Meeting of the Working Group on Theory of Hadronic Matter under Extreme Conditions
Dubna, October 31- November 3 2016

Glueballs in the Hot Plasma

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CONTENTS

Introduction to Glueballs

Review by Vincent Mathieu, N.K. and Vicente Vento Int. J. Mod. Phys. E **18**, 1 (2009)

• Glueballs in MIT bag Model: two gluon states in cavity

Jaffe and Johnson Phys.Lett.B60 (1976) 201.

$$E = \frac{4\pi B R^3}{3} + \sum_i n_i \frac{x_i}{R}.$$

Energy modes $E_i = x_i/R$ are fixed from boundary condition in cavity:

$$n_\mu G_a^{\mu\nu}(x) = 0 \; at \;\; r = R.$$

$$M(0^{++}) \approx M(2^{++}) \approx 1 GeV, \;\; M(0^{-+}) \approx M(2^{-+}) \approx 1.3 GeV$$

• Results for glueball masses in some of modern phenomenological constituent gluon models based on non-perturbative QCD:

Gerasimov, Kaidalov and Simonov; Anisovich et al; Efimov and Ganbold, Lubovitskij et al Mathieu et al
are in general agreement with lattice results

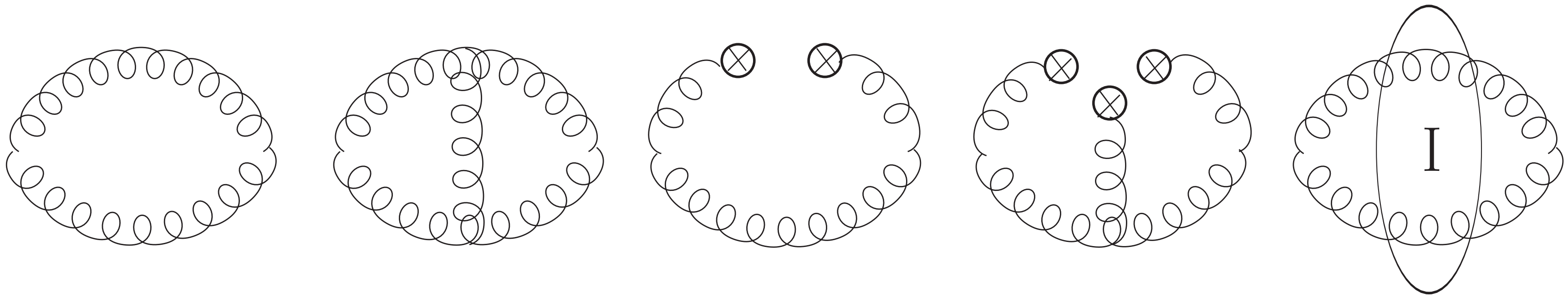
- But some models:

Vento, Molodtsov et al Mennessier, Minkowski, Ochs, Narison
suggest more light lowest mass 0^{++} glueball (due to σ-glueball mixing)

$$M(0^{++}) \approx 0.5 \div 1.0 GeV.$$

- Glueballs in QCD Sum Rules

S.Narison, H.Forkel, Harnett,Moats and Steele.



(a) (b) (c) (d) (e)

Figure 1: The diagrams (a) and (b) represent pQCD contributions, diagram (c) represents the contribution arising from the gluon condensate $< 0|\alpha_s G^2|0 >$, diagram (d) is the contribution from three-gluon condensate $< 0|gG^3|0 >$ and diagram (e) is so-called direct instanton contribution.

