

Observation and branching fraction measurements of $\chi_{cJ} \rightarrow p\bar{p}K_S^0K_S^0$

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Based on $(2.712 \pm 0.014) \times 10^9$ $\psi(3686)$ events collected with the BESIII detector, the decays $\chi_{cJ} \rightarrow p\bar{p}K_S^0K_S^0$ ($J = 0, 1, 2$) are observed for the first time with statistical significances exceeding 5σ . The measured branching fractions are $\mathcal{B}(\chi_{c0} \rightarrow p\bar{p}K_S^0K_S^0) = (7.25 \pm 0.28 \pm 0.35) \times 10^{-5}$, $\mathcal{B}(\chi_{c1} \rightarrow p\bar{p}K_S^0K_S^0) = (1.33 \pm 0.12 \pm 0.07) \times 10^{-5}$, and $\mathcal{B}(\chi_{c2} \rightarrow p\bar{p}K_S^0K_S^0) = (2.51 \pm 0.16 \pm 0.12) \times 10^{-5}$, where the first uncertainties are statistical and the second systematic. In addition, no significant structures are observed in the $p\bar{p}$, pK_S^0 , and $\bar{p}K_S^0$ mass spectra.

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I. INTRODUCTION

Precise measurements of charmonium decay properties are important for testing perturbative quantum chromodynamics (QCD) predictions and constraining nonperturbative QCD models [1–3]. The P -wave charmonium states χ_{cJ} ($J = 0, 1, 2$) are ideal for such studies, as they are abundantly produced via radiative transitions from $\psi(3686)$. Moreover, these states exhibit very high hadronization efficiency in their decays, with an exceptionally strong tendency to decay into light hadrons (such as π and K mesons). According to the Particle Data Group (PDG) [4], the total branching fraction of χ_{cJ} ($J = 0, 1, 2$) into light hadrons is approximately 70%, making them excellent laboratories for studying the interplay between perturbative quark-gluon dynamics and nonperturbative hadron formation.

The decays $\chi_{cJ} \rightarrow p\bar{p}K^+K^-$ have been observed with branching fractions ($\mathcal{B}$) at 10^{-4} level [5]. These imply that the $\chi_{cJ} \rightarrow p\bar{p}K_S^0K_S^0$ decays are hopefully detectable at BESIII. In addition, an enhancement structure was observed near the $p\bar{p}$ invariant-mass threshold in the radiative decay of $J/\psi \rightarrow \gamma p\bar{p}$ [6,7]. Various theoretical models have been proposed to explain this enhancement, but no definitive conclusion has been reached [8–10]. Studies of the decays of $\chi_{cJ} \rightarrow p\bar{p}K_S^0K_S^0$ present additional information of possible $p\bar{p}$ threshold structures, and also offer an opportunity to search for excited baryon states in the pK_S^0 or $\bar{p}K_S^0$ systems.

The BES experiment performed the first search for the $\chi_{c0,1,2} \rightarrow p\bar{p}K_S^0K_S^0$ decays in 2006 [11], yielding upper

limits on their branching fractions at 90% confidence level, corresponding to 8.8×10^{-4} , 4.5×10^{-4} and 7.9×10^{-4} , respectively. In this paper, we report the first observations and the branching fraction measurements of $\chi_{c0,1,2} \rightarrow p\bar{p}K_S^0K_S^0$ by analyzing $(2.712 \pm 0.014) \times 10^9$ $\psi(3686)$ events [12] collected with the BESIII detector. In addition, the $p\bar{p}$, pK_S^0 , and $\bar{p}K_S^0$ mass spectra are also examined.

II. BESIII DETECTOR AND MONTE CARLO SIMULATION

The BESIII detector [13] records symmetric e^+e^- collisions provided by the BEPCII storage ring [14] 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 $\sqrt{s} = 3.773 \text{ GeV}$.

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 [15–17]. About 83% of the data used in this analysis benefits from this upgrade.

Simulated samples produced with a GEANT4-based [18] Monte Carlo (MC) package, which includes the geometric

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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 [19].

