DESY 13–198 ISSN 0418-9833
November 2013

Search for $C = +$ charmonium states in $e^+e^- \to \gamma + X$ at BEPCII/BESIII

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Abstract

We extend our original study in Ref. [1] on the production of $C = +$ charmonium states $X = \eta_c(1S/2S)$ and $\chi_{cJ}(1P/2P)$ in $e^+e^- \to \gamma + X$ at B factories to the BEPCII/BESIII energy region with $\sqrt{s} = 4.0$-5.0 GeV. In the framework of nonrelativistic QCD factorization, the cross sections are estimated to be as large as 0.1-0.9 pb. The results could be used to search for the missing $2P$ charmonium states or to estimate the continuum backgrounds in the resonance region.

PACS numbers: 12.38.Bx, 12.39.Jh, 14.40.Pq

I. INTRODUCTION

In the last ten years there have been a number of exciting discoveries of new hidden charm states, i.e., the so-called XYZ mesons (see Ref. [2] for a comprehensive review). Among these states, some of the $C = +$ states around 3.9 GeV may be the candidates for the missing $2P$ charmonia. E.g., the $Z(3930)$ should be $\chi_{c2}(2P) = \chi'_{c2}$ according to its production rate and quantum numbers measured by the Belle Collaboration [3], and the $X(3872)$ could be a mixed state of the $\chi_{c1}(2P) = \chi'_{c1}$ and the $D^0\bar{D}^{*0} + c.c.$ continuum as suggested in Ref.[4].

Four years ago, we proposed to search for the missing $2P$ charmonium states in the process $e^+e^- \to \gamma\chi_{cJ}(2P)$ and to further identify the nature of the relevant XYZ states [1]. The cross section of the process is calculated within the framework of NRQCD factorization [5] at the next-to-leading order (NLO) in α_s, and the results are consistent with a similar but independent calculation in Ref. [6]. Phenomenologically, we evaluated the cross sections at the center of mass (c.o.m.) energy at B-factories, i.e., $\sqrt{s} = 10.6$ GeV, and found that they are no more than several tens fb [1]. Needless to say, the same processes can also be used to search for these states at BEPCII/BESIII with the c.o.m energy $\sqrt{s}$ above 4 GeV. Since the cross sections roughly scale as $1/s^2$ with the energy, they should be significantly enhanced at BEPCII/BESIII as compared with those at the B-factories.

However, there are many vector resonances lying in the energy region above 4 GeV, such as $\psi(4040, 4160, 4415)$, $Y(4260, 4350, 4660)$ etc., which can decay to the $2P$ charmonium states through the electric dipole (E1) transitions between charmonia [7] or some other exotic mechanisms. To clarify the situation, one need to separate the resonance contributions from the non-resonance ones. From this point of view, it is also necessary to reevaluate the cross section of $e^+e^- \to \gamma\chi_{cJ}(2P)$ at the BEPCII/BESIII energy region to estimate the magnitude of the non-resonance contribution.

On the other hand, by compared with the theoretical results, the measurements of the cross sections $e^+e^- \to \gamma X$, where X denotes any $C = +$ charmonia, would also be used to testify the production mechanism and the universality of the NRQCD long-distant matrix elements (LDMEs), especially when the resonance contributions are not important. This could be the case for the production of $\eta_c^{(\prime)}$ since in the nonrelativistic case, the amplitudes of the magnetic-dipole (M1) transitions between $\eta_c^{(\prime)}$ and higher vector chamonia are strongly suppressed. Therefore, we will also evaluated the cross section for the production of $\eta_c^{(\prime)}$ at the BEPCII/BESIII energy region.

We organize our paper as follows. In Section II, we will briefly review the framework of the calculations. The numerical results and the phenomenology discussions will be presented in section III. The last section is a short summary.

II. FRAMEWORK OF CALCULATION

Based on the NRQCD factorization formula [5], the amplitude for $e^+e^- \to \gamma + X(^{2S+1}L_J)$ can be expressed as

$$\mathcal{M}(e^+e^- \to \gamma + X) = \sum_{S,L}\sum_{s_1,s_2}\sum_{i,j}\int \frac{d^3\mathbf{q}}{(2\pi)^3 2q^0}\delta(q^0 - \frac{\mathbf{q}^2}{2m_c})\psi_{LL_z}(\mathbf{q})\langle s_1,s_2|SS_z\rangle$$
$$\langle LL_z, SS_z|JJ_z\rangle\langle i,j|1\rangle\mathcal{A}(e^+e^- \to \gamma + c^i_{s_1}(\frac{P}{2}+q) + \bar{c}^j_{s_2}(\frac{P}{2}-q)) \quad (1)$$

