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EXOTIC NATURE OF THE SCALAR G(1590) MESON

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The scalar meson G(1590) (new name $f_0(1590)$) discovered by the GAMS group[1] at the IHEP, Serpukhov, has immediately been interpreted[2] as a gluonic gg bound state (called gluonium or glueball) due to its dominant decays into the "gluonium rich" channels $\eta\eta$[1] and $\eta'\eta$[3]. However, such an interpretation is not probably consistent with the suppressed $f_0(1590) \to \pi\pi$ and $f_0(1590) \to K\bar{K}$ decays[1] since it has been shown[4] that despite of naive expectations[5] based on the OZI rule (or on $1/N_c$ counting, see, e.g.[6]) the width of the 0^{++} gluonium $\sigma \sim gg$ with the mass m_σ decaying, for instance, into $\pi\pi$ is strongly mass-dependent, i.e. $\Gamma(\sigma \to \pi\pi) = 0.6\ \mathrm{GeV} \times (m_\sigma/1\ \mathrm{GeV})^5$ [4] and thus σ is unobservably wide for $m_\sigma \gtrsim 1$ GeV. Moreover, if $f_0(1590)$ were gg one expects its production in the radiative J/Ψ decays with at least $BR(J/\Psi \to \gamma f_0(1590)) = O(10^{-3})$[7] which is also probably inconsistent with the bound $BR(J/\Psi \to \gamma f_0(1590)) < 6\times10^{-4}$[8].

These discrepancies were the reasons to interpret $f_0(1590)$ as an $SU(3)_f$ singlet quarkonium $S_0 \sim (1/3)^{1/2}(u\bar{u}+d\bar{d}+s\bar{s})$[9] (or, more generally, as a mixture of σ and S_0) and/or as a hybrid $q\bar{q}g$ state[10]. We shall show here that the properties of $f_0(1590)$ can be reasonably explained if this state is approximately a half-and-half mixture of σ and S_0.

In order to see how such a picture of $f_0(1590)$ arises let us recall briefly the results of a detailed phenomenological analysis[11] of the couplings of σ as well as $q\bar{q}$ scalar nonet mesons S_i $(i = 0,1,\ldots,8)$ to the pairs of the pseudoscalars. This analysis was based on the assumption[12] that effective couplings of the 0^{++} $q\bar{q}$ nonet mesons S_i $(i = 0,\ldots,8)$ to pairs of the pseudoscalars ϕ_i $(i = 0,\ldots,8)$ are of the following forms

$$\mathcal{L}_{S\phi\phi}(x) = \frac{\gamma}{f_0} d_{kij}\tilde{S}_k(x)(\partial_\mu\phi_i(x))(\partial^\mu\phi_j(x)), \qquad (1)$$

where $f_0 = -f_\pi$ (f_π=93 MeV is the pion-decay constant), γ is a parameter and $d_{kij} = (1/4)\mathrm{Tr}(\{\lambda_i,\lambda_j\}\lambda_k)$ with $\lambda_i, \lambda_j, \lambda_k$ $(i,j,k=0,\ldots,8)$ being the Gell-Mann λ matrices normalized to $\mathrm{Tr}(\lambda_i\lambda_j) = 2\delta_{ij}$. Here $\tilde{S}_k(x)$ $(k = 0,\ldots,8)$ are quantized parts of the $q\bar{q}$ scalar fields $S_k(x)$ with VEV's removed, i.e. $S_k(x) = \langle 0|S_k|0\rangle + \tilde{S}_k(x)$, where $\langle 0|S_k|0\rangle = (3/2)^{1/2} f_0\delta_{k0}$. The couplings (1)

have been suggested[12] in order to get experimentally acceptable widths of S_k decaying into the pseudoscalar mesons. For example, the $K_0^*(1350) \to K\pi$ decay[13] (unfortunately, not known very precisely) seems to require (1) with the value of γ from the interval

$$0.25 \le \gamma \le 0.35. \qquad (2)$$

The effective Lagrangian of the form

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\sigma)^2 + \frac{1}{4}\mathrm{Tr}(\partial_\mu U\partial^\mu U^+) - V + \mathcal{L}', \qquad (3)$$

has been constructed[11] so as to give (1). Here we neglect the quark mass term and assume the spontaneous breaking of chiral symmetry. The pure gg field $\sigma(x)$ and the $q\bar{q}$ 3x3 matrix field $U(x)$ are parametrized as follows[4]

$$\sigma(x) = \sigma_0 \exp\left(\frac{\tilde{\sigma}(x)}{\sigma_0}\right), \qquad (4)$$

