Observation of the helicity-selection-rule suppressed decay of the c2 charmonium state postprint

Authors: M. Ablikim[et al.]

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Abstract

The decays of c2 → K+K− 0, KSK± and + − 0 are studied using the (3686) data samples collected with the Beijing Spectrometer (BESIII). For the first time, the branching fractions of c2 → K∗K, c2 → a±(1320) /a02(1320) 0 and c2 → (770)± are measured. Here K∗K denotes both K∗±K and its isospin-conjugated process K∗0K0 + c.c., and K∗ denotes the resonances K∗(892), K2∗(1430) and K3∗(1780). The observations indicate a strong violation of the helicity selection rule in c2 decays into vector and pseudoscalar meson pairs. The measured branching fractions of c2 → K∗(892)K are more than 10 times larger than the upper limit of c2 → (770)± , which is so far the first direct observation of a significant U-spin symmetry breaking effect in charmonium decays.

Full Text

Preamble

Observation of the helicity-selection-rule suppressed decay of the c2 charmonium state M. Ablikim1, M. N. Achasov9,e, S. Ahmed14, X. C. Ai1, O. Albayrak5, M. Albrecht4, D. J. Ambrose44, A. Amoroso49A,49C, F. F. An1, Q. An46,a, J. Z. Bai1, O. Bakina23, R. Baldini Ferroli20A, Y. Ban31, D. W. Bennett19, J. V. Bennett5, N. Berger22, M. Bertani20A, D. Bettoni21A, J. M. Bian43, F. Bianchi49A,49C, E. Boger23,c, I. Boyko23, R. A. Briere5, H. Cai51, X. Cai1,a, O. Cakir40A, A. Calcaterra20A, G. F. Cao1, S. A. Cetin40B, J. Chai49C, J. F. Chang1,a, G. Chelkov23,c,d, G. Chen1, H. S. Chen1, J. C. Chen1, M. L. Chen1,a, S. Chen41, S. J. Chen29, X. Chen1,a, X. R. Chen26, Y. B. Chen1,a, X. K. Chu31, G. Cibinetto21A, H. L. Dai1,a, J. P. Dai34,j, A. Dbeyssi14, D. Dedovich23, Z. Y. Deng1, A. Denig22, I. Denysenko23, M. Destefanis49A,49C, F. De Mori49A,49C, Y. Ding27, C. Dong30, J. Dong1,a,

