Studies of Charmonium at BESIII

X. C. Ai on behalf of the BESIII Collaboration[1,a)]

[1]*Institute of High Energy Physics, Chinese Academy of Sciences*

[a)]Corresponding author: aixc@ihep.ac.cn
URL: http://www.aip.org

Abstract. In recent years, lots of studies of charmonium decays have been performed at BESIII based on large data samples of J/ψ, $\psi(3686)$ and $\psi(3770)$. Recent results in searches for radiative transitions of $\psi(3770)$ and rare phenomena in charmonium decays, and studies of light hadrons structures and properties will be presented.

INTRODUCTION

The BESIII detector at the BEPCII collider has accumulated the world's largest data samples of e^+e^- collisions in the τ-charm region, including J/ψ, $\psi(3686)$, $\psi(3770)$ and the XYZ data. These data samples provide a clean and simple environment to study the production and decay mechanisms of charmonium states including not only J/ψ, $\psi(3686)$, $\psi(3770)$, but also η_c, $\eta_c(2S)$ and χ_{cJ} which are available by the γ transition of $\psi(3686)$ and $\psi(3770)$.

Results in this presentation are based on 2.92 fb^{-1} data sample taken at $\sqrt{s} = 3.773$ GeV, 1.06×10^8 $\psi(3686)$ events and 1.31×10^9 J/ψ events.

SEARCH FOR $\psi(3770)$ RADIATIVE TRANSITIONS

The nature of the excited $J^{PC} = 1^{--}$ $c\bar{c}$ bound states above the $D\bar{D}$ threshold is of interest but still not well known. The $\psi(3770)$ resonance, as the lightest charmonium state lying above the open charm threshold, is generally assigned to be a dominant 1^3D_1 momentum eigenstate with a small 2^3S_1 admixture [1]. It has been thought almost entirely to decay to $D\bar{D}$ states [2, 3]. Unexpectedly, the BES Collaboration found a large inclusive non-$D\bar{D}$ branching fraction, (14.7 $\pm$ 3.2)%, by utilizing various methods [4, 5, 6, 7]. A later work by the CLEO Collaboration found a contradictory non-$D\bar{D}$ branching fraction,$(3.3 \pm 1.4^{+6.6}_{-4.8})$% [8]. The BES results suggest substantial non-$D\bar{D}$ decays, although the CLEO result finds otherwise. In the exclusive analyses, various non-$D\bar{D}$ decay modes have been observed, including hadronic transitions $\psi(3770) \to J/\psi\pi^+\pi^-$ [9, 10], $\pi^0\pi^0 J/\psi$, $\eta J/\psi$ [10], the $E1$ transitions $\gamma\chi_{cJ}$ (J = 0, 1) [11, 12], and the decay to light hadrons $\phi\eta$ [13]. The sum of the observed non-$D\bar{D}$ exclusive components still makes up less than 2% of all decays [14], which motivates the search for other exclusive non-$D\bar{D}$ final states.

Search for $\psi(3770) \to \gamma\eta_c$ and $\gamma\eta_c(2S)$

The radiative transitions $\psi(3770) \to \gamma\eta_c(\eta_c(2S))$ are supposed to be highly suppressed by selection rules, considering the $\psi(3770)$ is predominantly the 1^3D_1 state. However, due to the non-vanishing photon energy in the decay, higher multipoles beyond the leading one could contribute [15]. Recently, the partial decay widths $\Gamma(\psi(3770) \to \gamma\eta_c(\eta_c(2S))$ have been calculated in Ref. [15] by considering contributions from the intermediate meson loop (IML) mechanism.

Using the $\psi(3770)$ data sample, the radiative transitions $\psi(3770) \to \gamma\eta_c(\eta_c(2S))$ through the decay process $\psi(3770) \to K^0_S K^\pm\pi^\mp$ have been searched for [16]. Figure 1 shows the invariant-mass spectrum of $K^0_S K^\pm\pi^\mp$ for selected candidates, together with the estimated backgrounds in the η_c mass region (Fig. 1(a)) and in the $\chi_{c1} - \eta_c(2S)$ mass region (Fig. 1(b)). No significant η_c and $\eta_c(2S)$ signals are observed. The upper limits on the branching fractions at a 90% C.L. have been set: $\mathcal{B}(\psi(3770) \to \gamma\eta_c) < 6.8 \times 10^{-4}$ and $\mathcal{B}(\psi(3770) \to \gamma\eta_c(2S)) < 2.0 \times 10^{-3}$. The upper limit for $\Gamma(\psi(3770) \to \gamma\eta_c)$ is within the error range of the theoretical predictions of IML [15] and lattice QCD calculations [17]. However, the upper limit for $\Gamma(\psi(3770) \to \gamma\eta_c(2S))$ is much larger than the prediction and is limited by statistics and the systematic error.