$$M(0^{++}) \approx 1.5GeV, \quad M(0^{-+}) \approx M(2^{++}) \approx 2GeV$$

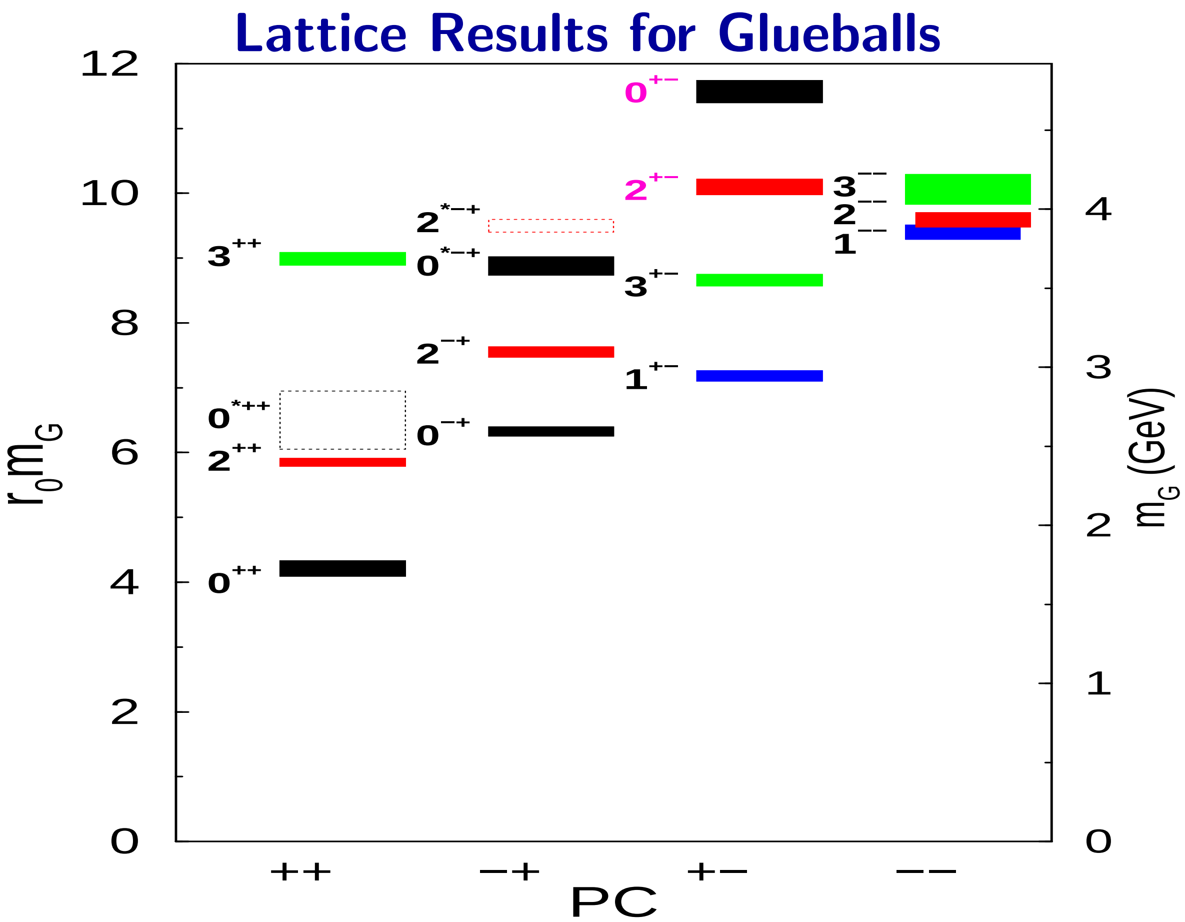


Figure 2: The mass spectrum of glueballs in pure $\mathrm{SU_C}(3)$ gauge theory by Morningstar and Peardon calculation (1999) in an anisotropic lattice ($6^3 \times 30$, $8^3 \times 40$, $10^3 \times 50$ and $15^3 \times 45$). The masses are given in units of the hadronic scale r_0 along the left vertical axis and in GeV along the right vertical axis ($r_0^{-1} = 410 \pm 20 MeV$).

All lattice calculations are now consistent and shown that without the quarks in pure $SU(3)_c$ the masses of the lowest states are

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

- Recent result in unquenched QCD by Gregory et al JHEP10(2012) 170 (2+1 flavor, $m_\pi = 360$ MeV)

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

- Very recent result for $N_f = 2$ by Y.Chen et al (Lattice 2016, Southampton, July 24-30)

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

- No substantial difference from the quenched results but $m_\pi \approx 580$ MeV is very large!)

• The size of scalar glueball is very small $r_{0^{++}} \approx 0.2 fm$!!! but the size of tensor is big $r_{2^{++}} \approx 0.8 fm$

The reason is strong attraction induced by instantons in 0^{++} channel.