L. Y. Dong1, M. Y. Dong1,a, Z. L. Dou29, S. X. Du53, P. F. Duan1, J. Z. Fan39, J. Fang1,a, S. S. Fang1, X. Fang46,a, Y. Fang1, R. Farinelli21A,21B, L. Fava49B,49C, F. Feldbauer22, G. Felici20A, C. Q. Feng46,a, E. Fioravanti21A, M. Fritsch14,22, C. D. Fu1, Q. Gao1, X. L. Gao46,a, Y. Gao39, Z. Gao46,a, I. Garzia21A, K. Goetzen10, L. Gong30, W. X. Gong1,a, W. Gradl22, M. Greco49A,49C, M. H. Gu1,a, Y. T. Gu12, Y. H. Guan1, A. Q. Guo1, L. B. Guo28, R. P. Guo1, Y. Guo1, Y. P. Guo22, Z. Haddadi25, A. Hafner22, S. Han51, X. Q. Hao15, F. A. Harris42, K. L. He1, F. H. Heinsius4, T. Held4, Y. K. Heng1,a, T. Holtmann4, Z. L. Hou1, C. Hu28, H. M. Hu1, T. Hu1,a, Y. Hu1, G. S. Huang46,a, J. S. Huang15, X. T. Huang33, X. Z. Huang29, Z. L. Huang27, T. Hussain48, W. Ikegami Andersson50, Q. Ji1, Q. P. Ji15, X. B. Ji1, X. L. Ji1,a, L. W. Jiang51, X. S. Jiang1,a, X. Y. Jiang30, J. B. Jiao33, Z. Jiao17, D. P. Jin1,a, S. Jin1, T. Johansson50, A. Julin43, N. Kalantar-Nayestanaki25, X. L. Kang1, X. S. Kang30, M. Kavatsyuk25, B. C. Ke5, P. Kiese22, R. Kliemt10, B. Kloss22, O. B. Kolcu40B,h, B. Kopf4, M. Kornicer42, A. Kupsc50, W. K¨uhn24, J. S. Lange24, M. Lara19, P. Larin14, H. Leithoff22, C. Leng49C, C. Li50, Cheng Li46,a, D. M. Li53, F. Li1,a, F. Y. Li31, G. Li1, H. B. Li1, H. J. Li1, J. C. Li1, Jin Li32, K. Li13, K. Li33, Lei Li3, P. R. Li7,41, Q. Y. Li33, T. Li33, W. D. Li1, W. G. Li1, X. L. Li33, X. N. Li1,a, X. Q. Li30, Y. B. Li2, Z. B. Li38, H. Liang46,a, Y. F. Liang36, Y. T. Liang24, G. R. Liao11, D. X. Lin14, B. Liu34,j, B. J. Liu1, C. X. Liu1, D. Liu46,a, F. H. Liu35, Fang Liu1, Feng Liu6, H. B. Liu12, H. H. Liu1, H. H. Liu16, H. M. Liu1, J. Liu1, J. B. Liu46,a, J. P. Liu51, J. Y. Liu1, K. Liu39, K. Y. Liu27, L. D. Liu31, P. L. Liu1,a, Q. Liu41, S. B. Liu46,a, X. Liu26, Y. B. Liu30, Y. Y. Liu30, Z. A. Liu1,a, Zhiqing Liu22, H. Loehner25, Y. F. Long31, X. C. Lou1,a,g, H. J. Lu17, J. G. Lu1,a, Y. Lu1, Y. P. Lu1,a, C. L. Luo28, M. X. Luo52, T. Luo42, X. L. Luo1,a, X. R. Lyu41, F. C. Ma27, H. L. Ma1, L. L. Ma33, M. M. Ma1, Q. M. Ma1, T. Ma1, X. N. Ma30, X. Y. Ma1,a, Y. M. Ma33, F. E. Maas14, M. Maggiora49A,49C, Q. A. Malik48, Y. J. Mao31, Z. P. Mao1, S. Marcello49A,49C, J. G. Messchendorp25, G. Mezzadri21B, J. Min1,a, T. J. Min1, R. E. Mitchell19, X. H. Mo1,a, Y. J. Mo6, C. Morales Morales14, N. Yu. Muchnoi9,e, H. Muramatsu43, P. Musiol4, Y. Nefedov23, F. Nerling10, I. B. Nikolaev9,e, Z. Ning1,a, S. Nisar8, S. L. Niu1,a, X. Y. Niu1, S. L. Olsen32, Q. Ouyang1,a, S. Pacetti20B, Y. Pan46,a, P. Patteri20A, M. Pelizaeus4, H. P. Peng46,a, K. Peters10,i, J. Pettersson50, J. L. Ping28, R. G. Ping1, R. Poling43, V. Prasad1, H. R. Qi2, M. Qi29, S. Qian1,a, C. F. Qiao41, L. Q. Qin33, N. Qin51, X. S. Qin1, Z. H. Qin1,a, J. F. Qiu1, K. H. Rashid48, C. F. Redmer22, M. Ripka22, G. Rong1, Ch. Rosner14, X. D. Ruan12, A. Sarantsev23,f, M. Savri´e21B, C. Schnier4, K. Schoenning50, W. Shan31, M. Shao46,a, C. P. Shen2, P. X. Shen30, X. Y. Shen1, H. Y. Sheng1, W. M. Song1, X. Y. Song1, S. Sosio49A,49C, S. Spataro49A,49C, G. X. Sun1, J. F. Sun15, S. S. Sun1, X. H. Sun1, Y. J. Sun46,a, Y. Z. Sun1, Z. J. Sun1,a, Z. T. Sun19, C. J. Tang36, X. Tang1, I. Tapan40C, E. H. Thorndike44, M. Tiemens25, I. Uman40D, G. S. Varner42, B. Wang30, B. L. Wang41, D. Wang31, D. Y. Wang31, K. Wang1,a, L. L. Wang1, L. S. Wang1, M. Wang33, P. Wang1, P. L. Wang1, W. Wang1,a, W. P. Wang46,a, X. F. Wang39, Y. Wang37, Y. D. Wang14, Y. F. Wang1,a, Y. Q. Wang22, Z. Wang1,a, Z. G. Wang1,a, Z. H. Wang46,a, Z. Y. Wang1, Z.

