A number of charmonium-like states have been observed in B-factory experiments. Recently the BESIII experiment has joined this search with a unique data sample collected at the different center of mass energies ranging from 3.9 GeV to 4.42 GeV in which they found new charmonium-like states with non-zero electric charge. We review the status of experimental searches for quarkonium-like states and also other types of non-\(q\bar{q}\) meson or non-\(qqq\) baryons that are predicted by QCD-motivated models. We mainly focus on results from the B-factories and BESIII.

Keywords:

PACS numbers:

1. Introduction

Mesons and baryons are formed from color-singlet combinations of quarks. All non-\(q\bar{q}\) mesons and non-\(qqq\) baryons predicted by QCD-motivated models are expected to be in color-singlet multi-quark combinations.

Color-singlet multiquark states can be formed from colored diquarks and diantiquarks: a pentaquark is predicted to contain two diquarks and one antiquark, the \(H\)-dibaryon contains three diquarks, and tetraquark mesons contain a diquark and diantiquark. Multiquark states can also be formed by molecules of two (or more) color-singlet \(q\bar{q}\) mesons and/or \(qqq\) baryons that are bound together by the exchange of virtual \(\pi\sigma,\omega\), etc. mesons. In this way, Pentaquarks, the \(H\)-dibaryon, baryonium and tetraquark mesons can be formed. If these exist, where are they?

2. Pentaquark

A pentaquark is a predicted baryonic bound state of four quarks and one antiquark. In the 2003, two experiments, LEPS and CLAS, reported the existence of a positive strangeness baryon that they called the \(\Theta^+\). After that, a number of experiments reported the observation of confirming signals and even other new types of pentaquarks. But later, high-statistics experiments with higher statistics could not
reproduce these signals suggesting that the LEPS-CLAS results were due to statistical effects rather than a real resonance. Therefore the existence of the pentaquark is still an open question.

3. The $H$-dibaryon

The possibility of a six-quark state was first proposed by R.L. Jaffe in 1977. He dubbed it the $H$-dibaryon, and predicted it to have a strangeness=$-2$ and baryon number=$+2$. Such a state could possibly be either a tightly bound diquark triplet or a hyperon-hyperon molecular type state. Jaffe’s original prediction was $0^+$ di-hyperon with the mass that is about 80 MeV below the $2m_{\Lambda}$ threshold. His original specific prediction was ruled out by observation of a double-$\Lambda$ hypernuclei events. Especially the “NAGARA” event observed in double-$\Lambda$ hypernuclei, $^6\Lambda\Lambda He$, which greatly narrowed the mass window of the $H$ to be $M_H > 2m_{\Lambda} - B_{\Lambda\Lambda}$ MeV, with binding energy $B_{\Lambda\Lambda} = 7.25 \pm 0.19^{+0.18}_{-0.11}$, corresponding to a lower limit of the $H$ mass to be $2223.7\text{MeV}/c^2$.

Although Jaffe’s original prediction for $B_H \sim 80$ MeV has been ruled out, the theoretical case for an $H$-dibaryon with a mass near $2m_{\Lambda}$ remains concrete. Recent Lattice QCD results indicate the existence of an $H$-dibaryon with the mass close to the $2m_{\Lambda}$ threshold and this motivated a Belle search for the $H$ near the mass of the $2m_{\Lambda}$ threshold. For an $H$ mass below $2m_{\Lambda}$ threshold, the $H$ would decay via a $\Delta S = 1$ weak-interaction with a number of possible decay channels: $\Lambda p\pi^-$, $\lambda n$, $\Sigma p$, and $\Sigma n$. For an $H$ mass above the $2\Lambda$ threshold and below the mass of $\Xi p$, the $H$ would decay strongly into $\Lambda\Lambda$ almost 100% of the time.

Belle searched for the $H$-dibaryon production in inclusive $\Upsilon(1,2S) \to HX$; $H \to \Lambda p\pi^-$ and $\Lambda\Lambda$ process using data sample containing 102 million events of $\Upsilon(1S)$ and 158 million events of $\Upsilon(2S)$ collected with Belle detector operating at the KEKB $e^-e^+$ collider. The dominant decay mechanism for the narrow $\Upsilon(nS)$ resonances ($n=1,2$ and $3$) is annihilation into three gluons. Each gluon materializes as quark-antiquark pairs and, since the $\Upsilon$ states are flavor SU(3) singlets, $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ pairs are produced in nearly equal numbers. This strangeness-rich high-density quark environment in a limited volume of phase space is ideal for producing multi-quark hadron states, especially $S = -2$, $H$-dibaryon.