T. Schafer and E. V. Shuryak, Phys. Rev. Lett. **75**, 1707 (1995)

Experiment

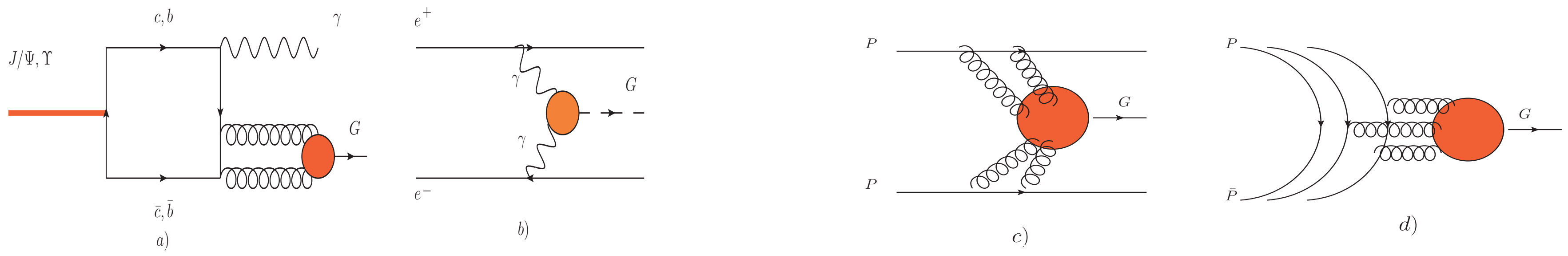


Figure 3: Glueball production in a) heavy quarkonium radiative decays (BESIII,Belle, BaBar, LHCb) , b) in photon-photon fusion (BESIII, Belle, BaBar), c) in the central meson production (RHIC, LHC), d) in proton-antiproton annihilation (PANDA)

