PROCEEDINGS OF SCIENCE

Tetraquarks

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Tetraquark states are composed of two quarks and two antiquarks and represent a type of exotic hadronic state that extends beyond the conventional quark model of one-quark-and-one-antiquark mesons and three-quark baryons. In this review, we summarize the experimental advances in the study of tetraquark states, highlighting various configurations of quark flavors. We show the lineshape measurement of the $X(3872)$, observation of charged quarkonium states consisting of a heavy quark-antiquark pair alongside a light quark-antiquark pair, discoveries of tetraquark states with four distinct flavors, with a pair of heavy quarks and a pair of light antiquarks, or with two-pairs of charm-anticharm quarks.

International Conference on Exotic Atoms and Related Topics and Conference on Low Energy Antiprotons (EXA-LEAP2024)
26-30 August 2024
Austrian Academy of Sciences, Vienna.

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PoS(EXA-LEAP2024)040

1. Introduction

In the conventional quark model, mesons are formed from one quark and one antiquark, while baryons consist of three quarks. However, in the first decade of the 21st century, numerous quarkonium-like states were discovered at the two B-factories, BaBar and Belle [1]. While some of these states are promising candidates for traditional quarkonium, many others exhibit exotic properties that suggest the observation of unconventional states, such as multi-quark states, hadronic molecules, or hybrids [2].

The BaBar and Belle experiments concluded their data collection in 2008 and 2010, respectively, yet their data continue to be utilized for various physics analyses. Since 2008, the BESIII [3] and LHCb [4] experiments have started data collection and have significantly contributed to the study of exotic hadrons. Most discoveries of such states have been made at these four experiments.

Figure 1 presents a timeline of the discoveries related to some of the new hadrons, beginning with the observation of the $X(3872)$ in 2003 [5]. In this article, we discuss recent experimental progress, focusing specifically on states that may consist of two quarks and two antiquarks, referred to as tetraquark states. This includes the $X(3872)$, $Z_c(3900)$, $T_{cc}(3875)$, $X(2900)$, $X(6900)$, and their associated states.

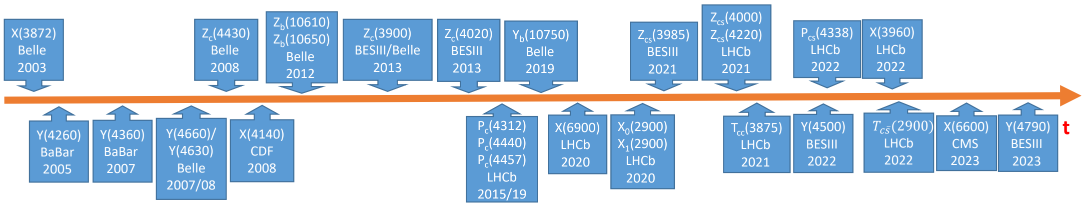

Figure 1: Timeline of the discoveries of some heavy exotic states from experiments.

2. The $X(3872)$

The $X(3872)$ was observed in 2003 by the Belle experiment [5], and confirmed very soon by the CDF [6] and $D0$ [7] experiments in $p\bar{p}$ collision.

The mass of the $X(3872)$ has been measured as 3871.64 ± 0.06 MeV [8], which is lower than the mass threshold of $\bar{D}^0 D^{*0}$, 3871.69 ± 0.11 MeV, by 0.05 ± 0.12 MeV, to be compared with the bounding energy of the deuteron of 2.2 MeV.

The width measurements are less precise and model dependent since the $X(3872)$ is very narrow and the mass resolution of the experiments is usually much larger than the intrinsic width. Fitting the $\pi^+\pi^- J/\psi$ invariant mass distribution with a Breit-Wigner (BW) function, LHCb reported a width of about 1 MeV (the mass resolution is 2.4–3.0 MeV); and the fit with a Flatté function with constraints from other measurements yields a FWHM of 0.22 MeV which depends strongly on the $X(3872) \to \bar{D}^0 D^{*0}$ coupling [9, 10].

