Charmonium study at BESIII

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We present measurements of the charmonium state $h_c(^1P_1)$, η_c and $\eta_c(2S)$, using a sample of 1.06×10^8 $\psi(3686)$ events collected with the BESIII detector at the BEPCII storage ring. The results include the masses, widths, production and decay rates of these resonances, which shed light on the investigation of the charmonium spectroscopy.

1 Introduction

BESIII [1] is a major upgrade of the BESII experiment at the BEPCII accelerator [2] for studies of hadron spectroscopy as well as $\tau-$charm physics [3]. The design peak luminosity of the double-ring e^+e^- collider, BEPCII, is 10^{33} cm^{-2}s^{-1} at center-of-mass energy of 3.78 GeV. The BESIII detector with a geometrical acceptance of 93% of 4π consists of a main drift chamber (MDC) with momentum resolution 0.5% at 1 GeV/^{c}, an electromagnetic calorimeter (EMC) with energy resolution 2.5% at 1.0 GeV, a Time-Of-Flight counter (TOF), a superconductor magnet with a magnetic strength of 1 T, and a muon chamber system (MUC) made of resistive plate chambers.

Based on 106×10^6 [4] $\psi(3686)$ events taken in 2009, the charmonium spectroscopy is widely studied, and here we focused on the measurement of $h_c(^1P_1)$, η_c and $\eta_c(2S)$.

2 Measurement of $h_c(^1P_1)$ using $\psi(3686) \to \pi^0 h_c(^1P_1)$

Knowledge is sparse on the spin singlet state $h_c(^1P_1)$ although the charmonium family of mesons has been studied for many years. The CLEO Collaboration first observed the $h_c(^1P_1)$ in the cascade process $\psi(3686) \to \pi^0 h_c$, $h_c \to \gamma\eta_c$ in both inclusive and exclusive measurements [5]. The E835 experiment [6] found the evidence of $p\bar{p} \to h_c \to \gamma\eta_c$ by scanning the antiproton energy. There are also some theoretical predictions [7,8,9] about the production and decays of $h_c(^1P_1)$, which can be tested with the largest $\psi(3686)$ data sample at BESIII.

Both E1-tagged and inclusive method in $h_c \to \gamma\eta_c$ are performed at BESIII to study the process $\psi(3686) \to \pi^0 h_c(^1P_1)$. The results are shown in Fig. 2. The mass and width of $h_c(^1P_1)$ are determined to be $M_{h_c} = 3525.40 \pm 0.13 \pm 0.18$ MeV/c^2 and $\Gamma_{h_c} = 0.73 \pm 0.45 \pm 0.28$ MeV from the E1 tagged method. The mass split $\Delta M_{hf} \equiv < M(1^3P) > -M(^1P_1) = -0.10 \pm 0.13 \pm 0.18$ MeV/c^2 is consistent with no strong spin-spin interaction. The branching fractions are determined to be $\mathcal{B}(\psi(3686) \to \pi^0 h_c(^1P_1)) = (8.3 \pm 1.3 \pm 1.0) \times 10^{-4}$ and $\mathcal{B}(h_c(^1P_1) \to \gamma\eta_c) = (54.3 \pm 6.7 \pm 5.2)\%$, which are first measurement and agree with the theoretical predictions [7]. Exclusive measurements are also performed with sixteen η_c decay channels [10], and the mass and width are measured to be $M_{h_c} = 3525.31 \pm 0.11 \pm 0.14$ MeV/c^2 and $\Gamma_{h_c} = 0.70 \pm 0.28 \pm 0.22$ MeV from the simultaneous fit on the recoil-mass of π^0 as shown in Fig. 2. The measurements are consistent with the previous values at CLEO-c [11].

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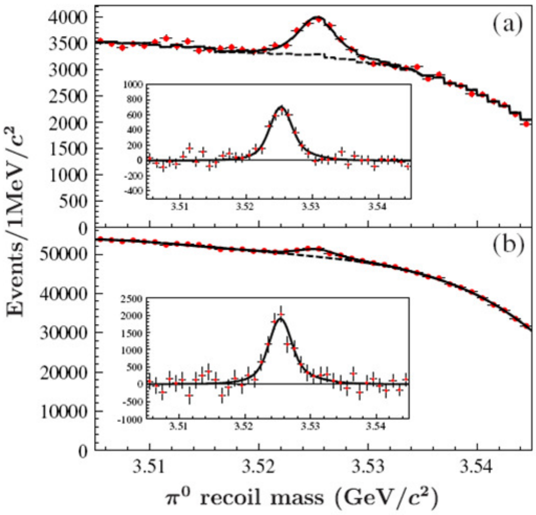

Figure 1: (a)The π^0 recoil-mass spectrum and fit for the E1-tagged analysis of $\psi(3686) \to \pi^0 h_c$, $h_c \to \gamma\eta_c$. (b)The π^0 recoil-mass spectrum and fit for the inclusive analysis of $\psi(3686) \to \pi^0 h_c$.