with $\sigma_0 = \langle 0|\sigma|0\rangle$, and[14]

$$U(x) = [\exp(i\lambda_j\phi_j/2f_\pi)](\lambda_i S_i)[\exp(i\lambda_j\phi_j/2f_\pi)], \qquad (5)$$

where $\phi_j(x)$ $(j = 0,\ldots,8)$ and $S_i(x)$ $(i = 0,\ldots,8)$ are the fields of the pseudoscalar and scalar $q\bar{q}$ mesons, respectively. The potential V is an arbitrary chiral U(3)xU(3) symmetric function of σ and U and is assumed to obey the trace anomaly equation[4,11,12]

$$(\theta^\mu_\mu)_{an} = 4V - \sigma\frac{\partial V}{\partial\sigma} - S_i\frac{\partial V}{\partial S_i} - \phi_i\frac{\partial V}{\partial\phi_i}, \qquad (6)$$

where the anomalous trace $(\theta^\mu_\mu)_{an}$ of the hadronic energy-momentum tensor of QCD is given in the following form[15]

$$(\theta^\mu_\mu)_{an} = -\frac{9}{8}\frac{\alpha_s}{\pi}G^a_{\mu\nu}G^{\mu\nu}_a, \qquad (7)$$

where $G^a_{\mu\nu}$ are the gluonic field strength tensors. Thus, the dimension 4 operator (7) should play the role of an interpolating field for the gluonium σ, i.e., we assume the following identification[4]

$$(\theta^{\mu}_{\mu})_{an} = -\frac{9}{8}G_o\left(\frac{\sigma(x)}{\sigma_o}\right)^4 = -\frac{9}{8}G_o\left(1 + \frac{4\tilde{\sigma}(x)}{\sigma_o} + O(\tilde{\sigma}^2)\right), \quad (8)$$

since we ascribe a conventional dimension 1 to σ and U. Here $G_o = \langle 0|(\alpha_s/\pi)G^a_{\mu\nu}G^{\mu\nu}_a|0\rangle$ is a gluon condensate with "standard" values (see, e.g. /16/ and references therein) lying in the interval 0.012–0.018 GeV^4. In accordance with (6) $\mathcal{L}'$ in (3) is of dimension 4 and represents a derivative coupling needed to obtain (1) from (3). It is required /11/ that $\mathcal{L}'$ being a combination of the simplest derivative terms like $K_1 = (3/2) \times [Tr(UU^+)]^{-1}\, Tr(\partial_\mu U \partial^\mu U^+ UU^+)$, etc. (for more details see /11/) does not change the correct kinetic term of the fields $\tilde{S}_i$ and ϕ_i in (3) obtained already from $(1/4)Tr(\partial_\mu U \partial^\mu U^+)$ before adding $\mathcal{L}'$. Then besides (1) (what, in fact, was demanded in the construction of $\mathcal{L}'$) we also get /11/ :

$$\mathcal{L}_{\sigma\phi\phi}(x) = \frac{1-\gamma}{\sigma_o}\tilde{\sigma}(x)(\partial_\mu\phi_i(x))^2. \quad (9)$$

Expanding the potential V in terms of the fields $\tilde{S}_i$, ϕ_i and $\tilde{\sigma}$:

$$V = V_o + \frac{1}{2}M^2_{\sigma\sigma}\tilde{\sigma}^2 + \frac{1}{2}M^2_{oo}\tilde{S}^2_o + M^2_{\sigma o}\tilde{\sigma}\tilde{S}_o + \ldots \quad (10)$$

and combining (10) with (6) and (8) we find

$$\sigma_o^2 M^2_{\sigma\sigma} - \frac{3}{2}f_o^2 M^2_{oo} = \frac{9}{2}G_o, \quad (11)$$

$$\sigma_o M^2_{\sigma o} + \sqrt{\frac{3}{2}}f_o M^2_{oo} = 0.$$

Instead of $\tilde{\sigma}$ and $\tilde{S}_o$ we shall use physically more relevant fields G and ϵ defined as follows

$$G = \tilde{\sigma}\sin\theta + \tilde{S}_o\cos\theta, \quad (12)$$
$$\epsilon = \tilde{\sigma}\cos\theta - \tilde{S}_o\sin\theta,$$

where the mixing angle θ is given by

$$\tan 2\theta = -\frac{2M^2_{\sigma o}}{M^2_{\sigma\sigma} - M^2_{oo}}. \quad (13)$$

