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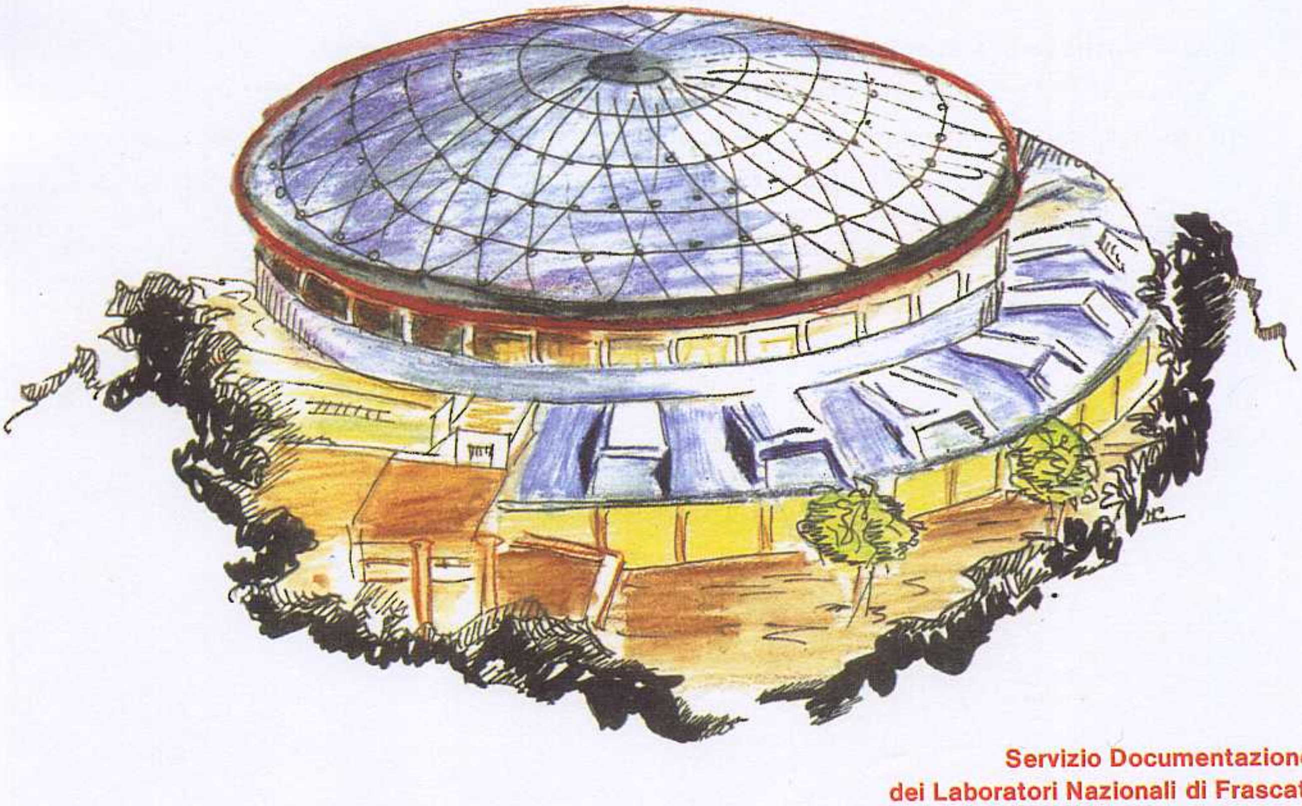

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ON POSSIBLE STRANGE PARTNERS OF THE f_2/AX RESONANCE

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Abstract

We consider the possibility of the existence of strange partners and of partners with hidden strangeness of the 2^{++} $I = 0$ resonance f_2/AX. These states exist if the f_2/AX is a $qq\bar{q}\bar{q}$ state and cannot exist if it is a glueball or a $\bar{N}N$ bound state. We discuss also other members of the four-quark family which can be constructed from scalar diquarks.

