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EXOTIC NATURE OF THE SCALAR $G(1590)$ MESON[1)]

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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.

I. INTRODUCTION

The scalar meson $G(1590)$ (new name $f_0(1590)$) discovered by the GAMS group [1] at the IHEP, Serphukov, 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. $\Gamma(\sigma \to \pi\pi) = 0.6\,\text{GeV}\,(m_\sigma/1\,\text{GeV})^5$ [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 $BR(J/\Psi \to \gamma f_0(1590)) = 0(10^{-3})$ [7], which is also probably inconsistent with the bound $BR(J/\Psi \to \gamma f_0(1590)) < 6 \times 10^{-4}$ [8].

These discrepancies were the reasons to interpret $f_0(1590)$ as an $SU(3)_f$ singlet quarkonium $S_0 \sim (1/3)^{1/2}(u\bar{u} + d\bar{d} + s\bar{s})$ (or, more generally, as a mixture of σ and S_0) [9] 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.

II. THEORETICAL ASPECTS OF THE PROBLEM

In order to see how much a picture of $f_0(1590)$ arises let us recall briefly the results of a detail phenomenological analysis [11] of the couplings of σ as well

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[2)] Laboratory of Theoretical Physics, JINR, DUBNA, USSR. Permanent address: Fyzikálny ústav CEFV SAV, Dúbravská cesta 9, 842 28 BRATISLAVA, Czechoslovakia 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 the pairs of the pseudoscalars Φ_i ($i = 0, \ldots, 8$) are of the following forms

$$\mathscr{L}_{S\Phi\Phi}(x) = \frac{\gamma}{f_0} d_{kij} \tilde{S}_k(x) (\partial_\mu \Phi_i(x)) (\partial^\mu \Phi_j(x)), \quad (1)$$

where $f_0 = -f_\pi$ ($f_\pi = 93$ 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

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

The effective Lagrangian of the form

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

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 $q\bar{q}$ 3×3 matrix field $\mathscr{U}(x)$ are parametrized as follows [4]

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

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

$$\mathscr{U}(x) = [\exp(\mathrm{i}\lambda_j \Phi_j/2f_\pi)](\lambda_i S_i)[\exp(\mathrm{i}\lambda_j \Phi_j/2f_\pi)], \quad (5)$$

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 $U(3) \times U(3)$ symmetric function of σ and $\mathscr{U}$ and is assumed to obey the trace anomaly equation [4, 11, 12]

$$(\Theta^\mu_\mu)_{an} = 4V - \sigma\frac{\partial V}{\partial \sigma} - S_i \frac{\partial V}{\partial S_i} - \Phi_i \frac{\partial V}{\partial \Phi_i}, \quad (6)$$

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

$$(\Theta^\mu_\mu)_{an} = -\frac{9}{8}\frac{\alpha_S}{\pi} G^a_{\mu\nu} G^{\mu\nu}_a, \quad (7)$$

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]

$$(\Theta^\mu_\mu)_{an} = -\frac{9}{8} G_0 \left(\frac{\sigma(x)}{\sigma_0}\right)^4 = -\frac{9}{8} G_0 \left(1 + \frac{4\tilde{\sigma}(x)}{\sigma_0} + O(\tilde{\sigma}^2)\right), \quad (8)$$

since we ascribe a conventional dimension 1 to σ and $\mathscr{U}$. Here $G_0 = \langle 0|(\alpha_S/\pi) G^a_{\mu\nu} G^{\mu\nu}_a|0\rangle$ 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) $\mathscr{L}'$ in (3) is of dimension 4 and represents a derivative coupling needed to obtain (1) from (3). It is required [11] that $\mathscr{L}'$ being a combination of the simplest derivative terms like $K_1 = (3/2)\,[\mathrm{Tr}\,(\mathscr{U}\mathscr{U}^+)]^{-1}\,\mathrm{Tr}\,(\partial_\mu \mathscr{U} \partial^\mu \mathscr{U}^+ \mathscr{U}\mathscr{U}^+)$, 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 $(1/4)\,\mathrm{Tr}\,(\partial_\mu \mathscr{U} \partial^\mu \mathscr{U}^+)$ before adding $\mathscr{L}'$. Then besides (1) (what, in fact, was required in the construction of $\mathscr{L}'$) we also get [11]:

$$\mathscr{L}_{\sigma\Phi\Phi}(x) = \frac{1-\gamma}{\sigma_0} \tilde{\sigma}(x) (\partial_\mu \Phi_i(x))^2. \quad (9)$$