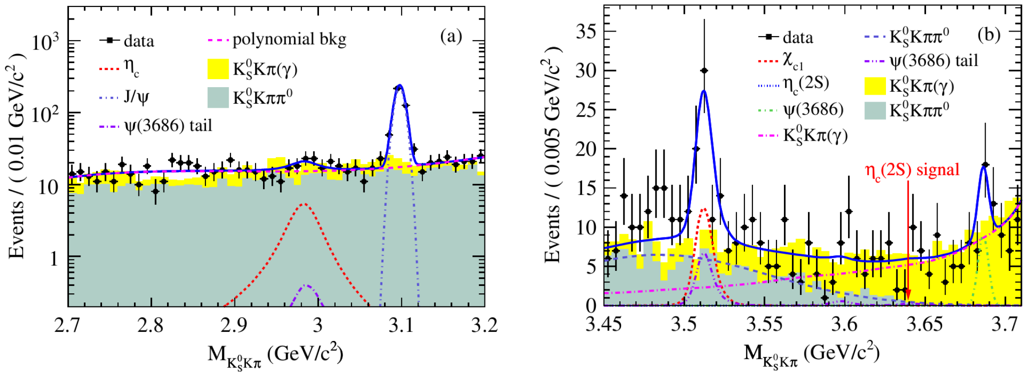

FIGURE 1. Invariant-mass spectrum for $K_S^0K^{\pm}\pi^{\mp}$ from data with the estimated backgrounds and best-fit results superimposed in the (a) η_c and (b) χ_{c1} and $\eta_c(2S)$ mass regions. Dots with error bars are data. The shaded histograms represent the background contributions and the solid lines show the total fit results.

Measurement of the Branching Fraction for $\psi(3770) \to \gamma\chi_{cJ}$

Within an S-D mixing model [1], Refs. [18, 19, 20] predict the partial widths for $\psi(3770)$ $E1$ radiative transitions, but with large uncertainties. Up to now, the transition $\psi(3770) \to \gamma\chi_{c2}$ has not been observed. Precision measurements of partial widths of the $\psi(3770) \to \gamma\chi_{c1,2}$ processes are critical to test the theoretical predictions, and to better understand the nature of the partial widths of the $\psi(3770)$, as well as to find the origin of the non-$D\bar{D}$ decays of $\psi(3770)$.

Using the $\psi(3770)$ data sample, the $\psi(3770)$ $E1$ transitions $\psi(3770) \to \gamma\chi_{c1,2}$ have been studied [21] by reconstructing χ_{cJ} using the decay $\chi_{cJ} \to \gamma J/\psi$. Figure 2 shows the invariant-mass distribution of the higher energetic photon and J/ψ. Clear peak corresponding to the χ_{c1} signal is observed while there is no significant signal of χ_{c2}. The branching fraction of $\psi(3770) \to \gamma\chi_{c1}$ is measured to be $\mathcal{B}(\psi(3770) \to \gamma\chi_{c1}) = (2.48 \pm 0.15 \pm 0.23) \times 10^{-3}$, which is the most precise measurement to date. The upper limit on the branching fraction of $\psi(3770) \to \gamma\chi_{c2}$ at 90% C.L. is $\mathcal{B}(\psi(3770) \to \gamma\chi_{c2}) < 0.64 \times 10^{-3}$.

