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Observation of the first hidden-charm strange tetraquark at BESIII

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In the last ten years, a whole set of new particles that do not fit into the constituent quark model has populated the mass region above the open-charm threshold. The Beijing Spectrometer (BESIII), installed at the Beijing Electron Positron Collider (BEPCII), can access these states both in electron-positron annihilations and from the decays of charmonium(-like) states. In this proceeding, the discovery of the $Z_{cs}(3985)^-$ at BESIII with a mass of $3982.5^{+1.8}_{-2.6} \pm 2.1$ MeV$/c^2$ will be addressed. The resonance was observed by analyzing data collected at five center-of-mass energy points in the range from 4.628 GeV to 4.698 GeV, with a total integrated luminosity of 3.7 fb^{-1}. The observed properties of the $Z_{cs}(3985)^-$ makes it a strong candidate for the predicted open-strange charmonium-like tetraquark with the minimal structure $c\bar{c}s\bar{u}$.

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1. Introduction

The Quantum Chromodynamics (QCD) theory [1, 2] predicted the existence of exotic hadrons in addition to the conventional meson and baryon. Exotic hadrons include e.g. glueball, hybrid, molecule, multi-quark state. Searching for exotic states therefore provides a test of QCD. It provides new insights into internal structure and dynamics of hadrons. In recent years, some unconventional XYZ particles [3] have been discovered experimentally. At BESIII, we have observed a series of Z_c states [4-11],which are non-strange hidden-charm tetraquark candidates. Assuming SU(3) flavor symmetry, if we replace the u or d quark in Z_c with an s quark, we could expect the existence of a Z_{cs} [12]. Theoreticaly prediction shows that the Z_{cs} could decay into e.g. KJ/ψ, D_sD^*, D_s^*D. Taking the Z_c state as a reference, the decay rate of the Z_{cs} to open charm final state is expected to be larger than the decay rate to hidden charm final state. Hence, a promising method to search for the Z_{cs} state is through its decays to D_sD^* and D_s^*D. At BESIII, we searched for Z_{cs}^- through $e^+e^- \to K^+Z_{cs}^-$, $Z_{cs}^- \to (D_s^-D^{*0} + D_s^{*-}D^0)$.

2. Observation of the $Z_{cs}(3985)^-$ at BESIII

BEPCII extended the energy limit to 4.7 GeV in 2019-2020. With the BESIII detector, we have collected 3.7 fb^{-1} data accumulated from 4.628 GeV to 4.698 GeV, which were used to search for Z_{cs}^- [13]. A partial reconstruction method is implemented to study $e^+e^- \to K^+(D_s^-D^{*0} + D_s^{*-}D^0)$. Only the bachelor K^+ and the D_s^- are reconstructed. The signature in the recoil mass spectrum of $K^+D_s^-$ is used to identify the signal process. The Z_{cs}^- is searched for in the recoil side of K^+. The D_s^- is reconstructed with two tag modes: $D_s^- \to K_S^0K^-$ and $D_s^- \to K^+K^-\pi^-$, which have large branching fractions. For the decay $D_s^- \to K^+K^-\pi^-$, to further improve the signal purity, we only retain the D_s^- candidates consistent with $D_s^- \to \pi^-\phi, \phi \to K^+K^-$, and $D_s^- \to K^-K^*(892), K^*(892) \to K^+\pi^-$.

Figure 1 shows the invariant mass distributions of $M(K^+K^-\pi^-)$ and $M(K_S^0K^-)$ at $\sqrt{s} =$ 4.681 GeV, in which D_s^- peaks are clearly evident. Figure 2 shows the recoil mass distribution $RM(K^+D_s^-) + M(D_s^-) - m(D_s^-)$. The original distribution $RM(K^+D_s^-)$ is corrected by the nominal mass in PDG ($m(D_s^-)$). The new variable $RM(K^+D_s^-) + M(D_s^-) - m(D_s^-)$ provides improved resolution. A clear peak is seen in this distribution at the nominal D^{*0} mass (1-C kinematic fit is not performed). This peak corresponds to the final state $K^+D_s^-D^{*0}$. There is also a contribution from $K^+D_s^{*-}D^0$, which appears to be a broader structure beneath the $K^+D_s^-D^{*0}$ signal.

