Evidence for the Direct Two-Photon Transition from $\psi(3686)$ to $J/\psi$

Roy A. Briere  
*Carnegie Mellon University, rbriere@andrew.cmu.edu*

C. L. Liu  
*Carnegie Mellon University*

BESIII Collaboration

Follow this and additional works at: [http://repository.cmu.edu/physics](http://repository.cmu.edu/physics)

Part of the Physics Commons

Published In  
*Physical Review Letter, 109, 17, 172002.*

This Article is brought to you for free and open access by the Mellon College of Science at Research Showcase @ CMU. It has been accepted for inclusion in Department of Physics by an authorized administrator of Research Showcase @ CMU. For more information, please contact research-showcase@andrew.cmu.edu.
Evidence for the Direct Two-Photon Transition from $\psi(3686)$ to $J/P$
The two-photon transition $\psi(3686) \rightarrow \gamma \gamma J/\psi$ is studied in a sample of $1.06 \times 10^8$ $\psi(3686)$ decays collected by the BESIII detector. The branching fraction is measured to be $(3.1 \pm 0.6(stat)^{+0.8}_{-1.0}(syst)) \times 10^{-4}$ using $J/\psi \rightarrow e^+e^-$ and $J/\psi \rightarrow \mu^+\mu^-$ decays, and its upper limit is estimated to be $4.5 \times 10^{-4}$ at the 90% confidence level. This work represents the first measurement of a two-photon transition among charmonium states. The orientation of the electric dipole transitions, the strength of coupled-channel effects, and accompanying relativistic corrections may be more important [4]. However, the two-photon transition $\psi(3686) \rightarrow \gamma \gamma J/\psi$ is more sensitive to the coupled-channel effect and thus provides a unique opportunity to investigate these issues [5].

Two-photon spectroscopy has been a very powerful tool for the study of the excitation spectra of a variety of charmonium states. The orientation of the electric dipole transitions, the strength of coupled-channel effects will likely be hard to establish, since the accompanying relativistic corrections may be more important [4]. However, the two-photon transition $\psi(3686) \rightarrow \gamma \gamma J/\psi$ is more sensitive to the coupled-channel effect and thus provides a unique opportunity to investigate these issues [5].
This work studies the two-photon process in quarkonium states as a natural extension of atomic hydrogen, and positronium [6]. Studying the analogous process in quarkonium states is a natural extension of this work, in order to gain insight into nonperturbative QCD phenomena. But, so far, two-photon transitions in quarkonia have eluded experimental observation [7–9]. For example, in a study of $\psi(3686) \rightarrow \gamma \chi_{cJ}(J=0,1,2)$ reported by the CLEO Collaboration [9], the upper limit for $\mathcal{B}(\psi(3686) \rightarrow \gamma \gamma J/\psi)$ was estimated to be $1 \times 10^{-3}$.

This Letter presents the first evidence for the two-photon transition $\psi(3686) \rightarrow \gamma \gamma J/\psi$, as well as studies of the orientation of the $\psi(3686)$ decay plane and the $J/\psi$ polarization in the decay. The branching fractions of double $E1$ transitions $\psi(3686) \rightarrow \gamma(\gamma J/\psi)\chi_{cJ}$, through $\chi_{cJ}$ intermediate states are also reported. The data analyzed were obtained by the BESIII experiment [10] viewing electron-positron collisions at the BEPCII collider. An integrated luminosity of 156.4 pb$^{-1}$ was obtained at a center-of-mass energy $\sqrt{s} = M(\psi(3686)) = 3.686$ GeV. The number of $\psi(3686)$ decays in this sample is estimated to be $(1.06 \pm 0.04) \times 10^8$ [11]. In addition, 42.6 pb$^{-1}$ of continuum data were taken below the $\psi(3686)$, at $\sqrt{s} = 3.65$ GeV, to evaluate the potential backgrounds from non-resonant events.

