Observation of $\chi_{cJ} \to 3(K^+K^-)$

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By analyzing $(27.12 \pm 0.14) \times 10^8$ $\psi(3686)$ events collected with the BESIII detector operating at the BEPCII collider, the decay processes $\chi_{cJ} \to 3(K^+K^-)$ ($J = 0, 1, 2$) are observed for the first time with statistical significances of 8.2σ, 8.1σ, and 12.4σ, respectively. The product branching fractions of $\psi(3686) \to \gamma\chi_{cJ}$, $\chi_{cJ} \to 3(K^+K^-)$ are presented and the branching fractions of $\chi_{cJ} \to 3(K^+K^-)$ decays are determined to be $\mathcal{B}_{\chi_{c0}\to 3(K^+K^-)} = (10.7 \pm 1.8 \pm 1.1) \times 10^{-6}$, $\mathcal{B}_{\chi_{c1}\to 3(K^+K^-)} = (4.2 \pm 0.9 \pm 0.5) \times 10^{-6}$, and $\mathcal{B}_{\chi_{c2}\to 3(K^+K^-)} = (7.2 \pm 1.1 \pm 0.8) \times 10^{-6}$, where the first uncertainties are statistical and the second are systematic.

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I. INTRODUCTION

Experimental studies of charmonium states and their decay properties are important to test quantum chromodynamics (QCD) models and QCD-based calculations. In the quark model, the $\chi_{cJ}(J = 0, 1, 2)$ mesons are identified as ^3P_J charmonium states. Unlike the vector charmonium states J/ψ and $\psi(3686)$, however, the χ_{cJ} mesons cannot be directly produced in e^+e^- collisions due to parity conservation, and our knowledge about their decays is relatively deficient. These P-wave charmonium mesons are produced abundantly via radiative $\psi(3686)$ decays, with branching fractions of about 9%, thereby offering a good opportunity to study various χ_{cJ} decays. Currently, theoretical studies indicate that the color octet mechanism [1] may substantially influence the decays of the P-wave charmonium states. However, some discrepancies between these theoretical calculations and experimental measurements have been reported in Refs. [2–5]. Therefore, intensive measurements of exclusive χ_{cJ} hadronic decays are highly desirable to understand the underlying χ_{cJ} decay dynamics.

In this paper we present the first observation and branching fraction measurements of $\chi_{cJ} \to 3(K^+K^-)$ by analyzing $(27.12 \pm 0.14) \times 10^8$ $\psi(3686)$ events [6] collected with the BESIII detector [7].

II. BESIII DETECTOR AND MONTE CARLO SIMULATION

The BESIII detector [7] records symmetric e^+e^- collisions provided by the BEPCII storage ring [8] in the center-of-mass energy range from 2.0 to 4.95 GeV, with a peak luminosity of 1×10^{33} cm^{-2} s^{-1} achieved at $\sqrt{s} =$ 3.77 GeV. The cylindrical core of the BESIII detector covers 93% of the full solid angle and consists of a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identification modules interleaved with steel. The charged-particle momentum resolution at 1 GeV/c is 0.5%, and the dE/dx resolution is 6% for electrons from Bhabha scattering. The EMC measures photon energies with a resolution of 2.5% (5%) at 1 GeV in the barrel (end cap) region. The time resolution in the TOF barrel region is 68 ps, while that in the end cap region was 110 ps. The end cap TOF system was upgraded in 2015 using multigap resistive plate chamber technology, providing a time resolution of 60 ps [9–11].

Simulated data samples produced with a Geant4-based [12] Monte Carlo (MC) package, which includes the geometric description of the BESIII detector and the detector response, are used to determine detection efficiencies and to estimate backgrounds. The simulation models the beam energy spread and initial state radiation (ISR) in the e^+e^- annihilations with the generator KKMC [13]. The inclusive MC sample includes the production of the $\psi(3686)$ resonance, the ISR production of the J/ψ, and the continuum processes incorporated in KKMC [13]. All particle decays are modeled with EvtGen [14] using branching fractions either

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taken from the Particle Data Group (PDG) [5], when available, or otherwise estimated with Lundcharm [15]. Final state radiation from charged final state particles is incorporated using the PHOTOS package [16]. An inclusive MC sample containing 2.7×10^9 generic $\psi(3686)$ decays is used to study background. To account for the effect of intermediate resonance structure on the efficiency, each of these decays is modeled by the corresponding mixed signal MC samples, in which the dominant decay modes containing resonances of ϕ are mixed with the phase-space signal MC samples. The mixing ratios are determined by examining the corresponding invariant mass as discussed in Sec. VI.