These $\Upsilon(1,2S)$ decays are a rich source of 6-quark antideuteron production, as demonstrated by large branching fraction of $\sim 3 \times 10^{-5}$ measured by the ARGUS and CLEO experiments. The physics of near-threshold $S$-wave Feshbach resonances ensure that an $H$-dibaryon in this mass region should be very similar in character to a $\Lambda\Lambda$ version of the deuteron. Moreover, since the $\Upsilon(1S)$ and $\Upsilon(2S)$ are Flavor-SU(3) singlets, $S = -2$ counterparts of the antideuteron should be produced with sensitivities below or at the rate for antideuteron production.

The Fig. shows results from the Belle search for $H$-dibaryon masses below and above the $2m_{\Lambda}$ threshold. For masses below threshold (left), the $H$ is searched for as a peak in the $\Lambda p\pi^-$ invariant mass distribution in inclusive $\Upsilon(1,2S) \to \Lambda p\pi X$ and
its charge conjugate decays. For masses above threshold (right), the \( H \) is searched for in the invariant mass distribution of \( \Lambda \Lambda \) pairs from \( \Upsilon(1,2S) \rightarrow \Lambda \Lambda X \). The continuum-subtracted \( M(\Lambda p\pi^-) \) (left) and \( M(\Lambda \Lambda) \) (right) distributions have no evident \( H \rightarrow \Lambda p\pi^- \) and \( H \rightarrow \Lambda \Lambda \) signals.

Figure 2 shows the corresponding \( M_H - 2m_\Lambda \) dependent upper limits at 90% CL for \( B(\Upsilon(1,2S) \rightarrow HX)B(H \rightarrow \Lambda p\pi^- and \Lambda \Lambda) \). These are all more than an order of magnitude lower than the averaged PDG value of \( B(\Upsilon(1,2S) \rightarrow \bar{d}X) \), plotted as an

Fig. 1. The top and left (right) panel shows the continuum-subtracted \( M(\Lambda p\pi^-) \) (\( M(\Lambda \Lambda) \)) distribution (upper) and fit residuals (lower) for the combined \( \Upsilon(1S) \) and \( \Upsilon(2S) \) data samples. The curve shows the results of the background-only fit using an ARGUS-like threshold function to model the background. Gaussian fit function for expected signals is superimposed assuming \( B(\Upsilon \rightarrow HX) = (1/20) \times B(\Upsilon \rightarrow \bar{d}X) \). The corresponding \( M(\bar{\Lambda}p\pi^+) \) (\( M(\bar{\Lambda}\bar{\Lambda}) \)) distributions in the bottom left (right) panel.

Fig. 2. Upper limits at 90% CL for \( B(\Upsilon(1,2S) \rightarrow HX)B(H \rightarrow f) \) for a narrow (\( \Gamma = 0 \)) \( H \)-dibaryon vs. \( M_H = 2m_\Lambda \) threshold. The vertical dotted line indicate the \( M_H = 2m_\Lambda \) threshold. The UL branching fraction below (above) the \( 2m_\Lambda \) threshold are for \( f = \Lambda p\pi^- (f = \Lambda \Lambda) \). The horizontal dotted line indicates the average PDG value for \( B(\Upsilon(1,2S) \rightarrow \bar{d}X) \).
horizontal dotted line. No evidence was found for a signal in any of these modes, and the most stringent branching-fraction upper limits on $H$-dibaryon production are determined for masses near the $2m_\Lambda$ threshold.

4. Candidate of baryonium

Ten years ago, the BESII experiment reported the observation of a peculiar threshold enhancement in the $p\bar{p}$ invariant mass distribution in the radiative decay process $J/\psi \to \gamma p\bar{p}$ using 58M $J/\psi$ events. A fit to the enhancement in the $M(p\bar{p})$ distribution near the $M = 2m_p$ mass threshold with an $S$-wave Breit-Wigner function gave a below threshold peak value of $M = 1859^{+3}_{-10}\text{(stat)}^{+5}_{-25}\text{(syst)}$ MeV/c² and an upper limit on the full width of $\Gamma < 30$ MeV at the 90% CL. The enhancement could not be explained by final state interactions (FSI) between the $p$ and $\bar{p}$ and there was no corresponding any known resonance states listed in the standard table that could account for this state.

