. We may only hope that the lowest states with $L = 1$ and $I = 0$, 1 and 2, which have the masses around 1.3, 1.4 and 1.6 GeV, respectively, may be relatively narrow.

In the vicinity of $\mathcal{N}\overline{\mathcal{N}}$ threshold different models predict resonances with rather high spins (up to $J = 4$). This may be the reason which causes the fast rise of higher partial waves observed in low-energy $\mathcal{N}\overline{\mathcal{N}}$ scattering. The amplitude and partial-wave analyses of $\mathcal{N}\overline{\mathcal{N}}$ interaction give many wide resonances in the region $(1.9 \div 2.9)$ GeV.

Recently there has been a report from Serpukhov of a resonance in the system $\phi\pi^0$ with mass $M = (1480 \pm 40)$ MeV, width $\Gamma = (130 \pm 60)$ MeV and quantum numbers $I = 1$, $J^{PC} = 1^{--}$ [12]. This particle, which has been called «C-meson», cannot be a usual $\overline{q}$-q meson, because its decay is forbidden by OZI rule and it cannot be produced in $\pi^- p \to \omega\pi^0 n$ reaction. In RSM model it can be interpreted as a lowest $L = 1$ excitation of the sq-$\overline{s}\overline{q}$ trajectory, each quark cluster being a spin singlet) see ([12-18]). If this interpretation is correct, a strange exotic meson 1^{--} ($I = 1/2$) in $(1360 \div 1380)$ MeV region should also exist. Furthermore the C/ρ(1480) meson should have the partner in isospin C_0/ω with $I = 0$. Probably one of the best ways to study exotic meson spectroscopy is to use the annihilation of low-energy antiprotons. In this case at least nonstrange antidiquarks are already present in the initial state.

3. – Unusual narrow exotic $B = 0$ states near 3.1 GeV (M-baryonium or q^3-$\overline{q}^3$ system).

Recently in two experiments in CERN and Serpukhov [19,20] narrow peaks near 3.1 GeV have been found ($\Gamma \lesssim (20 \div 30)$ MeV) in the mass spectrum $\Lambda\overline{p}$ + pions: U^+/M_s^+, U^0/M_s^0, U^-/M_s^- and U^{--}/M_s^{--}. The BIS-2 collaboration at

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(14) A. T. Aerts, P. J. Mulders and J. J. de Swart: *Phys. Rev. D*, 21, 1370, 2653 (1980).
(15) A. B. Kaidalov: in *Elementarnye chastitsy* (*Elementary particles*), *Proocedings of the X ITEP School of Physics*, No. 2 (Energoatomizdat, Moscow, 1983), p. 3.
(16) L. A. Kondratyuk, B. V. Martemyanov, M. G. Schepkin: *Sov. J. Nucl. Phys.*, 46, 1552 (1987).
(17) D. Alde, F. Binon, K. Brickman *et al.*: *Sov. J. Nucl. Phys.*, 44, 120 (1986).
(18) L. A. Kondratyuk, Yu. V. Ralchenko and A. V. Vasilets: preprint ITEP-17 (Atominform, Moscow, 1987).
(19) M. Bourquin, R. M. Brown, H. J. Burckhart, P. Extermann, M. Gailloud, W. M. Gibson, J. C. Gordon, P. Jacot-Guillarmod, Ph. Rosselet, P. Schirato, H. W. Siebert, V. J. Smath, K.-P. Streit and J. J. Thresher: *Phys. Lett. B*, 172, 113 (1986).
(20) A. N. Aleev *et al.*: JINR Rapid Communications, No. 19-86 (Dubna, 1986).