Y. Wang1, T. Weber22, D. H. Wei11, P. Weidenkaff22, S. P. Wen1, U. Wiedner4, M. Wolke50, L. H. Wu1, L. J. Wu1, Z. Wu1,a, L. Xia46,a, L. G. Xia39, Y. Xia18, D. Xiao1, H. Xiao47, Z. J. Xiao28, Y. G. Xie1,a, Y. H. Xie6, Q. L. Xiu1,a, G. F. Xu1, J. J. Xu1, L. Xu1, Q. J. Xu13, Q. N. Xu41, X. P. Xu37, L. Yan49A,49C, W. B. Yan46,a, W. C. Yan46,a, Y. H. Yan18, H. J. Yang34,j, H. X. Yang1, L. Yang51, Y. X. Yang11, M. Ye1,a, M. H. Ye7, J. H. Yin1, Z. Y. You38, B. X. Yu1,a, C. X. Yu30, J. S. Yu26, C. Z. Yuan1, Y. Yuan1, A. Yuncu40B,b, A. A. Zafar48, Y. Zeng18, Z. Zeng46,a, B. X. Zhang1, B. Y. Zhang1,a, C. C. Zhang1, D. H. Zhang1, H. H. Zhang38, H. Y. Zhang1,a, J. Zhang1, J. J. Zhang1, J. L. Zhang1, J. Q. Zhang1, J. W. Zhang1,a, J. Y. Zhang1, J. Z. Zhang1, K. Zhang1, L. Zhang1, S. Q. Zhang30, X. Y. Zhang33, Y. Zhang1, Y. Zhang1, Y. H. Zhang1,a, Y. N. Zhang41, Y. T. Zhang46,a, Yu Zhang41, Z. H. Zhang6, Z. P. Zhang46, Z. Y. Zhang51, G. Zhao1, J. W. Zhao1,a, J. Y. Zhao1, J. Z. Zhao1,a, Lei Zhao46,a, Ling Zhao1, M. G. Zhao30, Q. Zhao1, Q. W. Zhao1, S. J. Zhao53, T. C. Zhao1, Y. B. Zhao1,a, Z. G. Zhao46,a, A. Zhemchugov23,c, B. Zheng14,47, J. P. Zheng1,a, W. J. Zheng33, Y. H. Zheng41, B. Zhong28, L. Zhou1,a, X. Zhou51, X. K. Zhou46,a, X. R. Zhou46,a, X. Y. Zhou1, K. Zhu1, K. J. Zhu1,a, S. Zhu1, S. H. Zhu45, X. L. Zhu39, Y. C. Zhu46,a, Y. S. Zhu1, Z. A. Zhu1, J. Zhuang1,a, L. Zotti49A,49C, B. S. Zou1, J. H. Zou1 (BESIII Collaboration)

7 China Center of Advanced Science and Technology, Beijing 100190, People’ s Republic of China

8 COMSATS Institute of Information Technology, Lahore, Defence Road, Off Raiwind Road, 54000 Lahore, Pakistan

10 GSI Helmholtzcentre for Heavy Ion Research GmbH, D-64291 Darmstadt, Germany

Typeset by REVTEX

19 Indiana University, Bloomington, Indiana 47405, USA

20 (A)INFN Laboratori Nazionali di Frascati, I-00044, Frascati, Italy; (B)INFN and University of Perugia, I-06100, Perugia, Italy 21 (A)INFN Sezione di Ferrara, I-44122, Ferrara, Italy; (B)University of Ferrara, I-44122, Ferrara, Italy

23 Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia

24 Justus-Liebig-Universitaet Giessen, II. Physikalisches Institut, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany

39 Tsinghua University, Beijing 100084, People' s Republic of China

40 (A)Ankara University, 06100 Tandogan, Ankara, Turkey; (B)Istanbul Bilgi University, 34060 Eyup, Istanbul, Turkey; (C)Uludag University, 16059 Bursa, Turkey; (D)Near East University, Nicosia, North Cyprus, Mersin 10, Turkey