To estimate the shape of the combinatorial background, we use wrong-sign combinations of D_s^- and K^- candidates, rather than the right-sign D_s^- and K^+ candidates. The wrong sign distribution agrees with the data distribution in the sideband regions. No peaking background is observed in the wrong-sign events. The number of background events within the signal region is estimated to be $N_b = 282.6 \pm 12.0$ from the fit to the sideband data with a linear function. The slope of the function is determined from the wrong-sign data. In addition, the wrong-sign events would be used to represent the combinatorial background distribution in the recoil mass of K^+. This technique has been well validated by MC simulations and data sideband events.

Figure 3 shows the recoil mass distribution $RM(K^+)$. Figure 3 shows the same distribution at 4.681 GeV after subtracting the combinatorial background. An enhancement is evident in the

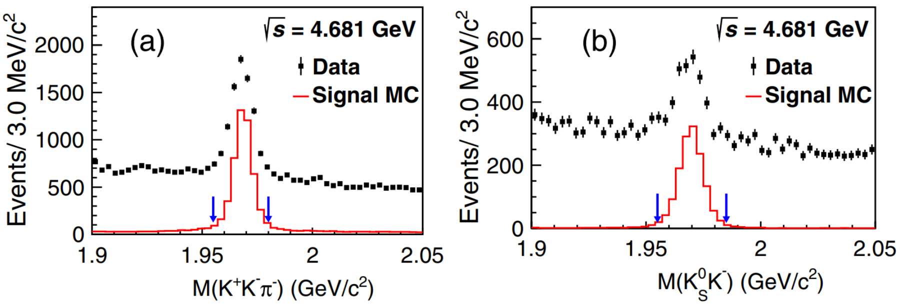

Figure 1: Distributions of the invariant mass $M(K^+K^-\pi^-)$ and $M(K_S^0K^-)$ in data and MC simulations at $\sqrt{s} = 4.681$ GeV. The $Z_{cs}(3985)^-$ signal MC component is normalized to the observed D_s^- yield in dat. Arrows indicate the mass region requirements.

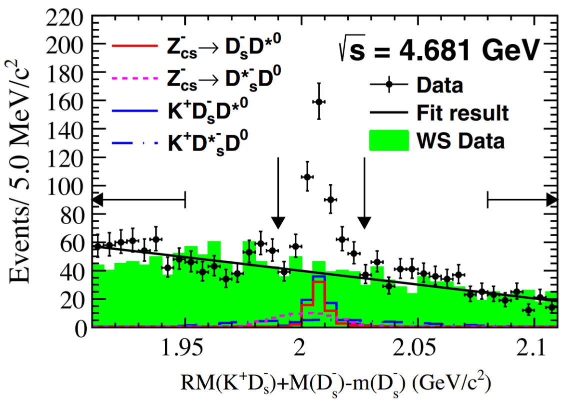

Figure 2: Distribution of the $K^+D_s^-$ recoil mass in data and signal MC samples at $\sqrt{s} = 4.681$ GeV. Horizontal arrows indicate the sidebands and vertical arrows indicate the signal region. The magnitudes of the three-body nonresonant processes and $Z_cs(3985)^-$ signal processes are scaled arbitrarily. The histogram of wrong-sign events is scaled by a factor of 1.18 to match the sideband data.

region below 4 GeV. Some processes containing D_s^{**} states have potential contributions to the $RM(K^+)$ spectrum. For example, $e^+e^- \to D_{s1}^*(2536)^+(K^+D^{*0})D_s^-$, $e^+e^- \to D_{s2}^*(2573)^+(K^+D^0)D_s^{*-}$, and $e^+e^- \to D_{s1}^*(2700)^+(K^+D^{*0})D_s^-$ have exactly the same final state as our signal channel, which could be peaking background in the $RM(K^+)$ spectrum. We check the D_s^{**} states listed in PDG one by one, and estimate their production cross sections by studying several control samples. The contribution from processes containing D_s^{**} states would be considered in the fit of $RM(K^+)$ distribution. We have checked the interference between any two processes containing D_s^{**} states, and the interference between the process containing a D_s^{**} state and non-resonance process. The study shows that the interference effect could not produce a narrow peak in the $RM(K^+)$ spectrum.

