

$\mathcal{R}(3780)$ Resonance Interpreted as the 1^3D_1 -Wave Dominant State of Charmonium from Precise Measurements of the Cross Section of $e^+e^- \rightarrow \text{Hadrons}$

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 (Received 5 December 2023; revised 24 October 2024; accepted 31 October 2024; published 11 December 2024)

We report the precise measurements of the cross section of $e^+e^- \rightarrow \text{hadrons}$ at center-of-mass energies from 3.645 to 3.871 GeV. We thereby perform the most precise study of the cross sections and find a complex system composed of three resonances of $\mathcal{R}(3760)$, $\mathcal{R}(3780)$, and $\mathcal{R}(3810)$. For the first time, we measure the $\mathcal{R}(3810)$ electronic width to be $(19.4 \pm 7.4 \pm 12.1)$ eV. For the $\mathcal{R}(3760)$ resonance, we measure the mass to be $(3751.9 \pm 3.8 \pm 2.8)$ MeV/ c^2 , the total width to be $(32.8 \pm 5.8 \pm 8.7)$ MeV, and the electronic width to be $(184 \pm 75 \pm 86)$ eV. For the $\mathcal{R}(3780)$ resonance, we measure its mass to be $(3778.7 \pm 0.5 \pm 0.3)$ MeV/ c^2 , total width to be $(20.3 \pm 0.8 \pm 1.7)$ MeV, and electronic width to be $(265 \pm 67 \pm 83)$ eV. Forty-seven years ago, the $\psi(3770)$ resonance was discovered, and was subsequently interpreted as the 1^3D_1 -wave dominant state of charmonium. However, our analysis of the total-hadron cross sections indicates that the $\psi(3770)$ is not a single state, but a complex system composed of the $\mathcal{R}(3760)$, $\mathcal{R}(3780)$, and $\mathcal{R}(3810)$ resonances. Among these, we interpret the $\mathcal{R}(3780)$ is a resonance dominated by the 1^3D_1 charmonium state.

DOI: [10.1103/PhysRevLett.133.241902](https://doi.org/10.1103/PhysRevLett.133.241902)

In 1977, the MARK-I Collaboration discovered a single resonance denoted the $\psi(3770)$ in $e^+e^- \rightarrow \text{hadrons}$ at center-of-mass (c.m.) energies from 3.73 to 3.87 GeV, and interpreted it as the 1^3D_1 -wave dominant state of charmonium [1,2]. Twenty years ago, the BES Collaboration reported the observation of seven occurrences of the non-open-charm (nOC) hadron decay $\psi(3770) \rightarrow J/\psi\pi^+\pi^-$ [3]. Because of the fact that the mass of the $\psi(3770)$ resonance is higher than the open-charm (OC) threshold, this observation overturned the conventional knowledge that mesons containing charm quarks with masses above the OC-pair thresholds decay entirely to OC final states via the strong interaction. The observation of this decay was confirmed two [4] and three [5] years later. This observation inspired researchers to study the production and decay of meson resonances in the OC energy region, in particular, to study the line shape of $e^+e^- \rightarrow \text{hadrons}$ cross sections at energies from 3.65 to 3.88 GeV [6,7]. In this Letter, we denote these meson resonances as X_{aboveOC} [8], which encompass both heavy $c\bar{c}$ states, i.e., $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$, and potential non- $c\bar{c}$ states, such as four-quark states, OC-pair molecular states, hadro-charmonium states, and hybrid charmonium states, expected by quantum chromodynamics

(QCD). Discovery of these non- $c\bar{c}$ states would be an important validation of QCD predictions. Precise measurements of the resonance parameters of X_{aboveOC} states provide valuable data for understanding the nature of the X_{aboveOC} states.

The charmonium model [9] predicts that the 1^3D_1 state should decay more than 99% of the time into open-charm final states. However, subsequent studies showed that about 15% of $\psi(3770)$ decays are into nonopen-charm final states [6,10–12]. These observations suggested that there are probably undiscovered states [13] with masses around 3.773 GeV/ c^2 , which decay into nonopen-charm final states with large branching fractions. In 2008, the BES-II experiment observed for the first time a double-peaked structure named the $\mathcal{R}s(3770)$ [14] in $e^+e^- \rightarrow \text{hadrons}$ at c.m. energies around 3.77 GeV, which is composed of two Breit-Weigner (BW) structures with masses close to 3763 and 3781 MeV [14], respectively. Reference [15] interprets one of the two BW contributions in the double-peak structure as a possible molecular open-charm threshold resonance. An alternative interpretation is a p -wave resonance of a four-quark ($c\bar{c}q\bar{q}$) state [16]. In 2021, BESIII observed the $\mathcal{R}(3760)$ in $e^+e^- \rightarrow J/\psi X$ with a significance of 5.3σ [17], hence establishing the double-peak structure as two resonances, and ruling out the explanations that an enhancement of the cross section for $e^+e^- \rightarrow \text{hadrons}$ at c.m. energies near 3.76 GeV [14] is due to the $e^+e^- \rightarrow D\bar{D}$ continuum process (cnt $D\bar{D}$) interfering with the decay $\psi(3770) \rightarrow D\bar{D}$, or due to $\psi(3686) \rightarrow D\bar{D}$ decays at energies above the $D\bar{D}$ threshold [18]. Recently,

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BESIII observed three resonant structures around 3.77 GeV, labeled as $\mathcal{R}(3760)$, $\mathcal{R}(3780)$, and $\mathcal{R}(3810)$ in $e^+e^- \rightarrow$ non-OC hadrons [19], but could not measure their electronic widths. All of these observations bring into question the conventional interpretation that the $\psi(3770)$ is the 1^3D_1 -wave dominant state of charmonium and indicate the necessity of rediscovering this state.

