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Results of XYZ states from experiments

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Since the first XYZ particle $X(3872)$ was observed in 2003, many exotic states have been found by spectroscopy studies in beauty and charm hadrons. In this paper, the latest XYZ results are reviewed, mainly including $X(3872), X(3915), Y(4260), Y(4360), Y(4660), Z_c(3900), Z_c(4020)$ and $Z(4430)$. The spin parties of X and Z particles have been studied, and the comparison between different final states in Y particles has been done, which are helpful to understand the nature of XYZ particles.

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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 up 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, and more than three quarks. These particles are called exotic states and hard 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 radiative transition and hadronic transitions. The two B-factories, BaBar and Belle work in the bottomonium region and the data taken can be used to study charmonium states through 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 XYZ particles by B meson decays.

2. X particles

$X(3872)$ was firstly observed in Belle in 2003 from B meson decay in the $\pi^+\pi^-J/\psi$ invariant mass spectrum [2]. This particle is subseqeuntly confirmed by other experiments, such as D0, CDF, Babar, LHCb and BESIII. Its mass is measured to be $(3871.69 \pm 4.1 \pm 6.3)$ MeV/c^2, 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 $\pi^+\pi^-J/\psi$, $\pi^+\pi^-\pi^0J/\psi$, $D^0\bar{D}^{*0}$, $D^0\bar{D}^0\pi^0$, $\gamma J/\psi$ and $\gamma\psi(2S)$. In the proton anti-proton collision, the isospin partners were not found. It could decay to $\rho J/\psi$ and $\omega J/\psi$, which are different isopsin states. Since $X(3872)$ could decay to $\gamma J/\psi$, the C parity is determined to be even. CDF collaboration used 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 charmoniumlike states such as ψ or Y . With data samples collected with the BESIII detector operating at the BEPCII storage ring at center-of-mass 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].

$X(3915)$ was firstly observed in the decay of $B \to K\omega J/\psi$ at Belle [9]. By the study of $B^{0,+} \to J/\psi\omega K^{0,+}$, Babar confirmed this particle [10]. In the process of $\gamma\gamma \to \omega J/\psi$, Belle observed the charmonium-like state related to $X(3915)$ [11]. In the same process, Babar confirmed the the existence of the charmonium-like resonance $X(3915)$ decaying to $J/\psi\omega$ with a significance of 7.6 standard deviations, including systematic uncertainties [12]. A spin-parity analysis supports the assignment $J^P = 0^+$ and therefore the identification of the signal as due to the $\chi_{C0}(2P)$ resonance. But in 2017, with a full amplitude analysis of the process of $e^+e^- \to J/\psi D\bar{D}$, a new charmonium-like state $X^*(3860)$ is observed with a significance of 6.5σ [13]. The $J^{PC} = 0^{++}$ hypothesis is favored over the 2^{++} hypothesis at the level of 2.5σ. The new state $X^*(3860)$ seems to be a better candidate for the $\chi_{C0}(2P)$ charmonium state than the $X(3915)$, since its properties are well matched to expectations for the $\chi_{C0}(2P)$ resonance.

3. Y particles

With e^+e^- collision, many vectors with quantum numbers $J^{PC} = 1^{--}$ could be generated. There are several states as $Y(4260)$, $Y(4360)$ and $Y(4660)$, 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 at BaBar in the $\pi^+\pi^- J/\psi$ mass spectrum around 4.26 GeV [14] , which is later confirmed by Belle and CLEO, its mass is above open charmonium threshold. Besides $Y(4260)$, 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 [15]. BaBar did 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 [16], which was confirmed by Belle using the same method in the same final states. Another peak around 4.66 GeV was observed in Belle data [17], which is recently confirmed by BaBar. The peak around 4.66 GeV is also observed in the final states of $\Lambda_c^+\Lambda_c^-$ [18]. The mass and width are 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 [19]. BESIII indicates different trend for energy dependence comparing with Belle, which could influence the Y(4660) parameters [20]. More data from BESIII at threshold and above 4.6 GeV will be helpful to figure it out in the future.

BESIII collected e^+e^- collision data at center-of-mass (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 systematical. 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 [21]. In 2017, BESIII presented 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 [22]. 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 [23]. BESIII reported 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 $D^0 D^{*-}\pi^+ + c.c.$ [24]. 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 [25]. 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.