With $(225.2 \pm 2.8) \times 10^6$ $J/\psi$ events sample collected with the BESIII detector, a partial wave analysis that included $I = 0$ FSI between $p$ and $\bar{p}$ gave a mass and upper limit on the width of $M = 1832^{+19}_{-5}^{+18}_{-17} \pm 19\text{(model)}$ MeV/c² and $\Gamma < 76$ MeV at the 90% CL. The fitted mass peak is about 40 MeV below the $M = 2m_p$ mass threshold. Also the $\gamma$ polar angle and $p\bar{p}$ decay angle distributions favor the $J^{PC} = 0^{-+}$ quantum number assignment over any other possibility with statistical significances that are larger than 6.8$\sigma$.

One proposed interpretation for this enhancement is that it is baryonium, i.e. a deuteron-like proton-antiproton bound state produced by standard nuclear forces mediated by $\pi$, $\sigma$ and/or $\omega$ exchanges. For such a state with mass below the $2m_p$ mass threshold, the $p$ and $\bar{p}$ would annihilate to mesons, while above threshold it would be expected to “fall apart” to $p\bar{p}$ final states almost 100% of the time. Since $p\bar{p}$ annihilation to $\pi^+\pi^-\eta'$ or $3(\pi^+\pi^-)$ are common and dominant channels for $I = 0$, $J^{PC} = 0^{-+}$, $p\bar{p}$ annihilations searches for the same state in the radiative processes $J/\psi \to \gamma\pi^+\pi^-\eta'$ and $J/\psi \to \gamma 3(\pi^+\pi^-)$ were pursued by BESIII with the same $J/\psi$ data sample.

A dramatic peak was seen in the $M(\pi^+\pi^-\eta')$ spectrum at $M = 1837 \pm 3^{+5}_{-3}$ MeV/c², very similar to the one measured from $p\bar{p}$ mass, also the cosine of the $\gamma$ polar angle distribution is consistent with the form of $0^{-+}$. Although the mass and $J^{PC}$ are consistent with those in the $p\bar{p}$ channel, the broad width ($\Gamma = 190 \pm 9^{+38}_{-36}$ MeV) is not. Two more new states at higher masses, dubbed $X(2120)$ and $X(2370)$, are also observed in the same $M(\pi^+\pi^-\eta')$ mass distribution. Recently, BESIII reported the results of a study of the radiative process $J/\psi \to \gamma 3(\pi^+\pi^-)$, where a clear peak near $2m_p$ was seen with mass $M = 1842.2 \pm 4.2^{+7.1}_{-2.6}$ MeV/c² and width $\Gamma = 83 \pm 14 \pm 11$ MeV consistent with the the $p\bar{p}$ values. Are these peaks observed in the $p\bar{p}$, $\pi\pi\eta'$ and $3\pi^+\pi^-$ mass distribution all from the same state? The masses are consistent with each other, but the width measured from $p\bar{p}$ is significantly narrower than the width of the $\pi^+\pi^-\eta'$ enhancement. These reso-
nances could come from different sources or there may be more than one resonance contributing to the $\pi\pi\eta'$ peak. To clarify all these, further study is needed including the measurement of $J^{PC}$ for the $X(1842) \rightarrow 3(\pi^+\pi^-)$ signal.

