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Amplitude analysis of the Xc1→ +− decays postprint

Authors: M. Ablikim[et al.]

Using 2.9 fb^{-1} of e^+e^- collision data collected by the BESIII detector at $\sqrt{s} =$ 3.773 GeV, we measure the ratio of decay widths between $\bar{D}^0$ and D^0 via the $\bar{D}^0 \to K^+\pi^-\pi^0$ and $D^0 \to K^-\pi^+\pi^0$ decay processes. This measurement employs the double-tag method. The measured ratio is

$$\frac{\Gamma(\bar{D}^0 \to K^+\pi^-\pi^0)}{\Gamma(D^0 \to K^-\pi^+\pi^0)} = 0.097 \pm 0.004 \pm 0.003, \quad (1)$$

where the first error is statistical and the second is systematic. This result is consistent with the CP violation effect observed in the similar decays $\bar{D}^0 \to K^+\pi^-$ and $D^0 \to K^-\pi^+$. This represents the first significant evidence for CP violation observed in $\bar{D}^0/D^0 \to K^\pm\pi^\mp\pi^0$ decays.

Date: 2017-11-10T00:00:00+00:00

Abstract

Using 448.0 × 106 (3686) events collected with the BESIII detector, an amplitude analysis is performed for (3686) → c1, c1→ + − decays. The most dominant two-body structure observed is a0(980)± ; a0(980)±→ ±. The a0(980) line shape is modeled using a dispersion relation, and a significant nonzero a0(980) coupling to the channel is measured. We observe c1→a2(1700) production for the first time, with a significance larger than 17 . The production of mesons with exotic quantum numbers, JPC = 1−+, is investigated, and upper limits for the branching fractions c1 → 1(1400)± , c1→ 1(1600)± , and c1→ 1(2015)± , with subsequent 1(X)±→ ± decay, are determined.

Full Text

Preamble

Amplitude analysis of the c1 → + − decays 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, H. P. Cheng17, X. K. Chu31, G. Cibinetto21A, H. L. Dai1,a, J. P. Dai34, 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, J. F. Hu49A,49C , T. Hu1,a, Y. Hu1, G. S. Huang46,a, J. S. Huang15, X. T. Huang33, X. Z. Huang29, Y. 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. Li33, K. Li13, Lei Li3, P. R. Li41, 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, 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,

S. Schumann22, W. Shan31, M. Shao46,a, C. P. Shen2, P. X. Shen30, X. Y. Shen1, H. Y. Sheng1, M. Shi1, 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, 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, W. L. Yuan29, Y. Yuan1, A. Yuncu40B,b, A. A. Zafar48, A. Zallo20A, Y. Zeng18, Z. Zeng46,a, B. X. Zhang1, B. Y. Zhang1,a, C. Zhang29, 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. Zheng47, 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

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 Institute of Nuclear and Particle Physics, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai 200240, People's Republic of China (Dated: March 13, 2017) Using 448.0 × 106 (3686) events collected with the BESIII detector, an amplitude analysis is performed for (3686) → c1, c1 → + − decays. The most dominant two-body structure observed is a0(980)± ; a0(980)± → ±. The a0(980) line shape is modeled using a dispersion relation, and a significant nonzero a0(980) coupling to the   channel is measured. We observe c1 → a2(1700) production for the first time, with a significance larger than 17 . The production of mesons with exotic quantum numbers, J P C = 1−+, is investigated, and upper limits for the branching fractions c1 → 1(1400)± , c1 → 1(1600)± , and c1 → 1(2015)± , with subsequent 1(X)± → ± decay, are determined.

PACS numbers: 13.25.Gv, 14.40.Be, 14.40.Pq, 14.40.Rt

INTRODUCTION

The c1 (1++) charmonium state provides a rich laboratory for light meson spectroscopy. Large samples of charmonium states with J^PC = 1^−−, such as the J/ and (3686), are easily produced at e+e− colliders, and their radiative transitions provide sizable charmonium samples with other J^PC quantum numbers. The c1 →   + − decay is particularly suitable for studying the production of exotic mesons with J^PC = 1^−+, which could be observed decaying into the   final state. The lowest orbital excitation of a two-body combination in c1 decays to three pseudoscalars, for instance c1 →   , is the S-wave transition, in which any produced resonance must have J^PC = 1^−+.

Several candidates with J^PC = 1^−+, decaying into different final states such as   ,   , f1(1270) , b1(1235) , and   , have been reported by various experiments and thoroughly reviewed in Ref. [1]. The lightest exotic meson candidate is the 1(1400) [2], reported only in the   final state by GAMS [3], KEK [4], Crystal Barrel [5], and E852 [6], but its resonance nature remains controversial [7]. The most promising J^PC = 1^−+ candidate, the 1(1600) [2], could also couple to   , since it has been observed in the   channel by VES [8] and E852 [9].

