RECENT RESULTS FROM CHARMONIUM SPECTROSCOPY AT BESIII*

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Recent BESIII results on studies related to the charmonium-like X, Y, and Z states are presented. This includes the observation of new charged and neutral Z_c and the production of $X(3872)$ and χ_{c1} in electron–positron annihilations at center-of-mass energies above 4 GeV.

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1. Introduction

The BESIII experiment [1] has started taking data in 2009. Since then, large data samples of electron–positron annihilations at center-of-mass energies corresponding to the J/ψ, ψ' and $\psi(3770)$ resonances have been recorded. More recently, data were taken in the energy region above 4 GeV, where energies up to about 4.4 GeV are accessible. This allows studies of the X, Y, and Z states recently observed in the charmonium mass region. These states have properties which are not in alignment with expectations for charmonium states. Therefore, it is speculated that some of these states are exotic matter, where interpretations include *e.g.* $c\bar{c}$ hybrids, glueballs, hadronic molecules, tetraquarks and hadrocharmonia. To reach a firm conclusion about the exact nature of these states, more experimental information together with refined theoretical approaches are mandatory. In the following, recent BESIII results related to these important questions will be summarized.

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2. Charged and neutral charmonium-like Z_c

Motivated by recent observations of charged charmonium-like and bottomonium-like states, BESIII investigated systematically final states with hidden and open charm in electron–positron annihilations in the energy range above 4 GeV. In the following, results of these efforts will be discussed.

2.1. Final states with a charmonium state

In 2013, the BESIII Collaboration observed a signal in the invariant $J/\psi\pi^+$ mass distribution [2] for the process $e^+e^- \to J/\psi\pi^+\pi^-$, where data has been taken at a center-of-mass energy ($\sqrt{s}$) corresponding to the peak of the $Y(4260)$ cross section. The signal is referred to as $Z_c(3900)^+$. It is parameterized with an S-wave Breit–Wigner function convolved with a function accounting for the experimental resolution, yielding a mass of $(3899.0 \pm 3.6 \pm 4.9)$ MeV/c^2 and a width of $(46 \pm 10 \pm 20)$ MeV. Here and throughout, the first uncertainties are statistical and the second systematical. The $Z_c(3900)^+$ was also observed by the Belle Collaboration at the same time in e^+e^- annihilations with radiative return to the $Y(4260)$ [3] and was shortly afterwards confirmed in direct e^+e^- annihilations at $\sqrt{s} = 4.17$ GeV in CLEO-c data [4].

Since the $Z_c(3900)^+$ couples to a $c\bar{c}$ state and carries electric charge, it is speculated that it is *e.g.* a tetraquark, a hadronic molecule, or a hadrocharmonium among other explanations [5–18]. It may be noted that $Z_c(3900)^+$ is close to the $D\overline{D}^*$ threshold, which might be related to its nature.

Evidence for a structure in the invariant $J/\psi\pi^0$ mass distribution in the isospin-related channel $e^+e^- \to J/\psi\pi^0\pi^0$ in CLEO-c data is also reported in Ref. [4]. BESIII investigated the same reaction at center-of-mass energies near the $Y(4260)$ and $Y(4360)$. Preliminary results of this analysis are reported here. At $\sqrt{s} = 4.23$, 4.26, and 4.36 GeV, a significant structure in the invariant $J/\psi\pi^0$ mass distribution is observed (Fig. 1). Overlaid on data points is the result of a fit, which is applied to all three data samples using common fit parameters for the Breit–Wigner function to describe the signal. The fit yields a mass and width value of (3894.8 ± 2.3) MeV/c^2 and (29.6 ± 8.2) MeV, respectively, where the errors are statistical only. The result is consistent with the values obtained for the charged $Z_c(3900)^+$ and the values reported for $Z_c(3900)^0$ in Ref. [4]. If $Z_c(3900)^+$ and $Z_c(3900)^0$ have the same spin-parity, they would establish an isospin triplet. For any interpretation, it is necessary to determine the spin-parity of the $Z_c(3900)^+$ and $Z_c(3900)^0$.

