

Study of Open-Charm Decays and Radiative Transitions of the $X(3872)$

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The processes $X(3872) \rightarrow D^{*0}\bar{D}^0 + \text{c.c.}, \gamma J/\psi, \gamma\psi(2S)$, and γD^+D^- are searched for in a 9.0 fb^{-1} data sample collected at center-of-mass energies between 4.178 and 4.278 GeV with the BESIII detector. We observe $X(3872) \rightarrow D^{*0}\bar{D}^0 + \text{c.c.}$ and find evidence for $X(3872) \rightarrow \gamma J/\psi$ with statistical significances of 7.4σ and 3.5σ , respectively. No evident signals for $X(3872) \rightarrow \gamma\psi(2S)$ and γD^+D^- are found, and the upper limit on the relative branching ratio $R_{\gamma\psi} \equiv \{\mathcal{B}[X(3872) \rightarrow \gamma\psi(2S)]\}/\{\mathcal{B}[X(3872) \rightarrow \gamma J/\psi]\} < 0.59$ is set at 90% confidence level. Measurements of branching ratios relative to decay $X(3872) \rightarrow \pi^+\pi^-J/\psi$ are also reported for decays $X(3872) \rightarrow D^{*0}\bar{D}^0 + \text{c.c.}, \gamma\psi(2S), \gamma J/\psi$, and γD^+D^- , as well as the non- $D^{*0}\bar{D}^0$ three-body decays $\pi^0 D^0\bar{D}^0$ and $\gamma D^0\bar{D}^0$.

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Since the discovery of the $X(3872)$ in 2003 [1] by the Belle Collaboration, many properties of this exotic state have been reported, including its mass, an upper limit (UL) on its width, and its J^{PC} quantum numbers [2,3]. The ratio of the branching fraction (BF) of $X(3872) \rightarrow \gamma\psi'$ [in this Letter we use the notation ψ' to denote the $\psi(2S)$ resonance] to $X(3872) \rightarrow \gamma J/\psi$, $R_{\gamma\psi} \equiv \{\mathcal{B}[X(3872) \rightarrow \gamma\psi']\}/\{\mathcal{B}[X(3872) \rightarrow \gamma J/\psi]\}$, is predicted to be in the range $(3-4) \times 10^{-3}$ if the $X(3872)$ is a $D^{*0}\bar{D}^0$ molecule [4,5], 0.5–5 if it is a molecule-charmonium mixture [6], and 1.2–15 if it is a pure charmonium state [7–13]. LHCb reported a 4.4σ evidence for the decay $X(3872) \rightarrow \gamma\psi'$ with

$R_{\gamma\psi} = 2.46 \pm 0.64 \pm 0.29$ [14], which is in good agreement with the BABAR result $R_{\gamma\psi} = 3.4 \pm 1.4$ [15]. On the other hand, the Belle Collaboration reports an upper limit of $R_{\gamma\psi} < 2.1$ at the 90% confidence level (C.L.) [16]. $X(3872)$ is produced at BESIII via the radiative decay from the $Y(4260)$ state [17,18] with a background level lower than at other experiments. This makes BESIII particularly well suited for studies of $X(3872)$ decays to final states containing photons and π^0 mesons.

With BESIII we cannot measure absolute BFs of $X(3872)$ decays since the cross section of $e^+e^- \rightarrow \gamma X(3872)$ is unknown. Instead, we determine their ratios to the $\pi^+\pi^-J/\psi$ mode. As discussed in Ref. [4], the BF ratio of $\{\mathcal{B}[X(3872) \rightarrow D^{*0}\bar{D}^0 + \text{c.c.}]\}/\{\mathcal{B}[X(3872) \rightarrow \pi^+\pi^-J/\psi]\}$ can be reliably calculated if the $X(3872)$ is a weakly bound molecule, in which case the ratio is predicted to be around 0.08 for a binding energy of 0.7 MeV. Additionally, the decay width to γD^+D^- is predicted to be 0.2 keV for the molecular case.

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In this Letter, we report the study of $X(3872) \rightarrow D^{*0}\bar{D}^0$, $\gamma J/\psi$, $\gamma\psi'$, and γD^+D^- using e^+e^- annihilation data collected with the BESIII detector at center-of-mass energies ranging from 4.178 to 4.278 GeV. The total integrated luminosity is 9.0 fb^{-1} . Charge-conjugate modes are implied throughout. A detailed description of the BESIII detector and the upgrade of the time-of-flight system can be found in Refs. [19,20].