5. Doubly charged partner states of $D_{s0}^+(2317)$

The $D_{s0}^+(2317)$, hereafter referred to as the $D_{s0}^+$, was first observed by BaBar\textsuperscript{12} as a narrow peak in the $D_{s0}^+\pi^0$ mass spectrum produced in $e^+e^-$ annihilation to $D_{s0}^+\pi^0+X$ process and subsequently confirmed by CLEO\textsuperscript{13} and Belle. Its production in $B$ meson decay were also established by both Belle\textsuperscript{14} and BaBar\textsuperscript{15}. It is generally considered to be the conventional $I(J^P) = 0(0^+)$ p-wave $c\bar{s}$ meson, but its mass $M_{D_{s0}^+} = 2317.8 \pm 0.6$ MeV/$c^2$\textsuperscript{11} is very similar as the one $M_{D^*_s} = 2318 \pm 29$ MeV of the non-strange $0^+$ P-wave $D^*_s$ state, in spite of the mass difference between the $s$ and $u$ (or $d$) quarks which is known as $m_s - m_u(d) \sim 100$ MeV. Furthermore, Potential model and lattice QCD published prior to its discovery all predicted $0^+$ P-wave $c\bar{s}$ meson mass to be well above the $m_{D^0} + m_{K^+} = 2358.6$ MeV threshold with a large partial decay width for $D_{s0}^+ \rightarrow DK$. This discrepancy has led to considerable theoretical speculation that the $D_{s0}^+$ is not a simple $c\bar{s}$ meson, but instead a four

![Fig. 3](image-url)
quarks state such as $DK$ molecule or diquark-diantiquark state.

Among these four quarks models, Terasaki’s assignment to $I=1$ iso-triplet four-quark meson is favored by various existing experimental data. If this is the production process of $D_{s0}^{+}$, it should have doubly charged $I_Z=1$ ($F_1^{++}$) and neutral $I_Z=0$ ($F_1^{0}$) partners. The Ref. also predicted that isospin invariance insures that the product branching fraction $B(B^+ \rightarrow D^- F_1^{++},0)B(F_1^{++},0 \rightarrow D_s^+ \pi^{+-})$ will be nearly equal to $B(B^+ \rightarrow D\bar{D}_{s0}^+)B(D_{s0}^+ \rightarrow D_s^+ \pi^0)$.

Preliminary results from a Belle search uncovered no evidence for the predicted state and established a stringent branching fraction limits to be $B(B^+ \rightarrow D^- F_1^{++}(2317))B(F_1^{++}(2317) \rightarrow D_s^+ \pi^+) < 0.28 \times 10^{-4}$ at 90% CL that is a factor of about 30 below the predicted level. This makes possible eliminating the tetra-quark interpretation of the $D_{sJ}$ meson family.

A by-product from this search are measurements of the branching fractions for the decay processes of $B^+ \rightarrow D_{s0}^+ D^0$ and $B^0 \rightarrow D_{s0}^+ D^-$ with sub-decay $D_{s0}^+ \rightarrow D_s^+ \pi^0; D_s^+ \rightarrow K^+ K^-\pi^+$, which is significantly improved and used for the above upper limits calculations for the doubly charged partner state. Figure 3 shows the $M_{bc}$ (left), $M(D_{s0}^{++})$ (center) and $\Delta E$ (right) distribution for $B \rightarrow D\bar{D}_{s0}$ candidate events. Each distributions are projections of events that are in the signal regions of other two quantities for modes: a) $B^0 \rightarrow D^- D_{s0}^+ D^- \rightarrow K^+\pi^-\pi^-$, b) $B^\pm \rightarrow \bar{D}D_{s0}^\pm; \bar{D}^0 \rightarrow K^+\pi^-\pi^+$ and c) $B^\pm \rightarrow \bar{D}^0 D_{s0}^\pm; \bar{D}^0 \rightarrow K^+\pi^-$. The curves in each plot show the results of unbinned three-dimensional likelihood fit. From the fit result, the product branching fraction is determined to be $B(B^0 \rightarrow D^- D_{s0}^+)B(D_{s0}^+ \rightarrow D_s^+ \pi^0) = 10.0 \pm 1.2 \pm 1.0 \pm 0.5) \times 10^{-4}$ and $B(B^+ \rightarrow D\bar{D}_{s0}^+)B(D_{s0}^+ \rightarrow D_s^+ \pi^0) = (7.8^{+1.3}_{-1.2} \pm 1.0 \pm 0.5) \times 10^{-4}$, where the first error is statistical, the second is the systematic error, and the third one reflects the errors on the PDG world average $D$ and $D_s^+$ branching fraction values. All these measurements were used Belle full data containing 772 million $\bar{B}B$ meson pairs collected at the $\Upsilon(4S)$ resonance. These results agree well with the average of the BaBar and previous Belle measurement with substantial improvement in precision.