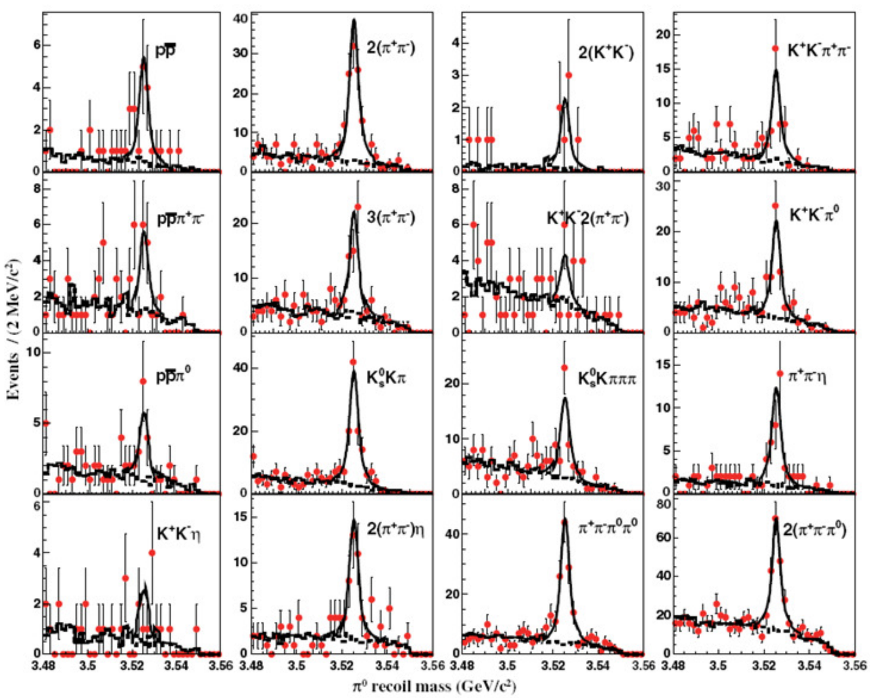

Figure 2: The simultaneously fitted π^0 recoil mass spectra in $\psi(3686) \to \pi^0 h_c$, $h_c \to \gamma\eta_c$, $\eta_c \to X_i$ for the 16 final states X_i

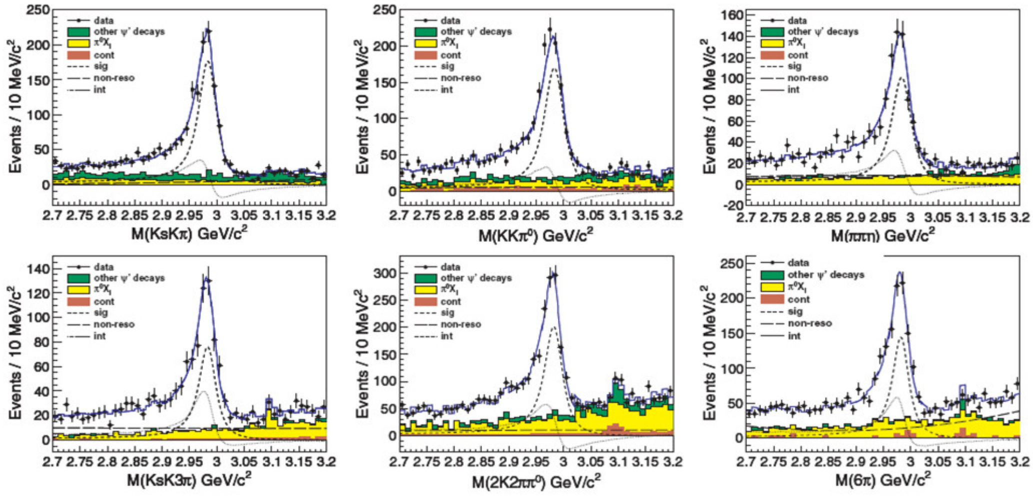

Figure 3: The fit results on the $M(X_i)$ invariant mass distributions for the decays $K_S K^+\pi^-$, $K^+K^-\pi^0$, $\eta\pi^+\pi^-$, $K_S K^+\pi^+\pi^-\pi^-$, $K^+K^-\pi^+\pi^-\pi^0$, and $3(\pi^+\pi^-)$, respectively.

