QCD vacuum, confinement, meson masses

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Abstract

The QED and QCD vacuum energy in a self-dual field with constant strength is considered. It is turned out that in the quantum electrodynamics of a system of charged fermion and boson fields the minimum of vacuum energy is realized with zero self-dual photon field if the number of fermions exceeds the number of bosons and (2) the lightest charged particles are fermions. Namely, this situation takes place in Nature.

In the QCD the global stability of the quark-gluon system takes place if the number of quarks with different flavors is equal to or more than two. The existence of massless self-interacting gluons leads to the QCD vacuum which can be realized with nonzero self-dual gluon fields. The result is the analytical confinement of quarks and gluons, i.e. quark and gluon propagators are entire analytical functions in p^2- complex plane, and the origin of stable states - hadrons.

It is shown that in the framework of analytical confinement, when quark and gluon propagators are induced by a vacuum self-dual gluon field with constant strength, the masses of meson with quantum numbers $Q = J^P$ and quark constituents $m_1,\ m_2$ are described with reasonable accuracy by the formula

$$M_Q(m_1, m_2) = (m_1 + m_2)\left[1 + \frac{A_Q}{(m_1^2 + 1.13 m_1 m_2 + m_2^2)^{0.625}}\right],$$

where a constant positive parameter A_Q is unique for all mesons with quantum numbers $Q = J^P$.

Sets of mesons $J^P = 0^-,\ 1^-,\ 0^+,\ 1^+,\ 2^+,\ 3^-$ for $n = 0$ and $1^-,\ 2^+$ for $n > 0$ and different flavor constituent quarks ($u = d,\ s,\ c,\ b$) are considered.

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1 Introduction.

The basic problem of modern particle physics yet unsolved is to explain the structure of hadrons as bound states of quarks and gluons in the framework of QCD. The main difficulty lies in the fact that QCD itself does not give a clear analytical picture of the behavior of quarks and gluons in the so-called confinement region where their hadronization takes place. For QCD this region is the domain of a strong coupling regime where reliable analytical methods for successful calculations are absent. One should remark that analytical strong coupling methods are missing not only for QCD but for any quantum field model too.

In most approaches within the standard QCD (see, for example, chiral dynamics approach [1, 2, 3, 4]) different symmetry arguments are used to avoid direct calculations in the confinement region and thus to obtain some effective hadron theory with new phenomenological constants like F_π and so on.

The approaches (see [5, 6]), which try to draw a connection between QCD and hadron characteristics, use the Schwinger-Dyson equation to get the quark Green function in the confinement region (for this aim an appropriate form of the gluon propagator and quark-gluon vertex should be found) and then use the Bethe-Salpeter equation to calculate the spectrum and other characteristics of hadrons as bound states of quarks and gluons. Practically from the beginning this program leads to numerical calculations so that the analytical picture of the confinement and hadronization is not so transparent.

In any case, this program starts from the physical viewpoint that confinement and hadronization of quarks take place at the same distances. Therefore, the knowledge of the behavior of quark and gluon propagators at these distances gives a direct way of calculating meson masses and other meson characteristics using the Bethe-Salpeter equation in the ladder approximation implying that the coupling constant α_s is small enough.

I completely share this point of view. Physically, if bound states are formed at large distances, where confinement plays the main role, it is evident that a correct description of confinement should lead to a reasonable description of bound states. The basic point is how to find the quark and gluon propagators in the confinement region. The standard point of view is the quark confinement is a result of nonperturbative self-interaction of gluons. This idea is used in approaches mentioned above [5, 6]. However, another point of view is possible. In papers [9, 10, 11, 8] we developed a model based on the assumption that the QCD vacuum is realized by a self-dual homogeneous vacuum gluon field which is the classical solution of the Yang-Mills equations. This field is not connected with the QCD coupling constant and the principal statement is that the minimum of vacuum energy of a quark and gluon system is realized by a nonzero self-dual homogeneous gluon field. The propagators of quarks and gluons in this field can be calculated in the explicit form and they are entire analytic functions in the p^2-complex plain. It means that the self-dual homogeneous vacuum gluon field leads to the analytic confinement of quarks.