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The ASTERIX collaboration at LEAR has found a new 2^{++} resonance with isospin 0 in the $\pi^+\pi^-$ decay mode, which was called AX(1565) [1]. Recently, the Crystal Barrel collaboration has observed a very clear signal in the $\pi^0\pi^0$ channel with the quantum numbers of AX(1565) and a mass of 1515 MeV [2]. Also the OBELIX collaboration has observed a peak at a mass of about 1560 MeV in the $\pi^+\pi^-$ final state [3]. Finally, the E-760 Collaboration at Fermilab [4] has seen a bump in the $\pi^0\pi^0$ invariant mass spectrum in the region of the AX resonance from $\bar{p}p$ annihilation at three values of the total energy $\sqrt{s}$ between 3.1 and 3.5 GeV. The peak has been seen rather far from the phase space boundary (in contrast with annihilation at rest).

The f_2/AX resonance can not be fit into the usual $q\bar{q}$ 2^{++} nonet. It is also too light to be considered as a candidate into a 2^{++} glueball or hybrid state [5]. In ref. [6] it was proposed to treat it as a quasinuclear $\bar{N}N$ bound state and some problems which might prevent to identify it as a $qq\bar{q}\bar{q}$ state were outlined. According to ref. [6], the coherent attraction due to tensor forces generated by the one-boson exchange potential leads to a series of $\bar{N}N$ bound states with isospin $I = 0$. The estimation of absorption effects performed in the framework of the one-channel optical model shows [7] that the absorption does not destroy the deeply bound states. However, the one-channel optical-model approach to the treatment of annihilation effects was strongly criticized earlier (see e.g. [8]). It was shown that, if the absorption effects are described in the more general coupled-channel approach, the account of annihilation can destroy completely the predictions of the nonrelativistic potential model. Another and even more important problem is that for the calculation of deeply bound hadronic states one should involve the quark-antiquark color interaction but not only the colorless interaction between nucleon and antinucleon as in ref.[6]. Therefore the interpretation of the f_2/AX resonance may still be regarded as an open problem and it is important to compare with data the most distinctive features of different models.

In this paper we reconsider the $qq\bar{q}\bar{q}$ model of the f_2/AX resonance and show that there is not any serious obstacle to identify it with a four-quark state composed of two scalar color-triplet diquarks. In this case there must exist the strange partners of f_2/AX with mass in the region 1630 – 1680 MeV and partners with hidden strangeness with mass around 1750 - 1860 MeV. These resonances will decay into $K\pi$ and $K\bar{K}$, $\eta\eta$ and $\eta\pi$ systems, respectively, and can be produced in $\bar{p}p$ annihilation in flight. The existence of strange partners is the essential feature of the $qq\bar{q}\bar{q}$ model of the f_2/AX resonance. Such partners do not appear if f_2/AX is a glueball or a $\bar{N}N$ bound state [6]. We discuss also other members of the four-quark family, which can be constructed from scalar color-triplet diquarks.We show, for example, that the 1^{--} C(1480) resonance, which was found in the $\pi^0\phi$ channel [9], can also be well incorporated into this family as a four-quark state with hidden strangeness.

To discuss the orbital excitations of four-quark systems we shall use here the relativistic string model (RSM) with spin-orbit coupling which was applied for description of Regge trajectories of hadrons in ref. [10]. This QCD motivated model arises when we consider orbitally excited states of mesons and baryons as stretched rotating bags [11]. Then, if we assume that the effective masses of quarks or quark clusters at the string ends, which depend on their localizations, can be treated as constants, a possible approach is an "effective" theory which involves purely geometrical variables and can be described by the Nambu action [12]. The total angular momentum (spin) and the energy (mass) of a string rotating at the frequency ω with two quark clusters at the string ends can be written in the form:

$$J = s_1 + s_2 + \sum_{i=1,2} \frac{\nu}{2\omega^2}\left(\arcsin v_i + \frac{v_i}{\gamma_i}\right)$$

