PROCEEDINGS OF SCIENCE

XYZ States at BESIII

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In recent years, a new class of exotic charmonium-like states, also referred to as XYZ states, have been discovered. Being incompatible with the simple quark-antiquark model, they are candidates for non-standard hadrons such as tetraquarks, meson molecules, and hybrids. The BESIII experiment operating at the electron-positron collider BEPCII at IHEP (Beijing) has accumulated a large amount of data in the tau-charm mass region and offers unique access to the study of XYZ states. In this proceeding, the latest results on XYZ states at BESIII are presented.

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1. Introduction

Charmonium spectroscopy has a long history going back to the 70's, when the J/ψ and ψ' states were discovered [1, 2, 3]. Charmonia below the open-charm threshold can be very accurately described by simple non-relativistic potential models [4, 5]. Above the threshold, the situation is different: Many predicted states have not been discovered, while many unpredicted have. They exhibit properties, that hardly match the expected pattern of conventional charmonium made from a $c\bar{c}$ quark pair [6, 7, 8]. In order to underline their unknown nature, they are labeled exotic charmonium-like resonances or XYZ states. One of their unconventional features is, that they all show a relative strong coupling to hidden-charm decay products, in contrast to pure $c\bar{c}$ states, which are expected to decay almost entirely into $D\bar{D}$ meson pairs. According to a widely accepted convention,[1] the neutral exotics with quantum numbers other than 1^{--} are referred to as X states, the ones with 1^{--} are called Y states. Charged charmonium-like (and hence inherently non-$c\bar{c}$) resonances are termed Z states.

If they are non-standard charmonium states, they must be something else. They are considered as candidates for tetraquarks, meson molecules, hybrid mesons, or hadro-quarkonium. In principal, all of those classes of hadrons are allowed in QCD, but so far no unambiguous identification of them is possible. With its unique capabilities, the BESIII experiment is making a significant contribution to the deeper understanding of exotic hadrons and QCD in general.

After a brief description of the BESIII experiment, the most recent results of BESIII involving XYZ states are presented.

2. The BESIII Experiment

The BESIII (BEijing Spectrometer III) experiment is recording data from e^+e^- collisions in the energy range of $2-4.6\,\mathrm{GeV}$ provided by the BEPCII accelerator at the institute of high energy physics in Beijing.

The BESIII detector is a magnetic spectrometer covering the polar angle regime of $|\cos\theta| < 0.93$. The inner part consists of a helium based multiwire drift chamber, a plastic scintillator time-of-flight system, and an CsI(Tl) electromagnetic calorimeter. These subdetectors are located inside a 1 T magnetic field provided by a superconducting solenoid magnet. Its return yoke serves as an absorber for a muon identifier made from resistive plate chambers. In 2015, the plastic scintillators in the endcap time-of-flight system were replaced by multigap resistive plate chambers with an improved timing resolution [9, 10]. A more detailed description of the BESIII detector can be found in reference [11].

Since its start of operation in 2009, BESIII collected the world's largest data samples in the charmonium region. The relevant data sets for the study of XYZ states are mainly recorded at collision energies above 4 GeV summing up to an integrated luminosity of approximately $12\,\mathrm{fb}^{-1}$. However, most of the following studies are based only on a fraction of that data.

[1] The PDG uses a different one.