Serpukhov has indicated possible resonance structures M_φ^0, M_φ^-, and M_φ^+ in the channels $\Lambda\bar{p}K^+$ + pions at a mass 3.26 GeV and width $\Gamma \lesssim 30$ MeV. In addition, the CERN experiment noted another possible resonance in the channel $\Lambda\bar{p}\pi^+\pi^-\pi^-$ near 3.4 GeV. These resonances cannot be weakly decaying. As the flavour of U-resonances is apparently exotic ($I \geqslant 3/2$) they were identified with a qs-$\bar{q}^2$ baryonium (see, *e.g.*, review (7) and references therein). However it is very doubtful to interpret them as T-baryonium states $(q^2)_3$-$(\bar{q}^2)_3$, because the latter could hardly be so narrow. More popular is the identification of them with M-diquonium resonances where the diquarks qs and $\bar{q}^2$ have color 6 charges. Since the color 6 charges cannot be neutralized by the creation of a single $q\bar{q}$ pair, such a model can explain why the main decay channels of U/M_s-resonances contain apart from $B\bar{B}$-pair also one or more mesons. The 3.14 and 3.4 GeV can be identified with Regge recurrences $J^P = 4^-$ and 5^+ of the M-diquonium trajectory with $I = 3/2$, $S = 1$. It is dubious however that a M-diquonium state with such a high spin like 4 or 5 may be so narrow. Indeed, there is comparatively large probability for cascade decays of U/M_s into M-diquonium states with lower spins and one or more pions.

Another possibility is to identify the U/M_s-resonances with a $6q$ state $(q^2s)_8$-$(\bar{q}^3)_8$ which contains a color octet flux tube. The main decay channel of this system is related to the tunnelling of quark through flux tube. In this case it is very easy to explain why the channel $\Lambda\bar{p}$ + pions can be dominant (2 diquarks q^2 and $\bar{q}^2$ pick up q and $\bar{q}$ from the vacuum and form $\bar{B}B$, while two $q\bar{q}$ pairs produce pions). The M_φ meson can be identified with the ground state of the system $(q^2s)_8$-$(\bar{q}^2s)_8$ and the state 3.4 GeV with a member of the $(q^2s)_8$-$(\bar{q}^3)_8$ family corresponding to a different configuration of quarks cluster spins ($\Delta E \sim 300$ MeV would correspond to spin-spin splitting of 3.4 and 3.1 GeV states).

To have confidence in this identification of U/M_s meson it is necessary to known its spin. High spin ($J = 5$, 6) would support the $(q^2)_6$-$(\bar{q}^2)_6$ model, while the low spin would correspond to the $6q$-model with octet string.

4. – Broad and narrow nonstrange dibaryon in stringlike model.

Well-known candidates for $I = 1$ nonstrange dibaryons are ${}^1D_2(2140)$, ${}^3F_3(2260)$, ${}^1G_4(2480)$, ${}^3H_5(2700)$, ${}^1I_6(2900)$ etc. (see, *e.g.*, ref. (7)). They can be put on Regge trajectory with a slope which corresponds to the string tension for the color triplet flux tube. This trajectory can be described by the stretched rotating bag with the configuration $(4q)_3 - (q^2)_{\bar{3}}$.

In ref. (21) the description of dibaryon spectra was made with the help of the

(21) L. A. KONDRATYUK, B. V. MARTEMYANOV and M. G. SCHEPKIN: *Sov. J. Nucl. Phys.*, 45, 1252 (1987).

TABLE II. – *The masses of the stringlike states* $Q_{I_1J_1}$-$D_{I_2J_2}$, *where* $Q_{I_1J_1} \equiv (4q)_{I_1J_1}$, $D_{I_2J_2} \equiv (2q)_{I_2J_2}$.

J^P, I	Q_{01}-D_{11} $m(Q_{01}) = 1.04\,\text{GeV}$	Q_{01}-D_{11} $m(Q_{01}) = 1.14\,\text{GeV}$	Q_{12}-D_{00} $m(Q_{12}) = 1.3\,\text{GeV}$	M_{exp} (GeV)
3^-, 1	2.09	2.19	2.19	2.25 ± 0.05
4^+, 1	2.43	2.52	2.54	2.43 ± 0.07
5^-, 1	2.70	2.79	2.82	2.70 ± 0.10
6^+, 1	2.94	3.03	3.06	2.90 ± 0.10
7^-, 1	3.16	3.25	3.27	?
	Q_{01}-D_{00}	Q_{01}-D_{00}		
2^-, 0	1.95	2.05		
3^+, 0	2.31	2.41		
4^-, 0	2.60	2.70		
5^+, 0	2.85	2.95		