Although the statistics are low at BESIII experiment, the high efficiencies of reconstructing all the $X(3872)$ decay modes and the very good mass resolution in the $\bar{D}^0 D^{*0}$ mode ($<$ 1 MeV) make it possible to measure the lineshape of the $X(3872)$ state [11]. BESIII determined the pole locations of the $X(3872)$ based on a simultaneous fit to the data samples of $X(3872) \to D^0\bar{D}^0\pi^0$ and $X(3872) \to \pi^+\pi^- J/\psi$, with the $X(3872)$ produced in $e^+e^- \to \gamma X(3872)$ process [12]. The parameterization of the $X(3872)$ lineshape, with the effect of D^{*0} width taken into account, is developed in Ref. [13]. The fit results and the lineshape of the $X(3872)$ are shown in Fig. 2. The lineshape parameters are determined to be $g = (0.16 \pm 0.10^{+1.12}_{-0.11})$, $\Gamma_0 = (2.67 \pm 1.77^{+8.01}_{-0.82})$ MeV and $M_X = (3871.63 \pm 0.13^{+0.06}_{-0.05})$ MeV. Here g denotes the effective coupling constant of the $X(3872)$ to neutral and charged $D^*\bar{D}$; the constant Γ_0 represents all the channels except $D^*\bar{D}$, and is separated into three parts: $\Gamma_0 = \Gamma_{\pi^+\pi^- J/\psi} + \Gamma_{\text{known}} + \Gamma_{\text{unknown}}$; and M_X is the mass of the $X(3872)$. The FWHM of the lineshape is determined to be $(0.44^{+0.13}_{-0.35}{}^{+0.38}_{-0.25})$ MeV. Two poles are found on the first and second Riemann sheets corresponding to the $D^{*0}\bar{D}^0$ branch cut. The pole location on the first sheet is much closer to the $D^{*0}\bar{D}^0$ threshold than the other, and is determined to be $(7.04 \pm 0.15^{+0.07}_{-0.08})$ MeV above the $D^0\bar{D}^0\pi^0$ threshold with an imaginary part $(-0.19 \pm 0.08^{+0.14}_{-0.19})$ MeV.

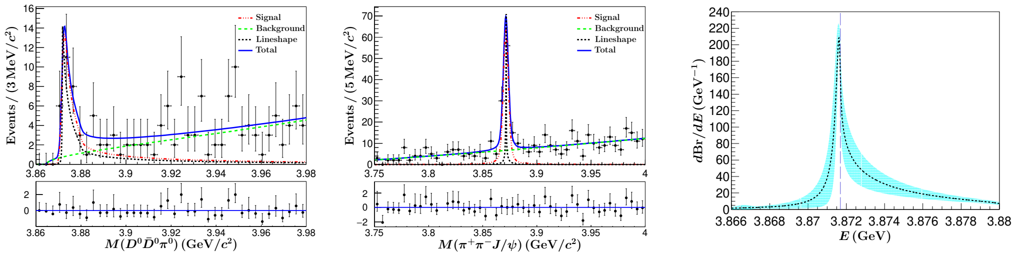

Figure 2: The fit to the $D^0\bar{D}^0\pi^0$ (left) and $\pi^+\pi^- J/\psi$ (middle) invariant mass distributions [11]. Data are taken from Ref. [12]. The $X(3872)$ lineshape at the best estimation is shown in right panel. The vertical dashed line indicates the position of $D^{*0}\bar{D}^0$ threshold.

Belle measured the $X(3872)$ lineshape with $B \to X(3872)K \to D^0\bar{D}^{*0}K$ [14]. The peak near the threshold in the $D^0\bar{D}^{*0}$ invariant mass spectrum is fitted using a relativistic BW function. Belle determined a mass of $(3873.71^{+0.56}_{-0.50} \pm 0.13)$ MeV and a width of $(5.2^{+2.2}_{-1.5} \pm 0.4)$ MeV. The peak is also studied using a Flatté lineshape and the lower limit on the $D\bar{D}^*$ coupling constant g is determined to be 0.075 at 95% credibility. A coupled channel analysis of the data used in this analysis and those in $X(3872) \to \pi^+\pi^- J/\psi$ decay is highly recommended to get reliable information about the $X(3872)$ lineshape.

The radiative decays $X(3872) \to \gamma\psi(2S)$ and $X(3872) \to \gamma J/\psi$ have been measured before by the BaBar [15], Belle [16], LHCb [17], and BESIII [12] experiments, but the signal significance of $X(3872) \to \gamma\psi(2S)$ is not high. The measurements of the ratio of the branching fractions, $\mathcal{B}(X(3872) \to \gamma\psi(2S))/\mathcal{B}(X(3872) \to \gamma J/\psi)$, only agree marginally among the experiments.