The upgraded BEPCII [12] at Beijing is a two-ring electron-positron collider. The BESIII detector [10] is an approximately cylindrically symmetric detector which covers 93% of the solid angle around the collision point. In the order of increasing distance from the interaction point, the subdetectors include a 43-layer main wire drift chamber (MDC), a time-of-flight system with two layers in vertical bands. As indicated in Fig. 1(c), the continuum data are seen from the decays $\psi(3686) \rightarrow \pi^0(\eta)J/\psi$ (two vertical bands), and $\psi(3686) \rightarrow \pi^0(\eta)J/\psi$ (three horizontal bands). As indicated in Fig. 1(a), the continuum energy resolution for showers in the EMC is 5% for a muon. To suppress non-$J/\psi$ decay leptons, we require the momentum of each lepton to be larger than 0.8 GeV/$c$. A vertex fit (VF) constrains the production vertex, which is updated run-by-run, and the tracks of the dilepton candidates to a common vertex; only events with $\chi^2_{VF}/d.o.f. < 20$ are accepted.

Reconstructed EMC showers unmatched to either charged track and with an energy larger than 25 MeV in the barrel region ($|\cos \theta| < 0.80$) or larger than 50 MeV in the end caps ($0.86 < |\cos \theta| < 0.92$) are used as photon candidates. To reject bremsstrahlung photons, showers matching the initial momentum of either lepton within $10^8$ are also discarded. Showers from noise, not originating from the beam collision, are suppressed by requiring the EMC cluster time to lie within a 700 ns window near the event start time.

Events are required to have only two photon candidates. A kinematic fit (KF) constrains the vertexed dilepton to the nominal mass of the intermediate $J/\psi$ and the resulting $J/\psi$ and photon candidates to the known initial four-momentum of the $\psi(3686)$. The KF fit quality $\chi^2_{KF}$ is required to be $\chi^2_{KF}/d.o.f. < 12$. For convenience, we use $\gamma_{lg}$ ($\gamma_{sm}$) to denote the larger (smaller) energy photon. As indicated in Fig. 1(a), $J/\psi$ candidates are identified with the requirement that the recoil mass of the two photons, $M_{\gamma\gamma\text{-recoil}}$, is within $(3.08, 3.14)$ GeV/$c^2$.

Scatter plots of recoiling mass $M_{\gamma\gamma\text{-recoil}}$ from the lower energy photon $\gamma_{sm}$ versus the invariant mass of two photons $M_{\gamma\gamma}$ are shown in Fig. 1, where clear resonance bands are accepted. In the combined data set (solid line) of MC simulation of $\psi(3686)$ decays (shaded histogram) and continuum backgrounds (dashed line), before the KF is applied. The arrows indicate the window to select a $J/\psi$ candidate. Bottom: scatter plots of $M_{\gamma\gamma\text{-recoil}}$ versus $M_{\gamma\gamma}$ for the $\gamma\gamma e^+e^-$ channel, in (a) data, (b) continuum data, and (d) MC simulated signal, after applying the KF constraint and the $M_{\gamma\gamma\text{-recoil}}$ window. The corresponding plots for the $\gamma\gamma \mu^+\mu^-$ channel are very similar.
backgrounds are most dominant at the tops of the plots, of which the primary sources include the Bhabha scattering, the dimuon process, and the initial-state radiation production of \( J/\psi \). These backgrounds are excluded by discarding events with \( M_{m\gamma\gamma} > 3.6 \text{ GeV}/c^2 \). To suppress backgrounds from \( \psi(3686) \rightarrow \pi^0(\eta)J/\psi \), the diphoton invariant mass \( M_{\gamma\gamma} \) is required to be larger than 0.15 GeV/$c^2$ and the recoil momentum of the diphoton must be larger than 0.25 GeV/$c$.