One of nonevident features of this field consists in the following. One can ask why this field does exist in QCD and leads to the quark confinement but why a similar field does not exist for the photon field in QED and we do not observe the confinement of electrons, for example?

It is possible to introduce a self-dual homogeneous photon field leading to electron confinement in QED, where any local self-interaction of photons is absent. Then the vacuum energy of a system of charged particles under consideration in this field should be calculated. It was shown (see [7]) that in QED, first, the global stability of a system of charged particles takes place if the number of charged fermions exceeds the number of charged bosons. Second, in QED the minimum of the vacuum energy of a system of charged fermions and bosons is realized with zero self-dual photon field (no confinement) if the lightest charged particles are fermions. Namely, this situation takes place in the Nature. This result explains why all stable basic particles (leptons and baryons) are fermions and the lightest charged stable particle is electron.

In QCD due to the local self-interaction gluons play a double role - they are carriers of strong interaction and they are standard vector boson particles with zero mass. In QCD, the global stability of a quark-gluon system takes place if the number of quarks with different flavors is equal or is more than two. Maybe this is the reason why the SU_2 isotopic flavor group of the lightest u and d quarks is picked out? The minimum of the vacuum energy of a system of quarks and gluons is realized with nonzero self-dual gluon field. It is a direct consequence of the existence of massless self-interacting gluons. As a result, this field leads to the quark and gluon confinement.

One can add that the standard physical picture of the confinement is understood as the existence of a static increasing potential between two quarks. The problem of confinement of one single quark is not formulated at all. This picture is stable in time.

In the case of the analytical confinement induced by a self-dual homogeneous gluon field the physical picture of the confinement looks different from previous one. Quark and gluons are fluctuations in space and time. They arise in a small space region and disappear in a short time interval. In other words, the confinement exists in space and time. One can think that in some sense quarks and gluons themselves realize a physical hadron vacuum (details see in [8]).

The manifestation of this gluon configuration in the spectrum and weak decays of light mesons, their excited states, and glueballs was studied in papers [10, 12, 13, 17, 8]. Our preliminar calculations showed that a self-dual homogeneous gluon field could be considered as a good candidate for realization of the QCD gluon vacuum. However, any calculations in this model are quite cumbersome, so that it is difficult to "see forest among trees". I have always hold to the point of view that if a physical theoretical model is reasonable, then simple formulas describing some general physical correlations should exist. I try to realize this idea in the present paper. The point is that the quark propagator in a self-dual homogeneous gluon field has a quite specific form and this specific behavior can lead to nontrivial correlations between meson masses.

One should stress that the analytical confinement leads to a mechanism of forming bound states which is quite different comparable to a potential picture. In addition, one can remark that any potential approach in particle physics is a very rough approximation because calculations in framework of the relativistic Bethe-Salpeter equation show that the nonrelativistic limit can be realized only for very small coupling constants as in QED where $\alpha = \frac{1}{137}$, but not in QCD where $\alpha_s \sim 1$ (see [14]).

Let us turn to physical reality and consider the meson mass spectrum in the Meson Summary Table in the Particle Data Group [15]. Each meson has certain quantum numbers $Q = (J^P, n)$, where J is the total moment, P is parity and $n = 0, 1, 2, ...$ is a radial quantum number. From a theoretical point of view mesons are bound states of two quarks q_1 and q_2 with different flavors, i.e. with different masses m_1 and m_2. Then $J = \ell, \ell \pm 1$ where $\ell = 0, 1, 2, ...$ is the orbital moment of two quark systems. Mesons are described by currents of the type

$$\mathcal{J}_{\mathcal{N}} = \mathcal{J}_{FQ} = (\bar{q}_1 V_Q q_2),$$

with a definite quantum number $\mathcal{N} = FQ$, $\;Q = (J^P, n)$, where F is a flavor and $V_Q = V_{(J^P,n)}$ is a relevant vertex which does not depend on flavor.

We can assume that the structure of dynamic equations is the same for mesons with a fixed quantum number $Q = (J^P, n)$ but different flavor quarks m_1 amd m_2. In other words, the meson mass should be described by the formula

$$M_{\mathcal{N}} = M_{FQ} = F_Q(m_1, m_2),$$

where the functions $F_Q(m_1, m_2)$ are different for different quantum numbers $Q = (J^P, n)$.

