With the ability to run above 4 GeV, the BESIII experiment located in the Beijing Electron Positron Collider (BEPCII), has becoming a pioneer in searching and studying charmoniumlike states (XYZ particles). In 2013, BESIII Collaboration discovered a charged charmoniumlike state $Z_c(3900)$, which is confirmed immediately experimentally, and provides the best candidate for a four quark state by now. Continuous studies by BESIII Collaboration show new decay behavior of $Z_c(3900)$, and there are possible partner particle $Z_c(4020)/Z_c(4025)$ existing. By scanning above 4 GeV, BESIII also reveals the potential connection between $Y(4260)$ and $X(3872)$ for the first time, which may help us understand XYZ particles in a new sight.

1 Introduction

By decades, people know from the quark model\(^1\) that hadron matter existing in our universe is composed of 3 quarks (baryon) or quark-anti-quark pairs (meson). However, QCD (the theory to describe strong force, which bind quarks together), allows new forms of matter in our universe, such as multi-quark states, hybrid states, glue balls and so on. Such kind of new hadrons are called exotic states. On the other hand, we never saw an exotic hadron firmly in experiment. In the last ten years, many new particles in the charmonium (bound state of charm quark and anti-charm quark) mass region was observed. These new particles show different feature with normal charmonium state, and might be good candidate for exotic states (they are called charmoniumlike states or XYZ particles). In 2003, the Belle experiment observed a new charmoniumlike state $X(3872)\(^2\)$, which is a good candidate of four quark state. Later, the BaBar experiment observed another new charmoniumlike state $Y(4260)\(^3\)\(^4\)$, which also might be exotic.

Although the process in charmoniumlike state is promising for evidence of exotic hadron, there is still big difficulty in how to distinguish them from conventional charmonium states. However, this ambiguous situation changed since 2013, when a new charged charmoniumlike state $Z_c(3900)$ discovered by the BESIII Collaboration\(^5\), and immediately confirmed by Belle Collaboration\(^6\) and CLEO-c data\(^7\). $Z_c(3900)$ carries electric charged, which obvious can not be normal charmonium states. The minimal quark content of $Z_c(3900)$ should be four quark combination\(^8\).

The BESIII experiment is an $e^+e^-$ machine running in the charmonium energy region. In this talk, we present the recent XYZ physics results from the BESIII Collaboration, based on the high luminosity data sets collected above 4 GeV.
2 Observation of $Z_c(3900)$ at BESIII

The BESIII detector has collected 525 pb$^{-1}$ data at $e^+e^-$ central-of-mass (CM) energy (4.260 ± 0.001) GeV. With this data sample, we analyze the $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ process. The Drift Chamber is used to catch 4 charged tracks ($\pi^+\pi^- e^+e^-$), and the calorimeter is used to separate electrons and muons. We use the published Belle and BABAR$^9$ $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ cross section line shapes to do radiative correction. The Born order cross section at $\sqrt{s} = 4.260$ GeV is measured to be $\sigma^B(e^+e^- \rightarrow \pi^+\pi^- J/\psi) = (62.9 \pm 1.9 \pm 3.7)$ pb. The good agreement between BESIII, Belle$^6$ and BABAR$^9$ for $\pi^+\pi^- J/\psi$ cross section measurement confirms the BESIII analysis is valid and unbiased.

After obtained the cross section, we turn to investigate the intermediate state in $Y(4260) \rightarrow \pi^+\pi^- J/\psi$ decays. We got 1595 $\pi^+\pi^- J/\psi$ signal events with a purity of $\sim$90%. The Dalitz plot of $Y(4260) \rightarrow \pi^+\pi^- J/\psi$ signal events shows interesting structures both in the $\pi^+\pi^-$ system and $\pi\pi J/\psi$ system. In the $\pi\pi J/\psi$ mass distribution, a new resonance at around 3.9 GeV/c$^2$ (called $Z_c(3900)$ hereafter) was observed. For the $\pi^+\pi^-$ mass distribution, there are also interested structures, which can be modeled well by $0^+\pi^+$ resonance $\sigma(500)$, $f_0(980)$ and non-resonant S-wave $\pi^+\pi^-$ amplitude. The $D$-wave $\pi^+\pi^-$ amplitude is found to be small in data and they also do not form peaks in the $M(\pi^+J/\psi)$ mass spectrum. To extract the resonant parameters of $Z_c(3900)$, we use 1-dimensional unbinned maximum likelihood fit to the $M_{\text{max}}(\pi^+J/\psi)$ mass distribution (the larger one of $M(\pi^+J/\psi)$ and $M(\pi^-J/\psi)$ mass combination in each event), which is an effective way to avoid $Z_c(3900)^+$ and $Z_c(3900)^-$ components cross counting. Figure 1 (left) shows the fit results, with $M[Z_c(3900)] = (3899.0 \pm 3.6 \pm 4.9)$ MeV/c$^2$, and $\Gamma[Z_c(3900)] = (46 \pm 10 \pm 20)$ MeV. Here the first errors are statistical and the second systematic. The significance of $Z_c(3900)$ signal is estimated to be $> 8\sigma$ in all kinds of systematic checks.