6. The $XYZ$ quarkonium-like mesons

The $XYZ$ states are known as states that decay into final states containing a $c\bar{c}$ (or $b\bar{b}$) quark pair but do not fit into the conventional charmonium (bottomonium) spectrum. The $X(3872)$, a key member of this family, was first discovered as a peak in the $\pi^+\pi^- J/\psi$ mass by Belle in the $B \rightarrow \pi^+\pi^- J/\psi K$ decay process and confirmed by four different experiments and observed via five different decay channels. The quantum numbers were unambiguously determined to be $J^{PC}=1^{++}$ by the LHCb experiment by an analysis of the $B \rightarrow X(3872) K; X(3872) \rightarrow \pi^+\pi^- J/\psi$ decay chain. This result favors an exotic explanation of the $X(3872)$ state and disfavors a simple $c\bar{c}$ charmonium assignment. Recently, one more production channel was observed by BESIII, where a $6.3\sigma$ significance $X(3872)$ signal is reported in the process $e^+e^- \rightarrow \gamma X(3872)$ using data collected at the four center
of mass energies: $\sqrt{s} = 4.009, 4.229, 4.260$ and $4.360$ GeV. Large cross sections of $\gamma X(3872)$ are seen at $\sqrt{s} = 4.229$ and $4.260$, while cross section at $\sqrt{s} = 4.009$ and $4.360$ GeV were consistent with zero. This suggests the $X(3872)$ might be produced from the radiative transition of the $Y(4260)$ rather than from the $\psi(4040)$ or $Y(4360)$, but, with the current limited statistics, continuum production cannot be ruled out.

The charged charmonium-like state $Z(4430)^+$, as a controversial member, was first observed by Belle as a peak in the $\pi^+ J/\psi$ mass in $B \to K \pi^+ J/\psi$ decays. However, the search by BaBar didn’t confirm this signal. Belle also observed two more charged states, $Z_1^+$ and $Z_2^+$, that are seen in the final states $\pi^+ \chi_{c1}$ in the exclusive $B \to K \pi^+ \chi_{c1}$ decays. Recently Belle has reported the measurement of quantum numbers of the $Z(4430)$ by performing a full amplitude analysis of $B^0 \to \psi K^+ \pi^-$ in four dimensions. The table shows the results from 4-D fit, the preferred spin-parity hypotheses is $1^+$, which is favored over $0^−$ by $2.9\sigma$, but $0^−$ also cannot be ruled out with current statistics.

| $J^P$  | $0^−$ | $1^−$ | $1^+$ | $2^−$ | $2^+$ |
|-------|-------|-------|-------|-------|-------|
| Mass, MeV/c² | $4479 \pm 16$ | $4477 \pm 4$ | $4485 \pm 20$ | $4478 \pm 22$ | $4384 \pm 19$ |
| Width, MeV | $110 \pm 50$ | $22 \pm 14$ | $200 \pm 40$ | $83 \pm 25$ | $52 \pm 28$ |
| Significance | $4.5\sigma$ | $3.6\sigma$ | $6.4\sigma$ | $2.2\sigma$ | $1.8\sigma$ |

The $Y(4260)$ is a $J^{PC}=1^{−−}$ resonance peak that was discovered in the $e^+e^- \to \pi^+ \pi^- J/\psi$ cross section by BaBar. It was subsequently confirmed by CLEO, Belle and BESII. A remarkable feature of the $Y(4260)$ is its large partial width of $\Gamma(Y(4260) \to \pi^+ \pi^- J/\psi) > 1$ MeV which is much larger than that for typical charmonium. This motivated the Belle to investigate whether or not there is a corresponding structure in the bottomonium mass region. This study found that there is a large anomalous cross section for $e^+e^- \to \pi^+ \pi^- \Upsilon(nS)$ ($n=1,2,3$) for $e^+e^-$ cm energies around 10.9 GeV, near the $\Upsilon(5S)$ resonance. Belle subsequently found that $\Upsilon(5S)$ decays to $\pi^+ \pi^- \Upsilon(nS)$ final states are strong sources of charged, bottomonium-like states of $Z_b(10610)$ and $Z_b(10650)$.