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 [19]. All particle decays are modelled with EVTGEN [20,21] using branching fractions either taken from the PDG [4], when available, or otherwise estimated with LUNDCHARM [22,23]. Final state radiation from charged final state particles is incorporated using the PHOTOS package [24]. The signal MC events of the $\psi(3686) \rightarrow \gamma\chi_{cJ} (J=0, 1, 2)$ decays follow the angular distribution of $1 + \lambda \cos^2 \theta_\gamma$, where θ_γ denotes the polar angle of the radiative photon, and λ takes the values 1, $-1/3$, and $1/13$ for $J=0, 1$, and 2 , respectively [25]. The other decays are generated by the phase space (PHSP) model.

III. EVENT SELECTION

We reconstruct events from the charmonium transitions $\psi(3686) \rightarrow \gamma\chi_{cJ}$ followed by the hadronic decays $\chi_{cJ} \rightarrow p\bar{p}K_S^0K_S^0$. Signal events are required to contain at least six charged tracks and at least one photon candidate.

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 ($|\cos \theta| < 0.80$, where θ denotes the polar angle with respect to the z axis, the symmetry axis of the MDC) 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 degrees as measured from the interaction point (IP). In addition, the time information from the shower in the calorimeter relative to the event start time has to be less than 700 ns. For charged tracks not originating from K_S^0 decays, the distance of closest approach to the 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 dE/dx and TOF measurements to calculate likelihood values $\mathcal{L}(h)$ for each hadron hypothesis ($h = p, \pi$, and K).

Each K_S^0 candidate is reconstructed from two oppositely charged tracks satisfying $|V_z| < 20$ cm. The two charged tracks are assigned as $\pi^+\pi^-$ without imposing further PID criteria. They are constrained via vertex fit and second vertex fit to originate from a common vertex and are required to have an invariant mass within $|M_{\pi^+\pi^-} - m_{K_S^0}| < 0.012$ GeV/ c^2 , which corresponds to $\pm 3\sigma$ where $m_{K_S^0}$ is the K_S^0 nominal mass [4]. The decay length of the K_S^0 candidate is required to be greater than twice the vertex resolution away from the IP.

To suppress high background containing Λ or $\bar{\Lambda}$ in the final state, the $p\pi^-$ and $\bar{p}\pi^+$ invariant masses are required

to be outside the region of ± 0.012 GeV/ c^2 around the Λ nominal mass [4].

A four-momentum conservation constraint (4C) kinematic fit is applied to the events under the hypothesis of $e^+e^- \rightarrow \gamma p\bar{p}K_S^0K_S^0$, where the information on the two K_S^0 candidates is derived from the above second vertex fit. If multiple combinations survive in an event, the one with the smallest χ_{4C}^2 is retained. The χ_{4C}^2 selection is optimized using the figure of merit (FOM) $S/\sqrt{S+B}$, where S is the normalized signal yield from MC simulation (scaled by the measured branching fractions) and B is the normalized background from the inclusive MC sample (scaled to data). From this optimization, candidate events are required to satisfy $\chi_{4C}^2 < 50$.

Non- $K_S^0 \pi^+\pi^-$ combinations in the K_S^0 signal region may form peaking backgrounds around $M_{\chi_{cJ}}$ in the $M_{p\bar{p}K_S^0K_S^0}$ distributions. This kind of peaking background contribution is estimated with events in the one-dimensional (1D) K_S^0 sideband region of $(0.454, 0.478) \cup (0.518, 0.542)$ GeV/ c^2 . Two-dimensional (2D) $K_S^0K_S^0$ signal and sideband regions (SB) are also defined: the signal region contains both $\pi^+\pi^-$ pairs within the 1D K_S^0 signal region; SB1 contains one $\pi^+\pi^-$ pair in the 1D K_S^0 sideband region and one in the 1D K_S^0 signal region; and SB2 contains both pairs in the 1D K_S^0 sideband regions. Figure 1 shows the 1D and 2D $\pi^+\pi^-$ invariant-mass distributions along with the K_S^0 signal and sideband regions.

