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Charmonium spectroscopy from BESIII

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In this talk, we present the recent results on the charmonium spectroscopy from the BESIII experiment. The talk covers the measurements on the parameters (mass, width, and production rate) of the spin-singlet states $\eta_c(1S)$, $h_c(1P)$, $\eta_c(2S)$ and the studies of the transitions between the charmonium states $\chi_{cJ} \to \eta_c(1S)\pi^+\pi^-$, $\psi(2S)/\psi(4040) \to \eta J/\psi$, $\pi^0 J/\psi$ and $\psi(3770) \to \gamma\eta_c(1S)$, $\gamma\eta_c(2S)$.

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1. Introduction

The charmonium sector is an ideal place to study the non-perturbative strong interactions due to their energy scale. The BESIII [1] experiment at the BEPCII e^+e^- collider started data taking since 2009, and lots of data have been accumulated at the peak of the narrow vector charmonium resonances as well as above 4 GeV. Based on these data samples, the charmonium spectroscopy could be widely studied.

In this proceeding, we present the most recent results on the studies of the spin-singlet states $\eta_c(1S)$, $h_c(1P)$, $\eta_c(2S)$ and the transitions between the charmonium states.

2. Spin-singlet states

2.1 The $\eta_c(1S)$

With the largest $\psi(2S)$ sample collected by BESIII, the mass and width of $\eta_c(1S)$ were measured through $\psi(2S) \to \gamma\eta_c(1S)$. The $\eta_c(1S)$ is reconstructed by six exclusive modes: $K_S^0K\pi$, $K^+K^-\pi^0$, $\pi^+\pi^-\eta$, $K_S^0K3\pi$, $K^+K^-\pi^+\pi^-\pi^0$ and $3(\pi^+\pi^-)$. A simultaneous fit with the unique $\eta_c(1S)$ mass and width is performed on the $\eta_c(1S)$ mass spectra, as shown in Fig. 1, where the interference between the amplitudes of resonant and non-resonant processes is considered and the quantum numbers of the non-$\eta_c(1S)$ components are assumed to be 0^{-+}. The corresponding relative phases in different decay modes are found to be quite consistent and set to the same value in the simultaneous fit. The obtained results are $M_{\eta_c(1S)} = 2984.3 \pm 0.6 \pm 0.6$ MeV/$c^2$and $\Gamma_{\eta_c(1S)} = 32.0 \pm 1.2 \pm 1.0$ MeV. The results provided by BESIII are so far the most precise measurement of the properties of $\eta_c(1S)$, which are consistent with those from two-photon fusion, as well as $J/\psi \to \gamma\eta_c(1S)$ by CLEO-c [2].

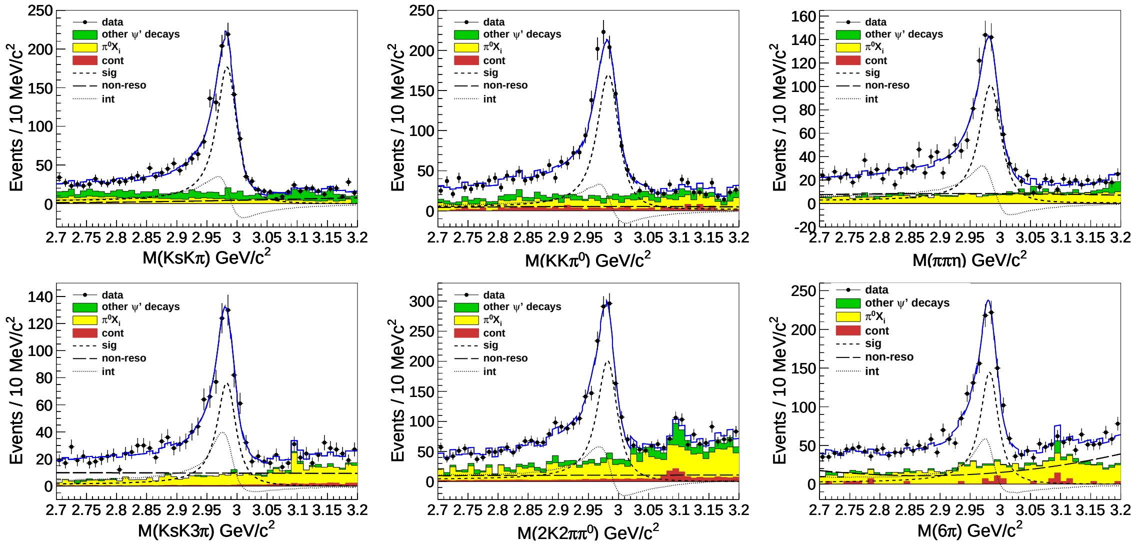

Figure 1: The invariant mass distributions for different $\eta_c(1S)$ decay modes with the simultaneous fit results superimposed.

