Observation of $\chi_{cJ} \rightarrow 4K^0_S$

(BESIII Collaboration)

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OBSERVATION OF $\chi_{cJ} \rightarrow 4K_S^0$

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I. INTRODUCTION

In the quark model, the $\chi_{cJ} (J = 0, 1, 2)$ mesons are the $^3P_J$ charmonium states. Since the $\chi_{cJ}$ mesons cannot be directly produced in $e^+e^-$ collisions, according to parity conservation, their decays are experimentally and theoretically not studied as extensively as the vector charmonium states $J/\psi$ and $\psi(3686)$. However, the $\chi_{cJ}$ mesons can be produced in radiative decays of the $\psi(3686)$ with branching fractions of about 9%, which provide a method to produce large $\chi_{cJ}$ samples in order to study $\chi_{cJ}$ decays.

Recent theoretical work indicates that the color octet mechanism (COM) [1] could have large contributions to the decays of the $P$-wave charmonium states. However, many contradictions still exist between these theoretical calculations and experimental measurements. For instance, theoretical predictions of $\chi_{cJ}$ decays to baryon-antibaryon pairs based on the COM [2-4] are inconsistent with experimental measurements [5]. Thus, more precise experimental results are mandatory to further understand $\chi_{cJ}$ decay dynamics. Furthermore, the $\chi_{c0}$ and $\chi_{c2}$ states are expected to decay via two-gluon processes into light hadrons, giving access to the investigation of glueball dynamics. Thus, comprehensive measurements of exclusive hadronic decays of $\chi_{cJ}$ are valuable.

For the decay modes of $\chi_{cJ} \rightarrow 4K$, the branching fractions of $\chi_{cJ}$ decays into $2(K^+K^-)$ and $K^+K^-K^0S_K$ have been measured by Belle [6] and BES [7] with results...
summarized in Table I. Measurements of the branching fractions of their isospin-symmetrical decays, $\chi_{cJ} \rightarrow 4K_S^0$, will shed light on the understanding of isospin invariance in the $\chi_{cJ} \rightarrow 4K$ decays. In this paper, by analyzing $(448.1 \pm 2.9) \times 10^6 \psi(3686)$ events [8] collected with the BESIII detector [9], we present the first measurements of the branching fractions of $\chi_{cJ}$ decays to $4K_S^0$.

II. BESIII DETECTOR AND MONTE CARLO SIMULATION

The BESIII detector is operated at the Beijing Electron Positron Collider II (BEPCII), which has reached a peak luminosity of $1.0 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ at a center-of-mass energy of $\sqrt{s} = 3.773$ GeV. The detector has a geometrical acceptance of 93% of the solid angle and is composed of four main components. A helium-gas-based main drift chamber (MDC) is used to track charged particles. The single wire resolution is better than 130 $\mu$m, which, together with a magnetic field of 1 T, leads to a momentum resolution of 0.5% for transverse momentum of 1 GeV/c. The energy loss per path length $dE/dx$ is measured with a resolution of 6%. The MDC is surrounded by a time-of-flight system built from plastic scintillators. It provides a $2\sigma K/\pi$ separation up to 1 GeV/c momentum with a time resolution of 80 (110) ps for the barrel (end caps). Particle energies are measured in the CsI(Tl) electromagnetic calorimeter (EMC), which achieves an energy resolution for electrons of 2.5% (5%) at 1 GeV/c momentum and a position resolution of 6 mm (9 mm) for the barrel (end caps). Outside of the magnet coil, a muon counter composed of resistive plate chambers provides a spatial resolution of better than 2 cm. A more detailed description of the detector can be found in Ref. [9].

A GEANT4-BASED [10] Monte Carlo (MC) simulation package is used to optimize the event selections and estimate the signal efficiency and the background level. The event generator KKMC [11] simulates the electron-positron annihilation and the production of the $\psi$ resonances. Particle decays are generated by EVTGEN [12] for the known decay modes with branching fractions from the Particle Data Group (PDG) [5] and Lundcharm [13] for the unknown ones. An inclusive MC sample containing $506 \times 10^6$ generic $\psi(3686)$ decays is used to study background. The $\psi(3686) \rightarrow \gamma \chi_{cJ}$ decays are generated assuming an electric-pole $(E1)$ transition [14], in which the polar angle $\theta$ of the radiative photon is distributed with the $(1 + \cos^2 \theta)$, $(1 - 1/4 \cos^2 \theta)$, and $(1 + 1/4 \cos^2 \theta)$ for $\chi_{c0}$, $\chi_{c1}$, and $\chi_{c2}$ decays [15]. The $E1$ transition width is proportional to $E^3$, where $E$ is the energy of the emitted photon [16]. The $\chi_{cJ} \rightarrow 4K_S^0$ and $K_S^0 \rightarrow \pi^+\pi^-$ decays are generated in phase space (PHSP) distribution. The $\chi_{cJ}$ states are simulated using a relativistic Breit-Wigner incorporated within the helicity amplitudes in the EVTGEN package [12].