The couplings $G\phi\phi$ and $\epsilon\phi\phi$ can easily be deduced from (1), (9) and (12). They are

$$\mathcal{L}_{G\phi\phi}(x) = g_{G\phi\phi}G(x)(\partial_\mu\phi_i(x))^2, \quad (14)$$
$$\mathcal{L}_{\epsilon\phi\phi}(x) = g_{\epsilon\phi\phi}\epsilon(x)(\partial_\mu\phi_i(x))^2,$$

where

$$g_{G\phi\phi} = \frac{1-\gamma}{\sigma_o}\sin\theta + \sqrt{\frac{2}{3}}\frac{\gamma}{f_o}\cos\theta, \quad (15)$$

$$g_{\epsilon\phi\phi} = \frac{1-\gamma}{\sigma_o}\cos\theta - \sqrt{\frac{2}{3}}\frac{\gamma}{f_o}\sin\theta.$$

Analyzing couplings (15) within $1/N_c$ counting we have shown /11/ that regardless of a value of θ the heavier meson of the pair G and ϵ plays the role of an effective quarkonium while the lighter one is an effective gluonium since its coupling to $\phi\phi$ is $O(1/N_c)$ as should be for a gluonium /6/ .

The quark model and the recent QCD lattice calculations /17/ (taken seriously despite of existing reservations) suggest that the masses M_{oo} and $M_{\sigma\sigma}$ of S_o and σ, respectively, are approximately equal to each other and they have values around 1.3 GeV, i.e. we assume (for more discussions, see /11/):

$$M_{oo} = M_{\sigma\sigma} = M \simeq 1.3\ \text{GeV}. \quad (16)$$

Then $M^2 f_o^2 \approx 0.015\ GeV^4$ which coincides with the "standard" values of G_o /16/ , and thus we have approximately $M^2 f_o^2 = G_o$. Combining this with (11) we find

$$\sigma_o = \sqrt{6}\, f_o, \quad (17)$$

and (after diagonalizing the squared mass matrix):

$$M_G = \sqrt{\frac{3}{2}}M \simeq 1590\ \text{MeV}, \quad (18)$$
$$M_\epsilon = \frac{1}{\sqrt{2}}M \simeq 920\ \text{MeV},$$

where we have used the value (16) for M. Labelling here the lighter meson as ϵ we must consistently choose $\theta = -45^o$ in (12), i.e.

$$G = \frac{1}{\sqrt{2}}(\tilde{S}_o - \tilde{\sigma}), \quad (19)$$
$$\epsilon = \frac{1}{\sqrt{2}}(\tilde{S}_o + \tilde{\sigma}).$$

It is evident from (1), (9), (14), (15) and (17) that for $\theta = -45^{\circ}$ and $\gamma = 1/3$, e.g. the decays of the heavier state G into $\pi\pi$ and $K\bar{K}$ are automatically suppressed due to "$\phi\phi$ destructive" nature of G (19). On the other hand, its lighter companion ϵ (19) is "$\phi\phi$ constructive", so the decay $\epsilon \to \pi\pi$ should be enhanced. From (15), (17) and with $\theta = -45^{\circ}$ we get

$$g_{G\phi\phi} = \frac{3\gamma - 1}{2\sqrt{3}\, f_0}, \qquad g_{\epsilon\phi\phi} = \frac{1 + \gamma}{2\sqrt{3}\, f_0}. \tag{20}$$

To have more realistic picture in which the ninth pseudoscalar meson η' has a nonzero mass m_0 the so-called axial U(1) symmetry of (3) must be broken. Within the effective Lagrangian approach[14] this can be done explicitly by adding to (3) a term (see, e.g.[18] and references therein)

$$\mathcal{L}_{U(1)} = \frac{3}{m_0^2 f_\pi^2} Q^2 + \frac{i}{2} Q\, \mathrm{Tr}(\ln U - \ln U^+), \tag{21}$$

where $Q = (\alpha_s/16\pi)\epsilon_{\mu\nu\rho\tau} G_a^{\mu\nu} G_a^{\rho\tau}$ and

$$m_0^2 = m_{\eta'}^2 + m_\eta^2 - 2m_K^2 \simeq 0.73\ \mathrm{GeV}^2, \tag{22}$$

obtained from a fit of the pseudoscalar meson masses. However, having dimension 8 the first term in (21) is not consistent with (6), so instead of (21) one has to add to (3) the following term[19]