Monte Carlo (MC) simulations of \( \psi(3686) \) decays are used to understand the backgrounds and also to estimate the detection efficiency. At BESIII, the simulation includes the beam energy spread and treats the initial-state radiation with KKMC [13]. Specific decay modes from the Particle Data Group (PDG) [14] are modeled with EVTGEN [15], and the unknown decay modes with Lundcharm [16]. The detector response is described using GEANT4 [17]. For the \( J=0 \) structure in this work. Generic \( \psi(3686) \) decay samples serve for understanding the background channels; dominant backgrounds were generated with high statistics. Angular distributions of the cascade \( E1 \) transitions \( \psi(3686) \rightarrow \gamma\chi_{cJ} \rightarrow \gamma\gamma J/\psi \) are assumed to follow the formulas in Ref. [18]. Note that the \( \chi_{cJ} \) line shapes were simulated with the Breit-Wigner distributions weighted with \( E_1^3 E_2^1 \) to account for the double \( E1 \) transitions and extended out to \( \pm 200 \text{ MeV}/c^2 \) away from the nominal masses, using masses and widths in the PDG [14]. Here, \( E_1(E_2) \) is the energy of the radiative photon \( \gamma_1(\gamma_2) \) in the rest frame of the mother particle \( \psi(3686)(\chi_{cJ}) \).

The yield of the signal process \( \psi(3686) \rightarrow \gamma\gamma J/\psi \), together with those of the cascade \( E1 \) transition processes, is estimated by a global fit to the spectrum of \( M_{m\gamma\gamma\text{-recoil}} \). The fit results are shown in Fig. 2. The shape and magnitude of \( \psi(3686) \) decay backgrounds were fixed based on MC simulation. Non-\( \psi(3686) \) decay backgrounds are estimated in continuum data, scaling by luminosity, and the \( 1/s \) dependence of the cross sections. This scaling is verified by the good description of the \( J/\psi \) backgrounds in the \( M_{\gamma\gamma\text{-recoil}} \) distribution shown in Fig. 1(a).

**FIG. 2 (color online).** (a) Unbinned maximum likelihood fit to the distribution of \( M_{m\gamma\gamma\text{-recoil}} \) in data with combination of the two \( J/\psi \) decay modes. Thick lines are the sum of the fitting models, and long-dashed lines are the \( \chi_{cJ} \) shapes. Short-dashed lines represent the two-photon signal processes. The light shaded histogram is \( \psi(3686) \) decay backgrounds (yellow), and the dark shaded histogram is non-\( \psi(3686) \) backgrounds (green), with the fixed amplitude and shape taken from MC simulation and continuum data. (b) The number of standard deviations, \( n_\sigma \), of data points from the fitted curves in (a). The rates of the signal process and sequential \( \chi_{cJ} \) processes are derived from these fits. (c) Distributions of \( M_{\gamma\gamma\text{-recoil}} \) in data (signals and known backgrounds) with the kinematic requirement \( 3.44 \text{ GeV}/c^2 < M_{m\gamma\gamma\text{-recoil}} < 3.48 \text{ GeV}/c^2 \) and with the removal of \( \chi_{cJ} \) and \( M_{\gamma\gamma\text{-recoil}} \) selections. (d) Stacked histograms of the three \( \chi_{cJ} \) components in (c).

**Table I.** For different channels: the number of observed signals \( n_e \) (\( n_\mu \)) and detection efficiency \( \epsilon_e \) (\( \epsilon_\mu \)) in the \( \gamma\gamma e^+e^- (\gamma\gamma \mu^+\mu^-) \) mode; the absolute branching fractions. On the bottom, the relative branching fractions \( R_{MN} = \frac{B_{\chi_{cJ}}}{B_{\gamma\gamma J}} \), where \( B_{\gamma\gamma J} = B(\psi(3686) \rightarrow \gamma\gamma J/\psi) \), are listed. Here, the first errors are statistical and the second are systematic.