$$M = \sum_{i=1,2} \frac{\nu}{\omega}\left(\arcsin v_i + \frac{1}{v_i\gamma_i}\right) + \Delta E(L, s_1, s_2) \qquad (1)$$

where s_1 and s_2 are the projections of the cluster spins onto the axis of rotation, v_1 and v_2 are their velocities, $\gamma_i = (1 - v_i^2)^{-1/2}$, ν is the string tension which is determined by the quark color charges at the string ends, $\Delta E\ (L, s_1, s_2) = - \omega s_1\ (\gamma_1 - 1) - \omega s_2(\gamma_2 - 1)$ is the correction to the energy due to the spin-orbit interaction. At the ends of the string, the following equilibrium conditions hold

$$\omega\, m_i v_i \gamma_i^2 = \nu \qquad (i=1,2) \qquad (2)$$

The parameters of the model are the effective masses m_1, m_2 of the quark clusters at the string ends and the string tension ν. If they are chosen from the set of equations (1) - (2) for each value of $L = J - s_1 - s_2$, we can find v_1 , v_2 and the rotation frequency ω. Then all the quantities, including spin-orbit term, can be evaluated. The calculated Regge trajectories are not linear, however the nonlinearities are comparatively small for meson and baryon Regge trajectories composed of light quarks. As we shall also see below, our main predictions do not depend essentially on the specific model for Regge trajectories: calculated according eqs.(1)-(2) or assumed linear.

The assertion that the orbitally excited $qq\bar{q}\bar{q}$ states should exist may be regarded as a consequence of the existence of meson and baryon Regge trajectories with the almost identical slopes $\alpha' = 1/(2\pi\nu) = 0.9\ \mathrm{GeV}^{-2}$ (see, for example, ref.[10]). If meson resonances correspond to rotating string with color-triplet charges (quark and antiquark) at its ends, baryon resonances should then correspond to $q - q^2$ configuration, where the diquark has the same color charge as an antiquark. If the quark in this system is replaced by an antidiquark, we obtain the diquonium state with color-triplet diquarks. Therefore the very existence of meson and baryon Regge trajectories with identical slopes implies the existence of $q^2 - \bar{q}^2$ Regge trajectory with the same slope.

The diquonium Regge trajectories were discussed previously in refs. [13÷15] assuming a linear relation between M^2 and J. In ref. [16] they were discussed in the framework of RSM. There are two kinds of nonstrange color-triplet diquarks: a scalar diquark $D_{00} \equiv q^2$ with s= I = 0 and a vector diquark $D_{11} \equiv q^2$ with s= I = 1 (s is the spin of diquark, I is the isospin). So it is possible to construct three different types of $qq\bar{q}\bar{q}$ mesons without strange quarks [13]:

$$A = |\, D_{00} - \overline{D}_{00} > ; \qquad B^{\pm} = |\, D_{00} - \overline{D}_{11} > \pm \, |\, \overline{D}_{00} - D_{11} > ; \qquad C = |\, D_{11} - \overline{D}_{11} > \tag{3}$$

where the state A has isospin 0, the states $B^{\pm}$ have isospin 1 and the state C is degenerated with respect to isospin (I = 0 ,1 ,2).

The main shortcoming of all $qq\bar{q}\bar{q}$ models is the prediction of a very rich spectrum of mesonic states. Even if we take into account only the rotational excitation mode of the string and neglect all the other modes we would have 34 Regge trajectories in the nonstrange sector: one A trajectory, six B trajectories and nine C trajectories ($(2s_1+1)(2s_2+1) = 9$) for each value of the isospin I = 0, 1 or 2.

The overwhelming majority of the predicted four-quark states are of the C-type. Many should have exotic quantum numbers and some of them, with I = 2 and L = 0 or 1, are predicted below 2 GeV [13, 15, 16]. Up to now, such states have not been observed experimentally.

