EXOTIC HADRONS

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Introduction

- Hidden and open exotica

- Ordinary hadrons: $q\bar{q}$ ($\pi^+ = (u\bar{d})$ etc.) or qqq systems ($p = (uud), \Delta^{++} = (uuu)$) etc.

- Constituent Quark Model predicts quantum numbers: for mesons $J^{PC} = 0^{-+}, 0^{++}, 1^{--}, 1^{++}$ etc.
for baryons: $J^P = (1/2)^+, (3/2)^+$ etc.

- Quark-gluon exotica: $q^n\bar{q}^m$ or $q^n\bar{q}^m G^k$ systems
Can have different quantum numbers in comparison with the ordinary hadrons.

Quark-quark, quark-gluon and gluon-gluon interactions in QCD

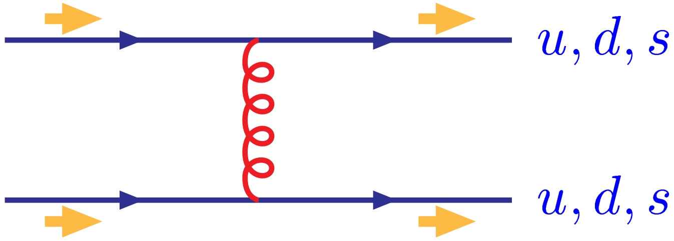
Confinement forces-long range interaction

$$V_{ij} = \sigma|r_{ij}|$$

or quarks and gluons inside the Bag with radius R

$$E_{conf} = \frac{4}{3}\pi R^3 B.$$

Quark-quark one-gluon exchange (OGE) -short range interaction



$$V^{OGE}_{q_i q_j} = \sum_{i,j} \frac{\lambda'}{m_i^* m_j^*} \lambda_i^a \lambda_j^a \vec{\sigma}_i \vec{\sigma}_j$$

Instanton induced forces-intermediate range interaction

QCD vacuum is not empty place. There are strong fluctuations of vacuum gluon fields, called instantons.

$$\boxed{A^a_\mu = \frac{2}{g_s}\eta_{a\mu\nu}\frac{(x-x_0)_\nu}{(x-x_0)^2+\rho^2}}$$

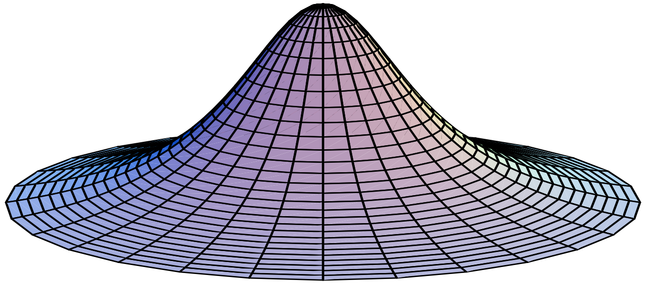
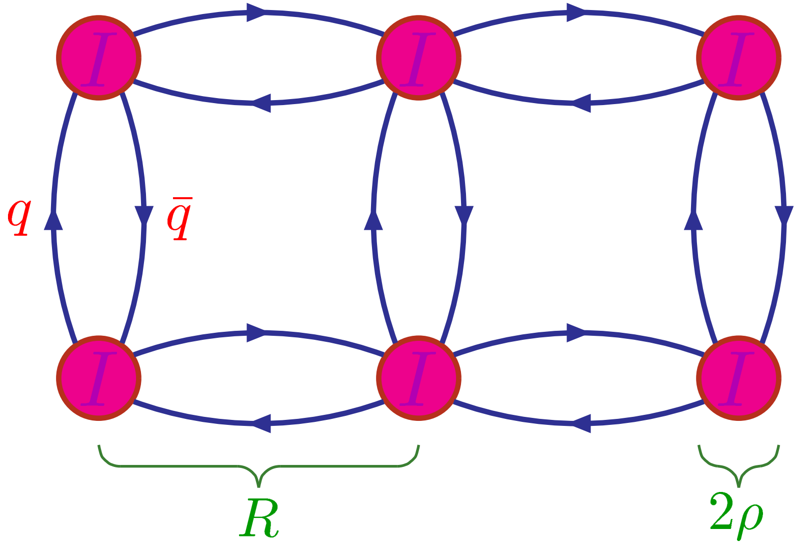


Figure 1: Instanton solution in QCD.