6.1. The bottomonium-like mesons

Two charged bottomonium-like states, the $Z_b(10610)$ and $Z_b(10650)$, have been observed in the $\pi^+ \Upsilon(nS)$ and $\pi^+ h_b(mS)$ mass at Belle experiment in the decay process $\Upsilon(10680) \to \pi^+ \pi^- \Upsilon(nS)$ ($n=1,2,3$) and $\pi^+ \pi^- h_b(mP)$ ($m=1,2$). Since they have non-zero electric charge, they must contain a minimum of four quarks.

The mass of the $Z_b(10610)$ is $+(2.7 \pm 2.1)$ MeV above the $M_B + M_B^*$ threshold mass, while the $Z_b(10650)$ is $+(2.0 \pm 1.8)$ MeV above the $2M_B^*$. The proximity to
the $BB^*$ and $B^*\bar{B}^*$ threshold mass suggest that these $Z_b$ states may be a molecular type state formed by two mesons. This interpretation can be checked by studying the $Z_b \rightarrow BB^*$ and $Z_b \rightarrow B^*\bar{B}^*$ in the $\Upsilon \rightarrow \pi B(B^*)B^*$ three body decay. Figure 4 shows two distinct peaks at the masses of $Z_{b}(10610)$ and $Z_{b}(10650)$. In this fit the mass was fixed to the earlier measurements. This three body decay analysis is extended to $\Upsilon(10860) \rightarrow \Upsilon(nS)\pi^+\pi^-$ and $\Upsilon(10860) \rightarrow h_b\pi^+\pi^-$ to measure not only the newly observed $Z_b$ states but also the fractions of individual contribution to the whole three-body signals. The relative fractions for $Z_b$ are

$$
\frac{\mathcal{B}(Z_b(10610) \rightarrow BB^*)}{\mathcal{B}(Z_b(10610) \rightarrow \pi^+(60))} = 6.2 \pm 0.7 \quad \text{and} \quad \frac{\mathcal{B}(Z_b(10650) \rightarrow B^*\bar{B}^*)}{\mathcal{B}(Z_b(10650) \rightarrow \pi^-(60))} = 2.8 \pm 0.4,
$$

here statistical errors added only.

We started these $\Upsilon(5S)$ mass region search to see $Y(4260)$ analogy in $b$ quark sector. Then we found two charged bottomonium-like states which are the smoking guns for non $q\bar{q}$ mesons, then the next questions are “are there $c$-quark versions of $Z_b$ states?” The answer is followed in the next section.

### 6.2. The charmonium-like mesons

Search for new states were mostly confined to analyses of B-factory data including Belle and BaBar, now it has been expanded to include investigations of $Y(4260)$ and $Y(4360)$ resonance decays using data from BESIII. BESIII/BEPCII(Beijing Electron Positron Collider) has been operating as a $Y$ factory for the past six months, collecting large data samples of $e^+e^-$ annihilation events at 13 different CM energies from 3.9 GeV to 4.42 GeV, especially, at the peaks of the $Y(4230)$ (1090.0 pb$^{-1}$), $Y(4260)$ (826.8 pb$^{-1}$) and the $Y(4360)$ (5 pb$^{-1}$) resonances, allowing in-depth studies for the decay properties of these states.

Previous studies of these resonances were done at the B-factories using the radiative return process, which provides rather low luminosities in the charm threshold region. BESIII studied the process $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at a center of mass energy...
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of 4.26 GeV using 525 pb$^{-1}$ data. The Born cross section is measured to be $(62.9 \pm 1.9 \pm 3.7)$ pb, which is consistent with the existing results from the BaBar$^{27}$, CLEO$^{28}$ and Belle$^{29}$ experiments. In addition, a surprising structure was observed at the mass of $(3899 \pm 3.6 \pm 4.9)$ MeV/\(c^2\) and the width of $(46 \pm 10 \pm 20)$ MeV in the \(\pi^\pm J/\psi\) mass spectrum. The ratio \(R\) of the production rates is obtained to be \((21.5 \pm 3.3\,\text{(stat)} \pm 7.5\,\text{(syst)})\%\).

At the same time Belle also measured the cross section for \(e^+e^- \rightarrow \pi^+\pi^- J/\psi\) between 3.8 GeV and 5.5 GeV with 967 fb$^{-1}$ data sample collected by the Belle detector at or near the \(Y(nS)\) \((n=1,2,...,5)\) resonances.\(^{36}\) The \(Y(4260)\) is observed and its resonant parameters are determined. In the \(Y(4260)\) signal region, the peak state \(Z(3900)^\pm\) is observed 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 in the \(\pi^\pm J/\psi\) mass spectrum with a statistical significance larger than 5.2\(\sigma\). This new charged state is refer to as the \(Z_c(3900)\) or \(Z_c(3895)\).

