

Measurements of the branching fractions of $\chi_{cJ} \rightarrow 2K^+2K^-\omega$ and $\phi K^+K^-\omega$ decays

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Using a data sample of $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$ events collected with the BESIII detector operating at the BEPCII collider, we report the first observation of the decays $\chi_{cJ} \rightarrow 2K^+2K^-\omega$ and $\chi_{cJ} \rightarrow \phi K^+K^-\omega$ ($J = 0, 1, 2$) via the radiative transitions $\psi(3686) \rightarrow \gamma\chi_{cJ}$. The branching fractions of these decays are measured for the first time, and the statistical significance for each signal exceeds 10σ .

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I. INTRODUCTION

Experimental studies of charmonium states and their decay properties play an important role in testing quantum chromodynamics (QCD) models and QCD based calculations [1–3]. In the quark model, the χ_{cJ} ($J = 0, 1, 2$) mesons are the ^3P_J charmonium states. Experimentally, they have not been investigated as extensively as the vector charmonium states J/ψ and $\psi(3686)$. At the BESIII experiment, χ_{cJ} mesons are rarely produced directly in e^+e^- collisions; however, they are abundantly produced through the radiative decays of $\psi(3686)$, whose branching fractions are approximately 9% for each χ_{cJ} state [4], thereby providing a large data sample for study. At present, the sum of all measured branching fractions of χ_{cJ} decays is still far below unity, and knowledge of exclusive multibody decays remains limited. Therefore, the search for additional multibody χ_{cJ} decay modes is essential for improving our understanding of their decay dynamics and for identifying possible intermediate resonant structures.

In 2009, 2012, and 2021, BESIII collected a total of $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$ events [5]. Owing to the abundant production of χ_{cJ} states in the radiative decays of $\psi(3686)$, the BESIII detector provides an ideal environment for searching for new multibody χ_{cJ} decay modes. By analyzing this data sample, we report the first observations and measurements of branching fraction of the decays $\chi_{cJ} \rightarrow 2K^+2K^-\omega$ and $\chi_{cJ} \rightarrow \phi K^+K^-\omega$.

II. BESIII DETECTOR AND MONTE CARLO SIMULATION

The BESIII detector [6] records symmetric e^+e^- collisions provided by the BEPCII storage ring [7] in the center-of-mass energy range from 1.84 to 4.95 GeV, with a peak luminosity of $1.1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ achieved at $\sqrt{s} = 3.773$ 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 (TI) electromagnetic calorimeter (EMC). These components are enclosed in a superconducting solenoidal magnet that provides 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 [8–10]. About 83% of the data used in this analysis benefit from this upgrade.

Simulated data samples produced with a GEANT4-based [11] Monte Carlo (MC) package, which includes the geometric description [12] 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 [13,14]. 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].

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TABLE I. Fractions (in %) of different subprocesses in $\chi_{cJ} \rightarrow 2K^+2K^-\omega$, where the uncertainties are statistical only. No other significant resonances are observed in data due to the limited sample size; the fractions of $2K^+2K^-$ (nonresonant) and ϕK^+K^- in the simulation were determined iteratively from the corresponding invariant-mass distributions as discussed in Sec. IV.

Resonance source	χ_{c0}	χ_{c1}	χ_{c2}
$\chi_{cJ} \rightarrow 2K^+2K^-\omega$ (nonresonant)	45.0 ± 2.4	44.7 ± 3.5	38.8 ± 3.3
$\chi_{cJ} \rightarrow \phi K^+K^-\omega$	55.0 ± 2.4	55.3 ± 3.5	61.2 ± 3.3

All particle decays are modeled with EVTGEN [15,16], using branching fractions either taken from the Particle Data Group (PDG) [4] when available, or otherwise estimated with LUNDCHARM [17,18]. Final state radiation from charged final state particles is incorporated using the PHOTOS package [19]. An inclusive MC sample of 2.7×10^9 generic $\psi(3686)$ events is used to study background.

A signal MC sample for the decay $\chi_{c0,1,2} \rightarrow 2K^+2K^-\omega$ is generated, with 500,000 events for each of the three states, resulting in a total of 1.5 million events. These samples include potential resonances according to the fractions listed in Table I. Another independent signal MC sample for the decay $\chi_{cJ} \rightarrow \phi K^+K^-\omega$ is generated according to phase space (PHSP), also containing 500,000 events per resonance, leading to a total of 1.5 million events. The $\psi(3686) \rightarrow \gamma\chi_{cJ} (J=0,1,2)$ decays are generated with the P2GCJ [15] models. The decays $\phi \rightarrow K^+K^-$ are generated by the VSS [20] model, which describes a vector meson decaying to a pair of pseudoscalar mesons. The decays $\omega \rightarrow \pi^+\pi^-\pi^0$ are generated with the OMEGA_DALITZ [15] model. All other signal decays are generated according to PHSP.