Instanton liquid model for QCD vacuum [Shuryak, Diakonov, Petrov ...]



One can introduce the "density" of instantons

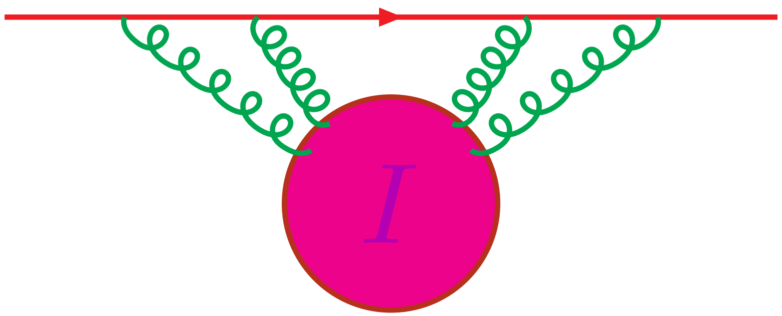
$$n_I(\rho) \sim exp\left(-\frac{2\pi}{\alpha_s(\rho)}\right)$$

R - distance between instantons
$\rho \approx$ 0.3 fm - instanton size

If $R >> \rho \rightarrow$ vacuum is a "gas" of instantons

If $R \approx 3\rho \rightarrow$ vacuum is an instanton "liquid"

Quarks in the instanton field



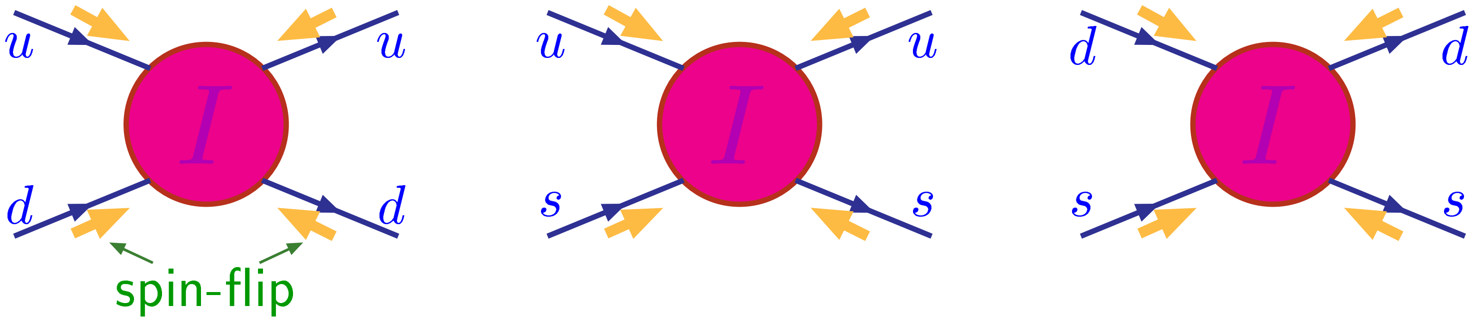
Dirac equation of motion

$$-\imath\gamma^{\mu}\mathcal{D}_{\mu}\psi_n = \lambda_n\psi_n$$

$$\mathcal{D}_{\mu} = \partial_{\mu} - \imath\frac{g_s}{2}A_{\mu}^{a}t_a$$

A_{μ}^{a} is the instanton field

Quark-quark instanton-induced interaction [t'Hooft, 1976]



$$V^{inst}_{q_i q_j} = \sum_{i \neq j} \frac{\lambda}{m_i^* m_j^*} \left\{ 1 + \frac{3}{32} \lambda_i^a \lambda_j^a \vec{\sigma}_i \vec{\sigma}_j \right\}$$

Features:

1) Non-zero only for different quark flavors

2) Quark spin-flip differs from the perturbative one gluon exchange

Multiquark interactions induced by instantons

For N_f=3, $q = u, d, s$ $\Rightarrow$ six-quark effective interaction induced by instantons

In $m_u = m_d = m_s \to 0$ limit

$$H_{t'Hooft} = \int d\rho n(\rho) \left(4\pi^2\rho^3\right)^3 \frac{1}{6N_C(N_C^2-1)} \varepsilon_{f_1f_2f_3}\varepsilon_{g_1g_2g_3} \times$$

$$\times \left\{ \frac{2N_C+1}{2N_C+4} \bar{q}_R^{f_1} q_L^{g_1} \bar{q}_R^{f_2} q_L^{g_2} \bar{q}_R^{f_3} q_L^{g_3} + \right.$$

