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Search for $C = +$ charmonium and XYZ states in $e^+e^- \rightarrow \gamma + H$ at BESIII

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ABSTRACT: Within the framework of nonrelativistic quantum chromodynamics, we study the production of $C = +$ charmonium states H in $e^+e^- \rightarrow \gamma + H$ at BESIII with $H = \eta_c(nS)$ ($n=1, 2, 3$, and 4), $\chi_{cJ}(nP)$ ($n=1, 2$, and 3), and $^1D_2(nD)$ ($n=1$ and 2). The radiative and relativistic corrections are calculated to next-to-leading order for S and P wave states. We then argue that the search for $C = +$ XYZ states such as $X(3872)$, $X(3940)$, $X(4160)$, and $X(4350)$ in $e^+e^- \rightarrow \gamma + H$ at BESIII may help clarify the nature of these states. BESIII can search for XYZ states through two body process $e^+e^- \rightarrow \gamma H$, where H decay to $J/\psi\pi^+\pi^-$, $J/\psi\phi$, or $D\bar{D}$. This result may be useful in identifying the nature of $C = +$ XYZ states. For completeness, the production of $C = +$ charmonium in $e^+e^- \rightarrow \gamma + H$ at B factories is also discussed.

KEYWORDS: QCD Phenomenology, NLO Computations

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1 Introduction

During the last 10 years, many heavy quarkonium or heavy quarkonium-like XYZ states had been discovered (more details can be found in ref. [1] and related papers). The $X(3872)$ state is the first and the most famous state among them. It was discovered by the Belle collaboration [2], and confirmed by the CDF [3], D0 [4], BaBar [5], LHCb [6], and CMS [7] collaborations. One of the most conspicuous properties of $X(3872)$ is its mass, which is close to the $D^0 \bar{D}^{*0}$ threshold within 1 MeV; hence, $X(3872)$ is suggested to be a $D^0 \bar{D}^{*0}$ molecule [8–11]. The contribution of the charged component $D^+ D^{*-}$ is also considered in ref. [12, 13]. The molecular model may have difficulty explaining the production cross-sections of $X(3872)$ in hadron colliders (which may be large in some phenomenological models [14]) [15]. The quantum numbers of $X(3872)$ have been determined to be $J^{PC} = 1^{++}$ by the LHCb collaboration [16]. The J^{PC} of $X(3872)$ is the same as $\chi_{c1}(nP)$. On the contrary, the mass 3.872 GeV seems too low for a $\chi_{c1}(2P)$ state. The coupled-channel and screening effects may draw its mass down to 3.87 GeV [17]. However, the next-to-leading order (NLO) prediction of $X(3872)$ production in hadron colliders within nonrelativistic quantum chromodynamics (NRQCD) disfavors the interpretation of $X(3872)$ as pure $\chi_{c1}(2P)$ [18]. The possibility that $X(3872)$ might be a mixed state with the $\chi_{c1}(2P)$ and the $D^0 \bar{D}^{*0}$ components was proposed in ref. [19]. The prompt $X(3872)$ hadroproduction is studied at NLO in α_s [20] and the result is consistent with the CMS [7] and the CDF data [3]. This idea is also favored the data of some other measurements and predictions [15, 17, 21, 22].

Besides $X(3872)$, other $C = +$ XYZ states are listed in table 1. These states are particularly interesting and the interpretations of their nature are still inconclusive [23]. $X(3915)$ ($X(3945)$ or $Y(3940)$) and $Z(3930)$ are assigned as the $\chi_{c0}(2P)$ and $\chi_{c2}(2P)$ states by the Particle Data Group [24]. However this identification may be called into

State	$m(\Gamma)$ in MeV	J^{PC}	Production (Decay)	Ref.
$X(3872)$	3871.68 ± 0.17 (< 1.2)	1^{++}	$B \rightarrow K (\pi^+ \pi^- J/\psi)$	[2]
			$p\bar{p} \rightarrow (\pi^+ \pi^- J/\psi) + \dots$	[3, 34]
			$B \rightarrow K (\omega J/\psi)$	[35, 36]
			$B \rightarrow K (D^0 \bar{D}^*)$	[37, 38]
			$B \rightarrow K (\gamma J/\psi, \gamma \psi(2S))$	[39]
			$pp \rightarrow (\pi^+ \pi^- J/\psi) + \dots$	[6, 7, 16]
$X(3915)$	3917.5 ± 2.7 (27 ± 10)	0^{++}	$B \rightarrow K (\omega J/\psi)$	[40, 41]
			$e^+ e^- \rightarrow e^+ e^- (\omega J/\psi)$	[36, 42]
$Z(3930)$	3927.2 ± 2.6 (24 ± 6)	2^{++}	$e^+ e^- \rightarrow e^+ e^- (D\bar{D})$	[43]
$X(3940)$	3942_{-8}^{+9} (37_{-17}^{+27})	J^{P+}	$e^+ e^- \rightarrow J/\psi (D\bar{D}^*)$	[44]
$Y(4140)$	4143.0 ± 3.1 (12_{-6}^{+9})	J^{P+}	$B \rightarrow K (\phi J/\psi)$	[45]
$X(4160)$	4156_{-25}^{+29} (139_{-60}^{+110})	J^{P+}	$e^+ e^- \rightarrow J/\psi (D^{*+} \bar{D}^{*-})$	[44]
$Y(4274)$	$4274.4_{-6.7}^{+8.4}$ (32_{-15}^{+22})	J^{P+}	$B \rightarrow K (\phi J/\psi)$	[45]
$X(4350)$	$4350.6_{-5.1}^{+4.6}$ ($13.3_{-10.0}^{+18.4}$)	$0/2^{++}$	$e^+ e^- \rightarrow e^+ e^- (\phi J/\psi)$	[46]

Table 1. $C = +$ XYZ states. $X(3915)$ ($X(3945)$, and $Y(3940)$) is assumed to be the $\chi_{c0}(2P)$ state for their compatible properties. $Z(3930)$ is considered as $\chi_{c2}(2P)$ [1, 33].