III. EVENT SELECTION

In this analysis, the ϕ , ω , and π^0 mesons are reconstructed via their decays $\phi \rightarrow K^+K^-$, $\omega \rightarrow \pi^+\pi^-\pi^0$, and $\pi^0 \rightarrow \gamma\gamma$, respectively. The branching fractions of $\chi_{cJ} \rightarrow 2K^+2K^-\omega$ and $\chi_{cJ} \rightarrow \phi K^+K^-\omega$ are measured via the radiative decays of $\psi(3686) \rightarrow \gamma\chi_{cJ}$. The signal candidates are required to have six charged tracks with zero net charge and at least three photon candidates.

Charged tracks in an event are required to have a polar angle θ with respect to the beam direction within the MDC acceptance $|\cos\theta| < 0.93$, and a distance of closest approach to the interaction point (IP) within 10 cm along the beam direction and 1 cm in the plane transverse to the beam direction. Particle identification (PID) for charged tracks is based on the measurements of the dE/dx in the MDC and the flight time in the TOF, which are combined to form a likelihood $\mathcal{L}(h)$ ($h = \pi$ and K) for each hadron h hypothesis. Charged tracks with $\mathcal{L}(K) > \mathcal{L}(\pi)$ are

identified as kaons, while those with $\mathcal{L}(\pi) > \mathcal{L}(K)$ are identified as pions.

Photon candidates are identified using showers in the EMC. The deposited energy of each shower must be greater than 25 MeV in the barrel region ($|\cos\theta| < 0.80$), where θ denotes the polar angle with respect to the MDC axis, and greater than 50 MeV in the end-cap region ($0.86 < |\cos\theta| < 0.92$). To exclude showers that originate from charged tracks, the angle between the EMC shower and the position of the closest charged track at the EMC must be greater than 10 degrees, 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.

In order to suppress backgrounds and improve the mass resolution, a five-constraint (5C) kinematic fit is performed under the hypothesis of $\psi(3686) \rightarrow \gamma 2K^+2K^-\pi^+\pi^-\pi^0$. The fit constrains the total four-momentum of the final-state particles to that of the colliding beams, and an additional constraint requires the invariant mass of the photon pair to equal the nominal π^0 mass [4]. If more than one photon combination yields a convergent fit, the candidate with the smallest χ_{5C}^2 is retained; events with $\chi_{5C}^2 < 40$ are kept for further analysis.

Potential background contributions from $\psi(3686)$ decays are studied by analyzing the inclusive MC sample with the generic event type analysis tool TopoAna [21]. No significant peaking backgrounds containing both χ_{cJ} and ω mesons are observed. To suppress the background from the decay $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$, a requirement is imposed on the recoil mass of $\pi^+\pi^- (RM(\pi^+\pi^-))$, defined as

$$RM(\pi^+\pi^-) = \sqrt{[\sqrt{s} - (E_{\pi^+} + E_{\pi^-})]^2 - (\vec{p}_{\pi^+} + \vec{p}_{\pi^-})^2}, \quad (1)$$

where $E_{\pi^+(\pi^-)}$ and $\vec{p}_{\pi^+(\pi^-)}$ are the energy and momentum of the positive (negative) pions, respectively. We require $|RM(\pi^+\pi^-) - M(J/\psi)| > 0.015 \text{ GeV}/c^2$, where $M(J/\psi)$ is the nominal mass of J/ψ [4]. Continuum background is evaluated with a data sample collected at $\sqrt{s} = 3.650 \text{ GeV}$ with an integrated luminosity of 454.33 pb^{-1} [22]. Only a few events survive the selection, so this contribution is negligible.

IV. BRANCHING FRACTION

A. $\chi_{cJ} \rightarrow 2K^+2K^-\omega$

To determine the signal yields of the decays $\chi_{cJ} \rightarrow 2K^+2K^-\omega$, a 2D fit is performed to the distribution of $M(2K^+2K^-\omega)$ versus $M(\pi^+\pi^-\pi^0)$ for the selected candidates in data. In the 2D fit, events are divided into four categories: the “signal” category contains candidates with both $2K^+2K^-\omega$ from the χ_{cJ} decay and $\pi^+\pi^-\pi^0$ from the ω decay; “BKGI” contains candidates with $2K^+2K^-\omega$