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

$$V = V_0 + \frac{1}{2} M^2_{\sigma\sigma} \tilde{\sigma}^2 + \frac{1}{2} M^2_{00} \tilde{S}_0^2 + M^2_{\sigma 0} \tilde{\sigma} \tilde{S}_0 + \ldots \quad (10)$$

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

$$\sigma_0^2 M^2_{\sigma\sigma} - \frac{3}{2} f_0^2 M^2_{00} = \frac{9}{2} G_0,$$
$$\sigma_0 M^2_{\sigma 0} + \sqrt{\frac{3}{2}} f_0 M^2_{00} = 0. \quad (11)$$

Instead of $\tilde{\sigma}$ and $\tilde{S}_0$ we shall use physically more relevant fields G and ε defined as follows

$$G = \tilde{\sigma} \sin\Theta + \tilde{S}_0 \cos\Theta,$$
$$\varepsilon = \tilde{\sigma}\cos\Theta - \tilde{S}_0 \sin\Theta, \quad (12)$$

where the mixing angle Θ is given by

$$\tan 2\Theta = -\frac{2M^2_{\sigma 0}}{M^2_{\sigma\sigma} - M^2_{00}}. \quad (13)$$

The couplings $G_{\Phi\Phi}$ and $\varepsilon_{\Phi\Phi}$ can easily be deduced from (1), (9) and (12). They are

$$\mathscr{L}_{G\Phi\Phi}(x) = g_{G\Phi\Phi} G(x)\,(\partial_\mu \Phi_i(x))^2,$$
$$\mathscr{L}_{\varepsilon\Phi\Phi}(x) = g_{\varepsilon\Phi\Phi}\varepsilon(x)\,(\partial_\mu \Phi_i(x))^2, \tag{14}$$

where

$$g_{G\Phi\Phi} = \frac{1-\gamma}{\sigma_0}\sin\Theta + \sqrt{\frac{2}{3}}\frac{\gamma}{f_0}\cos\Theta,$$
$$g_{\varepsilon\Phi\Phi} = \frac{1-\gamma}{\sigma_0}\cos\Theta - \sqrt{\frac{2}{3}}\frac{\gamma}{f_0}\sin\Theta. \tag{15}$$

Analyzing couplings (15) within the $1/N_c$ 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 it 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_{00} and $M_{\sigma\sigma}$ of S_0 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]):

$$M_{00} = M_{\sigma\sigma} = M \approx 1.3 \text{ GeV}. \tag{16}$$

Then $M^2 f_0^2 \approx 0.015$ GeV^4, which coincides with the "standard" values of G_0 [16], and thus we have approximately $M^2 f_0^2 = G_0$. Combining this with (11) we find

$$\sigma_0 = \sqrt{6} f_0 \tag{17}$$

and (after diagonalizing the squared mass matrix):

$$M_G = \sqrt{\frac{3}{2}} M \approx 1590 \text{ MeV},$$
$$M_\varepsilon = \frac{1}{\sqrt{2}} M \approx 920 \text{ MeV}, \tag{18}$$

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

$$G = \frac{1}{\sqrt{2}}(\tilde{S}_0 - \tilde{\sigma}),$$
$$\varepsilon = \frac{1}{\sqrt{2}}(\tilde{S}_0 + \tilde{\sigma}). \tag{19}$$

It is evident from (1), (9), (14), (15) and (17) that for $\Theta = -45°$ 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 $\varepsilon \to \pi\pi$ should be enhanced. From (15), (17) and with $\Theta = -45°$ we get

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

To have a 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 Langrangian approach [14] this can be done explicitly by adding to (3) a term (see, e.g. [18] and references therein)

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

where $Q = (\alpha_s/16\pi)\,\varepsilon_{\mu\nu\varrho\tau} G_a^{\mu\nu} G_a^{\varrho\tau}$ and

$$m_0^2 = m_{\eta'}^2 + m_\eta^2 - 2m_K^2 \approx 0.73 \text{ GeV}^2 \tag{22}$$

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]