where P is the momentum of X state, $2q$ is the relative momentum between c and $\bar{c}$, $\langle LL_z; SS_z|JJ_z\rangle$, $\langle s_1; s_2|SS_z\rangle$ and $\langle i,j|1\rangle = \delta_{i,j}/\sqrt{N_c}$ are the spin-SU(2), angular momentum C-G coefficients and color-SU(3) C-G coefficient for $c\bar{c}$ pair projecting onto appropriate bound states, respectively, and $\mathcal{A}$ is the standard Feynman amplitude denoting $e^+e^- \to \gamma + c^i_{s_1}(\frac{P}{2}+q) + \bar{c}^j_{s_2}(\frac{P}{2}-q)$.

At leading order (LO), the perturbative part includes only pure QED contribution. The cross sections can be computed straightforwardly by implementing the formulas described in Ref.[1]. For the convenience of discussion, we list the analytical results here, which are

$$\sigma(e^+e^- \to \gamma + \eta_c) = \frac{3\alpha^3 e_c^4 |R_S(0)|^2(1-r)}{s^2 m_c}\int d\Omega(1+\cos^2(\theta)) \quad \text{(2a)}$$

$$\sigma(e^+e^- \to \gamma + \chi_{c0}) = \frac{3\alpha^3 e_c^4 |R'_P(0)|^2(1-3r)^2}{s^2 m_c^3(1-r)}\int d\Omega(1+\cos^2(\theta)) \quad \text{(2b)}$$

$$\sigma(e^+e^- \to \gamma + \chi_{c1}) = \frac{18\alpha^3 e_c^4 |R'_P(0)|^2}{s^2 m_c^3(1-r)}\int d\Omega(1+2r+(1-2r)\cos^2(\theta)) \quad \text{(2c)}$$

$$\sigma(e^+e^- \to \gamma + \chi_{c2}) = \frac{6\alpha^3 e_c^4 |R'_P(0)|^2}{s^2 m_c^3(1-r)}\int d\Omega(1+6r+6r^2+(1-6r+6r^2)\cos^2(\theta)) \quad \text{(2d)}$$

where $r = 4m_c^2/s$, θ is the angle between γ and the initial e^+e^- beam axis.

At QCD one-loop level, only the virtual corrections are involved. We adopt the on-shell renormalization scheme to remove the ultraviolet divergences, in which the renormalization constants are chosen to be

$$\delta Z_2^{\rm OS} = -\frac{1}{\varepsilon_{UV}} + \gamma_E - 4 - \frac{2}{\varepsilon_{IR}} - \log(\frac{4\pi\mu^2}{m^2}),$$
$$\delta Z_1^{\rm OS} = \delta Z_2^{\rm OS}. \tag{3}$$

Note that we omit the coefficient in front of the self-energy renormalization constant and part of the infrared divergence term in δZ_2^{OS}. The cancelation of the infrared divergences is checked both numerically and analytically, and the Coulomb singularities are absorbed into the long-distance matrix elements, i.e. the wave functions in Eq.(2), through matching the results between full QCD and NRQCD calculations. More details of our computation can be found in Ref.[1].

Before presenting the numerical results, we would like to address some of the potential problems of the NRQCD factorization approach. The Born cross sections in Eq.(2) show that in the case of P-wave production, there exists the $\frac{1}{(1-r)}$ singularity, while in the case of S-wave production it disappears. If m_c was set to be $M_X/2$, the cross sections for χ_{cJ} production would be divergent near the threshold region, where $r \to 1$. One can find that the appearance of the singularity near the threshold is due to the fact that the recoil photon is soft. It can be easily derived that in the soft limit, the interactions between the photon and charm and anti-charm quark are proportional to $a_1 = \frac{(P+q)^\alpha}{P\cdot k}$ and $a_2 = -\frac{(P-q)^\alpha}{P\cdot k}$, respectively, where k is the momentum of the soft photon. In the S-wave case the total contribution of a_1 and a_2 terms is zero, while in the P-wave case it is non-zero. This is similar to the un-canceled infrared divergences in the color singlet contributions to the P-wave decay [5]. This indicates that the NRQCD factorization approach will be broken down when r is close to 1.

