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Review on the Study of Multi-quark States

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Abstract In this short review, study of multi-quark states is briefly introduced. Theoretical study of four-quark states, pentaquark states and dibaryons is simply reviewed. Experimental signals relevant to multi-quark states are listed.

Key words multi-quark state, tetraquark state, pentaquark state, dibaryon

1 Introduction

The constituent quark model is the basic framework to understand hadrons. In this model, a meson consists of a quark and an antiquark, a baryon consists of three quarks. Exotic hadrons are those beyond the ordinary $q\bar{q}$ mesons and qqq baryons, which include multi-quark states (more than three constituent quarks and/or antiquarks), hybrids (with constituent quarks/antiquarks and gluons) and glueballs (with pure constituent gluons). The most popularly concerned multi-quark states are four-quark state (with baryon number $B=0$) $q^2\bar{q}^2$, pentaquarks $q^4\bar{q}$ ($B=1$) and dibaryons (or hexaquarks with $B=2$) q^6. Some lately comprehensive reviews to these states could be found in references[1—5] and therein.

Multi-quark state was firstly conjectured to exist when the idea of quark[6] was introduced, and four-quark state was supposed to exist in a consistent description of the hadron scattering amplitudes[7] before the advent of QCD. Multi-quark state was extensively studied in late 70's. Later, the studies of exotic moved onto glueball and hybrid. Recently, the study of multi-quark state has been revived for the first report of pentaquark $\Theta^+(1540)$[8]. In this short review, I will give a brief introduction to the developments of multi-quark state based mainly on the constituent quark model.

2 Four-quark state

In the constituent quark model, four-quark states are usually classified by $[qq][\bar{q}\bar{q}]$ and $[q\bar{q}][q\bar{q}]$ according to their intrinsic structures[9]. The $[qq][\bar{q}\bar{q}]$ (denoted as tetraquark state or baryonium sometimes) is composed of a diquark qq and an anti-diquark $\bar{q}\bar{q}$. It was studied early in the MIT bag model and potential model[9—11]. This kind of state was denoted as "baryonium" for its strong coupling to baryon-antibaryon channels and weak coupling to meson channels. As for the $[q\bar{q}][q\bar{q}]$, there are two kinds of $[q\bar{q}][q\bar{q}]$ four-quark states. The first kind consists of two color octet $q\bar{q}$ clusters. The second kind (denoted as "molecule") is composed of two lightly bound color singlet $q\bar{q}$ mesons which attracts each other. "Molecule" has been studied widely [12—16]. The internal dynamics of $[qq][\bar{q}\bar{q}]$ and $[q\bar{q}][q\bar{q}]$ is expected to be different, which may exhibit through their strong decays.

In this review, we will concentrate on the intrinsic color, flavor and spin structures of four-quark state in the constituent quark picture. For the tetraquark state, the two quark cluster [qq] may be in the color representation $\bar{3}$ or 6, while the two anti-quark cluster $[\bar{q}\bar{q}]$ may be in the color representation 3 or $\bar{6}$. Therefore the final color singlet is produced from the $\bar{3}\otimes 3$

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or the $6\otimes\bar{6}$.

In the early MIT bag model[9], the color singlet tetraquark state is built from $\bar{3}\otimes 3$. It was predicted to be a broader resonance than the $q\bar{q}$ mesons and to decay mainly into mesons channels. In a color junction model[10] with diquark involved in, the tetraquark state is built from both $\bar{3}\otimes 3$ and $6\otimes\bar{6}$. It was predicted that the former tetraquark state's decay into baryon and antibaryon was dominant, while its decay into mesons was more difficult. The latter tetraquark state $q_6^2-\bar{q}_{\bar{6}}^2$ ("mock-diquonia") was predicted to be weakly coupled to meson and "baryonium" channels.

The color configuration of $[q\bar{q}][q\bar{q}]$ is simple. The $[q\bar{q}]$ may be in the color representation 1 or 8, and the final color singlet is produced from $1\otimes 1$ ("molecule") or $8\otimes 8$. In the molecule, the $[q\bar{q}]$ is a color singlet meson, and it is combined with another color singlet meson to make a bound state. The interaction among quarks is very complex. The short range interactions among quarks may be described by the chromomagnetic part of the one gluon exchange interaction[17] with the color operators $\lambda(i)\cdot\lambda(j)$ involved, or by the Goldstone boson ($SU(3)_{\mathrm{F}}$ octet of pseudoscalar mesons) exchange interaction[18] with the flavor operators $\tau(i)\cdot\tau(j)$ involved. The long range attraction between the two $q\bar{q}$ clusters is described by a pion exchange.