48 University of the Punjab, Lahore-54590, Pakistan

49 (A)University of Turin, I-10125, Turin, Italy; (B)University of Eastern Piedmont, I-15121, Alessandria, Italy; (C)INFN, I-10125, Turin, Italy

53 Zhengzhou University, Zhengzhou 450001, People' s Republic of China

a Also at State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, People' s Republic of China b Also at Bogazici University, 34342 Istanbul, Turkey c Also at the Moscow Institute of Physics and Technology, Moscow 141700, Russia d Also at the Functional Electronics Laboratory, Tomsk State University, Tomsk, 634050, Russia e Also at the Novosibirsk State University, Novosibirsk, 630090, Russia f Also at the NRC "Kurchatov Institute" , PNPI, 188300, Gatchina, Russia g Also at University of Texas at Dallas, Richardson, Texas 75083, USA h Also at Istanbul Arel University, 34295 Istanbul, Turkey i Also at Goethe University Frankfurt, 60323 Frankfurt am Main, Germany j Also at Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education; Shanghai Key Laboratory for Particle Physics and Cosmology; Institute of Nuclear and Particle Physics, Shanghai 200240, People' s Republic of China

The decays of c2 → K+K− 0, KSK± and + − 0 are studied with the (3686) data samples collected with the Beijing Spectrometer (BESIII). For the first time, the branching fractions of c2 → a2(1320) 0 and c2 → (770)± are measured. Here K* denotes both K*K and its isospin-conjugated process K*0K0 + c.c., and K* refers to the resonances K*(892), K*2(1430) and K*3(1780). The observations indicate a strong violation of the helicity selection rule in c2 decays into vector and pseudoscalar meson pairs. The measured branching fractions of c2 → K*(892)K are more than 10 times larger than the upper limit of c2 → (770)± , which represents the first direct observation of a significant U-spin symmetry breaking effect in charmonium decays.

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The helicity selection rule (HSR) [1-3] is one of the most important consequences of perturbative quantum chromodynamics (pQCD) at leading twist accuracy. In the charmonium energy region, although there are observations that pQCD plays a dominant role, there are also many hints that non-perturbative mechanisms can become important [3-6]. Exclusive decays of the P-wave charmonium state c2 → VP, where V and P denote light vector and pseudoscalar mesons, respectively, are ideal for testing the HSR and pinning down the mechanisms that may violate the leading pQCD approximation.

One reason the decays of c2 → VP are of great interest is that this process is ideal for probing the long-range interactions arising from intermediate D-meson loop transitions. As pointed out in Ref. [7], if the intermediate D-meson loops provide the non-perturbative mechanism to violate the HSR, this can be identified by measurements of c2 → (770)± .

In this Letter, we present a partial wave analysis (PWA) of the process (3686) → c2, c2 → KK (denoting K+K− 0 and KSK±) and a measurement of c2 → + − 0. We have two (3686) samples of (106.8 ± 1.4) × 10ˆ6 events (160 pb−1) [8] and (341.1 ± 2.1) × 10ˆ6 events (510 pb−1) [9] collected in 2009 and 2012 by BESIII [10], respectively. Only the 2009 data sample is used in the analysis of c2 → KK , and the full data sample is used in c2 → + − 0 since it has a smaller branching fraction. An independent sample of about 44 pb−1 taken at √s = 3.65 GeV is utilized to investigate the potential background from the continuum process. A sample of Monte Carlo (MC) simulated events of generic (3686) decays (inclusive MC sample) is used to study backgrounds. The optimization of the event selection and the estimation of physics backgrounds are performed with Monte Carlo simulations of (3686) inclusive/exclusive decays.