The measurements of the parameters of the $\psi(3770)$ resonance that are used in the determination of world average values [1,2,6,18,20–24] do not consider the effects of $\mathcal{R}(3760)$ and $\mathcal{R}(3810)$ decays. It is possible, therefore, that the world-average value of the $\psi(3770)$ parameters may be biased. To overcome this problem, it is important to measure and analyze the total cross sections for $e^+e^- \rightarrow$ hadrons with high accuracy. Such measurements will both improve the understanding of the known states, and help to interpret one of the $\mathcal{R}(3760)$, $\mathcal{R}(3780)$, and $\mathcal{R}(3810)$ as the 1^3D_1 -wave dominant state of charmonium.

In this Letter, we report measurements of the total cross sections for $e^+e^- \rightarrow$ hadrons at c.m. energies from 3.645 to 3.871 GeV, measurements of the $\mathcal{R}(3760)$, $\mathcal{R}(3780)$, and $\mathcal{R}(3810)$ resonance parameters, the first measurement of the $\mathcal{R}(3810)$ electronic width, and interpretation of each of the three resonances as a specific physical state. The data samples used in the measurements were collected at 42 c.m. energies with the BESIII detector at the BEPCII accelerator in 2010. The total integrated luminosity of the data sample is 75.5 pb^{-1} .

The BESIII detector is described in detail in Ref. [25]. The detector response is studied using samples of Monte Carlo (MC) events which are simulated with a GEANT4-based [26] detector simulation software package. Simulated samples for all $q\bar{q}$ vector states (i.e. $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, and $c\bar{c}$ resonances) and their decays to hadrons are generated using the MC event generators KKMC [27], EVTGEN [28], and LUNDCHARM [29]. Possible sources of background are estimated with MC simulated events generated using KKMC [27], and the event generators BABAYAGA [30] and TWOGAM [31]. The detection efficiency is determined using six different MC simulations to describe the process $e^+e^- \rightarrow$ hadrons: (i) $e^+e^- \rightarrow$ light-hadrons continuum processes including lower-mass resonances (CPLMR) with masses below $2 \text{ GeV}/c^2$, (ii) $J/\psi \rightarrow$ hadrons, (iii) $\psi(3686) \rightarrow$ hadrons, (iv) $\psi(3770) \rightarrow D^0\bar{D}^0$, (v) $\psi(3770) \rightarrow D^+D^-$, and (vi) $\psi(3770) \rightarrow \text{nOC}$. These events include initial and final-state radiation (ISR/FSR).

Inclusive hadronic events of $e^+e^- \rightarrow$ hadrons are selected from the charged and neutral-particle final states. In order to suppress background contributions from $e^+e^- \rightarrow \ell^+\ell^-$ ($\ell = e, \mu, \tau$), each event is required to have more than two charged tracks in the final state [10]. These tracks are required to satisfy the selection criteria described in Ref. [19]. To separate beam-associated background events, we determine the longitudinal position of

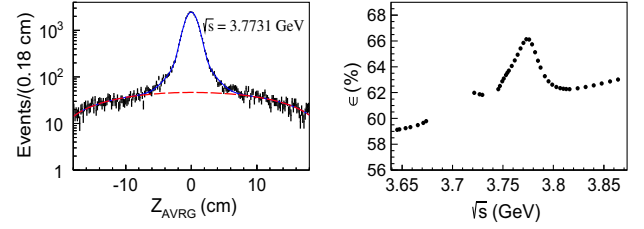


FIG. 1. Left: distribution of the averaged z position of charged tracks for the events selected from the data collected at $\sqrt{s} = 3.7731 \text{ GeV}$, where the dots with error bars represent data, the solid line is the best fit, and the dashed line is the fitted background shape. Right: weighted average efficiency ϵ for selection of the events for $e^+e^- \rightarrow$ hadrons at the 42 energies.

the event vertex, i.e. the average z position of charged tracks in the direction of the beam line. Figure 1 (left) shows the distribution of the average z for the events selected from the data sample collected at the c.m. energy $\sqrt{s} = 3.7731 \text{ GeV}$. The distribution is fitted with a double-Gaussian function (using a common peak) to describe the signal contribution, and a second-order Chebychev polynomial function to describe the background. The fit yields the number of candidates for hadronic events to be $N_{\text{had,fit}}^{\text{obs}} = 35\,235 \pm 225$. We determine the number of hadronic candidate events for the data samples collected at the other energies in a similar manner.