One way to explain this fact is to assume that states with low orbital momenta L = 0 or 1 are so broad that they can not be seen in experiments. The C- type mesonic states with L = 2 would lie above $\Delta\bar{N}$ or $\Delta\bar{\Delta}$ thresholds and since they decay mainly into $\bar{N}\Delta$, $\bar{\Delta}N$ or $\bar{\Delta}\,\Delta$ channels they could escape observation. However, despite of these arguments, the fact that up to now we do not have any good candidate for exotic four-quark states with I = 2 is not very encouraging.

Another possibility is to explain the absence of a big variety of $qq\bar{q}\bar{q}$ states making the hypothesis that only scalar diquarks, as more dynamically stable objects if compared with vector diquarks, may form $qq\bar{q}\bar{q}$ states. This stability can be due to the color magnetic spin-spin forces as well as to spin-dependent nonperturbative effects [17]. The fit of Δ and N Regge trajectories [10] using eqs. (1) - (2) shows in fact that the effective mass of the scalar diquark is by 300 MeV less than the mass of the vector diquark.

If the last hypothesis is correct, then only states which belong to an A- type Regge trajectory can exist and the total number of predicted four-quark states will be significantly reduced.

Let us consider nevertheless both possibilities. A resonance 2^{++} with I = 0 may lie either on a C-type Regge trajectory or on an A -type Regge trajectory.

In the first case, the low-lying 2^{++} $qq\bar{q}\bar{q}$ meson is formed by two diquarks with $s_1 = s_2 = 1$ in S-wave. The mass of this state was estimated to be 1.55 GeV[13]. Since all four quarks are in S-wave, nothing can prevent their rearrangement into two colorless $q\bar{q}$ subsystems. Therefore, such a state can easily decay and is expected to be very broad. Thus an identification of the f_2/AX resonance with this state meets with difficulties. An other problem of this identification is that it will lead to the existence of $qq\bar{q}\bar{q}$ mesons with I = 1 and I = 2 and the same mass of f_2/AX. Now, no such resonances with I = 1 and 2 were found in the mass region of f_2/AX .

The other possibility is to identify the f_2/AX with the D-wave state of two scalar diquarks (A-type meson). Predicting the mass of this state at 1.9 GeV Jaffe [13] assumed that the intercept of an A -trajectory should be calculated in the spherical bag model neglecting the color-magnetic spin-spin interaction between quarks. This assumption is however arbitrary.

In RSM the mass of a 2^{++} A-type meson is predicted around 1.7 GeV [11]. The spin-spin interaction is taken into account through the parametrization of the diquark masses. The effective masses of quark q and diquark D_{00} were found by fitting the experimental masses of the $\omega_3(1670)$ and N(1680) resonances, which were regarded as L =2 excitations of $q-\bar{q}$ and $q-D_{00}$ strings. The third parameter of the model, the string tension, was fixed by the slope of the $\rho-\omega$ Regge trajectory. Therefore the shift of the mass of the 2^{++} state from 1.9 to 1.7 GeV can be considered as the effect of color-magnetic interaction.

There are still some other effects which may decrease the mass of a 2^{++} A-type meson.

1) The coupling to hadronic channels decreases usually the energy of the state calculated without loop corrections. This shift may be of the order of the meson width, i.e. of the order of 100-150 MeV.
2) The state f_2/AX can have admixtures of other components like glueballs, hybrids, etc., which can shift its mass downward.
3) The effective mass of diquark D_{00} may also be different in the three- and four-quark sectors.The mass scale of the string model was up to now normalized to $q-\bar{q}$ and 3q sectors by the fits to meson and baryon Regge trajectories. But we do not know how good the predictions of this model will be when extrapolated to the four-quark sector.

Therefore it is quite possible that, due to the corrections 1)÷3), the mass of a D-wave A-type meson will be around the mass of the f_2/AX resonance.