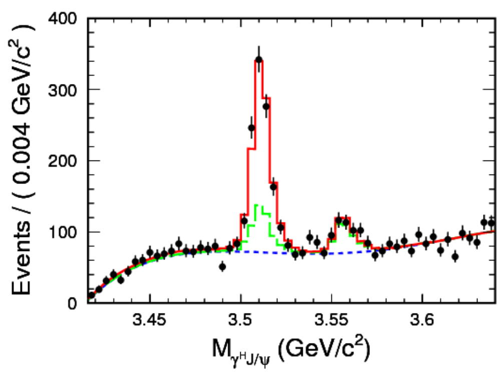

FIGURE 2. Invariant mass spectrum of higher energetic photon and J/ψ selected from data. The dots with error bars represent the data. The solid (red) line shows the fit. The dashed (blue) line shows the smooth background. The long-dashed (green) line is the sum of the smooth background and the contribution from $e^+e^- \to (\gamma_{ISR})\psi(3686)$ production.

SEARCH FOR RARE PHENOMENA IN CHARMONIUM DECAYS

Search for Isospin-violating Transition $\chi_{c0,2} \to \pi^0\eta_c$

Based upon an effective-field theoretical approach, theoretical calculations give qualitative insights in the isospin-breaking mechanisms in charmonium decays below $D\bar{D}$ threshold [22]. Currently, for such a theory, quantitative predictions of individual branching fractions of isospin-forbidden decays of charmonium require more constraints from experimental data.

Using the $\psi(3686)$ data sample, the hadronic isospin-violating transitions $\chi_{c0,2} \to \pi^0\eta_c$ have been searched for through $\eta_c \to K_S^0 K^\pm\pi^\mp$ decays [23]. No statistically significant signal is observed and upper limits on the branching fractions for the processes $\chi_{c0,2} \to \pi^0\eta_c$ have been obtained. The results are $\mathcal{B}(\chi_{c0} \to \pi^0\eta_c) < 1.6\times10^{-3}$ and $\mathcal{B}(\chi_{c2} \to \pi^0\eta_c) < 3.2\times10^{-3}$. These are the first upper limits on $\mathcal{B}(\chi_{c0,2} \to \pi^0\eta_c)$ that have been reported so far. These limits might help to constrain non-relativistic field theories and provide insight in the role of charmed-meson loops to the various transitions in charmonium and charmonium-like states.

Search for C-parity Violation in $J/\psi \to \gamma\gamma, \gamma\phi$

In the Standard Model (SM), C invariance is held in strong and electromagnetic (EM) interactions. Until now, no C-violating processes have been observed in EM interactions. Any evidence for C violation in the EM sector would immediately indicate physics beyond the SM.

Using the $\psi(3686)$ data sample, the decays of $J/\psi \to \gamma\gamma$ and $\gamma\phi$ have been searched for via $\psi(3686) \to J/\psi\pi^+\pi^-$ [24]. No significant signal is observed for $J/\psi \to \gamma\gamma$ and $J/\psi \to \gamma\phi$. The upper limits for the branching fractions of $J/\psi \to \gamma\gamma$ and $J/\psi \to \gamma\phi$ are set to be $\mathcal{B}(J/\psi \to \gamma\gamma) < 2.7\times10^{-7}$ and $\mathcal{B}(J/\psi \to \gamma\phi) < 1.4\times10^{-6}$, respectively. The upper limit on $\mathcal{B}(J/\psi \to \gamma\gamma)$ is one of magnitude more stringent than the previous upper limit [25], and $\mathcal{B}(J/\psi \to \gamma\phi)$ is the first upper limit for this channel.

Observation of OZI-suppressed Decay $J/\psi \to \pi^0\phi$

A full investigation of J/ψ decaying to a vector meson (V) and a pseudoscalar meson (P) can provide rich information about SU(3) flavor symmetry and its breaking, probe the quark and gluon content of the pseudoscalar mesons, and determine the electromagnetic amplitudes [26, 27, 28].

Using the J/ψ data sample, the first evidence for a doubly OZI suppressed electromagnetic J/ψ decay $J/\psi \to \pi^0\phi \to K^+K^-\gamma\gamma$ has been reported [29]. A clear structure in the K^+K^- invariant mass spectrum around 1.02 GeV/c^2 is observed, which can be attributed to interference of $J/\psi \to \pi^0\phi$ and $J/\psi \to K^+K^-\pi^0$ decays. Figure 3 shows the fit to the invariant mass spectrum of K^+K^- with the background events estimated with π^0 sidebands subtracted. Due to the interference, two possible solutions are found. The corresponding measured values of the branching fraction of $J/\psi \to \pi^0\phi$ are $(2.94 \pm 0.16 \pm 0.16)\times10^{-6}$ and $(1.24 \pm 0.33 \pm 0.30)\times10^{-7}$, respectively.