question [25]. The experimental results for these $C = +$ states have induced renewed theoretical interest in understanding the nature of charmonium-like states. The double charmonium production in $e^+ e^-$ annihilation at B factories [26, 27] turned out to be a possible way to identify the $C = +$ charmonium or charmonium-like states, recoiling against the easily reconstructed 1^{--} charmonium J/ψ and $\psi(2S)$. In addition to $\eta_c, \eta_c(2S)$, χ_{c0} , $X(3940)$ (decaying into $D\bar{D}^*$), and $X(4160)$ (decaying into $D^* \bar{D}^*$) have also been observed in double charmonium production at B factories. However, χ_{c1} and χ_{c2} states are missing in production associated with J/ψ at B factories. Identifying the $C = +$ charmonium states H in the $e^+ e^- \rightarrow \gamma^* \rightarrow \gamma + H$ process at B factories is also proposed [28, 29]. The quantum chromodynamics (QCD) corrections of $e^+ e^- \rightarrow \gamma^* \rightarrow \gamma + H$ at B factories are calculated in ref. [30, 31]. The relativistic correction of $e^+ e^- \rightarrow \gamma^* \rightarrow \gamma + \eta_c$ is also included in ref. [31]. Indirect measurement of quarkonium in the two-photon process is also proposed [32].

Recently, BESIII reports the cross-sections of $e^+ e^- \rightarrow \gamma X(3872)$ [47, 48]

$$\begin{aligned}
 \sigma[e^+ e^- \rightarrow \gamma X(3872)] \times \text{Br}[J/\psi \pi \pi] &< 0.12 \text{ pb} \quad \text{at } 90\% \text{ CL.} & \sqrt{s} &= 4.009 \text{ GeV} \\
 \sigma[e^+ e^- \rightarrow \gamma X(3872)] \times \text{Br}[J/\psi \pi \pi] &= 0.29 \pm 0.10 \pm 0.02 \text{ pb} & \sqrt{s} &= 4.230 \text{ GeV} \\
 \sigma[e^+ e^- \rightarrow \gamma X(3872)] \times \text{Br}[J/\psi \pi \pi] &= 0.36 \pm 0.13 \pm 0.03 \text{ pb} & \sqrt{s} &= 4.260 \text{ GeV} \\
 \sigma[e^+ e^- \rightarrow \gamma X(3872)] \times \text{Br}[J/\psi \pi \pi] &< 0.39 \text{ pb} \quad \text{at } 90\% \text{ CL.} & \sqrt{s} &= 4.360 \text{ GeV} \quad (1.1)
 \end{aligned}$$

Where $\text{Br}[J/\psi \pi \pi]$ means $\text{Br}[X(3872) \rightarrow J/\psi \pi \pi]$. And the studies of $\psi(4160) \rightarrow X(3872) \gamma$ [49] and $\psi(4260) \rightarrow X(3872) \gamma$ [50] are proposed to probe the molecular content of the $X(3872)$.

Many NLO relativistic and radiative corrections for heavy quarkonium production are considered within nonrelativistic QCD (NRQCD) [51]. By introducing the color octet mechanism, one can obtain the infrared-safe calculations for the decay rates of P wave [52–54] and D wave [55–57] quarkonium states. The color octet contributions of the diphoton decay of P wave quarkonium states are calculated in ref. [58]. $O(\alpha_s v^2)$ corrections to the decays of h_c, h_b and η_b are studied in ref. [59, 60]. The NLO QCD corrections [61–71], relativistic corrections [72–79], and $O(\alpha_s v^2)$ corrections [80, 81] largely compensate for the discrepancies between theoretical values and experimental measurements at B factories. The contributions of higher-order QCD corrections for charmonium production [18, 20, 82–89] and polarization [90–93] in hadron colliders are also significant. The relativistic corrections to J/ψ hadroproduction are significant [94–96].

We calculate the production of $C = +$ charmonium at e^+e^- annihilation at BESIII to test the nature of $C = +$ XYZ states. Our paper is organized as follows. The calculational framework is given in section 2. The numerical results of the cross-sections of $C = +$ charmonium are discussed in section 3. A discussion of $X(3872)$ and other $C = +$ XYZ states is given in section 4. The summary is given in section 5.

2 The framework of the calculation

In the NRQCD factorization framework, we can express the amplitude in the rest frame of H as [28, 30, 31]

$$\begin{aligned} \mathcal{A}(e^-(k_1)e^+(k_2) \rightarrow H_{c\bar{c}}(^{2S+1}L_J)(2p_1) + \gamma) \\ = \sum_{L_z S_z} \sum_{s_1 s_2} \sum_{jk} \int d^3\vec{q} \Phi_{c\bar{c}}(\vec{q}) \langle s_1; s_2 | SS_z \rangle \langle 3j; \bar{3}k | 1 \rangle \\ \times \mathcal{A} \left[e^-(k_1)e^+(k_2) \rightarrow c_j^{s_1}(p_1 + q) + \bar{c}_k^{s_2}(p_1 - q) + \gamma(k) \right], \end{aligned} \quad (2.1)$$

where $\langle 3j; \bar{3}k | 1 \rangle = \delta_{jk}/\sqrt{N_c}$, is the color Clebsch-Gordan coefficient for $c\bar{c}$ pairs projecting out appropriate bound states, and $\langle s_1; s_2 | SS_z \rangle$ is the spin Clebsch-Gordan coefficient. $\mathcal{A} \left[e^-(k_1)e^+(k_2) \rightarrow c_j^{s_1}(p_1 + q) + \bar{c}_k^{s_2}(p_1 - q) + \gamma(k) \right]$ is the quark level scattering amplitude. In the rest frame of H , $q = (0, \vec{q})$, and $p_1 = (\sqrt{m_c^2 + \vec{q}^2}, 0, 0, 0)$. $\Phi_{c\bar{c}}^H(\vec{q})$ is the $c\bar{c}$ component wave function of hadron H in momentum space. For $v^2 = \vec{q}^2/m_c^2 \ll 1$ [51], we can expand eq. (2.1) with v^2 :

$$\begin{aligned} \mathcal{A}(q) = \mathcal{A}(0) + \left. \frac{\partial \mathcal{A}(\vec{q})}{\partial \vec{q}^\alpha} \right|_{q=0} \vec{q}^\alpha + \left. \frac{\partial^2 \mathcal{A}(\vec{q})}{\partial \vec{q}^\alpha \partial \vec{q}^\beta} \right|_{q=0} \frac{\vec{q}^\alpha \vec{q}^\beta}{2} \\ + \left. \frac{\partial^3 \mathcal{A}(\vec{q})}{\partial \vec{q}^\alpha \partial \vec{q}^\beta \partial \vec{q}^\delta} \right|_{q=0} \frac{\vec{q}^\alpha \vec{q}^\beta \vec{q}^\delta}{3!} + \dots \end{aligned} \quad (2.2)$$