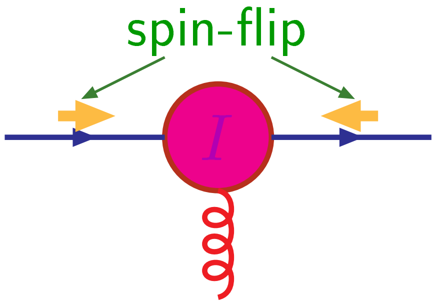
$\frac{1}{N_C}$correction

$$\left. + \frac{3}{8(N_C+2)} \bar{q}_R^{f_1} q_L^{g_1} \bar{q}_R^{f_2} \sigma_{\mu\nu} q_L^{g_2} \bar{q}_R^{f_3} \sigma_{\mu\nu} q_L^{g_3} + (R \leftrightarrow L) \right\}$$

Very important in some processes: $K \to \pi\pi$ decays, $\Delta I = 1/2$ rule, CP violation, etc ..

Quark-gluon interactions induced by instantons

Anomalous quark-gluon chromomagnetic moment [N.K. Phys.Lett.**B426** (1998) 149], D.Diakonov Prog. Par. Nucl. Phys. **51** (2003) 173

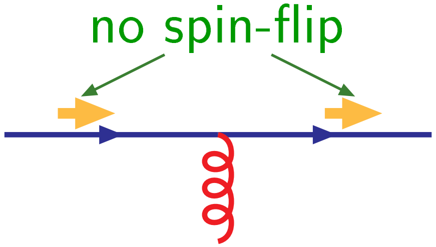


$$\Delta\mathcal{L} = -\imath\mu_a \frac{g_s}{2m_q^*}\bar{q}\sigma_{\mu\nu}t^a q G^a_{\mu\nu}$$

Within Instanton Liquid Model

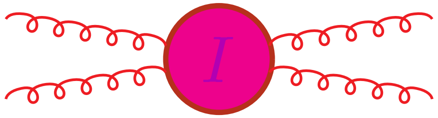
$$\mu_a = -\frac{3\pi(m_q^*\rho_c)^2}{4\alpha_s(\rho_c)} \approx -1.$$

is large at $\alpha_s(\rho_c) \approx 0.5$.



pQCD quark-gluon vertex

$$\Delta\mathcal{L} = g_s \bar{q}\gamma_\mu t^a q A^a_\mu$$



Four-gluon vertex induced by instantons which contributes to the glueball masses

Multiquark hadrons

- Constituent quark model with one-gluon exchange (OGE) (Isgur etc.):
problems: too large spin-orbital splitting, too small η' mass ($U(1)_A$ problem)

- Bag model with OGE(Bogoliubov, Jaffe etc).
problem: $\alpha_s \approx 2$ and $B_{MIT} \approx 1/10 B_{QCD}$

- Constituent quark model with one-pion exchange (Glozman, Riska)
problem: description of mesons: too large $\rho - \omega$ splitting etc.

- Chiral and soliton models (Brown, Rho, Diakonov, Petrov etc.)
problem: mesons

Instanton effects in ground hadron states

Bag model estimations of instanton effects in usual hadrons: N.K. (1985), N.K. and A.Dorokhov (1985-1990). Instanton effects in constituent quark model: Shuryak and Rosner (1989); Petry et al (1990).

In simple constituent quark model mass formula is

$$M_h = E_{conf} + \sum_i N_i m_i + E_{I2} + E_{OGE},$$

where N_i is number of the quarks with flavor i in the state, E_{conf} is confinement (bag energy).

Four-, five- and six- quark hadrons

R.L. Jaffe (1978) predicted many exotic $q^2\bar{q}^2$ exotic hadronic states within MIT bag model with pQCD one-gluon exchange

D. Strottman (1979) five-quark multiquark states within MIT bag

N.K.,A. Dorokhov and Yu.Zubov (1989) $q^2\bar{q}^2$ state within bag model with instanton interaction

N.K.,A. Dorokhov (1986) six-quark $udsuds$ H-$(\Lambda\Lambda)$ dihyperon instanton induced stable state

S.B.Gerasimov (1992) nonstrange dibaryon with small width.