III. EVENT SELECTION

We reconstruct events from the decay chain of the charmonium transitions $\psi(3686) \rightarrow \gamma \chi_{cJ}$ followed by the hadronic decays $\chi_{cJ} \rightarrow 4K_S^0$ and $K_S^0 \rightarrow \pi^+\pi^-$. A photon candidate is defined as a shower detected within the EMC exceeding an energy deposit of 25 MeV in the barrel region (covering the region $|\cos\theta| < 0.8$, where $\theta$ is the polar angle with respect to the positron beam direction) or of 50 MeV in the end caps ($0.86 < |\cos\theta| < 0.92$). To suppress the electronics noise and beam background, the clusters are required to start within 700 ns after the

![FIG. 1. The distributions of $\sigma_l$ and $L/\sigma_l$ for all $K_S^0$ candidates.](image-url)
estimated collision timing and fall outside a cone angle of 10° around the nearest extrapolated charged track. All charged tracks are required to originate from the interaction region defined as $|V_z| < 20$ cm and $|\cos \theta| < 0.93$, where $V_z$ denotes the distance of the closest approach of the reconstructed track to the interaction point (IP) in the $z$ direction. Candidate events must have eight charged tracks with zero net charge and at least one good photon. The $K_0^0$ candidates are reconstructed using vertex fits by looping over all oppositely charged track pairs in an event (assuming the tracks to be $\pi^\pm$ without particle identification). To suppress the combinatorial background, the reconstructed decay lengths ($L$) of the $K_0^0$ candidates are required to be more than twice their standard deviations ($\sigma_L$). The distributions of $\sigma_L$ and $L/\sigma_L$ for all $K_0^0$ candidates are shown in Fig. 1.

The invariant mass of $\pi^+\pi^-$ ($M_{\pi^+\pi^-}$) must be within the $K_0^0$ signal region, defined as 12 MeV/$c^2$ around the $K_0^0$ nominal mass [5]. The $M_{\pi^+\pi^-}$ distribution for all $K_0^0$ candidates is shown in Fig. 2. To further suppress combinatorial background, a four-momentum conservation constraint (4C) is applied to the events. The $\chi^2_{4C}$ of the kinematic fit is required to be less than 200. To reduce the difference of the distributions of $\chi^2_{4C}$ between data and MC simulation, we correct the track helix parameters of MC simulation in the 4C kinematic fit.

**FIG. 2.** The $M_{\pi^+\pi^-}$ distribution for all $K_0^0$ candidates. The arrows indicate the mass window of the $K_0^0$ signal, where the dots with error bars are from data and the histogram is from the PHSP signal MC sample scaled to the amount of data events.

**FIG. 4.** Fit to the $M_{4K_0^0}$ distribution of the candidate events of $\psi(3686) \rightarrow \chi_c J, \chi_c J \rightarrow 4K_0^0$. The points with error bars are data, the blue curve is the overall fit, and the red curve is the fitted background.

**FIG. 3.** The $\chi^2_{4C}$ distribution after corrections, where the dots with error bars are from data and the histogram is from the PHSP signal MC sample scaled to the amount of data events.

**FIG. 5.** The $M_{2K_0^0}$ and $M_{3K_0^0}$ distributions for all $2K_0^0$ and $3K_0^0$ combinations, where the dots with error bars are from data and the histogram is from the PHSP signal MC sample scaled to the amount of data events.
The $\chi^2$ distribution after corrections is shown in Fig. 3, in which the consistency between data and MC simulation is reasonable. The spectrum of the invariant mass of the $4K_S^0$ ($M_{4K_S^0}$) of the accepted candidate events is shown in Fig. 4. Clear $\chi_{0}$, $\chi_{c1}$ and $\chi_{c2}$ signals are observed.

We further examine the possible substructures in the $\chi_{c1} \rightarrow 4K_S^0$. Figure 5 shows the distribution of invariant masses of $2K_S^0$ ($M_{2K_S^0}$) and $3K_S^0$ ($M_{3K_S^0}$). No obvious structure is found.