If the f_2/AX resonance lies on an A-type Regge trajectory with the standard value for the slope $\alpha' = 0.9$ GeV^{-2} and corresponds to a D-state, then other states on this trajectory will have masses of about 1190 MeV for J = L = 1 and 1850 MeV for J = L = 3. These predictions are valid for linear Regge trajectory. In the string model (1)-(2), Regge trajectories have nonlinearities and if we fix the D-wave state at 1515 MeV we find the eigen-value 1100 MeV for the P-wave 1^{--} state and 1840 MeV for the F-wave 3^{--} state. Of course the string model can not be applied to the S-wave 0^{++} state. This state is expected to be rather broad.

There are, however, good chances that the 1^{--} state may be not very broad, because the centrifugal barrier and attractive color-magnetic forces can suppress the probability of quark tunneling along the string. The same arguments can also be applied to the 2^{++} and 3^{--} states, if the latter is below the $\bar{N}N$ threshold. Otherwise, it would decay into the $\bar{N}N$ channel through the break of the string, becoming broader.

If we identify the f_2/AX resonance with a $qq\bar{q}\bar{q}$ state then, independently of the specific $qq\bar{q}\bar{q}$ model, we predict the existence of its strange partners $A_s = | qs - \bar{q}\bar{q} >$ and $A_{\bar{s}} = | qq - \bar{q}\bar{s} >$ with strangeness S = ±1, and the state with hidden strangeness $A_{s\bar{s}} = | qs - \bar{q}\bar{s} >$ decaying into kaons, ϕ and η mesons.

The strange states A_s and $A_{\bar{s}}$, as K or K* mesons, have isospin I = 1/2 and decay into $K\pi$, $K\pi\pi$, $K\pi\pi\pi$,... final states.

The states with hidden strangeness $A_{s\bar{s}}$ are degenerated in isospin I = 0 or 1. The existence of the states with hidden strangeness and charges Z = +1 and -1 makes the states $A_{s\bar{s}}$

very distinctive from the families of η and ϕ mesons which have isospin I = 0. Therefore good channels to look for such states are $\phi\,\pi^-$, $\phi\,\pi^+$, K^-K^0 or $K^+\bar{K}^0$, etc.

To estimate the masses of the A_s and $A_{s\bar{s}}$ states we must know the mass difference of strange and nonstrange scalar diquarks. The fit of Σ and Λ Regge trajectories in RSM [18] shows that the difference of the masses of the strange and nonstrange diquarks with s = 0 is about 140 MeV and is almost the same as for strange and nonstrange quarks. Then, for example, the masses of 2^+ states A_s and $A_{s\bar{s}}$ calculated using the equations (1) - (2) turn out to be about 160 and 340 MeV heavier, respectively, than the mass of the nonstrange 2^+ state.

In the case of a linear A - type Regge trajectory we assume that the masses of the A_s and $A_{s\bar{s}}$ states should be increased by 120 -150 MeV for each unit of strangeness (open or hidden), as it happens for the K* and ϕ Regge trajectories.

In Table 1 the masses of the 1^{--} , 2^{++} and 3^{--} A - type mesons are shown. The masses have been calculated using eqs.(1) - (2) with ν = 0.1822 GeV^2 (RSM) and linear Regge trajectories (LRT). The parameters , the mass of the diquark D_{00} in RSM and the intercept M_0^2 in LTR, were normalised to the mass 1515 MeV of the D-wave state.

A possible candidate for an $A_{s\bar{s}}$ state is represented by the so called "Landsberg resonance" C(1480) discovered time ago at Serpukhov [9] in the reaction $\pi^- p \to C(1480)n$, $C(1480) \to \phi\,\pi^0$ at the momentum of 32.5 GeV/c. This resonance has mass and width respectively M = (1480 ± 40) MeV, Γ= (130 ± 60) MeV and quantum numbers $J^{PC} = 1^{--}$, $I^G = 1^+$. The state can not be an usual $q\bar{q}$ meson, because its decay is OZI forbidden and it has not been found in the reaction $\pi^- p \to \omega\,\pi^0 n$. Therefore, it was supposed that this resonance is a four -quark state with hidden strangeness. According to Table 1 , mass and quantum numbers of C(1480) suggest its identification with L = 1 $A_{s\bar{s}}$ state.