3 Measurement the mass and width of η_c with $\psi(3686) \to \gamma\eta_c$

Properties of the lowest-lying S-wave spin singlet charmonium state, the η_c, are not well understood although it has been observed for many years. Early measurements of the properties of the η_c using J/ψ radiative transitions [12] found a mass and width near 2978 MeV/c^2 and 10 MeV, respectively. However, recent experiments, including photon-photon fusion and B decays, have reported a significantly higher mass and a much larger width [13]. The most recent study by the CLEO-c experiment [14], using both $\psi(3686) \to \gamma\eta_c$ and $J/\psi \to \gamma\eta_c$, pointed out a distortion of the η_c line shape in $\psi(3686)$ decays, but similar effect is not observed in $\psi(3686) \to \pi^0 h_c$, $h_c \to \gamma\eta_c$ at BESIII [10].

We measured the η_c mass and width using the radiative transition $\psi(3686) \to \gamma\eta_c$ by reconstructing η_c from six decay modes, including $K_S K^+\pi^-$, $K^+K^-\pi^0$, $\eta\pi^+\pi^-$, $K_S K^+\pi^+\pi^-\pi^-$, $K^+K^-\pi^+\pi^-\pi^0$, and $3\pi^+\pi^-$. A simultaneous fit with unique η_c mass and width is performed on the η_c mass spectra as shown in Fig. 3. The η_c line shapes were successfully described using a combination of the energy dependence of the hindered-M1 transition matrix elements and a full interference with nonresonant $\psi(3686)$ radiative decays where the quantum number of the non-η_c components are assumed to be 0^{-+}. The fit yields $M = 2983.9 \pm 0.6 \pm 0.6$ MeV/c^2, $\Gamma = 31.3 \pm 1.2 \pm 0.9$ MeV, and $\phi = 2.40 \pm 0.07 \pm 0.47$ rad (constructive) or $\phi = 4.19 \pm 0.03 \pm 0.47$ rad (destructive). Our results are consistent with those from photon-photon fusion and B decays. From this measurement, we determine the hyperfine mass splitting to be $\Delta M_{hf}(1S)_{c\bar{c}} = M(J/\psi) - M(\eta_c) = 112.6 \pm 0.8$ MeV/c^2, which agrees well with recent lattice computations [15] as well as quark-model prediction [16].

4 First observation of the M1 transition $\psi(3686) \to \gamma\eta_c(2S)$

The $\eta_c(2S)$ was first observed by the Belle collaboration in the B decays [17] and was confirmed in the two-photon production of $K_S^0 K^\pm \pi^\mp$ [18] as well as in the double-charmonium production process $e^+e^- \to J/\psi c\bar{c}$ [19]. But it was absent in the M1 radiative transition of $\psi(3686) \to \gamma\eta_c(2S)$ [20,21]. The branching fractions are predicted to be $\mathcal{B}(\psi(3686) \to \gamma\eta_c(2S)) = (0.1 - 6.2) \times 10^{-4}$ by many authors [22].

BESIII made the first observation of $\psi\prime \to \gamma\eta_c(2S)$, with $\eta_c(2S) \to K\bar{K}\pi$. Fig. 4 shows the simultaneous fit to the $K\bar{K}\pi$ mass spectrum, where the yields of $\eta_c(2S)$ events are 81$\pm$14 for the $K_S^0 K^\pm K^\mp$ channel and 46$\pm$11 for the $K^+K^-\pi^0$ channel. The combined statistical significance of

