

Exotica possibility of new observations by BES

Ailin-Zhang

Department of Physics, Shanghai University, China

October 10, 2007

Incompleteness of existed studies of four-quark state and glueball with QCD sum rule approach is analyzed. The masses of the lowest lying scalar and pseudo-scalar glueball were determined with sum rules. The masses of some four-quark states and their first orbital excitations were attempted to be obtained through a combination of the sum rule with the constituent quark model. Exotica possibility of the new observations by BES is discussed.

Outline

- QCD sum rules and exotic states
- 0^{++} and 0^{-+} glueballs
- 0^{++} and 1^{--} tetraquark states
- Exotica possibility of the new observations by BES
- Conclusions and discussions

QCD sum rules and exotic states

♠ QCD (SVZ) sum rules

M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, Nucl. Phys. B147, 385 (1979)

Nonperturbative method of relating fundamental parameters of QCD Lagrangian and vacuum to parameters of hadrons

QCD & Vacuum *sum rule* Hadron

- Correlator

$$i \int d^4x e^{iqx} \langle 0 | T(j_\Gamma(x) j_\Gamma^\dagger(0)) | 0 \rangle \quad (1)$$

$j_\Gamma(x)$: interpolating current(local operator)

- Dispersion relation

$$\Pi_P(q^2) = \frac{1}{\pi} \int ds \frac{\text{Im} \Pi(s)}{s - q^2 - i\epsilon} \quad (2)$$

- OPE(Operator Product Expansion)

$$i \int d^4x e^{iqx} T(j_\Gamma(x) j_\Gamma^\dagger(0)) = \sum_n C_n^\Gamma(q^2) O_n \quad (3)$$

Hard (coefficients)+soft (condensates)

fundamental parameters of QCD Lagrangian (coefficients)+unive
parameters of vacuum (condensates)

- Spectral density

$Im\Pi(s) \sim$ bound state (or resonance)+continuum

Duality relation: $Im\Pi(s) = Im\Pi^{QCD}(s), s > s_0$ (threshold)

- Borel transformation

- ♠ Interpolating currents (Local operators)

To detect the properties of hadrons, suitable interpolating currents corresponding to the hadrons are employed

Can local operators detect internal structures in exotic hadrons?

- ♠ Exotic states

Normal hadron: $q\bar{q}$ Meson; qqq Baryon

Glueball: GG , GGG ...

Multi-quark state: $(q\bar{q})(q\bar{q})$, $(qq)(\bar{q}\bar{q})$, H , dibaryon, ...

Hybrid: $q\bar{q}g$

0^{++} and 0^{-+} glueballs

♠ 0^{++} glueball

The existence of glueball was first mentioned by Fritzsche and Gell-Mann

V.A. Novikov, M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, Nucl. Phys. **B165**, 67 (1980)

$$j_s = \alpha_s G_{\mu\nu}^a G_{\mu\nu}^a \quad (4)$$

$$m_\sigma = 700 \text{ MeV}$$

S. Narison, Nucl. Phys. **B509**, 312 (1998)

$$m = 1.5 \pm 0.2 \text{ GeV}$$

Tao Huang, Hong-Ying Jin and Ailin Zhang, Phys. Rev. **D59**, 034026 (1999)

Moment, $m = 1.7 \text{ GeV}$

D. Harnett and Tom Steele, Nucl. Phys. **A695**, 205 (2001)

Gaussian sum rule, Instanton, Double resonance model

Heavier: $m = 1.4 \text{ GeV}$; Lighter: $M \approx 1.0 - 1.25 \text{ GeV}$

H. Forkel, Phys. Rev. **D71**, 054008 (2005)

Instantons,

$$m = 1.25 \pm 0.2 \text{ GeV}$$

♠ 0^{-+} glueball

V.A. Novikov, M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, Nucl. Phys. **B191**, 301 (1981)

$$j_{ps} = \alpha_s G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a \quad (5)$$

$$m = 2 - 2.5 \text{ GeV}$$

S. Narison, Nucl. Phys. **B509**, 312 (1998)

$$m = 2.05 \pm 0.19 \text{ GeV}$$

Ailin Zhang and Tom Steele, Nucl. Phys. A728, 165 (2003)

