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Hadron spectroscopy at BESIII

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Hadron spectroscopy is one of the main physical goals of BESIII. Fruitful results have been reported by BESIII on hadron spectroscopy in recent years. In this report, we present the recent results from BESIII on the hadron spectroscopy, including XYZ states, baryon spectroscopy and light hadron spectroscopy.

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1. Introduction

The study of hadron spectroscopy plays an important role in understanding the non-perturbative properties of QCD. It is the bridge which connects lattice QCD calculation and phenomenological models like the quark model. Hadron spectroscopy also provides the platform to search for and study physics beyond the standard model, such as multiquarks, glueballs and hybrids, which are expected by QCD.

BEPCII is a double-ring multi-bunch e^+e^- collider running in the τ-charm energy region. The BESIII detector [1], has a geometrical acceptance of 93% of 4π solid angle. Since 2009, it has accumulated about 1.3 billion J/ψ events, 0.5 billion $\psi(3686)$ events, 2.9 fb^{-1} at the peak of the $\psi(3770)$ resonance for charm physics, and about 5 fb^{-1} data above 4 GeV for XYZ physics. These data samples offers us great opportunity to study the hadron spectroscopy. In this report, we present the recent results from BESIII on the hadron spectroscopy, including XYZ states, baryon spectroscopy and light hadron spectroscopy.

2. XYZ states

The quarkonium potential model is very successful in predicting the masses of the charmonium-like states below the $D\bar{D}$ threshold, like the firmly established states J/ψ, η_c and χ_{cJ}. Above the $D\bar{D}$ threshold, some of the predicted states by the potential model haven't been found by experiment. Meanwhile, we have found abundant family of charmonium-like states not fit in the model in recent years. These so called XYZ states have stimulated considerable theoretical and experimental efforts in explaining their unusual properties.

2.1 The X states

$X(3872)$ is a 1^{++} state close to $\bar{D}^0D^{*0}$ threshold. It was first observed in 2003 by Belle in $B^\pm \to K^\pm\pi^+\pi^-J/\psi$ decays [2]. Among several explanations of its nature, the most popular one is a $\bar{D}^0D^{*0}$ molecular state or a mixture of χ'_{c1} and $\bar{D}^0D^{*0}$ state. At BESIII, $X(3872)$ is observed in $e^+e^- \to \gamma\pi^+\pi^-J/\psi$ with 6.3 σ at four energy points above 4 GeV [3], as shown in Fig. 1 (left). The measured mass of the $X(3872)$ is $(3871.9 \pm 0.7 \pm 0.2)$ MeV$/c^2$, in agreement with previous results. The fit to energy-dependent cross section with a $Y(4260)$ resonance, a linear continuum, or a E1-transition phase space shows that $Y(4260)$ resonance describes the data best, as shown in Fig. 1 (right). The result strongly supports the existence of the radiative transition process $Y(4260) \to \gamma X(3872)$.

The lightest charmonium state above the $D\bar{D}$ threshold is the $\psi(3770)$. There have been no definitive observations of its two D-wave spin-triplet partner states yet. Phenomenological models predict that the $\psi(1^3D_2)$ charmonium state has large decay widths to $\gamma\chi_{cJ}$ [4]. And at Belle, $X(3823)$ was first observed in $B \to \gamma K\chi_{c1}$ with 3.8 σ [5]. At BESIII, $X(3823)$ is searched through the channel $e^+e^- \to \pi\pi\gamma\chi_c$, and the simultaneous fit to recoiling mass of $\pi^+\pi^-$ of $\gamma\chi_{c1}$ and $\gamma\chi_{c2}$ events shows the signal with 6.7 σ. The measured mass, width, relative branching fraction of $\mathscr{B}(X(3823) \to \gamma\chi_{c1})/\mathscr{B}(X(3823) \to \gamma\chi_{c2})$ suggest the state to be a good candidate of $\psi(1^3D_2)$.