In the NRQCD factorization formula, only m_c rather than M_x enters into the short-distance coefficients, and the value of m_c is widely chosen to be the current quark mass, which is in the range of $1.2 \sim 1.6$ GeV. The mass difference between M_X and $2m_c$ is attributed to the non-perturbative effects. In this work, we are concentrating on the $4 \sim 5$ GeV energy region, thus the minimum value of $1-r$ is about 0.36, which can be treated as being far from zero. Therefore, our results of the short-distance parts are safe and the factorization should work well. On the other hand, since the masses of the X,Y,Z states are close to 4 GeV,

TABLE I: Numerical values of the radial wave functions at the origin $|R_{nl}^{(l)}(0)|^2$ for chamonium calculated with the QCD (B-T) potential in Ref.[8].

States	$1S$	$2S$	$3S$	$1P$	$2P$
$\|R_{nl}^{(l)}(0)\|^2$	0.81 GeV^3	0.529 GeV^3	0.455 GeV^3	0.075 GeV^5	0.102 GeV^5

we make up some factors to remedy the phase space integrals as a compensation for the calculations in the non-relativistic limit. The factor for $\eta_c(mS)$ production is $\frac{(1-M^2_{\eta_c(mS)}/s)^3}{(1-4m_c^2/s)^3}$ since the $\gamma^* \to \gamma + \eta_c(mS)$ is a P-wave process, and the factor for $\chi_{cJ}(nP)$ production is $\frac{1-M^2_{\chi_{cJ}(nP)}/s}{1-4m_c^2/s}$ since $\gamma^* \to \gamma + \chi_{cJ}(nP)$ is predominantly an S-wave process.

III. NUMERICAL RESULTS AND DISCUSSIONS

Now we proceed to present the numerical results. For simplicity, we refer to the Born cross section as QED contribution and the one-loop correction as the QCD contribution. We choose m_c=1.5 GeV and $\alpha_s(2m_c)$=0.26, and the values of wave functions at the origin are taken from potential model calculations (see the results of the $B-T$-type potential in Ref.[8]), which are listed in Table I.

A. $e^+e^- \to \gamma + \eta_c(mS)$

The $\eta_c(1S)$ and $\eta_c(2S)$ have already been found for a long time. For the $\eta_c(3S)$, the $X(3940)$ [10] is one of the candidates. If we do not take into account the modification factor $\frac{(1-M^2_{\eta_c(mS)}/s)^3}{(1-4m_c^2/s)^3}$, the QED contribution to the cross section of $e^+e^- \to \gamma + \eta_c$ is $1.37 - 0.83$ pb for $4.04 < \sqrt{s} < 5$ GeV. The QCD contribution is negative, and is about -30% of the QED ones. The results of $\eta_c(2S)$ and $\eta_c(3S)$ can be easily obtained by replacing the wave function of 1S with those of 2S and 3S, respectively. Thus, up to the $\alpha^3\alpha_s$ order, the cross sections are

$$\sigma(e^+e^- \to \gamma + \eta_c(mS)) = \begin{cases} 0.87 \sim 0.54\text{pb}, & m=1 \\ 0.57 \sim 0.35\text{pb}, & m=2 \\ 0.49 \sim 0.30\text{pb}, & m=3 \end{cases} \qquad (4)$$

Setting $M_{\eta_c} = 2.907$ GeV, $M_{\eta_c(2S)} = 3.549$ GeV from PDG values [9], and assuming

X(3940) is the $\eta_c(3S)$ state [11], the factor $\frac{(1-M^2_{\eta_c(mS)}/s)^3}{(1-4m_c^2/s)^3}$ is almost 1 for η_c and varies from $0.12(3.2\times 10^{-4})$ to $0.47(0.21)$ for $m = 2(3)$ in the energy range of $4.04 < \sqrt{s} < 5$ GeV. The modification has such big effects on $\eta_c(2S)$ and $\eta_c(3S)$ production that we treat them as the largest uncertainty sources in our calculations and take the results before/after modification as the upper/lower bounds of our predictions. After the modification, the cross section of $\eta_c(3S)$ is very small, which may not be used to search for the $\eta_c(3S)$ state. However, the cross sections of $\eta_c(1S)$ and $\eta_c(2S)$ are large enough to be measured. It should be interesting to study the $\eta_c(1S/2S)$ production mechanism in the continuum energy region at BESIII. Moreover, another interesting mechanism for $\eta_c(mS)$ production at BESIII, which is through the direct photon collision, was studied in Ref. [12]. We find that the cross sections of $e^+e^- \to \gamma + \eta_c(mS)$ are larger than those of $e^+e^- \to e^+e^- + \eta_c(mS)$ at least by a factor of 5 in the energy region of $4 < \sqrt{s} < 5$ GeV.