The c2 candidates, produced in (3686) radiative decays, are reconstructed from the final states K+K− 0, KSK± , and + − 0. Each charged track is required to have a polar angle in the main drift chamber (MDC) that satisfies |cos | < 0.93, and have the point of closest approach to the e+e− interaction point within 10 cm in the beam direction (Vz) and 1 cm in the plane perpendicular to the beam direction (Vr). The energy loss dE/dx in the MDC and the information from the time-of-flight (TOF) system are combined to form particle identification (PID) confidence levels (C.L.) for the , K, and p hypotheses, and each track is assigned with the hypothesis corresponding to the highest C.L. The KS candidates are reconstructed from two oppositely charged tracks with loose vertex requirements (|Vz| < 30 cm and Vr < 10 cm) and without PID (assumed to be pions). Then the candidate with invariant mass closest to the KS nominal mass and the decay length provided by a secondary vertex fit algorithm greater than 0.25 cm is selected for further study in the decay (3686) → KSK± . The candidate events are required to have two charged tracks with zero net charge, where the tracks from the KS candidate are not taken into account. Two pions and one kaon are required for the decay (3686) → KSK± , and three pions are required for the decay (3686) → + − 0, respectively, and no PID requirement is applied for the decay (3686) → K+K− 0. The photon candidates are required to have energy larger than 25 (50) MeV in the Electromagnetic Calorimeter (EMC) barrel (end cap) region (|cos | < 0.93), and have an angle relative to the nearest charged tracks larger than 10°. To suppress electronic noise and energy deposits unrelated to the event, the EMC cluster time must be within 700 ns from the event start time. At least three and one photons are required for the decays

(3686) → + − 0/K+K− 0 and (3686) → KSK± , respectively.

A fit with four kinematic constraints (4C) enforcing four-momentum conservation between the initial (3686) and the final state is performed for each process. If there are more photons than required in one event, all possible combinations of photons are considered and only the one with the least ^2_4C of the kinematic fit is retained for further analysis. The ^2_4C is required to be less than 80 and 60 for the decays (3686) → K+K− 0 and (3686) → KSK± , respectively. The 0 candidate is reconstructed from the two selected photons whose invariant mass is closest to the 0 nominal mass, and satisfies |M - M 0| < 10 MeV/c^2. For the decay mode (3686) → + − 0, a 5C kinematic fit is performed with an additional 0 mass constraint, and ^2_5C < 60 is required. To remove the backgrounds from (3686) → 0 0J/ (J/ → l+l−, l = e,), the invariant mass of → + − 0 (→ 0, J/ →), and (3686) → K+K−/ + − is required to be less than 3.0 GeV/c^2 for the decay (3686) → K+K− 0/ + − 0. For the decay mode (3686) → + − 0, the 0 recoil mass is required to be less than 3.0 GeV/c^2 to suppress the background (3686) → 0. The region (0.7, 0.85) GeV/c^2 is required to veto the background (3686) → 0.

The KK invariant mass for the decays (3686) → K+K− 0 and (3686) → KSK± are shown in Fig. 1 Figure 1: see original paper and (b), respectively. The c1,2 signals appear prominently with a small background. From the analysis of the (3686) inclusive MC sample and the continuum data at √s = 3.65 GeV, the main backgrounds are from the decays (3686) → 0 0J/ and K1(1270)±K → K± 0 0/ (770)±KS. All of these backgrounds show a smooth distribution and do not produce a peak around the cJ mass region. Unbinned maximum likelihood fits are performed to the selected candidates, where the c1,2 signals are described with the MC simulated shapes convoluted with a Gaussian function accounting for the resolution difference between data and MC simulation, and the backgrounds are described with a 2nd order polynomial function. There are 1215 and 1176 candidate events for c2 → K+K− 0 and c2 → KSK± within the c2 signal region |MKK - M c2| 15 MeV/c^2. Non- 0 (K+K− 0 mode only) and non- c2 backgrounds are estimated with the events in the sideband regions, which are also used in the PWA as described in the following. The numbers of background events are estimated to be 240 and 80 for c2 → K+K− 0 and c2 → KSK± , respectively.

In the PWA, the process c2 → KK is assumed to proceed via the quasi two-body decays, i.e. c2 → K*K and c2 → a2K followed by K* → K and a2 → K . The amplitudes of the two-body decays are constructed with the helicity-covariant method [11]. For a particle decaying into two-body final states, i.e. A(J, m) → B(s,)C(,), where spin and helicity are indicated in the parentheses, its helicity covariant amplitude F , [11] is:

