Search for the radiative transition $\chi_{c1}(3872) \to \gamma\psi_2(3823)$

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Using 9.0 fb^{-1} of e^+e^- collision data collected at center-of-mass energies from 4.178 to 4.278 GeV with the BESIII detector at the BEPCII collider, we perform the first search for the radiative transition $\chi_{c1}(3872) \to \gamma\psi_2(3823)$. No signal is observed and the upper limit on the ratio of branching fractions $\mathcal{B}(\chi_{c1}(3872) \to \gamma\psi_2(3823), \psi_2(3823) \to \gamma\chi_{c1})/\mathcal{B}(\chi_{c1}(3872) \to \pi^+\pi^- J/\psi)$ is set at 0.075 at the 90% confidence level. Our result contradicts theoretical predictions under the assumption that the $\chi_{c1}(3872)$ is the pure charmonium state $\chi_{c1}(2P)$.

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I. INTRODUCTION

As the prototypical example of charmoniumlike XYZ states, the $\chi_{c1}(3872)$ has been extensively investigated in the past two decades since it was discovered by the Belle experiment [1] in 2003. From a global fit to the measurements by LHCb, BESIII, Belle, *BABAR*, and others, its mass and width are determined to be $\mathrm{M} = 3871.65 \pm 0.06~\mathrm{MeV}/c^2$ and $\Gamma = 1.19 \pm 0.21$ MeV, respectively [2]. Its spin, parity, and charge-conjugation parity quantum numbers are determined to be $J^{PC} = 1^{++}$ [3]. So far, the observed decay modes of the particle include $D^{*0}\overline{D^0}$ + c.c., $\pi^+\pi^- J/\psi$, $\omega J/\psi$, $\gamma J/\psi$, and $\pi^0\chi_{c1}$ [4–13]. Although tremendous effort has been made from both the experimental and theoretical sides, the interpretation of the $\chi_{c1}(3872)$ remains inconclusive. Due to the proximity of its mass to the $D^{*0}\overline{D^0}$ + c.c. mass threshold, it is conjectured to have a large $D^{*0}\overline{D^0}$ + c.c. molecular component [14,15]. Indeed, some theoretical models consider it to be a mixture of a conventional 2^3P_1 charmonium state $\chi_{c1}(2P)$ and a $D^{*0}\overline{D^0}$ + c.c. molecule [16,17].

Measurements of new $\chi_{c1}(3872)$ decay modes can help to improve our understanding of its internal structure. Reference [18] extracted the absolute branching fractions of the known $\chi_{c1}(3872)$ decays by performing a global fit of the absolute branching fraction of the $B^+ \to \chi_{c1}(3872)K^+$ channel measured by *BABAR* [19] together with information from other experiments. The fraction of $\chi_{c1}(3872)$ decays not observed in experiments is estimated to be $31.9^{+18.1}_{-31.5}\%$. The work is carried out by assuming the $\chi_{c1}(3872)$ has universal properties in different production and decay mechanisms. Meanwhile, Ref. [20] also reported the branching fractions with consideration of the threshold effect of $D^{*0}\overline{D^0}$ + c.c. and a possible bound state below the threshold or a virtual state in $B^+ \to \chi_{c1}(3872)K^+$ decay. If the $\chi_{c1}(3872)$ contains a component of the excited spin-triplet state $\chi_{c1}(2P)$, then the radiative decay $\chi_{c1}(3872) \to \gamma\psi_2(3823)$ could happen naturally via an E1 transition [21], where the $\psi_2(3823)$ is considered as the 1^3D_2 charmonium state. The BESIII experiment has reported the observation of $e^+e^- \to \gamma\chi_{c1}(3872)$ at center-of-mass energies $\sqrt{s} = 4.178$–4.278 GeV [22,23]. Using the $\chi_{c1}(3872)$ signal produced in these data samples, we search for the radiative transition $\chi_{c1}(3872) \to \gamma\psi_2(3823)$, where the $\psi_2(3823)$ is reconstructed with the cascade decay $\psi_2(3823) \to \gamma\chi_{c1}$, $\chi_{c1} \to \gamma J/\psi$, $J/\psi \to \ell^+\ell^-$ $(\ell = e, \mu)$. The branching