Monte Carlo (MC)-simulated event samples are produced with a GEANT4-based [21] framework. Large simulated samples of generic $e^+e^- \rightarrow$ hadrons events, which in total are 40 times the size of the data sample, are used to estimate background conditions. The simulation of inclusive MC samples is described in Ref. [22]. The signal process $e^+e^- \rightarrow \gamma X(3872)$ is generated assuming it is a pure electric dipole (E1) transition, and the subsequent $X(3872)$ decays are generated uniformly in the phase space except $X(3872) \rightarrow \gamma J/\psi(\gamma\psi')$, which is generated assuming a pure E1 transition too. The $X(3872)$ resonance is described with a Flatté formula with parameter values taken from Ref. [23].

When selecting $X(3872) \rightarrow \gamma J/\psi$ decays, we use lepton pairs ($\ell^+\ell^-$, $\ell = e, \mu$) to reconstruct the J/ψ , while for the $X(3872) \rightarrow \gamma\psi'$ selection, we exploit the decays $\psi' \rightarrow \pi^+\pi^-J/\psi$ ($J/\psi \rightarrow \ell^+\ell^-$) and $\psi' \rightarrow \mu^+\mu^-$. We use the same selection criteria for the charged tracks and photons as described in Ref. [18]. The invariant mass of the lepton pair is required to be $|M(\ell^+\ell^-) - m_{J/\psi(\psi')}| < 0.02 \text{ GeV}/c^2$ for the J/ψ or ψ' selection. We use throughout this Letter the notation m_{particle} to represent the mass of the specific particle listed in the Particle Data Group [24]. In the case of $X(3872)$ decays to charmed mesons, the $D^{*0} \rightarrow \gamma D^0$ and $\pi^0 D^0$ decays are used to reconstruct the D^{*0} . The D^0 is reconstructed via its $K^-\pi^+$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^+\pi^-$ decay modes, while the D^+ is reconstructed via its $K^-\pi^+\pi^+$ and $K^-\pi^+\pi^+\pi^0$ modes. The particle identification (PID) of kaons and pions is based on the dE/dx and time-of-flight information. Assumption of a given particle identification is based on the larger of the two PID hypotheses probabilities.

A kinematic fit is performed to the event, with the constraints on the masses of the π^0 and $D^{\pm/0}$ candidates and the initial four momentum of the colliding beams. When there are ambiguities due to multiphoton candidates in the same event, we choose the combination with the smallest χ^2 from the kinematic fit. The χ^2 of the kinematic fit is required to be less than 40 for $X(3872) \rightarrow \gamma J/\psi$ and less than 60 for the other modes. In addition, the χ^2 of the kinematic fit of the hypothesis under study should be smaller than those for hypotheses with extra or fewer photons. For all channels other than $X(3872) \rightarrow \pi^0 D^0\bar{D}^0$, there are two radiative photons. One is produced in e^+e^- annihilation directly and the other from $X(3872)$ or D^* decay. We denote the photon with larger energy after the kinematic fit as γ_H and the other γ_L . In these decays, π^0 and

η vetoes are imposed on the invariant mass of the photon pair $M(\gamma_L\gamma_H)$ to suppress further the possible π^0 and η background, i.e., $|M(\gamma_L\gamma_H) - m_{\pi^0(\eta)}| > 0.02(0.03) \text{ GeV}/c^2$.

For the decay $X(3872) \rightarrow \gamma J/\psi$, studies performed on the inclusive MC sample indicate that the dominant backgrounds are Bhabha and dimuon events for $J/\psi \rightarrow e^+e^-$ and $\mu^+\mu^-$, respectively. To suppress Bhabha events in the $J/\psi \rightarrow e^+e^-$ selection, the cosine of the polar angle of the selected photons $\cos\theta$ is required to be within the interval $[-0.7, 0.7]$. For $\sqrt{s} = 4.178\text{--}4.278 \text{ GeV}$, the energy of the photon from $e^+e^- \rightarrow \gamma X(3872)$ is always lower than that from $X(3872) \rightarrow \gamma J/\psi$. Background from $e^+e^- \rightarrow \gamma\chi_{c1,2}$ with $\chi_{c1,2} \rightarrow \gamma J/\psi$ is suppressed by requiring $|M(\gamma_L J/\psi) - m_{\chi_{c1,2}}| > 0.02 \text{ GeV}/c^2$. Here and below, $M(\gamma_{H/L} J/\psi) \equiv M(\gamma_{H/L} \ell^+ \ell^-) - M(\ell^+ \ell^-) + m_{J/\psi}$. Neither peaking nor $\chi_{c1,2}$ background is found in the $M(\gamma_H J/\psi)$ spectra.

