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Search for Glueballs

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Поиски глюболов

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Аннотация

В настоящее время появились новые экспериментальные данные коллаборации Crystal Barrel о мезонах в районе 1 ГэВ. Эти данные, совместно с данными групп GAMS и Mark-III, дают богатую информацию об экзотических мезонах. Основываясь на этом, мы предлагаем возможную структуру глюбольного сектора.

Abstract

New data for study of mesons in the mass region above 1 GeV are available now from the Crystal Barrel Collaboration. These, together with the results of GAMS and Mark-III, provide rich information about meson exotics. Based on these data we discuss a possible scheme for the glueball sector.

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A group of resonances with masses in the region 1–2 GeV which have been observed in the recent experiments of Crystal Barrel Collaboration [1] [4], GAMS [5]–[8] and the re-analysis of the Mark-III data [9, 10] can be interpreted as $q\bar{q}$-states only with difficulty. It looks like we face exotic mesons. We present here an interpretation of these resonances as glueballs. A striking result of these experiments is the existence in the 1–2 GeV mass region of a large number of scalar mesons, $I = 0$, $J^{PC} = 0^{++}$; not all of them can be fitted as $q\bar{q}$. We suggest that the existence of these resonances is a result of the colour symmetry surviving at large distances. The survival of the colour SU(3)-symmetry at hadronic distances, ~ 1 fm, is not trivial because gluons in this region cannot be treated as massless particles: it is the requirement of analyticity of hadron amplitudes or, speaking more generally, the requirement of confinement.

Up to now there are controversial statements about glueballs. An important agreement in favour of their existence is that in the spectroscopic models, which describe successfully $q\bar{q}$-states, glueballs originate as a natural generalization of these schemes. Glueballs are predicted in the bag model [11], the flux-tube model [12], and in the lattice calculus (see ref. [13, 14] and references therein).

We discuss glueballs here using an effective QCD-motivated Lagrangian which operates with constituent quarks and effective gluons. In the pure glueball sector this model gives the same results as the others do, for example, the bag model. But, in the model we now discuss, one can see a mechanism for generation of additional scalar mesons which are related to the colour symmetry surviving in the large-r region.

The paper is organized as follows. We discuss, first of all, the problem of surviving colour symmetry at large distances. A model with QCD-motivated effective Lagrangian is used to illustrate the mechanism by which the two extra scalar mesons appear in this case. After that, the scheme for the mesons in the mass region up to 2 GeV is presented. This scheme includes

1. $q\bar{q}$-states: S- and P-wave mesons and their radial excitations,
2. two-gluon glueballs: S-, P- and D-wave states,
3. two scalar mesons $I = 0$, $J^{PC} = 0^{++}$ which appear because of colour

symmetry conservation for effective massive gluons; below we call them scalarons.

The introduction of an effective massive gluon for quark-gluon physics at large r (or for soft-interaction physics) is a requirement of an analyticity of hadron amplitudes. Massless gluons give the wrong singularities, so we need to use some type of cut-off in the infrared region. It is believed that this cut-off has a dynamical origin, being a consequence of the confinement.

Here we explore the Higgs mechanism to generate the gluon mass. This mechanism provides gauge invariance naturally while restoring the correct analytical properties of hadron amplitudes. But it is an oversimplification in some respect. It ignores another feature of confinement: the impossibility of outflow of coloured particles without colour neutralization. We bypass this problem by not considering coloured particles in the initial and final states of amplitudes. So, we model by the Higgs mechanism the dynamics of creating effective gluon mass. It suggests that the Higgs particles have a dynamical origin.

Experience of working with hadron quark-gluon structure in the soft-interaction region shows that colour is realized as an SU(3)-symmetry, at least as a global one. The mechanism of the realization of the global SU(3) after spontaneous symmetry breaking of the local SU(3)-symmetry was studied in refs. [15]–[19], although for other problems. Here, considering an effective Lagrangian, we follow this prescription.

A simple mechanism of obtaining global colour symmetry and massive gluons is to introduce a scalar Higgs field which is a triplet of both the local colour group $SU(3)_\ell$, and some global $SU(3)_g$. So, we introduce nine Higgs fields $\phi_{k\ell}$: an $SU(3)_g$ triplet (index k) and an $SU(3)_\ell$ triplet (index ℓ).