In search of other decay modes of $Z_c(3900)^+$, BESIII investigated $e^+e^- \to h_c\pi^+\pi^-$ [19] between $\sqrt{s} = 3.9$ and 4.42 GeV, where the J/ψ in the final state is replaced by a h_c. The h_c is reconstructed via its radiative decay to η_c, while η_c is fully reconstructed in 16 hadronic final states. No significant

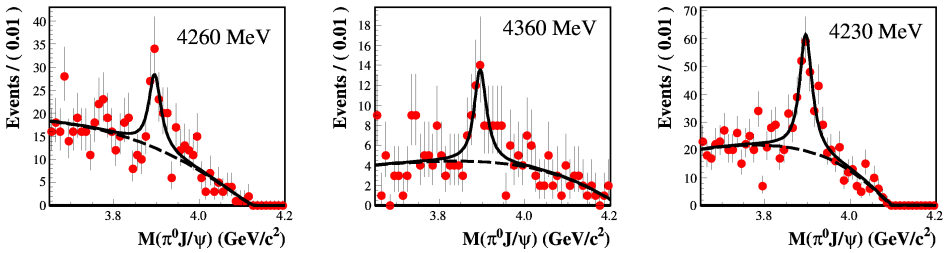


Fig. 1. Invariant $J/\psi\pi^0$ mass spectra for $e^+e^- \to J/\psi\pi^0\pi^0$ at center-of-mass energies of 4.26, 4.36 and 4.23 GeV. Overlaid to the data (points with error bars/red) is the result of the fit described in the text. The solid line corresponds to the sum of the signal and background functions, the dashed line to the background function.

$Z_c(3900)$ signal is observed and an upper limit for the $Z_c(3900)^+$ production cross section times branching fraction at $\sqrt{s} = 4.26$ GeV of 11 pb at 90% C.L. is set, which is considerably smaller than the corresponding product for $e^+e^- \to J/\psi\pi\pi$ reported in Ref. [2]. The invariant $h_c\pi^+$ mass spectrum at $\sqrt{s} = 4.23$, 4.26 and 4.36 GeV shows a clean signal at about 4.02 GeV/c^2, which is referred to as $Z_c(4020)^+$. The $Z_c(4020)^+$ signal is parameterized with a Breit–Wigner function, yielding a mass of $(4022.9 \pm 0.8 \pm 2.7)$ MeV/c^2 and a width of $(7.9 \pm 2.7 \pm 2.6)$ MeV.

Similarly, in a later analysis of $e^+e^- \to h_c\pi^0\pi^0$ [20], a significant signal ($Z_c(4020)^0$) was observed in the invariant h_c π^0 mass distribution at about the same mass as $Z_c(4020)^+$. The signal is parameterized with a Breit–Wigner function. Due to limited statistics, the width is fixed to the value obtained for the charged $Z_c(4020)^+$. The fit yields a mass of $(4023.9 \pm 2.2 \pm 3.8)$ MeV/c^2, consistent with the values of $Z_c(4020)^+$ within uncertainties.

As in the case of $Z_c(3900)$, further investigation is required to draw any firm conclusion about the nature of $Z_c(4020)$. Analogous to $Z_c(3900)$, the $Z_c(4020)$ is very close to the $D^*\overline{D}^*$ threshold.

2.2. Final states with charmed meson pairs

Due to the proximity of the $Z_c(3900)^+$ and $Z_c(4020)^+$ to the $D\overline{D}^*$ and $D^*\overline{D}^*$ thresholds, a search for similar structures in the corresponding open charm channels is highly motivated. The comparison of the partial Z_c decay widths to final states with a $c\bar{c}$ and a pair of open charm mesons may help to clarify their nature.