Table 1 – *Masses (in MeV) of the low - lying A-type mesons.*

State	$D_{00} - \overline{D_{00}}$		A_s and $A_{\bar{s}}$		$A_{s\bar{s}}$	
	(RSM)	(LTR)	(RSM)	(LRT)	(RSM)	(LRT)
1^{--}	1100	1090	1270	1210 -1240	1450	1330-1390
2^{++}	1515	1515	1675	1635 -1665	1855	1755-1815
3^{--}	1840	1850	2010	1960- 1990	2180	2090-2150
4^{++}	2120	2125	2310	2235-2275	2490	2365-2425

There is also a candidate into 1^{--} $D_{00} - \overline{D_{00}}$ state. The DESY-Frascati group [19] has seen the resonance in the e^+e^- - channel in the reaction $\gamma\, p \to p\, e^+e^-$ with mass 1097^{+16}_{-19} MeV and width $\Gamma = 31^{+24}_{-20}$ MeV. The strength of this resonance in the interference of the real part of the Compton diffractive photoproduction amplitude with the Bethe-Heitler amplitude is essentially smaller than the strength of ϕ - meson. As the coupling of the four-quark states to e^+e^- - channel is expected to be weaker as compared with $q\bar{q}$ - states (two pairs of quarks should annihilate!), the supression of its production in e^+e^- - channel is also a good argument in favour of four-quark interpretation of this resonance.

Conclusions. Trying to identify the f_2/AX resonance with a four-quark state we have presented arguments according to which four-quark states can most probably be formed only by scalar diquarks (A-type mesons). In this case we predict four-quark states only with the isospin I = 0 in the nonstrange sector, I = 1/2 in the strange sector and I = 0 or 1 in the sector with hidden strangeness.

There are three candidates into A-type mesons: the nonstrange f_2/AX resonance at 1500 - 1565 MeV with $J^{PC} = 2^{++}$, $I^G = 0^+$, the C - resonance with hidden strangeness and $J^{PC} = 1^{--}$, $I^G = 1^+$ at 1480 MeV and the 1^{--} (1100) -resonance , which has been seen in the e^+e^-- channel [19].

It would be very important to find other members of this family. It seems rather promising to search for these states using antiproton beams, because antiprotons contain antidiquarks. Since the f_2/AX resonance was clearly seen in $\bar{p}p$ annihilation, it could be also interesting to look, in particular, for the 2^+ partners of the f_2/AX with open and hidden strangeness and to confirm the existence of the C - resonance.

The A_s resonance could be produced in association with kaon in $\bar{p}p$ annihilation in reactions like $\bar{p}p \rightarrow K^0 A_s^0$, $A_s^0 \rightarrow K^- \pi^+$. However, because of its large mass, it can not be produced in annihilation at rest. The $A_{s\bar{s}}$ resonance could be produced in reactions like $\bar{p}p \rightarrow A_{s\bar{s}} + K\bar{K}$or $A_{s\bar{s}} + m\pi$, $A_{s\bar{s}} \rightarrow \phi$(or $\eta)\pi$, K^-K^+, $K^-K^+\pi$, etc., again in flight. The production of $A_{s\bar{s}}$ by low energy antiprotons is suppressed by phase space, especially in the first reaction. The second reaction can be suppressed by OZ1 rule. However, due to the admixture of hidden strangeness in nucleon and antinucleon [20], OZI rule is rather strongly violated in $\bar{p}p$ annihilation [21]. Therefore at low energy it might be interesting to look for $A_{s\bar{s}}$ production in $\bar{p}p$-annihilation in association with one or several pions. The masses of A_s and $A_{s\bar{s}}$ will most probably be below the thresholds of $K^*\rho$ (1663 MeV) and $K^*\bar{K}^*$ (1786 MeV) decay modes. In this case, the expected width of these states will be of the order of the f_2/AX total width. All these states can be studied by Crystal Barrel and OBELIX detectors at LEAR in the near future.

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