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TABLE I. The calculated values for $\mathcal{R}_{\chi_{c1}(2P)}$, by including as input values the partial decay widths $\Gamma_{\chi_{c1}(2P)\to\gamma\psi(1^3D_2)}$ and $\Gamma_{\psi(1^3D_2)\to\gamma\chi_{c1}(1P)}$ predicted by the NR and GI models and LQCD, the total widths, $\Gamma_{\chi_{c1}(3872)}$ and $\Gamma_{\psi_2(3823)}$, and the branching fraction $\mathcal{B}(\chi_{c1}(3872)\to\pi^+\pi^-J/\psi)$. The "$\cdots$" mean unavailable. The two values of the ratio for the LQCD case correspond to the results by taking the $\Gamma_{\chi_{c1}(2P)\to\gamma\psi(1^3D_2)}$ width from the NR and GI models as input, respectively.

$\Gamma_{\chi_{c1}(3872)} = 1190 \pm 210$ keV [2]
$\Gamma_{\psi_2(3823)} = 520 \pm 100$ keV [24]
$\mathcal{B}(\chi_{c1}(3872)\to\pi^+\pi^-J/\psi) = (3.8 \pm 1.2)\times 10^{-2}$ [2]

	NR [21]	GI [21]	LQCD [24]
$\Gamma_{\chi_{c1}(2P)\to\gamma\psi(1^3D_2)}$ (keV)	35	18	$\cdots$
$\Gamma_{\psi(1^3D_2)\to\gamma\chi_{c1}(1P)}$ (keV)	307	268	337 ± 27
$\mathcal{R}_{\chi_{c1}(2P)}$	0.46 ± 0.19	0.21 ± 0.09	$0.50 \pm 0.21,\ 0.26 \pm 0.11$

fraction ratio of this decay relative to the well-established $\chi_{c1}(3872)\to\pi^+\pi^-J/\psi$ decay, $\mathcal{R}_{\chi_{c1}(3872)} \equiv \mathcal{B}(\chi_{c1}(3872)\to\gamma\psi_2(3823), \psi_2(3823)\to\gamma\chi_{c1})/\mathcal{B}(\chi_{c1}(3872)\to\pi^+\pi^-J/\psi)$, is determined in this work.

Many theoretical models predict the partial widths of the radiative transitions between different conventional charmonium states. The partial widths of $\chi_{c1}(2P)\to\gamma\psi(1^3D_2)$ and $\psi(1^3D_2)\to\gamma\chi_{c1}(1P)$ are calculated with the nonrelativistic (NR) potential model and the Godfrey-Isgur (GI) relativistic potential model [21]. Recently, the partial width of $\psi(1^3D_2)\to\gamma\chi_{c1}(1P)$ was calculated with lattice QCD (LQCD) [24], and the total width of the $\psi(1^3D_2)$ was estimated according to the BESIII measurements and some phenomenological results. Combining these predictions with the total width of the $\chi_{c1}(3872)$, $\Gamma_{\chi_{c1}(3872)} = 1.19 \pm 0.21$ MeV, we calculated the theoretical branching factions $\mathcal{B}(\chi_{c1}(2P)\to\gamma\psi(1^3D_2)$ and $\mathcal{B}(\psi(1^3D_2)\to\gamma\chi_{c1}(1P))$, and then proceeded to the ratio of branching fractions, $\mathcal{R}_{\chi_{c1}(2P)} \equiv \mathcal{B}(\chi_{c1}(2P)\to\gamma\psi(1^3D_2), \psi(1^3D_2)\to\gamma\chi_{c1}(1P))/\mathcal{B}(\chi_{c1}(3872)\to\pi^+\pi^-J/\psi)$ by taking the branching fraction $\mathcal{B}(\chi_{c1}(3872)\to\pi^+\pi^-J/\psi) = (3.8 \pm 1.2)\times 10^{-2}$ from the PDG [2], as listed in Table I. It is worth pointing out that the total width of the $\chi_{c1}(3872)$ measured in experiments is highly dependent on the parametrization of its line shape. The value (1.19 ± 0.21 MeV) used here is from a global fit to the experimental measurements of the decay mode $\chi_{c1}(3872)\to\pi^+\pi^-J/\psi$ which describes the $\chi_{c1}(3872)$ line shape with a Breit-Wigner (BW) function. The decay $\chi_{c1}(3872)\to D^{*0}\overline{D^0}$ + c.c., however, will distort the line shape due to the proximity of its mass to the $D^{*0}\overline{D^0}$ + c.c. threshold. LHCb studied the $\chi_{c1}(3872)$ line shape with a Flatté model instead [25] and determined the full width at half maximum (FWHM) of the line shape to be $0.22^{+0.07+0.11}_{-0.06-0.13}$ MeV, which is much smaller than that obtained from the BW model. Recently, BESIII performed a coupled-channel analysis of the $\chi_{c1}(3872)$ line shape and reported a FWHM of $0.44^{+0.13+0.38}_{-0.35-0.25}$ MeV [26], consistent with the LHCb result. If the FWHM values provided by LHCb and BESIII are used to calculate $\mathcal{R}_{\chi_{c1}(2P)}$, the ratios shown in Table I will increase significantly. The experimental measurement of this ratio will help to determine whether the $\chi_{c1}(3872)$ is the conventional charmonium state, $\chi_{c1}(2P)$.