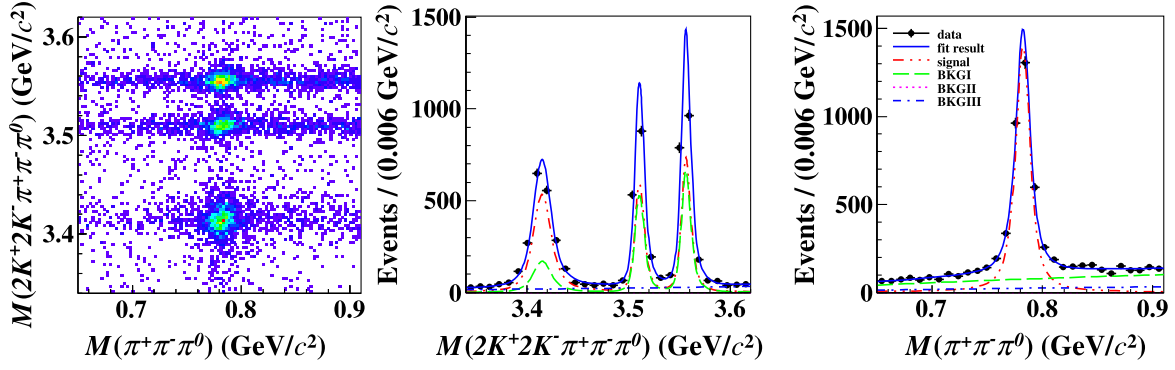


FIG. 1. First column is the distribution of $M(2K^+2K^-\pi^+\pi^-\pi^0)$ versus $M(\pi^+\pi^-\pi^0)$. The second and third columns show the projections of the 2D fit to the $M(2K^+2K^-\pi^+\pi^-\pi^0)$ and $M(\pi^+\pi^-\pi^0)$ distributions, respectively. Data are shown as the dots with error bars, the blue solid curves are the fit results, the red dashed curves are the fitted signal shapes, the green dashed curves are the BKG I events, the pink dashed curves are the BKG II events, and the blue dashed curves are the BKG III events.

from the χ_{cJ} decay and $\pi^+\pi^-\pi^0$ from continuum backgrounds; the “BKGII” contains candidates with $2K^+2K^-\omega$ from continuum backgrounds and $\pi^+\pi^-\pi^0$ from the ω decay; “BKGIII” contains candidates with both $2K^+2K^-\omega$ and $\pi^+\pi^-\pi^0$ from continuum backgrounds, as well as

incompletely reconstructed events with similar final states. The corresponding probability-density functions (PDFs) are constructed as,