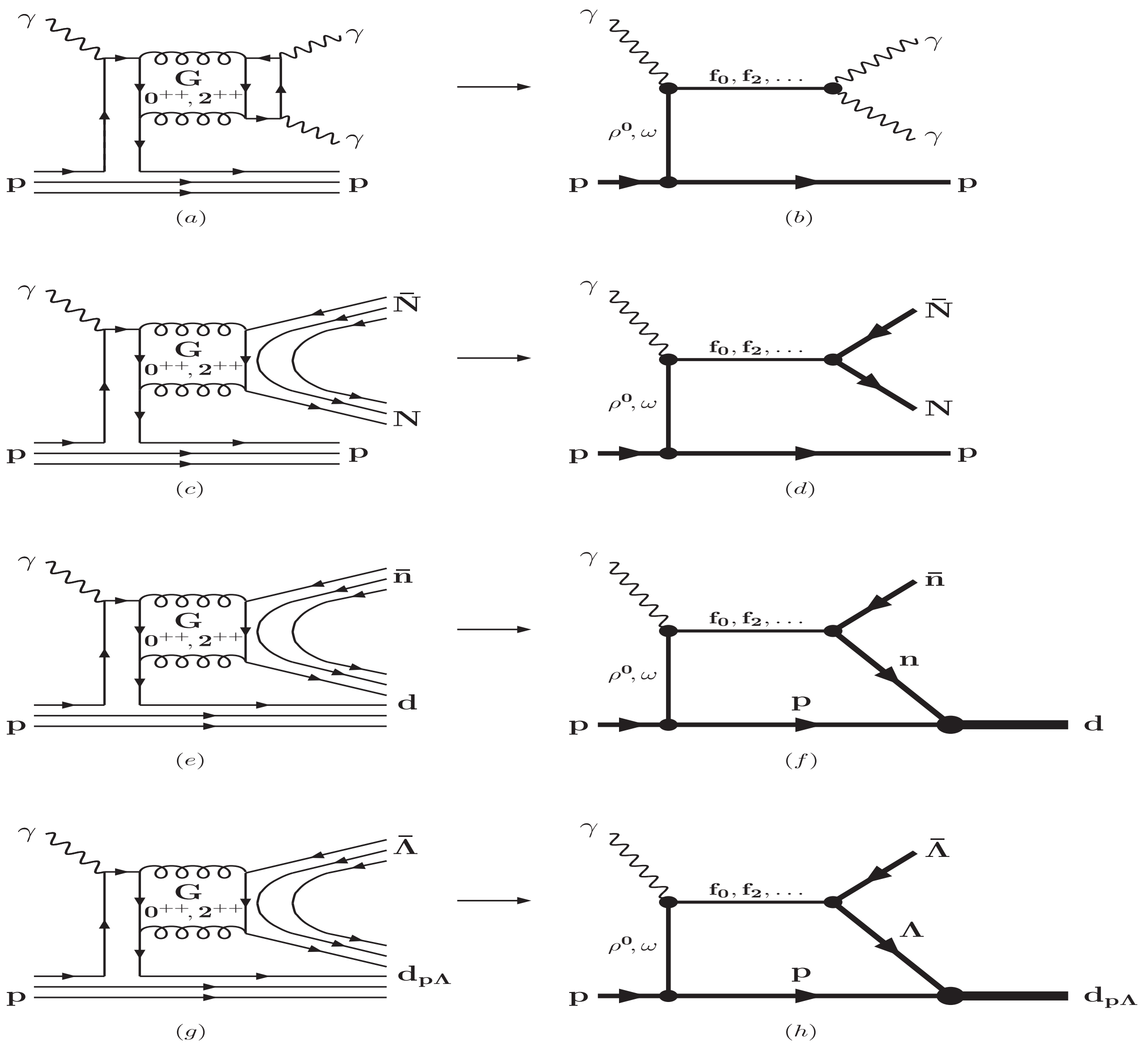


Figure 4: The production of glueballs in γ-proton collision. Proposal for GlueX (JLab) by Lyubovitskij et al arXiv:1605.01035.

- Glueball production in heavy quark weak decays

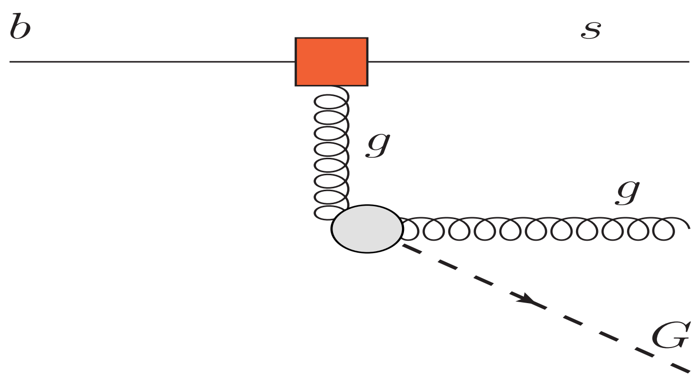


Figure 5: Glueball production in B meson weak decay (LHCb,Belle-II,BaBar)

X. G. He and T. C. Yuan, "Glueball Production via Gluonic Penguin B Decays," Eur. Phys. J. C **75**, no. 3, 136 (2015)

Scalar Glueball Candidates:

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

Pseudoscalar Glueball Candidates:

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

Tensor Glueball Candidate:

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

Problems with interpretation:

- Possible mixing with $\bar{q}q$ and $\bar{q}^2q^2$states
- Many states with the same quantum numbers above $M \approx 1GeV$.

Glueballs with exotic quantum numbers (three-gluon bound states-oddballs)

$$J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$$

Production and decays modes of exotic glueballs were discussed in L. Bellantuono, P. Colangelo and F. Giannuzzi, "Holographic Oddballs," JHEP **1510**, 137 (2015) and
D. Parganlija, "Glueballs and vector mesons at NICA," arXiv:1601.05328 [hep-ph]

Problem: The calculation of the masses and decay modes within QCD is very difficult task. The Lattice calculation gives very large mass for exotic glueballs, for example, for 0^{--}, they obtain $M_G = 5166 \pm 1000$ MeV Gregory et al JHEP, v.1210 (2012),170

The fist attempt to calculate masses of oddballs within QCD sum rules was done in C. F. Qiao and L. Tang,"Finding the 0^{--} Glueball," Phys. Rev. Lett. **113**, no. 22, 221601 (2014) and in "Mass Spectra of 0^{+-}, 1^{-+}, and 2^{+-} Exotic Glueballs," Nucl. Phys. B **904**, 282 (2016).

Recalculation exotic glueball masses within QCD sum rule is in progress (N.K. A.Pimikov, Pengming Zhang, Hee-Jung Lee)

- Experiments: BESIII, JLab, COMPASS, PANDA,BELLE-II, BaBar,RHIC, LHCb

Signature for glueballs

• Large branching to decay to mesons with strangeness, for example $0^{++} \to K\bar{K}$.

• Large branching to decay to η and η', for example, $0^{++} \to \eta\eta$ and $0^{-+} \to \eta'\sigma$.

• Weak coupling to $\gamma\gamma$ (determined by glueball-quarkonia mixing) .