The fitted signal yield $N_{\text{had,fit}}^{\text{obs}}$ is contaminated by a peaking background from several sources, e.g., $e^+e^- \rightarrow (\gamma)\ell^+\ell^-$, $e^+e^- \rightarrow (\gamma)e^+e^-\ell^+\ell^-$, and $e^+e^- \rightarrow (\gamma)e^+e^-$ hadrons. Knowing the cross sections for these processes, and using large samples of MC simulated events, the number of peaking background events is estimated to be $N_b = 1547 \pm 4$, where the uncertainty is due to the statistical uncertainty of the integrated luminosity of the data sample. Subtracting N_b from $N_{\text{had,fit}}^{\text{obs}}$ yields $N_{\text{had}}^{\text{obs}} = (33688 \pm 225)$ signal events.

The weighted average (WA) efficiency ϵ for the selection of hadronic events is determined using $\epsilon = \sum_1^6 w_i \epsilon_i$, where w_i is the ratio of the number of the hadronic events selected from the i th MC simulation component over the total number of the MC simulated hadronic events from the aforementioned six MC simulation components, while ϵ_i is the corresponding efficiency. Since the branching fraction for $\psi(3770) \rightarrow \text{nOC}$ includes all contributions from decays of the full structure $\mathcal{R}_s(3770)$ [14], this efficiency includes all contributions from the decays of the BW structures contained in $\mathcal{R}_s(3770)$ [14]. Figure 1 (right) shows the WA efficiencies for the 42 energies used in this analysis.

At $\sqrt{s} = 3.7731 \text{ GeV}$, the WA efficiency is 66.13%. The integrated luminosity of the data collected at $\sqrt{s} = 3.7731 \text{ GeV}$ is $\mathcal{L} = (1831.63 \pm 4.49) \text{ nb}^{-1}$. The signal yield $N_{\text{had}}^{\text{obs}}$ divided by both the luminosity and WA efficiency yields the measured observed cross section $\sigma_{\text{had}}^{\text{obs}} = (27.813 \pm 0.198) \text{ nb}$, where the uncertainty is of

statistical origin and accounts for the number of observed events, the MC sample size and the statistical uncertainty of the luminosity measurement. This result is in good agreement with the value $\sigma_{\text{had}}^{\text{obs}} = 27.680 \pm 0.272$ nb from Ref. [10]. Similarly, we determine the cross sections $\sigma_{\text{had}}^{\text{obs}}(s)$ at the other energies. The systematic uncertainty on the cross section arises from the track and event-selection criteria, which leads to the assignment of a total systematic uncertainty of 2.89% for all cross sections [19].

We perform a least- χ^2 fit to the observed cross sections $\sigma_{\text{had}}^{\text{obs}}(s)$, which is modeled by

$$\begin{aligned} \sigma_{\text{had}}^{\text{obs}}(s) = & f_c \sigma_{\mu^+\mu^-}^{\text{born}}(s) + \int_0^{1-\frac{4m_\pi^2}{s}} dx \sigma_{J/\psi}^{\text{dress}}(s') \mathcal{F}(x, s) \\ & + \int_0^\infty dw \mathcal{G}(s, w) \int_0^{1-\frac{4m_\pi^2}{s}} dx \sigma_{\psi(3686)}^{\text{dress}}(s') \mathcal{F}(x, s). \end{aligned} \quad (1)$$

In Eq. (1), the first term represents the observed cross section for CPLMR, where $\sigma_{\mu^+\mu^-}^{\text{born}}(s)$ is the born cross section for the $e^+e^- \rightarrow \mu^+\mu^-$ continuum process and f_c is a free parameter. The second term represents the observed cross section of $J/\psi \rightarrow$ hadrons including the ISR correction, where $\sigma_{J/\psi}^{\text{dress}}(s')$ is the dressed cross section (i.e., including vacuum polarization effects) for $J/\psi \rightarrow$ hadrons, $s' = s(1-x)$, with x a parameter relating to the total energy of the emitted ISR photons [32], $\mathcal{F}(x, s)$ is the sampling function [32], and m_π is the mass of the pion. The third term describes the observed cross sections for the hadronic decays of the states or structures with masses above 3.680 GeV, $\sigma_{\psi(3686)}^{\text{dress}}(s') = \sigma_{\psi(3686)}^{\text{dress}}(s') + \sigma_{X_{\text{aboveOC}}}^{\text{dress}}(s')$, in which $\sigma_{\psi(3686)}^{\text{dress}}(s')$ is the dressed cross section for $\psi(3686) \rightarrow$ hadrons, $\sigma_{X_{\text{aboveOC}}}^{\text{dress}}(s')$ is the total dressed cross section for $X_{\text{aboveOC}} \rightarrow$ hadrons, including the continuum $D\bar{D}$ production, $\mathcal{G}(s, w)$ is a Gaussian function describing the beam-energy spread (1.355 MeV), and w integrates over the energy. The dressed cross sections for J/ψ and $\psi(3686)$ decaying into hadrons are determined by $\sigma_{J/\psi}^{\text{dress}}(s') = |\mathcal{A}_{J/\psi}(s')|^2$ and $\sigma_{\psi(3686)}^{\text{dress}}(s') = |\mathcal{A}_{\psi(3686)}(s')|^2$, where $\mathcal{A}_{J/\psi}(s')$ and $\mathcal{A}_{\psi(3686)}(s')$ are parametrized by