F , = √(2J+1) gLS rLBL(r), where A → BC, gLS is the coupling constant for the partial wave with orbital angular momentum L and spin S (with z-projection), r is the relative momentum between the two daughter particles in the initial particle rest frame, and BL is the barrier factor [12]. The conservation of parity is applied in the equation. Recent measurements show that the contributions of higher order magnetic and electric multipoles in the (3686) radiative transition to c2 are negligible, and the E1 transition is the dominant process [13]. Hence, the helicity amplitudes are constructed to satisfy the E1 transition relation [14] and parity conservation, namely, F1,2 = √2F1,1 = √6F1,0 and F0,0 = 0. The corresponding gLS are taken as complex values. The relative magnitudes and phases are determined by an unbinned maximum likelihood fit to data with the package MINUIT [15]. The background contribution to the likelihood value is estimated with the events in the sideband regions and is subtracted [16]. For the PWA method check, input data is generated with inclusion of all states in the baseline solution, and coupling constants are fixed to the PWA solution. After the detector simulation and selection criteria, the same PWA fit procedure is performed, and the fit results are consistent with that of the input data within the statistical errors.

As shown in the Dalitz plots of Fig. 1(c) and (d), clear signals for K*(892) and K*2(1430) are observed in the K system. The resonances K*(892) and K*2(1430) in the K system as well as the a2(1320) in the KK system, which has a significance larger than 8 in both decay modes, are included in the baseline solution. For consistency, the K*3(1780) signal, which is of a significance larger than 5 in the decay c2 → KSK± but only 2 in c2 → K+K− 0, is also included. A contribution from the direct c2 → KK three-body decay, which is parameterized with a non-resonant component with spin-parity J^p = 2+ in the KK system, is also considered. Other possible excited K* states in the K system and the states in the KK system listed in PDG [17], which have a significance less than 5 , are not included, but they are considered as a source of systematic uncertainty. The coupling constants for the charge-conjugate modes are treated to be the same.

Figures 2 and 3(a)-(c) show the invariant mass distribution and the projection of the PWA for the decays c2 → K+K− 0 and c2 → KSK± , respectively. The signal yields for the individual processes with a given intermediate state and the corresponding statistical uncertainties are calculated according to the fit results. The resultant branching fractions for the decays c2 → K*K and c2 → a2(1320) are summarized in Table I. The branching fractions for the processes including charged K* intermediate states are consistent between the two decay modes, and are combined by considering the correlation of uncertainties between the two modes [18]. The K* isospin-conjugate modes are consistent with each other within 2 , as expected by isospin symmetry.

The large branching fraction of c2 → K*K is a direct indication of the significant HSR violation effects. Note that the helicity amplitude ratios, estimated with the fitted gLS (see Table II), suggest the dominance of F1,0 in the transition amplitudes. The amplitude F1,0 contributes to the leading HSR violation effects and scales as (ΛQCD/mc)^6 due to its asymptotic behavior [2, 7]. In comparison with the HSR conserving channel c2 → VV, which scales as (ΛQCD/mc)^4, the ratio of c2 → K*K to VV is expected to be suppressed by a factor of (ΛQCD/mc)^2 with ΛQCD 0.2 GeV/c^2 and the charm quark mass mc 1.5

GeV/c^2. However, the measured branching fraction of c2 → K*K appears to be the same order of magnitude as that for VV [19], which indicates a significant violation of HSR in c2 → VP.

TABLE II. The measured ratios of helicity amplitude squared $|F2,0|^{2/|F1,0|}2$, where the uncertainties are statistical only.

Decay Mode	Charged K*	Neutral K*
K+K− 0	0.046 ± 0.001	-
KSK±	0.042 ± 0.019	0.031 ± 0.018

In the analysis of the decay (3686) → c2, c2 → + − 0, the c2 signal is extracted by the requirement |MKK - M c2| 15 MeV/c^2. The potential background from direct e+e− annihilation is found to be negligible by studying the continuum data taken at √s = 3.65 GeV. The backgrounds from (3686) decay are investigated with the (3686) inclusive MC sample; the only surviving c2 events are those that directly decay to + − 0 without any intermediate state. There are also non- c2 backgrounds, which can be estimated by the events in the c2 sideband regions. Figure 3(d) shows the invariant mass of ± 0 for the selected candidates, together with the binned likelihood fit results. Here the fit components include the (770)± signal, the direct decay c2 → + − 0, and the non- c2 background. The (770)± signal and the direct c2 three-body decay are modeled with the MC simulated shapes convoluted with a Gaussian function with free parameters. The resonant parameters of the (770)± are set to the values in the PDG [17].