![Figure 1](image1.png)

Figure 1 – Fit to the $M_{\text{max}}(Z_c(3900) \rightarrow \pi^+\pi^- J/\psi)$ (left) and $M(Z_c(3900) \rightarrow D^0\overline{D}^{*+})$ (middle) and $M(Z_c(3900) \rightarrow D^+\overline{D}^{*0})$ (right) invariant mass distribution as described in the text. Dots with error bars are data, the solid curves show the total fit and the dashed curves are backgrounds contribution.

3 $e^+e^- \rightarrow \pi^+(DD^*)^-+c.c.$

The mass of $Z_c(3900)$ is a bit above $DD^*$ mass threshold, which motivates an assumption that $Z_c(3900)$ can coupling to $DD^*$. The BESIII Collaboration has performed the analysis of $e^+e^- \rightarrow \pi^+(DD^*)^-$ (here charge conjugation is always implied) with 525 pb$^{-1}$ data$^{10}$. The $(DD^*)^-$ system contains two combination: $D^0\overline{D}^{*-}$ and $D^-\overline{D}^{*0}$. In order to obtain more statistics, a good choice is to employed the partial reconstruction technique. The primary $\pi^+$ and $D$ meson are required to be detected, while the $D^*$ meson is missing. The final 4-momentum of $DD^*$ system is obtained through $e^+e^-$ initial momentum minus pion momentum, which is due to strict momentum conservation. Figure 1 (middle, right) shows the obtained $DD^*$ invariant mass distributions. An obvious peak is observed near $DD^*$ mass threshold, which corresponds to a resonance. An unbinned maximum likelihood fit gives mass $M = 3889.1 \pm 1.8$ MeV and width $\Gamma = 28.1 \pm 4.1$ MeV ($3891.8 \pm 1.8$ MeV and $27.8 \pm 3.9$ MeV) for the two data sets,
respectively. The pole position of this peak is calculated to be \( M_{\text{pole}} = 3883.9 \pm 1.5 \pm 4.2 \text{ MeV} \) and \( \Gamma_{\text{pole}} = 24.8 \pm 3.3 \pm 11.0 \text{ MeV} \), where the first errors are statistical and the second systematic.

The mass and width of the peak observed in \( DD^* \) final state agree with that of \( Z_c(3900) \). Thus, they are quite probably the same state. From the production cross section measurement, we also obtained \( \Gamma_{\left[Z_c(3900) \rightarrow DD^*\right]} = 6.2 \pm 1.1_{\text{stat}} \pm 2.7_{\text{sys}} \text{ GeV} \). That means \( Z_c(3900) \) has a much stronger coupling to \( DD^* \) than \( \pi J/\psi \). Further study of production angle distribution shows the \( DD^* \) peak favor \( J^P = 1^+ \) assignment.

### 4 \( Z_c(4020) \) and \( Z_c(4025) \)

Using about 3.3 fb\(^{-1} \) data, we also try to search charmoniumlike state in the \( e^+e^- \rightarrow \pi^+\pi^- h_c \) process\(^{11} \). The \( h_c \) resonance is reconstructed through its radiative decay \( h_c \rightarrow \gamma \eta_c \) (with \(~50\% \) branching ratio), and \( \eta_c \) resonance is reconstructed through 16 exclusive hadron decay channels (with \(~40\% \) branching ratios). After events selection, clear \( e^+e^- \rightarrow \pi^+\pi^- h_c \) signal events are observed, and the \( e^+e^- \) CM energy dependent production cross section \( \sigma_{e^+e^-}^Z \) in the \( \pi^+\pi^- h_c \) distribution is measured, which is at the same order of that \( \pi^+\pi^- J/\psi \)\(^{5,6,9} \).

By further checking the \( \pi^+h_c \) invariant mass distribution, a resonant structure was observed, as shown in Fig. 2 (left). The measured mass is \( M = 4022.9 \pm 0.8 \pm 2.7 \text{ MeV} \) and width is \( \Gamma = 7.9 \pm 2.7 \pm 2.6 \text{ MeV} \) for the resonance (denoted as \( Z_c(4020) \)), where the first errors are statistical and the second systematic. The significance of \( Z_c(4020) \) is estimated to be \( > 8.9\sigma \). And the production cross section \( \sigma_{e^+e^-}^Z(\pi^+\pi^- h_c) \) is measured to be \( \sim 10 \text{ pb} \) level at \( e^+e^- \) CM energy 4.23, 4.26, 4.36 GeV. The \( Z_c(3900) \) state is also searched, but find to be not significant in \( \pi^+\pi^- h_c \) process.

![Figure 2](image)

Figure 2 – \( M(\pi^+h_c) \) (left) invariant mass distribution for \( e^+e^- \rightarrow \pi^+\pi^- h_c \) data events and \( M(D^*D^*) \) (right) invariant mass distribution for \( e^+e^- \rightarrow \pi^+(D^*D^*)^- \) data events. Dots with error bars are data. The solid curves in both panel are fit results, the dashed curve in left panel is background and in the right panel is signal.