relativistic QCD string model with long-range spin-orbit coupling. It was found that the configuration Q_{01}-D_{11} (where $4q(Q_{01})$ and $2q(D_{11})$ clusters at the ends of the string have the quantum numbers $I = 0$, $S = 1$ and $I = 1$, $S = 1$) is apparently the most satisfactory to describe the $^3F_3$ series of dibaryons. The predicted series of dibaryons corresponding to the Q_{01}-D_{00} configuration is shown in table II for different masses of the $4q$ system. The most interesting state is the 2^- with the mass $(1.95 \div 2.05)$ GeV. The state 2^- cannot decay into two nucleons and its decay channel is $\pi\mathcal{N}\mathcal{N}$. If the state 2^- would be below $\pi\mathcal{N}\mathcal{N}$ threshold it would be very narrow with the main decay channel γnp and γd.

According to the mass hierarchy for multiquark clusters which is the consequence of the MIT bag model, the lowest $6q$-state with hidden color must be isoscalar. However during the last few years many evidences for narrow pp-states below and near 2 GeV (see, *e.g.*, ref. ([7,22])) have appeared. Such resonances cannot have isospin $I = 0$, probably their isospin is $I = 1$. In ref. ([21]) it was proposed to describe such resonances as systems consisting of three diquarks. It turns out that in the diquark model the lowest state has isospin $I = 1$ (for systems without strange quarks).

At first sight it seems possible to construct extremely light $6q$-state from three light D_{00} diquarks ($3m(D_{00}) = 660$ MeV). However the diquarks are bosons hence the coordinate wave function for colorless state must be antisymmetrical under permutations of diquarks: *i.e.* like $\varepsilon_{ijk} X_i^1 X_j^2 X_k^3$. In this case each diquark is in P-wave with respect to the centre of mass. The mass of this state is larger than 2.3 GeV.

The stringlike configurations $(D_{00} + D_{11})$-D_{00} and $(D_{00} + D_{11})$-D_{11} with two

([22]) B. TATISCHEFF: Review Talk at the *IX International Seminar on High Energy Physics Problems, Dubna, June 14-19, 1988.*

identical diquarks in P-wave have lower masses. The model predicts three states with isospon $I = 1$ in the mass region $(1.93 \div 2.02)$ GeV, corresponding to P-wave excitations of Q'_{11}-D_{00} system, where the Q'_{11} cluster is made of D_{00} and D_{11} diquarks. These three states correspond to three different ways of combining L and S into total angular momentum $J = L + S$. States with isospins $I = 0$, 1 and 2 in the mass interval $(2.1 \div 2.3)$ GeV, which correspond to P-wave excitation of Q'_{11}-D_{11} system, are also predicted (see fig. 1).

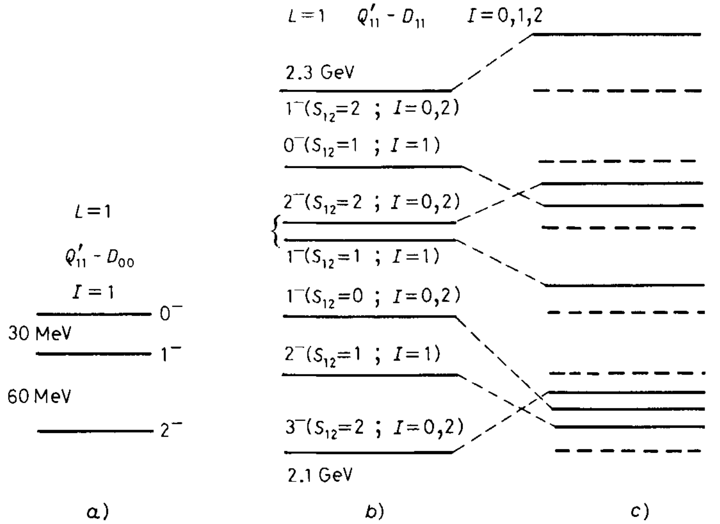

Fig. 1. – Spin-orbit and spin-spin splittings of dibaryon stringlike configurations Q'_{11}-D_{00} (a)) and Q'_{11}-D_{11} (b),c)) for $L = 1$. a) $\boldsymbol{L}\cdot\boldsymbol{S}_1$ splitting, b) $\boldsymbol{L}\cdot\boldsymbol{S}_{12}$ splitting, c) a $(\boldsymbol{L}\cdot\boldsymbol{S}_{12}) + b(\boldsymbol{S}_1\cdot\boldsymbol{S}_2)$.

