XYZ states in BESIII

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Abstract. Since the first XYZ particle $X(3872)$ was observed in 2003, many exotic states have been found by spectroscopy studies in beauty and charm sectors. In this paper, the latest XYZ results obtained by BESIII are reviewed, mainly including $X(3872), Y(4260), Y(4660), Z_c(3900)$ and $Z_c(4020)$. The spin parties of $Z_c(3900)$ have been studied. The comparison between different final states in Y states which are helpful to understand the nature of XYZ particles has been done.

1. Introduction

In 1960s, Gell-Mann and Zweig independently proposed the existence of quarks, which could describe the hadrons with two simple combinations: such as mesons are consists of $q\bar{q}$, and baryons are made of three quarks [1]. It is the lowest configuration, while quark mode allowed that there are hadrons with other combinations of quarks and gluons, such as glueballs, hybrids. These particles are called exotic states and difficult to be found. Until 2003 the first exotic candidate $X(3872)$ was found by the Belle collaboration, more exotic states are found with $c\bar{c}$ final states, which called XYZ or charmonium-like states. In the experiments, BESIII and CLEO-c works in charmonium region, the vector charmonium states could be generated directly, while other charmonium states can be studied through γ transition and hadronic transitions. The two B-factories, BaBar and Belle are working in the bottomonium region, use the taken data to study charmonium states through initial state radiative (ISR) process, two-photon process, double charmonium production or B meson decays. LHCb collected the world's largest data sample of beauty and charm hadrons, which provides great opportunities for studying B meson decays. In this paper, we mainly report the results of the XYZ states in the BESIII experiment.

2. Nature of $X(3872)$ state

$X(3872)$ is first observed by Belle in 2003 from B meson decay in the $\pi^+\pi^- J/\psi$ invariant mass spectrum [2]. This particle is subsequently confirmed by other experiments D0, CDF, Babar, LHCb and BESIII. Its mass is measured to be $3871.69 \pm 4.1 \pm 6.3$ MeV, which is close to the threshold of $D^0\bar{D}^{*0}$, and the width is less than 1.2 MeV due to the detector resolution. It could decay into $\pi^+\pi^- J/\psi$, $\pi^+\pi^-\pi^0 J/\psi$, $D^0\bar{D}^{*0}$, $D^0\bar{D}^0\pi^0$, $\gamma J/\psi$ and $\gamma\psi(2S)$. In the proton anti-proton collision, we do not find the isospin partners. Since it could decay to $\rho J/\psi$ and $\omega J/\psi$, there are different isopsin states. Since $X(3872)$ could decay to $\gamma J/\psi$, the C parity is determined to be even. CDF collaboration use helicity-amplitude analysis, by comparing angular distribution, to narrow the J^{pc} to 1^{++} or 2^{-+} [3]. In 2013 with 1 fb^{-1} data collected by LHCb, the only alternative assignment allowed by previous measurements, $J^{PC} = 2^{-+}$, is rejected with a confidence level equivalent to more than eight Gaussian standard deviations using the likelihood-ratio test in the full angular phase space [4]. In 2015, with full data collected in LHCb, the quantum number of $X(3872)$ is confirmed to be $J^{pc} = 1^{++}$, with the five-dimensional (5D) angular correlation analysis [5]. Since the $X(3872)$ is a 1^{++}state, it should be able to be produced through the radiative transition of an excited vector charmonium or charmonium-like states such as a ψ or a Y . With data samples collected with the BESIII detector operating at the BEPCII storage ring at center-of-mass (c.m.) energies from 4.009 to 4.420 GeV, the process $e^+e^- \to \gamma X(3872)$ is observed for the first time with a statistical significance of 6.3σ [6]. And in the $\omega J/\psi$ system, $X(3872)$ is observed with a significance more than 5σ [7]. The relative decay ratio of $X(3872) \to \omega J/\psi$ and $\pi^+\pi^- J/\psi$ is measured to be $R = 1.6^{+0.4}_{-0.3} \pm 0.2$. With a total of 9 fb^{-1} data collected in BESIII, a new decay mode of $X(3872) \to \pi^0\chi_{c1}$ is observed with a statistical significance of more than 5σ. The relative decay ratio is measure to be $0.88^{+0.33}_{-0.27} \pm 0.10$ by normalizing to the $X(3872) \to \pi^+\pi^- J/\psi$ [8].

3. Y particles

With e^+e^- collision, many vector particles with quantum numbers $J^{PC} = 1^{--}$ could be generated. There are several states like the $Y(4260)$, the $Y(4360)$, and the $Y(4660)$, whose behaviours are not like conventional charmonium states. They show strong coupling to hidden-charm final states, though their masses are above the open-charm thresholds.