We accept the hypothesis that the self-dual homogeneous gluon field really realizes the QCD gluon vacuum. This idea leads to analytical confinement. Quark and gluon propagators can be calculated in an explicit form. Thus the explicit form of the function $F_Q(m_1, m_2)$ can be evaluated. The specific form of the quark propagators (see below) leads to that the function $F_Q(m_1, m_2)$ with acceptable accuracy has the form

$$F_Q(m_1, m_2) = \mathcal{F}(m_1, m_2, A_Q), \tag{1}$$

where $\mathcal{F}(m_1, m_2, A)$ is a universal function the form of which does not depend on a quantum state $Q = (J^P, n)$. The constant parameter A_Q defines the quantum state and it is unique for all mesons with a given quantum number $Q = (J^P, n)$. It means that formula (1) is valid for excited states too. Different masses m_1 and m_2 in reality define different flavor quantum numbers of the state under consideration. We should like to stress that formula (1) is dictated by the specific form of the quark propagator in a self-dual homogeneous vacuum gluon field.

Let us come back to the Meson Summary Table in the Particle Data Group. In order to verify formula (1), we should select sets of mesons having the same quantum numbers $Q = (J^P, n)$

but different flavor constituents. For mesons with the zero radial number $n = 0$ there are only five sets with definite quantum numbers J^P which have as constituents all four quarks $u = d,\ s,\ c,\ b$. These sets are: pseudoscalar 0^- - ten mesons, vector 1^- - eight mesons, scalar 0^+ - four mesons, axial 1^+ - five mesons, and tensor 2^+ - six mesons (see Section 3). In addition, we consider tensor multiplet 3^- $(n = 0)$ containing three light mesons. We remark, the mesons 2^+ and 3^- are excited states.

For the radial numbers $n > 0$ only sets of vector mesons 1^- have as constituents all four quarks $u = d,\ s,\ c,\ b$. Four mesons 2^+ having as constituents quarks $u = d,\ s,\ b$ can be considered as states with $n = 1$.

The aim of this paper is to show that the representation (1) really takes place, i.e., this formula describes with reasonable accuracy sets of mesons with fixed quantum numbers Q and different quark constituents. Besides, we clarify the conditions providing this formula.

2 Bethe-Salpeter equation, analytical confinement and meson masses

Calculation of the mass M of a meson bound states with a quantum number Q of two constituent quarks with masses m_1 and m_2 in the framework of the Bethe-Salpeter equation in the ladder approximation is reduced to the diagonalization of the kernel (see [9, 8])

$$-1 = g^2\mathbf{Tr}(V_Q S_1 V_Q S_2) = \frac{\alpha_s}{\pi}\iint dy_1 dy_2 V_Q(y_1)\Phi_{J,1,2}(y_1 - y_2|p)V_Q(y_2), \tag{2}$$

where

$$\Phi_{J,1,2}(y_1 - y_2|p) = \int dx\ e^{i(px)}\mathrm{Tr}\left[\Gamma_J S_1(x + \mu_2(y_1 - y_2))\Gamma_J S_2(x - \mu_1(y_1 - y_2))\right]$$

where the quark-antiquark vertex Γ_J defines the corresponding quantum numbers of a bound states under consideration.

All calculations will be performed in the Euclidean space $\mathbf{R}^4$.

The quark propagator is chosen in the form induced by a vacuum self-dual gluon field with constant strength (for details see Appendix and [9, 8])

$$S(y, m) = \frac{\Lambda^2}{8\pi^2}\int\limits_0^1 \frac{du}{u^2}\tilde{S}(y, m, u)\cdot e^{-\frac{\Lambda^2 y^2}{2u}}\cdot\left(\frac{1-u}{1+u}\right)^{\frac{m^2}{4\Lambda^2}}. \tag{3}$$

The parameter Λ defines the confinement scale. The explicit form of the polynomial $\tilde{S}(y, m, u)$ in variables y and m will not be important in our calculations here but it can be found in [9].