- (i) signal: $S(x) \times S(y)$,
- (ii) BKG I: $S(x) \times C(y)$,

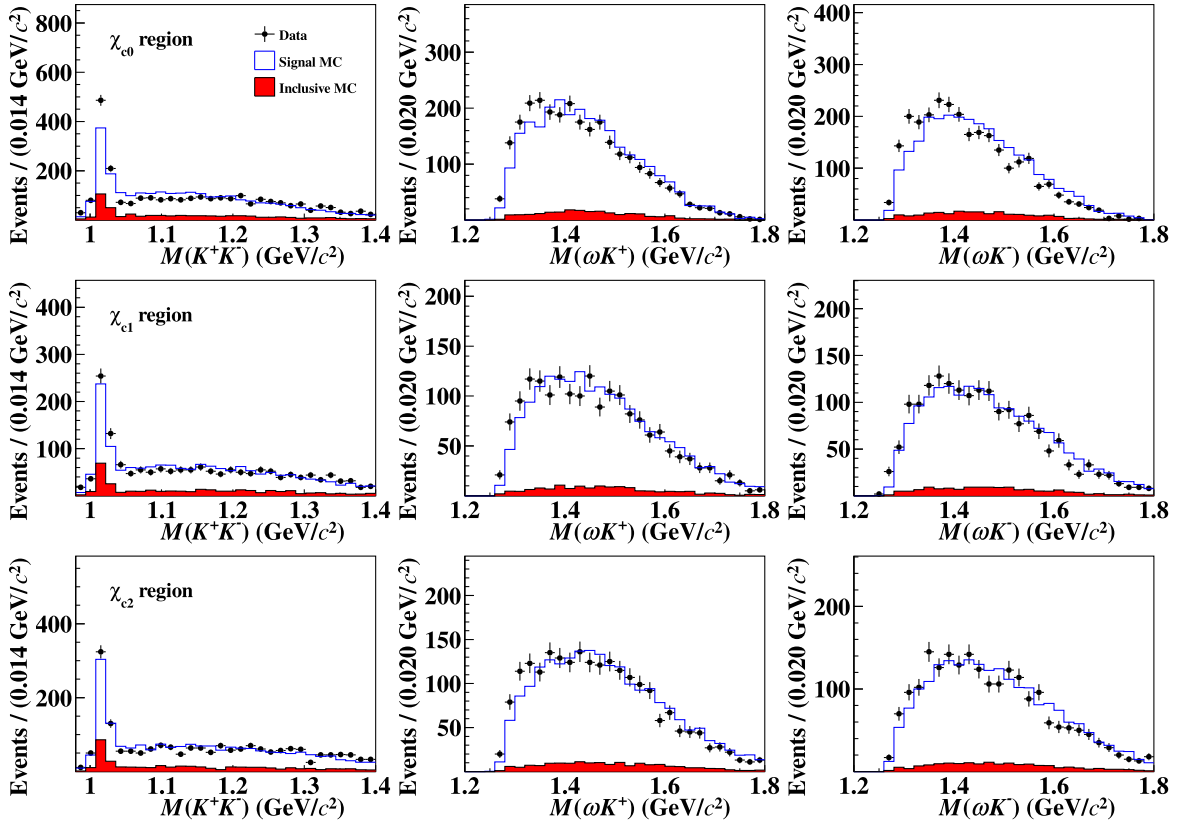


FIG. 2. Comparisons of the invariant masses of possible two-body combinations of the selected candidates of $\chi_{cJ} \rightarrow 2K^+2K^-\omega$. The top, middle, and bottom rows are for events in the χ_{c0} mass region $[3.385, 3.445]$ GeV/c^2 , the χ_{c1} mass region $[3.490, 3.530]$ GeV/c^2 , and the χ_{c2} mass region $[3.536, 3.576]$ GeV/c^2 , respectively. The dots with error bars are data, the blue curves are the signal MC samples, and the red histograms are the inclusive MC samples. Events are required to be within the ω signal region, defined as $|M(\pi^+\pi^-\pi^0) - M(\omega)| < 0.025$ GeV/c^2 .

- (iii) BKGII: $C(x) \times S(y)$,
- (iv) BKGIII: $C(x) \times C(y)$,

where x and y represent the two dimensions of the 2D fit, $S(i)$ are signal shapes derived from signal MC samples, $C(i)$ are second-order Chebyshev polynomials, and i denotes the different dimension.

Figure 1 shows the 2D fit results for the signal candidates. The statistical significance of each of the $\chi_{c0,1,2} \rightarrow 2K^+2K^-\omega$, calculated using $\Delta(\ln \mathcal{L}) = \ln \mathcal{L}_{\max} - \ln \mathcal{L}_0$ with $\Delta ndf = 1$, exceeds 10σ . Here, $\ln \mathcal{L}_{\max}$ and $\ln \mathcal{L}_0$ are the maximum likelihoods obtained with and without the signal component in the fit, respectively, and Δndf is the change in the number of degrees of freedom.

B. $\chi_{cJ} \rightarrow \phi K^+ K^- \omega$

Significant ϕ signals are observed in the $K^+ K^-$ invariant-mass distributions (Fig. 2), indicating the presence of $\chi_{cJ} \rightarrow \phi K^+ K^- \omega$. This measurement constitutes an independent observation with respect to $\chi_{cJ} \rightarrow 2K^+2K^- \omega$ discussed above. The ϕ signal region is defined as $M(K^+ K^-) \in [1.005, 1.035] \text{ GeV}/c^2$, and the ϕ sideband region is defined as $M(K^+ K^-) \in [1.045, 1.075] \text{ GeV}/c^2$.

For the decays $\chi_{cJ} \rightarrow \phi K^+ K^- \omega$ (with one ϕ and an additional $K^+ K^-$ pair), all $K^+ K^-$ combinations are retained. We use $M(K^+ K^-)_a$ and $M(K^+ K^-)_b$ to denote the invariant masses of the randomly assigned $K^+ K^-$ pairs. The 2D signal region is defined by requiring one $K^+ K^-$ combination to be in the ϕ signal region while the other $K^+ K^-$ combination is not in ϕ the mass region, i.e., $M(K^+ K^-)_{a(b)} \in [1.005, 1.035] \text{ GeV}/c^2$ && $M(K^+ K^-)_{b(a)} > 1.085 \text{ GeV}/c^2$. Similarly, the 2D sideband region is defined by requiring $M(K^+ K^-)_{a(b)} \in [1.045, 1.075] \text{ GeV}/c^2$ and $M(K^+ K^-)_{b(a)} > 1.085 \text{ GeV}/c^2$.

The 2D signal and sideband regions are shown in Fig. 3.

The peaking backgrounds in the $M(K^+ K^-)$ distributions in Fig. 2 do not simultaneously produce peaking backgrounds in the $M(\pi^+ \pi^- \pi^0)$ and $M(2K^+ 2K^- \omega)$ distributions. Other potential backgrounds are studied by analyzing the inclusive MC sample with the TopoAna [21]. No significant peaking backgrounds with both χ_{cJ} and ω are observed.