The first such state is observed in BaBar experiment in the $\pi^+\pi^- J/\psi$ mass spectrum around 4.26 GeV [9] , which is later confirmed by Belle and CLEO, its mass is above open charmonium threshold. Besides the $Y(4260)$, the Belle Collaboration indicated that there may exist another very broad structure $Y(4008)$ around 4.05 GeV in the measured $\pi^+\pi^- J/\psi$ mass spectrum [10]. BaBar does not find the Y(4008) signal in the same process $e^+e^- \to \pi^+\pi^- J/\psi$, which is needed to be clarified in future experiments. Besides the Y(4260), the study of $\pi^+\pi^-\psi(2S)$ final state at BaBar shows another structure around 4.35 GeV [11], which was confirmed by Belle using the same method in the same final states. Another peak around 4.66 GeV is observed in Belle data [12], which is recently confirmed by BaBar. The peak around 4.66 GeV is also observed in the final states of $\Lambda_c^+\Lambda_c^-$ [13]. The mass and width is consistent with $\pi^+\pi^-\psi(2S)$ final state results. By comparing the cross section of Y(4660) decay into Λ_c pair and $\pi^+\pi^-\psi(2S)$, Y(4660) baryonic coupling is 10 times larger than mesonic coupling. It is possible to be a hidden charm baryonium [14]. BESIII indicates different trend for energy dependence comparing with Belle, which could influence the Y(4660) parameters [15]. More data from BESIII at threshold and above 4.6 GeV will be helpful to figure it out in the future.

BESIII collects e^+e^- collision data at c.m. energies from 3.77 to 4.60 GeV. By measuring the cross sections of different final states, the line shape can be used to study the charmounium-like Y states. In the process of $e^+e^- \to \pi^+\pi^- J/\psi$, there are two resonances observed. The first resonance has a mass of $(4222.0 \pm 3.1 \pm 1.4)$ MeV/c^2 and a width of $(44.1 \pm 4.3 \pm 2.0)$ MeV, while the second one has a mass of $(4320.0 \pm 10.4 \pm 7.0)$ MeV/c^2 and a width of $101.4^{+25.3}_{-19.7} \pm 10.2$ MeV, where the first errors are statistical and second ones are systematic. The first resonance agrees with the $Y(4260)$ resonance reported by previous experiments, called $Y(4220)$. The precision of its resonant parameters is improved significantly. The second resonance is observed in $e^+e^- \to \pi^+\pi^- J/\psi$ for the first time [16]. In 2017, BESIII presentes a study of $e^+e^- \to \pi^+\pi^- h_c$ at the c.m. energies from 3.9 to 4.6 GeV as used in $\pi^+\pi^- J/\psi$ analysis. The measurements indicate that the cross section does decrease as c.m. energy increases to 4.6 GeV, and there are two resonant structures in the full energy range. The parameters of the low mass structure are consistent with $\pi^+\pi^- J/\psi$ analysis with a mass of$(4218.4^{+5.5}_{-4.5} \pm 0.9)$ MeV/c^2 and a width of $(66.0^{+12.3}_{-8.3} \pm 0.4)$ MeV [17]. BESIII measures $e^+e^- \to \pi^+\pi^-\psi(2S)$ using 5.1 fb^{-1} of data collected at 16 c.m. energies from 4.0 to 4.6 GeV with two decay modes $\psi(2S) \to \pi^+\pi^- J/\psi$ and $\psi(2S) \to$ neutrals J/ψ, where "neutrals" refers to $\pi^0\pi^0$, π^0, η, and $\gamma\gamma$. The measurement is almost background free, and BESIII measures the cross sections in good consistency with previous BaBar and Belle results, but with much improved precision. The data requires a lower-mass resonance with a mass of $(4209.5 \pm 7.4 \pm 1.4)$ MeV/c^2 and a width of $(80.1 \pm 24.6 \pm 2.9)$ MeV with a statistical significance of 5.8σ [18]. BESIII reports improved measurements of the production cross section of $e^+e^- \to D^0 D^{*-} \pi^+ + c.c.$ at C.M. energies from 4.05 to 4.60 GeV at 15 "XYZ data" points and 69 "R-scan data" points. The fit yields a mass of $(4228.6 \pm 4.1 \pm 6.3)$ MeV/c^2 and a width of $(77.0 \pm 6.8 \pm 6.3)$ MeV for the lower mass structure, and a mass of (4404.7 ± 7.4) MeV/c^2 and a width of (191.9 ± 13.0) MeV for the higher mass one, where the errors are statistical only for the higher mass structure. Since the lower mass resonance is in good agreement as the $Y(4220)$ observed in $\pi^+\pi^- J/\psi$ and $\pi^+\pi^- h_c$ modes, this indicates the first observation of the $Y(4220)$ decays into open-charm final state $D^0 D^{*-} \pi^+ + c.c.$ [19]. The cross section of the process $e^+e^- \to \omega\chi_{c0}$ is measured at c.m. energies from $\sqrt{s} = 4.178$ to 4.278 GeV using a data sample of 7 fb^{-1} collected with the BESIII. The dependence of the cross section on $\sqrt{s}$ shows a resonant structure with mass of $(4218.5 \pm 1.6 \pm 4.0)$ MeV/c^2 and width of $(28.2 \pm 3.9 \pm 1.6)$ MeV, respectively [20]. Figure 1 shows comparison of the measured mass and width of the $Y(4220)$ between the different processes. The masses are consistent with each other, while the widths are not. The widths from the processes $e^+e^- \to \pi^+\pi^- h_c$, $\pi^+\pi^-\psi(2S)$, and $\pi^+ D^0 D^{*-} + c.c.$ are larger than those from the processes $e^+e^- \to \omega\chi_{c0}$ and $\pi^+\pi^- J/\psi$. As the discrepancy existence, we could not draw a conclusion that they are from the same resonance. With the further precision measurements, we could find out the nature of these resonances.