The other parameters are

$$p^2 = -M^2, \qquad \mu = \frac{M}{m_1 + m_2}, \qquad \mu_1 = \frac{m_1}{m_1 + m_2}, \qquad \mu_2 = \frac{m_2}{m_1 + m_2}.$$

The vertex function V_Q is determined by the solution of the Bethe-Salpeter equation, but with acceptable accuracy it can be approximated at large distances $y^2 \sim \frac{1}{\Lambda^2}$ by

$$V_Q(y) \sim D(y) \approx D_0\ e^{-\frac{\Lambda^2}{2}y^2}. \tag{4}$$

Thus, the mass of a bound state with the quantum number Q is defined by the equation

$$\begin{aligned} -1 &= \frac{\alpha_s}{\pi}\int dy\ D_0^2 e^{-\frac{y^2}{4}}\int dx\ e^{i(px)}\mathrm{Tr}\left[\Gamma_Q S_1(x + \mu_2 y)\Gamma_Q S_2(x - \mu_1 y)\right] \\ &= \frac{\alpha_s}{\pi}\iint\limits_0^1 du_1 du_2 P_Q(u_1, u_2, \mu, \mu_1, \mu_2)e^{\frac{(m_1+m_2)^2}{2\Lambda^2}E(\mu,\mu_1,\mu_2,u_1,u_2)}. \end{aligned} \tag{5}$$

Here $P_Q(u_1,u_2,\mu,\mu_1,\mu_2)$ is a polynomial in parameters $\mu,\ \mu_1,\ \mu_2$ and its explicit form is defined by the spin structure of vertices and quark propagators. The quantum numbers $Q=(J^P,n)$ of bound states are defined by these polynomials. The explicit form of these polynomials will not be important in our arguments.

The function

$$E(\mu,\mu_1,\mu_2,u_1,u_2) \tag{6}$$
$$= \mu^2\cdot\frac{u_1u_2+2(\mu_1^2u_1+\mu_2^2u_2)}{u_1+u_2+2} - \frac{\mu_1^2}{2}\ln\left(\frac{1+u_1}{1-u_1}\right) - \frac{\mu_2^2}{2}\ln\left(\frac{1+u_2}{1-u_2}\right).$$

plays the main role in equation (5) and its behavior defines the meson mass spectrum. It is important that this function depends on masses of constituent quarks m_1 and m_2 and does not depend on quantum numbers of bound states, so that we can hope that the main features of a set of mesons with the same quantum number $Q=(J^P,n)$ are defined by masses of constituent quarks only.

The masses of all mesons, except pion π and kaon K, have masses more than sum of masses of constituent quarks, i.e. $\mu=\frac{M}{m_1+m_2}>1$, i.e. the function E is positive and has a positive maximum at a point $0<u_1^{(0)}<1$, $0<u_2^{(0)}<1$. Thus, one can write approximately

$$\iint\limits_0^1 du_1du_2P_Q(u_1,u_2,...)e^{\frac{(m_1+m_2)^2}{2\Lambda^2}E(\mu,\mu_1,\mu_2,u_1,u_2)} \approx C_Qe^{\frac{(m_1+m_2)^2}{2\Lambda^2}\mathcal{E}(M,m_1,m_2)},$$

where

$$(m_1+m_2)^2\mathcal{E}(M,m_1,m_2) = \max_{u_1,u_2}\ (m_1+m_2)^2E(\mu,\mu_1,\mu_2,u_1,u_2)$$
$$\approx \left[1.37m_1^2+1.55m_1m_2+1.37m_2^2\right]\left(\frac{M}{m_1+m_2}-1\right)^{1.6}.$$

Thus, equation (5) can be approximated by

$$1 \ \approx\ \frac{\alpha_s}{\pi}C_Qe^{\frac{(m_1+m_2)^2}{2\Lambda^2}\mathcal{E}(M,m_1,m_2)}. \tag{7}$$

The solution of this mass equation requires a weak coupling regime $\alpha_s<1$.

The approximate formula, which determines the mass of a meson in a quantum state $Q=(J^P,n)$ with constituent quarks with masses m_1 and m_2, looks like

$$M_Q(m_1,m_2)\approx(m_1+m_2)\left[1+\frac{A_Q}{(m_1^2+1.13m_1m_2+m_2^2)^{0.625}}\right]. \tag{8}$$

Here the positive constant A_Q is the same for all mesons with a given fixed quantum number $Q=(J^P,n)$.