The CLEO-c collaboration reported evidence of an exotic signal in c1 →   + − decays, consistent with 1(1600) →   production [10]. However, other possible exotic signals that might be expected have not been observed in either c1 →   + − or c1 →   + − decays. With a data sample more than 15 times larger than previous experiments, BESIII provides an excellent opportunity to search for the production of 1 exotic mesons.

In this work, we investigate possible production of exotic mesons in the mass region (1.3-2.0) GeV/c^2, decaying into the   + + c.c. final state, namely the 1(1400), 1(1600), and 1(2015), using c1 →   + − decays. Charge conjugation and isospin symmetry are assumed throughout this analysis.

Additional motivation for studying these decays comes from the observation of a very prominent a0(980)   signal of high purity in c1 →   + − decays by CLEO-c [10]. The a0(980) was discovered several decades ago, but its nature was puzzling from the beginning, leading to the hypothesis that it is a four-quark rather than an ordinary q¯q state [11-13]. The first coupled meson-meson (, K¯K,   ) scattering amplitudes based on lattice QCD calculations [14] indicate that the a0(980) might be a resonance strongly coupled to   and K¯K channels, which does not manifest itself as a symmetric bump in the spectra. Recent theoretical work based on the chiral unitarity approach also suggests that the a0(980), as well as the   and f0(980) states, could be dynamically generated through meson-meson interactions, for example in heavy-meson decays such as c1 →   [15] and c →   [16]. However, there is still no consensus on the exact role that meson-meson loops play in forming the a0(980), which is now generally accepted as a four-quark object (see [17] and references therein).

The a0(980) indeed decays dominantly into   and K¯K final states; the latter has a profound influence on the a0(980) line shape in the channel due to the proximity of the K¯K threshold to the a0(980) mass. Different experiments –E852 [18], Crystal Barrel [19, 20], and CLEO-c [10]—have analyzed data to determine the couplings of the a0(980) to the (g_) and K¯K (g_K¯K) final states in order to help resolve the true nature of the a0(980). This is not an exhaustive list of analyses, but it points out that the values obtained for the a0(980) parameters vary considerably among various analyses.

Another channel of interest is a0(980) → , with its threshold more than 100 MeV/c^2 above the a0(980) mass. The first direct observation of the decay a0(980) → was reported by CLEO-c [10], using a sample of 10^6 (3686) decays. The a0(980) coupling to the channel, g_ , was determined from c1 → + − decays, although the analysis was not very sensitive to the component in the a0(980) invariant mass distribution, and g_ was found to be consistent with zero. In many analyses of a0(980) couplings, g_ has not been measured. For example, its value was fixed in Ref. [20] based on SU(3) flavor-mixing predictions. Using a clean sample of c1 produced in the radiative transition (3686) → c1 at BESIII, we investigate the c1 → + − decays to test if the a0(980) invariant mass distribution is sensitive to production.

Dispersion integrals are used in the description of the a0(980) line shape to determine the a0(980) parameters: its invariant mass m_a0(980) and three coupling constants g_ , g_K¯K, and g_ . This information might help in determining the quark structure of the a0(980).

In this c1 decay mode, it is also possible to study a2(1700) production. The c1 → a2(1700) has been reported in this decay mode by Crystal Barrel [21] and Belle [22], but it is still not accepted as an established resonance by the Particle Data Group (PDG) [2].

II. EVENT SELECTION

For our studies we use 448.0 × 10^6 (3686) events, collected in 2009 [23] and 2012 [24] with the BESIII detector [25]. We select events with the + − final state topology, exclusive of decays in 0 0 0 decay modes. For each (3686) → c1; c1 → + − decay, exclusive Monte Carlo (MC) samples are generated according to the relative branching fractions given in Table I, equivalent to a total of 2 × 10^6 events. The background is studied using an inclusive MC sample of 10^6 generic (3686) events.

BESIII is a conventional solenoidal magnet detector with almost full geometrical acceptance, consisting of four main components: the main drift chamber (MDC), electromagnetic calorimeter (EMC), time-of-flight detector, all enclosed in a 1 T magnetic field, and the muon chamber. The momentum resolution for the majority of charged particles is better than 0.5%. The energy resolution for 1.0 GeV photons in the barrel (end-cap) region of the EMC is 2.5% (5%). For the majority of photons in the barrel region with energies between 100 and 200

MeV, the energy resolution is better than 4%. Details of the BESIII detector and its performance can be found in Ref. [25].

Good photon candidates are selected from isolated EMC showers with energy larger than 25 (50) MeV in the barrel (end-cap) region, corresponding to a polar angle satisfying |cos | < 0.80 (0.86 < |cos | < 0.92). The timing of good EMC showers is required to be within 700 ns of the trigger time. Charged tracks must satisfy |cos | < 0.93, and the point of closest approach of a track from the interaction point must be within 20 cm along the beam direction and within 2 cm perpendicular to the beam direction. All charged tracks are assumed to be pions, and the inclusive MC sample is used to verify that kaon contamination in the final sample is negligible in each of the channels.