The signal yields of $\chi_{cJ} \rightarrow \phi K^+ K^- \omega$ are determined by a 2D simultaneous fit to the distribution of $M(\phi K^+ K^- \pi^+ \pi^- \pi^0)$ versus $M(\pi^+ \pi^- \pi^0)$ for events in the ϕ signal and sideband regions of the selected candidates in data. In the simultaneous fit, the construction of the PDFs follows the approach described in Sec. IV A. The signal shapes of χ_{cJ} are described by the signal MC-simulated shapes, while the background shapes are described by a second-order Chebyshev polynomial. Events in the ϕ sideband region are normalized using a scale factor f , which is evaluated from the ratios of the background yields in the ϕ signal and sideband regions and is found to be

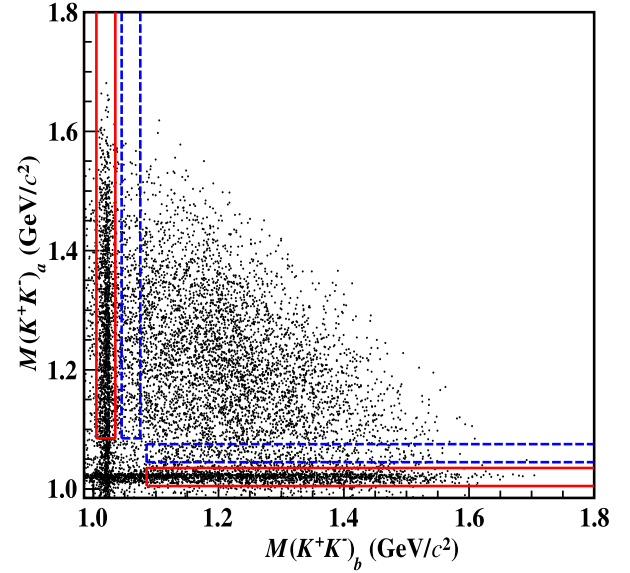


FIG. 3. Distribution of $M(K^+ K^-)_a$ versus $M(K^+ K^-)_b$ for the selected $\chi_{cJ} \rightarrow \phi K^+ K^- \omega$ candidates in data, where the red boxes show the $\phi K^+ K^-$ signal regions and the blue boxes show the $\phi K^+ K^-$ sideband regions. Events have been required to be within the ω signal region, defined as $|M(\pi^+ \pi^- \pi^0) - M(\omega)| < 0.025 \text{ GeV}/c^2$.

close to 1.0. Figure 4 shows the results of simultaneous fit. The net signal yield N_{net} is determined as

$$N_{\text{net}} = N_{\text{sig}} - f \cdot N_{\text{sid}}. \quad (2)$$

From this fit, the signal yields of $\chi_{c0,1,2} \rightarrow \phi K^+ K^- \omega$ are obtained, with the statistical significance larger than 10σ for each χ_{cJ} decay.

A search for $\chi_{cJ} \rightarrow \phi \phi \omega$ was also performed; no significant signal is observed, consistent with C-parity violation, and results are not reported.

C. Branching fractions

Detection efficiencies for $\psi(3686) \rightarrow \gamma \chi_{cJ}$ with $\chi_{cJ} \rightarrow 2K^+ 2K^- \omega$ are determined using mixed signal MC samples with fractions of $\chi_{cJ} \rightarrow \phi K^+ K^- \omega$, as summarized in Table I. The fractions of $\chi_{cJ} \rightarrow \phi K^+ K^- \omega$ are determined by a 2D simultaneous fit shown in Fig. 4.

The branching fractions of $\chi_{cJ} \rightarrow X$ ($2K^+ 2K^- \omega$ and $\phi K^+ K^- \omega$) are calculated using

$$\mathcal{B}(\psi(3686) \rightarrow \gamma \chi_{cJ}) \cdot \mathcal{B}(\chi_{cJ} \rightarrow X) = \frac{N_{\text{net}}}{N_{\psi(3686)} \cdot \epsilon \cdot \mathcal{B}(\text{sub})}, \quad (3)$$

where $\mathcal{B}(\psi(3686) \rightarrow \gamma \chi_{cJ})$ is the branching fraction of $\psi(3686) \rightarrow \gamma \chi_{cJ}$, $N_{\psi(3686)}$ is the total number of $\psi(3686)$ events in data, and ϵ is the detection efficiency. The factor $\mathcal{B}(\text{sub})$ equals to $\mathcal{B}(\omega \rightarrow \pi^+ \pi^- \pi^0) \cdot \mathcal{B}(\pi^0 \rightarrow \gamma \gamma)$ for