Now we should check this formula for real meson spectrum.

3 Meson masses

Let us choose in the Table Particle Group Data [15] mesons with the same quantum numbers but with different flavor masses. Mesons $Q=(J^P,n)$ can be represented in the form

$$\mathcal{M}(J^P,n)\ \Rightarrow\ \begin{pmatrix} uV_Q\bar{u} & uV_Q\bar{s} & uV_Q\bar{c} & uV_Q\bar{b} \\ & sV_Q\bar{s} & sV_Q\bar{c} & sV_Q\bar{b} \\ & & cV_Q\bar{c} & cV_Q\bar{b} \\ & & & bV_Q\bar{b} \end{pmatrix}. \tag{9}$$

3.1 Basic mesons with radial quantum number $n = 0$

In the Table Particle Group Data [15] for the radial quantum number $n = 0$ there are only five sets of mesons with fixed J^P having all four constituent quarks $u = d,\ s,\ c,\ b$

$$P(0^-,0) = \begin{pmatrix} \eta(547) & & D(1869) & B(5279) \\ & \eta'(957) & D_s(1968) & B_s(5369) \\ & & \eta_c(2979) & B_c(6400) \\ & & & \eta_b(9300) \end{pmatrix};$$

$$V(1^-,0) = \begin{pmatrix} \rho,\omega(782) & K^*(892) & D^*(2007) & B^*(5325) \\ & \phi(1020) & D_s^*(2112) & - \\ & & J/\psi(3100) & - \\ & & & \Upsilon(1S)(9460) \end{pmatrix};$$

$$S(0^+,0) = \begin{pmatrix} f_0(980) & - & - & - \\ & f_0(1370) & - & - \\ & & \chi_{c0}(3415) & - \\ & & & \chi_{b0}(9893) \end{pmatrix};$$

$$A(1^+,0) = \begin{pmatrix} a_1(1260) & K_1(1270 \div 1400) & - & - \\ & f_1(1420) & - & - \\ & & \chi_{c1}(3510) & - \\ & & & \chi_{b1}(9892) \end{pmatrix};$$

$$D(2^+,0) = \begin{pmatrix} f_2(1270) & K_2^*(1430) & D_2^*(2460) & - \\ & f_2'(1525) & - & - \\ & & \chi_{c2}(3556) & - \\ & & & \chi_{b2}(9912) \end{pmatrix}.$$

In our table we consider that $\eta = (u\bar{u})$ and $\eta' = (s\bar{s})$.

Here we shall consider mesons masses of which are larger then the sum of the masses of constituent quarks and should be described by formula (8). The light pseudoscalar mesons π and K are unique mesons the masses of which are smaller than the sum of the masses of constituent quarks. Therefore they are not described by formula (8).

In addition, we consider three excited states 3^-:

$$T(3^-,0) = \begin{pmatrix} \omega_3(1670) & K_3^*(1780) \\ & \phi_3(1850) \end{pmatrix}.$$

We will show that the masses of all these mesons with reasonable accuracy are described formula (8). Our parameters, which should be determined by fitting, are masses of constituent quarks $m_u = m_d,\ m_s,\ m_c,\ m_b$ (4 parameters) and parameters $A_P,\ A_V,\ A_S,\ A_A,\ A_D,\ A_T$ (6 parameters).

Our calculations consist in the following. We choose the quark masses according to Table 1 and calculate the constant A_Q for each the known set of mwsons with quantum number Q by formula

$$O_Q = \frac{1}{N_Q} \sum_{f_1,f_2:u,s,c,b} \left[1 - \frac{M_Q(m_{f_1}, m_{f_2}, A_Q)}{(M_{Q,f_1,f_2})_{\rm exp}}\right]^2, \qquad (10)$$

where N_Q is the number of known mesons with the quantum number Q. Value of O_Q gives the accuracy of our approximation for each given quantum number Q. The results are given in Table 2 and Figures 1-6.

Table 1. Quark masses.

m_f	m_u	m_s	m_c	m_b
Mev	260	434	1506	4732

Table 2. Parameters A_Q and O_Q for states with $n = 0$.