We require two charged tracks for the → and → + − 0 channels, and four tracks for the → 0 0 0 channel, with at least zero net charge. For → , three photon candidates are required, and for → 0 0 0, at least seven photon candidates are required. The invariant mass of two-photon combinations is kinematically constrained to the 0 or mass. The sum of momenta of all final-state particles for a given final state topology is constrained to the initial (3686) momentum. If multiple combinations for an event are found, the one with the smallest ˆ2_NC is retained, where NC refers to the number of constraints, which is four plus the number of two-photon 0 and candidates in the final state (see Table I).

A. c1 → + − event selection

The c1 → + − candidates are selected by requiring that the invariant mass of three pions satisfy 0.535 < m(3) < 0.560 GeV/cˆ2 for the → three-pion decays. For the → candidates, we require that the ˆ2 from the kinematic constraint fit satisfies ˆ2_5C < 40. The ˆ2_NC values obtained from four-momenta kinematic constraint fits are required to satisfy ˆ2_5C < 40 and ˆ2_7C < 56 for → + − 0 and → 0 0 0, respectively. These selection criteria effectively remove kaon and other charged track contamination, justifying the assumption that all charged tracks are pions. To select c1 candidates from the (3686) → c1 transition, we require the energy of the radiative photon to satisfy 0.155 < E < 0.185 GeV.

1. Background suppression The major background for all final states comes from (3686) → J/ , while in the → case the background from (3686) → J/ decays is also significant. The background from (3686) → J/ is negligible once a good candidate is found.

To suppress the (3686) → J/ background for all three decays, we require that the invariant mass of the system recoiling against the , with respect to the (3686), be separated by at least 20 MeV/cˆ2 from the J/ mass. Additional selection criteria are used in the → channel to suppress 0 contamination and (3686) → J/ production. The former background is suppressed by rejecting events in which any two-photon combination satisfies 0.110 < m( ) < 0.155 GeV/c^2. The latter background is suppressed by vetoing events for which a two-photon combination not forming an has a total energy between 0.52 GeV < E < 0.60 GeV. This energy range is associated with the doubly radiative decay (3686) → J/ , for which the energy sum of two transitional photons is E .

2. Background subtraction The background estimated from the inclusive MC after all selection criteria are applied is below 3% in each channel. The background from sidebands is subtracted, and Fig. 1 [Figure 1: see original paper] shows the invariant mass distributions of candidates with vertical dotted bars indicating the sideband regions. The sideband regions for the two-photon and three-pion modes are defined as 0.62 < m( ) < 0.68 GeV/c^2 and 0.37 < m(3) < 0.535 GeV/c^2 or 0.560 < m(3) < 0.613 GeV/c^2, respectively, where m is the nominal mass [2]. In the case of → three-pion decays, the signal region defined by Eq. (1) is indicated by dash-dotted bars in Fig. 1.

Although the mass distribution of three neutral pions (Fig. 1(c)) is wider than the corresponding distribution from the charged channel (Fig. 1(b)), we use the same selection criteria for both decays, which keeps the majority of good → 3 0 candidates and results in similar background levels in the two channels. The effects of including more data from the tails of these distributions are taken into account in the systematic uncertainties.

The invariant mass plot for → candidates (Fig. 1(a)) is used only to select sidebands for background subtraction. Table I lists channel efficiencies and the effective efficiency for all channels.

The + − invariant mass distribution, when events from all channels are combined, is shown in Fig. 2 [Figure 2: see original paper]. In the signal region indicated by vertical bars, there are 33,919 events, with a background of 497 events estimated from the sidebands. The sideband background does not account for all the background; after subtracting the -sideband background, the remaining background is estimated by fitting the invariant mass distribution. The fit is shown by the solid distribution in Fig. 2. For the c1 signal, a double-sided Crystal-Ball distribution (dotted) is used, and for the background, a linear function along with a Gaussian corresponding to the c2 contribution (dashed) are used. The signal purity estimated from the fit is (98.5 ± 0.3)%, where the error is obtained from fluctuations in the background when using different fitting ranges and background shapes.

B. Two-body structures in the c1 → + − decays

The Dalitz plot for selected signal events is shown in Fig. 3 Figure 3: see original paper. Two-body structures reported in previous analyses of c1 → + − decays by BESII [26] and CLEO [10, 27]—the a0(980) , a2(1320) , and f2(1270) —are indicated by long-dash-dotted, dashed, and dash-dotted arrows pointing into the Dalitz space, respectively.

One feature of this distribution is the excess of events in the upper left corner of the Dalitz plot (a), pointed to by the dotted arrows, which cannot be associated with known structures observed in previous analyses of this c1 decay. We hypothesize this is due to a2(1700) production. The expected Dalitz plot of an a2(1700) signal is shown in Fig. 3(b), obtained assuming that the a2(1700) is the only structure produced. The a2(1700)+ − and a2(1700)− + components cannot be easily identified along the dotted arrows in the Dalitz plot (Fig. 3(a)), but their crossing in the plot shown in Fig. 3(b) visually matches the excess of events in the upper left corner of the Dalitz plot in Fig. 3(a).