III. EVENT SELECTION

We reconstruct the events containing the charmonium transitions $\psi(3686) \to \gamma\chi_{cJ}$ followed by the hadronic decays $\chi_{cJ} \to 3(K^+K^-)$. The signal events are required to have at least six charged tracks and at least one photon candidate.

All charged tracks detected in the MDC are required to be within a polar angle (θ) range of $|\cos\theta| < 0.93$, where θ is defined with respect to the z axis, which is the symmetry axis of the MDC. The distance of closest approach to the interaction point (IP) must be less than 10 cm along the z axis, $|V_z|$, and less than 1 cm in the transverse plane, $|V_{xy}|$. Particle identification (PID) for charged tracks combines measurements of the energy deposited in the MDC ($\mathrm{d}E/\mathrm{d}x$) and the flight time in the TOF to form likelihoods $\mathcal{L}(h)(h = K, \pi)$ for each hadron h hypothesis. Those with likelihood for kaon hypothesis greater than that for pion hypothesis are assigned to be kaon candidates.

Photon candidates are identified using showers in the EMC. The deposited energy of each shower must be more than 25 MeV in the barrel region ($|\cos\theta| < 0.80$) and more than 50 MeV in the end cap region ($0.86 < |\cos\theta| < 0.92$). To exclude showers that originate from charged tracks, the angle subtended by the EMC shower and the position of the closest charged track at the EMC must be greater than 10° as measured from the IP. To suppress electronic noise and showers unrelated to the event, the difference between the EMC time and the event start time is required to be within [0, 700] ns.

A four-momentum conservation constraint (4C) kinematic fit is applied to the events. In each event, if more than one combination survives, the one with the smallest χ^2_{4C} value of the 4C fit is retained. Figure 1 shows the χ^2_{4C} distributions of the accepted candidate events for data and MC samples.

The requirement on χ^2_{4C} is optimized with the figure of merit (FOM),

$$\mathrm{FOM} = \frac{S}{\sqrt{S+B}}. \tag{1}$$

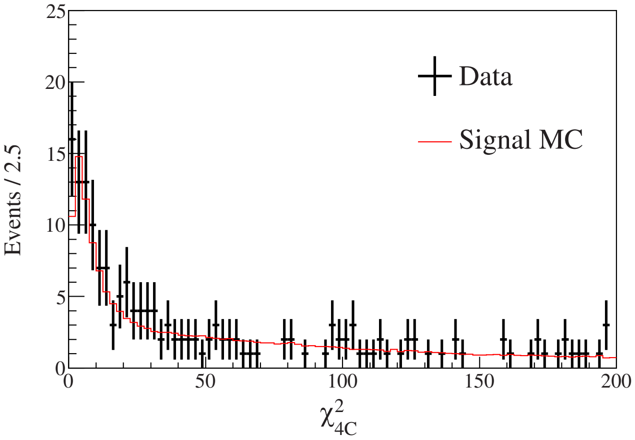

FIG. 1. Distributions of χ^2_{4C} of the accepted candidate events. The dots with error bars are data, and the red solid line is the signal MC sample that has been normalized to the data size.

Here S denotes the number of events from the signal MC sample, normalized according to the premeasured branching fractions; B denotes the number of background events from the inclusive MC sample, normalized to the data size. After optimization, we choose $\chi^2_{4C} < 50$ as the nominal requirement.

IV. BACKGROUND ANALYSIS

The continuum data collected at $\sqrt{s} = 3.650$ and 3.682 GeV, corresponding to an integrated luminosity of 800 pb^{-1} [17], are used to estimate the QED background. No event satisfies the same selection criteria applied to $\psi(3686)$ data. Furthermore, the inclusive MC sample is used to study all potential backgrounds from $\psi(3686)$ decays, and no event is observed in the χ_{cJ} signal regions. Consequently, all peaking background components are treated as negligible in this analysis.

V. DATA ANALYSIS

The distribution of the invariant mass of the $3(K^+K^-)$ combination, $M_{3(K^+K^-)}$, of the accepted candidate events is shown in Fig. 2. Clear χ_{c0}, χ_{c1}, and χ_{c2} signals are observed. The signal yields of $\chi_{cJ} \to 3(K^+K^-)$ are obtained from an unbinned maximum likelihood fit to this distribution.