LHCb updated the analysis [18] with 9 fb^{-1} data using the decay $B^+ \to X(3872)K^+$. The $X(3872) \to \gamma\psi(2S)$ process is observed for the first time and the ratio is measured to be $1.67 \pm 0.21 \pm 0.13$, where the first uncertainty is statistical and the second systematic. The measured ratio makes the interpretation of the $X(3872)$ as a pure $D^0\bar{D}^{*0}$ molecule less favorable, and strongly indicates a sizable compact charmonium or tetraquark component within it.

3. Charged quarkonium states and their siblings

A charged quarkonium-like state that decays into a pair of heavy quark-antiquark of the same flavor along with light hadrons must contain at least two quarks and two antiquarks.

The first reported charged charmonium-like state, $Z_c(4430)$, was observed in the $\pi^-\psi(2S)$ invariant mass distribution in $B \to K\pi^-\psi(2S)$ decays in the Belle experiment [19, 20]. However, this state was not confirmed by the BaBar experiment, which analyzed the same decay mode with similar statistics [21].

There were two other Z_c structures at masses 4050 and 4250 MeV/c^2 in $\pi^-\chi_{c1}$ system in $B \to K\pi^-\chi_{c1}$ decays [22] reported by the Belle, but they were not confirmed in a similar analysis by the BaBar experiment [23].

There were also two Z_b structures at masses 10610 and 10650 MeV/c^2 in $\pi^-\Upsilon(nS)$ ($n = 1, 2, 3$) and $\pi^-h_b(mP)$ ($m = 1, 2$) systems in e^+e^- annihilation at the $\Upsilon(5S)$ energy [24] reported by the Belle, but no other data samples can be used to confirm or falsify them.

The first confirmed tetraquark state is the $Z_c(3900)$ discovered in $\pi J/\psi$ by the BESIII [25] and Belle [26] experiments.

The BESIII experiment studied the $e^+e^- \to \pi^+\pi^-J/\psi$ process using a 525 pb^{-1} data sample at a c.m. energy of 4.26 GeV [25]. About 1500 signal events were observed and the cross section was measured to be $(62.9 \pm 1.9 \pm 3.7)$ pb. The intermediate states in this three-body system were studied by examining the Dalitz plot of the selected candidate events. In addition to the known $f_0(500)$ and $f_0(980)$ structures in the $\pi^+\pi^-$ system, a structure at around 3.9 GeV/c^2 was observed in the $\pi^\pm J/\psi$ invariant mass distribution with a statistical significance larger than 8σ, which is referred to as the $Z_c(3900)$. A fit to the $\pi^\pm J/\psi$ invariant mass spectrum (see Fig. 3) determined its mass to be $(3899.0 \pm 3.6 \pm 4.9)$ MeV/c^2 and its width to be $(46 \pm 10 \pm 20)$ MeV.

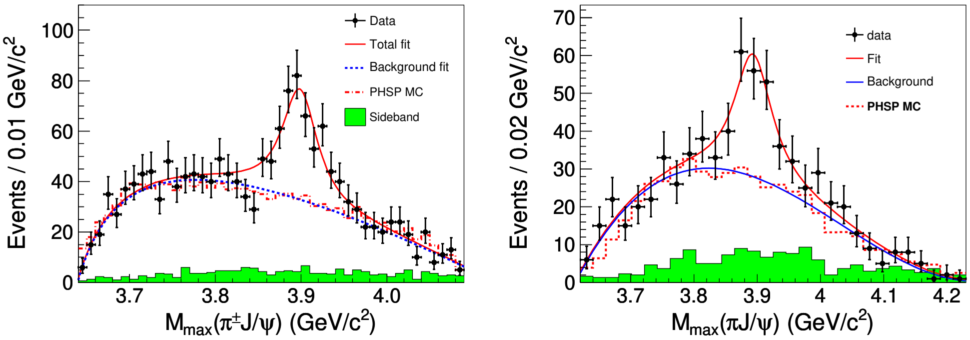

Figure 3: Unbinned maximum likelihood fit to the distribution of the $M_{\rm max}(\pi J/\psi)$ (left panel from BESIII [25] and right panel from Belle [26]). Points with error bars are data, the curves are the best fit, the dashed histograms are the phase space distributions and the shaded histograms are the non-$\pi^+\pi^-J/\psi$ background estimated from the normalized J/ψ sidebands.