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

where Y is a chiral invariant function of σ and $\mathscr{U}$, and is of dimension —4. One can choose, e.g.:

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

where a is an arbitrary parameter and $f(\mathscr{U})$ is the $U(3) \times U(3)$ invariant function of the field $\mathscr{U}$ 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 $\sigma\Phi_0\Phi_0$:

$$\mathscr{L}''_{S_0\Phi_0\Phi_0}(x) = -2a\sqrt{\frac{2}{3}}\frac{m_0^2}{f_0}\tilde{S}_0(x)\,\Phi_0^2(x),$$
$$\mathscr{L}''_{\sigma\Phi_0\Phi_0}(x) = -2(1-a)\frac{m_0^2}{\sigma_0}\tilde{\sigma}(x)\,\Phi_0^2(x). \tag{25}$$

We see from (23)—(25) that $(1-\alpha)$ 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 $|\alpha| \ll 1$.

In order to estimate α we introduce the $\eta\eta'$ 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

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

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, $\gamma = 0.3$ (2), $\Theta_{\eta\eta'} = -18°$, $A = 1.1$, $m_0^2 = 0.73$ GeV^2 (22) and $M_G = 1.59$ GeV, we predict the following partial widths of G from (14), (20) and (27)

$$\Gamma(G\to\pi\pi) \approx 11\ \text{MeV}, \qquad \Gamma(G\to K\bar{K}) \approx 12\ \text{MeV},$$
$$\Gamma(G\to\eta\eta) \approx 22\ \text{MeV}, \qquad \Gamma(G\to\eta\eta') \approx 75\ \text{MeV}, \tag{28}$$

which is in a good agreement with experiment [1,3] if we identify $G \equiv f_0(1590)$. We also find $\alpha \approx -0.22$, 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]

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

where $P_G/P_{\eta'} = 0.81$. Using $M^2 f_0^2 = G_0$ and combining (7), (8), (17)—(19) we obtain

$$\langle 0|\alpha_S G^a_{\mu\nu}G^{\mu\nu}_a|G\rangle = \frac{4\pi}{3\sqrt{3}}f_\pi M_G^2. \tag{30}$$

Then with the analogous estimate [7]

$$\langle 0|\alpha_S G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a|\eta'\rangle = \frac{4\pi}{3}\sqrt{\frac{3}{2}}f_\pi m_{\eta'}^2, \tag{31}$$

we predict $BR(J/\Psi\to\gamma G) \approx 0.13\, BR(J/\Psi\to\gamma\eta') \approx 5.5\times10^{-4}$, 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 "$\pi\pi$ constructive" companion ε (see (18)—(20)) has the large decay $\varepsilon(920)\to\pi\pi$ wioth the width $\Gamma(\varepsilon(920)\to\pi\pi) \approx 360$ MeV. The meson $\varepsilon(920)$ 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, Serphukov. It is worth to remark here that within the present picture the decay $f_0(1590)\to4\pi^0$ [21] is expected to go dominantly through $f_0(1590)\to\pi^0\pi^0\varepsilon(920)$ with an immediate decay $\varepsilon(920)\to\pi^0\pi^0$. Since, e.g., on the basis of (28) the width of $f_0(1590)$ when decaying into two pseudoscalars is only a hlaf of its full width [1, 3, 13] we may expect the branching ratio for the presumably dominant decay $f_0(1590)\to\pi\pi\varepsilon(920)\to4\pi$ to be about 50% in agreement with experiment [21].

III. CONCLUSION

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 state $a_0(980)$ 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 a dominant decay just into $\pi\pi$ as the 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 $\Gamma(f_0(1300)\to\pi\pi) \approx 223$ MeV and $\Gamma(f_0(1300)\to K\bar{K}) \approx 50$ 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

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

(where we neglect the phase space factor)

$$[(1-4m_\eta^2/M_8^2)/(1-4m_K^2/M_8^2)]^{1/2} \approx 0.83$$

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

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ЭКЗОТИЧЕСКАЯ ПРИРОДА СКАЛЯРНОГО *G*(1590) МЕЗОНА

Показано, что свойства GAMS *G*(1590) скалярного мезона могут быть резонно объяснены, когда это состояние является смешиванием состояний глюония gg и кваркония $q\bar{q}$ приблизительно в равной степени.