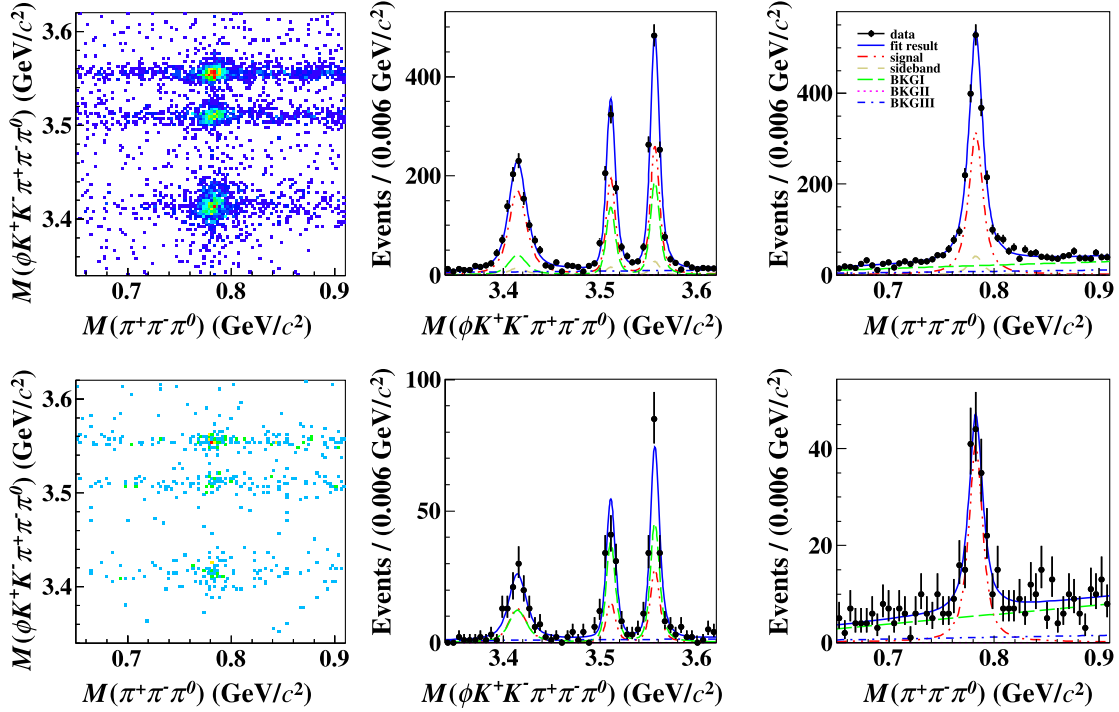


FIG. 4. First column is the distribution of $M(\phi K^+ K^- \pi^+ \pi^- \pi^0)$ versus $M(\pi^+ \pi^- \pi^0)$. The second and third columns show the projections of the 2D simultaneous fit to the $M(\phi K^+ K^- \pi^+ \pi^- \pi^0)$ and $M(\pi^+ \pi^- \pi^0)$ distributions in the signal region (top row) and sideband region (bottom row). Data are shown as dots with error bars. For both the top and bottom figures, the blue solid curves are the total fit results, the red dashed curves are the fitted signal shapes, the green dashed curves are the BKGI events, the pink dashed curves are the BKGII events, and the blue dashed curves are the BKGIII events. For the top figures, the brown dashed curves are the normalized sideband contributions.

$\chi_{cJ} \rightarrow 2K^+ 2K^- \omega$, and to $\mathcal{B}(\phi \rightarrow K^+ K^-) \cdot \mathcal{B}(\omega \rightarrow \pi^+ \pi^- \pi^0) \cdot \mathcal{B}(\pi^0 \rightarrow \gamma\gamma)$ for $\chi_{cJ} \rightarrow \phi K^+ K^- \omega$ [4]. Using this relation, the product branching fractions $\mathcal{B}(\psi(3686) \rightarrow \gamma \chi_{cJ}) \cdot \mathcal{B}(\chi_{cJ} \rightarrow X)$ are determined. The branching fractions

$\mathcal{B}(\chi_{cJ} \rightarrow X)$ are obtained by dividing this product by $\mathcal{B}(\psi(3686) \rightarrow \gamma \chi_{cJ})$, taken from the PDG [4]. All results for $\chi_{cJ} \rightarrow 2K^+ 2K^- \omega$ and $\chi_{cJ} \rightarrow \phi K^+ K^- \omega$ are summarized in Table II.

TABLE II. Signal yields, detection efficiencies, and the branching fractions for each signal decay, where the first uncertainties are statistical and the second ones systematic.

