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Spectroscopy at BESIII: A Selected XYZ Review

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Since 2003, a new group of exotic states has been identified, commonly known as XYZ states. These exotic states are incompatible with the quark-antiquark model and, therefore, are potential candidates for tetraquarks, mesonic molecules, and hybrids (e.g., gluon-quark states). Since the BESIII experiment started colliding e^+e^- beams in the energy range between 2.0 and 4.9 GeV, it has been a significant contributor to deepening our knowledge of this new family of states without a clear theoretical interpretation. Some of the most recent and noteworthy results from the BESIII collaboration, along with possible interpretations, are presented.

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1. Introduction

The BEijing Spectrometer III (BESIII) detector records e^+e^- collisions, generated by the BEijing Electron Positron Collider II (BEPCII) storage ring. This collider operates within the center-of-mass energy ($\sqrt{s}$) range spanning from 2.0 to 4.9 GeV. Hosted by the Institute of High Energy Physics (IHEP) in Beijing, People's Republic of China, the BESIII detector's characteristics and resolution details are elaborated in Ref. [1].

Since 2003, when the first clearly-exotic state was found [2], the charmonium spectrum has become populated by supernumerary non-conventional states, which don't fit potential model predictions, show strong couplings to hidden charm states, and can even exhibit a non-zero charge. These features make the nature of these exotic resonances not yet clear [3]. Thanks to its tuneable $\sqrt{s}$ in the charmonium range and leptonic beams, BESIII has been at the vanguard of the investigation of these exotic states. A selection of the latest results of the BESIII collaboration regarding the XYZ family is presented.

2. The $X(3872)$/$\chi_{c1}(3872)$ Structure

Observed for the first time in 2003 by the Belle Collaboration in the $\pi\pi J/\psi$ invariant mass [2], the X(3872) state has a mass lying near the D^0D^{*0} threshold, suggesting a possible molecular nature, supported also by its relatively small width (~1 MeV/c^2) [4]. On the other hand, the relatively large branching fraction ($\mathcal{B}$) for the radiative transition to hidden charm mesons [4] suggests an admixture of a conventional charmonium (namely, the $\chi_{c1}(2^3P_1)$ state) and a D^0D^{*0} molecule. BESIII is at the forefront of the X(3872) studies, thanks to its direct production mode(s) and clean leptonic environment.

2.1 The New $\omega X(3872)$ Production Mode

In the assumption that the $X(3872)$ state contains a component of the spin-triplet state $\chi_{c1}(2P)$, then the $e^+e^- \to \omega X(3872)$ production mode should exist. Indeed, BESIII observed the $e^+e^- \to \omega\chi_{cJ}(1P)$ transitions [5]. At $\sqrt{s}$ = [4.661, 4.951] GeV, Ref. [6] studies the $e^+e^- \to \omega X(3872) \to \omega\pi^+\pi^-J/\psi$ Born cross-section. Fitting the $\pi^+\pi^-J/\psi$ invariant mass, the $e^+e^- \to \omega X(3872)$ process is observed for the first time, suggesting a $\chi_{cJ}(2P)$ contribution to the X(3872) state.

2.2 $X(3872)$ to Light Hadrons

Assuming the loosely bound molecular nature, the $X(3872)$ size would be relatively large with the charm quarks being far away from each other [7], causing the light hadron decays to be suppressed. Ref. [8] searches for the $e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^-\eta$ process at $\sqrt{s}$ = [4.13, 4.34] GeV setting the upper limit (U.L.) on $\mathcal{B}(X(3872) \to \gamma\pi^+\pi^-\eta)$ at a 90% confidence level to be 1.4%. This result is in agreement with the $X(3872)$ loosely bound molecular nature and with Ref. [9], which estimates a $\mathcal{B}$ ~ [1 - 10] %.