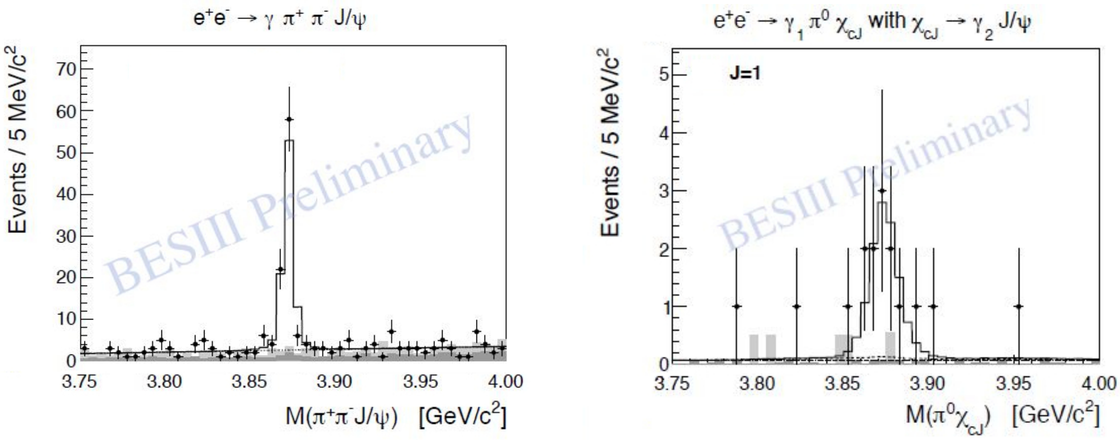

Figure 1: Preliminary $X(3872)$ signal in the reaction $e^+e^- \to \gamma X(3872)$ for the center-of-mass energy range $4.15\,\text{GeV} < \sqrt{s} < 4.30\,\text{GeV}$. In the left hand panel, the $X(3872)$ state is reconstructed via its decay to $\pi^+\pi^- J/\psi$ and the right hand panel, it is observed for the first time in the decay to $\pi^0\chi_{c1}$. The dots with error bars are data, the solid line is the fit and the gray histograms are background contribution estimated from Monte-Carlo and J/ψ sidebands.

3. Recent Results on X States

The most prominent example of XYZ states is probably the $X(3872)$, being the first exotic charmonium-like state discovered in 2003 in the $\pi^+\pi^- J/\psi$ subsystem of the $B^\pm \to K^\pm\pi^+\pi^- J/\psi$ decay [12]. Since then, it has been additionally observed in pp and $p\bar{p}$ collisions and in the decays to $\omega J/\psi$, $\gamma J/\psi$, $\gamma\psi'$, and $D^0\bar{D}^{*0} + c.c.$ In 2014, BESIII reported the production mechanism via $e^+e^- \to \gamma X(3872)$ at $\sqrt{s} = 4.23$ and $4.26\,\text{GeV}$ [13]. With much improved statistics of the newly recorded data between 4.0 and 4.6 GeV, a reanalysis is performed, c.f. Figure 1 left panel. The preliminary result only shows $X(3872)$ production at center-of-mass energies in the range of $4.15\,\text{GeV} < \sqrt{s} < 4.30\,\text{GeV}$ in support of the previous hypothesis of the $Y(4260) \to \gamma X(3872)$ decay.

Additionally, the new data motivates the search for the $X(3872) \to \pi^0\chi_{cJ}$ decay mode. Therefore, the reaction $e^+e^- \to \gamma\gamma\pi^0 J/\psi$ is studied, where a γ is combined with the J/ψ to form a χ_{cJ} candidate. For the $J = 1,2$, there is no significant signal, but for the $X(3872) \to \pi^0\chi_{c1}$ channel, a preliminary significance of $5.2\,\sigma$ is observed, c.f. Figure 1 right panel. This is the first observation of this decay channel. The preliminary branching ratio normalized to the one for the $\pi^+\pi^- J/\psi$ channel reads $\mathscr{B}(X(3872) \to \pi^0\chi_{c1})/\mathscr{B}(X(3872) \to \pi^+\pi^- J/\psi) = 0.88^{+0.31}_{-0.26} \pm 0.14$, where the first uncertainty is statistical and the second is systematic, as used throughout this proceeding. According to Dubynskiy and Voloshin [14], this new channel disfavors the $X(3872)$ viewed as a conventional charmonium state.

4. Recent Results on Y States

Due to the 1^{--} quantum numbers, BESIII is an excellent laboratory to study Y states, as they can be produced directly in formation $e^+e^- \to Y \to$ hadrons. They may be identified as structures in the cross section lineshape of the production of exclusive final states. In the following, the results with different final states are listed.