Here $\mathcal{A}(q) = \mathcal{A} \left[e^-(k_1)e^+(k_2) \rightarrow c_j^{s_1}(p_1 + q) + \bar{c}_k^{s_2}(p_1 - q) + \gamma(k) \right]$. We consider the Fourier transform between the momentum space and position space as: [51, 95],

$$\begin{aligned} \int d^3\vec{q} \Phi_{c\bar{c}}(\vec{q}) &\propto \sqrt{Z_{c\bar{c}}^H} R_{c\bar{c}}(0) \\ \int d^3\vec{q} \vec{q}^\alpha \Phi_{c\bar{c}}(\vec{q}) &\propto \sqrt{Z_{c\bar{c}}^H} R'_{c\bar{c}}(0) \end{aligned}$$

$$\begin{aligned} \int d^3\vec{q} \ \bar{q}^\alpha \bar{q}^\beta \Phi_{c\bar{c}}(\vec{q}) &\propto \sqrt{Z_{c\bar{c}}^H} R_{c\bar{c}}''(0) \\ \int d^3\vec{q} \ \bar{q}^\alpha \bar{q}^\beta \bar{q}^\delta \Phi_{c\bar{c}}(\vec{q}) &\propto \sqrt{Z_{c\bar{c}}^H} R_{c\bar{c}}'''(0). \end{aligned} \quad (2.3)$$

Here $Z_{c\bar{c}}^H$ is the probability of $c\bar{c}$ component in hadron H . $R_{c\bar{c}}(0)$ is the radial Schrodinger wave function at the origin. $R_{c\bar{c}}^l(0)$ is the derivative of the radial Schrodinger wave function at the origin

$$R_{c\bar{c}}^l(0) = \left. \frac{d^l R_{c\bar{c}}(r)}{d^l r} \right|_{r=0} \quad (2.4)$$

$R_{c\bar{c}}(0)$ corresponds to the $\mathcal{O}(v^0)$ S wave matrix element, $R_{c\bar{c}}'(0)$ corresponds to the $\mathcal{O}(v^0)$ P wave matrix element, $R_{c\bar{c}}''(0)$ corresponds to the $\mathcal{O}(v^2)$ S wave matrix element or $\mathcal{O}(v^0)$ D wave matrix element, and $R_{c\bar{c}}'''(0)$ corresponds to the $\mathcal{O}(v^2)$ P wave matrix element.

The wave function and its radial derivatives can also be written as long-distance matrix elements (LDMEs) as discussed in ref. [95]. For example,

$$\langle 0 | \mathcal{O}^{\chi_{c1}}(^3P_1^{[1]}) | 0 \rangle = \frac{27}{2\pi} |R'_{1P}(0)|^2, \quad (2.5)$$

We calculated the relativistic corrections for the S wave and P wave states and obtain two LDMEs for η_c , four LDMEs for χ_{cJ} , and one LDMEs for 1D_2 states. To simplify the discussion of the numerical result, we assumed that

$$\langle 0 | \mathcal{O}^{\chi_{cJ}}(^3P_J^{[1]}) | 0 \rangle = (2J+1) \langle 0 | \mathcal{O}^{\chi_{cJ}}(^3P_0^{[1]}) | 0 \rangle. \quad (2.6)$$

$$v^2 = \frac{\langle 0 | \mathcal{P}^H(^{2s+1}L_J^{[c]}) | 0 \rangle}{m_c^2 \langle 0 | \mathcal{O}^H(^{2s+1}L_J^{[c]}) | 0 \rangle}. \quad (2.7)$$

Then there is only one LDME for S wave, P wave, and D wave respectively. More details can be found in ref. [95].

The relativistic correction K factor is

$$\begin{aligned} K_{v^2}[\eta_c] &= -\frac{5v^2}{6} - \frac{rv^2}{1-r}, \\ K_{v^2}[\chi_{c0}] &= -\frac{(55r^2 - 28r + 13)v^2}{10(3r^2 - 4r + 1)} - \frac{rv^2}{1-r}, \\ K_{v^2}[\chi_{c1}] &= -\frac{(21r^2 + 30r - 11)v^2}{10(r^2 - 1)} - \frac{rv^2}{1-r}, \\ K_{v^2}[\chi_{c2}] &= -\frac{(90r^3 + 113r^2 + 4r - 7)v^2}{10(r-1)(6r^2 + 3r + 1)} - \frac{rv^2}{1-r}, \end{aligned} \quad (2.8)$$

where $r = 4m_c^2/s$. $-\frac{rv^2}{1-r}$ is the relativistic correction of the phase space. If we select $r \rightarrow 0$, the K_{v^2} factor is consistent with the K factor at large p_T in ref. [95].

Our leading order (LO) cross-sections of $e^+e^- \rightarrow \gamma^* \rightarrow \gamma + H$ are consistent with ref. [28, 30, 31]. The QCD corrections of $e^+e^- \rightarrow \gamma^* \rightarrow \gamma + H$ are consistent with

ref. [30, 31]. And the relativistic corrections of $e^+e^- \rightarrow \gamma^* \rightarrow \gamma + \eta_c$ are consistent with ref. [31, 78, 79].