II. BESIII DETECTOR AND DATASETS

The BESIII detector [27] has an effective geometrical acceptance of 93% of 4π. A helium-based main drift chamber (MDC) immersed in a 1 T solenoidal magnetic field measures the momentum of charged particles with a resolution of 0.5% at 1 GeV/c as well as the specific energy loss (dE/dx) with a resolution better than 6%. A CsI(Tl) crystal electromagnetic calorimeter (EMC) is used to measure energies and positions of photons, where the energy resolution for a 1.0 GeV photon is about 2.5% in the barrel and 5.0% in the end caps. A plastic scintillator time-of-flight (TOF) system, with a time resolution of 80 ps (110 ps) in the barrel (end cap), is used to identify the particles combined with the dE/dx information measured in the MDC. In addition, a multigap resistive plate chamber technology is used in the TOF end cap starting from 2015 to improve the time resolution to 60 ps [28]; the datasets in this work benefit from this improvement except for the data taken at $\sqrt{s} = 4.226$ and 4.258 GeV. A muon system interleaved in the steel flux return of the magnet based on resistive plate chambers with 2 cm position resolution provides powerful information to separate muons from pions.

The e^+e^- collision data collected at $\sqrt{s} = 4.178$–4.278 GeV are used in this analysis. The integrated luminosity at each energy point is measured with the Bhabha scattering process with a precision better than 1% [29] as listed in Table II. A GEANT4-based [30] software package is used to generate the Monte Carlo (MC) simulated data samples. The inclusive MC samples, used to estimate the backgrounds, include the open-charm hadronic processes, continuum processes, and the initial-state-radiation effects, and are generated with KKMC [31] in conjunction with EvtGen [32]. The signal MC samples

TABLE II. The datasets and their integrated luminosity at each energy point.

$\sqrt{s}$ (GeV)	Luminosity (pb^{-1})
4.178	3189.0
4.189	526.7
4.199	526.0
4.209	517.1
4.219	514.6
4.226	1101.0
4.236	530.3
4.244	538.1
4.258	828.4
4.267	531.1
4.278	175.7

$e^+e^- \to \gamma\chi_{c1}(3872)$, with the decay chain $\chi_{c1}(3872) \to \gamma\psi_2(3823)$, $\psi_2(3823) \to \gamma\chi_{c1}$, $\chi_{c1} \to \gamma J/\psi$, $J/\psi \to \ell^+\ell^-$ ($\ell = e, \mu$), are used to determine the detection efficiency. The $e^+e^- \to \gamma\chi_{c1}(3872)$ decay is simulated as an E1 transition according to the measurement from BESIII [22]. The $\chi_{c1}(3872) \to \gamma\psi_2(3823)$ and $\psi_2(3823) \to \gamma\chi_{c1}$ decays are produced with a phase space model.

III. EVENT SELECTION AND RESULT

According to the decay chain of the signal process, $e^+e^- \to \gamma\chi_{c1}(3872), \chi_{c1}(3872) \to \gamma\psi_2(3823), \psi_2(3823) \to \gamma\chi_{c1}, \chi_{c1} \to \gamma J/\psi$, $J/\psi \to \ell^+\ell^-$ ($\ell = e, \mu$), the final state contains a lepton pair from the J/ψ decay and four radiative photons. For the leptons, each corresponding charged track is required to have its point of closest approach to the beam axis within 1 cm in the radial direction and within 10 cm along the beam direction and to lie within the polar-angle coverage of the MDC, $|\cos\theta| < 0.93$, in the laboratory frame. We require exactly two good charged tracks in the candidate events. EMC information discriminates between the electrons and muons: electrons are required to deposit at least 0.8 GeV in the EMC, and the muons less than 0.4 GeV. Photons are reconstructed from isolated showers in the EMC, at least 10° away from any charged track, with an energy deposit of at least 25 MeV in both the barrel ($|\cos\theta| < 0.80$) and the end cap ($0.86 < |\cos\theta| < 0.92$) regions. In order to suppress electronic noise unrelated to the event, the EMC time t of the photon candidate must be in the range $0 \leq t \leq 700$ ns, consistent with collision events. We require at least four photons for each candidate event.

