XYZ mesons and Glueballs: effects of the quark-gluon mixing

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We present the new developments in the physics of XYZ mesons and glueballs and discuss the connection between properties of the XYZ mesons and glueballs, and the structure of the QCD vacuum. It is shown that the mixing between quark and gluon degree of freedoms induced by the nontrivial topological structure of the QCD vacuum might affect strongly the properties of the exotic hadrons. A new interpretation of the XYZ mesons as the mixing between radial excitations of light quark-antiquark systems and states with heavy quark content is suggested. We introduce also a new mechanism of quarkonia production in hadron-hadron collisions coming from the mixing of light and heavy quark sectors of QCD. This mechanism is based on the nontrivial topological structure of the QCD vacuum and might explain the polarization puzzle in inclusive J/Ψ production in high energy reactions. The possibility of big changes of the scalar and pseudoscalar glueball masses in the hot gluonic plasma is established and their consequences in the phase structure of QCD analyzed.

1 Introduction

Nowadays the study of the exotic hadrons is one of the hottest topics of hadron physics. Within the quark model the ordinary mesons are considered as bound states of quark-antiquark pairs and baryons are three-quark bound states. However, more complicated states which include additional quarks and/or valence gluons are not forbidden by QCD. There were three big waves in the history of the exotic hadrons. The first wave was created by the pioneering papers by Jaffe [1, 2] on spectroscopy of the four quark $q^2\bar{q}^2$ states within MIT bag model with light u, d, s quarks. These states we call now light tetraquarks. The second wave was created by the prediction of the $udud\bar{s}$ strange pentaquark state with very small width within the chiral soliton model [3]. The third and last wave was generated by the Belle Collaboration discovery of the $X(3872)$ meson with very small width and the mass near DD^* threshold [4]. Now we have many candidates for exotic tetraquark states with heavy quark content which are called the XYZ mesons. There are also several candidates for the heavy pentaquarks (see, for example, the recent reviews [5, 6]). A lot of the different microscopical models have been suggested to explain their unusual properties. We discuss a new approach to the XYZ mesons based on the possibility of a large mixing between radial excitations in the light quark and antiquark system and states with heavy quark content. Such mixing might be induced by the nonperturbative quark-gluon interaction related to the nontrivial topological structure of the QCD vacuum. The second part of this review is devoted to the modern status of glueballs which are the bound states of the gluons. We discuss the properties of these exotic hadrons including the possibility of the existence of the three-gluon bound states. And finally, we show that glueballs can influence strongly the properties of Quark-Gluon Plasma.

2 The exotic XYZ mesons

One of the main problems of the exotic hadron spectroscopy is the possibility of large mixings between exotic and nonexotic hadrons with the same quantum numbers. This mixing does not allow, in the most cases, to separate exotic states from the ordinary hadrons. The instantons, the strong fluctuations of the vacuum gluon fields, induce t'Hooft's multiquark interaction which can lead to the strong mixing of the different quark flavors (see review [15]). Due to the specific structure of t'Hooft's interaction it can violate the OZI rule in the channels with the quantum numbers 0^{-+} and 0^{++} as shown in Fig.1a. Since the instanton corresponds to a subbarrier transition between vacua with the different topological charge, the natural energy scale of this violation is related to the height of the potential barrier between these vacua. This height is given by the energy of the so-called sphaleron $E_{sph} = 3\pi/4\alpha_s(\rho_c)\rho_c \approx 2.8$ GeV with $\rho_c \approx 0.3$ fm being the average instanton size in the QCD vacuum [16]. For higher mass excitations one can expect that the instanton-anti-instanton molecules give an important contribution to the mixing between states with different quark flavors. Examples of such mixing between light quark-antiquark states and states with heavy quarks are shown in the Figs.1b, c and Fig.2. The nonperturbative interaction which governs that mixing is the quark-gluon effective interaction induced by instantons [17, 18]

$$\mathcal{L}_I = -i\frac{g_s\mu_a}{4M_q}\,\bar{q}\sigma^{\mu\nu}t^a q\, G^a_{\mu\nu} \tag{1}$$

where $G^a_{\mu\nu}$ is the gluon field strength, M_q is the effective mass of the light $u-, d-$ quarks in the vacuum and μ_a is the anomalous quark chromomagnetic moment (AQCM). An extension