We investigated the reactions $e^+e^- \to \pi^-(D\overline{D}^*)^+$ (where $(D\overline{D}^*)^+$ is a short-hand notation for the two isospin related $\overline{D}^0D^{*+}$ and $D^+\overline{D}^{*0}$ systems) [21] and $e^+e^- \to \pi^-D^{*+}\overline{D}^{*0}$ [22] at a center-of-mass energy of $\sqrt{s} = 4.26$ GeV. The reactions have been partially reconstructed, where the bachelor π^- and one of the D mesons is fully reconstructed.

For the $(D\overline{D}^*)^+$ systems, the D meson is reconstructed from either $K^-\pi^+$ or $K^-\pi^+\pi^+$ decays. The $\overline{D}^*$ is identified in the missing mass spectrum inferred from the initial e^+e^- and the reconstructed π^- and D four-vectors. The invariant $(D\overline{D}^*)^+$ mass distributions show a clear enhancement at the $(D\overline{D}^*)^+$ thresholds, referred to as $Z_c(3885)^+$. The enhancement is fitted using a Breit–Wigner function. Averaged over the two isospin modes a mass of $(3883.9 \pm 1.5 \pm 4.2)$ MeV/c^2 and a width of $(24.8 \pm 3.3 \pm 11.0)$ MeV is derived. The π^- decay angle distribution has been extracted in four bins of the decay angle. The distribution is consistent with a $Z_c(3885)^+$ spin-parity assignment of $J^P = 1^+$ and rules out 0^- as well as 1^-. An important question is whether or not $Z_c(3885)^+$ and $Z_c(3900)^+$ have the same origin. In a first step, it is necessary to determine the spin-parity of $Z_c(3900)^+$. However, if $Z_c(3885)^+$ and $Z_c(3900)^+$ are due to the same source, the ratio of the partial decay width for $D\overline{D}^*$ and $J/\psi\pi^+$ would be $6.2 \pm 1.1 \pm 2.7$, indicating a suppression of the open charm decay mode compared to conventional charmonium states, where the ratio is an order of magnitude larger.

For $e^+e^- \to \pi^- D^{*+}\overline{D}^{*0}$, the decay $D^+ \to K^-\pi^+\pi^+$ is reconstructed and a π^0 originating from a D^* decay is required in the event to suppress backgrounds. The $D^{*+}\overline{D}^{*0}$ system can be identified in the recoil of the D^+. The π^- recoil mass spectrum shows an enhancement at the $D^{*+}\overline{D}^{*0}$ threshold, referred to as $Z_c(4025)^+$. A Breit–Wigner function fitted to the enhancement yields a mass of $(4026.3 \pm 2.6 \pm 3.7)$ MeV/c^2 and a width of $(24.8 \pm 5.6 \pm 7.7)$ MeV. The statistics do not allow for a spin-parity analysis of $Z_c(4025)^+$. As for $Z_c(3885)^+$ and $Z_c(3900)^+$, this and further investigations of $Z_c(4025)^+$ and $Z_c(4020)^+$ are mandatory to draw further conclusions whether or not both are due to the same source.

3. Study on $X(3872)$ and $Y(4260)$

Since the $Y(4260)$ was observed by the BaBar, CLEO and Belle experiments, many theoretical models were proposed to interpret the $Y(4260)$, *e.g.*, as a quark–gluon charmonium hybrid, a tetraquark state, a hadrocharmonium, or a hadronic molecule. Searching for additional decay modes and measuring the line shape are very important for understanding the nature of the $Y(4260)$.

BESIII studied and observed for the first time the process $e^+e^- \to \gamma X(3872)$ at center-of-mass energies from 4.009 to 4.420 GeV [23]. The obtained mass of the $X(3872)$ ($(3871.9 \pm 0.7 \pm 0.2)$ MeV/c^2) is in agreement with previous measurements [24]. The product of the $X(3872)$ production cross section and its branching fraction to $J/\psi\pi^+\pi^-$ have been measured

at center-of-mass energies of 4.009, 4.229, 4.260, and 4.360 GeV (Fig. 2). The data is consistent with expectations for the radiative transition process $Y(4260) \to \gamma X(3872)$.