In the fit, the signal shape of each χ_{cJ} is described by Breit-Wigner functions convolved with a Gaussian. The widths and masses of Breit-Wigner functions are fixed to PDG averages [5] for $\chi_{c0,1,2}$, respectively. The parameters of the Gaussian are floated. From this fit, the signal yields of χ_{c0}, χ_{c1}, and χ_{c2}, $N^{\mathrm{obs}}_{\chi_{cJ}}$, are obtained to be 37.7 ± 6.2, 24.9 ± 5.1, and 46.4 ± 7.0, respectively. The statistical significances are estimated to be 8.2σ, 8.1σ, and 12.4σ for χ_{c0}, χ_{c1}, and χ_{c2} individually, which are determined by

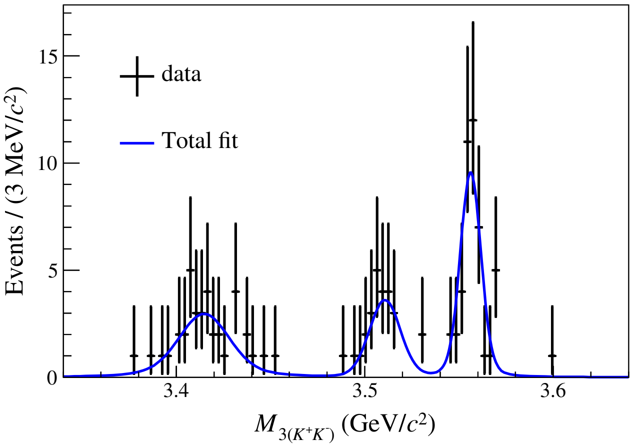

FIG. 2. Fit to the $M_{3(K^+K^-)}$ distribution of the accepted candidate events. The points with error bars are data and the blue curve is the overall fit.

comparing the fit likelihood values separately with and without each χ_{cJ} signal component.

VI. DETECTION EFFICIENCY

The efficiencies of detecting $\psi(3686) \to \gamma\chi_{cJ}$ with $\chi_{cJ} \to 3(K^+K^-)$ are determined with the mixed signal MC sample with fractions of the components of $\chi_{cJ} \to 2\phi(K^+K^-)$, $\chi_{cJ} \to \phi 2(K^+K^-)$, and $\chi_{cJ} \to 3(K^+K^-)$ derived from a three-dimensional fit on the three K^+K^- invariant mass spectra of the data events. Table I shows the fractions of the subresonant decays. The variations of these fractions are taken as systematic uncertainties. The obtained detection efficiencies for $\chi_{cJ} \to 3(K^+K^-)$ are $(13.3 \pm 0.1) \times 10^{-3}$, $(22.3 \pm 0.1) \times 10^{-3}$, and $(25.0 \pm 0.2) \times 10^{-3}$, respectively, including detector acceptance as well as reconstruction and selection efficiencies.

TABLE I. The fractions of the subresonant decays for the mixed signal MC events.

	$2\phi K^+K^-$	$\phi 2(K^+K^-)$	$3(K^+K^-)$
χ_{c0}	$0.480^{+0.167}_{-0.151}$	$0.038^{+0.306}_{-0.038}$	$0.481^{+0.139}_{-0.158}$
χ_{c1}	$1.000^{+0.131}_{-0.005}$	$0.000^{+0.125}_{-0.000}$	$0.000^{+0.041}_{-0.000}$
χ_{c2}	$0.783^{+0.243}_{-0.180}$	$0.217^{+0.179}_{-0.180}$	$0.000^{+0.222}_{-0.000}$

VII. BRANCHING FRACTION

For each decay $\psi(3686) \to \gamma\chi_{cJ}, \chi_{cJ} \to 3(K^+K^-)$, about 10.8×10^5 signal MC events are generated using a $1 + \lambda\cos^2\theta$ distribution, where θ is the angle between the radiative photon and beam directions, and $\lambda = 1, -1/3, 1/13$ for $J = 0, 1, 2$ in accordance with the expectations for electric dipole transitions [18]. Intrinsic width and mass values in the PDG [5] are used to simulate the χ_{cJ} states.