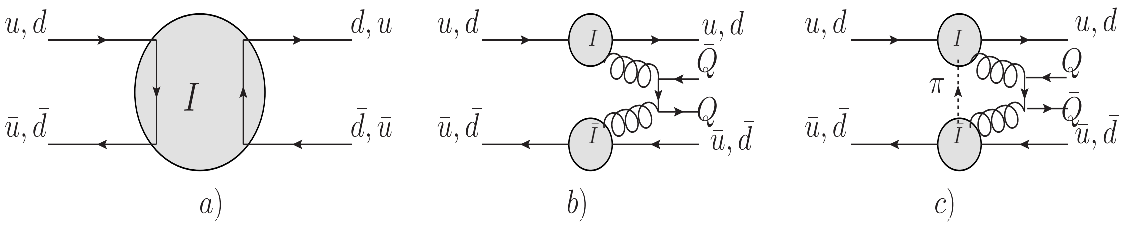

Figure 1: a) low energy mixing between light quarks induced by single instanton or anti-instanton , b) high energy mixing between light quarks and heavy quarks Q induced by the instanton-anti-instanton molecules and c) additional mixing induced by an additional pion exchange which is shown by the dashed line.

of Eq.1 which preserves the chiral symmetry was suggested by Polyakov and has the following form [9]

$$\mathcal{L}_I = -i\frac{g_s\mu_a}{4M_q}\bar{q}\sigma^{\mu\nu}t^a e^{i\gamma_5\vec{\tau}\cdot\vec{\phi}_\pi/F_\pi} q G^a_{\mu\nu}, \tag{2}$$

Figure 2: Additional mixing between heavy and light quarks in the $I = 0$ channel.

where $F_\pi = 93$ MeV is the pion decay constant [1]. Within the instanton model, the value of AQCM is [18]

$$\mu_a = -\frac{3\pi(M_q\rho_c)^2}{4\alpha_s(\rho_c)} \approx -0.38 \tag{3}$$

for $M_q \approx 170$ MeV in mean field approximation.

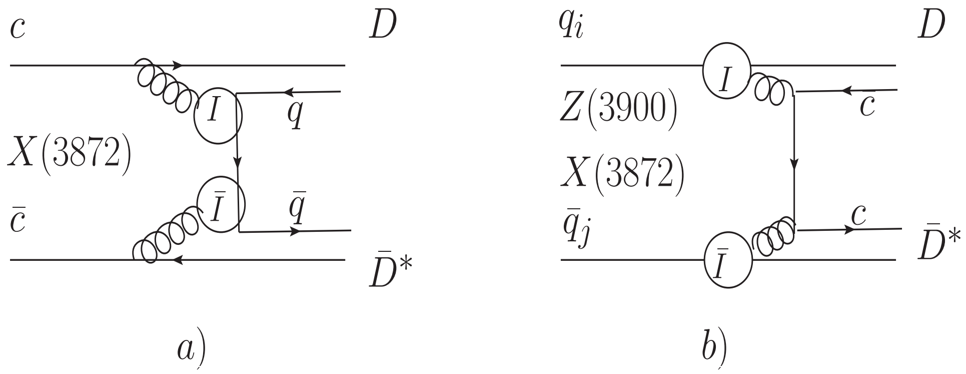

Figure 3: a) Mixing $c\bar{c}$ core with $D\bar{D}^*$ state, b) mixing the light radial excited state with $D\bar{D}^*$