To obtain the number of signal events, a simultaneous fit is performed on the mass spectra of $\gamma_H J/\psi$ with $J/\psi \rightarrow \mu^+\mu^-$ and e^+e^- . Throughout this Letter, we use an unbinned maximum-likelihood fit as the nominal fit method. The ratio of signal yields for $\mu^+\mu^-$ and e^+e^- modes is constrained to the ratio of the corresponding BF's, corrected by the ratio of the corresponding reconstruction efficiencies. In the fit, the signal distributions are described with shapes obtained from the MC simulation, and the backgrounds are described with a second-order Chebyshev polynomial. The signal yield, background normalization, and coefficients of the polynomial are free in this fit and the other fits in this Letter. The distributions of $M(\gamma_H J/\psi)$ as well as the fit results are shown in Fig. 1(a). The statistical significance for $X(3872) \rightarrow \gamma J/\psi$ is always greater than 3.5σ , evaluated with a range of alternative background shapes. The significance is calculated by comparing the likelihoods with and without the signal components included and taking the change in the number of degrees of freedom (NDF) into account. From the fit, we obtain $(20.1 \pm 6.2) \times 10^2$ BF- and efficiency-corrected $X(3872) \rightarrow \gamma J/\psi$ events, corresponding to 38.8 ± 11.9 and 18.4 ± 5.6 events for $J/\psi \rightarrow \mu^+\mu^-$ and e^+e^- , respectively. The goodness of the fit is $\chi^2/\text{NDF} = 27.8/52$ ($p = 1.0$).

For the decay $X(3872) \rightarrow \gamma\psi'$ with $\psi' \rightarrow \mu^+\mu^-$, the selection criteria for $\psi' \rightarrow \mu^+\mu^-$ are analogous as those for $J/\psi \rightarrow \mu^+\mu^-$. For the $\psi' \rightarrow \pi^+\pi^-J/\psi$ channel, we select events with the corrected mass $M(\pi^+\pi^-J/\psi) \equiv M(\pi^+\pi^-\ell^+\ell^-) - M(\ell^+\ell^-) + m_{J/\psi}$ satisfying $|M(\pi^+\pi^-J/\psi) - m_{\psi'}| < 0.006 \text{ GeV}/c^2$ as the signal-event candidates. The main background is $e^+e^- \rightarrow \pi^+\pi^-\psi'$, with $\psi' \rightarrow \gamma\gamma J/\psi$. We require $|M(\pi^+\pi^-)_{\text{recoil}} - m_{\psi'}| > 0.01 \text{ GeV}/c^2$ to suppress these events, where $M(\pi^+\pi^-)_{\text{recoil}}$ is the recoiling mass of the $\pi^+\pi^-$ system.

To determine the number of $X(3872) \rightarrow \gamma\psi'$ decays, similar fits are performed to the invariant-mass $M(\gamma\psi')$ distribution as described above, where γ includes γ_L and