In the flavor $SU(3)$ approximation, if the flavor is an independent degree of freedom, both the tetraquark state and the molecule state will give the same flavor multiplets: $(3\otimes 3)\otimes(\bar{3}\otimes\bar{3})=(3\otimes\bar{3})\otimes(3\otimes\bar{3})=27+10+\bar{10}+8+8+8+8+1+1$. In fact, as stated in the following, the diquark $[qq]$ and the anti-diquark $[\bar{q}\bar{q}]$ are in flavor $\bar{3}$ and 3 representation, respectively. The tetraquark makes the $SU(3)_{\mathrm{F}}$ nonet: $3\otimes\bar{3}=8+1$. The flavor octet and singlet of tetraquark state (or in molecule state) are the same as those in normal $q\bar{q}$ mesons. These multiplets are often called as crypto-exotic states, which may mix with $q\bar{q}$ mesons. Other flavor structures (exotic flavor) in the molecule states do not exist in normal $q\bar{q}$ mesons. Obviously, the exotic flavor molecule state may exhibit its flavor explicitly in a different way compared with the normal $q\bar{q}$ meson, and experiments could be designed to detect such states. The crypto-exotic flavor states are hard to be detected for their mixing with $q\bar{q}$ mesons.

The dynamics in four-quark states has not been uncovered, and the decay properties of four-quark states are unclear. There exist some arguments about their decay. As an interesting speculation, it was argued that the light (orbital angular momentum between the diquark and the anti-diquark $L=0$) tetraquark states decay into meson-meson channels, while the heavier ones ($L\geqslant 1$) decay mainly into baryon-antibaryon channels[9, 10]. Recently, some works about the dynamics and the decay mechanism for four-quark state are paid attention to Refs. [19—21].

Multi-quark state is in fact a many-body system. It has complex intrinsic structure, in which quarks have many different degrees of freedom such as color, flavor and spin, etc. These different degrees of freedom may make up different correlations. The most important strong correlation between pairs of quarks in multi-quark state is the diquark cluster $[qq]$. In history, diquark was first mentioned by Gell-Mann[6] and then applied successfully to many phenomena in strong interactions[19, 22—27]. Though the diquark is not an isolated cluster in multi-quark state, the diquark may be approximately regarded as a bound state composed of two quarks and may be used as degree of freedom. The diquark correlation was argued to be most important for the light multi-quark states[1, 28, 29]. According to Refs. [1,2,19,25,26,29], the two quarks correlate antisymmetric in color, flavor and spin, separately. In other words, the diquark is in a "good" diquark correlation $|qq,\bar{3}_{\mathrm{F}},\bar{3}_{\mathrm{C}},0\rangle$, in which the two quarks are in the color and flavor antitriplet representation $\bar{3}$.

The "molecule" mentioned above has also been studied in another way based on long range hadron dynamics instead of direct quark interactions. Since the nucleon-antinucleon $N\bar{N}$ bound state was first proposed to describe the properties of π[30], $N\bar{N}$ was subsequently used to describe "baryonium" with mass near the $N\bar{N}$ threshold and specific decay properties. In this quasi-nuclear picture, the interaction between two hadrons in the "molecule" is described by mesons exchange[5, 31]. This picture is also applied to other multi-quark states. In fact, the dynamics of four-quark state is quite unclear, and the decay properties of four-quark are known little.

In experiments, many four-quark state candidates have been assumed, but no one has been pinned down. $f_0(600)$ (or σ), $f_0(980)$, $a_0(980)$[32] and the unconfirmed $\kappa(800)$ was explained as the $[\mathrm{qq}][\bar{\mathrm{q}}\bar{\mathrm{q}}]$ four-quark states very early[9]. $f_0(980)$ and $a_0(980)$ were subsequently explained as K-$\bar{\mathrm{K}}$ molecule[11, 16]. However, so far, the existence of exotic mesons and baryons has not been definitely accepted due to contradictory results.

Θ^+ opened the Pandora's box to exotic hadron. The new observed $\mathrm{D}^{\star}_{\mathrm{SJ}}(2317)^{\pm}$[12, 32, 33](believed to be the 0^+ $1^3\mathrm{P}_0$ meson at present), X(3872)[19, 34, 35] and Y(4260)[36, 37] have ever been explained as four-quark states.

Very recently, BES collaboration has reported some new observations in low energy region. Apart from the near-threshold $\mathrm{p}\bar{\mathrm{p}}$ enhancement[38], X(1835) and X(1812) were observed[39, 40]. These observations were regarded as the four-quark candidates[3, 41] though they have not been confirmed by other experimental groups.