$$\mathcal{A}_S(s') = \sqrt{12\pi\Gamma_S^{ee}\mathcal{B}\Gamma_S^{\text{tot}}} / [(s' - M_S^2) + i\Gamma_S^{\text{tot}}M_S], \quad (2)$$

where S indicates J/ψ and $\psi(3686)$, M_S , Γ_S^{ee} , and Γ_S^{tot} are its mass, electronic width, and total width, respectively, and $\mathcal{B}$ is the branching fraction for $S \rightarrow$ hadrons. The dressed cross section for $X_{\text{aboveOC}} \rightarrow$ hadrons is modeled by

$$\begin{aligned} \sigma_{X_{\text{aboveOC}}}^{\text{dress}}(s') = & |\mathcal{A}_{\text{cnt}D\bar{D}}(s') + \mathcal{A}_{\mathcal{G}(3900)}(s')e^{i\phi_0} \\ & + \mathcal{A}_{\mathcal{R}(3760)}(s')e^{i\phi_1} + \mathcal{A}_{\mathcal{R}(3780)}(s')e^{i\phi_2} \\ & + \mathcal{A}_{\mathcal{R}(3810)}(s')e^{i\phi_3}|^2. \end{aligned} \quad (3)$$

In Eq. (3), the first term is the amplitude of the continuum $D\bar{D}$ production,

$$\mathcal{A}_{\text{cnt}D\bar{D}}(s') = [f_{D\bar{D}}(\beta_0^3 + \beta_+^3)\sigma_{\mu^+\mu^-}^{\text{born}}(s')]^{\frac{1}{2}}, \quad (4)$$

where β_0 and β_+ are the velocities [6] of the D^0 and D^+ mesons, respectively, and $f_{D\bar{D}}$ is a free parameter; The second term is the decay amplitude for the structure $\mathcal{G}(3900)$ [21,33], for which we use $\mathcal{A}_{\mathcal{G}(3900)}(s') = [\mathcal{C}e^{-(\sqrt{s'}-M_{\mathcal{G}})^2/(2\sigma_{\mathcal{G}}^2)}]^{\frac{1}{2}}$ as the amplitude, where $\mathcal{C}$ is a free parameter, $M_{\mathcal{G}}$ and $\sigma_{\mathcal{G}}$ are the peak position and standard deviation of the $\mathcal{G}(3900)$ structure, respectively. The combination of the first and second terms best describe the shape of the nonresonant $D\bar{D}$ cross sections. This shape is determined separately using data and fixed in fitting the measured $\sigma_{\text{had}}^{\text{obs}}(s)$ and their corresponding dressed cross sections below. We refer to this procedure as *cross-section spectrum separation*; The remaining terms: terms $\mathcal{A}_{\mathcal{R}(3760)}(s')$, $\mathcal{A}_{\mathcal{R}(3780)}(s')$, and $\mathcal{A}_{\mathcal{R}(3810)}(s')$ are the amplitudes for $\mathcal{R}(3760)$, $\mathcal{R}(3780)$, and $\mathcal{R}(3810)$ decaying into hadrons, respectively, and are described by Eq. (2), while ϕ_0 , ϕ_1 , ϕ_2 , and ϕ_3 in Eq. (3) are phases. For the $\mathcal{R}(3780)$, the energy dependent total width [6] is used in its amplitude.

The sum of the dressed-resonance cross sections and the observed-continuum- J/ψ (drocj) cross section is given by

$$\sigma_{\text{had}}^{\text{drocj}}(s) = f_c \sigma_{\mu^+\mu^-}^{\text{born}}(s) + \sigma_{J/\psi}^{\text{obs}}(s) + \sigma_{\psi(3686)}^{\text{dress}}(s), \quad (5)$$

where $\sigma_{J/\psi}^{\text{obs}}(s) = \int_0^{1-4m_\pi^2/s} dx \sigma_{J/\psi}^{\text{dress}}(s') \mathcal{F}(x, s)$. For the study of the decays of X_{aboveOC} states it is not necessary to perform radiative corrections for the first and second terms in Eq. (5).