$$\mathcal{L}'' = \frac{3}{m_0^2 f_\pi^2} Y(\sigma, U)\, Q^2 + \frac{i}{2} Q\, \mathrm{Tr}(\ln U - \ln U^+), \tag{23}$$

where Y is a chiral invariant function of σ and U, and is of dimension -4. One can choose, e.g.:

$$Y(\sigma, U) = a\, \frac{\langle 0 | f(U) | 0 \rangle}{f(U)} + (1 - a)\left(\frac{\sigma_0}{\sigma}\right)^4, \tag{24}$$

where a is an arbitrary parameter and f(U) is U(3)xU(3) invariant function of the field U and is of dimension 4. Eliminating Q(x) from (23) by the use of equations of motion and expanding (24) in terms of fields $\tilde{S}_i$ and $\tilde{\sigma}$ we find the following couplings $S_0\phi_0\phi_0$ and $\sigma\phi_0\phi_0$:

$$\mathcal{L}''_{S_0\phi_0\phi_0}(x) = -2a\sqrt{\frac{2}{3}}\, \frac{m_0^2}{f_0}\, \tilde{S}_0(x)\, \phi_0^2(x),$$
$$\mathcal{L}''_{\sigma\phi_0\phi_0}(x) = -2(1 - a)\, \frac{m_0^2}{\sigma_0}\, \tilde{\sigma}(x)\, \phi_0^2(x). \tag{25}$$

We see from (23)-(25) that (1-a) measures the strength of coupling between gluonic degrees of freedom σ and Q^2 (or, between gluonium σ and the "gluonium rich" channel ϕ_0^2), and such a coupling dominates if $|a| \ll 1$.

In order to estimate a we introduce $\eta\eta'$ mixing:

$$\phi_0 = \eta' \cos\theta_{\eta\eta'} - \eta \sin\theta_{\eta\eta'},$$
$$\phi_8 = \eta' \sin\theta_{\eta\eta'} + \eta \cos\theta_{\eta\eta'}, \tag{26}$$

where $\theta_{\eta\eta'}$ is the $\eta\eta'$ mixing angle. Then combining (14), (19), (20), (25) and (26) we get, e.g.

$$\frac{\Gamma(G \to \eta\eta')}{\Gamma(G \to \eta\eta)} = \frac{8}{[(A + 2)\tan\theta_{\eta\eta'}]^2}\, \frac{P_{\eta\eta'}}{P_{\eta\eta}},$$
$$\frac{\Gamma(G \to K\bar{K})}{\Gamma(G \to \eta\eta)} = 4\left(\frac{A}{A + 2}\right)^2 \frac{P_{K\bar{K}}}{P_{\eta\eta}}, \tag{27}$$

where

$$A = \frac{1}{2}\, \frac{3\gamma - 1}{3a - 1}\, \frac{M_G^2}{m_0^2}\, \frac{1}{\sin^2\theta_{\eta\eta'}},$$

and the ratios of the corresponding phase spaces are $P_{\eta\eta'}/P_{\eta\eta}$ = 0.43 and $P_{K\bar{K}}/P_{\eta\eta}$ = 1.08. Using, for instance, γ =0.3 (2), $\theta_{\eta\eta'} = -18^{\circ}$, A = 1.1, m_0^2 = 0.73 GeV^2 (22) and M_G = 1.59 GeV, we predict the following partial widths of G from (14), (20) and (27):

$$\Gamma(G \to \pi\pi) \simeq 11\ \mathrm{MeV}, \quad \Gamma(G \to K\bar{K}) \simeq 12\ \mathrm{MeV},$$
$$\Gamma(G \to \eta\eta) \simeq 22\ \mathrm{MeV}, \quad \Gamma(G \to \eta\eta') \simeq 75\ \mathrm{MeV}, \tag{28}$$

what is in good agreement with experiment[1,3] if we identify $G \equiv f_0(1590)$. We also find $a \simeq -0.22$, i.e. the dominant decays of $f_0(1590)$ into $\eta\eta$ and $\eta\eta'$[1,3] are mainly due to the coupling of σ contained in G (19) to ϕ_0^2[2].