Being near \( D^*D^* \) mass threshold, the \( Z_c(4020) \) state is also quite possible to be coupling to \( D^*D^* \). Using 827 pb\(^{-1} \) data collected at \( \sqrt{s} = 4.26 \text{ GeV} \), BESIII has studied the \( e^+e^- \rightarrow \pi^+(D^*D^*)^- \) (here charge conjugation is always implied) process\(^{12} \). In order to increase statistics, partial reconstruction technique is also employed. The primary charged pion, one \( D \) meson from charged \( D^* \) decay, and at least one \( \pi^0 \) from \( D^* \) decay are detected. The final 4-momentum of \( (D^*D^*) \) system is determined from initial momentum minus the primary pion momentum, due to strict momentum conservation.

Figure 2 (right) shows the \( (D^*D^*) \) invariant mass distribution. There is obvious excess for data events distribution over background estimation. We assume this enhancement is due to a resonant structure, and labeled it as \( Z_c(4025) \). The measured mass is \( M = 4026.3 \pm 2.6 \pm 3.7 \text{ MeV} \), and width is \( \Gamma = 24.8 \pm 5.6 \pm 7.7 \text{ MeV} \), where the first errors are statistical and the second systematic. The significance of \( Z_c(4025) \) is estimated to be \( 13\sigma \).
Charged charmoniumlike states $Z_c(4020)$ and $Z_c(4025)$ show up with a similar mass (near $D^*D^*$ threshold). Thus, they might be the same resonance. If we assume so, we can measure the relative decay width of $\Gamma(Z_c(4020)\rightarrow D^*D^*)/\Gamma(Z_c(4025)\rightarrow D^*D^*) \sim 9$. This behaves quite similar with $Z_c(3900)$, and hints $Z_c(4020)/Z_c(4025)$ is a partner of $Z_c(3900)$.

5 $e^+e^-\rightarrow \gamma X(3872)$

The $X(3872)$ was firstly observed by Belle Collaboration in $B \rightarrow K\pi^+\pi^-J/\psi^2$. After ten years of its discovery, its nature still keeps mysterious. Recently, the LHCb Collaboration determined its quantum number to be $J^{PC} = 1^{++}$.

Using $\sim 3.3$ fb$^{-1}$ data collected by BESIII, we have studied the $e^+e^-\rightarrow \psi/Y \rightarrow \gamma\pi^+\pi^-J/\psi$ process. Figure 3 (left) shows the obtained $\pi^+\pi^-J/\psi$ invariant mass distribution from the whole data sets. $X(3872)$ signal could be seen clearly. A fit to data events gives $M[X(3872)] = 3871.9 \pm 0.7_{\text{stat}} \pm 0.2_{\text{syst}}$ MeV, which agrees with other measurements very well. The significant $X(3872)$ signal is estimated to be 6.3$\sigma$. It’s worth to mention our measurement at BESIII provides another independent confirmation of the $X(3872)$ particle.

We also measured the $e^+e^-$ CM energy dependent production cross section of $\gamma X(3872)$. Figure 3 (right) shows the cross section line shape, which peaks near 4.26 GeV. We find pure phase space and linear shape describe the cross sections rather bad (with $\chi^2/ndf = 8.7/3$ and 5.5/2, respectively), while $Y(4260)$ line shape can describe the cross section line shape quite well (with $\chi^2/ndf = 0.49/3$). It strongly suggested the decay $Y(4260) \rightarrow \gamma X(3872)$.

![Figure 3](image_url)

Figure 3 – $M(\pi^+\pi^-J/\psi)$ (left) invariant mass distribution for $e^+e^-\rightarrow \gamma\pi^+\pi^-J/\psi$ events and energy dependent cross section of $e^+e^-\rightarrow \gamma X(3872)$ (right). Dots with error bars are data. In the left panel, the solid curve is fit, and the dashed one is background. In the right panel, the curves show different fit results.

6 Summary

With the large data sets taken above 4 GeV, the BESIII experiment could study $XYZ$ particles in a unique way. The charged charmoniumlike state $Z_c(3900)$ discovered recently by BESIII experiment give us solid evidence for an exotic hadron, probably a four quark state. Further study also shows $Z_c(3900)$ can couple to $DD^*$ final state strongly. BESIII also observed a new charged charmoniumlike state $Z_c(4020)$, a “partner” particle of $Z_c(3900)$. And a similar structure $Z_c(4025)$ (possible the same state as $Z_c(4020)$) was also found to be strongly coupling to $D^*D^*$.

In addition to charged states, BESIII also studied $X(3872)$ and $Y(4260)$ particles. We observe the first radiative decay of $Y(4260) \rightarrow \gamma X(3872)$, which connected the $X$ and $Y$ particles together. Considering the $Z_c(3900)$ was also observed at $\sqrt{s} = 4.26$ GeV, it hints us there may be common nature for these $XYZ$ particles, and suggest us understand them in a unified way.
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