STUDIES OF LIGHT HADRON STRUCTURES AND PROPERTIES

Study of $J/\psi \to \phi\pi^0 f_0(980)$

The nature of the scalar meson $f_0(980)$ is a long-standing puzzle [14]. In the study of J/ψ radiatively decaying into $\pi^+\pi^-\pi^0$ and $\pi^0\pi^0\pi^0$, BESIII observed the decay of $\eta(1405) \to \pi^0 f_0(980)$ with a large isospin violation and an anomalously narrow width of $f_0(980)$ [30]. One proposed explanation for these phenomena is the triangle singularity mechanism [31, 32].

Using the J/ψ data sample, the decays $J/\psi \to \phi\pi^0\pi^0\pi^0$ with $\phi \to K^+K^-$ are investigated [33]. The isospin-violating decay $J/\psi \to \phi\pi^0 f_0(980)$ is observed for the first time. Figure 4 shows the invariant mass spectrum of $\pi^+\pi^-$ (Fig. 4(a)) and $\pi^0\pi^0$ (Fig. 4(b)). A clear $f_0(980)$ exists for the $\pi^+\pi^-$ mode. The width obtained from the dipion mass spectrum is (15.3 ± 4.7) MeV/c^2, which is consistent with that in the study of $J/\psi \to \gamma\eta(1405) \to \gamma\pi^0 f_0(980)$ [30] and the prediction of a theoretical work [34] based on the triangle singularity mechanism [31, 32]. In the invariant mass spectra of $f_0(980)\pi^0$, there is evidence of a resonance around 1.28 GeV/c^2 for the $f_0(980) \to \pi^+\pi^-$ mode, which was identified as the axial-vector meson $f_1(1285)$.

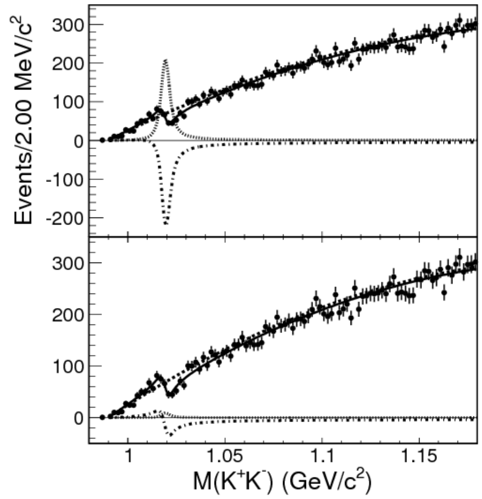

FIGURE 3. Fit to $M(K^+K^-)$ spectrum after sideband subtraction for Solution I (a) and Solution II (b). The red dotted curve denotes the ϕ resonance; the blue dashed curve is the non-ϕ contribution; the green dot-dashed curve represents their inter-ference; the blue solid curve is the sum of them.

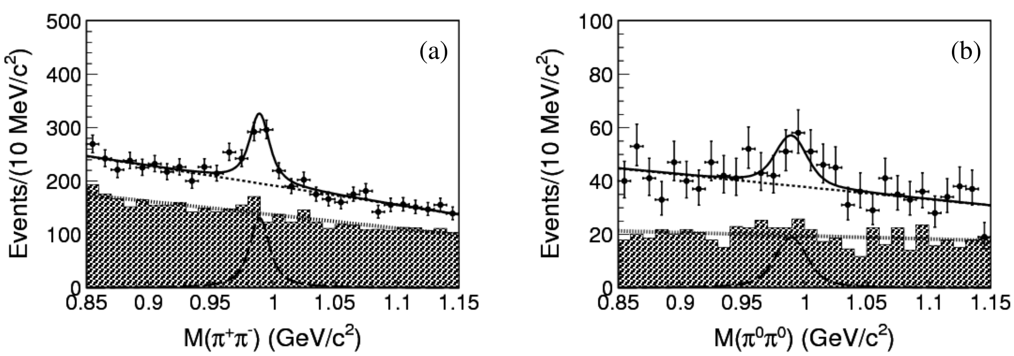

FIGURE 4. The spectra (a) $M(\pi^+\pi^-)$ and (b) $M(\pi^0\pi^0)$ (three entries per event) with K^+K^- in the ϕ signal region (black dots) and in the ϕ sideband regions (hatched histogram). The solid curve is the full fit, the long-dashed curve is the $f_0(980)$ signal, the dotted line is the non-ϕ background, and the short-dashed line is the total background.