4.1 $e^+e^- \to \pi^+\pi^- J/\psi$

The first Y state to be discovered is the $Y(4260)$ resonance observed by BaBar via the initial state radiation (ISR) technique in the process $e^+e^- \to \gamma_{ISR}Y(4260) \to \gamma_{ISR}\pi^+\pi^- J/\psi$ [15]. Soon, it was confirmed by CLEO and Belle [16, 17]. Until recently, the world average of the $Y(4260)$ mass and width were $(4251 \pm 9)\,\mathrm{MeV}/c^2$ and $(120 \pm 12)\,\mathrm{MeV}/c^2$, respectively [18]. Based on $9\,\mathrm{fb}^{-1}$, BESIII reported the most precise measurement of the $e^+e^- \to \pi^+\pi^- J/\psi$ cross section in the range of 3.77 to 4.60 GeV [19]. The observed lineshape of the cross section is incompatible with a single Breit-Wigner resonance. Instead, the structure can be modeled by two coherent resonances with a statistical sgnificance larger than $7.6\,\sigma$ over the single resonance hypothesis. The corresponding parameters of the first resonance are $m_1 = (4222.0 \pm 3.1 \pm 1.4)\,\mathrm{MeV}/c^2$ and $\Gamma_1 = (44.1 \pm 4.3 \pm 2.0)\,\mathrm{MeV}/c^2$ and the ones of the second resonance are $m_2 = (4320.0 \pm 10.4 \pm 7.0)\,\mathrm{MeV}/c^2$ and $\Gamma_2 = (101.4^{+25.3}_{-19.7} \pm 10.2)\,\mathrm{MeV}/c^2$. The first resonance is compatible with the one oberseved earlier by BESIII in the reaction $e^+e^- \to \omega\chi_{c0}$ [20].

4.2 $e^+e^- \to \pi^+\pi^- h_c$

Another reaction, that was investigated by BESIII, is $e^+e^- \to \pi^+\pi^- h_c$ [21]. The h_c is reconstructed via its radiative transition to $\gamma\eta_c$ and the reconstruction of 16 different exclusive decay channels of the η_c. The cross section lineshape in the region $3.90\,\mathrm{GeV} < \sqrt{s} < 4.60\,\mathrm{GeV}$ also reveals a double structure. A fit of two coherent Breit-Wigner amplitudes to the data results in the resonance parameters $m_1 = (4218.4^{+5.5}_{-4.5} \pm 0.9)\,\mathrm{MeV}/c^2$ and $\Gamma_1 = (66.0^{+12.3}_{-8.3} \pm 0.4)\,\mathrm{MeV}/c^2$ for the first one and $m_2 = (4391.5^{+6.3}_{-6.8} \pm 1.0)\,\mathrm{MeV}/c^2$ and $\Gamma_2 = (139.5^{+16.2}_{-20.6} \pm 0.6)\,\mathrm{MeV}/c^2$ for the second one. The mass of the first resonance is compatible with the state observed in the previous study, but its width is a little too large.

4.3 $e^+e^- \to \pi\pi\psi'$

BESIII also measured the cross section of $e^+e^- \to \pi^+\pi^-\psi'$ using 16 different energy points between 4.0 and 4.6 GeV with a total integrated luminosity of $5.1\,\mathrm{fb}^{-1}$ [22]. The ψ' is reconstructed via its decay to $X_i J/\psi$, where X_i stands for $\pi^+\pi^-$, $\pi^0\pi^0$, π^0, η, and $\gamma\gamma$. The observed cross section is compatible with the previous results from BaBar and Belle, that claimed the observation of a resonance at $\approx 4360\,\mathrm{MeV}/c^2$. However, the significantly improved precision implies again a more complex structure than a single resonance. A fit to the data with three resonances is performed. One of them models the lower tail of the $Y(4660)$ state and the other two are needed to describe the aforementioned structure. The parameters of the latter two are $m_1 = (4209 \pm 7.4 \pm 1.4)\,\mathrm{MeV}/c^2$, $\Gamma_1 = (80.1 \pm 24.6 \pm 2.9)\,\mathrm{MeV}/c^2$, $m_2 = (4383.8 \pm 4.2 \pm 0.8)\,\mathrm{MeV}/c^2$, and $\Gamma_2 = (84.2 \pm 12.5 \pm 2.1)\,\mathrm{MeV}/c^2$. The first resonance is compatible with the one observed in the above final states. The second resonance has a comparable mass as the second state seen in $e^+e^- \to \pi^+\pi^- h_c$, but with smaller width.