A four-constraint (4C) kinematic fit is applied to constrain the total four-momentum of the lepton pair and the four photons to that of the colliding beams, to suppress backgrounds and improve the resolution. For events with more than four photons, the combination with the best-fit quality corresponding to the minimum fit chi-square, χ^2_{4C}, is retained. The J/ψ is reconstructed by requiring the invariant mass $M(\ell\ell)$ of the lepton pair to satisfy $|M(\ell\ell) - m(J/\psi)| < 30$ MeV/c^2, where $m(J/\psi)$ is the nominal J/ψ mass. The selection criteria are optimized by maximizing the Punzi figure-of-merit $S/(\frac{a}{2} + \sqrt{B})$ [33], where the number of signal events (S) is determined with the signal MC sample, the background (B) is estimated with the inclusive MC, and the expected statistical significance (a) is set to be 3. The dominant background is from the process $e^+e^- \to \pi^0\pi^0 J/\psi$. After the J/ψ selection, we veto π^0 candidates by requiring that the invariant mass of all photon pairs is more than 15 MeV/c^2 away from the nominal π^0 mass. After these requirements, a seven-constraint (7C) kinematic fit with an additional three constraints on the masses of $M(\ell\ell)$, $M(\gamma\ell\ell)$, and $M(\gamma\gamma\ell\ell)$ to the nominal masses of J/ψ, χ_{c1}, and $\psi_2(3823)$, respectively, is applied to distinguish the radiative photon in each cascade decay. The best-fit combination with the minimum chi-square, χ^2_{7C}, is retained; $\chi^2_{7C} < 100$ is also required to further suppress the combinatorial backgrounds. One possible peaking background is $\psi_2(3823) \to \gamma\chi_{c2}, \chi_{c2} \to \gamma J/\psi$, the contribution of which is estimated according to the measurement of the branching fraction ratio of $\psi_2(3823) \to \gamma\chi_{c2}$ to $\psi_2(3823) \to \gamma\chi_{c1}$ in Ref. [34]. The ratio of the yields of $\psi_2(3823) \to \gamma\chi_{c2}$ to $\psi_2(3823) \to \gamma\chi_{c1,2}$, is about 1.5%, which is taken into account as a source of systematic uncertainty.

Figure 1 shows the distribution of the invariant mass of the radiative photon and the $\psi_2(3823)$, $M(\gamma\psi_2(3823))$ for the selected candidates, summed over all the energy points. No signal is observed in the $\chi_{c1}(3872)$ signal region in data. The three events around 3.93 GeV are very unlikely to be from the $\chi_{c2}(2P)$ decays since no $\chi_{c2}(2P)$ signal was observed in its more favorable radiative transition to $\psi(2S)$ [9]. After normalizing the MC samples according to the luminosity and cross section in data, the contributions of

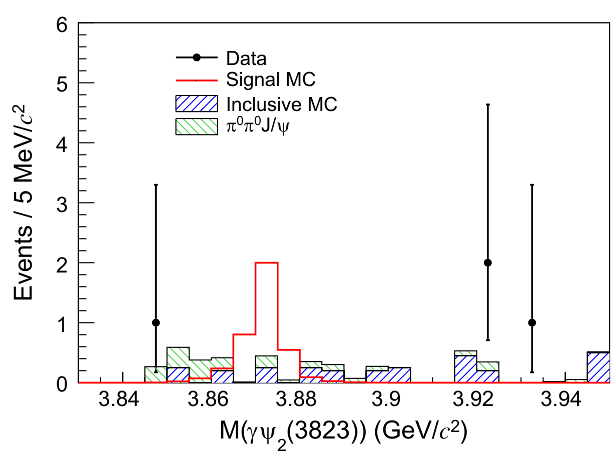

FIG. 1. Distribution of $M(\gamma\psi_2(3823))$. The dots with error bars are data, the red histogram is the signal MC sample with arbitrary scale, the filled blue histogram is the inclusive MC sample without the process $e^+e^- \to \pi^0\pi^0 J/\psi$, and the green stacked histogram is the contribution from $e^+e^- \to \pi^0\pi^0 J/\psi$.