In the fit, the BW parameters of the J/ψ and $\psi(3686)$ states are fixed to the central values given by the 2022 Particle Data Group [34]. $M_{\mathcal{G}}$, $\sigma_{\mathcal{G}}$, and $\mathcal{C}$ are fixed to $(3873.6 \pm 4.7 \pm 0.1)$ MeV/ c^2 , $(53.3 \pm 6.3 \pm 0.1)$ MeV, and $(1.07 \pm 0.29 \pm 0.03)$ nb $^{\frac{1}{2}}$, respectively, $f_{D\bar{D}}$ is fixed to $(0.212 \pm 0.177 \pm 0.006)$ nb $^{\frac{1}{2}}$, and ϕ_0 is fixed to zero degrees. These values are determined by separately fitting the cross sections of $e^+e^- \rightarrow D\bar{D}$ at energies from 3.74 to 3.99 GeV, measured using the BESIII data [35], in which we do not observe the $\mathcal{R}(3810)$; the first uncertainties are from the fits to the cross sections, and the second are due to the uncertainties in both the cross section measurements and the branching fraction for $\mathcal{R}(3760) \rightarrow D\bar{D}$ and $\mathcal{R}(3780) \rightarrow D\bar{D}$. In the fit, these branching fractions are fixed to $(85 \pm 6)\%$ [12], determined by fitting cross sections for $e^+e^- \rightarrow$ non- $D\bar{D}$ over 150 energy points from 3.65 to 3.87 GeV. We assume that the branching fractions for $\mathcal{R}(3760) \rightarrow$ hadrons, $\mathcal{R}(3780) \rightarrow$ hadrons, and $\mathcal{R}(3810) \rightarrow$ hadrons are all 100% in the fit. The other parameters are left free in the fit. Using Eq. (1) we fit the

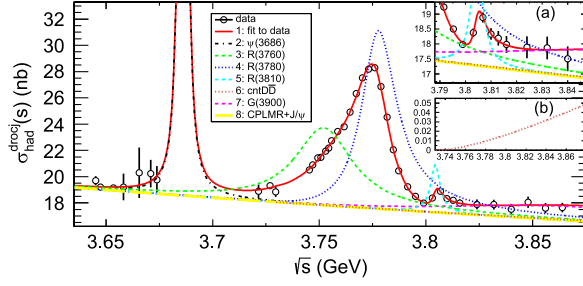


FIG. 2. Measured dressed-resonance cross sections and the observed-continuum- J/ψ cross sections for $e^+e^- \rightarrow \text{hadrons}$ with the fit superimposed (see text for details).

measured observed cross sections $\sigma_{\text{had}}^{\text{obs}}(s)$ to determine the values of the free parameters.

Inserting these parameter values into Eq. (1) and Eq. (5) yields the expected observed cross sections $\sigma_{\text{had}}^{\text{obs}}(s)$ and expected drocj cross sections $\sigma_{\text{had}}^{\text{drocj}}(s)$, which give the ISR correction factors $f_{\text{ISR}}(s) = \sigma_{\text{had}}^{\text{obs}}(s)/\sigma_{\text{had}}^{\text{drocj}}(s)$. Dividing the measured observed cross sections $\sigma_{\text{had}}^{\text{obs}}(s)$ by $f_{\text{ISR}}(s)$ yields the measured drocj cross sections $\sigma_{\text{had}}^{\text{drocj}}(s)$ [36]. The circles with error bars in Fig. 2 show the $\sigma_{\text{had}}^{\text{drocj}}(s)$ results.

Using Eq. (5) we fit the $\sigma_{\text{had}}^{\text{drocj}}(s)$ results and obtain the values for these parameters. The nominal fit returns six solutions with fit χ^2 less than 26. For four of the six solutions, the $\mathcal{R}(3780)$ electronic widths are less than 120 eV or larger than 415 eV, which are not consistent with 262 eV for the 1^3D_1 -wave dominant state, i.e., $\psi(3770)$ resonance [34], hence these are not physical solutions. Table I presents the values of the parameters for the remaining two solutions, where the first uncertainties are

TABLE I. Results from the fit to the measured cross sections of $e^+e^- \rightarrow \text{hadrons}$ showing the values of the mass M_i [in MeV/ c^2], total width Γ_i^{tot} [in MeV], electronic width Γ_i^{ee} [in eV], relative phase ϕ_i [in degree], and f_c , where i represents $\mathcal{R}(3760)$, $\mathcal{R}(3780)$, and $\mathcal{R}(3810)$.

Parameters	Solution I	Solution II
$M_{\mathcal{R}(3760)}$	$3752.6 \pm 4.2 \pm 2.8$	$3751.9 \pm 3.8 \pm 2.8$
$\Gamma_{\mathcal{R}(3760)}^{\text{tot}}$	$31.7 \pm 5.7 \pm 8.4$	$32.8 \pm 5.8 \pm 8.7$
$\Gamma_{\mathcal{R}(3760)}^{ee}$	$206 \pm 83 \pm 96$	$184 \pm 75 \pm 86$
ϕ_1	$-70 \pm 23 \pm 39$	$-49 \pm 29 \pm 27$
$M_{\mathcal{R}(3780)}$	$3778.6 \pm 0.5 \pm 0.3$	$3778.7 \pm 0.5 \pm 0.3$
$\Gamma_{\mathcal{R}(3780)}^{\text{tot}}$	$20.3 \pm 0.8 \pm 1.7$	$20.3 \pm 0.8 \pm 1.7$
$\Gamma_{\mathcal{R}(3780)}^{ee}$	$243 \pm 61 \pm 76$	$265 \pm 69 \pm 83$
ϕ_2	$131 \pm 16 \pm 15$	$151 \pm 23 \pm 17$
$M_{\mathcal{R}(3810)}$	$3804.5 \pm 0.9 \pm 0.9$	$3804.5 \pm 0.9 \pm 0.9$
$\Gamma_{\mathcal{R}(3810)}^{\text{tot}}$	$5.6 \pm 3.6 \pm 3.4$	$5.4 \pm 3.5 \pm 3.2$
$\Gamma_{\mathcal{R}(3810)}^{ee}$	$2.3 \pm 0.8 \pm 1.4$	$19.4 \pm 7.4 \pm 12.1$
ϕ_3	$81 \pm 22 \pm 18$	$-11 \pm 20 \pm 2$
f_c	$2.743 \pm 0.019 \pm 0.081$	$2.741 \pm 0.019 \pm 0.081$