A measurement performed at the Belle experiment that was released subsequent to the BESIII paper reported the observation of the $Z_c(3900)$ state (referred to as $Z(3900)^+$ in the Belle paper) produced via the ISR process with a mass of $(3894.5 \pm 6.6 \pm 4.5)$ MeV/c^2 and a width of $(63 \pm 24 \pm 26)$ MeV with a statistical significance larger than 5.2σ [26] (see Fig. 3).

These observations of the $Z_c(3900)$ were confirmed by an analysis of CLEO-c data at a c.m. energy of 4.17 GeV [27], with a mass and width that agree with the BESIII and Belle measurements. The $Z_c(3900)$ is thus the first confirmed tetraquark state, and its spin-parity quantum numbers are measured as $J^P = 1^+$ [28] and its isospin is $I = 1$.

The process $e^+e^- \to \pi^+\pi^- h_c$ was observed at c.m. energies of 3.90 – 4.42 GeV [29]. Although there are no clear structures in the $\pi^+\pi^-$ system, there is distinct evidence for an exotic charmoniumlike structure in the $\pi^\pm h_c$ system. The mass and width of the $Z_c(4020)$ were measured to be $(4022.9\pm0.8\pm2.7)$ MeV$/c^2$ and $(7.9\pm2.7\pm2.6)$ MeV, respectively. The statistical significance of the $Z_c(4020)$ signal is greater than 8.9σ.

Together with the $Z_c(4430)$ confirmed by the LHCb experiment in 2014 [30], these states seem to indicate that a new class of hadrons has been observed, and they are all states with minimal quark content of $c\bar{c}u\bar{d}$.

Recent studies try to search for states with one of the quarks replaced by a different quark, for example, the Z_{cs} states with quark content $c\bar{c}u\bar{s}$. BESIII announced observation of a near-threshold structure $Z_{cs}(3985)$ in the K^+ recoil-mass spectrum in $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ [31] with a mass of 3983 MeV and a width of about 10 MeV; and LHCb reported two resonances decaying into $K^\pm J/\psi$, the $Z_{cs}(4000)$ with a mass of 4003 MeV and a width of about 131 MeV, and the $Z_{cs}(4220)$ with a mass of 4216 MeV and a width of about 233 MeV [32]. The widths of the $Z_{cs}(3985)$ and $Z_{cs}(4000)$ are quite different, maybe one of them is the strange partner of the $Z_c(3900)$ with the d quark replaced with an s quark. Both BESIII [33] and LHCb [34] reported evidence for the neutral partners of the Z_{cs} states at around 4 GeV with quark content $c\bar{c}d\bar{s}$. These indicate that these states form isospin doublets.

The $Z_c(3900)$ ($Z_c(4020)$) and Z_{cs} states may form multiplets shown in Fig. 4, the missing states can be searched for with the existing or future data samples. There could be more such kind of multiplets considering different quark flavors, different spin and orbital angular momenta combinations.