The main feature of this model is the prediction of negative parity for lowest states which corresponds to the P-wave motion of two light diquarks. Another feature is that the splitting between states has two scales:

i) $\Delta E^{(1)} = (150 \div 200)$ MeV which corresponds to different orbital excitations and

ii) $\Delta E^{(2)} = (30 \div 60)$ MeV which corresponds to the spin-orbit and spin-spin splittings.

In this aspect the quark cluster model is different from the nonrelativistic rotational model of Tatischeff [22] according to which $E_L = a + bL(L+1)$, $b = (10 + 20)$ MeV. To discriminate between those models we should know the quantum numbers of resonances. There are conflicting results (see [7]). The data with better statistics performed at JINR [23] seems to be in favour of the diquark

[23] O. B. ABDINOV, A. A. BAYRAMOV, YU. A. BUDAGOV, A. M. DVORNIK, YU. F. LOMAKIN, A. A. MAILOV, V. B. FLYAGIN, YU. N. KHAZZHEEV and D. I. KHUBNA: *Sov. J. Nucl. Phys.*, 44, 1502 (1986).

model as they show the important contribution of P-wave in the pp-decays of 1.96 and 1.99 GeV resonances.

The dibaryons formed by diquarks could be very narrow provided the diquark radii were small. Estimates made by B. Z. Kopeliovich show that for diquark radii $(0.3 \div 0.4)$ fm the $\mathcal{N}\mathcal{N}$ decay widths of dibaryons may be less than 1 MeV (see ref. ([24])).

5. – Strange dibaryons ($\mathrm{DB_s}$) ($S = -1$ and -2) in stringlike model.

The spectra of strange dibaryons in the framework of stringlike model were discussed in ref. ([18]). In table III the spectra of orbital excited system Q'_{11}-$(qs)_{IJ}$ are listed, where Q'_{11} is the $4q$-cluster formed by the D_{00} and D_{11} diquarks in S-wave, $(qs)_{IJ}$ is the strange diquark $D^s_{\frac{1}{2}0}$ or $D^s_{\frac{1}{2}1}$.

TABLE III. – *Strange dibaryon masses for configuration* Q'_{11}-$(qs)_{IJ} = (D_{00} + D_{11})$-$(qs)_{IJ}$.

L	J^P	$I = 1/2,\ 3/2;\ Q'_{11}$-$D^s_{\frac{1}{2}0}$	J^P	$I = 1/2,\ 3/2;\ Q'_{11}$-$D^s_{\frac{1}{2}1}$
1	2^-	2027	3^-	2380
2	3^+	2381	4^+	2701
3	4^-	2666	5^-	2965
4	5^+	2913	6^+	3197

Each state in table III corresponds to the configuration with maximal angular momentum. The character of spin-orbit interaction is the same as for non-strange dibaryons with $L = 1$ (see fig. 1). The masses of Q'_{11}-qs dibaryons listed in table III were calculated using the mass of Q'_{11} cluster obtained from the experimentally observed narrow pp-resonances ($m(Q'_{11}) = 1.02$ GeV).

The lowest $L = 1$ state $\mathrm{DB_s^-}$ with $J^P = 2^-$ and isospin $I = 1/2$ or $3/2$ is of special interest. The uncertainties of the model predictions for the low-lying $L = 1$ states when we neglect the spin-spin interaction may be about $(50 \div 100)$ MeV. Therefore the mass of this state may lie in the interval $(2.03 \div 2.13)$ GeV. If the dibaryon mass were below $\mathcal{N}\Lambda$ threshold (2054 MeV), hypernuclei could strongly decay forming the strange dibaryon and fragments composed of nucleons. Therefore from the existence of Λ-hypernuclei it follows that $m(\mathrm{DB_s^-}) \geq m_\Lambda + m_{\mathcal{N}}$. Due to LS-coupling (see fig. 1) the strange $L = 1$ dibaryon will be split into three states 2^-, 1^- and 0^- which may lie below the $\Sigma\mathcal{N}$ threshold. In this case the lifetime of $\mathrm{DB_s^-}$ can be substantially higher than of Σ^--hyperon. So if the dibaryon $\mathrm{DB_s^-}$ is in the mass region $(2.08 \div 2.11)$ GeV, its lifetime may be $(10^{-7} \div 10^{-8})$ s.