$Q = J^P$	$P = 0^-$	$V = 1^-$	$S = 0^+$	$A = 1^+$	$D = 2^+$	$T = 3^-$
$A_Q(Gev^{1.25})$ $O_Q \cdot 10^{-3}$	0.0216 11	0.217 2.6	0.249 12	0.527 2.3	0.618 1.9	0.838 0.16

3.2 Radial exitations $n > 0$

Vector mesons 1^- ($\rho = u\bar{u}$, $\psi = c\bar{c}$, $\Upsilon = b\bar{b}$) have the most large number of radial excitations $n = 0 \div 5$. We compute constants $A_V(n)$ for $n = 0 \div 4$. The dependence of these constants on the radial quantum number n can be fitted by

$$A_V(n) \approx 0.1897 + 0.3236 \ln(n + 1) + 0.1634n.$$

This formula gives the constant $A_V(5) = 1.574$ for $n = 5$. Then the meson masses for $n = 5$ can be calculated. One can see that the agreement with the experimental masses is quite reasonable.

The results of calculations are given in Table 3.

Table 3. Radial excitations for vector 1^- mesons. The second number is the calculated meson mass in Mev.

n	$\rho = u\bar{u}$	$\psi = c\bar{c}$	$\Upsilon = b\bar{b}$	A_V	O_V
0	$\rho(770)$ - 778	$J/\psi(3100)$ - 3178	$\Upsilon(1S)(9460)$ - 9589	0.188	0.0079
1	$\rho(1450)$ - 1323	$\psi(2S)(3655)$ - 3530	$\Upsilon(2S)(10023)$ - 9853	0.585	0.0037
2	$\rho(1700)$ - 1699	$\psi(3770)$ - 3772	$\Upsilon(3S)(10365)$ - 10035	0.859	0.0011
3	$\rho(1900)$ - 2081	$\psi(4040)$ - 4018	$\Upsilon(4S)(10580)$ - 10220	1.137	0.0034
4	$\rho(2150)$ - 2390	$\psi(4160)$ - 4217	$\Upsilon(10860)$ - 10370	1.362	0.0049
5	$\rho(-)$ - 2698	$\psi(4415)$ - 4416	$\Upsilon(11020)$ - 10518	1.574	–

There are four tensor mesons 2^+ with the radial quantum numbers $n = 1$

$$D1(2^+,1) = \begin{pmatrix} f_2(1565) & K_2^*(1980) & - & - \\ & f_2(2010) & - & - \\ & & - & - \\ & & & \chi_{b2}(2P)(10268) \end{pmatrix}.$$

Results of calculations are given in Table 4.

Table 4. Tensor mesons 2^+.

	$n=0$	$n=1$
$u\bar{u}$	$f_2(1270)$ - 1336	$f_2(1565)$ - 1737
$u\bar{s}$	$K_2^*(1430)$ - 1445	$K_2^*(1980)$ - 1818
$s\bar{s}$	$f_2'(1525)$ - 1586	$f_2(2010)$ - 1939
$s\bar{c}$	$D_2^*(2460)$ - 2320	$-$ - 2772
$c\bar{c}$	$\chi_{c2}(1P)(3556)$ - 3537	$-$ - 3796
$b\bar{b}$	$\chi_{b2}(1P)(9912)$ - 9859	$\chi_{b2}(2P)(10268)$ - 10053
A_D $(Gev)^{1.25}$	0.594	0.886
O_D	0.0013	0.0051

4 Conclusion.

Our results can be formulated as follows:

- Confinement - quarks and gluons are fluctuations in time-space.
- Stability in a self-dual homogeneous field:
  - no confinement in QED - all basic particles are fermions and electron has the lowest mass;
  - confinement in QCD - gluons have zero mass.
- The structure of the quark propagetor in gluon vacuum field predetermines main features of meson spectrum.
- If mesons are described by quark currents of the type $(\bar{q}_1 V_Q q_2)$ the formula (8) correctly describes the mass dependence of mesons on masses of constituent quarks.
- The (anti)self-dual homogeneous field is a good candidate to be the vacuum gluon field.

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