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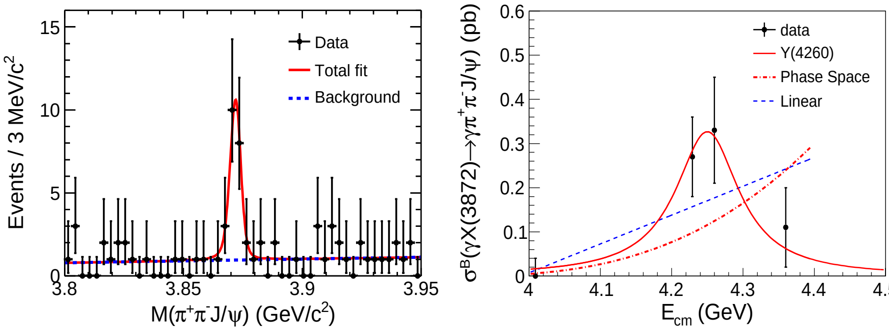

Figure 1: Fit to the $\pi^+\pi^-J/\psi$ invariant mass distribution (left); The fit to $\sigma^B[e^+e^- \to \gamma X(3872)] * \mathscr{B}[X(3872) \to \pi^+\pi^-J/\psi)]$ with a Y(4260) resonance, a linear continuum, or a E1-transition phase space term.

2.2 The Y states

The Y states, with spin-parity of 1^{--}, can be produced directly in e^+e^- annihilation. At BESIII, exclusive cross section line-shape measurement has been performed to study their decay properties.

Well above the $D\bar{D}$ threshold, the $Y(4260)$ state shows strong coupling to the $\pi\pi J/\psi$ final state, but relatively small coupling to open charm decay modes. These properties indicate that the $Y(4260)$ state is not a conventional state of charmonium. It's predicted that there might be a sizeable coupling between the $Y(4260)$ and the $\omega\chi_{c0}$ channel by considering the threshold effect [7]. BESIII studied the $e^+e^- \to \omega\chi_{c0}$ process, and measured the Born cross sections as a function of energy [8]. Assuming the signals come from a single resonance, the mass and width of the resonance are extracted. The parameters are inconsistent with those obtained by fitting a single resonance to the $\pi\pi J/\psi$ cross section [9]. This suggests that the observed $\omega\chi_{c0}$ signals are unlikely to originate from the $Y(4260)$. It's still an open question what's the nature of this structure [10, 11].

BESIII also measured cross section line-shape of $e^+e^- \to \eta J/\psi$ [12] and $e^+e^- \to \eta' J/\psi$ [13]. The result of $e^+e^- \to \eta J/\psi$ agrees with previous result from Belle [14]. And the line-shape shows a structure around 4.2 GeV. It might indicate the process of $\psi(4160) \to \eta J/\psi$. For $e^+e^- \to \eta' J/\psi$, we can not tell the line shape due to low statistics. The measured cross section is much lower than that of $\eta J/\psi$, which is lower than the NRQCD calculation.

2.3 Observation of the Z_c states

The charged $Zc(3900)$ was discovered by BESIII [15] and Belle [16] independently on the $\pi J/\psi$ invariant mass spectrum in the channel $e^+e^- \to \pi^+\pi^-J/\psi$. The state was later confirmed by CLEOc [17]. The $Zc(3900)$ discovered at BESIII, as shown in Fig. 2 (left), has a mass of $(3899.0 \pm 3.6 \pm 4.9)$ MeV/c^2 and a width of $(46 \pm 10 \pm 20)$ MeV. The mass is close to $D\bar{D}^*$ threshold. The structure couples to charmonium and has an electric charge, which is suggestive of a state containing more quarks than just a charm-anticharm quark pair. The neutral partner of $Zc(3900)$ was later found at BESIII through $e^+e^- \to \pi^0\pi^0J/\psi$ with 10 σ [18], as shown in Fig. 2 (right). The mass and width are determined to be $(3894.8 \pm 2.3 \pm 3.2)$ MeV/c^2 and $(29.6 \pm 8.2 \pm 8.2)$ MeV, respectively. Therefore, an isospin triplet is established for the $Zc(3900)$ state.