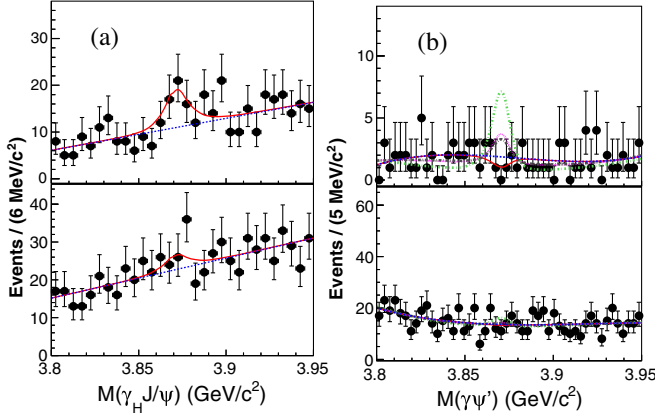


FIG. 1. (a) Fit results for $X(3872) \rightarrow \gamma J/\psi$ for the $\mu^+\mu^-$ (top) and e^+e^- (bottom) mode. (b) Fit results for $X(3872) \rightarrow \gamma\psi'$ for the $\pi^+\pi^-J/\psi$ (top) and $\mu^+\mu^-$ (bottom) mode. The points with error bars are from data, the red curves are the best fit. In (b), the rose-red dotted line represents the fit with the signal constrained to the expectation using $X(3872) \rightarrow \pi^+\pi^-J/\psi$ based on the relative ratios taken from a global fit [25]; the green dash-dotted lines are using $X(3872) \rightarrow \gamma J/\psi$ as the reference based on the LHCb measurement [14], and the gray long dashed lines are using $X(3872) \rightarrow \gamma J/\psi$ as the reference based on the Belle measurement [16].

γ_H . The distribution of $M(\gamma\psi')$ as well as the fitting results are shown in Fig. 1(b). The fit yields $(-1.1 \pm 5.2) \times 10^2$ BF- and efficiency-corrected $X(3872) \rightarrow \gamma\psi'$ events, corresponding to -0.9 ± 4.1 and -0.4 ± 1.6 $\psi' \rightarrow \pi^+\pi^-J/\psi$ and $\mu^+\mu^-$ events, respectively, and the goodness of the fit is $\chi^2/\text{NDF} = 45.0/58$ ($p = 0.89$). The UL of the number of BF- and efficiency-corrected events is calculated to be 1.0×10^3 at the 90% C.L. This is obtained by integrating the likelihood distribution of the fit as a function of signal yield after it is convolved with a Gaussian distribution with the width of the systematic uncertainty.

The ratio $R_{\gamma\psi'}$ can be determined from the above measurements. By sampling the signal yields of $X(3872) \rightarrow \gamma J/\psi$ and $X(3872) \rightarrow \gamma\psi'$ according to their likelihood distributions, a probability distribution that depends on $R_{\gamma\psi'}$ is obtained. After convolving this with a Gaussian distribution representing the uncommon systematic uncertainty between the two channels, the UL on $R_{\gamma\psi'}$ is determined to be 0.59 at the 90% C.L.

We also perform fits where the signal contribution is fixed to the expectation calculated from previous measurements. We fix the cross section of $e^+e^- \rightarrow \gamma X(3872)$, $X(3872) \rightarrow \pi^+\pi^-J/\psi$ production to the value reported in Ref. [17] and take the relative ratio $\{\mathcal{B}[X(3872) \rightarrow \gamma\psi']\}/\{\mathcal{B}[X(3872) \rightarrow \pi^+\pi^-J/\psi]\}$ from a global fit [25], or fix $X(3872) \rightarrow \gamma J/\psi$ to our own result and take $R_{\gamma\psi'}$ from an LHCb measurement [14] and from a Belle measurement [16]. The results, also shown in Fig. 1(b), have a goodness of fit of $\chi^2/\text{NDF} = 46.9/59$ ($p = 0.87$), $66.8/59$ ($p = 0.23$), and $46.0/59$