Gaussian sum rule, Higher-loop perturbative contributions,
Instantons

$$m = 2.65 \pm 0.33 \text{ GeV}, \Gamma < 530 \text{ MeV}$$

H. Forkel, Phys. Rev. **D71**, 054008 (2005)

Instanton, Topological charge screening effect

$$m = 2.2 \pm 0.2 \text{ GeV}$$

♠ three gluons glueballs

0^{++} scalar

J.I. Latorre, S. Narison and S. Paban, Phys. Lett. **B191**, 437 (1987)

S. Narison, Nucl. Phys. **B509**, 312 (1998)

$$j_{s3g} = g^3 f_{abc} G_{\mu\nu}^a G_{\nu\rho}^b G_{\rho\mu}^c \quad (6)$$

$$M_{s3g} = 3.1 \text{ GeV}$$

0^{-+} pseudoscalar

Gang Hao, Cong-Feng Qiao and Ailin Zhang, Phys. Lett. **B642**, 53 (2006)

$$j_{ps3g} = g^3 f_{abc} \tilde{G}_{\mu\nu}^a \tilde{G}_{\nu\rho}^b \tilde{G}_{\rho\mu}^c \quad (7)$$

$$M_{ps3g} = 1.9 - 2.7 \text{ GeV}$$

Two gluons glueballs will mix with three gluons glueballs!

Problems:

- ♣ Can these currents detect the corresponding glueballs?
- ♣ How to deal with the mixing effect?

0^{++} and 1^{--} tetraquark states

♠ References

Hadron scattering amplitudes: four-quark state
J.L. Rosner, Phys. Rev. Lett. **21**, 950 (1968)

- MIT bag model: $(Q^2)(\bar{Q}^2)$

spectrum, decays

R.L. Jaffe, Phys. Rev. **D15**, 267 (1977); **D15**, 281 (1977)

- Color junction model: $qq\bar{q}\bar{q}$

spectrum, decay

Hong-Mo Chan and H. Högaasen, Phys. Lett. **B72**, 121 (1977)

- Potential model: $qq\bar{q}\bar{q}$

J. Weinstein and N. Isgur, Phys. Rev. Lett, **48**, 659; Phys.Rev. **D27**, 588 (1983)

J. Weinstein and N. Isgur, Phys.Rev. **D41**, 2236 (1990)

N.A. Törnqvist, Phys. Rev. Lett, **67**, 556 (1991)(deuteron-like meson-meson states, one-pion exchange)

L.Y. Glozman and D. O. Riska, Phys. Rept, **268**, 263 (1996)
(pseudoscalar mesons ($SU(3)_F$ octet) exchange interaction)

- Effective Lagrangian:

D. Black, A.H. Fariborz, J. Schechter, Phys. Rev. **D59**, 074026 (1999)

- Relativistic quark model:

D. Ebert, R.N. Faustov, V.O. Galkin, Phys. Lett. **B634**, 214 (2006)

- QCD sum rules:

Ailin Zhang, Phys. Rev. **D61**, 114021 (2000)

Thomas Schafer, Phys. Rev. **D68**, 114017 (2003)

M.E. Bracco, A. Lozea, R.D. Matheus, *et al.*, Phys. Lett. **B624**, 217 (2005)

Hungchong Kim and Yongseok Oh, Phys. Rev. **D72**, 074012 (2005)

Hua-Xing Chen, A. Hosaka and Shi-Lin Zhu, Phys. Rev. **D74**, 054001 (2006)

Ailin Zhang, Tao Huang and Tom. Steele, Phys. Rev. **D76** , 036004 (2007)

- Other works:

N.N. Achasov, S.A. Devyanin and G.N. Shestakov, Phys. Lett. **B108**, 134 (1982);

N.N. Achasov and V.N. Ivanchenko, Nucl. Phys. **B315**, 465 (1989);

J.R. Pelaez, Phys. Rev. Lett. **92**, 102001 (2004);

L. Maiani, F. Piccinini, A.D. Polosa and V. Riquer, Phys. Rev. Lett. **19**, 212002 (2004); Phys. Rev. **D71**, 014028 (2005);