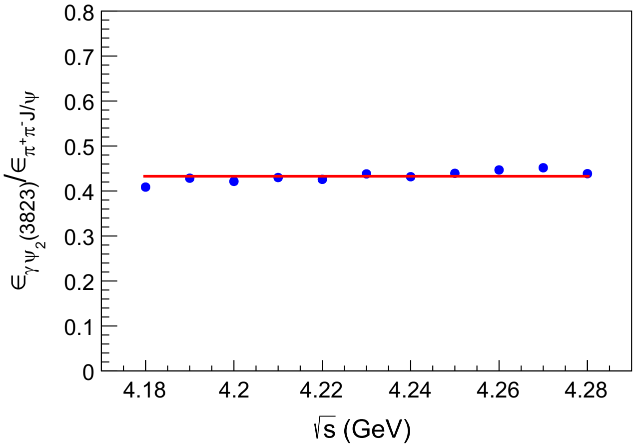

FIG. 2. Values of $\epsilon_{\gamma\psi_2(3823)}/\epsilon_{\pi^+\pi^- J/\psi}$ at each energy point (blue dots). The red line indicates the mean value.

the $e^+e^- \to \pi^0\pi^0 J/\psi$ process and of the other backgrounds, estimated with the inclusive MC sample, are also shown in Fig. 1.

The branching ratio $\mathcal{R}_{\chi_{c1}(3872)}$ is calculated as

$$\mathcal{R}_{\chi_{c1}(3872)} = \frac{N_{\rm obs} - r \cdot N_{\rm obs}^{\rm sdb}}{N_{\pi^+\pi^- J/\psi} \cdot \frac{\epsilon_{\gamma\psi_2(3823)}}{\epsilon_{\pi^+\pi^- J/\psi}} \cdot \mathcal{B}(\chi_{c1} \to \gamma J/\psi)}, \quad (1)$$

where $N_{\rm obs} = 0$ is the number of observed events from all data in the $\chi_{c1}(3872)$ signal region [3.855, 3.885] GeV/c^2 which covers around $\pm 3\sigma$ of the signal shape according to the signal MC distributions, $N_{\rm obs}^{\rm sdb} = 4$ is the number of the observed events in the $\chi_{c1}(3872)$ sideband region [3.840, 3.855] and [3.885, 3.940] GeV/c^2; r, the background scaling factor from the sideband regions to the signal region, is 0.474 based on the inclusive MC sample (taking into account its systematic uncertainty; see Sec. IV); $N_{\pi^+\pi^- J/\psi} = 80.7 \pm 9.0$ is taken from the BESIII measurement [10]; the branching fraction $\mathcal{B}(\chi_{c1} \to \gamma J/\psi) = 0.343 \pm 0.010$ is quoted from the PDG [2]; $\epsilon_{\gamma\psi_2(3823)}$ is the efficiency for the signal process reconstruction, determined with the signal MC sample; and $\epsilon_{\pi^+\pi^- J/\psi}$ is the efficiency of the process $\chi_{c1}(3872) \to \pi^+\pi^- J/\psi$ [10]. The efficiency ratio $\epsilon_{\gamma\psi_2(3823)}/\epsilon_{\pi^+\pi^- J/\psi}$ at each energy point is shown in Fig. 2, which is almost independent of the center-of-mass energy. The mean value with the standard deviation, $\epsilon_{\gamma\psi_2(3823)}/\epsilon_{\pi^+\pi^- J/\psi} = 0.433 \pm 0.004$, is used to calculate the $\mathcal{R}_{\chi_{c1}(3872)}$ value. The upper limit of $\mathcal{R}_{\chi_{c1}(3872)}$ at the 90% confidence level (CL) is computed with the TRolke program implemented in the ROOT framework [35] by assuming the background $N_{\rm obs}^{\rm sdb}$ and the denominator of $\mathcal{R}_{\chi_{c1}(3872)}$ follow Poisson and Gaussian distributions, respectively, where the systematic uncertainties discussed in the following section are taken as the standard deviation of the Gaussian function to be considered in the upper limit. We obtain an upper limit of $\mathcal{R}_{\chi_{c1}(3872)} < 0.075$ at the 90% CL.