A similar study, but with neutral pions was performed as well. The cross section of $e^+e^- \to \pi^0\pi^0\psi'$ at five different center-of-mass energies corresponding to 4.226, 4.258, 4.358, 4.416, and

4.600 GeV is approximately half the cross section of $e^+e^- \to \pi^+\pi^-\psi'$, as expected from isospin symmetry [23].

4.4 $e^+e^- \to K\bar{K}J/\psi$

The process $e^+e^- \to K^+K^-J/\psi$ as well as $e^+e^- \to K_S^0K_S^0J/\psi$ is investigated using 4.7 fb^{-1} of data spread across 14 different energy points between 4.2 and 4.6 GeV [24]. A structure at ≈ 4220 MeV is visible beeing compatible with the resonance seen in the above measurements. Additionally, the cross section bumps around 4500 MeV indicating a possible structure in the $K\bar{K}J/\psi$ system, that is absent in $\pi^+\pi^-J/\psi$. The cross section ratio of the charged mode (K^+K^-J/ψ) compared to the neutral mode ($K_S^0K_S^0J/\psi$) satisfies isospin symmetry.

4.5 $e^+e^- \to \eta h_c$

BESIII performed a search for the reaction $e^+e^- \to \eta h_c$ in the range $4.0\,\text{GeV} < \sqrt{s} < 4.6\,\text{GeV}$ [25]. Therefore, the data sets at 15 different center-of-mass energies with each $40-1090\,\text{pb}^{-1}$ were analyzed. Only at $\sqrt{s} = 4.23$ GeV, a significant cross section of $(9.5^{+2.2}_{-2.0} \pm 2.7)$ pb is measured, the energy, at which the integrated luminosity is largest (1090 pb^{-1}). Still, it is worth mentioning, that this energy is very close the mass of the resonance observed in the above channels. At $\sqrt{s} = 4.36$ GeV, there is evidence for a $e^+e^- \to \eta h_c$ cross section of $(10.0^{+3.1}_{-2.7} \pm 2.6)$ pb with a significance of 4.3 σ and a corresponding integrated luminosity of 540 pb^{-1}.

4.6 $e^+e^- \to \pi^+D^0D^{*-} + c.c.$

The production of the open-charm final state $\pi^+D^0D^{*-}$ is studied using the data sets collected at 84 different collision energies between 4.0 and 4.6 GeV divided into 15 high statistics data samples ($40-1090\,\text{pb}^{-1}$) and 69 samples with less than 20 pb^{-1} [26]. The charge conjugated mode is implied. Similar to most of the studies mention above, two structures show up in the cross section. The first one has a mass of $(4228.6 \pm 4.1 \pm 5.9)\,\text{MeV}/c^2$ and a width of $(77.1 \pm 6.8 \pm 6.9)$ MeV as determined from a fit of two coherent Breit-Wigner resonances and a phase space term. This is the first time, that a Y state is associated with an open-charm final state. The mass and width of the second resonance are around 4400 MeV and 200 MeV, respectively. However, the fit result is strongly model dependent and those values should be regarded as rough order-of-magnitude estimates.

5. Recent Results on Z States

In 2013, BESIII reported the discovery of the charged charmonium-like $Z_c(3900)^\pm$ state in the $\pi^\pm J/\psi$ subsystem of the $e^+e^- \to \pi^+\pi^-J/\psi$ process based on 525 pb^{-1} collected at $\sqrt{s} = 4.26$ GeV [27]. In order to determine the quantum numbers, a full amplitude analysis of the $e^+e^- \to \pi^+\pi^-J/\psi$ reaction was performed based on a total integrated luminosity of about 1.9 fb^{-1} at $\sqrt{s} = 4.23$ and 4.26 GeV [28]. In addition to the $Z_c(3900)^\pm$ contribution and a non-resonant three-body amplitude, the $\pi^+\pi^-$ system is modeled both with S-wave amplitudes in the form of σ, $f_0(980)$, and $f_0(1370)$ resonances as well as the D-wave with the $f_2(1270)$ resonance. Using a

The distributions of the $Z_c(3900)^\pm$ polar and the J/ψ helicity angle in the $Z_c(3900)^\pm \to \pi^\pm J/\psi$ decay are compared to the expectations from different spin and parity assignments to the $Z_c(3900)$ state. The data favors the $J^P = 1^+$ hypothesis by more than 7 σ over other J^P assumptions.