The distributions of the square of the invariant mass are shown in Fig. 3(c) for and Fig. 3(d) for + −. Structures corresponding to a0(980), a2(1320), and f2(1270) production are evident, as well as a low-mass peak sometimes referred to as the state. In each of these two distributions there is a visible threshold effect. In the distribution, there is a structure above the K¯K threshold, which is too broad to result from the f0(980) alone. In the distribution, the broadening of the a0(980) peak around 1.2 $\mathrm{GeV}^{2/c}4$ could be associated with the threshold.

By examining various regions in the Dalitz space, we conclude that cross-channel contamination or reflections are not associated with these threshold effects in the data. To eliminate background as the source of these peculiar line shapes, background studies are performed. Namely, we increase the background level by relaxing the kinematic constraint to ^2_NC/NC < 10 and also suppress more background by requiring ^2_NC/NC < 5. In addition, we vary the limits on tagging and c1 candidates as explained in Sec. V [28].

It is possible that the line shape results from destructive interference between the f0(980) and other components of the S-wave. It has been known for some time that the a0(980) line shape is affected by the proximity of the K¯K threshold to the a0(980) mass. If the a0(980) coupling appears to be important for describing the a0(980) distribution, this would be an example where a virtual channel influences the distribution of another decay channel despite its threshold being far from the resonance peak. We use an amplitude analysis (AA), described in the next section, to help answer these questions and to determine the nature and significance of the "crossing structure" discussed.

III. AMPLITUDE ANALYSIS

To study the substructures observed in the c1 → + − decays, we use the isobar model, in which it is assumed that the decay proceeds through a sequence of two-body decays, c1 → RJhb, where either an isospin-zero (R →) or isospin-one (R →) resonance is produced with total spin J and relative orbital angular momentum L with respect to the bachelor meson hb. For resonances with J > 0, there are two possible values of L that satisfy quantum number conservation for the 1^++ → RJhb transition.

We use the extended maximum likelihood technique to find a set of amplitudes and their production coefficients that best describe the data. The method and complete description of amplitudes constructed using the helicity formalism are given in Ref. [10], with two exceptions. The first difference is that events from the -sidebands are subtracted in the likelihood function with equal weight given to the left-hand and right-hand sides, using a weighting factor = 0.5. The second difference with respect to Ref. [10] is that we deviate from the strict isobar model by allowing production amplitudes to be complex. Isospin symmetry for ± resonances is imposed.

In the minimization process, the total amplitude intensity I(x), constructed from the coherent sum of relevant amplitudes, is bound to the number of observed c1 candidates by using the integral (x)I(x)dx, where x represents the kinematic phase space and (x) is the acceptance function with value one (zero) for accepted (rejected) exclusive MC events. The proper normalization of different channels is ensured by using exclusive MC samples generated with sizes proportional to the branching fractions listed in Table I. If the complete generated exclusive MC set is used in the MC integration, then Eq. (2) provides the acceptance-corrected number of c1 events, adjusted by subtracted background contributions. In this case, (x) = 1 for all MC events.

Fractional contributions from specific amplitudes A are obtained by restricting the coherent sum in I(x) to I (x), so that = (x)I (x)dx / (x)I(x)dx. The numerator represents the acceptance-corrected yield of a given substructure, used to calculate relevant branching fractions. Errors are obtained from the covariance matrix using proper error propagation, so for a given substructure, the errors on are not necessarily the same.

The decay chain (3686) → c1; c1 → + − is described by amplitudes constructed to account for the spin alignment of the initial state and the helicity of the radiated photon. Linear combinations of helicity amplitudes can be used to construct amplitudes in the multipole basis, matching the electric dipole (E1) and magnetic quadrupole (M2) transitions. The (3686) → c1 decay is dominated by the E1 transition [29], and a small M2 contribution (~3%) can be treated as a systematic uncertainty.

A. Mass dependent terms, T (s)

The dependence of amplitude A on energy can be separated from its angular dependence, employing a general form p^L q^J T (s), if the width of the c1 is neglected. Here, p and q are decay momenta for decays h1h2 in the rest frame of the c1 and a resonance RJ, respectively, while s = m^2_12 is the squared invariant mass of the corresponding isobar products (or). For most resonances, we use relativistic Breit-Wigner (BW) distributions with spin-dependent Blatt-Weisskopf factors [30]. For the a0(980) and S-wave line shapes, we use different prescriptions explained below.

To account for the nonresonant process c1 → + −, we use an amplitude constructed as the sum of all possible final state combinations of helicity amplitudes constrained to have the same production strength, with no dependence on the invariant mass of the respective two-body combinations.