([24]) B. Z. KOPELIOVICH and B. G. ZACHAROV: preprint E2-88-85 (Dubna, 1988).

In ref. ([18]) the cross-section of DB_s^- production in the reaction $\pi^- d \to K^+ DB_s^-$ was also estimated. It was found that it is 30 times less than the existing experimental upper limit ([25]) at 1.4 GeV/c and is about ~ 0.3 nb/sr at $\theta_{\text{c.m.}}^{\pi K} \sim 0°$.

It is also interesting to discuss stringlike configurations which are formed of diquarks with zero spin: $Q_{\frac{1}{2}0}^s\text{-}D_{00} \equiv (D_{00} + D_{\frac{1}{2}0}^s)\text{-}D_{00}$ and $Q_{\frac{1}{2}0}^s\text{-}D_{\frac{1}{2}0}^s \equiv (D_{00} + D_{\frac{1}{2}0}^s)\text{-}D_{\frac{1}{2}0}^s$. The first state corresponds to orbital excitation of diquark D_{00}, the second one to $D_{\frac{1}{2}0}^s$. For $L = 1$ the first state describes the dibaryon with quantum numbers $I = 1/2$, $J^P = 1^-$; the second one the $\widetilde{H}_1$-dihyperon with $S = -2$, $I = 1$, $J^P = 1^-$. Using the restriction $M(S = -1,\ I = 1/2,\ J^P = 1^-) \geqslant M(\Lambda) + M(\mathcal{N})$, we find $M(Q_{\frac{1}{2}0}^s) \geqslant 1$ GeV, so we conclude that $M(\widetilde{H}_1) \geqslant 2.11$ GeV. So the diquark model predicts a dihyperon $\widetilde{H}_1$ with isospin $I = 1$ (like bound states $\Sigma^-\Lambda$, $\Sigma^0\Lambda$, $\Sigma^+\Lambda$ which may lie below the $\Sigma\mathcal{N}$ threshold and therefore may be long-lived. The quantum numbers of this dihyperon are: $J^P = 1^-$, and the cross-section of its production in the reaction $K^- d \to K^+ \widetilde{H}_1^-$ at 1.5 GeV/c is $d\sigma/d\Omega \sim (0.2 \div 0.3)$ nb/sr for forward angles.

6. – The low-lying states of exotic dibaryons in diquark bag model.

In the previous sections we discussed only those dibaryons which corresponded to stringlike configurations or stretched rotating bags. If the color triplet diquarks were dynamically stable, it would be possible to consider spherically symmetrical configurations formed of three diquarks which correspond to S-wave motion of all three diquarks. In order to estimate the masses of these dibaryons we use the bag model and assume that the diquarks are confined in a spherical cavity with radius R. The mass of the bag is given by the formula

$$M = 4/3\,\pi R^3 B - Z_c/R + \sum_i E_i + \Delta E_{\text{cm}},$$

where $E_i = (m_i^2 + (\pi/R^2))^{\frac{1}{2}}$ and ΔE_{cm} is the colormagnetic interaction energy. We chose the parameters $B = 0.146$ GeV and $Z_0 = 1.84$ which are the same as in the ordinary MIT bag model. The diquark masses were taken to be equal to $M(D_{00}) = 220$ MeV, $M(D_{11}) = 550$ MeV and $M(D_{\frac{1}{2}0}^s) = 440$ MeV. The estimated dibaryon masses are listed in table IV.

Notice that the colormagnetic interaction reduces the calculated mass of $D_{11}\text{-}D_{00}\text{-}D_{11}$ state by ~ 180 MeV and can shift this state lower than the $\pi\mathcal{N}\mathcal{N}$ threshold.