Other potential background components from $\psi(3686)$ decays, which can not be described by the sidebands, are studied by analyzing the inclusive MC sample with the generic event type analysis tool, TopoAna [26]. No significant peaking background reactions are observed. Additionally, we examine data taken at $\sqrt{s} = 3.650$ GeV, corresponding to an integrated luminosity of 445.5 pb $^{-1}$ [27], to estimate

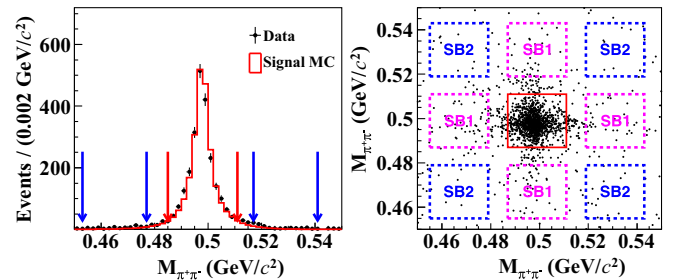


FIG. 1. (Left) The $M_{\pi^+\pi^-}$ distribution of the $\chi_{cJ} \rightarrow p\bar{p}K_S^0K_S^0$ candidates in data and signal MC samples, where both K_S^0 candidates are included. The red (blue) solid arrows indicate the 1D K_S^0 signal (sideband) regions. (Right) The distribution of $M_{\pi^+\pi^-}$ versus $M_{\pi^+\pi^-}$ (with the two $\pi^+\pi^-$ combinations randomly assigned) for $\chi_{cJ} \rightarrow p\bar{p}K_S^0K_S^0$ candidates in data. The red solid box denotes the 2D signal region, while the pink and blue dot-dashed boxes indicate the 2D SB1 and SB2 regions, respectively.

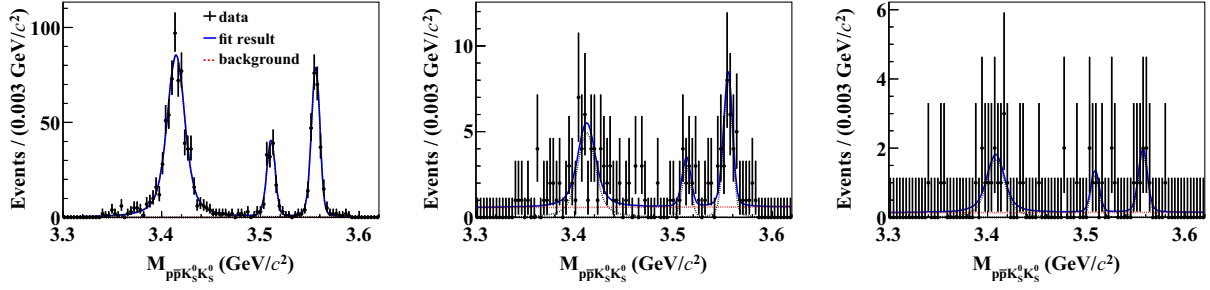


FIG. 2. Fits to the $M_{p\bar{p}K_S^0 K_S^0}$ distributions of the accepted candidates for $\chi_{cJ} \rightarrow p\bar{p}K_S^0 K_S^0$ in data in the K_S^0 signal region (left), SB1 region (middle) and SB2 region (right). The dots with error bars are data, the solid curves are the fit results, the dashed curves are the fitted combinatorial background shapes, and the black dash lines are the signal.

potential continuum production background. It is found to be negligible.

The net signal yields for the $\chi_{cJ} \rightarrow p\bar{p}K_S^0 K_S^0$ decays are determined as

$$N_{\text{net}}^{\chi_{cJ}} = N_{\text{sig}} - \frac{1}{2}N_{\text{SB1}} + \frac{1}{4}N_{\text{SB2}},$$

where N_{sig} , N_{SB1} , and N_{SB2} are the numbers of events in the 2D signal, SB1, and SB2 regions, respectively. To determine N_{sig} , N_{SB1} , and N_{SB2} , unbinned maximum likelihood fits are performed on the corresponding $M_{p\bar{p}K_S^0 K_S^0}$ distributions.

The signal yields are obtained by performing unbinned maximum likelihood fits to the mass spectra of the selected $M_{p\bar{p}K_S^0 K_S^0}$ in the 2D K_S^0 signal region or 2D sideband

regions. In the fit, the signal shapes of χ_{cJ} are modeled using the Breit-Wigner convoluted with a Gaussian function with free parameters, to account for differences in resolution between data and MC. The background is described by a linear function. Potential interference between the signal and the continuum background is neglected in the fit, as the K_S^0 peak is very narrow. The signal shapes in the $K_S^0 K_S^0$ signal and sideband regions share the same Gaussian function. Figure 2 shows the fit results. Based on these fits, the net signal yields ($N_{\text{net}}^{\chi_{cJ}}$) of χ_{c0} , χ_{c1} and χ_{c2} are determined to be 707.3 ± 27.4 , 138.0 ± 12.6 and 267.9 ± 17.3 , respectively. The statistical significances for these signals are found to be 36.2σ , 20.9σ and 30.1σ , respectively, evaluated by comparing the likelihoods with and without the signal component and taking into account the change in the number of degrees of freedom.