Source	$\chi_{cJ} \rightarrow 2K^+ 2K^- \omega$		
	χ_{c0}	χ_{c1}	χ_{c2}
N_{net}	1597 ± 48	839 ± 37	1070 ± 42
ϵ (%)	2.64	3.41	3.41
$\mathcal{B}(\psi(3686) \rightarrow \gamma \chi_{cJ}) \cdot \mathcal{B}(\chi_{cJ} \rightarrow 2K^+ 2K^- \omega) (\times 10^{-5})$	$2.53 \pm 0.08 \pm 0.24$	$1.03 \pm 0.05 \pm 0.10$	$1.31 \pm 0.05 \pm 0.13$
$\mathcal{B}(\chi_{cJ} \rightarrow 2K^+ 2K^- \omega) (\times 10^{-4})$	$2.60 \pm 0.08 \pm 0.26$	$1.06 \pm 0.05 \pm 0.11$	$1.40 \pm 0.05 \pm 0.15$
Source	$\chi_{cJ} \rightarrow \phi K^+ K^- \omega$		
	χ_{c0}	χ_{c1}	χ_{c2}
N_{sig}	949 ± 37	501 ± 28	724 ± 33
N_{sid}	67 ± 10	36 ± 9	71 ± 11
f	1.05 ± 0.03	1.03 ± 0.02	0.97 ± 0.02
N_{net}	878 ± 38	464 ± 29	655 ± 35
ϵ (%)	1.71	2.39	2.49
$\mathcal{B}(\psi(3686) \rightarrow \gamma \chi_{cJ}) \cdot \mathcal{B}(\chi_{cJ} \rightarrow \phi K^+ K^- \omega) (\times 10^{-5})$	$4.37 \pm 0.19 \pm 0.41$	$1.65 \pm 0.10 \pm 0.16$	$2.24 \pm 0.12 \pm 0.22$
$\mathcal{B}(\chi_{cJ} \rightarrow \phi K^+ K^- \omega) (\times 10^{-4})$	$4.49 \pm 0.19 \pm 0.44$	$1.70 \pm 0.11 \pm 0.17$	$2.39 \pm 0.13 \pm 0.24$

TABLE III. Relative systematic uncertainties in the measurements of the branching fractions of $\chi_{cJ} \rightarrow 2K^+2K^-\omega$ and $\chi_{cJ} \rightarrow \phi K^+K^-\omega$ (in %), where the “...” means negligible. The numbers before and after “/” denote the uncertainties for χ_{c0} (left), χ_{c1} (middle), and χ_{c2} (right), respectively.

Source	$\chi_{cJ} \rightarrow 2K^+2K^-\omega$	$\chi_{cJ} \rightarrow \phi K^+K^-\omega$
	$\chi_{c0}/\chi_{c1}/\chi_{c2}$	$\chi_{c0}/\chi_{c1}/\chi_{c2}$
$N_{\psi(3686)}$	0.5	0.5
$(K/\pi)^\pm$ PID	6.0	6.0
$(K/\pi)^\pm$ tracking	6.0	6.0
γ selection	3.0	3.0
π^0 reconstruction	1.0	1.0
ϕ mass window	...	0.2
Mass fit	0.6/1.1/1.2	0.2/0.4/0.8
MC generator	1.0/1.3/2.5	...
Kinematic fit	2.8/2.5/3.7	2.0/3.3/2.9
MC statistics	0.9/0.8/0.8	1.1/0.9/0.9
$\mathcal{B}(\psi(3686) \rightarrow \gamma\chi_{cJ})$	2.3/2.8/2.5	2.3/2.8/2.5
$\mathcal{B}(\text{sub})$	0.8	1.3
Total (without $\mathcal{B}(\psi(3686) \rightarrow \gamma\chi_{cJ})$)	9.6/9.6/10.2	9.4/9.8/9.7
Total (with $\mathcal{B}(\psi(3686) \rightarrow \gamma\chi_{cJ})$)	9.9/10.0/10.5	9.7/10.2/10.0

V. SYSTEMATIC UNCERTAINTY

Systematic uncertainties in the branching-fraction measurements arise from the sources listed in Table III. The total uncertainty is obtained by adding all contributions in quadrature.

The total number of $\psi(3686)$ events in data is measured to be $N_{\psi(3686)} = (2712.4 \pm 14.3) \times 10^6$ using the inclusive hadronic events, as described in Ref. [5]. The uncertainty of $N_{\psi(3686)}$ is 0.5%.

The systematic uncertainties of the tracking and PID for $(K/\pi)^\pm$ have been studied with the control samples of $J/\psi \rightarrow K^*\bar{K}$ and $J/\psi \rightarrow p\bar{p}\pi^+\pi^-$ in Ref. [23]. They are assigned as 1.0% for tracking or PID efficiencies per track.