The product of branching fractions of $\psi(3686) \to \gamma\chi_{cJ}$ with $\chi_{cJ} \to 3(K^+K^-)$ is calculated as

$$\mathcal{B}_{\chi_{cJ}\to 3(K^+K^-)} \cdot \mathcal{B}_{\psi(3686)\to\gamma\chi_{cJ}} = \frac{N^{\text{obs}}_{\chi_{cJ}}}{N_{\psi(3686)} \cdot \epsilon}, \tag{2}$$

where ϵ is the detection efficiency and $N_{\psi(3686)}$ is the total number of $\psi(3686)$ events in data. Combining the branching fractions of $\psi(3686) \to \gamma\chi_{cJ}$ decays quoted from the PDG [5], the branching fractions of $\chi_{cJ} \to 3(K^+K^-)$ are determined. The obtained results are summarized in Table II.

VIII. SYSTEMATIC UNCERTAINTY

The systematic uncertainties in the branching fraction measurements originate from several sources, as summarized in Table III. They are estimated and discussed below.

The total number of $\psi(3686)$ events in data has been measured to be $N_{\psi(3686)} = (27.12 \pm 0.14) \times 10^8$ with the inclusive hadronic data sample, as described in Ref. [6]. The uncertainty of $N_{\psi(3686)}$ is 0.5%.

The systematic uncertainty of the $K^\pm$ tracking or PID efficiencies is assigned as 1.0% per $K^\pm$ [19], which is estimated with the control sample of $J/\psi \to K^*\bar{K}$.

The systematic uncertainty in the photon detection is assumed to be 1.0% per photon with the control sample $J/\psi \to \pi^+\pi^-\pi^0$ [20].

TABLE II. Signal yields in data, detection efficiencies determined with the mixed signal MC sample with fractions of the components of $\chi_{cJ} \to 2\phi(K^+K^-)$, $\chi_{cJ} \to \phi 2(K^+K^-)$, and $\chi_{cJ} \to 3(K^+K^-)$ derived from a three-dimensional fit on the three K^+K^- invariant mass spectra of the data events, and branching fractions $\mathcal{B}(\psi(3686) \to \gamma\chi_{cJ}) \cdot \mathcal{B}(\chi_{cJ} \to 3(K^+K^-))$ and $\mathcal{B}(\chi_{cJ} \to 3(K^+K^-))$. Except for $\mathcal{B}_{\psi(3686)\to\gamma\chi_{cJ}}$, the uncertainties are statistical only.

	χ_{c0}	χ_{c1}	χ_{c2}
N_{obs}	37.7 ± 6.2	24.9 ± 5.1	46.4 ± 7.0
$\epsilon(\times 10^{-3})$	13.3 ± 0.1	22.3 ± 0.1	25.0 ± 0.2
$\mathcal{B}_{\psi(3686)\to\gamma\chi_{cJ}} \cdot \mathcal{B}_{\chi_{cJ}\to 3(K^+K^-)} (\times 10^{-7})$	10.5 ± 1.8	4.1 ± 0.9	6.8 ± 1.1
$\mathcal{B}_{\chi_{cJ}\to 3(K^+K^-)} (\times 10^{-6})$	10.7 ± 1.8	4.2 ± 0.9	7.2 ± 1.1

TABLE III. Relative systematic uncertainties in the branching fraction measurements (%). The last item is the systematic uncertainty of the introduced reference.

Source	χ_{c0}	χ_{c1}	χ_{c2}
$N_{\psi(3686)}$	0.5	0.5	0.5
$K^\pm$ tracking	6.0	6.0	6.0
$K^\pm$ PID	6.0	6.0	6.0
γ selection	1.0	1.0	1.0
Fractions of different subprocesses	3.3	0.8	2.4
$M_{3(K^+K^-)}$ fit	3.3	7.0	5.2
4C kinematic fit	3.0	3.0	3.0
Final state radiation	2.2	2.3	0.4
MC statistics	1.6	1.2	1.1
Sum	10.5	11.7	10.8
$\mathcal{B}(\psi(3686) \to \gamma\chi_{cJ})$	2.0	2.4	2.0
Total	10.7	11.9	11.0

To estimate the systematic uncertainties of the MC model for the $\chi_{cJ} \to 3(K^+K^-)$ decays, we compare our nominal efficiencies with those determined from the signal MC events after varying ±1 standard deviation of the relative fractions of the subresonant decays, including $\chi_{cJ} \to 2\phi K^+K^-$, $\chi_{cJ} \to \phi 2(K^+K^-)$, and $\chi_{cJ} \to 3(K^+K^-)$. The relative changes of efficiencies, which are 3.3%, 0.8%, and 2.4% for χ_{c0}, χ_{c1}, and χ_{c2} decays, respectively, are assigned as the corresponding systematic uncertainties.