| Channels          | \( n_e \)   | \( \epsilon_e(\%) \) | \( n_\mu \)   | \( \epsilon_\mu(\%) \) | \( B \times 10^{-4} \) |
|-------------------|-------------|-----------------------|-------------|-----------------------|----------------------|
| \( \gamma\gamma J/\psi \) | 564 \pm 116 | 22.4                  | 536 \pm 128 | 30.0                  | 3.1 \pm 0.6          |
| \( \gamma(\gamma J/\psi)_{\chi_{c0}} \) | 1801 \pm 60 | 19.3                  | 2491 \pm 69 | 26.0                  | 15.1 \pm 0.3         |
| \( \gamma(\gamma J/\psi)_{\chi_{c1}} \) | 59953 \pm 253 | 28.5                  | 81922 \pm 295 | 38.2                  | 337.7 \pm 0.9        |
| \( \gamma(\gamma J/\psi)_{\chi_{c2}} \) | 32171 \pm 187 | 27.5                  | 44136 \pm 219 | 37.1                  | 187.4 \pm 0.7        |
| \( R_{01} = \frac{B_{\gamma\gamma J}}{B_{\chi_{c0}}} \) | \( \frac{55.47 \pm 0.26 \pm 0.11}{4.45 \pm 0.09 \pm 0.18} \) | \( R_{02} = \frac{B_{\gamma\gamma J}}{B_{\chi_{c2}}} \) | \( 8.03 \pm 0.17 \pm 0.33 \) |
with the assumption of Gaussian distributions, the significance is evaluated to be $3.8\sigma$, which corresponds to a probability of a background fluctuation to the observed signal yield of $7.2 \times 10^{-5}$. The upper limit for $\mathcal{B}(\psi(3686) \rightarrow \gamma J/\psi)$ is estimated to be $4.5 \times 10^{-4}$ at the 90% confidence level, including systematic uncertainties.

In calculating $\mathcal{B}(\gamma J/\psi)$, a correction factor is included due to the interferences among $\chi_{cJ}$ states. This effect was checked by the variations of the observed signals in the global fit with inclusion of a floating interference component, which is modeled by the detector-smearred shape of a theoretical calculation [5]. It is found that relative changes on the signal yields are negative with lower bound of $-10\%$. Hence, a correction factor 0.95 is assigned and 5% is taken as systematic uncertainty.

A cross-check on our procedures is performed with the $M_{\gamma\gamma\text{recoil}}$ spectrum for the events in the region 3.44 GeV/c$^2 < M_{\gamma\gamma\text{recoil}} < 3.48$ GeV/c$^2$ without restrictions on $\chi_{K\pi}$ and $M_{\gamma\gamma\text{recoil}}$, as shown in Fig. 2(c). An excess of data above known backgrounds can be seen around the $J/\psi$ nominal mass, which is expected from the sought-after two-photon process. With the inclusion of the estimated yields of the signal process, the excess is well understood. The high-mass peak above the $J/\psi$ peak comes from the backgrounds of $\psi(3686) \rightarrow \pi^0\pi^0 J/\psi$ decays. This satellite peak can be well described in MC simulation. In Fig. 2(d), the three $\chi_{cJ}$ tails show distinguishable distributions; the small left bump is from the $\chi_{c1}$ tail, while the $\chi_{c0}$ tail is dominant at the right side. The distribution in data in Fig. 2(c) can only be well described by the simulated $\chi_{cJ}$ shapes.

The angle of the normal axis of the $\psi(3686)$ decay plane with respect to the $\psi(3686)$ polarization vector (aligned to the beam axis), $\beta$, can be determined in our data. The event rate may be expressed, to leading order, as $\frac{dN}{d\cos\beta} \propto 1 + \cos^2 \beta$. The measurement was carried out in the rest frame of the $\psi(3686)$, and the decay plane of the $\psi(3686)$ was determined with the momenta of the two decay particles $J/\psi$ and $\gamma_{\text{bg}}$. The signal yields in each angular bin were extracted by the global fit to the corresponding data set following the aforementioned procedure. After correction of the extracted signal yields with the detection efficiency, Fig. 3(a) shows the fit to the distribution of $|\cos\beta|$ for the sum of the two dilepton modes; we obtain $\alpha = 0.53 \pm 0.68$.