We can obtain a similar amplitude for the $D\bar{D}$ component in the molecule model. We can estimate the off-resonance amplitude of $e^+e^- \rightarrow H + \gamma$ from the $D\bar{D}$ component. The parton-level amplitudes may be compared with the hadron-level amplitudes:

$$\mathcal{A}[e^-(k_1)e^+(k_2) \rightarrow c\bar{c}(2p_1) + \gamma] \sim \mathcal{A}[e^-(k_1)e^+(k_2) \rightarrow D\bar{D}(2p_1) + \gamma] \quad (2.9)$$

By contrast, the $R_{c\bar{c}}^l(0) \sim v^{2l}R_{c\bar{c}}^S(0) \gg R_{D\bar{D}}(0)$ with the S wave $l = 0$ and P wave $l = 1$ for the binding energies of $c\bar{c}$ and $D\bar{D}$ are several hundreds of MeV and several MeV, respectively. If $Z_{c\bar{c}}^H \sim Z_{D\bar{D}}^H$, we can consider the $c\bar{c}$ contributions only.

In the numerical calculation, we consider the charm quark mass as half of the hadron mass consistent with the physical phase space. With a large charm quark mass, the wave functions at the origin are identified as the Cornell potential result in ref. [97]. The selected parameters are as follows:

$$\begin{aligned} m_c &= m_H/2, & \alpha_s &= 0.23, & \alpha &= 1/133, \\ v^2 &= 0.23, & R_{1S} &= 1.454\text{GeV}^3, & R_{2S} &= 0.927\text{GeV}^3, \\ R_{3S} &= 0.791\text{GeV}^3, & R'_{1P} &= 0.131\text{GeV}^5, & R'_{2P} &= 0.186\text{GeV}^5, \\ R''_{1D} &= 0.031\text{GeV}^7. \end{aligned} \quad (2.10)$$

The wave functions at origin for higher states are estimated as

$$\begin{aligned} R_{4S} &= 2 \times R_{3S} - R_{2S} = 0.655\text{GeV}^3, \\ R'_{3P} &= (R'_{1P} + R'_{2P})/2 = 0.159\text{GeV}^5, \\ R''_{2D} &= R''_{1D} = 0.031\text{GeV}^7. \end{aligned} \quad (2.11)$$

In the numerical result, “ σ_{LO} ” is the LO cross-section, “ σ_{v^2} ” is the cross-section including the LO and the relativistic correction, “ σ_{α_s} ” is the cross-section including the LO and the radiative correction, and “ σ_{α_s, v^2} ” is the cross-section including the LO, the relativistic correction, and the radiative correction. In addition, “LO” is the LO cross-section, “RC” is the relativistic correction, “QCD” is the radiative correction, and “Total” is the cross-section including the LO, the relativistic correction, and the radiative correction. For the LO, the cross-section is $\mathcal{O}(\alpha_s^0 v^0)$. Then the relativistic correction is proportional to v^2 , and the radiative correction is proportional to α_s . With a large charm quark mass, $\alpha_s(2m_c) = 0.23 \pm 0.03$ [30, 31]. And the uncertainty of v^2 is estimated as $v^2 = 0.23 \pm 0.03$ [51, 59, 60]. The uncertainty of the total cross sections from varying α_s and v^2 over these ranges is included in the tables of results.

3 Pure $C = +$ charmonium states

We can estimate the cross-sections for pure $C = +$ charmonium states H in $e^+e^- \rightarrow \gamma + H$ at BESIII with $H = \eta_c(nS)$ ($n=1, 2, 3$, and 4), $\chi_{cJ}(nP)$ ($n=1, 2$, and 3), and $^1D_2(nD)$

Figure 1. The cross-sections of $e^+e^- \rightarrow \eta_c + \gamma$ as a function of $\sqrt{s}$ in fb. The cross-section “ σ_{LO} ”, “ σ_{v^2} ”, “ σ_{α_s} ”, and “ σ_{α_s,v^2} ” are defined near the end of section 2.

Figure 2. The cross-sections of $e^+e^- \rightarrow \eta_{c2}(1D, 2D) + \gamma$ as a function of $\sqrt{s}$ in fb.

($n=1$ and 2). The masses of the lower states can be found in ref. [24], and the masses of the higher states are selected from ref. [17].

The cross-section of $e^+e^- \rightarrow \eta_c + \gamma$ as a function of $\sqrt{s}$ is shown in figure 1. The cross-sections of $e^+e^- \rightarrow \eta_{c2}(1D, 2D) + \gamma$ as a function of $\sqrt{s}$ are shown in figure 2. The numerical results for nS with $n = 1, 2, 3, 4$ and nD with $n = 1, 2$ are listed in table 2. We determined that the radiative and relativistic corrections are negative and large for $\eta_c(nS)$, respectively. The LO cross-sections for $\eta_{c2}(1D, 2D)$ is very small at BESIII; hence, the higher order corrections are ignored.

The cross-sections of $e^+e^- \rightarrow \chi_{cJ} + \gamma$ as a function of $\sqrt{s}$ are shown in figure 3, figure 4, and figure 5 for $J = 0, 1, 2$, respectively. The numerical results for $\chi_{cJ}(nP)$ with $n = 1, 2, 3$

$\sqrt{s}(\text{GeV})$		4.00	4.25	4.50	4.75	5.00	10.6	11.2
$\eta_c(1S)$ (2981)	LO	2781	2494	2192	1906	1652	117	95
	RC	-1332	-1033	-814	-650	-526	-25	-20
	QCD	-909	-807	-700	-598	-508	-22	-16
	Total	540 $\pm$ 210	653 $\pm$ 170	678 $\pm$ 140	658 $\pm$ 115	617 $\pm$ 95	70 $\pm$ 4	58 $\pm$ 3
$\eta_c(2S)$ (3639)	LO	563	684	706	679	629	58	48
	RC	-730	-563	-442	-352	-284	-13	-10
	QCD	-177	-221	-231	-222	-205	-13	-10
	Total	-344 $\pm$ 98	-100 $\pm$ 79	33 $\pm$ 65	105 $\pm$ 54	141 $\pm$ 46	32 $\pm$ 2	27 $\pm$ 2
$\eta_c(3S)$ (3994)	LO		233	337	374	377	44	36
	RC		-450	-352	-279	-225	-10	-8
	QCD		-72	-107	-121	-123	-10	-8
	Total		-288 $\pm$ 59	-122 $\pm$ 48	-27 $\pm$ 40	29 $\pm$ 33	24 $\pm$ 2	20 $\pm$ 1
$\eta_c(4S)$ (4250)	LO			133	198	225	34	28
	RC			-279	-221	-178	-8	-6
	QCD			-41	-63	-73	-8	-7
	Total			-186 $\pm$ 37	-86 $\pm$ 30	-26 $\pm$ 25	17 $\pm$ 1	15 $\pm$ 1
$\eta_{c2}(1D)$ (3796)	LO	4.0	6.4	7.3	7.3	7.0	0.71	0.58
$\eta_{c2}(2D)$ (4099)	LO		1.5	2.9	3.5	3.7	0.47	0.38