The systematic uncertainty of the fit to the $M_{3(K^+K^-)}$ spectrum includes two parts:

(i) The first is from the signal shape, which is estimated by varying the width of the χ_{cJ} state by ±1 standard deviation. The change of the fitted signal yield of each decay is negligible.

(ii) The second is due to the fit range estimated with alternative ranges of [3.225, 3.635], [3.225, 3.615], [3.215, 3.625], [3.235, 3.625], [3.225, 3.625] GeV/c^2. The maximum changes of the fitted signal yields, 3.0% for χ_{c0}, 2.8% for χ_{c1}, and 2.8% for χ_{c2}, are taken as the corresponding systematic uncertainties.

The systematic uncertainty resulting from the $M_{3(K^+K^-)}$ fit is determined be 3.3% for χ_{c0}, 7.0% for χ_{c1}, and 5.2% for χ_{c2}, when the two uncertainties discussed above are combined in quadrature.

The systematic uncertainty of the 4C kinematic fit comes from the inconsistency between the data and MC simulation of the track-helix parameters. We make helix parameter corrections to take the difference between the efficiencies with and without the corrections as the systematic uncertainties of the 4C kinematic fits are obtained to be 3% for all decays $\chi_{cJ} \to (K^+K^-)$ ($J = 0$, 1, 2).

The difference between the efficiencies with and without the final state radiation is taken as as the systematic uncertainty of the final state radiation, which are 2.2%, 2.3%, and 0.4% for χ_{c0}, χ_{c1}, and χ_{c2} decays, respectively.

The systematic uncertainties due to the statistics of the MC samples are 1.6%, 1.2%, and 1.1% for χ_{c0}, χ_{c1}, and χ_{c2} decays, respectively.

The systematic uncertainties from the branching fractions of $\psi(3686) \to \gamma\chi_{cJ}$ decays quoted from the PDG [5] are 2.0%, 2.4%, and 2.0% for χ_{c0}, χ_{c1}, and χ_{c2} decays, respectively.

We assume that all systematic uncertainties are independent and combine them in quadrature to obtain the total systematic uncertainty for each decay.

IX. SUMMARY

By analyzing $(27.12 \pm 0.14) \times 10^8$ $\psi(3686)$ events with the BESIII detector, the product branching fractions of $\psi(3686) \to \gamma\chi_{cJ}, \chi_{cJ} \to 3(K^+K^-)$ are determined to be $\mathcal{B}_{\psi(3686)\to\gamma\chi_{c0}} \cdot \mathcal{B}_{\chi_{c0}\to 3(K^+K^-)} = (10.5 \pm 1.8) \times 10^{-5}$, $\mathcal{B}_{\psi(3686)\to\gamma\chi_{c1}} \cdot \mathcal{B}_{\chi_{c1}\to 3(K^+K^-)} = (4.1 \pm 0.9) \times 10^{-5}$, and $\mathcal{B}_{\psi(3686)\to\gamma\chi_{c2}} \cdot \mathcal{B}_{\chi_{c2}\to 3(K^+K^-)} = (6.8 \pm 1.1) \times 10^{-5}$, where the uncertainties are statistical. The decays of $\chi_{cJ} \to 3(K^+K^-)$ are observed for the first time with statistical significances of 8.2σ, 8.1σ, and 12.4σ, respectively. We measure the branching fractions of $\chi_{cJ} \to 3(K^+K^-)$ to be $\mathcal{B}_{\chi_{c0}\to 3(K^+K^-)} = (10.7 \pm 1.8 \pm 1.1) \times 10^{-6}$, $\mathcal{B}_{\chi_{c1}\to 3(K^+K^-)} = (4.2 \pm 0.9 \pm 0.5) \times 10^{-6}$, $\mathcal{B}_{\chi_{c2}\to 3(K^+K^-)} = (7.2 \pm 1.1 \pm 0.8) \times 10^{-6}$, where the first uncertainties are statistical and the second are systematic. These results offer additional knowledge for understanding of the decay mechanisms of χ_{cJ} states.

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