from the fit to $\sigma_{\text{had}}^{\text{drocj}}(s)$, and the second are systematic. The two solutions have χ^2 values of 25.5 and 25.6 for 29 degrees of freedom (d.o.f.). Since no $\mathcal{R}(3810)$ is observed in the $D\bar{D}$ final state, the nonopen-charm branching fraction of $\mathcal{R}(3810)$ decay must be close to 100%. This indicates $\Gamma_{\mathcal{R}(3810)}^{ee} = 11.0 \pm 2.9 \pm 2.4$ eV, determined from $\Gamma_{\mathcal{R}(3810)}^{ee} \mathcal{B}_{\mathcal{R}(3810)}$ given in [19]. By comparing this value to those in Table I, we choose solution II as the baseline result. Compared with the measured values in Ref. [14], the precision of the $\mathcal{R}(3760)$ and $\mathcal{R}(3780)$ resonance parameters has improved by factors of 1.5 to 3.1.

The systematic uncertainties on the values of the parameters given in Table I originate from three sources: (i) the systematic uncertainties on the observed cross sections, (ii) the uncertainties of the fixed parameters, and (iii) the uncertainties on the c.m. energies. The estimations of these uncertainties are similar to those described in Ref. [19]. Adding these uncertainties in quadrature yields the total systematic uncertainty for each parameter value given in Table I.

Figure 2 also shows the fit to $\sigma_{\text{had}}^{\text{drocj}}(s)$, where the cross section described by solution II is superimposed on the results. Also shown are the fit results including one contribution to $\sigma_{\mathcal{R}(3760)}^{\text{dress}}(s)$ included at a time, which is added to the total observed hadronic cross sections of CPLMR and J/ψ . The inset (a) shows the cross-section data in the energy range from 3.788 to 3.847 GeV, while the dashedline in (b) only shows the cross sections of the continuum $D\bar{D}$ contribution. The measured mass of $\mathcal{R}(3780)$ is consistent within 1.5σ , and the measured mass of $\mathcal{R}(3760)$ and widths of $\mathcal{R}(3760)$ and $\mathcal{R}(3780)$ are consistent within 0.8σ with those [14,37] measured by BES-II. The values for the masses and total widths of the $\mathcal{R}(3760)$ and $\mathcal{R}(3810)$ measured in this work supersede those reported in Ref. [19].

To evaluate the significance of the $\mathcal{R}(3810)$ signal, we refit $\sigma_{\text{had}}^{\text{drocj}}(s)$ with the $\mathcal{R}(3760)$ mass and total width fixed to $(3739.9 \pm 4.2 \pm 2.6)$ MeV/ c^2 [19] and $(23.9 \pm 8.2 \pm 4.8)$ MeV [19], respectively. The original fit (fit-A) including the $\mathcal{R}(3810)$ returns $\chi^2 = 49.7$ for 31 d.o.f., while the fit (fit-B) excluding the $\mathcal{R}(3810)$ returns $\chi^2 = 116.7$ for 35 d.o.f. The significance for the $\mathcal{R}(3810)$, including systematic uncertainty, is determined to be 7.4σ from the change in χ^2 and number of degrees of freedom between the two fits. In an alternative approach, we refit $\sigma_{\text{had}}^{\text{drocj}}(s)$ with the $\mathcal{R}(3810)$ mass and total width fixed to $(3805.7 \pm 1.1 \pm 2.7)$ MeV/ c^2 [19] and $(11.6 \pm 2.9 \pm 1.9)$ MeV [19], respectively. The fit (fit-C) including the $\mathcal{R}(3760)$ returns $\chi^2 = 31.8$ for 31 d.o.f., while the fit (fit-D) excluding the $\mathcal{R}(3760)$ returns $\chi^2 = 289.8$ for 35 d.o.f. Comparing fit-C and fit-D, we calculate a significance for the $\mathcal{R}(3760)$ signal of 15.6σ , where systematic uncertainties have been taken into account.