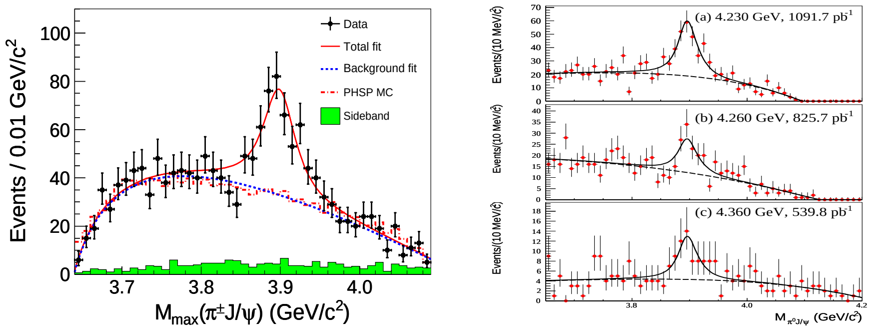

Figure 2: The $\pi J/\psi$ invariant mass spectrum for $Z_c(3900)^{\pm} \to \pi^{\pm} J/\psi$ (left) and $Z_c(3900)^0 \to \pi^0 J/\psi$ (right).

The $Zc(3900)$ mass is about 20 MeV above the $D\bar{D}^*$ mass threshold, which is suggestive of a virtual $D\bar{D}^*$ molecule-like structure or possibility of a diquark-diantiquark state. So it would be important to measure the rate for $Zc(3900)$ decays to $D\bar{D}^*$ and compare it to that for the $\pi\pi J/\psi$ final state. In the process of $e^+e^- \to \pi(D\bar{D}^*)$, BESIII observed an enhancement at threshold [19], as shown in Fig. 3. It's denoted as $Zc(3885)$, with the mass and width determined to be $(3883.9 \pm 1.5 \pm 4.2)$ MeV/c^2 and $(24.8 \pm 3.3 \pm 11.0)$ MeV, respectively. Its neutral partner was also found later at BESIII [20]. Compared with $Zc(3900)$, their masses and widths agree within 2σ. The angular distribution shows the spin-parity of $Zc(3885)$ favors 1^+, so it would be important to determine the spin-parity of $Zc(3900)$ to determine whether they are the same state. If they were the same state, the ratio of decay rates to open charm over the decay rates to $\pi J/\psi$ is much smaller than the expectation for traditional charmonium states like $\psi(4040)$. It indicates different dynamics in the $Y(4260) - Zc(3900)$ system.

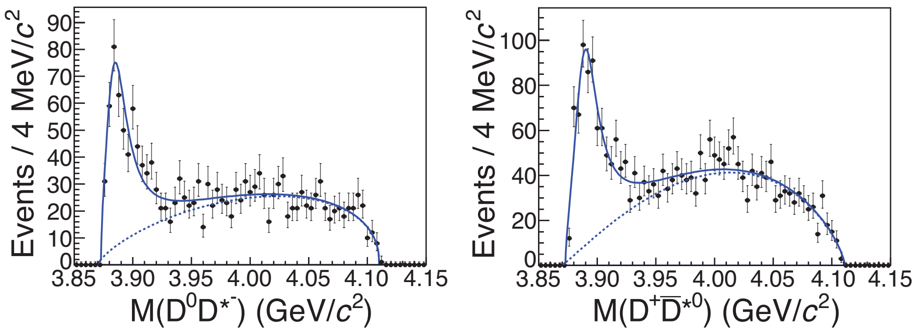

Figure 3: The $D^0 D^{*-}$ (left) and $D^+ \bar{D}^{*0}$ (right) invariant mass distributions. The dashed curves show the fitted non-resonant background. The enhancement is denoted as Zc(3885).