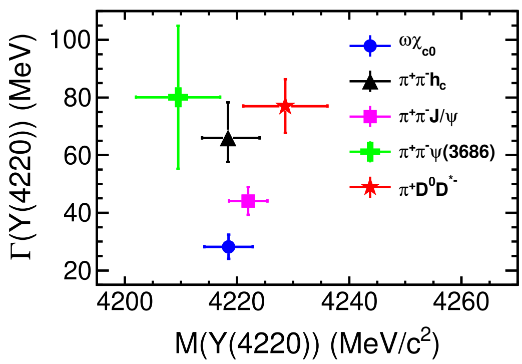

Figure 1. Mass and width of the $Y(4220)$ obtained from the processes $e^+e^- \to \omega\chi_{c0}$, $\pi^+\pi^- h_c$, $\pi^+\pi^- J/\psi$, $\pi^+\pi^-\psi(2S)$ and $\pi^+ D^0 D^{*-} + c.c.$

4. Z particles

The Z_c states are consist of a charmonium state and a pion. So at least there are four quarks in Z_c states. The BESIII experiment studies the $e^+e^- \to \pi^+\pi^- J/\psi$ process at a c.m. energy of 4.26 GeV using a 525 pb^{-1} data sample [21] . In the Belle experiment, the cross section of $e^+e^- \to \pi^+\pi^- J/\psi$ is measured from 3.8-5.5 GeV using the ISR method with a 967 fb^{-1} data sample collected at or near the Υ(nS) (n = 1, 2, 4, 5) resonances. Events in the $Y(4260)$ signal region are investigated [10]. Both experiments found the $Z_c(3900)$ particle in the spectrum of $M(\pi^\pm J/\psi)$, and the mass and width are consistent with each other. The $Z_c(3900)$ state is confirmed with CLEO-c data at a c.m. energy of 4.17 GeV, and a 3.5σ evidence for $Z_c(3900)^0$ is observed in $\pi^0\pi^0 J/\psi$ process [22]. With the data collected at c.m. energy ranges from 4.19-4.42 GeV, the BESIII experiment studies the process of $e^+e^- \to \pi^0\pi^0 J/\psi$. A neutral state $Z_c(3900)^0 \to \pi^0 J/\psi$ with a significance of 10.4σ is observed, with the mass and width measured to be $(3894.8 \pm 2.3 \pm 3.2)$ MeV/c^2 and $(29.6 \pm 8.2 \pm 8.2)$ MeV, respectively. The mass of $Z_c(3900)^0$ agreed with $Z_c(3900)^\pm$, and width is narrower. It is interpreted as the neutral partner of the $Z_c(3900)^\pm$. And the production rate of $e^+e^- \to \pi^0 Z_c(3900)^0$ is about a half of the rate of $e^+e^- \to \pi^+ Z_c(3900)^- + c.c.$, which determines the $Z_c(3900)$ is an iso-vector state [23]. Since the mass of $Z_c(3900)$ is about 20 MeV/c^2 above the $D\bar{D}^* + c.c.$ mass threshold, which is suggestive of a virtual $D\bar{D}^*$ molecule-like structure. The BESIII experiment studies $e^+e^- \to \pi^\pm(D\bar{D}^*)^\mp$ and observes the open-charm decay $Z_c(3900)^\pm \to (D\bar{D}^* + c.c.)^\pm$ with single-tag technique [24] and double-tag techinique [25]. A structure close to the threshold is observed in the $(D\bar{D}^*)^\pm$ invariant mass distributions, and fitted with a mass-dependent-width BW function. The pole mass and width are measured to be $(3883.9 \pm 1.5 \pm 4.2)$ MeV/c^2 and $(24.8 \pm 3.3 \pm 11.0)$ MeV with single-tag technique. For the double-tag technique, the pole mass and width are $(3881.7 \pm 1.6 \pm 1.6)$ MeV/c^2 and $(26.6 \pm 2.0 \pm 2.1)$ MeV, respectively. In an analysis of $e^+e^- \to \pi^0(D\bar{D}^*)^0$, the $Z_c(3900)^0 \to (D\bar{D}^*)^0$ is also observed [26] and agree with the expectation from isospin symmetry. Additional Z_c decay mode has been searched in BESIII with the process of $e^+e^- \to \pi^+\pi^-\pi^0\eta_c$ and intermediate states decay into $\rho\eta_c$ at c.m. energy 4.23, 4.26, and 4.36 GeV. In this analysis, η_c is reconstructed with 9 hadronic final states. An evidence of $e^+e^- \to \pi^\mp Z_c(3900)^\pm \to \pi^\mp\rho^\pm\eta_c$ is observed at $\sqrt{s} = 4.23$ GeV with a statistical significance of 4.3σ . No signal is observed at $\sqrt{s}$ =4.26 and 4.36 GeV and the upper limits of the production cross sections at the 90% confidence level (C.L.) are determined. BESIII determines the spin-parity of the Zc(3900) based on a PWA of $e^+e^- \to \pi^+\pi^- J/\psi$ events at $\sqrt{s} = 4.23$ and 4.26 GeV Amplitudes of the PWA are constructed with the helicity-covariant method, and J^P is determined to be 1^+ [27].