The photon-detection uncertainty is 1.0% per photon, and the π^0 -reconstruction uncertainty is 1.0% per π^0 , both estimated with $J/\psi \rightarrow \pi^+\pi^-\pi^0$ [24].

The systematic uncertainty associated with the ϕ mass window is estimated by studying the differences in mass resolution between data and signal MC simulation. The difference of the efficiencies between data and MC simulation is taken as the systematic uncertainty, which is 0.2%.

The systematic uncertainties of the signal yield extraction are estimated by examining the fits to the invariant mass spectra. The uncertainties from the signal shape are estimated by using signal MC simulated shapes convolved with a Gaussian resolution with free parameters. The uncertainties due to the background shape are estimated by varying the order of the Chebyshev polynomial. The largest differences between the fitted signal yields and the nominal values are taken as the uncertainties. The assigned

uncertainties due to the invariant mass fit are 0.6%, 1.1%, and 1.2% for $\chi_{c0,1,2} \rightarrow 2K^+2K^-\omega$, and 0.2%, 0.4%, and 0.8% for $\chi_{c0,1,2} \rightarrow \phi K^+K^-\omega$, respectively.

The systematic uncertainties due to the mixing of signal MC samples are examined by varying the fractions by $\pm 1\sigma$. The largest changes in the efficiencies are taken as the systematic uncertainties, which are 1.0%, 1.3%, and 2.5% for $\chi_{c0,1,2} \rightarrow 2K^+2K^-\omega$, respectively.

The systematic uncertainty from the kinematic fit is estimated by comparing the signal efficiencies before and after helix parameter correction, where the correction factors are taken from the previous study [25]. The changes in the signal efficiencies are assigned as the systematic uncertainties, which are 2.8%, 2.5%, and 3.7% for $\chi_{c0,1,2} \rightarrow 2K^+2K^-\omega$, and 2.0%, 3.3%, and 2.9% for $\chi_{c0,1,2} \rightarrow \phi K^+K^-\omega$, respectively.

The uncertainties due to the limited statistics of the signal MC samples are 0.9%, 0.8%, and 0.8% for $\chi_{c0,1,2} \rightarrow 2K^+2K^-\omega$, and 1.1%, 0.9%, and 0.9% for $\chi_{c0,1,2} \rightarrow \phi K^+K^-\omega$, respectively.

The uncertainties from the branching fractions quoted in the PDG [4] are 2.3%, 2.8%, and 2.5% for $\psi(3686) \rightarrow \gamma\chi_{c0,1,2}$, 0.8% for $\mathcal{B}(\omega \rightarrow \pi^+\pi^-\pi^0) \cdot \mathcal{B}(\pi^0 \rightarrow \gamma\gamma)$, and 1.3% for $\mathcal{B}(\phi \rightarrow K^+K^-) \cdot \mathcal{B}(\omega \rightarrow \pi^+\pi^-\pi^0) \cdot \mathcal{B}(\pi^0 \rightarrow \gamma\gamma)$.

VI. SUMMARY

Using $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$ events collected with the BESIII detector, the decays $\chi_{c0,1,2} \rightarrow 2K^+2K^-\omega$ and $\chi_{c0,1,2} \rightarrow \phi K^+K^-\omega$ are observed for the first time with statistical significance exceeding 10σ . The branching fractions are

$$\begin{aligned}
\mathcal{B}(\chi_{c0} \rightarrow 2K^+2K^-\omega) &= (2.60 \pm 0.08 \pm 0.26) \times 10^{-4}, \\
\mathcal{B}(\chi_{c1} \rightarrow 2K^+2K^-\omega) &= (1.06 \pm 0.05 \pm 0.11) \times 10^{-4}, \\
\mathcal{B}(\chi_{c2} \rightarrow 2K^+2K^-\omega) &= (1.40 \pm 0.05 \pm 0.15) \times 10^{-4}, \\
\mathcal{B}(\chi_{c0} \rightarrow \phi K^+K^-\omega) &= (4.49 \pm 0.19 \pm 0.44) \times 10^{-4}, \\
\mathcal{B}(\chi_{c1} \rightarrow \phi K^+K^-\omega) &= (1.70 \pm 0.11 \pm 0.17) \times 10^{-4}, \\
\mathcal{B}(\chi_{c2} \rightarrow \phi K^+K^-\omega) &= (2.39 \pm 0.13 \pm 0.24) \times 10^{-4}.
\end{aligned}$$

These results expand the known decay modes of χ_{cJ} . Further observations of previously unobserved χ_{cJ} decays are anticipated, which will improve our understanding of charmonium decay mechanisms.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available because they are owned by a third party and the terms of use prevent public distribution. The data are available from the authors upon reasonable request.

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