The polarization of $J/\psi$ should be helpful in understanding the mechanism of the transition process [19]. The polarization parameter $\alpha$ can be evaluated from the angular distribution of the decay rate, expressed as

![Graph](image-url)

**Fig. 3.** (a) The corrected distribution of the normal angle $\beta$ of the $\psi(3686)$ decay plane, and (b) the helicity angle $\theta_3$ of $J/\psi$ decays. The curves in (a) and (b) present the fits of functions $P_0(1 + a \cos^2 \beta)$ and $P_0(1 + a \cos^2 \theta_3)$, respectively.

| Systematic uncertainty (%) | $B_{\text{sig}}$ | $B_{\chi_{c0}}$ | $B_{\chi_{c1}}$ | $B_{\chi_{c2}}$ | $R_{01}$ | $R_{02}$ | $R_{21}$ |
|-----------------------------|-----------------|----------------|----------------|----------------|---------|---------|---------|
| Lepton track                | 2(2)            | 2(2)           | 2(2)           | 2(2)           |         |         |         |
| Photon shower               | 2               | 2              | 2              | 2              |         |         |         |
| Number of photons           | 10(3)           | 1(1)           | 1(1)           | 1(1)           | 2(⋅⋅⋅)  | 2(⋅⋅⋅)  | (⋅⋅⋅)   |
| KF, $\chi_{K\pi}$ requirement | 2(2)           | 2(2)           | 2(2)           | 2(2)           |         |         |         |
| $\chi_{cJ}$ widths          | $-^{15}_{+25}$  | 3              | ⋯              | ⋯              | 4       | 4       | 0.2     |
| $M_{\gamma\gamma\text{recoil}}$ resolution | 4(5)           | ⋯ (⋅⋅⋅)        | ⋯ (⋅⋅⋅)        | ⋯ (⋅⋅⋅)        | ⋯ (⋅⋅⋅) | ⋯ (⋅⋅⋅) | ⋯ (⋅⋅⋅) |
| Other background            | 4(2)            | 1(1)           | ⋯ (⋅⋅⋅)        | ⋯ (⋅⋅⋅)        | ⋯ (⋅⋅⋅) | ⋯ (⋅⋅⋅) | ⋯ (⋅⋅⋅) |
| $\chi_{cJ}$ interference    | 5               | 1              | ⋯              | ⋯              | 1       | 1       | ⋯       |
| Fitting                     | 8(5)            | 1(1)           | ⋯ (⋅⋅⋅)        | ⋯ (⋅⋅⋅)        | 1(1)    | 1(1)    | ⋯ (⋅⋅⋅) |
| Spin structure              | 20              | 1              | ⋯              | ⋯              | 1       | 1       | ⋯       |
| Number of $\psi(3686)$      | 4               | 4              | 4              | 4              |         |         |         |
| $\mathcal{B}(J/\psi \rightarrow \ell^+ \ell^-)$ | 1               | 1              | 1              | 1              |         |         |         |
| $\mathcal{B}(J/\psi \rightarrow \ell^+ \ell^-)$ | 14(8)           | 3(3)           | 3(3)           | 3(3)           | 2(1)    | 2(1)    | (⋅⋅⋅)   |
| Total                       | 16(25)          | 6(3)           | 5              | 5              | 4       | 4       | 0.2     |