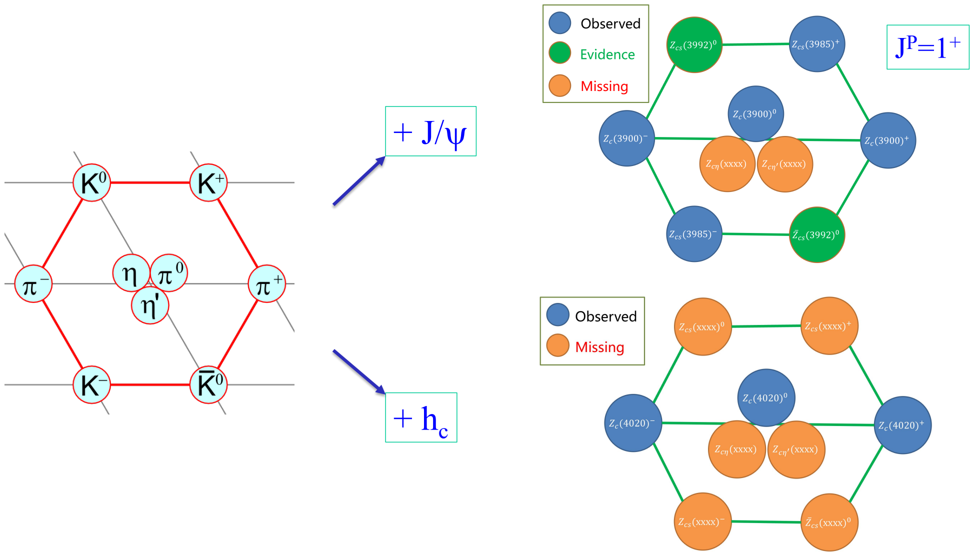

Figure 4: The possible multiplets of the $Z_c(3900)$ and $Z_c(4020)$.

4. Tetraquark states with four distinct flavors

LHCb experiment observed two new resonances with four different flavors with mass of $2908 \pm 11 \pm 20$ MeV and width of $136 \pm 23 \pm 13$ MeV, which decay to $D_s^+\pi^+$ and $D_s^+\pi^-$, respectively, from a combined amplitude analysis for the decays $B^0 \to \overline{D}^0 D_s^+\pi^-$ and $B^+ \to D^- D_s^+\pi^+$, which are related by isospin symmetry. The former state indicates the first observation of a doubly charged open-charm tetraquark state with minimal quark content $c\bar{s}u\bar{d}$, and the latter state is a neutral tetraquark composed of $c\bar{s}\bar{u}d$ ($T_{c\bar{s}}$). Both states are found to have spin-parity 0^+, and their resonant parameters are consistent with each other, which suggests that they belong to an isospin triplet [35].

Tetraquark states T_{cs} with four different flavors ($cs\bar{u}\bar{d}$) have been search for at LHCb and evidence (3.9σ) for two states ($X_0(2900)$ and $X_1(2900)$) in D^-K^+ system were reported from a PWA of $B^+ \to D^+D^-K^+$ events by the LHCb experiment [36]. They are good candidates for the flavor partners of the $T_{c\bar{s}}$ states, and more flavor partners with other quark contents and spin-parities are expected.

5. Tetraquark state with two charmed quarks

LHCb also reported new observation of a state with two charmed quarks, $T_{cc}(3875)$ with a mass a few hundred keV lower than the D^0D^{*+} threshold and a width much less than 1 MeV [37]. If it is interpreted as a molecule of two charmed mesons, its size will be around 7.5 fm, pretty large than a normal hadrons of 1 fm.

6. Tetraquark states with two pairs of charmed quark-antiquark

The LHCb, ATLAS, and CMS experiments have reported the observation of states decaying into two charmonium states [38–40]. The $X(6900)$ has been observed by all three experiments, and CMS has identified a new structure, $X(6600)$, with a significance exceeding 5σ, as well as evidence for another new structure, $X(7300)$, with a local significance of 4.1σ. The masses, widths, and significances of these states have been determined using model-dependent methods that do not account for potential interference between the resonances. These findings present strong candidates for tetraquark states comprising two pairs of charm-anticharm quarks.

7. Summary and Perspectives

Over the past two decades, tetraquark states with various quark configurations have been observed. Some of these states are located near the thresholds of two heavy mesons, such as the $X(3872)$ ($\bar{D}^0D^{*0}$), $Z_c(3900)$ ($\bar{D}^0D^{*+}$), $Z_c(4020)$ ($\bar{D}^{*0}D^{*+}$), Z_{cs} ($\bar{D}^0D_s^{*+}$), and $T_{cc}(3875)$ (D^0D^{*+}). Conversely, other states, such as the $Z_c(4430)$, $Z_{cs}(4220)$, and $X(6900)$, are not situated close to such thresholds. This observation suggests that we have detected hadronic molecules near the thresholds, as well as hadronic states exhibiting different quark configurations, like compact tetraquark states. Further results are anticipated from experiments such as Belle II, BESIII, LHCb, and others.

Acknowledgments:

We would like to express our gratitude to the organizers for the invitation to present a talk at the conference in such a beautiful city. This work is supported in part by National Key Research and Development Program of China (No. 2020YFA0406300), and National Natural Science Foundation of China (NSFC, No. 12361141819).

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