I.V. Anikin, B. Pire and O.V. Teryaev, Phys. Lett. **B626**, 86 (2005);

D.Melikhov and B. Stech, Phys. Rev. **D74**, 034022 (2006)

- Review:

S. Godfrey and J. Napolitano, Rev. Mod. Phys. **71**, 1411 (1999)

C. Amsler and N.A. Törnqvist, Phys. Rept. **389**, 61 (2004)

D. V. Bugg, Phys. Rept. **397**, 257 (2004)

R.L. Jaffe, Phys. Rept. **409**, 1 (2005)

E. Klempt, A. Zaitsev, arXiv:0708.4016 [hep-ph]

♠ Four-quark states

Four-quark state: consists of four quarks and anti-quarks

Intrinsic quarks/anti-quarks may make clusters

Spacial extension of clusters:

$$(qq)(\bar{q}\bar{q}), \quad (q\bar{q})(q\bar{q})$$

♣ $(qq)(\bar{q}\bar{q})$ (tetraquark state, baryonium)

Diquark qq cluster: strong correlation between pairs of quarks

The diquark correlation may be most important for the light multi-quark states

Color, Flavor, Spin, et al

♣ $(q\bar{q})(q\bar{q})$ (Molecule state, Color $8 \otimes 8$ $(q\bar{q})(q\bar{q})$ state)

Color, Flavor, Spin, et al

♣ Mixing

The correlations of color, flavor, spin, *et al.* are inter-related (symmetry constraints)

Color singlet

Crypto-exotic states: Diquark $[qq]$ and anti-diquark $[\bar{q}\bar{q}]$ are in flavor $\bar{3}$ and 3 representation, respectively, and the tetraquark is in $SU(3)_F$ nonet: $3 \otimes \bar{3} = 8 + 1$; $(q\bar{q})(q\bar{q})$ may be in the same flavor representations

The Crypto-exotic four-quark state is in the same flavor representations as those in normal $q\bar{q}$ meson

◇ $(qq)(\bar{q}\bar{q})$ will mix with $(q\bar{q})(q\bar{q})$

◇ Flavor Crypto-exotic four-quark state will mix with $q\bar{q}$

$$|meson\rangle = |q\bar{q}\rangle + |(qq)(\bar{q}\bar{q})\rangle + |(q\bar{q})(q\bar{q})\rangle + \dots$$

Intrinsic color, flavor configurations could not be distinguished except that some special observable is established
Unfortunately, no such an observable has been definitely set up

♣ Quark dynamics

- Tetraquark state
- Molecule state
- Color 8×8 $(q\bar{q})(q\bar{q})$ state: ?

Not very clear!

♠ Interpolating currents

- $(q\bar{q})(q\bar{q})$

Ailin Zhang, Phys. Rev. **D61**, 114021 (2000): "Four-quark state in QCD"

- $(q\bar{q})^2, (qq)(\bar{q}\bar{q})$

Thomas Schafer, Phys. Rev. **D68**, 114017 (2003): "Instantons and scalar multiquark states: From small to large N_c "

- $(cq)(\bar{q}\bar{q})$

M.E. Bracco, A. Lozea, R.D. Matheus, F.S. Navarra, M. Nielsen, Phys. Lett. **B624**, 217 (2005): "Disentangling two- and four-quark state pictures of the charmed scalar mesons"

- $(cu)(\bar{s}\bar{u})$

Hungchong Kim and Yongseok Oh, Phys. Rev. **D72**, 074012 (2005): " $D_s(2317)$ as a four-quark state in QCD sum rules"

- $(ud)(\bar{s}\bar{s})$

Hua-Xing Chen, A. Hosaka and Shi-Lin Zhu, Phys. Rev. **D74**, 054001 (2006): "Exotic tetraquark $ud\bar{s}\bar{s}$ of $J^P = 0^+$ in the QCD sum rule"

♣ Leading order in perturbative contribution

♣ Structure in current (operator) picture \rightarrow Structure in constituent quark picture

♣ Diquark in operator picture \rightarrow Diquark in constituent quark picture

Problems:

♣ Fierz transformation (re-arrangement)

$$(qq)(\bar{q}\bar{q}) \rightarrow (q\bar{q})(q\bar{q})$$

$$\begin{aligned} j_{(dq)^2} = & \frac{1}{4} \{ (\bar{q}\gamma_5\bar{\tau}^a q)(\bar{q}\gamma_5\bar{\tau}^a q) + (\bar{q}\bar{\tau}^a q)(\bar{q}\bar{\tau}^a q) + (\bar{q}\gamma_\mu\bar{\tau}^a q)(\bar{q}\gamma_\mu\bar{\tau}^a q) \\ & + (\bar{q}\gamma_5\gamma_\mu\bar{\tau}^a q)(\bar{q}\gamma_5\gamma_\mu\bar{\tau}^a q) - \frac{1}{2}(\bar{q}\sigma_{\mu\nu}\bar{\tau}^a q)(\bar{q}\sigma_{\mu\nu}\bar{\tau}^a q) \} \end{aligned}$$

where $\bar{\tau}^a = (\vec{\tau}, i)$

♣ Renormalization group improvement

All these currents will mix with each other under the renormalization

Conclusions:

- In view of the sum rule approach, there is no definite difference among these currents. The internal constituent quark structures of multi-quark state can hardly be detected through the couplings of interpolating currents to hadrons
- In principle, there is no direct way to turn the operator picture into the constituent quark picture
- Diquark: meaningful in constituent quark picture; not meaningful in operator picture in the framework of QCD sum rules

◇ Prescriptions (?)

- Mixing

Interpolating currents: Mixing currents $((qq)(\bar{q}\bar{q}) + (q\bar{q})(q\bar{q}))$

Hadrons saturation: Mixture of hadrons

- Constituents

Diquark: SVZ sum rule

Four-quark state: Constituent quark model

♠ Diquark and SVZ sum rule

The diquark picture was applied to weak hadron decays and was postulated to be computed reliably with SVZ sum rules

H.G. Dosch, M. Jamin and B. Stech, Z. Phys. **C42**, 167 (1989); M. Jamin and M. Neubert, Phys. Lett. **B238**, 387 (1990)

The diquark current with flavor (sq)

$$j_i(x) = \epsilon_{ijk} s_j^T(x) C O q_k(x) \quad (8)$$

An updated analysis was performed
Ailin Zhang, Tao Huang and Tom Steele, Phys. Rev. **D76**,
036004 (2007)

The most "suitable" masses of diquark m_{qq} and m_{sq} :

$$m_{qq} \sim 400 \text{ MeV}, \quad s_0 = 1.2 \text{ GeV}^2$$

$$m_{sq} \sim 460 \text{ MeV}, \quad s_0 = 1.2 \text{ GeV}^2$$

The mass scale of diquark is the same as that of the constituent quark

The results obtained here are consistent with the fit of L. Maiani, F. Piccinini, A.D. Polosa, V. Riquer (Phys. Rev. **D71**, 014028 (2005))

$$m_{[ud]} = 395 \text{ MeV}, \quad m_{[sq]} = 590 \text{ MeV}$$

The diquark masses may be determined with QCD sum rule

The mass determined by sum rules may be regarded as the constituent diquark masses(?)

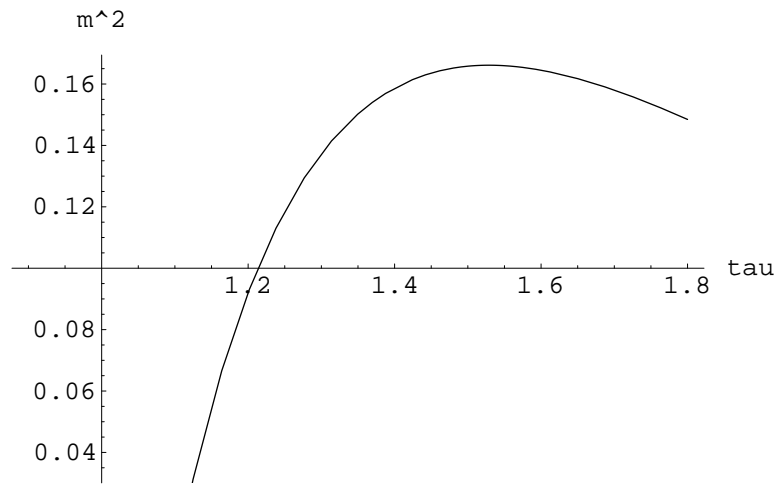


Fig. 1: τ dependence of m^2_{0+} for qq good diquark with $s_0 = 1.2 \text{ GeV}^2$.