In general, a high radially excited state of a light quark-antiquark system can mix easily with states which have a heavy quark content, if they have the same quantum numbers and approximately the same mass. It might be that the $X(3872)$ and the $Z_c(3900)$ are result of the mixing of molecular states and/or tetraquark charmed hidden states with high radial excitations of a light quark system, by the mechanism shown in Fig.1b, c and Fig.3b. A recent paper in the spirit of this idea was presented by Coito [13]. In the case of such mixing one should observe the decays of the XYZ mesons to final states without heavy quarks. The absence of these decay modes in present experiments might be related to the existence of many nodes in the wave function of the light quark system. One can estimate, for example, that light quark $q\bar{q}$ systems with radial numbers $n_r \sim 7-8$ have approximately the same mass as the $X(3872)$ and the $Z_c(3900)$. The many node structure of the wave function might lead to a very small overlap of the initial and final wave functions in the decay. These strong effect of the many nodes in wave function in decays is well known phenomenon. In particular, Brodsky and Karliner in [14] used it to explain the small rate of $\Psi(2S) \to \rho\pi$ in comparison with $J/\Psi \to \rho\pi$. Therefore, the

[1] For simplicity we consider only the $N_F = 2$ case.

mixing of high excited states in light quark-antiquark systems with heavy quark states might be behind of the unusual properties of XYZ mesons.

3 The J/Ψ polarization puzzle

There is a longstanding problem to explain the absence of transverse polarization of J/Ψ in the inclusive production at high energy. The transverse polarization was predicted by perturbative QCD and it comes from the fragmentation of on-shell gluon to charm-anticharm pair (see review [19]). Such polarization is in disagreement with the measurement at TEVATRON [20] and at LHC [21, 22]. In a recent paper the polarization of gluons in the constituent quark induced

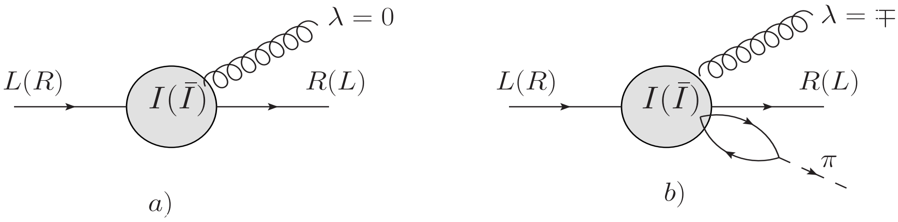

Figure 4: Diagram a) shows the quark-gluon vertex generated by the instanton, and diagram b) describes the quark-gluon-pion vertex induced by the instanton.

by instantons was calculated [23]. The diagram without pion, Fig.4a, produces no polarization of the gluons [9]. However, the diagram with an additional pion, Fig.4b, leads to polarization of the gluons. In this case the instanton and anti-instanton provide a polarization of opposite sign. The contribution of the instantons to the J/Ψ polarization in proton-proton collisions is presented in Fig.5. It is evident, that such mechanism leads to a longitudinal polarization of the J/Ψ because the perturbative vertex with a hard gluon does not change the helicity of the charm quark. From the another side, one can consider this new mechanism as the contribution

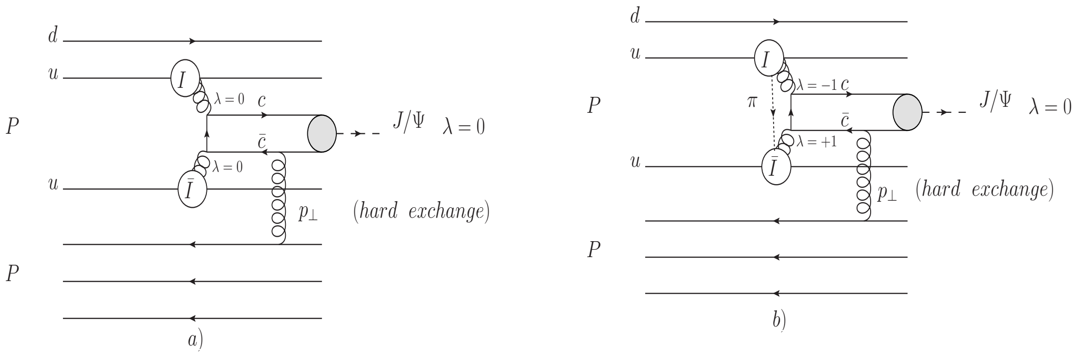

Figure 5: Example of diagrams which lead to the longitudinal polarization of J/Ψ induced by instanton-anti-instanton pair a) without pion exchange and b) with pion exchange.

to the inclusive production of the quarkonia coming from the mixing of light quarks with a state having heavy quark content.