IV. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties on $\mathcal{R}_{\chi_{c1}(3872)}$ arise mainly from the estimations of r, the possible peaking background of $\psi_2(3823) \to \gamma\chi_{c2} \to \gamma\gamma J/\psi$, $N_{\pi^+\pi^- J/\psi}$, $\epsilon_{\gamma\psi_2(3823)}/\epsilon_{\pi^+\pi^- J/\psi}$, and $\mathcal{B}(\chi_{c1} \to \gamma J/\psi)$. The background scaling factor r is determined from the inclusive MC samples including the process $e^+e^- \to \pi^0\pi^0 J/\psi$. We use a first or second order polynomial function to fit the $M(\gamma\psi_2(3823))$ distribution from the inclusive MC samples; the r value is calculated several times using the parameters from the fit and varying them within 1σ. The value $r = 0.474$ is chosen from the obtained values since it provides the most conservative upper limit. The contribution of the potential peaking background of $\psi_2(3823) \to \gamma\chi_{c2} \to \gamma\gamma J/\psi$ is estimated with the related measurements mentioned previously within one uncertainty, and the result providing the most conservative $\mathcal{R}_{\chi_{c1}(3872)}$ upper limit is retained.

Both statistical and systematic uncertainties of $N_{\pi^+\pi^- J/\psi}$ contribute as sources of systematic uncertainty, where the statistical part (11.2%) is obtained by assuming that $N_{\pi^+\pi^- J/\psi}$ follows a Poisson distribution, and the systematic part (4.1%) is obtained from Ref. [10] where the dominant contribution is from the parametrization of the $\chi_{c1}(3872)$ signal shape. The systematic uncertainty (2.9%) due to $\mathcal{B}(\chi_{c1} \to \gamma J/\psi)$ is taken from the PDG [2]. The systematic uncertainty of $\epsilon_{\gamma\psi_2(3823)}/\epsilon_{\pi^+\pi^- J/\psi}$ comes mainly from the tracking (2.0%), the photon selection (3.0%), and the kinematic fit (2.2%) uncertainties, estimated with the control sample $e^+e^- \to \pi^0\pi^0 J/\psi$. The systematic uncertainty due to the π^0 veto is mainly caused by potential differences in the angular distributions of the radiative photon between the data and the signal MC sample, and it is estimated by changing the angular distribution of the radiative γ in $\chi_{c1}(3872) \to \gamma\psi_2(3823)$ to $1 \pm \cos^2\theta$ (from flat) in the generator model. The relative difference of 5.3% between the efficiencies obtained with the photon angular distributions of $1 - \cos^2\theta$ and $1 + \cos^2\theta$ is taken as the systematic uncertainty.

TABLE III. The relative systematic uncertainties on $\mathcal{R}_{\chi_{c1}(3872)}$. Systematics on the sideband scaling ratio r are treated separately (see text).

Item		Systematic (%)
$N_{\pi^+\pi^- J/\psi}$	Statistical	11.2
	Systematic	4.1
$\epsilon_{\gamma\psi_2(3823)}/\epsilon_{\pi^+\pi^- J/\psi}$	Tracking	2.0
	Photon	3.0
	Kinematic fit	2.2
	π^0 veto	5.3
$\mathcal{B}(\chi_{c1} \to \gamma J/\psi)$		2.9
Sum		14.1

The systematic uncertainties are listed in Table III. The total systematic uncertainty is obtained by summing all systematic uncertainties in quadrature, assuming they are uncorrelated.

V. SUMMARY

In summary, we search for the radiative decay $\chi_{c1}(3872) \to \gamma\psi_2(3823)$ for the first time by using the e^+e^- collision data accumulated at $\sqrt{s} = 4.178$–4.278 GeV with the BESIII detector. No signal is observed, and the upper limit on the branching fraction ratio $\mathcal{R}_{\chi_{c1}(3872)}$ is determined to be 0.075 at the 90% CL. This upper limit is more than 1σ below the theoretical calculations of $\mathcal{R}_{\chi_{c1}(3872)}$ under the assumption that the $\chi_{c1}(3872)$ is the pure charmonium state $\chi_{c1}(2P)$, listed in Table I, and much smaller than the predictions based on the FWHMs measured by LHCb and BESIII [25,26]. Our result therefore indicates that the $\chi_{c1}(3872)$ is not a pure $\chi_{c1}(2P)$ charmonium state.

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