We consider a Lagrangian L which contains two parts: (i) Lagrangian of QCD, L_{QCD}, and (ii) the Lagrangian for coloured Higgs fields, L_H:

$$\begin{aligned} L &= L_{QCD} + L_H \\ L_H &= -\frac{1}{2} Tr(D^\mu \phi)^+ D_\mu \phi + V(\phi). \end{aligned} \tag{1}$$

Here $D_\mu = \partial_\mu - i/2\, g \lambda_a A^a_\mu$. The field ϕ has two indices and both run over three values: $k = 1, 2, 3$ and $i = 1, 2, 3$. It is enough to restrict ourselves in

the potential $V(\phi)$ to terms ϕ^4 :

$$V(\phi) = -a\,Tr\,\phi^+\phi + A(Tr\,\phi^+\phi)^2 + B\,Tr\,\phi^+\phi\phi^+\phi - C(det\,\phi + det\,\phi^+), \quad (2)$$

where $3A + B > 0$, $a > 0$ and $C > 0$.

The colour symmetry is realized after spontaneous symmetry breaking as a global SU(3)-symmetry. The new basis contains:

1. 8 massive gluons (colour octet, $J^P = 1^-$) with mass

$$m_G^2 = \frac{1}{6} g^2 v^2, \quad (3)$$

where $\langle \phi_{ki} \rangle = \frac{1}{\sqrt{6}} \delta_{ki} v$ and $(3A + B)v^2 = 3a + \sqrt{3/2} C v$;

2. 8 massive colour Higgs mesons (colour octet, $J^P = 0^+$) with mass

$$m_H^2 = \frac{2}{3} B v^2 + \sqrt{\frac{2}{3}} C v; \quad (4)$$

3. 2 massive scalarons (colour singlets, $J^{PC} = 0^{++}$) with masses

$$M_1 = \sqrt{\frac{3}{2}} C v, \qquad M_2 = \frac{2}{3}(3A + B)v^2 - \frac{1}{\sqrt{6}} C v. \quad (5)$$

We discuss the sector of low-lying exotic mesons which contains two-gluon glueballs (GG) with $L = 0, 1, 2$, gluon-higgs hybrids (GH), and two-higgs mesons (HH). It looks reasonable to estimate the masses of these composite particles as a sum of the masses of their constituents: $M(GG) \simeq 2m_G$, $M(GH) \simeq m_G + m_H$ and $M(HH) \simeq 2m_H$. We choose

$$m_G = 0.75 \text{ GeV}, \qquad m_H \geq 1.25 \text{ GeV}. \quad (6)$$

With these masses we restrict ourselves to consideration of two-gluon glueballs: GH- and HH-states are in the mass region above 2 GeV.

We suggest the following scheme for glueballs in S-, P-, and D-wave states. A square bracket indicates a mixing between GG and $q\bar{q}$ states:

$$S : \begin{bmatrix} 0^{++}(1505) \\ f_0(1590) \end{bmatrix}, \qquad \begin{bmatrix} 2^{++}(1780) \\ f_2(1710) \end{bmatrix}$$

$$P : \begin{bmatrix} 0^{-+}(1440) \\ \eta(1295) \\ \eta' \end{bmatrix}, \; 1^{-+}(1910) \; , \; 2^{-+}(?) \tag{7}$$

$$D : \; 0^{++}(2100), 1^{++}(?), 2^{++}(?), 2^{++}(?), 3^{++}(?), 4^{++}(?).$$

According to the rules of the $1/N$-expansion [20, 21], a glueball can easily mix with nearby $q\bar{q}$-states, so it is possible that some glueballs are spread over neighbouring mesons. We suppose that just this happens with S-wave 0^{++}- and 2^{++}-glueballs: they are corresponding mixtures of $f_0(1505)$ $f_0(1590)$ mesons and $f_2(1780)$–$f_2(1710)$ mesons. The same happens with the P-wave 0^{-+}-glueball: it is a mixture of $\iota(1440)$,$\eta(1295)$, η' and maybe even η. Such an admixture of low-lying mesons to the 0^{-+}-glueball can explain the shift of $\iota(1440)$ to the lower mass region. There is another important consequence: mesons which are mixtures of glueball and $q\bar{q}$-states do not obey flavour-blindness in their decay as is expected for pure glueball states.