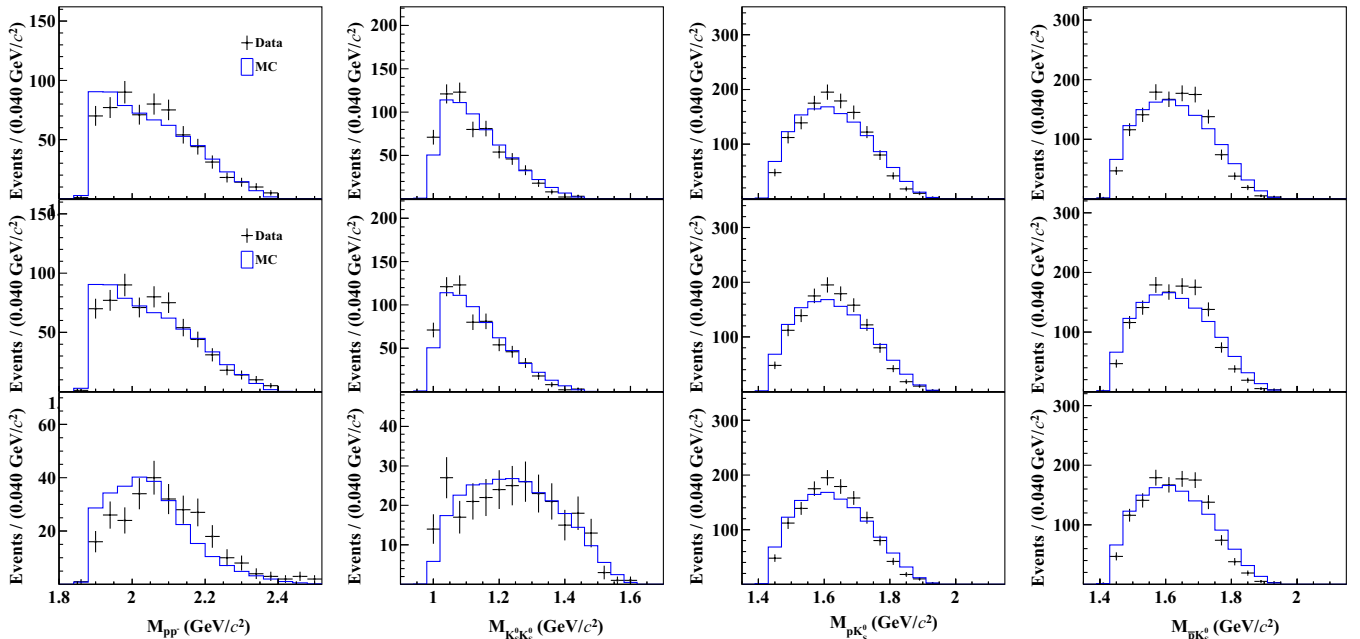


FIG. 3. Comparisons of the distributions the invariant masses of two-body combinations of the candidates for (top) χ_{c0} , (middle) χ_{c1} , and (bottom) χ_{c2} decaying into $p\bar{p}K_S^0 K_S^0$. The black dots with error bars are data and the blue histograms are the signal MC sample. Events have been required to fall in the χ_{c0} , χ_{c1} , and χ_{c2} signal regions defined as $[3.385, 3.445]$ GeV/c², $[3.490, 3.530]$ GeV/c² and $[3.535, 3.575]$ GeV/c², respectively. There are two entries for $M_{pK_S^0}$ and $M_{\bar{p}K_S^0}$.

TABLE I. The quantities used for determining the branching fractions of $\chi_{cJ} \rightarrow p\bar{p}K_S^0K_S^0$, where the first uncertainties are statistical and the second systematic.