Study of $\chi_{cJ} \to \eta' K^+K^-$

Until now, $K_0^*(1430)$ has been observed in $K_0^*(1430) \to K\pi$ only, but it is also expected to couple to $\eta' K$ [35, 36]. $\chi_{c1} \to \eta' K^+K^-$ is a promising channel to search for $K_0^*(1430)$ and study its properties while decays of $\chi_{c0,2} \to K_0^*(1430)K$ are forbidden by spin-parity conservation.

Using the $\psi(3686)$ data sample, the decay $\chi_{cJ} \to \eta' K^+K^-$ with $\eta' \to \gamma\rho^0$ and $\eta' \to \eta\pi^+\pi^-$, $\eta \to \gamma\gamma$ is studied for the first time [37]. Abundant structures on the K^+K^- and $\eta K^\pm$ invariant mass spectra are observed for χ_{c1} candidate events, and a partial wave analysis is performed for the decay $\chi_{c1} \to \eta' K^+K^-$. Figure 5 shows the comparisons of data and fit projections in terms of the invariant mass spectra of $\eta' K^\pm$ for χ_{c1} candidate events. The partial branching fractions of χ_{c1} decay processes with intermediate states $f_0(980)$, $f_0(1710)$, $f_2'(1525)$ and $K_0^*(1430)$ are measured for the first time.

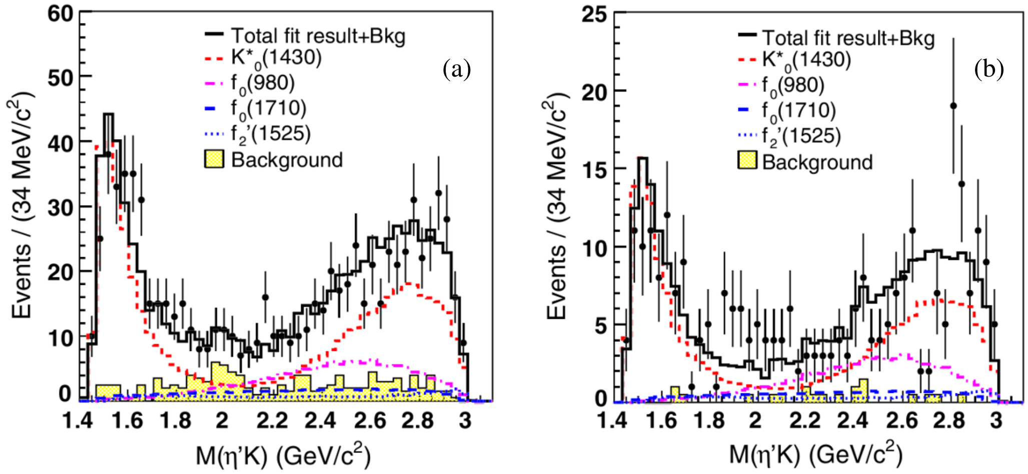

FIGURE 5. The invariant mass distribution of $\eta' K^{\pm}$ within the χ_{c1} mass range for (a) $\eta' \to \gamma\rho^0$ mode and (b) $\eta' \to \eta\pi^+\pi^-$ mode.

Study of χ_{cJ} Decaying into $\phi K^*(892)\bar{K}$

The nature of the axial-vector candidate, $h_1(1380)$ is still controversial [38, 39]. The direct observation of the $h_1(1380)$ in experiments and the precise measurement of its resonance parameters may shed light on its nature and aid in identifying the ground state axial-vector meson nonet in the quark model.