Most multiquarks should have very large widths.

But there is light exotic baryon antidecuplet (D. Diakonov, V. Petrov and M. Polyakov, (1997))

which includes Θ^+ state with very small width, smaller then 15 MeV,

and its minimal quark content is $udud\bar{s}$

Predicted mass was $M_\Theta = 1530$ MeV

Constituent model explanations with quark correlatons:

Jaffe and Wilczek model based on diquark correlations

Karliner and Lipkin (2003) triquark-diquark model based on one-gluon exchange induced $ud\bar{s}$ and ud clustering

Θ^+-pentaquark - $(ud\bar{s})(ud) \to$ bound state

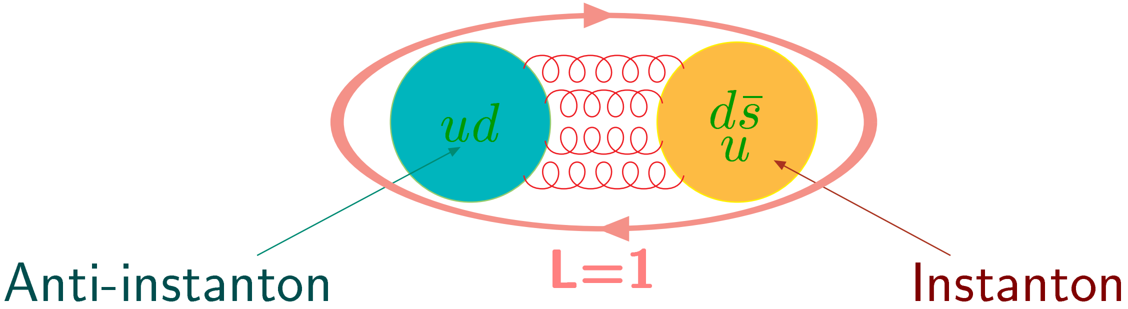
N.I.K., H.-J. Lee, V.Vento, Phys. Lett. B594 (2004) 87

Instantons produce specific flavor- and spin-dependent interactions

$\Rightarrow$ very light $(ud\bar{s})$ triquark, $m_{3q} = 750$ MeV

$\Rightarrow$ very light (ud) diquark, $m_{2q} = 440$ MeV

Picture of the pentaquark in instanton triquark-diquark model



Full QCD sum rule analysis of the pentaquark

H.-J. Lee, N.I.K., V.Vento, Phys. Rev. D73 (2006) 014010

Correlator:

$$\Pi(q^2) = i \int d^4x \; e^{iq\cdot x} \langle 0|T\eta_\Theta(x)\bar{\eta}_\Theta(0)|0\rangle = \hat{q}\Pi_1(q^2) + \Pi_2(q^2)$$

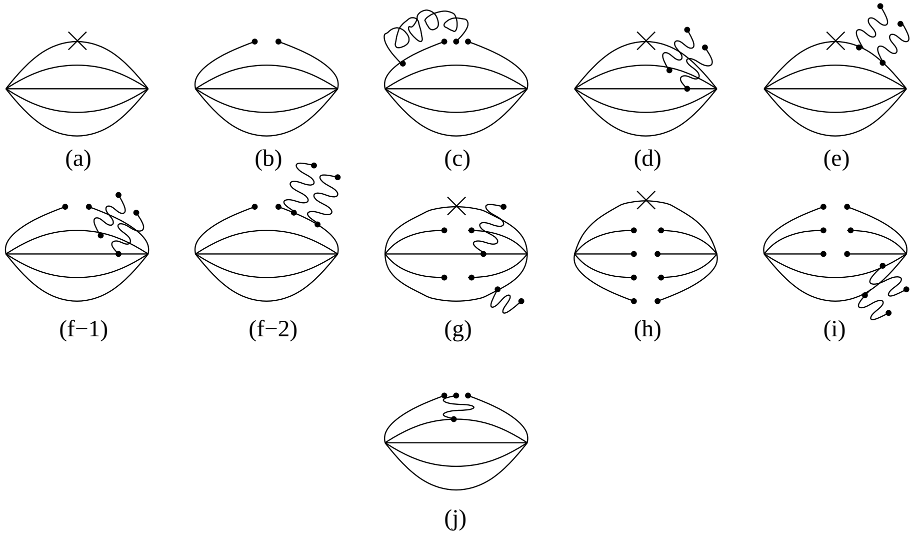


Figure 2: Diagrams contributing to the chirality odd pentaquark sum rule in our calculation up to dimension $d = 13$ operators.