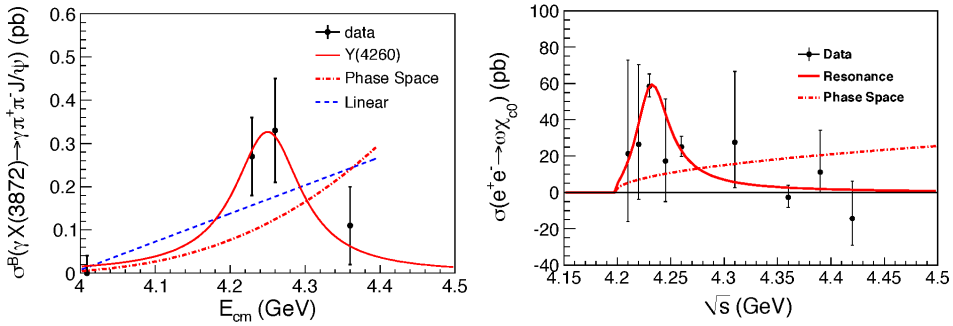


Fig. 2. Left: Measured cross section of $e^+e^- \to J/\psi\pi^+\pi^-$ (dots with error bars) with fit results using a single resonance lineshape (solid line), a phase-space (dash-dotted line) and a linear term (dashed line) overlaid. Right: Measured cross section of $e^+e^- \to \omega\chi_{c0}$ (dots with error bars), overlaid is the result of a fit using a single resonance (solid line) and a phase-space term (dash-dotted line).

In a more recent study, the process $e^+e^- \to \omega\chi_{cJ}$ (with $J = 0, 1, 2$) at 9 center-of-mass energies in the range of 4.21 to 4.42 GeV [25] has been investigated. At 4.23 and 4.26 GeV, $e^+e^- \to \omega\chi_{c0}$ is observed for the first time and the cross sections are measured to be $(55.4 \pm 6.0 \pm 5.9)$ pb and $(23.7 \pm 5.3 \pm 3.5)$ pb, respectively. For other reactions and energies, no significant signal is found and upper limits of the cross sections have been set. The $\omega\chi_{c0}$ cross section is extracted in dependence of $\sqrt{s}$ (Fig. 2). Assuming the $\omega\chi_{c0}$ events come from the decay of a single resonance, the mass and width of the resonance are determined from a fit to the extracted cross section to be $(4230 \pm 8 \pm 6)$ MeV/c^2 and $(38 \pm 12 \pm 2)$ MeV, respectively. The parameters are inconsistent with those obtained by fitting a single resonance lineshape to the $J/\psi\pi^+\pi^-$ cross section [26]. This suggests that it is unlikely that the observed $\omega\chi_{c0}$ events originate from decays of the $Y(4260)$.

4. Summary

Recent results of the campaign started at BESIII to improve our understanding of the X, Y, and Z states in the charmonium mass region have been presented. This includes the observation of new charged and neutral Z_c in final states with hidden and open charm and the observation of the new decay mode $Y(4260) \to \gamma X(3872)$.

More than ten years after the discovery of the $X(3872)$, the study of X, Y and Z states is a very active field today and will continue to be exciting with new results to come from BESIII and other experiments together with refined theoretical approaches to reveal the nature of these states.

REFERENCES

[1] M. Ablikim *et al.* [BESIII Collab.], *Nucl. Instrum. Methods* **A614**, 345 (2010) [arXiv:0911.4960 [physics.ins-det]].

[2] M. Ablikim *et al.* [BESIII Collab.], *Phys. Rev. Lett.* **110**, 252001 (2013) [arXiv:1303.5949 [hep-ex]].

[3] Z. Liu *et al.* [Belle Collab.], *Phys. Rev. Lett.* **110**, 252002 (2013) [arXiv:1304.0121 [hep-ex]].