The possible existence of the exotic resonance 1^{-+} in the mass region 1700–2000 MeV is very important for the glueball scheme. A resonance at 1910 MeV is reported by GAMS [8]: it decays to $\eta\eta'$ but not $\eta\eta$, and they suggest $J^{PC} = 1^{-+}$, though this needs confirmation.

Resonances $2^{++}(1780)$ and $0^{++}(2100)$ were observed in the re-analysis of Mark-III data $J/\psi \to \gamma 4\pi$ [10]. Around $2^{++}(1780)$ GAMS claims 2^{++}-resonance at 1810 MeV [5]: it looks like it may be the same state.

The resonances $2^{-+}(1650)$ and $2^{-+}(1850)$ were recently seen [4] in Crystal Barrel data $p\bar{p} \to \eta\pi^0\pi^0\pi^0$ decaying purely to $a_2(1320)\pi$ and $f_2(1270)\eta$ correspondingly. Mark III data on $J/\psi \to \gamma(\eta\pi\pi)$ [23] also show a peak at 1850 MeV, though no J^P analysis has been done. The resonance $2^{-+}(1850)$ can be considered as a candidate for 2^{-+}-glueball. An alternative is that $2^{-+}(1650)$ and $2^{-+}(1850)$ are the D-wave $q\bar{q}$-states, partners of $\pi_2(1670)$ and $K_2(1770)$.

The scheme for glueballs should be complemented by a $q\bar{q}$-scheme. The basic $^3P_1$, $^3P_2$ and $^1P_1$ $q\bar{q}$-multiplets are fixed now, but not the $^3P_0$-multiplet. Below we discuss three possible variants for this multiplet. These variants depend on how one assigns $f_0(975)$, $a_0(980)$ and $f_0(1000)$, the broad resonance in the region of 1000 MeV.

1.The first scheme assigns $f_0(975)$ and $a_0(980)$ as $q\bar{q}$-states:

		radial excitations
$^1S_0(0^{-+})$	η, η', π, K	$\eta(1295), \eta'(1440), \pi(1300), K(1460)$
$^3S(1^{--})$	ω, ϕ, ρ, K^*	$\omega(1390), \phi(1680), \rho(1450), K^*(1410)$
$^3P_0(0^{++})$	$f_0(975), f_0'(1240), a_0(980), K(1430)$	$f_0(1335), \begin{bmatrix} f_0(1590) \\ f_0(1505) \end{bmatrix}, a_0(1400), ?$
$^1P_1(1^{+-})$	$h_1(1170), h_1'(1380), b_1(1235), K_1(1270)$	
$^3P_1(1^{++})$	$f_1(1285), f_1'(1510), a_1(1260), K_1(1430)$	
$^3P_2(2^{++})$	$f_2(1270), f_2'(1525), a_2(1320), K_2^*(1430)$	$f_2(1640), \begin{bmatrix} f_2(1710) \\ f_2(1780) \end{bmatrix}, \rho_2(1690), ?$

Concerning the radial excitations of the S-wave multiplets (0^- and 1^-) we remark only about $\eta'(1440)$. It is possible, that in the region of $\iota(1440)$ there are two poles. We suppose that this is the case, and $\eta'(1440)$ is just the second pole. $\eta(1295)$, as well as η' and η, has a large admixture of the glueball component, as discussed above; for the sake of simplicity we do not especially emphasize this in the Table.

In this variant, the $^3P_0(0^{++})$-radial excitations are heavier than the basic states by 350–400 MeV, less than for S-wave $q\bar{q}$-states. But that does not seem to be an argument against this variant: the same mass-splitting occurs for $^3P_2(2^{++})$-states. Such a decrease of the mass splitting looks quite possible.

A merit of this variant is that the location of the first scalaron is obvious: it explains the broad resonance in the region of 1000 MeV. In this mass region two poles definitely exist near the $K\bar{K}$ threshold. However, a counter argument[23] to the variant being discussed is that these two poles may correspond a single state whose second and third poles are separated in both mass and width by coupling between $\pi\pi$ and $K\bar{K}$ channels. A second disadvantage of this variant is that $f_0'(1240)$ is not well established as an $s\bar{s}$ state. However, for the moment we ignore these difficulties and suppose that $f_0(975)$ has both narrow second and third sheet poles, as argued by Morgan and Pennington[24]. In this scheme the scalaron corresponds to the broad enhancement observed in the pion-pion $I = 0$, $J^{PC} = 0^{++}$ S-wave.