	χ_{c0}	χ_{c1}	χ_{c2}
N_{sig}	724.6 ± 27.1	142.3 ± 12.4	281.1 ± 17.0
N_{SB1}	41.8 ± 8.4	10.7 ± 4.1	30.0 ± 6.4
N_{SB2}	14.2 ± 4.4	4.3 ± 2.6	7.2 ± 3.0
$N_{\chi_{cJ}}^{\text{net}}$	707.3 ± 27.4	138.0 ± 12.6	267.9 ± 17.3
ϵ (%)	7.69 ± 0.07	8.21 ± 0.03	8.65 ± 0.03
$\mathcal{B}(\psi(3686) \rightarrow \gamma\chi_{cJ}) \cdot \mathcal{B}(\chi_{cJ} \rightarrow p\bar{p}K_S^0K_S^0) (10^{-6})$	$7.09 \pm 0.27 \pm 0.31$	$1.30 \pm 0.12 \pm 0.06$	$2.39 \pm 0.15 \pm 0.10$
$\mathcal{B}(\chi_{cJ} \rightarrow p\bar{p}K_S^0K_S^0) (10^{-5})$	$7.25 \pm 0.28 \pm 0.35$	$1.33 \pm 0.12 \pm 0.07$	$2.51 \pm 0.16 \pm 0.12$

Figure 3 presents the invariant mass distributions of two-body combinations accepted $\chi_{c0,1,2} \rightarrow p\bar{p}K_S^0K_S^0$ candidates. No obvious structures in the $p\bar{p}$, pK_S^0 and $\bar{p}K_S^0$ invariant mass spectra have been observed.

IV. BRANCHING FRACTION

The product branching fractions of $\psi(3686) \rightarrow \gamma\chi_{cJ}$ and $\chi_{cJ} \rightarrow p\bar{p}K_S^0K_S^0$ are calculated as

$$\begin{aligned} & \mathcal{B}(\psi(3686) \rightarrow \gamma\chi_{cJ}) \cdot \mathcal{B}(\chi_{cJ} \rightarrow p\bar{p}K_S^0K_S^0) \\ &= \frac{N_{\chi_{cJ}}^{\text{net}}}{N_{\psi(3686)} \cdot \epsilon \cdot \mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-)^2}, \end{aligned} \quad (1)$$

where $N_{\psi(3686)}$ is the total number of $\psi(3686)$ events in data, ϵ is the detection efficiency and $\mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-)$ is the branching fraction of $K_S^0 \rightarrow \pi^+\pi^-$ quoted from the PDG [4].

According to Eq. (1), we obtain the product branching fractions, $\mathcal{B}(\psi(3686) \rightarrow \gamma\chi_{cJ}) \cdot \mathcal{B}(\chi_{cJ} \rightarrow p\bar{p}K_S^0K_S^0)$, and by combining our results with the world average values of $\mathcal{B}(\psi(3686) \rightarrow \gamma\chi_{cJ})$ [22], we obtain $\mathcal{B}(\chi_{cJ} \rightarrow p\bar{p}K_S^0K_S^0)$. All relevant quantities are summarized in Table I.

Our analysis procedure has been validated via input-output checks with 50 simulated samples. Each simulated sample has the same size as the real data. The same analysis procedure as the data analysis is performed on each simulated sample. The average of the measured branching fractions agrees well with the input branching fraction, thereby ensuring that there is no bias in the analysis procedure.

V. SYSTEMATIC UNCERTAINTY

The systematic uncertainties in the branching fraction measurements arise from several sources, as summarized in Table II, and are discussed below.

The total number of $\psi(3686)$ events in data is measured to be $N_{\psi(3686)} = (2.712 \pm 0.014) \times 10^9$ with the inclusive hadronic events, as described in Ref. [12]. The systematic uncertainty of $N_{\psi(3686)}$ is 0.5%.

The tracking efficiency of protons is studied using a control sample of $J/\psi \rightarrow p\bar{p}\pi^+\pi^-$. The difference in tracking efficiency between data and MC simulation is assigned as the systematic uncertainty is 1.0% per track. Using the same control sample, the systematic uncertainty due to the PID of proton is also assigned to be 1.0% per track [28].

The systematic uncertainty of the K_S^0 reconstruction, including tracking efficiency, K_S^0 mass window, vertex fit and second vertex fit, is estimated by using control samples of $J/\psi \rightarrow K^*(892)^\pm \bar{K}^\mp$ and $J/\psi \rightarrow \phi K^*(892)^\pm \bar{K}^\mp$. The systematic uncertainty of the K_S^0 reconstruction is assigned to be 1.5% [29].