[4] T. Xiao, S. Dobbs, A. Tomaradze, K.K. Seth, *Phys. Lett.* **B727**, 366 (2013) [arXiv:1304.3036 [hep-ex]].

[5] Q. Wang, C. Hanhart, Q. Zhao, *Phys. Rev. Lett.* **111**, 132003 (2013) [arXiv:1303.6355 [hep-ph]].

[6] F.-K. Guo, C. Hidalgo-Duque, J. Nieves, M.P. Valderrama, *Phys. Rev.* **D88**, 054007 (2013) [arXiv:1303.6608 [hep-ph]].

[7] G. Li, *Eur. Phys. J.* **C73**, 2621 (2013) [arXiv:1304.4458 [hep-ph]].

[8] J.-R. Zhang, *Phys. Rev.* **D87**, 116004 (2013) [arXiv:1304.5748 [hep-ph]].

[9] J. Dias, F. Navarra, M. Nielsen, C. Zanetti, *Phys. Rev.* **D88**, 016004 (2013) [arXiv:1304.6433 [hep-ph]].

[10] M. Voloshin, *Phys. Rev.* **D87**, 091501 (2013) [arXiv:1304.0380 [hep-ph]].

[11] E. Braaten, *Phys. Rev. Lett.* **111**, 162003 (2013) [arXiv:1305.6905 [hep-ph]].

[12] E. Wilbring, H.-W. Hammer, U.-G. Meißner, *Phys. Lett.* **B726**, 326 (2013) [arXiv:1304.2882 [hep-ph]].

[13] D.-Y. Chen, X. Liu, T. Matsuki, *Phys. Rev.* **D88**, 036008 (2013) [arXiv:1304.5845 [hep-ph]].

[14] Y.-R. Liu, *Phys. Rev.* **D88**, 074008 (2013) [arXiv:1304.7467 [hep-ph]].

[15] Q. Wang, C. Hanhart, Q. Zhao, *Phys. Lett.* **B725**, 106 (2013) [arXiv:1305.1997 [hep-ph]].

[16] Y. Dong, A. Faessler, T. Gutsche, V.E. Lyubovitskij, *Phys. Rev.* **D88**, 014030 (2013) [arXiv:1306.0824 [hep-ph]].

[17] X.-H. Liu, G. Li, *Phys. Rev.* **D88**, 014013 (2013) [arXiv:1306.1384 [hep-ph]].

[18] S. Prelovsek, L. Leskovec, *Phys. Lett.* **B727**, 172 (2013) [arXiv:1308.2097 [hep-lat]].

[19] M. Ablikim *et al.* [BESIII Collab.], *Phys. Rev. Lett.* **111**, 242001 (2013) [arXiv:1309.1896 [hep-ex]].

[20] M. Ablikim *et al.* [BESIII Collab.], *Phys. Rev. Lett.* **113**, 212002 (2014) [arXiv:1409.6577 [hep-ex]].

[21] M. Ablikim *et al.* [BESIII Collab.], *Phys. Rev. Lett.* **112**, 022001 (2014) [arXiv:1310.1163 [hep-ex]].

[22] M. Ablikim *et al.* [BESIII Collab.], *Phys. Rev. Lett.* **112**, 132001 (2014) [arXiv:1308.2760 [hep-ex]].

[23] M. Ablikim *et al.* [BESIII Collab.], *Phys. Rev. Lett.* **112**, 092001 (2014) [arXiv:1310.4101 [hep-ex]].

[24] K. Olive *et al.* [Particle Data Group], *Chin. Phys.* **C38**, 090001 (2014).

[25] M. Ablikim *et al.* [BESIII Collab.], arXiv:1410.6538 [hep-ex].

[26] B. Aubert *et al.* [BaBar Collab.], *Phys. Rev. Lett.* **95**, 142001 (2005) [arXiv:hep-ex/0506081].