Similar to $\pi\pi J/\psi$, we can replace the J/ψ with h_c, and study the πh_c invariant mass spectrum. And a distinct structure, referred as $Zc(4020)$, is observed by BESIII in $e^+e^- \to \pi^+\pi^- h_c$ [21], as shown in Fig. 4 (left). Simultaneous fit to the $\pi^{\pm} h_c$ at three energy points yields 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, respectively. Similar to $Zc(3900)$, $Zc(4020)$ couples to charmonium and has electric charge, so it cannot be a conventional charmonium state. At the same time, $Zc(3900)$ is not significant in the πh_c spectrum. The significance is about 2 σ. The neutral $Zc(4020)$ is observed in $e^+e^- \to \pi^+\pi^- h_c$, as shown in Fig. 4 (right).

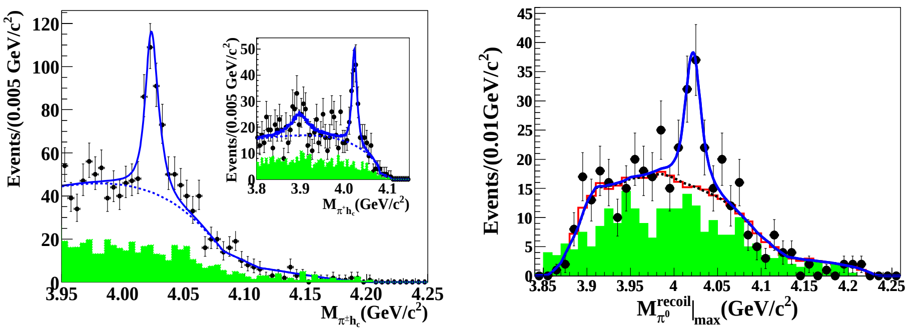

Figure 4: The $\pi^{\pm}h_c$ invariant mass distribution for $Zc(4020)^{\pm} \to \pi^{\pm}h_c$ (left) and the recoiling mass of π^0 for $Zc(4020)^0 \to \pi^0 h_c$ (right).

Similar to the previous case of $Zc(3900)/Zc(3885)$, BESIII has also studied the process of $e^+e^- \to \pi D^*\bar{D}^*$, since $Zc(4020)$ is near the mass threshold of $D^*\bar{D}^*$. In the recoil mass spectrum of π, a structure near $D^*\bar{D}^*$ threshold, denoted as $Zc(4025)$, is observed [23, 24], as shown in Fig. 5. The fit 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. Its resonance parameters agree with $Zc(4020)$ within 1.5 σ. Amplitude analysis with larger statistics is needed to determine the spin and parity of these states to clarify their nature and relationship.

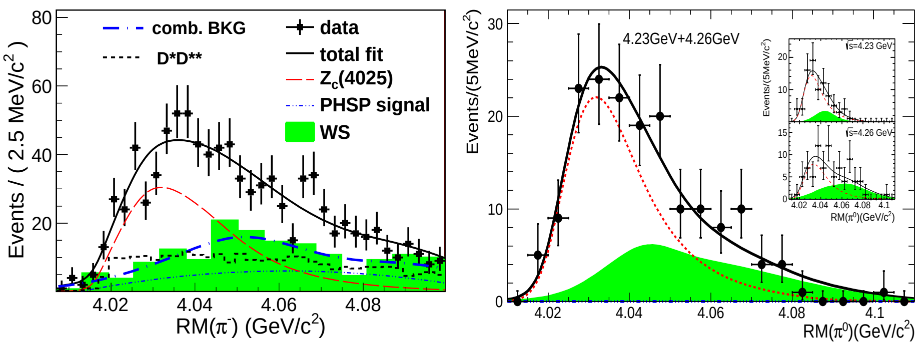

Figure 5: The recoiling mass of π in process of $e^+e^- \to \pi(D*\bar{D}*)$ (a) $Zc(4025)^{\pm} \to (D^*\bar{D}^*)^{\pm}$, (b) $Zc(4025)^0 \to (D^*\bar{D}^*)^0$.