Table 2. The cross-sections of $e^+e^- \rightarrow H + \gamma$ for $\eta_c(nS)$ with $n = 1, 2, 3, 4$ and $\eta_{c2}(nD)$ for $n = 1, 2$ charmonium states in fb. The labels LO, RC, QCD and Total are defined near the end of section 2. The masses of $\eta_c(3S)$, $\eta_c(4S)$, $\eta_{c2}(1D)$, and $\eta_{c2}(2D)$ are selected from ref. [17]. The other mass can be found in ref. [24].

are listed in table 3, table 4, and table 5 for $J = 0, 1, 2$, respectively. We determined that the QCD corrections are large but negative and the relativistic corrections are large and positive. Hence, many P wave states can be searched at BESIII.

The NRQCD requires that the energy of photon at the center of the mass frame of e^+e^-

$$E_\gamma = \frac{s - M_H^2}{2\sqrt{s}} \sim \sqrt{s} - M_H + \mathcal{O}[(1 - M_H/\sqrt{s})^2] \quad (3.1)$$

be larger than $\Lambda_{QCD} \sim 300 \text{ MeV} \sim m_c v^2$. Although this process is a QED process, the prediction is not reliable and only a reference value if this requirement is not satisfied. If we replace a photon with a gluon, the soft photon contributions correspond to the long-distance color octet contributions [31, 51].

Figure 3. The cross-sections of $e^+e^- \rightarrow \chi_{c0} + \gamma$ as a function of $\sqrt{s}$ in fb. The cross-section “ σ_{LO} ”, “ σ_{v^2} ”, “ σ_{α_s} ”, and “ σ_{α_s,v^2} ” are defined near the end of section 2.

$\sqrt{s}(\text{GeV})$		4.25	4.50	4.75	5.00	10.6	11.2
$\chi_{c0}(1P)$ (3415)	LO	328	132	53	21	1.81	1.6
	RC	268	107	48	22	-0.77	-0.63
	QCD	-228	-107	-52	-26	-0.38	-0.29
	Total	368 ± 46	131 ± 20	49 ± 9	17 ± 4	1.42 ± 0.11	1.22 ± 0.09
$\chi_{c0}(2P)$ (3918)	LO	1991	665	271	119	1.30	1.18
	RC	3102	680	230	96	-0.64	-0.54
	QCD	-1013	-384	-177	-89	0.39	0.30
	Total	4080 ± 426	962 ± 102	324 ± 38	127 ± 17	1.04 ± 0.10	0.94 ± 0.08
$\chi_{c0}(3P)$ (4131)	LO		1073	384	164	0.82	0.75
	RC		1600	391	140	-0.44	-0.38
	QCD		-551	-223	-107	0.29	0.23
	Total		2121 ± 220	554 ± 59	198 ± 23	0.67 ± 0.07	0.61 ± 0.06

Table 3. The cross-sections of $e^+e^- \rightarrow \chi_{c0}(nP) + \gamma$ with $n = 1, 2, 3$ in fb. The labels LO, RC, QCD and Total are defined near the end of section 2. The $\chi_{c0}(2P)$ is considered as $X(3915)(X(3945)/Y(3940))$ [1, 33]. The mass of $\chi_{c0}(3P)$ are selected from ref. [17]. The other mass can be found in ref. [24].

4 $C = +$ XYZ states

$X(4160)$ and $Y(4274)$ are found in the B decay $B \rightarrow K + H \rightarrow K + \phi J/\psi$ by CDF collaboration [45]. No signal of $X(4160)$ or $Y(4274)$ is reported by B factories. Hence, the cross-sections for $X(4160)$ or $Y(4274)$ at BESIII may be too small to measure. The

Figure 4. The cross-sections of $e^+e^- \rightarrow \chi_{c1} + \gamma$ as a function of $\sqrt{s}$ in fb. The cross-section “ σ_{LO} ”, “ σ_{v^2} ”, “ σ_{α_s} ”, and “ σ_{α_s, v^2} ” are defined near the end of section 2.

$\sqrt{s}(\text{GeV})$		4.25	4.50	4.75	5.00	10.6	11.2
$\chi_{c1}(1P)$ (3511)	LO	3874	2392	1597	1124	23.5	18.5
	RC	1296	459	168	52	-4.8	-3.8
	QCD	-1791	-1091	-715	-492	-6.5	-4.9
	Total	3379 ± 288	1760 ± 154	1051 ± 96	685 ± 65	12 ± 1	10 ± 1
$\chi_{c1}(2P)$ (3901)	LO	8854	4244	2495	1624	25.7	20.0
	RC	9585	2297	789	312	-4.9	-3.9
	QCD	-4041	-1967	-1152	-741	-7.7	-5.7
	Total	14397 ± 1357	4573 ± 394	2131 ± 182	1195 ± 105	13 ± 1	10 ± 1
$\chi_{c1}(3P)$ (4178)	LO		1073	384	164	0.82	0.75
	RC		1600	391	140	-0.44	-0.38
	QCD		-551	-223	-107	0.29	0.23
	Total		2121 ± 220	554 ± 59	198 ± 23	0.7 ± 0.1	0.6 ± 0.1

Table 4. The cross-sections of $e^+e^- \rightarrow \chi_{c1}(nP) + \gamma$ with $n = 1, 2, 3$ in fb. The labels LO, RC, QCD and Total are defined near the end of section 2. The masses of $\chi_{c1}(2P, 3P)$ are selected from ref. [17]. And the mass of $\chi_{c1}(1P)$ can be found in ref. [24].

cross-sections of $e^+e^- \rightarrow \gamma H$ for $X(3872)$, $X(3940)$, $X(4160)$, and $X(4350)$ are discussed here. The 1^{--} resonance contributions are ignored here.