Our result for the Θ^+ pentaquark mass was larger than what was given by soliton model:

$$M_{\Theta^+} \approx 1.75 GeV$$

Parity of pentaquark is positive in agreement with soliton model prediction but signal for bound state was weak and rather sensitive to the parameters of QCD vacuum (value of vacuum condensates, instanton size etc.)

Experimental situation around pentaquarks is very controversial (usually statistics in experiment is small, production cross-section is difficult to estimate etc.)

For example, the most famous experimental peak for Θ^+ pentaquark production at LEPS (Japan) might explain by rescattering and experimental cuts effects:
A. M. Torres and E. Oset, "Study of the $\gamma d \to K^+ K^- np$ reaction and an alternative explanation for the '$\Theta^+(1540)$ pentaquark' peak," Phys. Rev. C **81** (2010) 055202.

Recent Evidence for nonstrange pentaquark : V. Kuznetsov *et al.*, "Evidence for Narrow N*(1685) Resonance in Quasifree Compton Scattering on the Neutron," arXiv:1003.4585 [hep-ex].

Tetraquarks-$q^2\bar{q}^2$ mesons

- Origin of $J^{PC}=0^{++}$ $\sigma(f_0(600))$, $f_0(980)$, $a_0(980)$ mesons-$q\bar{q}$ or $q^2\bar{q}^2$ mesons?
(Jaffe,Achasov, Maiani, Volkov with collaborators)

- H. J. Lee and N. I. K., "Instanton interpolating current for sigma-tetraquark," Phys. Lett. B **642**, 358 (2006).

- Within QCD sum rule approach the chirality structure of tetraquark interpolating current is very important:

$$J^\sigma = aJ_S^\sigma + bJ_{PS}^\sigma \tag{1}$$

where

$$\begin{aligned} J_S^\sigma &\sim (u_R C d_R - u_L C d_L)(\bar{u}_R C \bar{d}_R - \bar{u}_L C \bar{d}_L)\ , \\ J_{PS}^\sigma &\sim (u_R C d_R + u_L C d_L)(\bar{u}_R C \bar{d}_R + \bar{u}_L C \bar{d}_L). \end{aligned}$$

scalar and pseudoscalar diquark components of tetraquark.

- Good stability of the QCD sum rules for tetraquark with interpolating current with maximum and minimum chirality $a = \pm b$.
  The mass of $f_0 \approx 780$ MeV

- The $\sigma(f_0(600))$ and $f_0(980)$ couple strongly to the current with different chirality structure ($a = b$ and $a = -b$) and with the same flavor structure?

- Instanton induced mixing between $q\bar{q}$ with $q^2\bar{q}^2$ mesons:
  G. '. Hooft, et al (2008).

XYZ mesons-hidden exotics candidates in charm sector

Result of BELLE experiment (B-factory KEK,Japan) Narrow resonance X(3872), $J^{PC} = 1^{++}$ with decays $J/\Psi\pi^+\pi^-$, $J/\Psi\rho$, $J/\Psi\omega$, $\Gamma < 2.3$ MeV!!!

- Many anothers anomalous XYZ States Charmonium like states with small widths were observed by Bella, CDF, D0, BaBar, BESII Collaborations

Hybrids

Quark-antiquark-gluon states can have exotic quantum numbers:
$J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$ etc.

- Hybrid Candidates-Open exotics

$\pi_1(1400)$ with $J^{PC} = 1^{-+}$
Experiments: E852, VES, Crystal Barrel
M. Alekseev *et al.* [COMPASS Collaboration], "Observation of a $J^{PC} = 1^{-+}$ exotic resonance in diffractive dissociation of 190 GeV/c pi- into pi- pi- pi+," arXiv:0910.5842 [hep-ex].

Glueballs

- Recent review: V. Mathieu, N. Kochelev and V. Vento, “The Physics of Glueballs,” Int. J. Mod. Phys. E **18** (2009) 1

- Glueballs in MIT bag Model: two gluon states

R.L.Jaffe and K. Johnson(1976)

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

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

Kaidalov and Simonov (2000);Anisovich et. al(2006),V. Mathieu, F. Buisseret,C. Semay,B. Silvestre-Brac, F.Brau (2006-2008).
are in general agreement with lattice results

- But some models:

Vento (2006), Ochs and Minkowski (2004-2008) 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 (1998); H.Forkel.