### IV. BACKGROUND STUDIES

The continuum data taken at $\sqrt{s} = 3.65$ GeV, corresponding to an integrated luminosity of 44.45 pb$^{-1}$ [17], are used to estimate the QED background. No events within this sample satisfy the same selection criteria applied to the main data sample. Studies of the signal MC events of $\psi(3686) \rightarrow \gamma \chi_{c1}, \chi_{c1} \rightarrow 4K_S^0$ decays show that the signals containing misformed $K_S^0$ can be ignored safely. In addition, the inclusive MC sample is used to study all potential backgrounds from $\psi(3686)$ decays. Only two background events of $\psi(3686) \rightarrow K^{*0}(892)K_S^0f_2^{(1525)}$ and $K^{*0}(892)K_S^0f_0(1710)$ survive. Further studies with large exclusive MC samples show that the two background sources only form a uniform distribution across the fit range. Thus, all peaking background components are negligible in this analysis.

### V. BRANCHING FRACTIONS

The signal yields $N_{\psi}^{J}$ are obtained by fitting to the $M_{4K_S^0}$ distribution. The $M_{4K_S^0}$ distribution is fitted using an unbinned maximum likelihood fit. In the fit, each $\chi_{c1}$ signal is described with the MC simulated shape, which is the probability density function translated by utilizing the RooHistPDF class [18] in RooFit [19], convolved with a Gaussian function with free parameters to take into account the resolution difference between data and MC simulation. Since the background level is very low, as discussed in Sec. IV, the background shape is assumed to be flat. The signal yields of $\chi_{0}$, $\chi_{c1}$ and $\chi_{c2}$ are fitted to be 319.4 ± 19.0, 21.6 ± 5.2 and 68.0 ± 8.7, respectively. The statistical significances are estimated to be 26.5$\sigma$, 5.9$\sigma$ and 11.4$\sigma$ for $\chi_{0}$, $\chi_{c1}$ and $\chi_{c2}$ individually, which are determined by comparing the fit likelihood values with and without each $\chi_{c1}$ signal separately. The obtained corrected efficiencies for $\chi_{c1} \rightarrow 4K_S^0$ are (5.51 ± 0.03)% (6.19 ± 0.04)% and (6.08 ± 0.04)% respectively, including detector acceptance as well as reconstruction and selection efficiencies.

The branching fraction is calculated with

$$B_{\chi_{c1} \rightarrow 4K_S^0} = \frac{N_{\psi}^{J}}{N_{\psi}(3686)} \cdot B^{J}_{\psi(3686) \rightarrow \gamma \chi_{c1}} \cdot B^{J}_{K_S^0 \rightarrow \pi^+ \pi^-} \cdot \epsilon,$$

where $\epsilon$ is the efficiency, $N_{\psi}(3686)$ is the number of $\psi(3686)$ events, $B^{J}_{\psi(3686) \rightarrow \gamma \chi_{c1}}$ and $B^{J}_{K_S^0 \rightarrow \pi^+ \pi^-}$ are the branching fractions of the PDG fit of $\psi(3686) \rightarrow \gamma \chi_{c1}$ decays and $K_S^0 \rightarrow \pi^+ \pi^-$ decay [5].

### VI. SYSTEMATIC UNCERTAINTIES

The systematic uncertainties in the measurements of $B_{\chi_{c1} \rightarrow 4K_S^0}$ originate from several sources, as summarized in Table II. They are estimated and described below.

The number of $\psi(3686)$ events has been measured to be $N_{\psi}(3686) = (448.1 ± 2.9) \times 10^6$ with the inclusive hadronic data sample, as described in Ref. [8]. The uncertainty of the total number is 0.6%

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

The systematic uncertainty associated with $K_S^0$ reconstruction is determined to be 1.5% per $K_S^0$ with the control samples of $J/\psi \rightarrow K^{*0}(892)K^+$, $K^{*0}(892) \rightarrow K^0\pi^+$ and $J/\psi \rightarrow \phi K_S^0 K^\mp \pi^\pm$ in Ref. [21].

To estimate the systematic uncertainties of the MC model for the $\chi_{c1} \rightarrow 4K_S^0$ decay, we compare our nominal efficiency with that determined from the signal MC events after mixing some possible sub-resonant decays, including $\chi_{c1} \rightarrow f_0(1500) f_0(1500), \chi_{c1} \rightarrow K_S^0 f_0(1500), \chi_{c1} \rightarrow K^0 f_0(1500) f_0(1500), \chi_{c1} \rightarrow K^0 f_0(1500) f_0(1500), \chi_{c1} \rightarrow K^0 f_0(1500) f_0(1500)$. Further studies with large exclusive MC samples show that the two background sources only form a uniform distribution across the fit range. Thus, all peaking background components are negligible in this analysis.

The systematic uncertainties are estimated as the relative changes of efficiencies, which are 0.4%, 0.2% and 0.2% for $\chi_{0}, \chi_{c1}$ and $\chi_{c2}$, respectively.