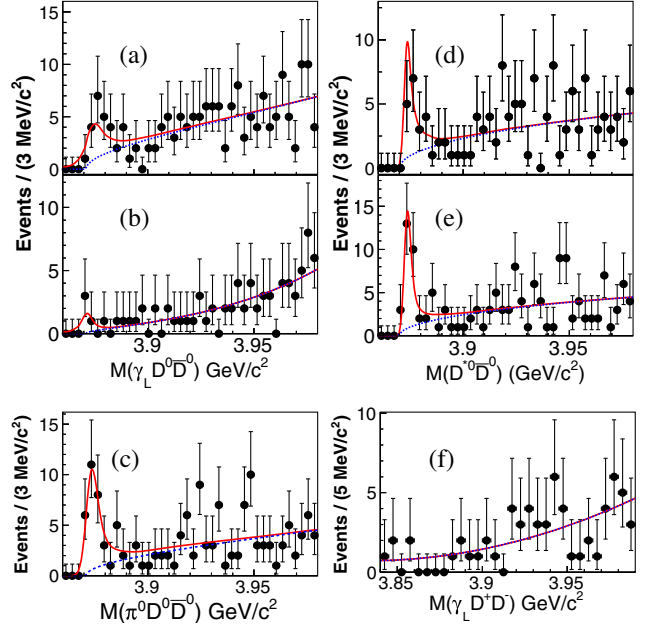


FIG. 2. $M(\gamma_L D^0 \bar{D}^0)$ with $M(\gamma_L D^0)$ (a) in or (b) below the D^{*0} mass window. (c) $M(\pi^0 D^0 \bar{D}^0)$ with $M(\pi^0 D^0)$ in the D^{*0} mass window. Simultaneous fit results for $X(3872) \rightarrow D^{*0} \bar{D}^0$ with (d) $D^{*0} \rightarrow \gamma D^0$ and (e) $D^{*0} \rightarrow \pi^0 D^0$ mode. (f) Fit results for $X(3872) \rightarrow \gamma_L D^+ D^-$. The points with error bars are from data, the red curves are the best fit, and the blue dashed curves are the background components.

($p = 0.89$) for the BESIII, LHCb, and Belle hypotheses, respectively. Our result for $R_{\gamma\psi'}$ is 2.8σ lower than that reported by the LHCb Collaboration, corresponding to a p value of 0.0048 calculated with $p = \int_0^\infty \int_{R_0}^\infty \mathcal{L}(R) G(R_0) \times dR dR_0$, where $\mathcal{L}(R)$ is the likelihood distribution in this Letter and $G(R)$ is the Gaussian-assumed likelihood profile of the uncertainty of LHCb measurement.

We consider the possibility of nonresonant three-body production to the final states $\gamma D^0 \bar{D}^0$ and $\pi^0 D^0 \bar{D}^0$, in addition to the well-established decay $X(3872) \rightarrow D^{*0} \bar{D}^0$. We only search for $X(3872)$ with $\gamma_L D^0 \bar{D}^0$ because the photon energy in $X(3872) \rightarrow \gamma D^0 \bar{D}^0$ is always lower than that in $e^+e^- \rightarrow \gamma X(3872)$. The mass spectra $M(\gamma_L D^0 \bar{D}^0)$ and $M(\pi^0 D^0 \bar{D}^0)$ are shown in Fig. 2 for the case when $M(\gamma_L/\pi^0 D)$ lies in [Fig. 2(a)] or out of [Fig. 2(b)] the D^{*0} mass region and when $M(\pi^0 D^0 \bar{D}^0)$ lies in this mass range [Fig. 2(c)]. We fit the three mass spectra individually and use an efficiency matrix determined from MC simulation that accounts for migrations of true events between the mass ranges to determine the number of produced events in each category. The signal yields for nonresonant three-body $X(3872) \rightarrow \gamma D^0 \bar{D}^0$ production and the decay $X(3872) \rightarrow D^{*0} \bar{D}^0$ ($D^{*0} \rightarrow \gamma D^0$) are found to be 1.3 ± 0.7 and 20.5 ± 7.4 , respectively, and the corresponding yields for $X(3872) \rightarrow \pi^0 D^0 \bar{D}^0$ and $X(3872) \rightarrow D^{*0} \bar{D}^0$ ($D^{*0} \rightarrow \pi^0 D^0$) decays are -0.5 ± 2.3 and 36.1 ± 7.7 , respectively. The yields for the three-body decays are

TABLE I. Relative branching ratios and UL on branching ratios compared with $X(3872) \rightarrow \pi^+\pi^-J/\psi$ [18,27], where systematic uncertainties have been taken into account.

Mode	Ratio	UL
$\gamma J/\psi$	0.79 ± 0.28	...
$\gamma\psi'$	-0.03 ± 0.22	< 0.42
$\gamma D^0 \bar{D}^0$	0.54 ± 0.48	< 1.58
$\pi^0 D^0 \bar{D}^0$	-0.13 ± 0.47	< 1.16
$D^{*0} \bar{D}^0 + \text{c.c.}$	11.77 ± 3.09	...
$\gamma D^+ D^-$	$0.00^{+0.48}_{-0.00}$	< 0.99
$\omega J/\psi$	$1.6^{+0.4}_{-0.3} \pm 0.2$ [18]	...
$\pi^0 \chi_{c1}$	$0.88^{+0.33}_{-0.27} \pm 0.10$ [27]	...

not significant, and so we set ULs at the 90% C.L. of 8.7 events for $X(3872) \rightarrow \gamma D^0 \bar{D}^0$ and 2.3 events for $X(3872) \rightarrow \pi^0 D^0 \bar{D}^0$, corresponding to 3.2×10^2 and 1.2×10^2 BF- and efficiency-corrected events, respectively. Here systematic uncertainties, which are discussed later, are taken into account.