The fact that no known process can explain the observed enhancement in the $RM(K^+)$ spectrum, indicates that the structure corresponds to a new state, denoted $Z_{cs}(3985)^-$. A simultaneous unbinned maximum likelihood fit is applied to $RM(K^+)$ spectrum from data taken at five center-of-mass energies. The $Z_{cs}(3985)^-$ signal is described with a S-wave Breit-Wigner with mass dependet width with phase-space factor. The potential interference effect between any two components is neglected. From this fit, we get the resonance parameters of this new structure to

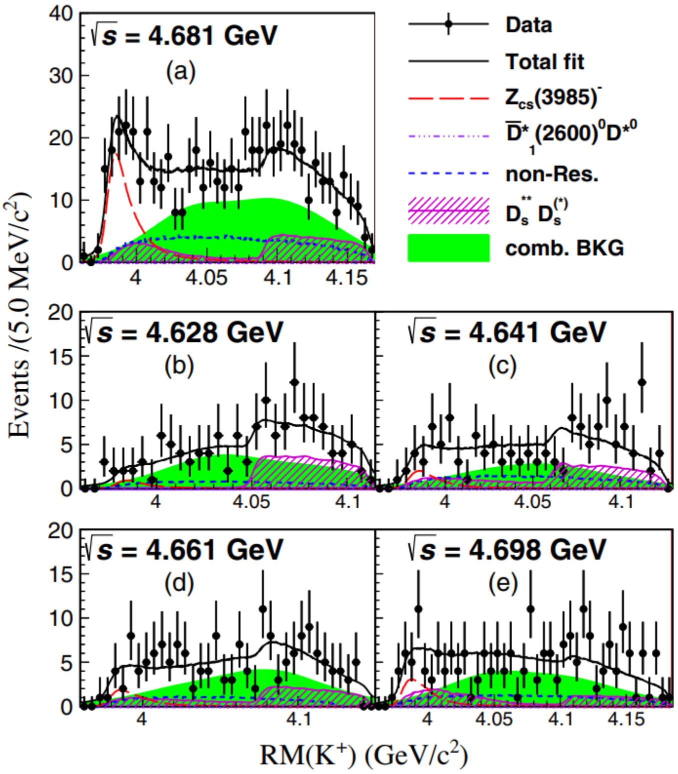

Figure 3: Simultaneous unbinned maximum likelihood fit to the K^+ recoil-mass spectra in data at $\sqrt{s} =$ 4.628, 4.641, 4.661, 4.681, and 4.698 GeV. Note that the size of the $D^{*0}\bar{D}_1^*(2600)^0(\to D_s^- K^+)$ component is consistent with zero.

be $m_0(Z_{cs}(3985)^-) = (3985.2^{+2.1}_{-2.0} \pm 1.7)$ MeV/c^2 and $\Gamma_0(Z_{cs}(3985)^-) = (13.8^{+8.1}_{-5.2} \pm 4.9)$ MeV, which correspond to the pole position parameters $m_{\rm pole}(Z_{cs}(3985)^-) = (3982.5^{+1.8}_{-2.6} \pm 2.1)$ MeV/c^2 and $\Gamma_{\rm pole}(Z_{cs}(3985)^-) = (12.8^{+5.3}_{-4.4} \pm 3.0)$ MeV. The significance of $Z_{cs}(3985)^-$ considering systematic uncertainties and look-elsewhere effect is evaluated to be 5.3σ. The mass of $Z_{cs}(3985)^-$ is only a few MeV higher than the threshold of $D_s^- D^{*0}$ and $D_s^{*-} D^0$. It contains at least four quarks $c\bar{c}s\bar{u}$ and be a strong candidate for the predicted open-strange charmonium-like tetraquark state.

3. Comparison with results from LHCb

The LHCb Collaboration observed a new structure from its decaying into the $J/\psi K^+$ final state [14]. The structure is denoted as $Z_{cs}(4000)^+$, which has a pole mass of $4003 \pm 6^{+4}_{-14}$ MeV, and a pole width of $131 \pm 15 \pm 26$ MeV. The masses of $Z_{cs}(3985)^-$ and $Z_{cs}(4000)^+$ are close, but the widths are quite different. The LHCb Collaboration tried to fix the mass and width of $Z_{cs}(4000)^+$ to values of $Z_{cs}(3985)^-$ state, but the log-likelihood of the fit is much worse. Therefore, there is no evidence that the $Z_{cs}(4000)^+$ is the same as the $Z_{cs}(3985)^-$.