2.2 The $h_c(1P)$

BESIII has measured [3] the $h_c(1P)$ in the π^0 recoil mass distribution for $\psi(2S) \to \pi^0 h_c(1P)$, and $h_c(1P) \to \gamma\eta_c(1S)$ with both E1-tagged and E1-untagged method previously. In order to reduce background and improve the precision, 16 exclusive hadronic decay processes of $\eta_c(1S)$ in $h_c(1P) \to \gamma\eta_c(1S)$ are used to reconstruct $\eta_c(1S)$ [4]. A simultaneous fit to the π^0 recoil mass spectra of the 16 decay modes yields the results $M_{h_c(1P)} = 3525.31 \pm 0.11 \pm 0.14$ MeV/c^2, $\Gamma_{h_c(1P)} = 0.70 \pm 0.28 \pm 0.22$ MeV, and mass splitting $\Delta M_{hf}(1P) = -0.01 \pm 0.11 \pm 0.15$ MeV/c^2 which is consistent with the lowest-order expectation that the 1P hyperfine splitting is zero. The sum of all the decay modes is shown in Fig. 2(a). These results are consistent with the previous BESIII inclusive results [3] and CLEO-c exclusive results [5]. The process $h_c(1P) \to p\bar{p}$ is also searched by BESIII, but no significant signal is found as shown in Fig. 2(b). The upper limit on the branching fraction is determined to be $\mathscr{B}(h_c(1P) \to p\bar{p}) < 1.7 \times 10^{-4}$ at the 90% C.L..

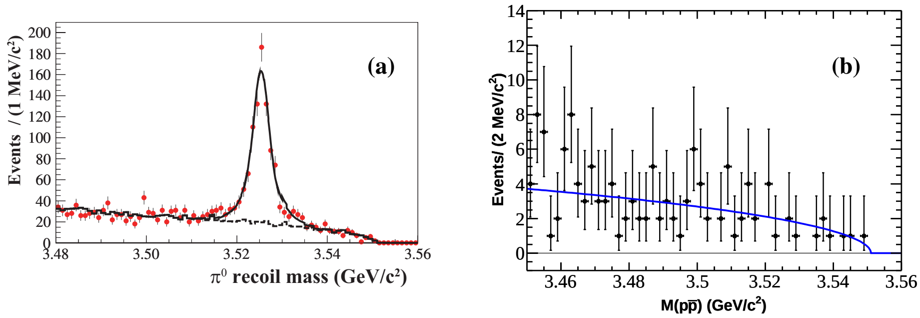

Figure 2: (a) The summed π^0 recoil-mass spectrum of 16 decay modes of $\eta_c(1S)$ in $h_c(1P) \to \gamma\eta_c(1S)$, where the line is the fit result; (b) The $p\bar{p}$ invariant-mass spectrum for $\psi(2S) \to \pi^0 p\bar{p}$, where the blue curve shows the fit results.

2.3 The $\eta_c(2S)$

The first radial excitation of $\eta_c(1S)$, $\eta_c(2S)$, is poorly understood relative to the other charmonium states below open-charm threshold. BESIII observed the M1 transition $\psi(2S) \to \gamma\eta_c(2S)$ with the decay mode $\eta_c(2S) \to K\bar{K}\pi$. A simultaneous fit to the mass spectra of $K_S^0 K\pi$ and $K^+K^-\pi^0$, as shown in Fig. 3, gives the mass and width fo $\eta_c(2S)$: $M_{\eta_c(2S)} = 3637.6 \pm 2.9 \pm 1.6$ MeV/$c^2$and $\Gamma_{\eta_c(2S)} = 16.9 \pm 6.4 \pm 4.8$ MeV. The product branching fraction is determined to be $\mathscr{B}(\psi(2S) \to \gamma\eta_c(2S)) \times \mathscr{B}(\eta_c(2S) \to K\bar{K}\pi) = (1.30 \pm 0.20 \pm 0.30) \times 10^{-5}$. Using the result $\mathscr{B}(\eta_c(2S) \to K\bar{K}\pi) = (1.9 \pm 0.4 \pm 1.1)\%$ from BaBar [6], the M1 transition rate is $\mathscr{B}(\psi(2S) \to \gamma\eta_c(2S)) = (6.8 \pm 1.1 \pm 4.5) \times 10^{-4}$.