2.3 A coupled-channel analysis of the $X(3872)$ line-shape with BESIII data

At $\sqrt{s}$ = [4.178, 4.278] GeV, Ref. [10] studies the $X(3872)$ production line-shape via its $D^0\bar{D}^0\pi^0$ and $\pi^+\pi^-J/\psi$ decays. A simultaneous fit to the invariant masses of the two $X(3872)$ decay channels allows BESIII to estimate the $X(3872)$ mass and width and its effective coupling constant to the

$D^*\bar{D}$ system. Furthermore, the fit allowed the identification in the Riemann space of two poles associated with the $X(3872)$ state. The Effective Range Expansion (E.R.E.) parameters [11] are also estimated, and a $\bar{X}_A$[1] $= 0.82^{+0.12}_{-0.36}$ is calculated, suggesting a similar compositeness to the deuteron. At the same time, the E.R.E. parameters scattering length and effective range (r_e) are both found to be negative, pointing to an elementary component for the $X(3872)$ (the deuteron has a positive r_e).

3. The $Y(4230)$ Vectorial State

The $Y(4230)$ resonance was observed for the first time by the BaBar collaboration [13], while BESIII allowed disentangling two resonant structures around 4.23 GeV/c^2 and 4.32 GeV/c^2. Looking at the inclusive hadronic cross-section, the $Y(4230)$ state appears as a dip around 4.26 GeV, suggesting a non-standard $c\bar{c}$ structure. BESIII discovered many of its decay channels and observed the transition to the $X(3872)$ [14] and the $Z_c(3900)$ [15] states suggesting a possible common nature.

3.1 The $Y(4230) \to K^0_S K^0_S (J/\psi/\phi)$ Cross-sections

Using 36 energy points at $\sqrt{s} = [4.128, 4.951]$ GeV, Ref. [16] studies the $e^+e^- \to K^0_S K^0_S J/\psi$ Born cross-section. Already measured by the Belle collaboration [17], which provided only an U.L., BESIII finally observed for the first time the $Y(4230) \to K^0_S K^0_S J/\psi$ process.

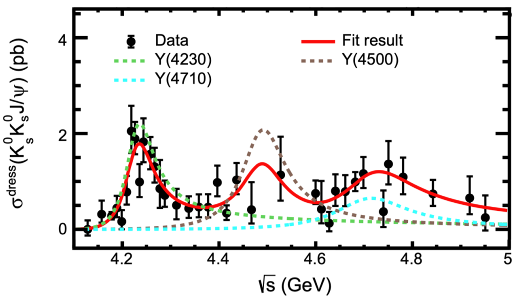

Figure 1: Fit to the $e^+e^- \to K^0_S K^0_S J/\psi$ dressed cross-section (black dots with error bars). One of the four solutions is shown. The red solid curve is the fit result, a coherent sum of three Breit-Wigner functions: the green, brown, and cyan dashed curves represent the $Y(4230)$, $Y(4500)$, and $Y(4710)$ states, respectively.

Restricting to $\sqrt{s}$ = [3.773, 4.701] GeV, Ref. [18] analyses the $e^+e^- \to K\bar{K}\phi$. In Ref. [19], the $Y(4230)$ is interpreted as a compact tetraquark $cs\bar{c}\bar{s}$, which would lead to decays into final states containing $s\bar{s}$. No evidence for a resonant contribution is found, suggesting the $Y(4230)$ "prefers" to preserve its charm content.

3.2 Charming Excited Cross-Sections

$Y(4230)$ resonance decays to open-charm meson states can be used as probes for the nature of this vector state. Ref. [20] studies the $e^+e^- \to \pi^+ D^{*0} D^{*-}$ process at $\sqrt{s} = [4.19, 4.95]$ GeV. The $e^+e^- \to \pi^+ D^{*0} D^{*-}$ cross-section study allows BESIII to extract a $Y(4230)$ electronic width measurement of ~40 eV, disfavouring the hybrid interpretation under lattice QCD calculation [21] and agreeing with Ref. [22], which rejects the interpretation of this state as a pure hybrid state.

[1]A quantitative estimation of the compositeness of a state [12]. For example, the deuteron has $\bar{X}_A = 0.9$.