| Systematic uncertainty (%) | $B_{\text{sig}}$ | $B_{\chi_{c0}}$ | $B_{\chi_{c1}}$ | $B_{\chi_{c2}}$ | $R_{01}$ | $R_{02}$ | $R_{21}$ |
|-----------------------------|-----------------|----------------|----------------|----------------|---------|---------|---------|
| Lepton track                | 2(2)            | 2(2)           | 2(2)           | 2(2)           |         |         |         |
| Photon shower               | 2               | 2              | 2              | 2              |         |         |         |
| Number of photons           | 10(3)           | 1(1)           | 1(1)           | 1(1)           | 2(⋅⋅⋅)  | 2(⋅⋅⋅)  | (⋅⋅⋅)   |
| KF, $\chi_{K\pi}$ requirement | 2(2)           | 2(2)           | 2(2)           | 2(2)           |         |         |         |
| $\chi_{cJ}$ widths          | $-^{15}_{+25}$  | 3              | ⋯              | ⋯              | 4       | 4       | 0.2     |
| $M_{\gamma\gamma\text{recoil}}$ resolution | 4(5)           | ⋯ (⋅⋅⋅)        | ⋯ (⋅⋅⋅)        | ⋯ (⋅⋅⋅)        | ⋯ (⋅⋅⋅) | ⋯ (⋅⋅⋅) | ⋯ (⋅⋅⋅) |
| Other background            | 4(2)            | 1(1)           | ⋯ (⋅⋅⋅)        | ⋯ (⋅⋅⋅)        | ⋯ (⋅⋅⋅) | ⋯ (⋅⋅⋅) | ⋯ (⋅⋅⋅) |
| $\chi_{cJ}$ interference    | 5               | 1              | ⋯              | ⋯              | 1       | 1       | ⋯       |
| Fitting                     | 8(5)            | 1(1)           | ⋯ (⋅⋅⋅)        | ⋯ (⋅⋅⋅)        | 1(1)    | 1(1)    | ⋯ (⋅⋅⋅) |
| Spin structure              | 20              | 1              | ⋯              | ⋯              | 1       | 1       | ⋯       |
| Number of $\psi(3686)$      | 4               | 4              | 4              | 4              |         |         |         |
| $\mathcal{B}(J/\psi \rightarrow \ell^+ \ell^-)$ | 1               | 1              | 1              | 1              |         |         |         |
| $\mathcal{B}(J/\psi \rightarrow \ell^+ \ell^-)$ | 14(8)           | 3(3)           | 3(3)           | 3(3)           | 2(1)    | 2(1)    | (⋅⋅⋅)   |
| Total                       | 16(25)          | 6(3)           | 5              | 5              | 4       | 4       | 0.2     |
\( \frac{dN}{d\cos\theta} \propto 1 + \alpha \cos^2 \theta \). Here, \( \alpha = \frac{\Gamma_\ell^+ + \Gamma_\ell^+}{\Gamma + \Gamma_\ell^+ + \Gamma_\ell^+} \) (with \( \Gamma_\ell^+ \) and \( \Gamma_\ell^+ \) being the transversely and longitudinally polarized decay widths, respectively) and the helicity angle \( \theta_\ell \) is defined as the angle of the lepton in the \( J/\psi \) rest frame with respect to the \( J/\psi \) boost direction in the laboratory frame. For fully transverse (longitudinal) polarization, \( \alpha = +1(-1) \). Figure 3(b) shows the distribution of \( |\cos \theta_\ell| \) for the sum of the two dilepton modes, after correcting the signal yields for the detection efficiency and the lepton final state radiation effect. Our fit result is \( \alpha = 0.08 \pm 0.42 \).

Sources of systematic errors on the measurement of branching fractions are listed in Table II. Uncertainties associated with the efficiency of the lepton tracking and identification were studied with a selected control sample and the efficiency of the lepton tracking and identification were studied with a selected control sample associated with the efficiency of the lepton tracking and identification were studied with a selected control sample. The reported branching fractions of \( B J/\psi \rightarrow \gamma(\gamma J/\psi)_{X_{\ell}} \) are consistent with the world-average results [14]. The reported relative branching fractions of \( B J/\psi \rightarrow \gamma(\gamma J/\psi)_{X_{\ell}} \) are obtained with the world’s best precision.