To investigate whether the parameterizations for the continuum $D\bar{D}$ amplitudes could be responsible for the cross-section enhancement around 3.76 GeV shown in Fig. 2, we remove both the $\mathcal{R}(3760)$ and $\mathcal{R}(3810)$ amplitudes and either replace $\sqrt{f_{D\bar{D}}}$ in Eq. (4) with an exponential factor $f_{\text{NR}} e^{-(p_{D^0} + p_{D^+})^2/\lambda^2}$ [38] in the fit (fit-E), or use a threshold function $(\sqrt{s} - 2m_{D^0})^d e^{-h\sqrt{s}-ts}$ [21] to replace $\mathcal{A}_{\text{cont}D\bar{D}}(s')$ in Eq. (3) in the fit (fit-F), where p_{D^0} (p_{D^+}) and m_{D^0} (m_{D^+}) are the momentum and mass of the D^0 (D^+) meson, respectively. Here f_{NR} , λ , d , h , and t are parameters describing the shape of the continuum $D\bar{D}$ contribution. In the fits, the values for these parameters are fixed to those determined by analyzing the cross sections for $e^+e^- \rightarrow D\bar{D}$ using the function given in Eq. (3). Fit-E and fit-F return $\chi^2 = 119.1$ (probability value $\text{PV} \leq 2 \times 10^{-10}$) and $\chi^2 = 225.8$ ($\text{PV} \leq 1 \times 10^{-28}$) for 37 d.o.f., respectively, indicating that fit-E and fit-F are strongly incompatible with the data.

The vector dominance model (VDM) assumes that the $\psi(3686)$ can decay into $D\bar{D}$ pairs at energies above the $D\bar{D}$ production threshold [39]. To check the validity of the VDM approach, we remove the amplitude $\mathcal{A}_{\mathcal{R}(3810)}(s')$, and replace the amplitude $\mathcal{A}_{\mathcal{R}(3760)}(s')$ in Eq. (3) with $\mathcal{A}_{\psi'}(s') = \sqrt{12\pi\Gamma_{\psi'}^{ee}\Gamma_{\psi'}^{D\bar{D}}}/[(s' - M_{\psi'}^2) + i\Gamma_{\psi'}^{\text{tot above } D\bar{D}} M_{\psi'}(s')] [18]$ in the fit (fit-G), where ψ' is the $\psi(3686)$, while $\Gamma_{\psi'}^{\text{tot above } D\bar{D}}$ and $\Gamma_{\psi'}^{D\bar{D}}$ are the total and $D\bar{D}$ widths of this resonance, respectively. $\Gamma_{\psi'}^{\text{tot above } D\bar{D}}$ is chosen to be energy dependent and defined as that for $\psi(3770)$ [6,23] with branching fractions $B_{00}[\psi(3686) \rightarrow D^0\bar{D}^0]$ and $B_{+-}[\psi(3686) \rightarrow D^+D^-]$ fixed to 56% and 44%, respectively. In fit-G, the values for $\Gamma_{\psi'}^{\text{tot above } D\bar{D}}$, $\Gamma_{\psi(3686)}^{D\bar{D}}$ and ϕ_1 are fixed to those determined by analyzing the cross sections for $e^+e^- \rightarrow D\bar{D}$ using the function given in Eq. (3). Fit-G returns $\chi^2 = 139.4$ ($\text{PV} \leq 9 \times 10^{-14}$) for 37 d.o.f. This poor goodness of fits indicates that the VDM approach alone cannot explain the $\mathcal{R}(3760)$ and $\mathcal{R}(3810)$ structures [40].

The *cross-section spectrum separation* technique performed in fitting these $\sigma_{\text{had}}^{\text{drocj}}(s)$ accurately separates the final states of $\mathcal{R}(3760)$, $\mathcal{R}(3780)$, and $\mathcal{R}(3810)$ decays to hadrons from the final states of nonresonant decay to $D\bar{D}$, thereby achieving the most precise measurement of the parameters of the three resonances. The results returned from fitting $\sigma_{\text{had}}^{\text{drocj}}(s)$ make clear that the $\psi(3770)$ is a complex system composed of the $\mathcal{R}(3760)$, $\mathcal{R}(3780)$, and $\mathcal{R}(3810)$ resonances. In other words, the $\psi(3770)$ [1,2] resonance is a single BW artifact that is compatible with less precise measurements of the cross section of $e^+e^- \rightarrow \text{hadrons}$ at energies from 3.73 to 3.87 GeV, where the three BW structures [labeled as $\mathcal{R}(3760)$, $\mathcal{R}(3780)$, and $\mathcal{R}(3810)$ in the Letter] cannot be distinguished. Therefore, the $\psi(3770)$ cannot itself be the 1^3D_1 -wave dominate state of charmonium.