2.4 Summary of XYZ states

To summarize, BESIII has observed or confirmed a series of charmonium-like states beyond the conventional quark model, using about 5 fb^{-1} data sample above 4 GeV. Great efforts have been paid both in theory and experiment to explain their nature. We have learned that Z_c states contain at least four quarks, and are likely to be tetra-quark or molecular state. We have also learnt that XYZ states can be inter-translated. For example, we have observed the decay of $Y(4260)$ to $X(3872)$, and $Y(4260)$ to $Zc(3900)$. However, relationship between X and Z_c states remains unclear. With larger statistics of data to be collected, BESIII is promising to resolve these XYZ puzzles.

3. Baryon spectroscopy

In the standard model, the baryon is made up of three quarks. The model is very successful in describing the ground state baryons. However, the picture predicts more excited states. One example is the missing N^* states. These predicted N^* states around 2 GeV were not observed by experiment. If these states don't exist, it may suggest that the three-quark picture may be replaced by the di-quark configuration, which has fewer effective degrees of freedom.

At BESIII, we can access the N^*, Λ^*, Σ^*, and Ξ^* states. It's a favorable environment to search for hybrid baryons $(qqqg)$ and missing baryons like N^*, which has strong coupling to g^3N. The results would be complementary to the πN scattering experiments.

To search for the missing N^* states, BESIII has performed partial wave analysis (PWA) in $\psi' \to p\bar{p}\pi^0$ [25]. The PWA shows $7N^*$ intermediate states. $N(2300)$ and $N(2570)$ are observed for the first time, with no evidence for $N(1885)$ or $N(2065)$. BESIII has also studied the Ξ^* states. In the PDG, we have 11 Ξ^* states observed so far, while only $\Xi(1530)$ properties are reasonably well known. In $\psi' \to K\Lambda\bar{\Xi}$, BESIII confirmed the existence of $\Xi(1690)$ and $\Xi(1820)$ [26].

Λ_c is the lightest charmed baryon with the quark component cud. According to the Heavy Quark Effective Theory, the $u-d$ quarks can be treated as a diquark that has zero spin and isospin. Using a double-tag method, BESIII gives the first measurement of the absolute hadronic branching fractions of the Λ_c baryon [27], in the 30 years since the Λ_c discovery. 12 Cabibbo-favored Λ_c decay rates are measured based on a sample of 567 pb^{-1} of e^+e^- collisions at the $\Lambda_c\Lambda_c$ production threshold, as shown in Fig. 6. The measurement provides important input to Λ_b physics as Λ_b decay dominantly to Λ_c. The results can also be used to constrain the fragmentation functions of charm and bottom quarks by counting inclusive heavy flavor baryons [28].

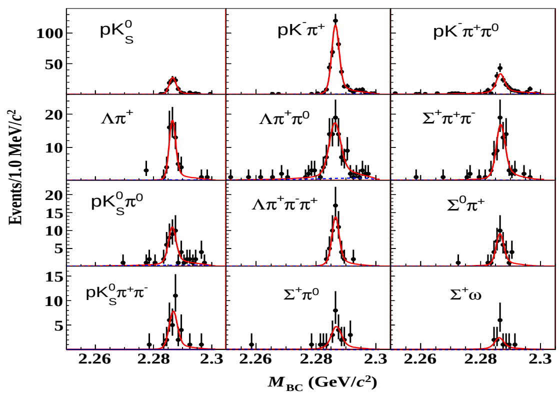

Figure 6: Fits to the double-tag M_{BC} distributions in data for Λ_c 12 Cabibbo-favored modes.

4. Light hadron spectroscopy

4.1 Structures around 1.85 GeV in J/ψ radiative decay

For light hadron spectroscopy, one interesting topic at BESIII is the abundant structures around 1850 MeV. BES first observed a strong enhancement at $p\bar{p}$ mass threshold [29]. To explain its nature, we search for the possible decay channels of a hypothesized $p\bar{p}$ bound state. Several resonances, denoted as $X(1810)$, $X(1835)$, $X(1840)$, $X(1870)$, with close masses are observed. These states could be interpreted as $p\bar{p}$ bound states, second radial excitation of η or pseudoscalar glueball. Systematic PWA work in different channels is needed to confirm whether they could be the same state. The PWA in $J/\psi \to \gamma K_s K_s \eta$ shows the $X(1835)$ to be a 0^{-+} state [30]. And a recent analysis observes a significant abrupt change in the slope of $\eta'\pi^+\pi^-$ invariant mass spectrum at $p\bar{p}$ mass threshold, in the channel $J/\psi \to \gamma\eta'\pi^+\pi^-$ where $X(1835)$ was first observed. Two models describing the $\eta'\pi^+\pi^-$ line shape both support that existence of a $p\bar{p}$ molecule-like or bound state with significance greater than 7σ [31].