([25]) E. D'AGOSTINI, G. AURIEMMA, J. P. DE BRION, A. CAILLET, J. B. CHEZE, J. DERRE, G. MAREL, G. MARINI, G. MARTELLOTTI, F. MASSA, A. NIGRO, E. PAULI, C. PIGOT, A. RAMBALDI, A.S. RENCROFT, C. E. ROOS, A. SCIUBBA, G. VRANA, J. WATERS and M. WEBSTER: *Phys. Lett. B*, **104**, 330 (1981).

TABLE IV. – *Dibaryon masses in the diquark bag model.*

Diquark structure	J^P	S	I	M(MeV)
D_{00}-D_{11}-D_{11}	1^+	0	0 or 2	2000
D_{11}-D_{11}-D_{11}	0^+	0	3	2360 (*)
	3^+	0	0	
	1^+, 2^+	0	1 or 2	
D_{00}-D_{11}-$D^s_{\frac{1}{2}0}$	1^+	-1	1/2, 3/2	2060
D_{11}-$D^s_{\frac{1}{2}0}$-$D^s_{\frac{1}{2}0}$	1^+	-2	1	2120
$D^s_{\frac{1}{2}0}$-D_{00}-$D^s_{\frac{1}{2}0}$	0^+	-2	0	1940

(*) The colormagnetic interaction was not taken into account.

The 1^+ dibaryon in this model is degenerate in isospin and the degenerate levels can have $I=0$, 1, 2. The state with $I=2$ can be compared with the dibaryon below the $\pi\mathcal{N}\mathcal{N}$ threshold which was observed by Los Alamos-Tel Aviv group in the reaction $\pi^- d \to \pi^+ X^-$ and $\pi^+ d \to \pi^- X^{+++}$ recently (see, *e.g.*, ref. ([22])). The state D_{11}-D_{11}-D_{11} with isospin $I=3$ and $J^P=1^+$ can also occur below the $\pi\pi\mathcal{N}\mathcal{N}$ threshold. It is interesting that the H^0 dihyperon (which is the diquark analog of the H particle predicted by Jaffe) may lie even in the vicinity of $\mathcal{N}\mathcal{N}$ threshold. Note that the nucleon mass calculated in the same model (nucleon is treated as D_{00}-q system) turns out to be about 1 GeV and agrees with experiment rather well.

7. – Conclusion.

According to the diquark model there may exist a variety of narrow dibaryons. In particular the model predicts the nonstrange dibaryon with $I=2$, $J^P=1^+$ which can be below $\pi\mathcal{N}\mathcal{N}$ threshold and the strange dibaryon with $I=3/2$ ($J^P=2^-$, 1^- or 0^-) below $\Sigma\mathcal{N}$ threshold. In the strange $S=-2$ sector the model predicts the dihyperons $H_1(1^+)$ and $\widetilde{H}_1(1^-)$ with $I=1$ ($J^P=1^+$ for the spherical state and $J^P=1^-$ for the stringlike state with $L=1$). These H_1 and $\widetilde{H}_1$ states are predicted to be below the $\Sigma\Lambda$ threshold. The dihyperon state H_0 with $I=0$, $J^P=0^+$ (which is the analog of the Jaffe H-particle) is predicted below $\Lambda\mathcal{N}$ threshold. The cross-sections of the string strange dihyperon production in the reactions $\pi^- d \to K^+ X^-$ and $K^- d \to K^+ X^-$ are about $(0.2 \div 0.3)$ nb/sr at 1.5 GeV/c.

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The results of sect. **5** were obtained together with Yu. V. Ralchenko and we are very grateful to him for collaboration. We are also grateful to Yu. A. Simonov and I. I. Strakovsky for useful discussions.

APPENDIX

Relativistic QCD string model with spin-orbit coupling.

The theory of string in QCD arises apparently when the gauge degrees of freedom are integrated over. Then we have the effective theory which involves purely geometrical variables and can be described by the Nambu action [26]. The rotation modes of the string with massless quarks at the ends describe linear Regge trajectories

$$M^2 = 2\pi\nu l\,.$$

In this simplest version of the string model only one parameter is introduced—the string tension ν.