B. $e^+e^- \to \gamma + \chi_{c0}(nP)$

The QED contribution to $\gamma+\chi_{c0}$ production is about 120 fb at $\sqrt{s} = 4.04$ GeV. However, the corresponding QCD contribution is about -119 fb, which almost cancel the QED contribution entirely. Furthermore, we find that when $\sqrt{s}$ becomes larger the total contribution becomes even negative. Therefore, due to the large theoretical uncertainty we will not do any phenomenological discussion for $\gamma + \chi_{c0}$ production here.

C. $e^+e^- \to \gamma + \chi_{c1}(nP)$

The QED contribution to $\gamma + \chi_{c1}(1P)$ production changes from 2.60 pb to 0.68 pb when $\sqrt{s}$ varies from 4.04 to 5.0 GeV, and it becomes 50% smaller after including the QCD contribution. Furthermore, if we use the modified phase space factor with $M_{\chi_{c1}} = 3.511$ GeV, we obtain the QCD+QED result

$$\sigma(e^+e^- \to \gamma + \chi_{c1}) = 0.70 - 0.25 \text{ (pb)} \quad \text{for } 4.04 < \sqrt{s} < 5 \text{ GeV}. \tag{5}$$

Unlike the η_c and χ_{c0} case, the QCD contribution also changes the angular distribution slightly. For example, at $\sqrt{s} = 4.26$GeV, the QED contribution to $\frac{d\sigma}{d\cos(\theta)}$ is proportional to $1 + 4.1 \times 10^{-3}\cos^2(\theta)$, while the QED+QCD contribution is proportional to $1 + 5.8 \times 10^{-3}\cos^2(\theta)$.

The $\chi_{c1}(2P)$ state has not been observed yet. In some models, the $X(3872)$ is treated as a mixture of χ'_{c1} and $D^0\bar{D}^{*0}$ molecule [4]. Recently, by studying its prompt production cross section at hadron colliders, it was obtained that the size of the χ'_{c1} component in $X(3872)$ is about 30% $\sim$ 40% [13, 14]. If simply choosing $M_{\chi_{c1}(2P)} = 3.872$GeV, we predict that

$$\sigma(e^+e^- \to \gamma + \chi_{c1}(2P)) = 0.43 - 0.26 \text{ (pb)} \quad \text{for } 4.04 < \sqrt{s} < 5 \text{ GeV}. \tag{6}$$

In general, if $\chi_{c1}(2P)$ mass is above the open flavor threshold $M_D + M_{D^*} = 3.872$GeV, its predominantly decay mode may be $\chi_{c1}(2P) \to DD^*$ [15]. On the other hand, if $M(\chi_{c1}(2P)) < 3.872$GeV, similar to the $1P$ state case, it will decay mainly into light hadrons, and its total width will be about one MeV. In some potential model calculations [11, 16], its E1 transition decay width $\Gamma(\chi_{c1}(2P) \to \gamma + \psi')$ is about 50 $\sim$ 80 KeV. Based on our calculation and above analysis, we infer that there are some chances to find the missing $\chi_{c1}(2P)$ state at BESIII whether its mass above or below the DD^* threshold through the $e^+e^- \to \gamma + \chi_{cJ}(2P)$ process in the continuum region of $4.04 < \sqrt{s} < 5$ GeV.

Particularly, if $X(3872)$ is a mixed state of χ'_{c1} and $D^0\bar{D}^{*0}$ components, it can also be detected through the mode $X(3872) \to J/\psi\pi^+\pi^-$, but the cross section $\sigma(e^+e^- \to \gamma + X(3872))$ should be smaller than that in (6) by a factor of 3 since the probability of χ'_{c1} in $X(3872)$ is only about 30% $\sim$ 40% [13, 14].

D. $e^+e^- \to \gamma + \chi_{c2}(nP)$

The $\chi_{c2}(2P)$ state was observed in the $\gamma\gamma$ collision by Belle Collaboration [17]. Its mass is about 3.927 GeV [9]. The QED contributions to the $\gamma + \chi_{c2}(1P)$ and $\gamma + \chi_{c2}(2P)$ cross sections are in the range from 2.5 pb to 0.48 pb and 3.1 pb to 0.55 pb, respectively, for $4.04 < \sqrt{s} < 5$ GeV. The QCD contributions are also negative and are about -60% of the QED contributions. Using the modified phase space factor, we get that the QED+QCD contributions are

$$\sigma(e^+e^- \to \gamma + \chi_{c2}(nP)) = \begin{cases} 0.48 \sim 0.13 \text{ pb}, & n = 1 \\ 0.24 \sim 0.14 \text{ pb}, & n = 2 \end{cases} \tag{7}$$

The QCD contribution changes the angular distribution slightly as well. For example, at $\sqrt{s} = 4.26$GeV, $\frac{d\sigma}{d\cos(\theta)}$ changes from $1 - 9.2 \times 10^{-2} \cos^2(\theta)$ to $1 - 9.9 \times 10^{-2} \cos^2(\theta)$.