3 Pentaquark state

Quarks in $\mathrm{q}^4\bar{\mathrm{q}}$ pentaquark may correlate strongly and form cluster to give a more complicated intrinsic color, flavor and spin structure. Similar analysis could be performed as the previous four-quark state case. The exact intrinsic properties of pentaquark such as color, flavor, spin, mass, width, parity, production mechanism and decay will not be discussed here for lack of space. Detailed descriptions of the pentaquark state could be found in Refs. [1,2,4,42,43] and therein.

Pentaquark state had not received much attention before 2003. Low-lying pentaquark $\mathrm{q}^4\bar{\mathrm{q}}$ was studied early in MIT bag model[44]. The anticharmed strange baryon $\mathrm{P}(\bar{\mathrm{c}}\mathrm{uuds})$ was proposed and studied in 1987[45, 46]. These states have been searched for with null result. In 1997[47], a $S=1$, $J^{\mathrm{P}}=\frac{1}{2}^+$ pentaquark (Z^+, now called Θ^+) was predicted in the chiral soliton model. This predicted state has surprising features with mass 1530MeV and width less than 15MeV. This exotic $\Theta^+(1540)$[8] was first reported at Spring-8 with minimum quark content $\mathrm{uudd}\bar{\mathrm{s}}$, and was subsequently confirmed by over 10 experiments such as the CLAS[48], DIANA[49], SAPHIR[50], HERMES[51], COSY-TOF[52], ZEUS[53], SVD[54] and most recent DIANA[55] collaborations. With different probes (photons, electrons, protons, neutrons) and targets (protons, neutrons, nuclei), these experiments gave positive results. However, the signal has not been observed by many other experiments[56—59]. It seems more worse for Θ^+ that the latest dedicated high-statics and high-resolution experiments undertaken at Jefferson Laboratory[60, 61] reported null result.

Another exotic $\mathrm{ddss}\bar{\mathrm{u}}$ baryon Φ^{--} with $S=-2$, $Q=-2$ at 1860MeV was observed[62], but it was not observed by WA89 collaboration[63].

Motivated by the Θ^+, an anti-charmed analogue Θ_{c} at 2985±50MeV was conjectured theoretically[64], and then a near $\mathrm{uudd}\bar{\mathrm{c}}$ $\Theta_{\mathrm{c}}(3099)$ was reported by experiment[65]. Unfortunately, Babar[66] reported a negative result about this state.

Both positive and negative results remain in experiments. It is not the time now to speak the end of pentaquark (the existence of pentaquark is still not conclusive) though it seems that more and more experiments do not support the existence of pentaquark.

There have been hundreds of theoretical articles concerned with this object since the report of Θ^+. The study of pentaquark was performed in almost every possible model, which included chiral soliton model[47, 67, 68], diquark models[25—27], skyrme model[69], QCD sum rules[70, 71], large N_{c}[72] and other models[73—75].

Lattice theory is believed to be the most rigorous non-perturbative method based on QCD, and is applied to many phenomena successfully. Four-quark states were evaluated by some groups[76—78], pentaquark was evaluated recently[79—81]. However, the study of pentaquark on lattice is inconclusive.

Some studies find the pentaquark resonance, while some studies find no signal. Furthermore, the parity of pentaquark is predicted to have different signs in different groups. Obviously, lattice cannot yet provide reliable, quantitative insight into multi-quark phenomena at the present time.

4 Dibaryon

Dibaryon H (dihyperon), as a single 6-quark hadron instead of a loosely bounded S-wave state of two baryons like the deuteron, was first predicted to exist in the MIT bag model[82]. The H and other dibaryons have been extensively studied[83—87], but nothing has been found by experiments.

5 Summary

In summary, there are some multi-quark state candidates, but no one has so far been identified experimentally. Theoretical developments have been pushed ahead by the report of Θ^+, for example, the diquark has drawn people's great interest. However, the phenomenological models should not be taken too seriously. The stability of multi-quark state against strong decays, their intrinsic quark strong correlation and the mixing effects among hadrons have not yet been well understood. The dynamics in multi-quark state (also in ordinary hadron) is still unclear. People even do not know which dynamical framework should be used to study multi-quark state. Multi-quark state is still an open topic to both theory and experiment.

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多夸克态研究简述

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摘要　介绍了多夸克态的研究现状. 主要介绍了四夸克态、五夸克态和双重子态的理论研究. 并列举了实验上观察到的可能是多夸克态的粒子或共振态.

关键词　多夸克态　四夸克态　五夸克态　双重子态

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