XYZ states at BESIII

Riccardo Farinelli
INFN, Sezione di Ferrara, via G. Saragat 1, 44122 Ferrara, Italy
E-mail: rfarinelli@fe.infn.it

Abstract. The BESIII experiment at the Beijing Electron Positron Collider (BEPCII) provided a significant contribution to the charmonium-like state spectroscopy thanks to the large data samples collected in the center of mass energy region between 3.8 and 4.6 GeV. New and surprising resonant states have been discovered. Their interpretation goes beyond the traditional quark and anti-quark model paradigm of the charmonium: for example, the two isospin triplets $Z_c(3900)$ and $Z_c(4020)$ that are electrically charged quarkonium-like states. In this proceeding, it will be reported recent studies on XYZ states made by BESIII in particular the radiative transition between various states, i.e. in the channel $Y(4260) \rightarrow \gamma X(3872)$.

1. Introduction

The charmonium spectrum is described by $c$ and $\bar{c}$ quarks bound together by strong interaction and by secondary order effects depending on their quantum numbers that combine $L$ and $S$ to $J=0, 1, 2$. The potential model predicts the masses of the resonances as a function of their quantum number up to the production threshold of $2M_D$ and found in a very good agreement with the experimental measurements [1]. However, above threshold there are many predicted states, but only few of them have been observed. In the last decades several experiments like BESIII, BaBar, CLEO-C, D0 and others have discovered some states that seem not to match with potential prediction. These ones have been labeled as ”exotic states”. First of all the $X(3872)$, seen for the first time in 2003 by Belle [2]: due to its narrow width of few MeV, it can not be explained as an ordinary $c\bar{c}$ state. Afterward, $Y$ states with quantum number $1^{--}$ such as $Y(4260)$, $Y(4660)$, and so on [5], have been discovered. These overpopulate the region of the vector state and do not fit the potential model. To complete the family of exotic states there are the $Z$ states such as $Z(4020)$ and $Z(3900)$, discovered in the invariant mass spectrum of the decay $\pi^+ J/\psi$, which are evidently exotic since they are charged and have been interpreted as possible tetraquarks, quark molecules or hybrids [4]. A connection point between these exotic states is their probability to decay in conventional $c\bar{c}$ states through a photon or a pion emission, contrarily to the states above the open charm threshold that decay mainly in $D$ mesons instead of $c\bar{c}$ states. The nature of this particle family is unclear and to understand them better it is necessary to extend the knowledge of their decay channels, quantum number and cross section.

BESIII (BEijing Spectrometer) is a spectrometer that studies the $e^+e^-$ collisions produced by BEPCII (Beijing Electron-Positron Collider) in the energy range between 2 and 4.6 GeV. In such reactions charmed states can be directly produced with quantum numbers $1^{--}$ such as $J/\psi$ and other $c\bar{c}$ states or the $Y$ states. The mail goals of the experiment is to investigate the charm region and the XYZ states.
2. Y states

The Y states have been observed for the first time by BaBar in the initial state radiation process $\pi^+\pi^- J/\psi$: Y(4260) is a resonance with quantum number $-^--$ confirmed by Belle, CLEO-C and BESIII [3, 6]. In this proceeding are presented the results found in the channels $e^+e^- \rightarrow \pi^+\pi^- J/\psi$, $e^+e^- \rightarrow \pi^+\pi^- h_c$ and $e^+e^- \rightarrow \omega h_c$. The Y(4260) is a resonance studied at BESIII with 9.05 fb$^{-1}$ data collected. This Y state suggests the existence of two resonances on the decay channel $\pi\pi J/\psi$ [7], one compatible with the one discovered by Belle and BaBar Y(4260) [3, 6]: $M = 4222 \pm 3.1 \pm 1.4$ MeV/$c^2$ and $\Gamma = 44.1 \pm 4.3 \pm 2.0$ MeV; plus another resonance with $M = 4320 \pm 10.4 \pm 7.0$ MeV/$c^2$ and $\Gamma = 101.4 \pm 25.3 \pm 10.2$ MeV compatible with the Y(4360) seen by BaBar [5] in the spectrum of $M(\pi^+\pi^- \psi(2S))$. The study has been performed with two different data sets and two different fits: one uses three Breit-Wigner functions to search the Y(4008) [6] discovered by Belle and the other two Breit-Wigner and an exponential function for the background. The result does not confirm the resonance Y(4008) seen by Belle. The lineshape of the Born cross section as function of the energy has been measured and it is shown in Fig. 1.