4 Glueballs

The glueballs, the bound states of the gluons, are now widely under discussion (see the reviews [24, 25]). Different approaches including MIT bag model, several types of the constituent models, holographic QCD, QCD sum rule methods and the lattice simulation were used to extract the information on the spectrum and quantum numbers of the glueballs. One direct way based on the first principals of QCD to calculate the glueball spectrum are lattice calculations. At the present, the old [26] and more recent lattice calculations [27] in quenched QCD, i.e. the theory without quarks, are in the agreement and the result for the low mass of the glueballs in pure $SU(3)_c$ is

$$M(0^{++}) \approx\ 1.7\ GeV, M(2^{++}) \approx\ 2.4\ GeV, M(0^{-+}) \approx\ 2.6\ GeV$$

One of the interesting features of lattice calculations is that in the unquenched QCD with light quarks the result for the lowest mass of glueballs practically does not change [28]

$$M(0^{++}) = 1.795(60)\ GeV, \quad M(2^{++}) = 2.620(50)\ GeV,$$

for 2+1 flavor and $m_\pi = 360$ MeV. A more recent result for $N_f = 2$ and $m_\pi \approx 580$ MeV is [29]

$$M(0^{++}) = 1.624(141)GeV, M(0^{-+}) = 2.738(153)GeV, \ M(2^{++}) = 2.516(95)GeV.$$

There are many candidates for the glueball states. For the scalar glueballs we have the following mesons

$$f_0(600), \quad f_0(980), \quad f_0(1370), \quad f_0(1500), \quad f_0(1710), \quad f_0(1790),$$

For pseudoscalar glueball the candidates are

$$\eta(1405), \quad X(1835), \quad X(2120), \quad X(2370), \quad X(2500)$$

In the case of the tensor glueballs there are two candidates

$$f_J(2220), \quad f_2(2340).$$

One of the main problems of the glueball spectroscopy is the possible large mixings of the glueballs with ordinary and exotic quark states which leads to the difficulties in disentangling the glueballs in the experiments (see recent discussion in [30]). The example of such mixing is presented in Fig.6. The contribution of the mixing presented in Fig.6a was considered in [31] within the QCD sum rule method, and it was shown to be very important. One of the suitable ways to avoid this problem and obtain a clear prediction for the glueballs is to study the glueballs with exotic quantum numbers. $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, etc\ldots$ which cannot mix with ordinary quark-antiquark states. However, the calculation of the masses and decay modes of these exotic glueballs is very difficult because one should consider states with a large number of gluons. For example, Lattice calculations give a very large mass $M_G = 5.17$ GeV with a large uncertainty for the 0^{--} exotic three-gluon glueball. The first attempt to calculate the masses of the glueballs with exotic quantum number was done in ref. [32, 33] within the QCD sum rule approach and a rather small mass for 0^{--} glueball was found. However in a recent paper [34], it was shown that the interpolation current for the gluonic state used in [32, 33] has an anomaly and cannot be applied for the glueball calculations. In ref. [34] a new interpolating current for the 0^{--} glueball has been suggested. The derived QCD sum rules are consistent