One can consider also the case when the masses of quarks sitting at the string ends are finite $m_1,\ m_2 \neq 0$ [27-30]. The masses m_1, m_2 should be viewed as effective (constituent) masses, determined mainly by the localization of quarks in longitudinal and transversal directions at the string ends.

In some approximation the string can be considered as the stretched bag with the volume energy density B [31-34]. Then the linear energy density of the stretched bag (which is equivalent to the string tension) can be expressed through B and the color charges of quarks (or quark clusters) sitting at the string ends [31]

$$\nu = (8\pi\alpha_c B f_c^2)^{\frac{1}{2}}, \tag{A.1}$$

where $f_c^2 = 0$, 4/3, 10/3 and 3 for the representations 1,3(3*), 6 and 8 of $SU(3)_c$.

In series of papers [11,15,21,35] the model of the rotating string was applied for the description of orbital excitations of nonstrange mesons and baryons. Those hadrons were considered as stringlike objects with quarks or diquarks sitting at the string ends. This approach is similar to the stretched rotating bag model which was used for description of the orbital excitations of hadrons in refs. [32,33]. However there are two important differences:

i) We do not use the assumption on the linear relation between M^2 and l. In fact for a classical string with massive quarks at the ends it is not linear for finite l. The heavier the quarks or quark clusters the larger the nonlinearity. To find the spectrum we solve the string equations. In fact describing the orbitally

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(35) L. A. KONDRATYUK, B. V. MARTEMYANOV and M. G. SCHEPKIN: preprint ITEP-135 (Atominform, Moscow, 1987).

excited hadrons we use the quasi-classical approach choosing in the classical solutions integer values of orbital angular momentum.

ii) We take into account spin effects (and in particular long-range spin-orbit coupling) using the effective Hamiltonian for a string.

We take into account ls-coupling using the method described in ref. ([36]). The main assumptions is that the string contains in the comoving frame only the color electric field. Then the ls-term in the effective Hamiltonian is due to the Thomas precession and the contribution to the total energy of a system is of the form

$$\Delta E_{ls} = -\sum_{i=1}^{2} \boldsymbol{s}_{q_i} \cdot \boldsymbol{\omega}(\gamma_i - 1) \tag{A.2}$$

where $\boldsymbol{\omega}$ is the rotation frequency, $\boldsymbol{s}_{q_i}$ is the quark spin operator, γ_i is the Lorentz factor.

Equation (A.2) shows that the energetically preferable configuration of quark spins corresponds to the orientation of spin s_i parallel to the orbital momentum l. The result (A.2) is completely relativistic and the typical magnitude of ls-term for nonstrange mesons is $(150 \div 200)$ MeV.

The basic equations of the model express the mass and the angular momentum of the string through the quark (or quark cluster) masses and the string tension:

$$\begin{cases} M = E_l + \Delta E_{ls} = \sum_i E_{q_i} + E_\nu + \Delta E_{ls}\,, \\ \boldsymbol{J} = \boldsymbol{l} + \boldsymbol{s}\,, \qquad \boldsymbol{l} = \sum_i \boldsymbol{l}_{q_i} + \boldsymbol{l}_\nu\,, \qquad \boldsymbol{s} = \boldsymbol{s}_{q_1} + \boldsymbol{s}_{q_2}\,. \end{cases} \tag{A.3}$$

For string rotating with frequency ω the quark (E_{q_i}, l_{q_i}) and string (E_ν, l_ν) contributions to mass and angular momentum are given as follows:

$$\begin{cases} E_{q_i} = m_i \gamma_i\,, \qquad l_{q_i} = \dfrac{1}{\omega} m_i v_i^2 \gamma_i\,, \qquad \gamma_i = (1 - v_i^2)^{-\frac{1}{2}}\,, \\ E_\nu = \dfrac{\nu}{\omega} \sum_{i=1}^{2} \arcsin v_i\,, \qquad l_\nu = \dfrac{\nu}{2\omega^2} \sum_{i=1}^{2} \left(\arcsin v_i + \dfrac{v_i}{\gamma_i} \right). \end{cases} \tag{A.4}$$

It is also necessary to take into account the equilibrium conditions for the system «string + quarks»

$$v_i \omega m_i \gamma_i^2 = \nu\,, \qquad i = 1, 2\,. \tag{A.5}$$

The set of equations (A.3)-(A.5) should be solved for specific values of m_i, ν and l. At first it is necessary to find the velocities of quarks v_1, v_2 and the rotation frequency. Then all the quantities including the spin-orbit term (A.2) can be calculated. The configuration with $J = l + S_{q_1} + S_{q_2}$ will have a minimal energy.