BESIII measures cross sections of $e^+e^- \to \pi^+\pi^- h_c$ at c.m. energies of 3.90– 4.42 GeV with $h_c \to \gamma\eta_c$ and η_c decays into 16 hadronic final states. A new resonance $Z_c(4020)$ is observed with mass of $(4022.9 \pm 0.8 \pm 2.7$ MeV/c^2 and width of $7.9 \pm 2.7 \pm 2.6$ MeV [28]. BESIII also observes $e^+e^- \to \pi^0\pi^0 h_c$ at $\sqrt{s}$ =4.23, 4.26, and 4.36 GeV for the first time. The measured Born cross sections are about half of those for $e^+e^- \to \pi^+\pi^- h_c$ [29]. The mass of $Z_c(4020)$ is slightly higher than the $D^*\bar{D}^*$ threshold, so it may couples to $D^*\bar{D}^*$ final state. The BESIII experiment studies the $e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp$ process using data at $\sqrt{s}$ =4.26 GeV [30]. The Born cross section is measured to be $(137 \pm 9 \pm 15)$ pb. In the recoil mass spectrum of $\pi^\mp$, a structure is observed with the mass of $(4026.3 \pm 2.6 \pm 3.7)$ MeV/c^2 and the width of $(24.8 \pm 5.6 \pm 7.7)$ MeV, respectively. Also its neutral partner is searched with the processes of $e^+e^- \to (D^{*0}\bar{D}^{*0})\pi^0$ and $(D^{*+}D^{*-})\pi^0$ [31]. In the recoil mass of π^0, a structure is observed with the mass of of $(4025.5^{+2.0}_{-4.7} \pm 3.1)$ MeV/c^2 and width of $(23.0 \pm 6.0 \pm 1.0)$ MeV. By comparing the ratio of $\sigma(e^+e^- \to Z_c(4020)^0\pi^0 \to (D^*\bar{D}^*)^0\pi^0)$ and $\sigma(e^+e^- \to Z_c(4020)^+\pi^- \to (D^*\bar{D}^*)^+\pi^-)$, it is compatible at $\sqrt{s} = 4.26$ GeV, which is expected from isospin symmetry.

BESIII studies the process $e^+e^- \to \pi^+\pi^-\psi(2S)$ using 5.1 fb^{-1} of data at 16 c.m. energy points from 4.0 to 4.6 GeV [32]. A charged charmonium-like structure is observed in the $\pi^\pm\psi(2S)$ invariant mass spectrum at c.m. energy 4.416 GeV. A fit with a S-wave BW function yields a mass of $M = (4032.1 \pm 2.4)$ MeV/c^2. The width of the intermediate state varies over a wide range for different kinematic regions of data at $\sqrt{s} = 4.416$ GeV.

5. Summary

Great progresses in understand XYZ states have been achieved recently. The properties of $X(3872)$, such as the mass, quantum number, production and decays are studied. The quantum numbers of $Z_c(3900)$ have been determined. Many studies for Y(4260) structure are done in BESIII. The relations between exotic states are built. But there are still many remain unanswered questions. More data is expected to understand the nature of XYZ states in the future.

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