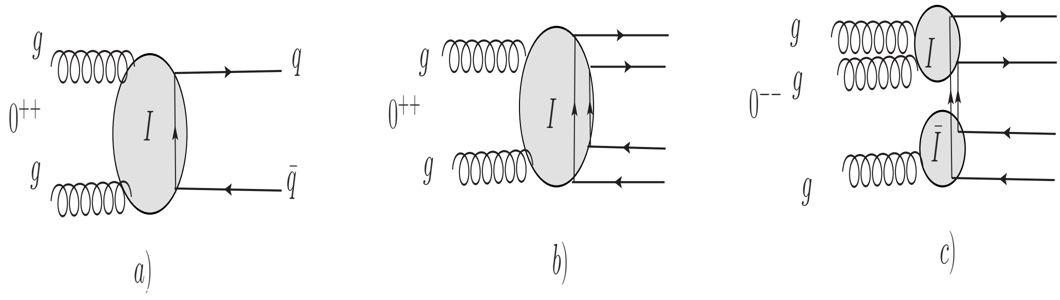

Figure 6: a) Mixing 0^{++} glueball with a quark-antiquark state, b) mixing of this glueball with a tetraquark, and c) mixing of the exotic three gluon 0^{--} state with an exotic tetraquark.

and stable. The resulting value for the mass of the 0^{--} glueball state is $M_G = 6.3^{+0.8}_{-1.1}$ GeV and an upper limit for the total width $\Gamma_G \leq 235$ MeV has been obtained. It has been also argued that the mixing of this glueball state with 0^{--} tetraquark is expected to be very small. Therefore, the exotic 0^{--} glueball can be considered a pure gluon state. At the present, the Belle Collaboration is searching for this state [35].

5 Glueballs in Quark-Gluon Plasma

In experiments at RHIC and LHC a new type of nuclear matter the so-called strongly interacted quark-gluon plasma has been discovered (see review [38]). It behaves as a liquid and does not have the expected gas-like behavior. There are many experiments planned at the running and future facilities to investigate the properties of such new matter. It is very important from the point of view of theory of the strong interactions to find the fundamental reason which leads to such behavior of quark-gluon matter. One possible way is to investigatethe simpler case of pure Gluodynamics, the theory without quarks. Recently very precise lattice results for the Equation of State (EoS) of this theory at finite T below and above the deconfinement temperature T_c were presented [39]. They challenge our understanding of QCD dynamics at finite temperatures. One of the puzzles is a very spectacular behavior of the trace anomaly, $I/T^4 = (\epsilon - 3p)/T^4$, as a function of T. In particular, just above T_c it rapidly grows untill $T_G \approx 1.1T_c$ and then it decays as $I/T^4 \sim 1/T^2$ untill $T \approx 5T_c$. A mechanism which can explain such anomalous behavior has been suggested in ref. [40]. The mechanism is based on the possibility of a large change of the glueball masses above the T_c. The starting point is the relation between the lowest scalar glueball mass, m_G, and the gluon condensate, $G^2 =< 0|\frac{\alpha_s}{\pi}G^a_{\mu\nu}G^a_{\mu\nu}|0>$ at $T = 0$, which appears naturally in the dilaton approach [41]

$$m_G^2 f_G^2 = \frac{11N_c}{6} < 0|\frac{\alpha_s}{\pi}G^a_{\mu\nu}G^a_{\mu\nu}|0>, \tag{4}$$

where f_G is the glueball coupling constant to gluons. Lattice calculations show that the gluon condensate decreases roughly by a factor two at $T = T_c$ due to the strong suppression of its electric component, while slightly above T_c the condensate vanishes very rapidly due to the cancellation between its magnetic and electric components [42]. The temperature behavior of the condensate at $T_G \geq T \geq T_c$ can be described by the equation [43]

$$G^2(T) = G^2\left[1 - \left(\frac{T}{T_G}\right)^n\right]$$

and the mass of scalar and pseudoscalar glueballs for $T_G \geq T \geq T_c$ are given by

$$m(T) = m_0\sqrt{1 - \left(\frac{T}{T_G}\right)^4}.$$

The possible dynamical reason for the decrease of scalar and pseudoscalar glueball masses above T_c is the strong attraction between gluons induced by instanton-antiinstanton molecules shown in Fig.7. Such a molecular structure of the instanton vacuum is expected above T_c For the quark-antiquark channel the effect of the instanton-antiinstanton induced interaction was discussed in [45] and it was shown to be strong. For the gluon-gluon interaction the effect should be even stronger because it is enhanced by factor $S_0^2 \approx 10^2$, where $S_0 \approx 10$ is the instanton action. The rapid decrease of the scalar and preudoscalar glueball masses above