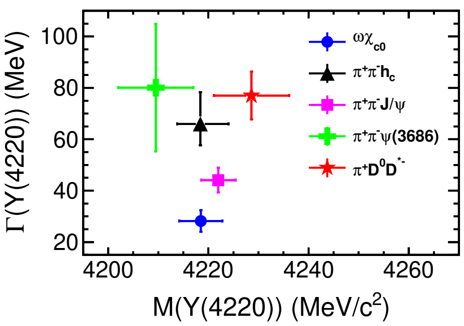

Figure 1: Mass and width of the $Y(4220)$ obtained from the processes $e^+e^- \to \omega\chi_{c0}$, $\pi^+\pi^- h_c$, $\pi^+\pi^- J/\psi$, $\pi^+\pi^-\psi(2S)$ and $\pi^+ D^0 D^{*-} + c.c.$

4. Z particles

Among all the exotic hadron candidates, the Z states are unique, since they are observed in a final state with a conventional charmonium plus a pion, and the lowest configuration is four quarks, which must be exotic. The first such kind of state observed in experiments is $Z(4430)$, which is observed in Belle in B meson decays, shown as a peak in the $\pi^{\pm}\psi(2S)$ mass spectrum [26]. But this is not confirmed by Babar using a two dimensional analysis, and BaBar found the data can be explained as the reflection of the K^* states in the $K\pi$ mass spectrum. After BaBar paper, there are two updated analysis from Belle, first also using two dimensional analysis with the same data used in the first publication, and then a four dimensional Dalitz analysis to a larger data sample. Both updatings confirmed the existence of $Z(4430)$, but found a higher mass and wider width. The existence of $Z(4430)$ remains questionable until 2014, confirmed by LHCb. The same four dimensional analysis as performed at the latest Belle publication is used, the $Z(4430)$ is confirmed with a significance larger than 10σ and the measured mass and width are consistent with latest Belle result, beside, the quantum number is also determined to be 1^+ by comparing the likelihood values with different quantum number hypothesises. Another important measurement in the LHCb paper is the Argand diagram for the $Z(4430)$ amplitude, which should show a counter clock signature in the real and imaginary $Z(4430)$ amplitude plane. The large data sample at LHCb makes it possible to release the assumption of a BW function, and measure the real and imaginary parts as a function of mass, which is consistent with a resonance behaviour character [27].

The BESIII experiment studied 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 [28] . 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 [15]. Both experiments found the $Z_c(3900)$ particle in the spectrum of $M(\pi^{\pm}J/\psi)$. The $Z_c(3900)$ state was confirmed shortly with CLEO-c data at a C.M. energy of 4.17 GeV, and the mass and width agreed very well with the BESIII and Belle measurements. In addition, a 3.5σ evidence for $Z_c(3900)^0$ in the CLEO-c data was also reported in $\pi^0\pi^0 J/\psi$ process [29]. BESIII measured the cross sections of $\pi^0\pi^0 J/\psi$ with data at C.M. energy range from 4.19-4.42 GeV. A neutral state $Z_c(3900)^0 \to \pi^0 J/\psi$ with a significance of 10.4σ was 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. This state decays to $\pi^0 J/\psi$ and its mass is close to that of $Z_c(3900)^{\pm}$, so it is interpreted as the neutral partner of the $Z_c(3900)^{\pm}$. The measured production rate of $e^+e^- \to \pi^0 Z_c(3900)^0$ is about half of that for $e^+e^- \to \pi^+ Z_c(3900)^- + c.c.$, which is consistent with the isospin symmetry expectation. This determines the $Z_c(3900)$ is an iso-vector state [30]. BESIII determined 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^+ [31]. BESIII measured 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 [32]. 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 $e^+e^- \to \pi^+\pi^- h_c$ [33].

5. Summary

Great progresses have been achieved recently. The properties of $X(3872)$, such as the mass, quantum number, production and decays are studied. The quantum numbers of two Z states ($Z_c(3900)$, $Z(4430)$) have been determined. Many studies for Y(4260) structure are done in BE-

SIII. 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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