• Perturbative coupling to the heavy quarks. Clear signal in the radiative decays of heavy quarkonia

Mixing between glueballs and quarkonia

There are many approaches to include effects of mixing to glueball spectroscopy. For example in 0^{++}, to consider $f_0(1370), f_0(1500), f(1710)$ as admixture of quark-antiquark octet-singlet states with glueball (see Hai-Yang Cheng et al arXiv:15.03.0682, Giacosa et al Phys.Rev., D72 (2005) 094006 etc).

In pseudoscalar channel 0^{-+} the possible mixing is between states η, η' and glueball. For heavy pseudoscalar glueball $M_G \approx 2.6$ GeV (quenched lattice QCD result) the possible large mixing with $\eta_c(2983)$ state (Kochelev and Dong-Pil Min Phys. Rev. D **72** (2005) 097502)

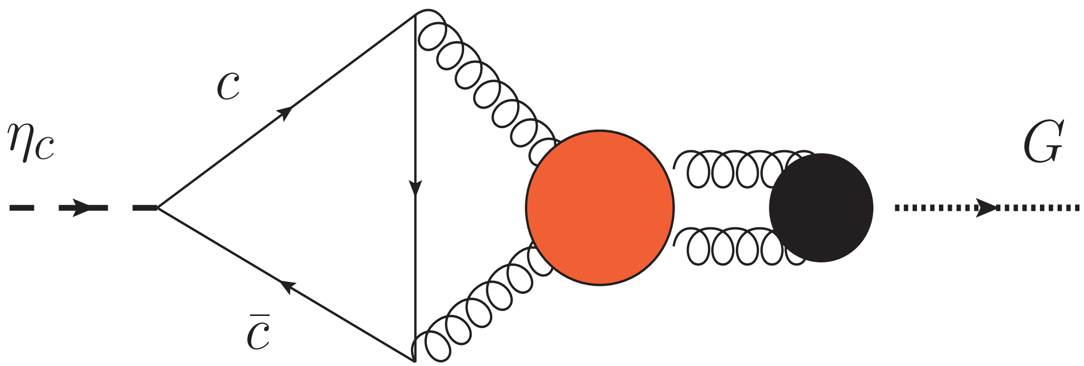


Figure 6: The $\eta_c - 0^{-+}$ glueball mixing induced by instantons

Glueballs in the hot quark-gluon plasma

• **Experiments at RHIC and LHC discovered a new type of nuclear matter- strongly interacted quark-gluon plasma (QGP)**!

• **It looks like as some liquid and does not have expected gas-like behavior.**

• **It is very important from point of view of theory of strong interaction to find the reason for such behavior (glueballs, instantons,monopoles etc.) Fundamental reason is also to understand the role of nonperturbative structure of strong interaction in evolution of our Universe, structure of stars etc.**

New experiments on QGP properties are planed at NICA (Dubna) , FAIR (Darmstadt), RHIC(Brookhaven) and LHC (CERN)

Glueballs production in high energy collisions

The early stage of high multiplicity pp, pA and AA collisions is represented by a nearly quarkless, hot and pure gluon plasma. It should be abundant production of glueballs in such events.

V. Vento,
"Glueball enhancement by color de-confinement," Phys. Rev. D **75**, 055012 (2007)

H. Stoecker *et al.*,
"Glueballs amass at RHIC and LHC Colliders! - The early quarkless 1st order phase transition at $T = 270$ MeV
- from pure Yang-Mills glue plasma to GlueBall-Hagedorn states," J. Phys. G **43**, no. 1, 015105 (2016)

Three phases of gluon matter

N.K. EPJA (2016) **52**:186

- Recent lattice calculation of so-called interaction measure (trace anomaly gives the information about deviation from noninteracted, massless gas of particles) $\Delta(T) = (\epsilon - 3p)/T^4$ discovered its very spectacular behavior above $T_c \approx 270$ MeV . More precisely, just above T_c the trace anomaly grows rapidly up to $T_G \approx 1.1 T_c$ and then it decreases as $I/T^4 \sim 1/T^2$ up to $T \approx 5T_c$.