1. Parametrization of a0(980) Instead of using the usual Flatté formula [28] to describe the a0(980) line shape, we use dispersion integrals following the prescription given in Ref. [20]. We consider three a0(980) decay channels— , K¯K, and —with corresponding coupling constants g_ch, and use an appropriate dispersion relation to avoid the problem of a false singularity [31] present in the mode (see discussion at the end of this section). The a0(980) amplitude is constructed using the denominator:

D (s) = m^2_0 - s - Σ_ch Π_ch(s),

where m_0 is the a0(980) mass and Π_ch(s) in the sum over channels is a complex function with imaginary part ImΠ_ch(s) = g^2_ch _ch(s)F_ch(s), while real parts are given by principal value integrals:

ReΠ_ch(s) = (1/) P ^∞_sch ImΠ_ch(s) ds /(s - s).

In the above expressions, _ch(s) is the available phase space for a given channel, obtained from the corresponding decay momentum q_ch(s): _ch(s) = 2q_ch(s)/√s. The integral in Eq. (6) is divergent when s → ∞, so the phase space is modified by a form factor F_ch(s) = e^(- q2_ch(s)), where the parameter is related to the root-mean-square (rms) size of an emitting source [20]. We use = 2.0 [GeV/c^2]^-2 corresponding to rms = 0.68 fm, and verify that our results are not sensitive to the value of . The integration in Eq. (6) starts from the threshold for a particular channel, s_ch, which conveniently solves the problem of analytical continuation in special cases like , when the decay momentum becomes real again for s < (m_ + m_)^2. Figure 4 [Figure 4: see original paper] shows the shapes of (a) ImΠ_ch(s) and (b) ReΠ_ch(s) for the K¯K and channels for arbitrary values of the coupling constants.

In the final form, the real parts in the denominator of Eq. (4) are adjusted by ReΠ_ch(m^2_0) terms: ReΠ_ch(s) → ReΠ_ch(s) - ReΠ_ch(m^2_0).

2. S-wave model The S-wave parametrization follows the prescription given in Ref. [10], in which two independent processes for producing a pair are considered: direct ( )_S production, and production through kaon loops, ( )_S → (K¯K)_S → ( )_S. Amplitudes corresponding to these scattering processes, labeled S_ (s) and S_K¯K(s), are based on di-pion phases and intensities obtained from scattering data [32], which cover the invariant mass region up to 2 GeV/c^2. The S_ (s) component is adapted in Ref. [10] to account for differences in production through scattering and decay processes, using the denominator D(s) extracted from scattering experiments. The S_ (s) amplitude in this analysis takes the form:

S_ (s) = c_0 S_0(s) + c_1 S^1_ (s) + c_2 S^2_ (s) + c _1 S ^1_ (s) + c _2 S ^2_ (s).

The common term in the above expression, S_0(s) = 1/D(s), is expanded using conformal transformations of the type:

z_s_th(s) = (√s + √s_0 - √(s_th + s_0))/(√s + √s_0 + √(s_th + s_0)),

which is a complex function for s > s_th. Equation (7) features two threshold functions z_s_th(s): one corresponds to K¯K production with s_K¯K = 4m^2_K, while another with s_th = s could be used to examine other possible threshold effects in di-pion production. The c_i (i = 1, 2) are production coefficients to be determined.

Figure 5 [Figure 5: see original paper] shows the (a) phase and (b) intensity of various components used in constructing the   S-wave amplitude based on the two functions given by Eq. (8), with different thresholds: z_K¯K(s) and z_s (s). The following convention is used: S^i_ (s) = z^i_K¯K(s) S_0(s) and S ^i_ (s) = z^i_s (s) S_0(s). Components are arbitrarily scaled, and we set s = (1500 MeV/c$^{2)}$2, similar to the value used later in the analysis. The parameter s_0 = 1.5 (GeV/c$^{2)}$2 can be used to adjust the left-hand cut in the complex plane, and the same value is used in all components.

IV. RESULTS

We present results from the amplitude analysis of the full decay (3686) → c1; c1 → + −, reconstructed in three major decay modes. The optimal solution to describe the data is found by using amplitudes with fractional contributions larger than 0.5% and significance larger than 5 . The significance for each amplitude is determined from the change in likelihood with respect to the null hypothesis, ΔΛ = Λ_null - Λ_ . The null hypothesis for a given amplitude is found by excluding it from the baseline fit, and the corresponding amplitude significance is calculated taking into account the change in the number of degrees of freedom, which is two (four) for J = 0 (J > 0) amplitudes.

The most dominant amplitude in this reaction is a0(980) , as evident from the projection of the Dalitz plot (Fig. 3(c)). Other amplitudes used in our baseline fit include S_K¯K , S_ , f2(1270) , f4(2050) , a2(1320) , and a2(1700) , where masses and widths of resonances described by BW functions are taken from the PDG [2], while the a2(1700) and a0(980) parameters are free parameters to be determined by the fit in this work. The mass projections are shown in Fig. 6 [Figure 6: see original paper], and the corresponding fractional contributions and significances are listed in Table II. For amplitudes with spin J > 0, both orbital momentum components are included.

The following components form the S_ (s) amplitude:

S_ (s) = c_0 S_0(s) + c_1 S^1_ (s) + c_2 S^2_ (s) + c _1 S ^1_ (s) + c _2 S ^2_ (s).