The fitted signal yields are 14.7 ± 3.9 and 8.9 ± 3.1, and the corresponding resultant branching fractions are (0.64 ± 0.18 ± 0.07) × 10^−5 and (2.1 ± 0.7 ± 0.2) × 10^−5 for c2 → (770)±   and c2 → + − 0, respectively, where the first uncertainties are statistical and the second are systematic. Since the statistical significance for the c2 → (770)±   is only 2.8 , the upper limit at the 90% C.L. for the branching fraction is set to 1.1 × 10^−5 by the Feldman-Cousins approach with systematic uncertainties considered [20].

The uncertainties from the branching fractions of (3686) → c2, + −, 0 → , KS → + −, a2(1320) → KK, and K* → K are quoted from the PDG [17]. The uncertainty on the number of (3686) events is about 0.8% [8, 9]. The uncertainties associated with the tracking and PID are 1% for every charged track [21]. The uncertainty related with EMC shower reconstruction efficiency is 1% per shower [21]. The uncertainties associated with the kinematic fit are estimated to be 0.5% and 0.6% for the 4C and 5C fit, respectively, by using a method to correct the charged-track helix parameters [22]. The uncertainty associated with the KS reconstruction is estimated to be 2.5% [22]. The uncertainties related with the 0 selection, the requirements on the 0 recoil mass and the   background veto (in (770)±   mode only) are negligible.

In the decay c2 → (770)± , the uncertainties due to the bin size and the fit range in the fit are estimated by repeating the fit with alternative bin sizes and fit ranges. The uncertainty due to the shape of c2 → + − 0 is estimated by replacing the MC simulated line shape with a 3rd polynomial function. The uncertainty due to the shape of the background is estimated by changing the c2 sideband regions.

In the decay c2 → KK , the uncertainties due to the contribution from K*(1410) and K*(1680) are estimated by including these states in the fit. The uncertainties associated with the backgrounds are determined by changing the c2 and 0 sideband regions. The spin density matrix corresponding to the E1 transition [14] is used in the nominal fit. To estimate the uncertainty, contributions from the quadrupole (M2) and other high order multipoles to the matrix [13] are included in the fit, and the changes in the final results are treated as a systematic uncertainty. The uncertainties associated with the resonance parameters of intermediate states are estimated by varying their values by 1 of their uncertainties quoted in the PDG [17]. The uncertainty due to the barrier radius [12] when calculating BL(r) in Eq. (1) is estimated by alternative fits with r = 0.25 or 0.75 fm, respectively, where r = 0.6 fm is the nominal value. The uncertainty associated with the direct three-body decay c2 → KK is estimated by alternative fits with other spin-parity hypotheses, e.g. a 0− or 3− non-resonant component in the KK or K systems. The largest changes in the signal yields are taken as systematic uncertainties. Assuming all the systematic errors are independent, the overall systematic uncertainty is obtained by taking the quadrature sum of the individual values.

In summary, the HSR-suppressed processes c2 → K*(892)K and c2 → (770)± are studied with the (3686) data collected by BESIII for the first time. The branching fractions of c2 → K*(892)±K and c2 → K*(892)0K0 + c.c. are measured to be (1.5 ± 0.1 ± 0.2) × 10^−4 and (1.3 ± 0.2 ± 0.2) × 10^−4, respectively, which are rather sizeable with respect to those of the HSR-conserving decay c2 → VV [17, 19]. These branching fractions are at least one order of magnitude larger than the upper limit of the branching fraction of c2 → (770)± (1.1 × 10^−5). It is worth noting that this phenomenon is anticipated by the HSR violation mechanism proposed in Ref. [7]. Namely, the HSR violation in c2 → K*(892)K occurs via the intermediate meson loops due to the large U-spin symmetry breaking, while that in c2 → (770)± is due to isospin symmetry breaking. Due to the large mass difference between s and u/d quarks, the U-spin symmetry is broken more severely in comparison with isospin symmetry. This results in the larger decay branching for c2 → K*(892)K than that for c2 → (770)± . The results are crucial for further quantifying the HSR violation mechanisms [7] and also provide deeper insights into the underlying strong interaction dynamics in the charmonium energy region.

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