Idea is to relate such unusual behavior to the strong changing of the glueball masses above T_c

Our 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 (J. R. Ellis and J. Lanik, Phys. Lett. B **150** (1985) 289.)

$$m_G^2 f_G^2 = \frac{11N_c}{6} < 0|\frac{\alpha_s}{\pi} G^a_{\mu\nu} G^a_{\mu\nu}|0 >, \tag{1}$$

where f_G is the glueball coupling constant to gluons. Lattice calculations show that the gluon condensate decreases roughly by 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. The temperature behavior of the condensate at $T_G \geq T \geq T_c$ can be described by the equation

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

In the case of a temperature dependent boson mass in a hot plasma trace anomaly is (see, for example, P. Castorina, D. E. Miller and H. Satz, Eur. Phys. J. C **71** (2011) 1673)

$$\Delta(T) = \frac{N_G}{2\pi^2}\int_0^\infty dx \frac{x^2}{\sqrt{x^2+m(T)^2/T^2}(e^{\sqrt{x^2+m(T)^2/T^2}}-1)} \times \frac{m(T)^2}{T^2}\left[1-\frac{T}{m(T)}\frac{dm(T)}{dT}\right], \quad (2)$$

where $N_G = 2$ for two glueball states and the mass function for $T_G \geq T \geq T_c$ is given by

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

Possible dynamical reason for the decreasing of scalar and pseudoscalar glueball mass above T_c is strong attraction induced by instanton-antiinstanton molecules. (For quark-antiquark channel it was discussed in G. E. Brown, C. H. Lee, M. Rho and E. Shuryak, Nucl. Phys. A **740**, 171 (2004) due to rearrangement of instanton medium from random instantons to instanton-antiinstanton molecular phase above T_c E. M. Ilgenfritz and E. V. Shuryak, Nucl. Phys. B **319**, 511 (1989)).

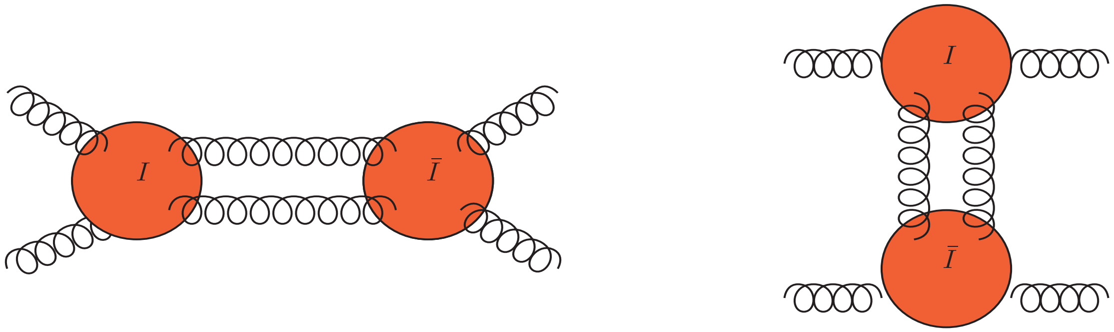


Figure 7: Gluon-gluon interaction induced by instanton-antiinstanton molecules.

Above T_G the massless glueballs can dissociate to massless gluons due to the process $G + G \rightarrow gluon + gluon$, therefore, at $T > T_G$ one should have a mixed glueball-gluon phase.

At very large temperature we have a free gluon gas and the contribution of glueballs to the pressure should be suppressed with respect to the free gluon case by a factor $(T_G/T)^\lambda$ with $\lambda > 0$. Based on the scaling in the trace anomaly $I(T)/T^4(T/T_c)^2$ observed in lattice calculation we use $\lambda = 2$. The pressure above T_G is the sum of glueball and gluon pressures

$$P(T)_{T>T_G} = \frac{N_G \pi^2}{90} T^4 \left(\frac{T_G}{T}\right)^2 + \frac{N_g \pi^2}{90} T^4 \left[1 - \left(\frac{T_G}{T}\right)^2\right],$$

where $N_g = 2(N_c^2 - 1) = 16$ is the number of the gluon degrees of freedom We obtain for the scale anomaly at $T > T_G$

$$\Delta(T) = \frac{(N_g - N_G)\pi^2}{45} \left(\frac{T_G}{T}\right)^2. \quad (3)$$