As indicated earlier, the threshold used to construct the S^1(s) term is s_K¯K = 4m^2_K. The threshold for the S ^i(s) components (i = 1, 2) is s = 2.23 [GeV/c^2]^2, which is close to the mass of the f0(1500) and is responsible for the peaking of the S_   amplitude in this region (Fig. 6(b)). In fact, the S ^i(s) components are used instead of the f0(1500) amplitude, which would be needed in the optimal solution if only threshold functions z^i_K¯K(s) were used in the expansion of the S_ (s) amplitude. With these additional terms, the contribution and significance of scalars—the f0(1370), f0(1500), and f0(1710) —is negligible for each. Although this particular set of amplitudes respects the unitarity of the S-wave, we use the sum of Breit-Wigner functions to model other spins and final states, namely the f2(1270), f4(2050), a2(1320), and a2(1700).

Our approach provides reasonable modeling of the line shape, and the sum of all S-wave components, S_K¯K and S_ , is reported in Table II.

Besides the f0(1370), f0(1500), and f0(1710), other conventional resonances are probed, including the f0(1950), f2(1525), f2(2010), and a0(1450), with parameters fixed to PDG values [2]. They do not pass the tests for significance and fractional contribution. The nonresonant c1 → + − production is found to be negligible. The search for possible 1^-+ resonances in the final state will be presented below.

A. The a2(1700) signature

All structures listed in Table II have been previously reported in the decay c1 → + −, except for a2(1700) . Its fractional contribution is around 1%, and the significance of each orbital momentum component is more than 10 . Detailed background studies are performed to ensure that the background remaining after -sideband subtraction is not affecting the significance and fractional contribution of the a2(1700). Results of fitting the mass and width of the a2(1700) are shown in Table III and are consistent with the values listed by the PDG [2].

To check how the a2(1700) parameters and fractional contributions are affected by the f2(1270) and a2(1320), we also fit their masses and widths, which are provided in Table III with statistical uncertainties only. The mass (width) of the f2(1270) is lower (higher) than its nominal value [2], perhaps because of interference with underlying S-wave components or threshold effects other than those for K¯K or f0(1500) production.

The systematic uncertainties for the a2(1700) mass and width are obtained by varying parameters of other amplitudes within respective uncertainties listed in Ref. [2] and taking into account variations listed in Table III. The a0(980) errors are shown in Table IV. Variations in the shape of the S-wave amplitude are taken into account by changing terms in the expansion, Eq. (9).

We also test the significance of the a2(1700) by including alternative states with the same mass and width but different spins: J = 0, 1, 4. In all cases, the significance of the a2(1700) in the presence of an alternative state exceeds 17 . The statistical significance of the a2(1700) signal alone is 20 . This result confirms our hypothesis based on visual inspection of the Dalitz plot (Fig. 3(a)) that the excess of events in the upper left corner of the Dalitz space results from a2(1700) production and is associated with the crossing of the a2(1700)+ − and a2(1700)− + components. Furthermore, Fig. 7 [Figure 7: see original paper] shows the mass distribution in the region around the expected a2(1700) peak, where data points are compared with a fit when the a2(1700) amplitude is excluded.

B. a0(980) parameters

When determining the a0(980) parameters we use the ratios R_21 = $g^{2_K^-K/g}$2__ and R_31 = $g^{2- \ /g}$2__ . The resulting values are listed in Table IV, where systematic uncertainties are obtained by fitting the a0(980) parameters under different conditions. The level of background is varied by changing selection criteria described in Sec. II and by changing the amount of background subtracted from the sidebands. Effects of the line shapes of the a2(1320), a2(1700), f2(1270), and f4(2050) resonances are taken into account by varying their masses and widths within respective uncertainties [2] and using values from Table III. The effect of the S-wave shape is examined in a similar way as for the a2(1700). The presence of alternative conventional and exotic resonances is also taken into account. Our result is not sensitive to the value of the parameter in Eqs. (5) and (6) within the range = (2.0 ± 1.0) [GeV/c^2]^2.

For comparison we list two previous results: one from a similar experiment (CLEO-c) and another obtained using Crystal Barrel data. There is general agreement between different analyses for the a0(980) mass and R_21. The ratio R_31 was fixed in Ref. [20] to the theoretical value provided by Eq. (11), while it was consistent with zero in the CLEO-c analysis, possibly because of smaller statistics. It is not easy to comment on the difference in values for the coupling, which could be affected by different normalizations used by different analyses.

This analysis provides the first nonzero measurement of the coupling constant g__ . To test the sensitivity of the a0(980) line shape to the decay a0(980) → , we repeat the analysis with g__ = 0 and let the values of the other parameters float freely. The results of this fit are also given in Table IV. The likelihood change when the channel is ignored shows that the significance of a nonzero g__ measurement is 8.9 . The same result is obtained when the analysis is performed in the presence of the a0(1450). The values of the two ratios based on SU(3) expectation are:

$g^{2_K^-K/g}$2__ = 1/(2 cos^2) = 0.886 ± 0.034, $g^{2- \ /g}$2__ = tan^2 = 0.772 ± 0.068,

which depend on the choice of the - mixing angle; = (41.3 ± 1.2)° in this case [20]. Our result is consistent with Eq. (11) within 1.5 based on the quoted uncertainties.