It should be noted that strictly speaking the model considered is well justified for sufficiently large orbital momenta l. However, as was shown in ref. ([11,16,21,35]), the predictions of the model are in good agreement with the experimental meson

([36]) I. YU. KOBZAREV, B. V. MARTEMYANOV and M. G. SCHEPKIN: *Sov. J. Nucl. Phys.*, 44, 475 (1986).

and baryon spectra starting from $l = 2$. Some discrepancies which are found for low-lying states with $l = 1$ can be explained by configuration mixings and short-range spin-spin interaction. When the spin-spin interaction is absent the discrepancy with data does not exceed $(50 \div 100)$ MeV. To take into account the quantum operator nature of the sum $\boldsymbol{l} + \boldsymbol{s}_{q_1} + \boldsymbol{s}_{q_2}$ we use the following effective Hamiltonian:

$$M(l) = M_0(l) + \sum_i a_{ls}^{(i)} \frac{\boldsymbol{l} \cdot \boldsymbol{s}_i}{\sqrt{l(l+1)}} + \sum_{i>j} b_{ij}^{(s)} \boldsymbol{s}_i \cdot \boldsymbol{s}_j , \tag{A.6}$$

where $a_{ls}^{(i)} = \omega(\gamma_i - 1)$ and $b_{ij}^{(s)}$ define the spin-orbit and spin-spin interactions.

We take into account only the long-range part of spin-orbit coupling which gives inverse order of levels with fixed l. It is known from spectra of heavy quarkonia that for interquark distances $r \leqslant 0.5$ fm there is an important contribution of short-range spin-orbit term which is of Lorentz-vector type and is of opposite sign. There is also the short-range contribution of tensor and spin-spin types. We do not know how to include short-range spin-dependent forces into the string model. To estimate spin-spin splitting shown in fig. 1 we use the value $b_{ij}^{(s)}$ in (A.6) calculated from the value of the potential energy ([37])

$$v_{ij}^{(s)}(\boldsymbol{r}) = -\frac{3}{8} K_0 \frac{\exp[-r/r_0]}{m_i m_j r} \boldsymbol{s}_i \cdot \boldsymbol{s}_j \lambda_i^a \lambda_j^a \tag{A.7}$$

at $\langle r \rangle = 0.5$ fm. Then we found $b_{ss} \simeq (30 \div 40)$ MeV. The spectrum in fig. 1*c*) corresponds to the choice $b_{ss} = 30$ MeV. This estimate shows that the spin-spin interaction may change the ordering of $l = 1$ levels for quark clusters with $S_1 = S_2 = 1$.

([37]) R. K. Bhaduri, L. E. Cohler and Y. Nogami: *Nuovo Cimento A*, **65**, 376 (1981).

● RIASSUNTO (*)

Si discutono gli stati delle risonanze esotiche a molti quark $q^2\text{-}\bar{q}^2$, $q^3\text{-}\bar{q}^3$ e q^6 come sistemi composti di alcuni cluster di colore e in particolare di diquark. Si presta una particolare attenzione al problema delle risonanze dibarioniche strette (con stranezza $S = 0$, -1 e -2).

(*) *Traduzione a cura della Redazione.*

Многокварковые экзотические резонансы в струноподобной модели с дикварками.

Резюме (*). — Обсуждаются состояния многокварковых экзотических резонансов $q^2\text{-}\bar{q}^2$, $q^3\text{-}\bar{q}^3$ и q^6, как составные системы нескольких цветных кластеров и, в частности, ликварков. Особое внимание уделяется проблеме узких дибарионных резонансов (со странностью $S = 0$, -1, и -2).

(*) *Переведено редакцией.*