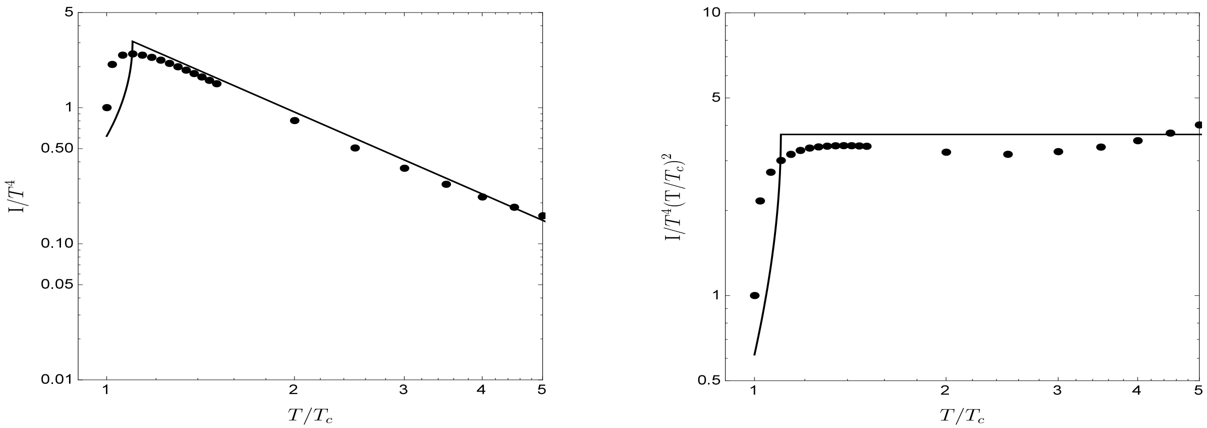


Figure 8: The trace anomaly $I(T)/T^4$ (left panel), and its scaling value $(I(T)/T^4)(T/T_c)^2$ (right panel) as the function of T/T_c. The lattice data presented by the bold spots.

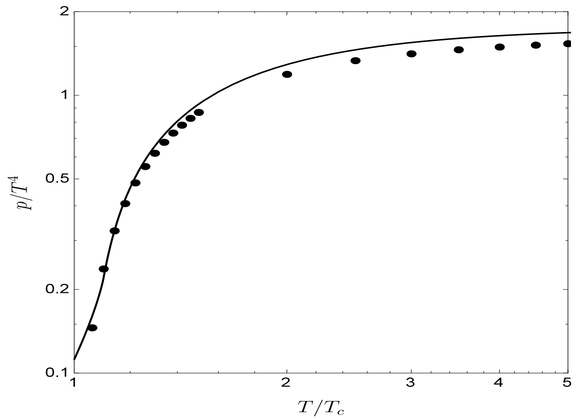


Figure 9: The pressure p/T^4 as the function of T/T_c compared with the lattice data.

In the pure Gluodynamics three different phases at finite T might exist

• In confinement regime, $T < T_c$., there is the gas of the massive glueballs

• Second phase is just above T_c at $T_G \geq T \geq T_c$, where $T_G \approx 1.1 T_c$. In this phase the main contribution to equation of state is coming from very light scalar and pseudoscalar glueballs.

• Above $T_G \approx 1.1 T_c$ there is a mixed phase of massless gluons and point-like scalar-pseudoscalar massless glueballs.

Signature of the light glueballs at NICA

The most promised candidates for scalar glueball are $f_0(500)$, $f_0(1500)$ and $f_0(1710)$ states. All of them have strong coupling to $\pi\pi$ channel. The task is for the looking of their mass changing in the $\pi\pi$ mass distribution in the large multiplicity events at NICA.

Tasks

• **Urgent task is the careful calculation of the temperature dependency of the masses of scalar and pseudoscalar glueballs in the Lattice.**

(In the paper N. Ishii, H. Suganuma and H. Matsufuru, "Glueball properties at finite temperature in SU(3) anisotropic lattice QCD," Phys. Rev. D 66, 094506 (2002)strong changing of glueball masses at $T < T_c$ was shown.)

• **Under investigation: Bose-Einstein Condensation of the glueballs in QGP and its influence to the properties of quark-gluon matter produced in heavy ion collisions; mixing between glueballs and quarkonia in QGP**

Conclusion

- **Glueball's properties are deeply related to the structure of QCD vacuum**

- Glueballs gives very important contribution to the EoS of the gluon plasma not only at $T < T_c$ but also at $T > T_c$.

- **The drastic changing of scalar and pseudoscalar glueball mass above deconfinement temperature might be the reason behind very unusual properties of Quark-Gluon Matter found at RHIC and LHC**

- **NICA can check the strong changing of the masses of glueballs above T_c in the events with the large multiplicity**

Thank you very much for your attention!