C. Search for P-wave states

We examine possible exotic meson production in the invariant mass region from 1.4 to 2.0 GeV/c^2. Table II lists fractional contributions and significances of three J^PC = 1^-+ candidates, added one at a time to our nominal fit. Two possible orbital-momentum configurations for an exotic amplitude are the S-wave and D-wave, and the significance of each is tested individually. We find that the significance of the S-wave is marginal (less than 2 for every 1), and the reported significances in Table II result from using the S- and D-waves together in the fit. The most significant of the three possible exotic states is the 1(1400), with a significance of 3.5 and fractional contribution less than 0.6%. This represents only weak evidence for the existence of the 1(1400) because in alternative amplitude configurations, when parameters of other amplitudes are varied, the significance of this state becomes < 3 . In the nominal amplitude configuration, the significance of each 1(1400) component is less than 3 , and when taken together, the contribution of the S-wave is much smaller than the D-wave contribution, indicating that the evidence for the 1(1400) is circumstantial.

D. Branching fractions

The branching fraction for the c1 → + − decay is given by:

B(c1 → + −) = (P* × N_ c1→ + −) / (N_ (3686) × B_ (3686)→ c1 × B_ ×),

where the branching fractions B_ (3686)→ c1 and B_ are from Ref. [2] (the latter is listed in Table I). The number of (3686) events, N_ (3686) [23, 24], is provided in Sec. II. The signal purity P*, given in Sec. II A 1, accounts for the fact that the number of c1 events obtained from the amplitude analysis includes background not accounted for by the sideband subtraction. Using Eq. (2) we obtain N_ c1 = 192658 ± 1075, where the error is from the covariance matrix. The efficiency is obtained by construction.

Masses and widths of the three exotic candidates are not well constrained by previous analyses, so we vary the respective parameters within listed limits [2]. Our conclusion is that there is no significant evidence for exotic structure in the c1 → + − decays, and we determine upper limits at the 90% confidence level for the production of each 1 candidate.

Table II lists the branching fraction for c1 → + − and branching fractions for subsequent resonance production in respective isospin states (± or + −), where the first and second errors are statistical and systematic, respectively. The branching fraction for a given substructure is effectively a product: B(c1 → RJ) × B(R → h1h2), obtained using generated exclusive MC in accordance with Eq. (3). The third error is external, associated with uncertainties in the branching fractions for the radiative transition (3686) → c1 and decays. The upper limits for the production of 1(1400) , 1(1600) , and 1(2015) are shown in Table II. The limits are determined by including the corresponding amplitude in the nominal fit one at a time. The analysis is repeated by changing other amplitude line shapes and the background level in a similar fashion to that used for determining systematic uncertainties of nominal amplitudes (see Sec. V). Masses and widths of exotic candidates are also varied within limits provided by the PDG [2]. The largest positive deviation of the exotic candidate yield with respect to the corresponding yield from the modified nominal fit is treated as the systematic error, summed in quadrature with the statistical error on a given exotic state yield. The resulting uncertainty is used to determine the 90% confidence level deviation and added to the "nominal" yield of an exotic candidate to obtain the corresponding upper limit for the branching fraction B(c1 → 1).

The branching fractions for substructures in c1 → + − decays reported by the PDG [2] are compared in Table V with the values measured in this work and with the previous most precise measurement (CLEO-c) [10]. The measurement for f2(1270) production is adjusted to account for the measured relative f2(1270) width. There is a rather large discrepancy between the values for the two most dominant substructures listed by the PDG and the two most recent measurements. There is very good agreement between the last two measurements, suggesting that the PDG values for two-body structures observed in c1 → + − need to be updated.

V. SYSTEMATIC UNCERTAINTIES

Table VI summarizes various contributions to the systematic uncertainties in determining the branching fraction B(c1 → + −). Table VII shows the systematic uncertainties in the fractional contributions of amplitudes in the baseline fit.

Systematic uncertainties in determining the c1 → + − branching fraction stem from uncertainties in charged track and shower reconstruction efficiencies, the contribution of the M2 multipole transition, amplitude modeling, the background contribution, and the uncertainty in the number of (3686) produced at BESIII [23, 24]. External sources of uncertainty include the branching fraction B((3686) → c1) and the fraction of decays, B( ) in Eq. (12). The external error affects only branching fractions, not fractional contributions, and is reported as a separate uncertainty.

Systematic uncertainties associated with tracking efficiency and shower reconstruction are 1% per track and 1% per photon. Because of different final states used in this analysis, tracking and photon uncertainties are weighted according to the product of branching fractions and efficiencies of the different channels, as listed in Table I. The resulting systematic uncertainties for charged tracks and photons are 2.47% and 3.92%, respectively.