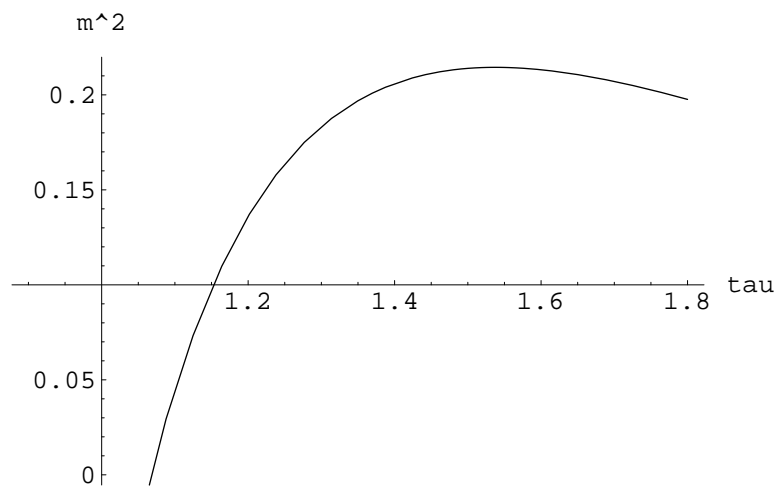


Fig. 2: τ dependence of m_{0+}^2 for sq good diquark with $s_0 = 1.2 \text{ GeV}^2$.

♠ Light tetraquark state

$[qq][\bar{q}\bar{q}]$ (L. Maiani L, Piccinini F, Polosa A.D, Riquer V. Phys. Rev. Lett. **93**, 212002 (2004))

Mass of the $L = 0$ tetraquark state:

$$M \approx 2m_{[qq]} - 3(\kappa_{qq})_{\bar{3}}$$

$$(\kappa_{qq})_{\bar{3}} = 103 \text{ MeV}, (\kappa_{sq})_{\bar{3}} = 64 \text{ MeV}$$

Mass of the $L = 1$ excited tetraquark state:

$$M \approx 2m_{[qq]} - 3(\kappa_{qq})_{\bar{3}} + B'_q \frac{L(L+1)}{2}$$

m_{qq} : constituent diquark mass

L : the orbital angular momentum between the diquark and the anti-diquark

$$B'_q = \left[\frac{\alpha_s(m_{qq}^2)}{\alpha_s(m_q^2)} \right]^2 \frac{m_{qq}}{m_q} B_q, \quad B_q = 0.495 \text{ GeV}$$

B'_q are very sensitive to Λ

Neutral tetraquark states consist of "good" diquark: the P-parity and the C-parity are the same $(-1)^L$

Possible J^{PC} of neutral tetraquark state: 0^{++} ($L = 0$), 1^{--} ($L = 1$), 2^{++} ($L = 2$), \dots

The constituent diquark mass is approximately regarded as the mass determined by QCD sum rules

Our results:

$$0^{++} [qq][\bar{q}\bar{q}] : \sim 490 \text{ MeV}$$

$$0^{++} [sq][\bar{q}\bar{q}] : \sim 610 \text{ MeV}$$

$$0^{++} [sq][\bar{s}\bar{q}] : \sim 730 \text{ MeV}$$

$$1^{--} [qq][\bar{q}\bar{q}] : \sim 490 + B'_q \text{ MeV}$$

$$1^{--} [sq][\bar{q}\bar{q}] : \sim 610 + B'_q \text{ MeV}$$

$$1^{--} [sq][\bar{s}\bar{q}] : \sim 730 + B'_s \text{ MeV}$$

Flavor dependence is explicit!