In the next stage of the analysis of the $X(3872) \rightarrow D^{*0} \bar{D}^0$ decays, the combination of $\gamma_L D^0$ or $\pi^0 D^0$ with an invariant mass closest to the D^{*0} nominal mass is taken as the D^{*0} candidate. For the channel $D^{*0} \rightarrow \gamma D^0$, the mass window for selecting the D^{*0} is $M(\gamma_L D^0) \in [m_{D^{*0}} - 0.006, m_{D^{*0}} + 0.006]$ GeV/ c^2 , while for $D^{*0} \rightarrow \pi^0 D^0$ it is $M(\pi^0 D^0) \in [m_{D^{*0}} - 0.004, m_{D^{*0}} + 0.004]$ GeV/ c^2 . The distributions of the corrected invariant mass $M(D^{*0} \bar{D}^0) \equiv M[\gamma(\pi^0) D^0 \bar{D}^0] - M[\gamma(\pi^0) D]$ are shown in Figs. 2(d) and 2(e) following these requirements, where contributions from nonresonant three-body processes are neglected.

To measure the $X(3872) \rightarrow D^{*0} \bar{D}^0$ signal, a simultaneous fit is performed to the corrected invariant-mass distributions. The ratio of the signal yields for $D^{*0} \rightarrow \gamma D^0$ and $\pi^0 D^0$ is constrained to the product of corresponding BFs and averaged reconstruction efficiencies. The signals are represented by MC-simulated shapes and the backgrounds by ARGUS functions [26], with thresholds fixed at $m_{D^{*0}} + m_{\bar{D}^0}$. The fit results are shown in Figs. 2(d) and 2(e). The number of efficiency- and BF-corrected $X(3872) \rightarrow D^{*0} \bar{D}^0$ events is $(30.0 \pm 5.4) \times 10^3$ and corresponds to 20.2 ± 3.6 and 25.5 ± 4.6 observed events for $D^{*0} \rightarrow \gamma D^0$ and $\pi^0 D^0$ modes, respectively. The goodness of fit is $\chi^2/\text{NDF} = 13.0/16$ ($p = 0.67$) after rebinning the data to satisfy the criterion that there are at least seven events in one bin. Varying the fit range and describing the background with alternative shapes always results in a signal fit that has a statistical significance greater than 7.4σ .

The invariant mass of the $\gamma D^+ D^-$ system following the $X(3872) \rightarrow \gamma D^+ D^-$ selection is shown in Fig. 2(f). No evident $X(3872)$ signal is found. This conclusion is quantified by performing an unbinned maximum-likelihood fit to the invariant-mass distribution, in which the signal component is described by a MC-simulated

shape and the background is represented by a second-order polynomial. The goodness of fit is $\chi^2/\text{NDF} = 6.2/5$ ($p = 0.29$). The fit yields $(0.0^{+0.5}_{-0.0}) X(3872)$ events. The UL on the number of the produced $X(3872) \rightarrow \gamma D^+ D^-$ is 2.8×10^3 events at the 90% C.L., with systematic uncertainties included in the calculation.

The decay channel $X(3872) \rightarrow \pi^+\pi^-J/\psi$ is reconstructed [17,18] to provide a normalization mode against which the rates of the other decays can be compared. This channel yields $93.9 \pm 11.4 X(3872) \rightarrow \pi^+\pi^-J/\psi$ events, corresponding to $(24.9 \pm 3.0) \times 10^2$ BF- and efficiency-corrected events. The relative ratios can then be obtained by sampling the number of produced events of $\gamma J/\psi$, $\gamma\psi'$, $\gamma D^0 \bar{D}^0$, $\pi^0 D^0 \bar{D}^0$, $D^{*0} \bar{D}^0$, and $\gamma D^+ D^-$ according to the likelihood distributions, compared with that of $\pi^+\pi^-J/\psi$. We convolve the distributions with a Gaussian whose width is the systematic uncertainty of each channel, where uncertainties in common with the $\pi^+\pi^-J/\psi$ channel are excluded. The ratios are listed in Table I for the modes studied in this Letter, together with $X(3872) \rightarrow \omega J/\psi$ and $\pi^0 \chi_{c1}$, whose production rates have recently been measured by BESIII [18,27].