The production of G mesons in the radiative J/Ψ decays can be estimated on the basis of the Euler-Heisenberg effective Lagrangian for the gluon-photon interactions. This gives, e.g.[7]

$$\frac{\Gamma(J/\Psi \to \gamma G)}{\Gamma(J/\Psi \to \gamma \eta')} = \frac{9}{64} \left| \frac{<0|\alpha_s G^a_{\mu\nu} G^{\mu\nu}_a | G>}{<0|\alpha_s G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a | \eta'>} \right|^2 \left(\frac{P_G}{P_{\eta'}}\right)^3, \qquad (29)$$

where $P_G/P_{\eta'} = 0.81$. Using $M^2 f_o^2 = G_o$ and combining (7), (8), (17)-(19) we obtain

$$<0|\alpha_s G^a_{\mu\nu} G^{\mu\nu}_a | G> = \frac{4\pi}{3\sqrt{3}} f_\pi M_G^2. \qquad (30)$$

Then with the analogous estimate[7]

$$<0|\alpha_s G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a | \eta'> = \frac{4\pi}{3}\sqrt{\frac{3}{2}} f_\pi m^2_{\eta'} \qquad (31)$$

we predict $BR(J/\Psi \to \gamma G) \approx 0.13\times BR(J/\Psi \to \gamma\eta') \approx 5.5\times10^{-4}$, that agrees with the bound[8] $BR(J/\Psi \to \gamma f_0(1590)) < 6\times10^{-4}$.

While the meson $G \equiv f_0(1590)$ is "ππ destructive" with the suppressed decay $G \to \pi\pi$ its "ππ constructive" companion ε (see (18)-(20)) has the large decay $\epsilon(920) \to \pi\pi$ with the width $\Gamma(\epsilon(920) \to \pi\pi) \simeq 360$ MeV. The meson ε (920) is a wide effective 0^{++} gluonium[11] and maybe, it has been seen recently by analyzing the AFS data obtained at the CERN's ISR[20]. On the other hand (as we have shown here) the analogous exotic state G (19) playing the role of an effective $SU(3)_f$ singlet scalar quarkonium (like η′ for pseudoscalars)[11] should be identified with the GAMS $f_0(1590)$ meson[1,3], discovered at the IHEP, Serpukhov. It is worth to remark here that within the present picture the decay $f_0(1590) \to 4\pi^0$[21] is expected to go dominantly through $f_0(1590) \to \pi^0\pi^0\epsilon(920)$ with an immediate decay $\epsilon(920) \to \pi^0\pi^0$. Since, e.g. on the basis of (28) the width of $f_0(1590)$ when decaying into two pseudoscalars is only a half of its full width[1,3,13] we may expect the branching ratio for the presumably dominant decay $f_0(1590) \to \pi\pi\epsilon(920) \to 4\pi$ to be about 50% in agreement with experiment[21].

In conclusion we note that the scalar $q\bar{q}$ octet members S_i ($i = 1,\ldots,8$) with couplings (1) correspond probably to the experimental states $a_0(980)$ and/or $a_0(1400)$[22], $K^*_0(1350)$ and $f_0(1300)$[13]. The meson $f_0(1300)$ is approximately the state $S_8 \sim (1/6)^{1/2}(u\bar{u}+d\bar{d}-2s\bar{s})$ and due to (1) it has dominant decay

just into ππ as experiment requires[13]. For example, using the mass $M_8 = 1.3$ GeV for $S_8 \equiv f_0(1300)$ and $\gamma = 0.3$ as before we estimate $\Gamma(f_0(1300) \to \pi\pi) \simeq 223$ MeV and $\Gamma(f_0(1300) \to K\bar{K}) \simeq$ $\simeq 50$ MeV from (1). The decay $S_8 \to \eta\eta$ is even more suppressed than the decay $S_8 \to K\bar{K}$ if the mixing (26) is taken into account. In fact, combining (1) and (26) we find

$$\frac{\Gamma(S_8 \to \eta\eta)}{\Gamma(S_8 \to K\bar{K})} = \cos^2\theta_{\eta\eta'}[\cos\theta_{\eta\eta'} + 2\sqrt{2}\sin\theta_{\eta\eta'}]^2, \qquad (32)$$

(where we neglect the phase space factor

$$[(1 - 4m^2_\eta/M^2_8)/(1 - 4m^2_K/M^2_8)]^{1/2} \simeq 0.83$$

($M_8 = 1.3$ GeV)), and such a suppression seems to be indicated by experiment[23], too.

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Экзотическая природа скалярного G(1590)-мезона

Показывается, что свойства скалярного ГАМС G(1590)-мезона могут быть разумно объяснены, если это состояние является приблизительно половина-на-половину смесью глюония gg и кваркония $q\bar{q}$.

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Exotic Nature of the Scalar G(1590) Meson

It is shown that the properties of the GAMS G(1590) scalar meson can be reasonably explained if this state is approximately a half-and-half mixture of gluonium gg and quarkonium $q\bar{q}$ states.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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