Figure 5. The cross-sections of $e^+e^- \rightarrow \chi_{c2} + \gamma$ as a function of $\sqrt{s}$ in fb. The cross-section “ σ_{LO} ”, “ σ_{v^2} ”, “ σ_{α_s} ”, and “ σ_{α_s, v^2} ” are defined near the end of section 2.

$\sqrt{s}(\text{GeV})$		4.25	4.50	4.75	5.00	10.6	11.2
$\chi_{c2}(1P)$ (3556)	LO	4724	2590	1562	1004	9.66	7.37
	RC	2385	880	376	173	-1.16	-0.93
	QCD	-2455	-1384	-851	-557	-6.27	-4.82
	Total	4655 $\pm$ 446	2087 $\pm$ 213	1086 $\pm$ 121	621 $\pm$ 76	2 $\pm$ 1	2 $\pm$ 1
$\chi_{c2}(2P)$ (3927)	LO	13419	5581	2931	1927	11.29	8.53
	RC	17835	3965	1355	565	-1.22	-0.99
	QCD	-6423	-2822	-1533	-926	-7.25	-5.52
	Total	24862 $\pm$ 2472	6723 $\pm$ 635	2754 $\pm$ 267	1368 $\pm$ 141	3 $\pm$ 1	2 $\pm$ 1
$\chi_{c2}(3P)$ (4208)	LO		8938	3607	1886	8.55	6.40
	RC		14212	2949	995	-0.83	-0.68
	QCD		-4210	-1803	-977	-5.43	-4.10
	Total		18941 $\pm$ 1933	4753 $\pm$ 451	1904 $\pm$ 182	2 $\pm$ 1	2 $\pm$ 1

Table 5. The cross-sections of $e^+e^- \rightarrow \chi_{c2}(nP) + \gamma$ with $n = 1, 2, 3$ in fb. The labels LO, RC, QCD and Total are defined near the end of section 2. $\chi_{c2}(2P)$ is considered as $Z(3930)$, [1, 33]. The mass of $\chi_{c2}(3P)$ are selected from ref. [17]. And the mass of $\chi_{c2}(1P)$ can be found in ref. [24].

4.1 $X(3872)$

In the light of the mixed state of the $\chi_{c1}(2P)$ and $D^0 \bar{D}^{*0}$ molecule, the cross-sections of $X(3872)$ at e^+e^- colliders can be expressed as [20]:

$$d\sigma[X(3872) \rightarrow J/\psi \pi^+ \pi^-] = d\sigma[\chi_{c1}(2P)] \times k, \quad (4.1)$$

Figure 6. The cross-sections of $e^+e^- \rightarrow \gamma X(3872) \rightarrow J/\psi \pi \pi + \gamma$ as a function of $\sqrt{s}$ in fb. The cross-section “ σ_{LO} ”, “ σ_{v^2} ”, “ σ_{α_s} ”, and “ σ_{α_s, v^2} ” are defined near the end of section 2. The uncertainty band of σ_{α_s, v^2} is from the uncertainty of $k = 0.018 \pm 0.04$. And k is defined as the probability $Z_{c\bar{c}}^{X(3875)}$ multiplied the branching fraction $Br[X(3872) \rightarrow J/\psi \pi^+ \pi^-]$.

where $k = Z_{c\bar{c}}^{X(3875)} \times Br[X(3872) \rightarrow J/\psi \pi^+ \pi^-]$. $Br[X(3872) \rightarrow J/\psi \pi^+ \pi^-]$ is the branching fraction for $X(3872)$ decay to $J/\psi \pi^+ \pi^-$. $Z_{c\bar{c}}^{X(3875)}$ is the probability of the $\chi_{c1}(2P)$ component in $X(3872)$. And $k = 0.018 \pm 0.04$ [19, 20].

To clarify the nature of $X(3872)$, we also give the numerical calculation of $e^+e^- \rightarrow \gamma X(3872) \rightarrow J/\psi \pi^+ \pi^- \gamma$ in this picture

$$\begin{aligned} & \sigma[e^+e^- \rightarrow \gamma X(3872)] \times Br[X \rightarrow J/\psi \pi \pi] \\ &= \sigma[e^+e^- \rightarrow \gamma \chi_{c1}(2P)(3872)] \times (0.018 \pm 0.004) \end{aligned} \quad (4.2)$$

The cross-section as a function of $\sqrt{s}$ is shown in figure 6. We can predict the cross-sections from the continuum contributions of the mixed state with the $\chi_{c1}(2P)$ components at the experimental data points, and the results are listed in table 6. We ignore the contributions of 1^{--} resonance here. We emphasize that if we select $\sqrt{s} = 4.009 \text{ GeV}$, the energy of photon $E_\gamma = 134 \text{ MeV}$ and smaller than $\Lambda_{QCD} \sim m_c v^2 \sim 300 \text{ MeV}$. Hence, NRQCD cannot accurately predict the cross-sections with a soft photon with $\sqrt{s} = 4.009 \text{ GeV}$ [51]. If $\sqrt{s} = 4.160 \text{ GeV}$, the energy of photon is $E_\gamma = 270 \text{ MeV}$. Although this process is a QED process, the prediction is not reliable and only a reference value [31]. We determined that the NRQCD prediction of the continuous contributions can be compared with the BESIII data of the cross-sections of $e^+e^- \rightarrow \gamma X(3872)$ [47, 48] in eq. (1.1).