With the same data sample, BESIII also searched for $\eta_c(2S) \to K_S^0 K3\pi$ [7] (Fig. 4(a)) and $\eta_c(2S) \to p\bar{p}$ [8] (Fig. 4(b)) in the decay $\psi(2S) \to \gamma\eta_c(2S)$. Evidence of $\eta_c(2S) \to K_S^0 K3\pi$ is reported with the product branching fraction $\mathscr{B}(\psi(2S) \to \gamma\eta_c(2S)) \times \mathscr{B}(\eta_c(2S) \to K_S^0 K3\pi) = (7.03 \pm 2.10 \pm 0.70) \times 10^{-6}$. But no significant $\eta_c(2S)$ signal is found in $\eta_c(2S) \to p\bar{p}$. The upper limit on the product branching fraction is set to be $\mathscr{B}(\psi(2S) \to \gamma\eta_c(2S)) \times \mathscr{B}(\eta_c(2S) \to p\bar{p}) < 1.4 \times 10^{-6}$ at the 90% C.L..

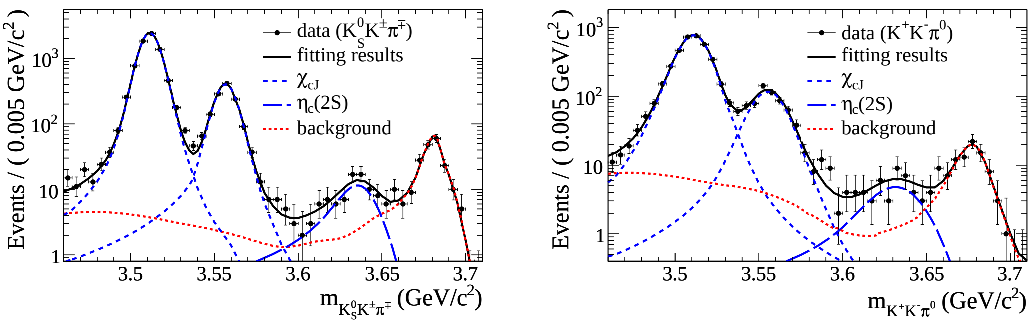

Figure 3: The simultaneous fit to the $K\bar{K}\pi$ mass spectrum.

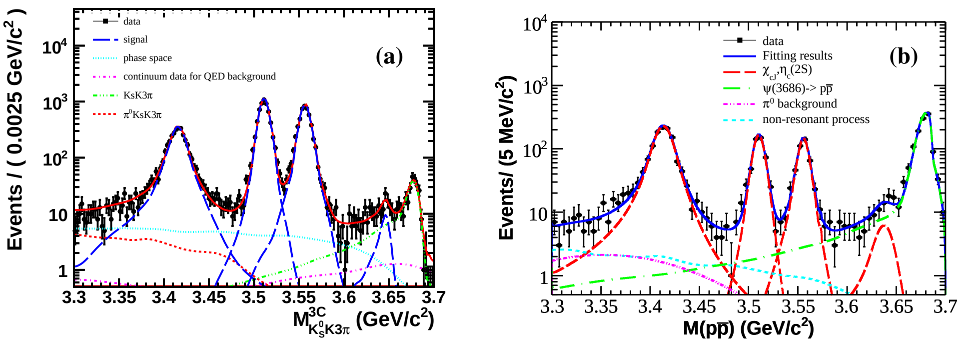

Figure 4: (a) The $K_S^0K3\pi$ mass spectrum in $\psi(2S) \to \gamma K_S^0 K3\pi$ with the fit results superimposed; (b) The $p\bar{p}$ mass spectrum in $\psi(2S) \to \gamma p\bar{p}$ with the fit results superimposed.