We correct the track helix parameters for MC simulation in the 4C kinematic fit. The change in detection efficiency is not more than 1.0% when varying the correction factors within one standard deviation around the nominal value. We, therefore, assume 1.0% as the systematic uncertainty of the 4C kinematic fit.

<table>
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<th>Source</th>
<th>$\chi_{0}$</th>
<th>$\chi_{c1}$</th>
<th>$\chi_{c2}$</th>
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<td>0.6</td>
<td>0.6</td>
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<tr>
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<td>6.0</td>
<td>6.0</td>
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<tr>
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<td>0.6</td>
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<td>Total</td>
<td>6.6</td>
<td>7.4</td>
<td>6.9</td>
</tr>
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</table>
To estimate the systematic uncertainties in the polar-angle distribution of single $K^0_S$, we use a reweighting method. New signal MC events are obtained by reweighting the polar-angle distribution of single $K^0_S$ in the signal MC events to data. The changes to the detection efficiencies are taken as the systematic uncertainties, which are 0.7%, 0.5% and 0.7% for $\chi c_0$, $\chi c_1$ and $\chi c_2$ decays, respectively.

The systematic uncertainties due to the fit range are estimated by a series of fits with alternative intervals. The standard deviations of the resulting branching fractions are assigned as the systematic uncertainties, which are 0.6%, 1.5% and 0.9% for $\chi c_0$, $\chi c_1$ and $\chi c_2$ decays, respectively.

To estimate the systematic uncertainties due to the signal shape, we use alternative signal shapes, a Breit-Wigner function smeared with a double Gaussian and a MC simulated shape ignoring the effect of the $\chi_c$ width on PHSP convolved with a Gaussian function, to describe each $\chi_c$ signal. The maximum deviations of the resulting branching fractions are assigned as the relevant systematic uncertainties, which are 0.4%, 2.8% and 1.7% for $\chi c_0$, $\chi c_1$ and $\chi c_2$ decays, respectively.

The systematic uncertainties due to the statistics of the MC samples are 0.6%, 0.5%, and 0.6% for $\chi c_0$, $\chi c_1$ and $\chi c_2$ decays, respectively.

The systematic uncertainties from the branching fractions of $\psi(3686) \rightarrow \gamma \chi_c$ and $K^0_S \rightarrow \pi^+ \pi^-$ decays quoted from the PDG [5] are 2.0%, 2.5% and 2.1% for $\chi c_0$, $\chi c_1$ and $\chi c_2$ decays and 0.07% for $K^0_S$, respectively.

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

**VII. CONCLUSION**

By analyzing $(448.1 \pm 2.9) \times 10^6 \psi(3686)$ events with the BESIII detector, the product branching fractions are determined to be $B_{\psi(3686) \rightarrow \gamma \chi c_0} = (0.564 \pm 0.033 \pm 0.037) \times 10^{-4}$, $B_{\psi(3686) \rightarrow \gamma \chi c_1} = (0.034 \pm 0.009 \pm 0.003) \times 10^{-4}$ and $B_{\psi(3686) \rightarrow \gamma \chi c_2} = (0.108 \pm 0.015 \pm 0.008) \times 10^{-4}$, where the first and second uncertainties are statistical and systematic, respectively. We measure for the first time the branching fractions of $\chi c_0 \rightarrow 4K_S^0$ decays to be $B_{\chi c_0 \rightarrow 4K_S^0} = (5.76 \pm 0.34 \pm 0.38) \times 10^{-4}$, $B_{\chi c_1 \rightarrow 4K_S^0} = (0.35 \pm 0.09 \pm 0.03) \times 10^{-4}$, $B_{\chi c_2 \rightarrow 4K_S^0} = (1.14 \pm 0.15 \pm 0.08) \times 10^{-4}$, where the first and second uncertainties are statistical and systematic, respectively. Combining the world averages of the branching fractions of the $\chi c_0 \rightarrow 2(K^+ K^-)$ decays, we obtain the branching fraction ratios $B_{\chi c_0 \rightarrow 4K_S^0}/B_{\chi c_0 \rightarrow 2(K^+ K^-)} = 0.204 \pm 0.028$, $B_{\chi c_1 \rightarrow 4K_S^0}/B_{\chi c_1 \rightarrow 2(K^+ K^-)} = 0.064 \pm 0.023$, and $B_{\chi c_2 \rightarrow 4K_S^0}/B_{\chi c_2 \rightarrow 2(K^+ K^-)} = 0.069 \pm 0.013$. Our results provide valuable data to explore isospin symmetry in $\chi_c \rightarrow 4K$ decays.

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