Many 1^{--} states with $M_H < 5 \text{ GeV}$ are also observed. When we only considered the continuum production, the resonance contributions can be estimated as that,

$$\sigma_{Res}[s] = \frac{12\pi\Gamma[Res \rightarrow e^+e^-]\Gamma[Res \rightarrow \gamma X]}{(s - M^2)^2 + (M\Gamma_{tot}[Res])^2}. \quad (4.3)$$

$\sqrt{s}(\text{GeV})$	4.15	4.2	4.25	4.3	4.35	4.45	4.55
LO	221 $\pm$ 49	180 $\pm$ 40	150 $\pm$ 33	127 $\pm$ 28	110 $\pm$ 24	84 $\pm$ 19	66 $\pm$ 15
RC	310 $\pm$ 69	208 $\pm$ 46	146 $\pm$ 32	106 $\pm$ 24	80 $\pm$ 18	47 $\pm$ 10	30 $\pm$ 7
QCD	-100 $\pm$ 22	-82 $\pm$ 18	-69 $\pm$ 15	-59 $\pm$ 13	-51 $\pm$ 11	-39 $\pm$ 9	-31 $\pm$ 7
Total	431 $\pm$ 96	306 $\pm$ 68	227 $\pm$ 51	175 $\pm$ 39	138 $\pm$ 31	92 $\pm$ 20	65 $\pm$ 14

$\sqrt{s}(\text{GeV})$	NRQCD prediction for continuum	BESIII [47, 48]
4.009		<120 at 90% CL.
4.160	401 $\pm$ 89	
4.230	255 $\pm$ 57	290 $\pm$ 100 $\pm$ 20
4.260	215 $\pm$ 48	360 $\pm$ 130 $\pm$ 30
4.360	133 $\pm$ 29	<390 at 90% CL.
4.415	105 $\pm$ 23	
4.660	47 $\pm$ 10	

Table 6. The cross-sections of $e^+e^- \rightarrow \gamma X(3872) \rightarrow J/\psi \pi \pi + \gamma$ in fb. The labels LO, RC, QCD and Total are defined near the end of section 2.

We take into account only one resonance and ignore other resonances here. If we ignore the interference between one resonance with continuum and other resonances, the γ energy dependence of the $\Gamma[Res \rightarrow \gamma X]$, and $D\bar{D}$ contributions of decay of $Res \rightarrow \gamma X$, we can estimate the resonance contributions. With $X(3872)$ considered as $2P$ states, the largest decay widths are $\psi(4040)$ and $\psi(4160)$, which are considered as the mixing of $\psi(3S)$ and $\psi(2D)$ [98, 99]. The $\Gamma[Res \rightarrow \gamma X]$ for other states will be less than 1 keV [99], and $\Gamma_{\text{tot}} \sim 100$ MeV, $\Gamma[Res \rightarrow e^+e^-] \sim 1$ keV. Hence, we ignore the contributions from other resonances. With the parameters for $\psi(4040)$ and $\psi(4160)$ [24, 99],

$$\begin{aligned} \Gamma[\psi(4040) \rightarrow e^+e^-] &= 0.87 \text{ keV} & \Gamma[\psi(4040) \rightarrow \gamma X] &= 40 \text{ keV} & \Gamma_{\text{tot}}[\psi(4040)] &= 80 \text{ MeV} \\ \Gamma[\psi(4160) \rightarrow e^+e^-] &= 0.83 \text{ keV} & \Gamma[\psi(4160) \rightarrow \gamma X] &= 140 \text{ keV} & \Gamma_{\text{tot}}[\psi(4160)] &= 103 \text{ MeV} \end{aligned}$$

Hence, we can determine the contributions of these parameters to $X(3872)\gamma \rightarrow J/\psi \pi^+ \pi^- \gamma$,

$$\begin{aligned} (\sigma_{\psi(4040)}[4.23] + \sigma_{\psi(4160)}[4.23]) \times k &= (62 \pm 14) \text{ fb}, \\ (\sigma_{\psi(4040)}[4.26] + \sigma_{\psi(4160)}[4.26]) \times k &= (37 \pm 8) \text{ fb}. \end{aligned} \tag{4.4}$$

If we considered the interference, the result would be more complex. On the other hand, we have calculated the quark-level intermediate states, which do not clearly deal with the hadron-level intermediate states.

4.2 $X(3940)$ and $X(4160)$

$X(3940)$ and $X(4160)$ are observed in $e^+e^- \rightarrow J/\psi(D\bar{D})$ at B factories [44]. In these measurements, the η_c and χ_{c0} are observed to recoil against the J/ψ , but the χ_{c1} and χ_{c2}

Figure 7. The cross-sections of $e^+e^- \rightarrow X(3940)(X(4160)) + \gamma$ as a function of $\sqrt{s}$ in fb. Z_{cc}^X is the probability of $\eta_c(3S)$ and $\chi_{c0}(3P)$ component in $X(3940)$ and $X(4160)$, respectively.

states have not yet been observed to do so [44]. The theoretical predictions are consistent with the experimental data [62, 70, 100, 101]. So there should be large $\eta_c(nS)$ and $\chi_{c0}(nP)$ component in $X(3940)$ and $X(4160)$, respectively. The mass of $\eta_c(3S)$ and $\chi_{c0}(3P)$ are predicted as 3994 MeV and 4130 MeV respectively [17]. From table 2 and table 3, we see that the cross-sections of $\eta_c(3S)$ is small, even negative at $\sqrt{s} < 5$ GeV. But $\chi_{c0}(3P)$ is large. The cross-sections as a function of $\sqrt{s}$ is shown in figure 7. Here $Z_{cc}^X \leq 1$ is the probability of $\eta_c(3S)$ and $\chi_{c0}(3P)$ component in $X(3940)$ and $X(4160)$, respectively. The BESIII collaboration can search for $X(3940)$ and $X(4160)$ in the process $e^+e^- \rightarrow \gamma + X(D\bar{D})$. The result may be useful in identifying the nature of $X(3940)$ and $X(4160)$.