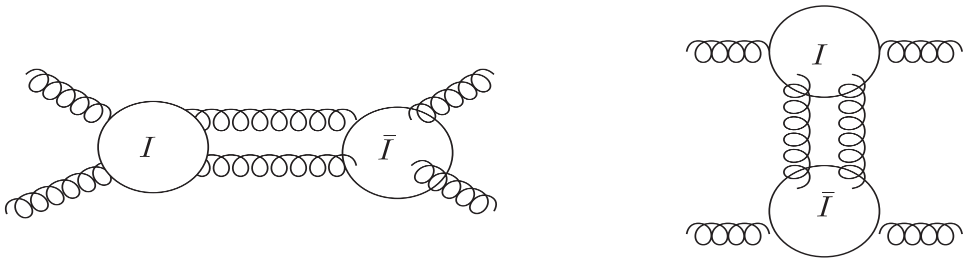

Figure 7: Gluon-gluon interaction induced by instanton-antiinstanton molecules.

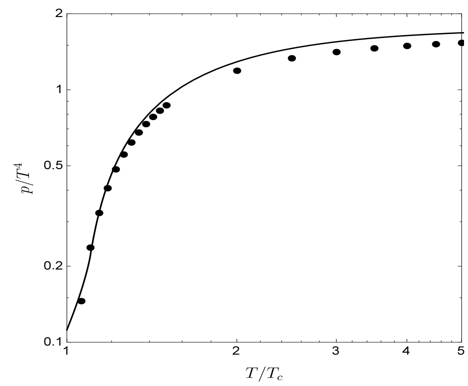

Figure 8: The pressure p/T^4 as the function of T/T_c in comparison with the lattice data [39].

T_c leads to a large contribution of these glueballs to the pressure of the gluon plasma and the sum of the glueball and free gluon contributions describe the lattice data very well as shown in Fig.8. Given these results we can describe three different phases of gluon matter [40]. The first phase is the confinement regime at $T < T_c$ and is described by a gas of massive glueballs.

The second phase appears just above T_c at $T_G \geq T \geq T_c$, where $T_G \approx 1.1T_c$. In this phase the main contribution to the EoS is coming from the very light scalar and pseudoscalar glueballs. Above the $T_G \approx 1.1T_c$ the third phase appears, a mixed phase of massless gluons and point-like scalar-pseudoscalar massless glueballs. The existence of such phases can be checked in high multiplicity events in relativistic heavy ion collisions where an abundant production of glueballs is expected [36, 37]. The most simple way is to look for the change of the scalar and pseudoscalar glueball masses in the two pion and three pion channels, correspondingly, as a function of multiplicity. Finally it should be also mentioned that the mixing between quark and gluon states can change strongly above T_c due to the transition between single instanton induced mixing to the mixing produced by instanton-antiinstanton molecules.

6 Conclusion

The exotic hadrons carry a very important information on the structure of the strong interactions and the properties of the exotic hadrons are very sensitive to the nonperturbative structure of QCD. We have shown that the XYZ mesons can arise as the result of a nonperturbative mixing between different configurations with and without heavy quark content. We have furthermore suggested a new mechanism for heavy quarkonia production at high energy which can be related to such mixing. We have also discussed the modern status of the glueballs and their mixing with quarkonia. Finally, we have predicted a drastic change of the scalar and pseudoscalar glueball masses above the deconfinement temperature in the gluonic plasma which has very exciting consequences at the level of the possible phase transitions at very high temperatures.

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