For the second scalaron there are several possibilities:

(i) The second scalaron is located near 1000 MeV just like the first one. Then the broad enhancement is due to two scalaron poles.

(ii) It is not excluded that in the region of $f_0(1335)$ there are two poles; then the second may be related to the second scalaron.

2. GAMS reported a resonance at 1740 MeV in the $\eta\eta$ system with $J^{PC} = 0^{++}$ or 2^{++} [7]. If $J^{PC} = 0^{++}$ it looks a candidate for the second scalaron. The first scalaron, being of the same nature, has to have a small width also: it is reasonable to identify it as $f_0(975)$. Then the $^3P_0$-multiplet includes the broad resonance $f_0(1000)$:

$$^3P_0(0^{++}): \quad f_0(1000),\ f_0'(1240),\ a_0(980),\ K(1430). \tag{8}$$

That agrees to the spectroscopic calculations which give the mass of the

lowest $0^{++}q\bar{q}$-state near 1000 MeV and the width of the order of 400-600 MeV [25].[26].

3.The third variant for the $^3P_0(0^{++})$ $q\bar{q}$-state is

$$^3P_0(0^{++}): \quad f_0(1335), \begin{bmatrix} f_0(1590) \\ f_0(1505) \end{bmatrix}, \; a_0(1400), \; K(1430). \qquad (9)$$

Then the radial excitations of these resonances are somewhere in the mass region 1650–1800 MeV, in the same region where the 2^+-radial excitations are located. In this variant it looks as possible to consider the resonances $f_0(975)$ and $a_0(980)$ as Gribov's minions[27]. Location of the scalarons is the same as in the variant 1.

The following candidates for glueballs

$$0^{++}(1550), \; 2^{++}(1750), \; 1^{-+}(1910), \; 0^{++}(2100) \qquad (10)$$

are fixed in all variants for $^3P_0$-multiplet: we can use their masses to estimate a position of others glueballs. In eq.(10) the average magnitudes are standing for the masses of the glueballs which are realized as a mixture of the resonances $f_0(1505)$–$f_0(1590)$ and $f_2(1710)$–$f_2(1780)$. If the glueball mass-splitting is treated as a perturbation then the following formula provides masses of the GG-states:

$$M = m + a\,J(J+1) + b\,S(S+1) + c\,L(L+1) \qquad (11)$$

Here S and L are total spin and orbital momentum of the GG-state. It gives m=1550 MeV, a=88 MeV, b= 55 MeV, and c=147 MeV, so we obtain the following masses for the glueballs 0^{-+}, 2^{-+} and 1^{++}:

$$P: \; 0^{-+}(1730), \; 2^{-+}(2260) \qquad (12)$$

$$D: \; 1^{++}(2280).$$

The masses of others D-wave glueballs calculated with use of eq.(11) are as follows: $2^{++}(2630)$, $2^{++}(2960)$, $3^{++}(3160)$ and $4^{++}(3860)$. The mass splitting term for these glueballs is too large to be considered as a perturbation therefor the calculated magnitudes should be regarded only as an indication that these resonances are probably in the region of large masses.

The mass of the pure 0^{-+}-glueball, without $q\bar{q}$-admixture, is 1730 MeV, less then the mass of the S-wave 2^{++}-glueball as argued in ref. [28].

The GH and HH states are located in the region of masses larger than 2 GeV. The GH-states in the S-, P-, and D-wave are as follows $S - 1^{--}$: $P - 0^{+-}, 1^{+-}, 2^{+-}$; $D - 1^{--}, 2^{--}, 3^{--}$. HH-states are possible with even L: $S - 0^{++}$; $D - 2^{++}$.

In conclusion, the scheme for exotic mesons in the mass region 1 2 GeV is suggested based on new data [1]-[10]. It includes S-, P- and D-wave two-gluon glueballs and two scalarons ($I = 0$, 0^{++}) whose existence is related to the survival of the colour SU(3) symmetry in the region of soft physics. For P-wave $q\bar{q}$-states there are three variants which differ in $^3P_0$-multiplets. In one of the variant there is a free place for minions of ref. [27].

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