4. Summary

The BESIII Collaboration studies the reactions $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ based on 3.7 fb^{-1}

of data collected at $\sqrt{s} = 4.628$, 4.641, 4.661, 4.681, and 4.698 GeV. A new structure, which is denoted as $Z_{cs}(3985)^-$, is observed near the $D_s^- D^{*0}$ and $D_s^{*-} D^0$ thresholds in the K^+ recoil-mass spectrum. The significance of $Z_{cs}(3985)^-$ is 5.3σ.

The quark composition of $Z_{cs}(3985)^-$ is most likely $c\bar{c}s\bar{u}$. Hence, it would become the first Z_{cs} tetraquark candidate observed. The cross section $\sigma^B[e^+e^- \to K^+ Z_{cs}(3985)^- + c.c.]$ times branching fraction $\mathscr{B}(Z_{cs}(3985)^- \to (D_s^- D^{*0} + D_s^{*-} D^0)$ at five center-of-mass energies are also measured. Comparing with the $Z_{cs}(4000)^+$ observed by the LHCb Collaboration, the $Z_{cs}(3985)^-$ is much narrower. There is no evidence that the $Z_{cs}(3985)^-$ and $Z_{cs}(4000)^+$ are the same structure.

References

[1] M. Gell-Mann, *A schematic model of baryons and mesons*, Phys. Lett. **8** 214 (1964).

[2] G. Zweig, *An SU(3) model for strong interaction symmetry and its breaking*, CERN-TH **412** 80 (1964).

[3] P.A. Zyla *et al.* (Particle Data Group), *Review of particle physics*, Prog. Theor. Exp. Phys. **2020**, 083C01 (2020) and 2021 update.

[4] M. Ablikim *et al.* (BESIII Collaboration), *Observation of a charged charmoniumlike structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV*, Phy. Rev. Lett. **110** 252001 (2013).

[5] M. Ablikim *et al.* (BESIII Collaboration), *Observation of $Z_c(3900)^0$ in $e^+e^- \to \pi^0\pi^0 J/\psi$*, Phy. Rev. Lett. **115** 112003 (2015).

[6] M. Ablikim *et al.* (BESIII Collaboration), *Observation of a charged charmoniumlike structure $Z_c(4020)$ and search for the $Z_c(3900)$ in $e^+e^- \to \pi^+\pi^- h_c$*, Phy. Rev. Lett. **111** 242001 (2013).

[7] M. Ablikim *et al.* (BESIII Collaboration), *Observation of $e^+e^- \to \pi^0\pi^0 h_c$ and a neutral charmoniumlike structure $Z_c(4020)^0$*, Phy. Rev. Lett. **113** 212002 (2014).

[8] M. Ablikim *et al.* (BESIII Collaboration), *Observatin of a charged $(D\bar{D}^*)^\pm$ mass peak in $e^+e^- \to \pi D\bar{D}^*$ at $\sqrt{s} = 4.26$ GeV*, Phy. Rev. Lett. **112** 022001 (2014).

[9] M. Ablikim *et al.* (BESIII Collaboration), *Observation of a neutral structure near the $D\bar{D}^*$ mass threshold in $e^+e^- \to (D\bar{D}^*)^0\pi^0$ at $\sqrt{s} = 4.226$ and 4.257 GeV*, Phy. Rev. Lett. **115** 222002 (2015).

[10] M. Ablikim *et al.* (BESIII Collaboration), *Observation of a charged charmoniumlike structure in $e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp$ at $\sqrt{s} = 4.26$ GeV*, Phy. Rev. Lett. **112** 132001 (2014).

[11] M. Ablikim *et al.* (BESIII Collaboration), *Observation of a neutral charmoniumlike state $Z_c(4025)^0$ in $e^+e^- \to (D^*\bar{D}^*)^0\pi^0$*, Phy. Rev. Lett. **115** 182002 (2015).

[12] M.B. Voloshin, *Strange hadrocharmonium*, Phys. Lett. B **798**, 135022 (2019).

[13] M. Ablikim *et al.* (BESIII Collaboration), *Observation of a near-threshold structure in the K^+ recoil-mass spectra in $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$*, Phy. Rev. Lett. **126** 102001 (2021).

[14] R. Aaij *et al.* (LHCb Collaboration), *Observation of new resonance decaying to $J/\psi K^+$ and $J/\psi\phi$*, Phy. Rev. Lett. **127** 082001 (2021).