3. Charmonium transitions

The hadronic transitions of ^3P_J states are seldom explored. Hadronic transitions of $\chi_{cJ} \to \eta_c(1S)\pi^+\pi^-$ $(J = 0,1,2)$ are searched for [9] using the $\psi(2S)$ data by BESIII. The $\eta_c(1S)$ is reconstructed with $K\bar{K}\pi$ final states. No signals are observed in any of the three χ_{cJ} states. The upper limits are determined to be $\mathscr{B}(\chi_{c0} \to \eta_c(1S)\pi^+\pi^-) < 0.07\%$, $\mathscr{B}(\chi_{c1} \to \eta_c(1S)\pi^+\pi^-) < 0.32\%$, and $\mathscr{B}(\chi_{c2} \to \eta_c(1S)\pi^+\pi^-) < 0.54\%$ at the 90% C.L.. The upper limit of $\mathscr{B}(\chi_{c1} \to \eta_c(1S)\pi^+\pi^-)$ is lower than the existing theoretical prediction by almost an order of magnitude.

The decays $\psi(2S) \to \eta J/\psi$ and $\pi^0 J/\psi$ were first observed thirty years ago. The branching-fraction ratio, $R = \frac{\mathscr{B}(\psi(2S)\to\pi^0 J/\psi)}{\mathscr{B}(\psi(2S)\to\eta J/\psi)}$, was suggested as a reliable way to measure the light-quark mass ratio m_u/m_d [10]. BESIII measured the corresponding branching fractions [11] $\mathscr{B}(\psi(2S) \to \pi^0 J/\psi) = (1.26 \pm 0.02 \pm 0.03) \times 10^{-3}$, $\mathscr{B}(\psi(2S) \to \eta J/\psi) = (33.75 \pm 0.17 \pm 0.86) \times 10^{-3}$, and the branching fraction ratio $R = \frac{\mathscr{B}(\psi(2S)\to\pi^0 J/\psi)}{\mathscr{B}(\psi(2S)\to\eta J/\psi)} = (3.74 \pm 0.06 \pm 0.04) \times 10^{-2}$. The precision of these measurements of $\mathscr{B}(\psi(2S) \to \pi^0 J/\psi)$ and R represent a significant improvement over previously published values. Using a 478 pb^{-1} data sample taken at $\sqrt{s} = 4.009$ GeV, BESIII also observed [12] the production of $e^+e^- \to \eta J/\psi$, and measured the Born cross section to be

$(32.1 \pm 2.8 \pm 1.3)$ pb. Assuming the $\eta J/\psi$ signal is from a hadronic transition of the $\psi(4040)$, the fractional transition rate is determined to be $\mathscr{B}(\psi(4040) \to \eta J/\psi) = (5.2 \pm 0.5 \pm 0.2 \pm 0.5) \times 10^{-3}$. The production of $e^+e^- \to \pi^0 J/\psi$ is searched for, but no significant signal is observed, and $\mathscr{B}(\psi(4040) \to \pi^0 J/\psi) < 2.8 \times 10^{-4}$ at the 90% C.L. is obtained.

The $\psi(3770)$ exclusive non-$D\bar{D}$ decays are not well understood. By using a 2.92 fb^{-1} data sample taken at $\sqrt{s} = 3.773$ GeV, BESIII searched for the radiative transitions $\psi(3770) \to \gamma\eta_c(1S)$ and $\gamma\eta_c(2S)$ through the hadronic decays $\eta_c(1S), \eta_c(2S) \to K_S^0 K\pi$. No significant signals are observed. The preliminary results of the upper limits on the product branching fractions are obtained: $\mathscr{B}(\psi(3770) \to \gamma\eta_c(1S)) \times \mathscr{B}(\eta_c(1S) \to K_S^0 K\pi) < 1.6 \times 10^{-5}$ and $\mathscr{B}(\psi(3770) \to \gamma\eta_c(2S)) \times \mathscr{B}(\eta_c(2S) \to K_S^0 K\pi) < 5.8 \times 10^{-6}$ at the 90% C.L..

4. Summary

In summary, based on the data samples collected by BESIII, lots of results about charmonium spectroscopy are obtained recently: $\eta_c(1S)$ mass and width have been measured in high precision with the interference between $\eta_c(1S)$ and the non-resonant amplitude considered; $h_c(1P)$ is also studied by exclusive analysis, and the precision has been improved; $\eta_c(2S)$ is observed in $\psi(2S)$ M1 transition for the first time; Studies of charmonium transitions impose stringent constrains on theory.

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