Systematic uncertainties considered in the analysis include the detection efficiency, subdecay BFs, mass window requirements, kinematic fit, initial-state radiative (ISR) correction, generator model, and background shapes. The uncertainties associated with the knowledge of the detection efficiency, including tracking efficiency (1% per track), photon detection efficiency (1% per photon), PID efficiency (1% per track), and π^0 reconstruction efficiency (1% per π^0) are assigned following the results of earlier BESIII studies [28,29]. The uncertainties listed for the modes that involve multiple subdecays are calculated and weighted according to the BF and efficiency as well as the correlations between the different decay channels used to reconstruct these states. The uncertainties on the BFs of the D meson, J/ψ , and ψ' decays are taken from Ref. [24].

The uncertainty associated with the mass window used to select J/ψ mesons, which arises from a difference in resolution between data and MC, is 1.6% [17] and that for selecting D mesons is 0.7% per D meson [30]. The systematic uncertainty associated with the efficiency of the kinematic fit is estimated using the method discussed in Ref. [31].

To assign the systematic uncertainty associated with the MC events generation, we take the change in reconstruction efficiency when varying the assumption of an E1 transition in $e^+e^- \rightarrow \gamma X(3872)$ and $X(3872) \rightarrow \gamma J/\psi(\psi')$ decays to pure phase space. We change the energy-dependent cross section line shape of the $Y(4260)$ [24] in the generator to the measured $e^+e^- \rightarrow \gamma X(3872)$ [18] line shape, and the difference on the reconstruction efficiency is taken as the systematic uncertainty due to the ISR correction. To estimate the uncertainty arising from the limited knowledge of the background shapes, we vary the shapes to different

order of polynomials in the fit and change the fit range at the same time. To incorporate the systematic uncertainty into the UL, the most conservative result in the various fits is taken as the final result. The effects on the modeling of the signal shapes from discrepancies between the mass resolution in data and MC simulation are negligible.

The systematic uncertainties of the kinematic fit (1%), ISR correction (1%), and background (4.0%) in $X(3872) \rightarrow \pi^+\pi^-J/\psi$ mode are taken from Ref. [18]. A summary of the systematic uncertainties of the relative ratios is presented in the Supplemental Material [32]. The common uncertainties have been canceled and the uncommon ones from $X(3872) \rightarrow \pi^+\pi^-J/\psi$ mode have been propagated into the results. The total systematic uncertainty is obtained by adding the individual components in quadrature.

In summary, using e^+e^- collision data taken at $\sqrt{s} = 4.178\text{--}4.278$ GeV, we observe $X(3872) \rightarrow D^{*0}\bar{D}^0 + \text{c.c.}$ and find evidence for $X(3872) \rightarrow \gamma J/\psi$ with significances of 7.4σ and 3.5σ , respectively. No evidence is found for the decays $X(3872) \rightarrow \gamma\psi'$ and $X(3872) \rightarrow \gamma D^+D^-$. The UL on the ratio $R_{\gamma\psi} < 0.59$ is obtained at the 90% C.L.; this is consistent with the Belle measurement [16] and the global fit [25], but challenges the LHCb measurement [14]. Our measurement, taking into account model predictions, suggests that the $X(3872)$ state is more likely a molecule or a mixture of molecule and charmonium, rather than a pure charmonium state. We also measure the ratios of BF's for $X(3872) \rightarrow \gamma J/\psi$, $\gamma\psi'$, $\gamma D^0\bar{D}^0$, $\pi^0 D^0\bar{D}^0$, $D^{*0}\bar{D}^0 + \text{c.c.}$, and γD^+D^- to that for $X(3872) \rightarrow \pi^+\pi^-J/\psi$. As discussed in Ref. [4], the relative ratios can be calculated on the assumption that the $X(3872)$ is a bound state of $D^{*0}\bar{D}^0$. We note, however, that no predictions are yet available for a binding energy of (0.01 ± 0.20) MeV, which is the value that is obtained from the most recent mass measurements [24]. Our measurement provides essential input to future tests of the molecular model for the $X(3872)$ meson.

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