4.2 Glueball candidates

Lattice QCD has given limits on the masses of the glueball candidates with different spin-parity. Glueballs are expected to be copiously produced in J/ψ radiative decays. However, in experiment, the mixing with nearby states makes it hard to be determined. BESIII is performing systematic PWA in a list of glueball-favored channels, including $J/\psi \to \gamma\eta\eta$ [32], $\gamma\pi^0\pi^0$ [33], $\gamma\phi\phi$ [34], $\gamma K_s K_s$, $\gamma\eta\eta'$, $\gamma\eta'\eta'$, ϕX, ωX etc.

4.3 η/η' physics

BESIII also has rich physics in η/η', which are produced through J/ψ radiative decay. Much lower background are expected at BESIII, compared with fixed target experiments. The studies on η/η' decays can test or constrain theoretical models like the Chiral Perturbation Theory and Vector Meson Dominance Model. They can also be used to search for new physics, like CP violation or a light invisible particle, beyond the standard model.

A recent analysis at BESIII that deals with the lepton pairs, i.e., the first observation of EM Dalitz decay $\eta' \to \gamma e^+e^-$ [35]. The spatial profile of the meson, described by the transition form factor (TFF), is extracted by comparing the measured invariant mass spectrum of the lepton pair with the QED calculation which assumes that the meson is a point-like particle, as shown in Fig. 7. The slope of the TFF corresponds to $(1.60 \pm 0.17(stat.) \pm 0.08(sys.))$ GeV^{-2}, which agrees within errors with the VMD model predictions. The result matches the best result in space-like region and would be useful input for the Hadronic light-by-light (HLbL) scattering contribution to $a_\mu = (g_\mu - 2)/2$.

5. Summary

To summarize, BESIII has collected large data samples in e^+e^- collisions at 2-4.6 GeV. It has achieved interesting and fruitful results on the hadron spectroscopy. For the study of charmonium-like states, abundant XYZ states, especially the isospin triplet $Zc(3900)$, $Zc(3885)$, $Zc(4020)$, $Zc(4025)$ have been observed. For the study of baryon spectrum, BESIII has searched for the missing excited N^* and Ξ^* states and also studied the baryon decay dynamics like the Λ_C. For the study of light hadron spectroscopy, BESIII has focused on the $p\bar{p}$ mass threshold enhancement, glueball candidates, and light hadron rare decays. BESIII will continue to run for 6-8 years. With larger data samples, more exciting results are expected to be coming out soon.

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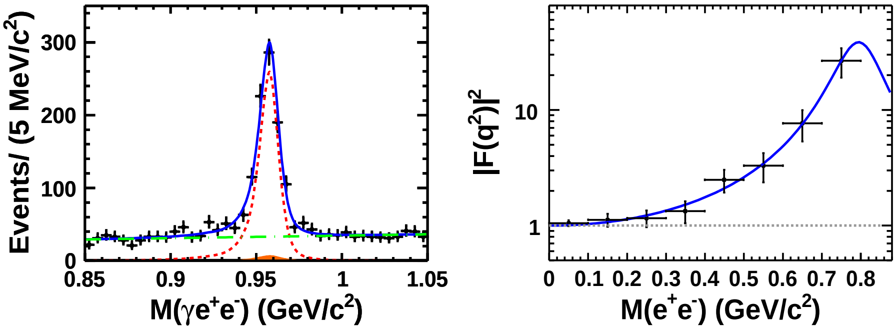

Figure 7: Invariant γe^+e^- mass distribution with clear signal of η' (left). The square of TFF, fitted with single-pole parametrization(right).

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