Exotic Hadrons in the QCD Sum Rule

Hua-Xing Chen
Research Center for Nuclear Physics, Osaka University, Ibaraki 567–0047, Japan

The theory of the strong interactions, Quantum Chromodynamics (QCD), originated from the systematics of hadron spectroscopy. The spectroscopy contains meson and baryon states, many of which are well classified by the quark model with quark contents $q\bar{q}$ and qqq. Besides the quark model, QCD allows much richer hadron spectrum such as multiquark states, hadron molecules, hybrid states, and glueballs etc. However the spectrum of QCD seem to saturate at $q\bar{q}$ and qqq. Therefore, we call these spectrum beyond $q\bar{q}$ and qqq exotic hadrons (exotica).

Exotica have been studied more than thirties years. R. L. Jaffe wrote two famous papers about scalar tetraquark states in 1976 [1, 2], whose structure is still not clear yet. In 2003, the pentaquark Θ^+ was observed in several experiments, but then several experiments denied its existence. After five years of intense study, the status of Θ^+ is still controversial [3]. There are many other exotic candidates, such as $\pi_1(1400)$ [4], $D_{sJ}(2317)$, $X(3872)$, and $Y(4260)$, etc. Their properties are difficult to be explained by the conventional picture of $q\bar{q}$ and qqq.

In order to study these exotica, lots of methods have been used. Although we have known a lot about QCD, but still there are many important and essential dynamical aspects that we need to clarify. As a doctor student in RCNP, Osaka University, I spent my latest three years on the study of QCD. I hope I contributed, although the time is not long, and my contribution is rather restricted. Now I am trying to graduate and changing my career in the research, and I am required to write this doctor thesis.

The method we used in this thesis is the QCD sum rule, which has proven to be a powerful and successful non-perturbative method for the past decades [5, 6]. An introduce of QCD sum rule is written in Chapter 1, which contains the SVZ sum rule, and the finite energy sum rule.

This thesis is separated into two parts. In the first part, we classify the interpolating fields (currents) for hadrons in QCD, which are used in the QCD sum rule analysis in the second part. QCD currents can contain quark fields, antiquark fields and gluon fields. The quark and antiquark fields are Dirac spinors, and so currents can also be spinors, such as baryon current

$$\epsilon_{abc} q_1^{aT} C \gamma_5 q_2^b q_3^c \, .$$

Currents can also be scalars other than matrices, such as the meson current

$$\bar{q}_1^a \gamma_5 q_2^a \, .$$

The notations and conventions we used are written in Chapter 1, where we construct meson currents ($\bar{q}q$), diquark currents (qq) and antidiquark currents ($\bar{q}\bar{q}$). In Chapters 2 and 3, we construct baryon currents and tetraquark currents, respectively. Chapter 4 is the discussion of color structure of multiquark currents.

After classifying current in the first part, we can start to perform the QCD sum rule analysis, which is the second part of this thesis. We have three important criteria:

1. Convergence of Operator Product Expansion (OPE),
2. Positivity of spectral density,
3. Sufficient amount of pole contribution.

We take $ud\bar{s}\bar{s}$ currents as an example and show our QCD sum rule analysis in Chapter 5. This procedure will be used in the following chapters: in Chapter 6, we study light scalar mesons; in Chapter 7, we study $Y(2175)$ as a tetraquark states; in Chapter 8, we study $\pi_1(1400)$, $\pi_1(1600)$ and $\pi_1(2015)$. In Chapter 9, the QCD sum rule is used to study the bottom baryons which contain heavy quarks.

Above I just gave a short introduction to my thesis. In my three years' research, I learned much and had a great deal of fun. I hope the readers would enjoy my thesis.

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