Reference\(^{39}\) also reports the observation of this charged state at a 6\(\sigma\) significance level in the analysis of 586 pb$^{-1}$ data taken at \(\sqrt{s}=4170\) MeV, with the CLEO-c detector at the CESR collider at the Cornell University. The search for \(Z_c\) was made in the same decay chain as the BESIII study, \(e^+e^- \rightarrow \pi^\pm Z_c^\pm, Z_c^\pm \rightarrow \pi^\pm J/\psi\), but the data was taken at \(\sqrt{s}=4170\) MeV, on the peak of the

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**Fig. 5.** Fit to the \(M_{\text{max}}(\pi^\pm J/\psi)\) distribution from BESIII (left) and Belle (right). The signal shape is parameterized with same function by using their own mass resolution as described in the text, while background shape is parametrized differently.
ψ(4160) \((2^3D_1)\) charmonium state. The measured results of the \(Z(3900)^\pm\) are \(M = (3886 \pm 4\,\text{(stat)} \pm 2\,\text{(syst)}\) MeV/c², \(\Gamma = (37 \pm 4\,\text{(stat)} \pm 8\,\text{(syst)})\) MeV, and \(R = \frac{\sigma(e^+e^- \to \pi^\pm\pi^0\gamma J/\psi)}{\sigma(e^+e^- \to \pi^\pm\pi^0\gamma \rho J/\psi)} = (32 \pm 8 \pm 10)\%\), These are all in good agreement with the \(Z_c(3900)\) signals reported by BESIII and Belle observed in the decay of \(Y(4260)\). In addition, the first evidence for the neutral member state, \(Z_c^0(3900)\), of isospin triplet is also reported which decaying into \(\pi^0J/\psi\) at a 3.5\(\sigma\) significance level.

After this conference, BESIII reported the observation of this charged state at one more decay channel: \(e^+e^- \to \pi^\pm(D\bar{D}^*)^\mp\) at the center of mass energy of 4.26 GeV using 525 pb⁻¹ data\(^{40}\). A distinct charged structure is observed near the threshold of \(m(D) + m(D^\pm)\) in the \((D\bar{D}^*)^\mp\) mass distribution, at \(M = (3883.9 \pm 1.5 \pm 4.2)\) MeV/c², which is 2\(\sigma\) and 1\(\sigma\), respectively, below those of the \(Z_c \to \pi^\pm J/\psi\) peak observed by BESIII and Belle. Here the large \(Z_c\) signal yield permitted the establishment of the \(J^P\) quantum number of the \(Z_c\) system to be 1\(^+\). Assuming the \(Z_c(3885) \to DD^{*-}\) signal and the \(Z_c(3900) \to \pi J/\psi\) signal are from the same source, the partial width ratio \(\Gamma(Z_c(3885) \to DD^{-*})/\Gamma(Z_c(3900) \to \pi J/\psi) = 6.2 \pm 1.1 \pm 2.7\) is determined.

More searches for new charged states at higher mass region were followed by exploiting these BESIII scan data sample. A charged charmonium-like structure is observed near the threshold of \(m(D^{*\pm}) + m(D^\pm)\) in the \(\pi^\pm\) recoil mass spectrum in the process \(e^+e^- \to (D^*\bar{D}^*)^\mp\pi^\mp\) at a center of mass energy of 4.26 GeV using a 827 pb⁻¹ data\(^{38}\). Here a partial reconstruction technique is used to identify \((D^*\bar{D}^*)^\mp\pi^\mp\) system, which requires only one \(\pi^\mp\) reconstruction from primary decay, the \(D^+\) from \(D^{*+} \to D^+\pi^0\), and at least one soft \(\pi^0\) from either \(D^{*+}\) or \(\bar{D}^*\pi^0\). The Fig.\(^{39}\) shows the \(\pi^\mp\) recoil mass spectrum in data and various components in its fit are described in the Ref.\(^{38}\). From the fit, the mass and width of the \(Z_c^+(4025)\) signal are measured to be \((4026.3 \pm 2.6\,\text{(stat)} \pm 3.7\,\text{(syst)}\)) MeV/c² and \((24.8 \pm 5.6\,\text{(stat)} \pm 7.7\,\text{(syst)})\) MeV, respectively, with the statistical significance > 10\(\sigma\). The ratio \(R = \frac{\sigma(e^+e^- \to Z_c(4025)^\pm\pi^\mp \to (D^*\bar{D}^*)^\mp\pi^\mp)}{\sigma(e^+e^- \to (D^*\bar{D}^*)^\mp\pi^\mp)}\) is determined to be \(0.65 \pm 0.09\,\text{(stat)} \pm 0.06\,\text{(syst)}\).