Improvement(?): Coulombic + linear confinement

It is reasonable to identify $f_0(600)$ (or σ), $f_0(980)$, $a_0(980)$ and the unconfirmed $\kappa(800)$ as the 0^{++} light tetraquark states

Exotica possibility of the new observations by BES

♠ Recent observations by BES (BESII detector: 58 million events sample of J/Ψ decays)

- $p\bar{p}$ enhancement was observed by BES in the radiative decay (Phys. Rev. Lett. **91**, 022001 (2003)); PDG

$$J/\Psi \rightarrow \gamma p\bar{p}$$

with $M = 1859_{-10}^{+3}(\text{stat})_{-25}^{+5}(\text{sys})$ (below $2m_p$) and $\Gamma < 30$ MeV if interpreted as a single 0^{-+} resonance

$C = +1$, Consistent with either $J^{PC} = 0^{-+}$ or 0^{++} quantum number assignment

Belle (M.-Z. Wang *et al.*, Phys. Lett. **B617**: 141 (2005))

$$B^- \rightarrow K^- p \bar{p}$$

BaBar (B. Aubert *et al.*, Phys. Rev. **D74**: 051101 (2006))

$$B^0 \rightarrow \bar{D}^0 p \bar{p}, \quad B^0 \rightarrow \bar{D}^{*0} p \bar{p}$$

Final state interaction? Baryonium? Threshold cusp?

- $X(1835)$ was observed by BES in the decay (Phys. Rev. Lett. **95**, 262001 (2005); PDG)

$$J/\Psi \rightarrow \gamma \pi^+ \pi^- \eta',$$

with $M = 1833.7 \pm 6.1(stat) \pm 2.7(syst)$ MeV and $\Gamma = 67.7 \pm 20.3 \pm 7.7$ MeV

Statistical significance of 7.7σ

Consistent with expectations for the state that produces the strong $p\bar{p}$ mass threshold enhancement

0^{-+} glueball? Baryonium?

- $X(1812)$ was observed by BES in the doubly OZI-suppressed decay (Phys. Rev. Lett. **96**, 162002 (2006); PDG)

$$J/\Psi \rightarrow \gamma \omega \phi$$

with $M = 1812_{-26}^{+19}(\text{stat}) \pm 18(\text{syst})$ MeV, $\Gamma = 105 \pm 20 \pm 28$ MeV

Statistical significance of more than 10σ

Favors $J^P = 0^+$

Rescatterings? Four-quark state?; Glueball? Hybrid?

- $X(1576)$ was observed by BES in the decay (Phys. Rev. Lett. **97**, 142002 (2006); PDG)

$$J/\Psi \rightarrow K^+ K^- \pi^0$$

with pole position $1576^{+49}_{-55}(\text{stat})^{+98}_{-91}(\text{syst})$ MeV- $i(409^{+11}_{-12}(\text{stat})^{+32}_{-67}$ MeV

Broad peak

$$J^{PC} = 1^{--}$$

Final state interaction? Tetraquark state?

♠ Possible interpretations

Final state interaction?

Threshold cups?

- Glueballs?

0^{++} or 0^{-+}

$p\bar{p}$ enhancement

$X(1835)$

$X(1812),$

Lower mass compared with the expected pure 0^{-+} glueball

- Four-quark states?

$$0^{++} \text{ or } 0^{-+}$$

All of them lie above the 0^{++} or 0^{-+} tetraquark states

$$1^{--}$$

$X(1576)$: first orbital excited 1^{--} tetraquark state? Orbital excitation of $a_0(980)$ or $f_0(980)$?

Exotic: very large excited energy $\sim 596 \text{ MeV}$

problems:

A whole family of 1^{--} tetraquark states corresponding to orbital excitations of $f_0(600)$ and $\kappa(800)$ are expected (?)

Conclusions and discussions

- The structure of interpolating currents has no direct correspondence to the constituent structure of hadrons
- Masses of diquarks were determined through SVZ sum rule, and masses of tetraquark states were constructed in terms of these diquarks
- The new observations by BES are unlikely to be the pure 0^{-+} pseuso-scalar glueball, they are unlikely to be the light four-quark states except that $X(1576)$ may be an exotic first orbital excited $(sq)(\bar{s}\bar{q})$ tetraquark state either

Thank you!