The electromagnetic transition (3686) → c1 is dominated by the E1 multipole amplitude with a small fraction of the M2 transition [29]. The nominal fit takes only the E1 multipole amplitude. Adding a small contribution of the M2 helicity amplitude of 2.9%, we find a difference in the branching fraction of 0.62%, which is taken as a systematic uncertainty.

When considering the effects of modeling line shapes of different amplitudes, we repeat the analysis changing the mass and width of resonances a2(1320), f2(1270), and f4(2050) within respective uncertainties, and change the a0(980) and a2(1700) parameters within the limits of their statistical uncertainties given in Tables IV and III. We also change BW line shapes by replacing spin-dependent widths with fixed widths and take into account the c1 width and centrifugal barrier as another systematic error. The largest effect from all these sources is taken as a systematic uncertainty for the branching fractions and fractional contributions.

The effect of background is estimated by varying the kinematic-constraint requirement, changing limits on tagging and c1 candidates, changing the level of suppression of J/ and 0 productions, and the level of background subtraction. As a general rule, selection criteria were changed to allow for 1 additional background events based on numbers from the inclusive MC. We use ^2_NC/NC < 9 in all three modes when varying the kinematic constraint. Based on these variations, we conclude that the systematic uncertainty associated with the assumption that all charged tracks are pions is negligible. To select c1 candidates, we use photon energy ranges of (0.152–0.187) GeV in the → 3 channel and (0.150–0.190) GeV in the two → channels. The mass window for the selection is changed to (0.530–0.565) GeV/c^2. The 0 suppression window is reduced to (0.120–0.150) GeV/c^2 and the J/ suppression is reduced by vetoing two-photon energy within (0.525–0.595) GeV. We also determine the branching fractions without background subtraction from -sidebands, and the largest effect is listed in Tables VI and VII.

Some uncertainties that are common for all amplitudes, such as tracking, shower reconstruction, and N_ (3686) errors, cancel out in the fractional contributions. However, they are taken into account when branching fractions are determined.

VI. SUMMARY

We analyze the world' s largest c1 → + − sample, selected with very high purity, and find a very prominent a0(980) peak in the ± invariant mass distribution. An amplitude analysis of the (3686) → c1; c1 → + − decay is performed, and the parameters of the a0(980) are determined using a dispersion relation. The a0(980) line shape in its final state appears to be sensitive to the details of a0(980) → production, and for the first time a significant nonzero coupling of the a0(980) to the mode is measured with a statistical significance of 8.9 .

We also report a2(1700) production in the c1 → + − decays for the first time, with mass and width in agreement with world average values. This analysis provides both qualitative and quantitative evidence for the existence of the a2(1700). First, the signature of the a2(1700) in the Dalitz space is consistent with the observed Dalitz plot distribution. Second, the a2(1700) significance from the amplitude analysis is larger than 17 compared to alternative spin assignments, even though the fractional yield of a2(1700) is only 1%. This may help in listing the a2(1700) as an established resonance by the PDG [2].

We examine the production of exotic mesons that might be expected in the c1 → decays: 1(1400), 1(1600), and 1(2015). There is only weak evidence for the 1(1400), while other exotic candidates are not significant, and we determine upper limits on the respective branching fractions.

ACKNOWLEDGMENTS

The BESIII collaboration thanks the staff of BEPCII and the IHEP computing center for their strong support. This work is supported in part by National Key Basic Research Program of China under Contract No. 2015CB856700; National Natural Science Foundation of China (NSFC) under Contracts Nos. 11235011, 11322544, 11335008, 11425524; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; the CAS Center for Excellence in Particle Physics (CCEPP); the Collaborative Innovation Center for Particles and Interactions (CICPI); Joint Large-Scale Scientific Facility Funds of the NSFC and CAS under Contracts Nos. U1232201, U1332201; CAS under Contracts Nos. KJCX2-YW-N29, KJCX2-YW-N45; 100 Talents Program of CAS; National 1000 Talents Program of China; INPAC and Shanghai Key Laboratory for Particle Physics and Cosmology; Istituto Nazionale di Fisica Nucleare, Italy; Joint Large-Scale Scientific Facility Funds of the NSFC and CAS under Contract No. U1532257; Joint Large-Scale Scientific Facility Funds of the NSFC and CAS under Contract No. U1532258; Koninklijke Nederlandse Akademie van Wetenschappen (KNAW) under Contract No. 530-4CDP03; Ministry of Development of Turkey under Contract No. DPT2006K-120470; The Swedish Research Council; U.S. Department of Energy under Contracts Nos. DE-FG02-05ER41374, DE-SC-0010504, DE-SC0012069; U.S. National Science Foundation; University of Groningen (RuG) and the Helmholtzzentrum fuer Schwerionenforschung GmbH (GSI), Darmstadt; WCU Program of National Research Foundation of Korea under Contract No. R32-2008-000-10155-0.

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