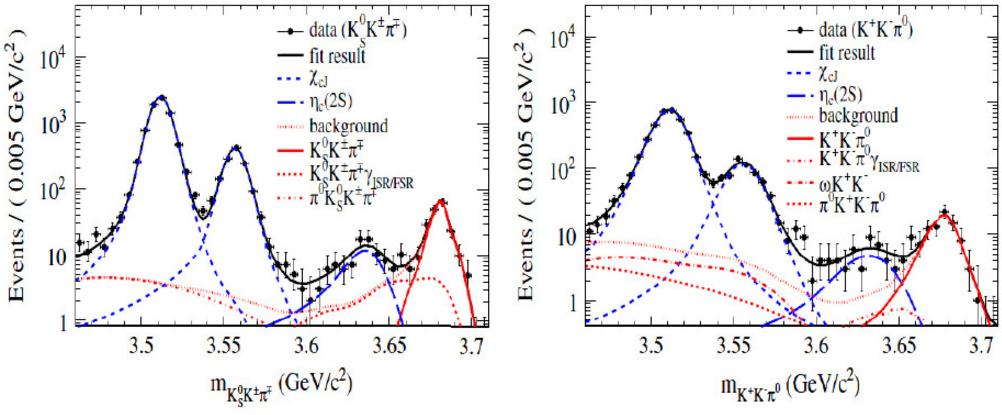

Figure 4: The simultaneous likelihood fit on the mass spectrum of $K_S K^\pm \pi^\mp$ (left panel) and $K^+K^-\pi^0$ (right panel).

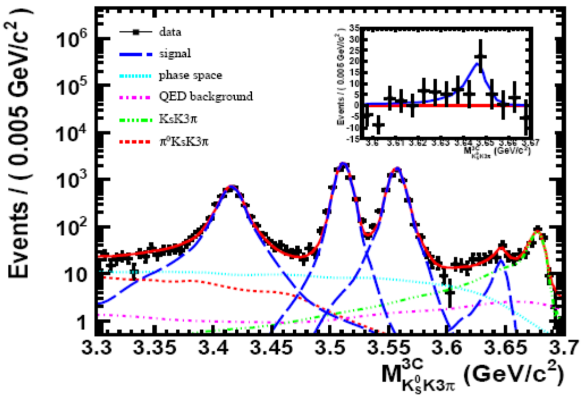

Figure 5: The fit results on the mass spectrum of $K_S K 3\pi$.

the signal in the two modes is 11.1 σ. The mass and width of $\eta_c(2S)$ are measured to be $M_{\eta_c(2S)} = 3637.6 \pm 2.9$ MeV/c^2 and $\Gamma_{\eta_c(2S)} = 16.9 \pm 6.4$ MeV, respectively. The product branching fraction is measured to be $\mathcal{B}(\psi(3686) \to \gamma\eta_c(2S)) \times (\eta_c(2S) \to K\bar{K}\pi) = (1.30 \pm 0.20) \times 10^{-5}$. Using the measurement of $\mathcal{B}(\eta_c(2S) \to K\bar{K}\pi) = (1.9 \pm 0.4 \pm 1.1)\%$ from the BARBAR experiment [23], we obtained the M1-transition branching fraction of $\mathcal{B}(\psi(3686) \to \gamma\eta_c(2S)) = (6.8 \pm 1.1 \pm 4.5) \times 10^{-4}$, which is consistent with the prediction from CLEO-c [21].

We also investigate the M1-transition $\psi(3686) \to \gamma\eta_c(2S)$ with $\eta_c(2S) \to K^0_S K^\pm \pi^\mp \pi^+ \pi^-$. Fig.5 shows the fit result to the mass spectrum of $K^0_S K^\pm \pi^\mp \pi^+ \pi^-$, from which the yield of $\eta_c(2S)$ is 57 ± 17 with a significance of 4.2σ. The mass of the $\eta_c(2S)$ is measured to be $3646.9 \pm 1.6 \pm 3.6$ MeV/c^2, and the width is $9.2 \pm 4.8 \pm 2.9$. Comparing with BESIII previous measurements [24], the width is consistent with each other within 1 standard deviation and the mass is about 2 standard deviations.

5 Summary

Based on the 1.06×10^8 $\psi(3686)$ data sample collected by BESIII detector at BEPCII, charmonium states $h_c(^1P_1)$, η_c, $\eta_c(2S)$ have been well studied: the absolute branching fractions of $\psi(3686) \to \pi^0 h_c(^1P_1)$, $h_c(^1P_1) \to \gamma\eta_c$ as well as the width of $h_c(^1P_1)$ are measured for the first time; parameters of η_c are measured with high precision, interference between η_c and the non-resonant amplitudes around the η_c mass is considered for the first time; first observation of M1-transition $\psi(3686) \to \gamma\eta_c(2S)$ with $K\bar{K}\pi$ final states and evidence for the $K_S K^\pm \pi^\mp \pi^+ \pi^-$.

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