BESIII has reported searches charged charmonium-like states at the \(\pi^\pm h_c\) mass

![Graph](image)

Fig. 6. Unbinned maximum likelihood fit to the \(\pi^-\) recoil mass spectrum in data. The \(Z_c^+(4025)\) signal shape is taken as the efficiency-weighted BW shape convoluted with a detector resolution function. See the text for a detailed description of the other components that were used in the fit.
distribution in the process $e^+ e^- \rightarrow \pi^+ \pi^- h_c$ at 13 different CM energies from 3.9 GeV to 4.42 GeV. Here three large statistics CM energies are 4.23 (1090.0), 4.26 (826.8), and 4.36 (544.5 pb$^{-1}$) GeV. The $h_c$ is reconstructed via $E1$ transition $h_c \rightarrow \gamma \eta_c$, and the $\eta_c$ is subsequently reconstructed from 16 different exclusive hadronic final states. An unbinned maximum likelihood fit is applied to $\pi^\pm h_c$ mass distribution summed over the 16 $\eta_c$ decay modes. Since each data sets at the CM energy of 4.23, 4.26 and 4.36 GeV shows similar structures, the same signal function with common mass and width is used to fit them simultaneously. Fig. 7 shows huge signal named $Z_c(4020)$ with its statistical significance greater than 8.9$\sigma$ and fit results give a mass of $(4021.8 \pm 1.0 \pm 2.5)$ MeV/c$^2$ and a width of $(5.7 \pm 3.4 \pm 1.1)$ MeV. The cross sections are also calculated at each CM energies points. Adding the $Z_c(3900)$ with mass and width fixed to the measurements of Ref. 35 in the fit results in only a 2.1$\sigma$ significance of it shown in the inset of Fig. 7. The $Z_c(4020)$ agrees within 1.5$\sigma$ of the $Z_c(4025)$ above which observed at CM energy 4.26 GeV.

7. Summary

The $J^{PC}=1^{--}$ $Y(4260)$ and $Y(5S)$ have no compelling interpretations. The $Y(4260)$ ($Y(5S)$) has huge couplings to $\pi^+ \pi^- J/\psi$ ($\pi^+ \pi^- Y(nS)$) that were not predicted in any model, and are strong sources of charged $Z_c$ ($Z_b$) states observed at $\pi^\pm J/\psi$, $\pi^\pm h_c$ ($\pi^\pm Y(nS), \pi^\pm h_b$) mass, and also with mass near $m(D^{(*)}) + m(D^{(*)}) + m(B^{(*)})$.

Numerous non$q\bar{q}$ mesons not specific to QCD have been found, such as a baryonium candidate in $J/\psi \rightarrow \gamma p\bar{p}$ at BESII and BESIII and XYZ mesons that contains $c\bar{c}$ and $b\bar{b}$ pairs together with light quarks $ud$ or $u\bar{u}$.

QCD motivated spectroscopies predicted by theorists do not seem to exist. No evidence was found for Pentaquarks, and an $H$ dibaryon with mass near $2m_N$ is excluded at stringent levels. No hint on $D_{s0}^{++}$ isospin partner state of $D_{s0}(2317)$ is observed.

![Fig. 7. Sum of the simultaneous fits to the $M_{\pi^\pm h_c}$ distributions at center-of-mass (CM) energies of 4.23 GeV, 4.26 GeV, and 4.36 GeV. The inset shows the sum of the simultaneous fit to the $M_{\pi^\pm h_c}$ distributions at 4.23 GeV and 4.26 GeV with $Z_c(3900)$ and $Z_c(4020)$.](image-url)
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