Using the $\psi(3686)$ data sample, the first measurement of $\chi_{cJ} \to \phi K_S^0 K^{\pm}\pi^{\mp}$ and $\chi_{cJ} \to \phi K^+ K^- \pi^0$ has been reported [40]. The decays are dominated by the three-body reaction χ_{cJ} decaying into $\phi K^*(892)\bar{K}$. The branching fractions for this reaction via neutral and charged $K^*(892)$ are measured for the first time. Figure 6 shows the invariant mass spectrum of $K\bar{K}\pi$, a significant excess of events above the phase space expectation is observed near the $K^*(892)\bar{K}$ mass threshold in the decays of $\chi_{c1,2}$ with a significance greater than 10σ. The observed structure has negative C parity, and is expected to be the $h_1(1380)$ state, considering its mass, width and decay through $K^*(892)\bar{K}$. The mass and width of the $h_1(1380)$ are determined to $(1412 \pm 4 \pm 8)$ MeV/c^2 and $(84 \pm 12 \pm 40)$ MeV, respectively. This is the first evidence of the $h_1(1380)$ in its decay to $K^*(892)\bar{K}$. Evidence is also found for the decays $\chi_{cJ} \to \phi\phi(1680)$ and $\chi_{cJ} \to \phi\phi(1850)$,but with significances less than 5σ.

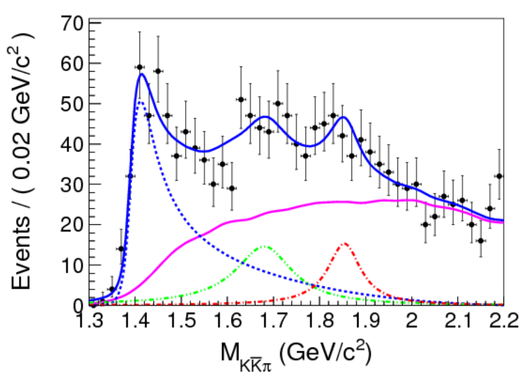

FIGURE 6. The sum of $K_S^0 K^{\pm}\pi^{\mp}$ and $K^{\pm}\pi^{\mp}\pi^0$ mass spectra in the χ_{c1} and χ_{c2} mass regions. The markers with error bars represent the data; the dash curve the $h_1(1380)$ signal; the dash-dot-dot curve the $\phi(1680)$ signal; and the dash-dot curve the $\phi(1850)$ signal.

SUMMARY

Based on 2.92 fb^{-1} data sample taken at $\sqrt{s}$ = 3.773 GeV, 1.06×10^8 $\psi(3686)$ events and 1.31×10^9 J/ψ events collected with BESIII detector at the BEPCII collider, studies have been performed to search for the radiative transitions of $\psi(3770)$ and rare decays of charmonium, and study light hadron structures and properties. The upper limits on branching fractions are set for radiative transitions of $\psi(3770)$, $\psi(3770) \to \gamma\eta_c(\eta_c(2S))$ and $\psi(3770) \to \gamma\chi_{c2}$, the isospin-violating decay $\chi_{c0,2} \to \pi^0\eta_c$, and C-violation decay $J/\psi \to \gamma\gamma$, $\gamma\phi$. The OZI-suppressed decay $J/\psi \to \pi^0\phi$ is observed for the first time. The isospin-violating decay $J/\psi \to \phi\pi^0 f_0(980)$, $f_0(980) \to \pi^+\pi^-$ is observed with the width of the $f_0(980)$ obtained from the dipion mass spectrum found to be much smaller than the world average value. The decay $\chi_{c1,2} \to \eta' K^+K^-$ is studied for the first time. Intermediate process $\chi_{c1} \to \eta' f_0(980)$, $\chi_{c1} \to \eta' f_0(1710)$, $\chi_{c2} \to \eta' f_2'(1525)$ and $\chi_{c1} \to K_0^*(1430)^{\pm}K^{\mp}$ are observed and their branching fractions are measured. The branching fractions of decay χ_{cJ} decaying into $\phi K^*(892)\bar{K}$ are measured for the first time and the first evidence of the $h_1(1380)$ in its decay to $K^*(892)\bar{K}$ is obtained. These measurements provide important information to understand the nature of $\psi(3770)$, the isospin-violation mechanism and properties of light hadrons, such as $f_0(980)$, $K_0^*(1430)$ and $h_1(1380)$.

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