4. The "New" Z_{cs} Resonances

New charged structures in the charmonium spectrum hint at an exotic nature, as they require a minimum quark content of at least four [3]. In 2021, BESIII found the first candidate with obvious open-strange content in the $D_s^- D^{*0} + D_s^{*-} D^0$ invariant mass, the $Z_{cs}(3985)$ [23]. Then, LHCb reported the $Z_{cs}(4000)$ candidate in the KJ/ψ final state [24], the mass of which is consistent with the $Z_{cs}(3985)$, but with a 10 times bigger width. These results call for more investigations.

4.1 The Spin Partner $Z_{cs}(3985)^0$

Using 5 datasets at $\sqrt{s} = [4.628, 4.699]$ GeV, Ref. [25] reports the evidence of a near-threshold structure in the $D_s^- D^{*+} + D_s^{*-} D^+$ invariant mass in the $e^+e^- \to K_S^0(D_s^- D^{*+} + D_s^{*-} D^+)$ process. Fig. 2 shows the K_S^0 recoil mass distributions for the 5 energy points with the fit superimposed; at $\sqrt{s}$ = 4.699 GeV, the evidence of the $Z_{cs}(3985)^0$ state is the most clear. The $Z_{cs}(3985)^0$ coupling to $D_s^- D^{*+} + D_s^{*-} D^+$ suggests a minimum quark content of $c\bar{c}s\bar{d}$. The $Z_{cs}(3985)^0$ mass is found to be consistent with predictions of Ref. [26] that hypothesised a neutral partner for the Z_{cs}^+ [23]. The Born cross-section multiplied by the decay's branching fraction was found to be compatible with the charged partner.

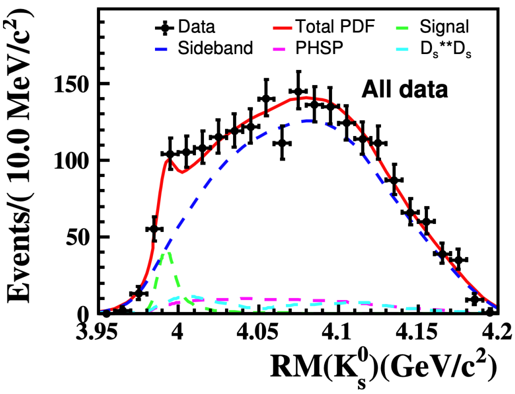

Figure 2: Combination of the simultaneous fit to the five K_S^0 recoil mass distributions. The green dashed curve highlights the $Z_{cs}(3985)^0$ signal, while the red solid curve refers to the total fit. The other three curves break down the background contributions: the pink dash-dotted one refers to the non-resonant process, the blue-dotted one to the combinatorial contribution, and the black dash-dotted one to the higher excited mesonic channels.

4.2 $Z_{cs}(3895)$ vs $Z_{cs}(4000)$

Regarding the $Z_{cs}(3895)$-$Z_{cs}(4000)$ debate, Ref. [27] studies the $e^+e^- \to K^+K^-J/\psi$ at $\sqrt{s} = [4.61, 4.95]$ GeV, investigating the KJ/ψ invariant mass. No significant Z_{cs} signal is found, hence, the suppression of the $Z_{cs}(3985) \to KJ/\psi$ decay with respect to the $D_s^- D^{*0} + D_s^{*-} D^0$ one disfavours Ref. [28] under the molecular state assumption, supporting the fact that the $Z_{cs}(3895)$ and the $Z_{cs}(4000)$ are two different states [29].

5. Summary

BESIII started taking data in 2008, and since then it has been exploring and shedding light on the charmonium spectrum and the XYZ states. The datasets above the $D\bar{D}$ threshold can shed new light on the nature of these exotic resonances and hint at possible connections between them and conventional charmonia, BESIII is competitive and complementary with respect to other experiments studying the same energetic region. With the current datasets and the inner tracker and accelerator upgrades [30], the BESIII Collaboration will provide more insights till 2030.

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