X.-R. Lu thanks Zhi-Guo He and De-Shan Yang for useful suggestions. We thank the staff of BEPCII and the computing center for their hard efforts. We are grateful for support from our institutes and universities and from the following agencies: Ministry of Science and Technology of China, National Natural Science Foundation of China, Chinese Academy of Sciences, Istituto Nazionale di Fisica Nucleare, U.S. Department of Energy, U.S. National Science Foundation, and National Research Foundation of Korea.

*Also at the Moscow Institute of Physics and Technology, Moscow 141700, Russia.

† On leave from the Bogolyubov Institute for Theoretical Physics, Kiev 03680, Ukraine.

‡ Also at University of Piemonte Orientale and INFN, Turin 10125, Italy.

§ Present address: INFN and University of Perugia, Perugia 06100, Italy.

∥ Also at the PNP, Gatchina 188300, Russia.

¶ Present address: Nagoya University, Nagoya 464-8601, Japan.

[1] N. Brambilla et al., Eur. Phys. J. C 71, 1534 (2011).

[2] Y.-Q. Chen, N. Brambilla, Y. Jia, and A. Vairo, Int. J. Mod. Phys. A 24, 295 (2009).

[3] E. J. Eichten, K. Lane, and C. Quigg, Phys. Rev. D 69, 094019 (2004); X. Liu, Phys. Lett. B 680, 137 (2009); T. Barnes, in Proceedings of the XIII International Conference on Hadron Spectroscopy, edited by V. Crede, P. Eugenio, and A. Ostrovidov, AIP Conf. Proc. No. 1257 (AIP, New York, 2010), p. 11.

[4] B. Q. Li and K. T. Chao, Phys. Rev. D 79, 094004 (2009).

[5] Z.-G. He, X.-R. Lu, J. Soto, and Y. Zheng, Phys. Rev. D 83, 054028 (2011).

[6] K. Pachucki, D. Leibfried, M. Weitz, A. Huber, W. König, and T. W. Hänsch, J. Phys. B 29, 177 (1996); A. Quattromani and F. Bassani, Phys. Rev. Lett. 50, 1258 (1983).

[7] J. Z. Bai et al. (BESIII Collaboration), Phys. Rev. D 70, 012006 (2004); M. Ablikim et al. (BESIII Collaboration), ibid. 71, 092002 (2005).

[8] N. E. Adam et al. (CLEO Collaboration), Phys. Rev. Lett. 94, 232002 (2005).

[9] H. Mendez et al. (CLEO Collaboration), Phys. Rev. D 78, 111102(R) (2008).

[10] M. Ablikim et al. (BESIII Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 614, 345 (2010).

[11] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D 81, 052005 (2010).

[12] C. Zhang, Sci. China Ser. G 53, 2084 (2010).

[13] S. Jadach, B. F. L. Ward, and Z. Was, Phys. Rev. D 63, 113009 (2001).

[14] J. Beringer et al. (Particle Data Group), Phys. Rev. D 86, 010001 (2012).
[15] R. G. Ping, Chinese Phys. C 32, 599 (2008).
[16] J. C. Chen, G. S. Huang, X. R. Qi, D. H. Zhang, and Y. S. Zhu, Phys. Rev. D 62, 034003 (2000).
[17] S. Agostinelli et al. (GEANT Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 506, 250 (2003); J. Allison et al., IEEE Trans. Nucl. Sci. 53, 270 (2006).
[18] G. Karl, S. Meshkov, and J. L. Rosner, Phys. Rev. D 13, 1203 (1976); M. A. Doncheski, H. Grotch, and K. J. Sebastian, ibid. 42, 2293 (1990).
[19] P. Artoisenet, J. P. Lansberg, and F. Maltoni, Phys. Lett. B 653, 60 (2007).
[20] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 104, 132002 (2010).