The potential model [9] predicts that only the charmonium 1^3D_1 state can be produced in e^+e^- collisions at c.m. energies from 3.732 to 3.871 GeV. A model called “a new spectroscopy” [16] proposes that a p -wave resonance of a four-quark ($c\bar{c}q\bar{q}$) state can be produced in e^+e^- collisions at c.m. energies above 3.732 GeV. This four-quark state can be either a simple four-quark bound state or an open charm molecular state. It is natural to interpret the $\mathcal{R}(3760)$ as an open charm pair molecular state [15], since its mass of $(3751.9 \pm 3.8 \pm 2.8) \text{ MeV}/c^2$ is $(12.6 \pm 4.7) \text{ MeV}/c^2$ higher than the D^+D^- production threshold $(3739.3 \pm 0.1) \text{ MeV}/c^2$ and its total width is $(32.8 \pm 5.8 \pm 8.7) \text{ MeV}$. As the $\mathcal{R}(3760)$ is also observed in nonopen charm hadron final states with a resonance peak at $(3739.7 \pm 4.7) \text{ MeV}/c^2$ [19], the $\mathcal{R}(3760)$ could also contain a component of the simple four-quark state. This feature is consistent with the four-quark state production and decay [16]. The $\mathcal{R}(3810)$ can be interpreted as a hadro-charmonium state [41], since no $\mathcal{R}(3810)$ is observed in the cross sections of $e^+e^- \rightarrow D\bar{D}$, and its mass, which is $(3804.5 \pm 0.9 \pm 0.9) \text{ MeV}/c^2$, is very close to the $h_c\pi^+\pi^-$ threshold $(3804.5 \pm 0.1) \text{ MeV}/c^2$. The $\mathcal{R}(3780)$ total width, which is $(20.3 \pm 0.8 \pm 1.7) \text{ MeV}$, is consistent with the range of possible values from 10 to 26 MeV predicted by the potential models [42–44] for the 1^3D_1 state. The potential model [44] also predicts that the total width of 1^3D_1 state is less (larger) than 7 (47) MeV for a mass of 3752 (3805) MeV, indicating that neither the $\mathcal{R}(3760)$ nor the $\mathcal{R}(3810)$ is the 1^3D_1 state. These experiment results and theoretical predictions lead us to interpret the $\mathcal{R}(3780)$ as a resonance dominated by the 1^3D_1 -wave charmonium state.

In summary, measurements of the total cross sections for $e^+e^- \rightarrow \text{hadrons}$ [45] at c.m. energies from 3.645 to 3.871 GeV have been performed with higher precision than in previous analyses. We have performed the most precise measurements of the parameters of the $\mathcal{R}(3760)$, $\mathcal{R}(3780)$, and $\mathcal{R}(3810)$ resonances. The $\mathcal{R}(3810)$ can be interpreted as a hadro-charmonium state. The $\mathcal{R}(3760)$ can be interpreted as an open-charm molecular state, but may contain a component from a four-quark state contribution. We have established that the $\psi(3770)$ is not a single resonance, but a complex system composed of the $\mathcal{R}(3760)$, $\mathcal{R}(3780)$, and $\mathcal{R}(3810)$ resonances. Among these, we interpret the $\mathcal{R}(3780)$ is a resonance dominated by the 1^3D_1 charmonium state. These results provide important experimental input to help in the understanding of the natures of $c\bar{c}$ and non- $c\bar{c}$ states.

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 R&D Program of China under Contracts No. 2009CB825204, No. 2020YFA0406300, No. 2020YFA0406400; National Natural Science Foundation of China (NSFC) under Contracts

No. 10935007, No. 11635010, No. 11735014,
 No. 11835012, No. 11935015, No. 11935016,
 No. 11935018, No. 11961141012, No. 12022510,
 No. 12025502, No. 12035009, No. 12035013,
 No. 12061131003, No. 12192260, No. 12192261,
 No. 12192262, No. 12192263, No. 12192264,
 No. 12192265, No. 12221005, No. 12225509,
 No. 12235017; the Chinese Academy of Sciences (CAS)
 Large-Scale Scientific Facility Program; the CAS Center
 for Excellence in Particle Physics (CCEPP); CAS Key
 Research Program of Frontier Sciences under Contracts
 No. QYZDJ-SSW-SLH003, No. QYZDJ-SSW-SLH040;
 100 Talents Program of CAS; the CAS Research Program
 under Code No. Y41G1010Y1; the CAS Other Research
 Program under Code No. Y129360; The Institute of
 Nuclear and Particle Physics (INPAC) and Shanghai Key
 Laboratory for Particle Physics and Cosmology; ERC
 under Contract No. 758462; European Union's Horizon
 2020 research and innovation programme under Marie
 Skłodowska-Curie grant agreement under Contract
 No. 894790; German Research Foundation DFG under
 Contracts No. 443159800, No. 455635585, Collaborative
 Research Center CRC 1044, FOR5327, GRK 2149; Istituto
 Nazionale di Fisica Nucleare, Italy; Ministry of
 Development of Turkey under Contract No. DPT2006K-
 120470; National Research Foundation of Korea under
 Contract No. NRF-2022R1A2C1092335; National Science
 and Technology fund of Mongolia; National Science
 Research and Innovation Fund (NSRF) via the Program
 Management Unit for Human Resources & Institutional
 Development, Research and Innovation of Thailand under
 Contract No. B16F640076; Polish National Science Centre
 under Contract No. 2019/35/O/ST2/02907; The Swedish
 Research Council; U.S. Department of Energy under
 Contract No. DE-FG02-05ER41374.

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