4.3 $X(4350)$

The $X(4350)$ is observed in the reaction $\gamma\gamma \rightarrow X \rightarrow \phi J/\psi$ at B factories [46]. And J^{PC} is 0^{++} or 2^{++} . So there should be large $\chi_{c0}(nP)$ or $\chi_{c2}(nP)$ component in $X(4350)$. In ref. [17], The mass of $\chi_{c2}(3P)$ is 4208 MeV, and the mass of $\chi_{c0}(3P)$ is 4131 MeV. Ignoring mass difference between $X(4350)$ and $\chi_{c0}(nP)$ or $\chi_{c2}(nP)$, we considered $X(4350)$ as $\chi_{c0}(3P)$ or $\chi_{c2}(3P)$. The wave function at origin is estimated as

$$R' = R'_{3P} = (R'_{1P} + R'_{2P})/2 = 0.159 \text{ GeV}^5, \quad (4.5)$$

The cross-sections of $e^+e^- \rightarrow X(4350) + \gamma$ as a function of $\sqrt{s}$ are shown in figure 8. Here Z_{cc}^X is the probability of $\chi_{c0}(3P)$ or $\chi_{c2}(3P)$ component in $X(4350)$. The cross-section for $\chi_{c2}(3P)$ is larger than $\chi_{c0}(3P)$ by a factor of 6. The result may be useful in identifying the nature of $X(4350)$.

5 Summary and discussion

While BESIII and Belle have collected a large amount of data, some final states may be searched by the experimentalists. We can estimate the possible number of events at BESIII

Figure 8. The cross-sections of $e^+e^- \rightarrow X(4350) + \gamma$ as a function of $\sqrt{s}$ in fb. $Z_{c\bar{c}}^X$ is the probability of $\chi_{c0}(3P)$ or $\chi_{c2}(3P)$ component in $X(4350)$.

H	Decay	Br	$Z_{c\bar{c}}^H$	4.23	4.26	4.66	10.6
η_c	$K\bar{K}\pi$	7.2%	1	9	9	5	1012
χ_{c0}	$2\pi^+2\pi^-$	2.2%	1	2	2		6
χ_{c1}	$\gamma l^+l^- (\gamma J/\psi)$	4.1%	1	29	27	5	101
χ_{c2}	$\gamma l^+l^- (\gamma J/\psi)$	2.3%	1	23	20	3	10
$\eta_{c2}(1D)$	$\gamma\gamma K\bar{K}\pi$	1.5%	1				2
$\eta_c(2S)$	$K\bar{K}\pi$	1.9%	1				123
$X(3872)(\chi_{c1}(2P))$	$\pi^+\pi^-l^+l^- (\pi^+\pi^-J/\psi)$	0.6%	0.36	6	5	1	6
$X(3915)(\chi_{c0}(2P))$	$\pi^+\pi^-\pi^0l^+l^- (\omega J/\psi)$	1%	1	9	8		2
$Z(3930)(\chi_{c2}(2P))$	$nK m\pi(D\bar{D})$	1%	1	57	46	4	6
$X(3940)(\eta_c(3S))$	$nK m\pi(D\bar{D})$	1%	1				48

Table 7. The possible number of events of $C = +$ charmonium and XYZ states through $e^+e^- \rightarrow \gamma + H$ at BESIII and Belle. The efficiency of detectors are selected as 20%. The integrated luminosity is $1.0 fb^{-1}@4.23$ GeV, $1.0 fb^{-1}@4.26$ GeV, $0.5 fb^{-1}@4.66$ GeV, and $1 ab^{-1}@10.6$ GeV. The decay mode of $nK m\pi$ corresponds to $D\bar{D}$ decay, and the branching ratio is estimated as 1%.

and Belle. The possible number of events is

$$N = \sigma[e^+e^- \rightarrow \gamma + c\bar{c}[n]] \times Z_{c\bar{c}}^H \times Br \times \mathcal{L} \times \epsilon, \quad (5.1)$$

where ϵ is the efficiency of detectors selected as 20%, Br is the branch ratio of H to the decay mode, and $\mathcal{L}$ is the luminosity. The result is listed in table 7.

As a summary, we study the production of $C = +$ charmonium states H in $e^+e^- \rightarrow \gamma + H$ at BESIII with $H = \eta_c(nS)$ ($n=1, 2, 3$, and 4), $\chi_{cJ}(nP)$ ($n=1, 2$, and 3),

and $^1D_2(nD)$ ($n=1$ and 2) within the framework of NRQCD. The radiative and relativistic corrections are calculated to next-to-leading order for S and P wave states. We then argue that the search for $C = + XYZ$ states such as $X(3872)$, $X(3940)$, $X(4160)$, and $X(4350)$ in $e^+e^- \rightarrow \gamma + H$ at BESIII may help clarify the nature of these states. BESIII can search for XYZ states through two body process $e^+e^- \rightarrow \gamma H$, where H decay to $J/\psi\pi^+\pi^-$, $J/\psi\phi$, or $D\bar{D}$. This result may be useful in identifying the nature of $C = + XYZ$ states. For completeness, the production of $C = +$ charmonium in $e^+e^- \rightarrow \gamma + H$ at B factories is also discussed.

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Note added. After this paper was submitted, a similar work appeared [102]. As mentioned in the “note added” part in their paper, the large difference appeared in the near-threshold production compared our results with theirs, and it mainly comes from the selection of the charm-quark mass, $M_X/2$ for ours and a fixed value $m_c = 1.5 \text{ GeV}$ for theirs. For $\eta_c(nS)$, the cross section is small, even negative in both papers. For $\chi_{cJ}(nP)$, they add a factor $(1 - M_{\chi_{cJ}(nP)}^2/s)/(1 - 4m_c^2/s)$. With $M_{\chi_{cJ}(nP)}^2 = 4m_c^2(1 + v^2)$, we can find the factor $(1 - M_{\chi_{cJ}(nP)}^2/s)/(1 - 4m_c^2/s) = 1 - rv^2/(1 - r)$. $rv^2/(1 - r)$ is just the second term of eq. (5.2). But the first terms for $\chi_{cJ}(nP)$ are positive and large at the threshold region $r \rightarrow 1$,

$$\lim_{r \rightarrow 1} K_{v^2}[\chi_{cJ}] = \frac{2v^2}{1 - r} - \frac{rv^2}{1 - r}. \quad (5.2)$$

In another word, only the second term of the relativistic correction is included in the factor $(1 - M_{\chi_{cJ}(nP)}^2/s)/(1 - 4m_c^2/s)$. The first term is more large, but it is positive.

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