In the decay channel $e^+e^- \rightarrow \pi^+\pi^- h_c$, with $h_c \rightarrow \gamma\eta_c$ and $\eta_c$ decays in 16 exclusive channels, a cross section compatible with $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ and $e^+e^- \rightarrow \pi^+\pi^- \psi(2S)$ has been measured. Two resonances have been measured: $M = 4218.4 \pm 5.5 \pm 0.9$ MeV/$c^2$ and $\Gamma = 66.0 \pm 12.3 \pm 0.4$ MeV, $M = 4391 \pm 6.3 \pm 1.0$ MeV/$c^2$ and $\Gamma = 139.5 \pm 16.2 \pm 0.6$ MeV [8]. The first one is compatible with the previous in $\pi\pi J/\psi$. The second one is a new resonance and it is incompatible with the others discovered in this region (see Fig. 2).

Another proposed Y state is the one observed for the first time in the process $e^+e^- \rightarrow \omega h_c$ in the data samples collected at a $\sqrt{s}$ between 4.21 and 4.42 GeV with $\omega \rightarrow \pi^+\pi^- \pi^0$, $h_c \rightarrow \pi\pi KK\chi_{c0}$. The measured Born cross section is $(55.4 \pm 6.0 \pm 5.9)$ pb at $\sqrt{s} = 4.23$ GeV and $(23.7 \pm 5.3 \pm 3.5)$ pb at 4.26 GeV. By assuming the $h_c(1^+,3^+)$ signals, a resonance has been measured with $M = 4230 \pm 8 \pm 6$ MeV/$c^2$ and $\Gamma = 38 \pm 12 \pm 2$ MeV. No resonances show up in the decay with $J=1,2$ states.

3. X states

Concerning the X states, in this proceeding only $e^+e^- \rightarrow \gamma X(3872)$ and $X(3872) \rightarrow \pi\pi J/\psi$ is presented, in the center of mass from 4.009 to 4.420 MeV, where the process has been observed with a significance of 6.3$\sigma$. The measured mass of the X(3872) is $(3871.9 \pm 0.7 \pm 0.2)$ MeV/$c^2$.
Figure 2. Right: Fit to the dressed cross section $e^+e^- \rightarrow \pi^+\pi^- h_c$ with coherent sum of two Breit-Wigner functions (solid curve). The dash (dash-dot) curve shows the contribution from the two structures $Y(4220) [Y(4390)]$. The dots with the errors are data. Left: The likelihood contours in the mass and width planes for $Y(4220)$ and $Y(4390)$.

Figure 3. Fit to the cross section $\sigma[e^+e^- \rightarrow \gamma X(3872)] \times B[X(3872) \rightarrow \pi^+\pi^- J/\psi]$ with three hypotheses: a $Y(4260)$ resonance (red solid curve), a linear continuum (blue dashed curve), or a E1-transition phase space term (red dotted-dashed curve). [10]. The cross section of this process has been measured for four different energies and its shape shows an increment at about 4260 MeV. The lineshape of the cross section has been described with three hypotheses: the phase space of E1 transition, a linear continuum or a resonant $Y(4260)$, see Fig. 3. The last one is the fit with the best $\chi^2$ and these observations strongly support the existence of the radiative transition process $Y(4260) \rightarrow \gamma X(3872)$.

4. Z states

The Z states are the one clearly exotic. They can decay in a $c\bar{c}$ state plus a charged particle such as a $\pi^+$, thus they are composed by four quarks and carry charge. We consider here the following Z decay channels: $e^+e^- \rightarrow \pi^\pm 0(\pi^\mp 0 J/\psi)$ [11, 12], $e^+e^- \rightarrow \pi^\pm 0(\pi^\mp 0 h_c)$ [15, 16], $e^+e^- \rightarrow \pi^\pm 0(DD^*)^\mp 0$ [13, 14] and $e^+e^- \rightarrow \pi^\pm 0(D^*D^*)^\mp 0$ [17, 18]. By the study of the mass spectrum $\pi^\pm J/\psi$ in the channel $\pi^\pm \pi^- J/\psi$ at the energy of 4.26 GeV a cross section of 62.9 $\pm 1.9 \pm 3.7$ pb has been measured with $L = 525$ pb$^{-1}$ and a mass $M = 3899.0 \pm 3.6 \pm 4.9$ MeV/c$^2$ and $\Gamma = 46 \pm 10 \pm 20$. The same resonance has been measured in $\pi^0\pi^0 J/\psi$ in the invariant mass spectrum of $\pi^0 J/\psi$. This is the neutral partner of the $Z^\pm(3900)$ and these three states
Figure 4. Summary of the Z states observed in the proposed eight channels. The four plots on the top row show the invariant mass (recoil mass) of the charged Z (the pion), while in the bottom part there is the neutral partner of the Z’s isospin triplet. From left to right: $Z_c(3900)^{\pm,0} \rightarrow \pi^{\pm,0}J/\psi$, $Z_c(3885)^{\pm,0} \rightarrow (D\bar{D}^*)^{\pm,0}$, $Z_c(4020)^{\pm,0} \rightarrow \pi^{\pm,0}h_c$, $Z_c(4025)^{\pm,0} \rightarrow (D^*\bar{D}^*)^{\pm,0}$