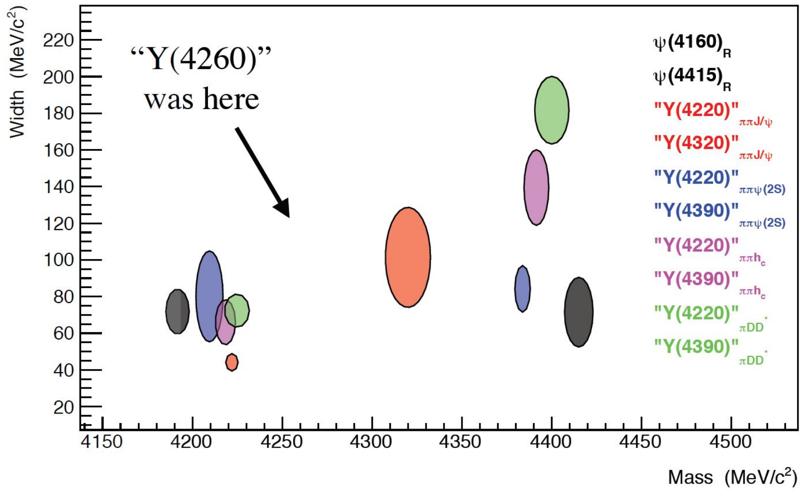

Figure 2: Overview of the resonance parameters of the two structures observed in the production of several exclusive hidden- or open-charm channels in e^+e^- collisions between 4.0 and 4.6 GeV, as determined using Breit-Wigner parameterization. The size of the ovals reflect the uncertainties of both the mass and the width. Additionally, the parameters of the established charmonium resonances $\psi(4160)$ and $\psi(4415)$ are shown in black. Courtesy to Ryan Mitchell.

Motivated by the $Z_c(3900)^{\pm}$ state appearing as a $\pi^{\pm}J/\psi$ resonance in $e^+e^- \to \pi^+\pi^-J/\psi$, an analysis of the $\pi^+\pi^-\psi'$ Dalitz plot was performed during the same analysis as in Section 4.3 [22]. For $\sqrt{s} = 4.416\,\text{GeV}$, a $\pi^{\pm}\psi'$ resonant structure is observed with a mass around 4030 MeV. A neutral isospin partner decaying into $\pi^0\psi'$ is observed at the same mass in the $e^+e^- \to \pi^0\pi^0\psi'$ reaction [23]. However, the used parameterizations cannot fully describe the data, in particular when other center-of-mass energies are taken into account. More data is needed for a deeper understanding of the dynamics in the $\pi\pi\psi'$ system.

6. Summary and Conclusion

During the last decade, BESIII has proven to be one of the leading experiments in the field of charmonium-like XYZ states. The latest contributions of BESIII include the discovery of the new decay mode $X(3872) \to \pi^0\chi_{c1}$. Furthermore, $\sqrt{s}$ dependent cross section measurements of the production of various hidden- or open-charm final states have been performed, viewing the $Y(4260)$ resonance from a new perspective. As shown in Figure 2, the parameters of resonances in different final states are clustering at a mass of around 4220 MeV and a width between 40 and 70 MeV. Probably, the $Y(4260)$ state should be called $Y(4220)$ state from now on. The resonances at higher masses are not as well in agreement. Additionally, BESIII determined the spin and parity quantum numbers of the famous $Z_c(3900)$ to be 1^+ and observed complex dynamics in the $e^+e^- \to \pi\pi\psi'$ Dalitz plot indicating an isospin triplet of $Z_c(4300)$ states decaying to $\pi\psi'$.

The BESIII experiment already collected more data and will continue to do so. A scan of the region above $\sqrt{s} = 4.2\,\text{GeV}$ with a step size of 10 MeV and 500 pb^{-1} per point is in progress and will result in even higher precision measurements of the hidden- and open-charm production cross section helping to understand the nature of the charmonium-like XYZ states.

In the near future, the accelerator will be upgraded and center-of-mass energies up to 4.9 GeV will be attainable, enabling a study of the $Y(4660)$ state at BESIII.

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