The systematic uncertainty in the photon detection is assigned as 1.0% per photon with the control sample of $J/\psi \rightarrow \pi^+\pi^-\pi^0$ [30].

The systematic uncertainty from the 4C kinematic fit is estimated by comparing the signal efficiencies with and without helix parameter correction, where the correction factors are taken from the previous study in Ref. [31]. The differences in the signal efficiencies are assigned as the

TABLE II. Relative systematic uncertainties in the measurements of the branching fractions of $\chi_{cJ} \rightarrow p\bar{p}K_S^0K_S^0$ (in percent).

Source	χ_{c0}	χ_{c1}	χ_{c2}
$N_{\psi(3686)}$	0.5	0.5	0.5
Tracking	2.0	2.0	2.0
PID	2.0	2.0	2.0
K_S^0 reconstruction	3.0	3.0	3.0
Photon detection	1.0	1.0	1.0
4C kinematic fit	0.3	0.4	0.3
MC model	0.6	0.4	0.1
Fit to $M_{p\bar{p}K_S^0K_S^0}$	0.1	0.9	0.3
MC statistics	0.4	0.4	0.4
$\mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-)$	0.2	0.2	0.2
$\mathcal{B}(\psi(3686) \rightarrow \gamma\chi_{cJ})$	2.0	2.5	2.1
Total for $\mathcal{B}(\psi(3686) \rightarrow \gamma\chi_{cJ}) \cdot \mathcal{B}(\chi_{cJ} \rightarrow p\bar{p}K_S^0K_S^0)$	4.3	4.4	4.3
Total for $\mathcal{B}(\chi_{cJ} \rightarrow p\bar{p}K_S^0K_S^0)$	4.8	5.1	4.8

systematic uncertainties, which are 0.3%, 0.4%, and 0.3% for $\chi_{c0,1,2} \rightarrow p\bar{p}K_S^0K_S^0$, respectively.

The systematic uncertainties of the MC model are estimated to be 0.6%, 0.4%, and 0.1%, for the χ_{c0} , χ_{c1} and χ_{c2} decays, which are the differences between the nominal and reweighted PHSP signal MC samples. Here, the latter ones are reweighted according to their $M_{p\bar{p}}$ versus $M_{K_S^0K_S^0}$ in data.

The systematic uncertainties of the fit to the $M_{p\bar{p}K_S^0K_S^0}$ distribution are evaluated from two aspects. The uncertainties due to the background shape are estimated by varying between first and second-order polynomial function. The uncertainties of the signal shape are examined by varying the parameters in the Breit-Wigner and resolution of Gaussian functions. Adding these two effects in quadrature yields the systematic uncertainties to be 0.1%, 0.9%, and 0.3% for $\chi_{c0,1,2} \rightarrow p\bar{p}K_S^0K_S^0$, respectively.

The uncertainties due to limited statistics of the signal MC samples are 0.4%, 0.4%, and 0.4% for $\chi_{c0,1,2} \rightarrow p\bar{p}K_S^0K_S^0$.

The branching fractions of the χ_{cJ} and K_S^0 decays are quoted from the PDG [4]. The corresponding uncertainties are 2.0%, 2.5%, 2.1% for $\psi(3686) \rightarrow \gamma\chi_{c0,1,2}$, and 0.07% for $K_S^0 \rightarrow \pi^+\pi^-$.

The total systematic uncertainty for each signal decay is obtained by adding all contributions in quadrature.

VI. SUMMARY

Using $(2.712 \pm 0.014) \times 10^9$ $\psi(3686)$ events collected with the BESIII detector, the decays $\chi_{cJ} \rightarrow p\bar{p}K_S^0K_S^0$ are observed for the first time with statistical significances exceeding 5σ for each signal decay. The measured branching fractions of $\chi_{cJ} \rightarrow p\bar{p}K_S^0K_S^0$ are summarized in Table I. It is worth noting that the $p\bar{p}$ invariant mass spectrum shows a slight deviation from MC samples near threshold. However, we have examined the $p\bar{p}$ invariant mass spectra for $\chi_{cJ} \rightarrow p\bar{p}K_S^0K_S^0$, and no significant enhancement around the $p\bar{p}$ mass threshold is found.

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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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