determine an isospin triplet and light up the mystery of the Z states. A similar analysis has been done in $e^+e^- \rightarrow \pi^{\pm}(D\bar{D}^*)^{\mp}$ and they have determined another Z triplet with $M = 3881.7 \pm 1.6 \pm 1.6$ MeV/$c^2$ and $\Gamma = 26.2 \pm 2.0 \pm 2.1$ MeV. These Z states are compatible with the ones in the channel $\pi J/\psi$ and they could be the same resonance that decays in two different channels. Same analogy can be done in $e^+e^- \rightarrow \pi^{\pm,0}(\pi^{\mp,0}h_c)$ and $e^+e^- \rightarrow \pi^{\pm,0}(D^*\bar{D}^*)^{\mp,0}$ channels that define another Z labeled Z(4020). The Z states decay from $c\bar{c}$ states with quantum numbers $1^{--}$ and similarly to the connection between the X and the Y, here we can assume that at the energy of 4.26 GeV a certain amount of Y states are produced and these decay in a Z plus a pion. A summary of these Z states is shown in Fig. 4.

5. Conclusion

The nature of the XYZ is still unknown but possible connections in this multitude of exotic states show up in the recent discoveries by BESIII in the $\tau$-charm region, such as the presence of two close but separated Y states, the isospin triplets for Z(3900) and Z(4020) discovered in several channels and the possible decay of the Y into X(3872) (radiative) or Z (hadronic).

References
[1] T. Barnes et al. Higher charmonia - Phys. Rev. D 72, (2005) 054026
[2] G. Pakhlova et al. [Belle Collaboration], Phys. Rev. Lett. 26, no.26
[3] B. Aubert et al. [BaBar Collaboration] Phys. Rev. Lett. 95, 142001 (2005)
[4] M. Ablikim et al. [BESIII Collaboration] Phys. Rev. Lett. 110, 252001 (2013)
[5] B. Aubert et al. [BaBar Collaboration] Phys. Rev. D 89, 111103(R)
[6] G. Pakhlova et al. [Belle Collaboration] Phys. Rev. Lett. 110, 252002 (2013)
[7] M. Ablikim et al. [BESIII Collaboration] Phys. Rev. Lett. 118, 092001 (2017)
[8] M. Ablikim et al. [BESIII Collaboration] Phys. Rev. Lett. 118, 092002 (2017)
[9] M. Ablikim et al. [BESIII Collaboration] Phys. Rev. Lett. 114, 092003 (2015)
[10] M. Ablikim et al. [BESIII Collaboration] Phys. Rev. Lett. 112, 092001 (2014)
[11] M. Ablikim et al. [BESIII Collaboration] Phys. Rev. Lett. 110, 252001 (2013)
[12] M. Ablikim et al. [BESIII Collaboration] Phys. Rev. Lett. 115, 112003 (2015)
[13] M. Ablikim et al. [BESIII Collaboration] Phys. Rev. Lett. 112, 022001 (2014)
[14] M. Ablikim et al. [BESIII Collaboration] Phys. Rev. Lett. 115, 222002 (2015)
[15] M. Ablikim et al. [BESIII Collaboration] Phys. Rev. Lett. 111, 242001 (2013)
[16] M. Ablikim et al. [BESIII Collaboration] Phys. Rev. Lett. 113, 212002 (2014)
[17] M. Ablikim et al. [BESIII Collaboration] Phys. Rev. Lett. 112, 132001 (2013)
[18] M. Ablikim et al. [BESIII Collaboration] Phys. Rev. Lett. 115, 182002 (2015)