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

- Lattice Results for Glueballs

C. J. Morningstar and M. J. Peardon, (1997); Y.Chen et al,(2006) .

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

Experiment

Scalar Glueball Candidates:

$$f_0(1500), \quad f_0(1710), \quad f_0(1790)$$

Pseudoscalar Glueball Candidates:

$$\eta(1440), \quad X(1835)$$

Tensor Glueball Candidate:

$$f_2(2000)$$

Problems with interpretation:

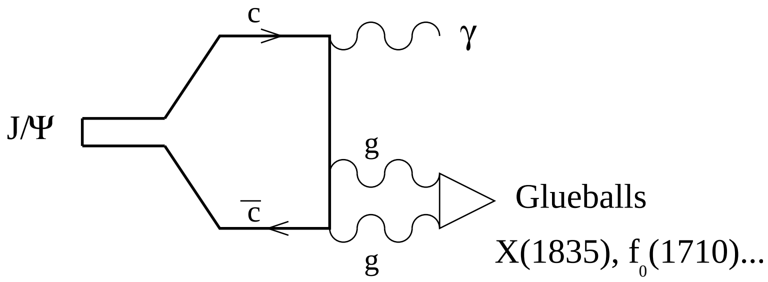
- Large widths
- Mixing with $\bar{q}q$ states
- Overlapping many states with the same quantum numbers-large density of states above $\approx 1.5GeV$.

BES's (Beijing Spectrometer, China) pseudoscalar glueball candidate

"X(1835) as the Lowest Mass Pseudoscalar Glueball and Proton Spin Problem"

N.K. and Dong-Pil Min Phys.Lett.B633(2006)283

BES (Beijing Spectrometer) Collaboration at the Beijing Electron-Positron Collider in China found resonance X(1835) in the reactions $J/\Psi \to \gamma p\bar{p}$ and $J/\Psi \to \gamma\eta'\pi^+\pi^-$.



Glueball production at BES spectrometer

Features: Strong coupling with η' which has large coupling to gluons and strong coupling of X(1835) with proton-antiproton channel.

Our suggestion was to consider this state as lowest mass of pseudoscalar glueball

Arguments:

- Parity doublet structure for hadron resonances: mass of pseudoscalar glueball should be approximately equal to mass of scalar glueball candidate $f_0(1710)$.

- Large coupling glueball X(1835) to proton can be related to the contribution of gluons to proton spin.

- Instanton model for QCD vacuum can provide microscopical model for explanation of parity doublet structure in hadron spectrum and large value of pseudoscalar glueball coupling to proton state.

- The deviation from lattice QCD prediction for lowest pseudoscalar glueball mass ($\approx 2.6GeV$) can be explained by mixing of glueball with quarkonium η_c

Role of Glueballs in Quark-Gluon Plasma

N. K. and Dong-Pil Min, Phys. Lett. B **650** (2007) 239; Phys. Rev. C **77** (2008) 014901

- **Experiments at BROOKHAVEN Relativistic Heavy Ion Collider (RHIC) with nucleus-nucleus collisions at very high energy (up to 200 GeV/Nucleon $\otimes$ 200 GeV/Nucleon) have discovered a new type of nuclear matter-STRONGLY INTERACTED QUARK-GLUON PLASMA at temperature above $T_c \approx 170 MeV$ (correspond to $10^{12} K$).**

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

- **New experiments for investigation of Quark-Gluon Plasma properties are planning at Large Hadron Collider (LHC) CERN, FAIR (Darmstadt, Germany) and NICA (JINR, Dubna).**

- **Enhancement of glueball production in QGP due to a large density of produced gluons.**

- **It was shown (N.K. and Dong-Pil Min) that masses of scalar and**

pseudoscalar glueballs are small above deconfinement temperature and these particles can play the role similar to the role of the pion in nuclear matter.

CONCLUSION

- **Vacuum fluctuation of gluon fields induce very strong correlations in space-time and color-spin-flavor spaces between quarks and gluons. It provides a important role of QCD vacuum structure in usual and in exotic hadrons.**

- **Glueballs may play very important role in Quark-Gluon plasma dynamics near T_c.**