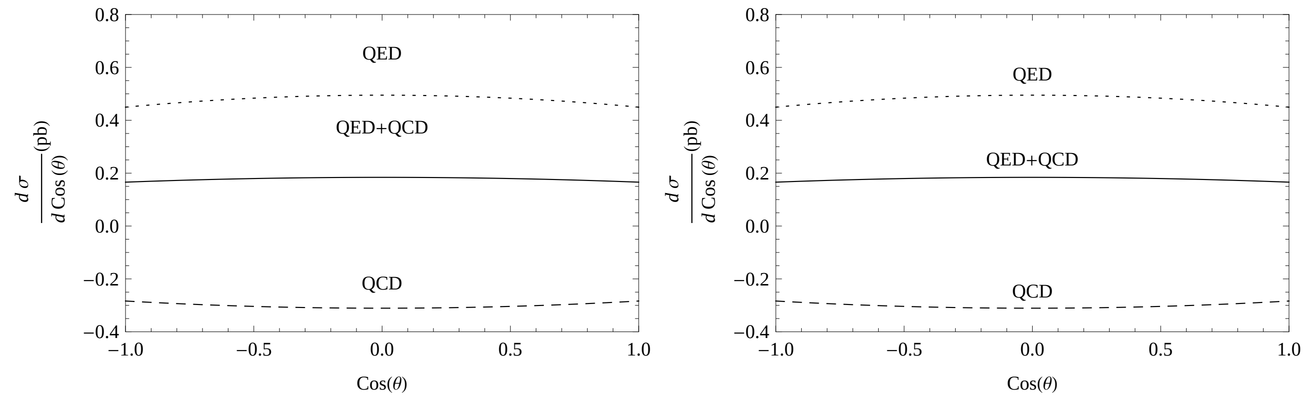

FIG. 1: The angular distributions of χ_{c1} (left) and χ_{c2} (right) production in $e^+e^- \to \gamma + \chi_{cJ}$ at $\sqrt{s} = 4.26$GeV. The dotted line denotes the QED contribution, the dashed line denotes the QCD contribution, and the total QED+QCD contribution is denoted by the solid line.

TABLE II: Predicted production cross sections of $\eta_c(1S/2S)$ and $\chi_c(1P/2P)$ at some typical energy points in the region of $\sqrt{s} = 4.0$-5.0 GeV..

	σ/pb						
$\sqrt{s}/GeV$	η_c	$\eta_c^{'}$	χ_{c0}	χ_{c1}	$\chi_{c1}^{'}$	χ_{c2}	$\chi_{c2}^{'}$
4.040	0.91	0.04	0.001	0.70	0.32	0.48	0.16
4.160	0.86	0.06	−0.005	0.64	0.40	0.41	0.23
4.260	0.81	0.08	−0.007	0.58	0.43	0.36	0.24
4.360	0.78	0.09	−0.008	0.53	0.43	0.31	0.23
4.415	0.76	0.10	−0.008	0.50	0.43	0.28	0.23
4.660	0.67	0.13	−0.006	0.40	0.39	0.20	0.19
5.000	0.55	0.14	−0.002	0.25	0.26	0.13	0.14

In Ref. [12], the production of $\chi_{c2}(1P/2P)$ through indirect photon collision in $4-5$ GeV was studied. After including the one-loop QCD corrections, the cross sections were found to be a few fb. It is much smaller than those in the $e^+e^- \to \gamma + \chi_{c2}(1P, 2P)$ process.

As references, in Table II we list the cross sections with the modified phase space factors for $e^+e^- \to \gamma + \eta_c(1S/2S)(\chi_{c1,2}(1P/2P))$ at some typical energy points in the region of $\sqrt{s} = 4.0$-5.0 GeV, and also show the angular distributions of χ_{c1} and χ_{c2} production at $\sqrt{s} = 4.26$ GeV.

IV. SUMMARY

In summary, we reevaluate the cross sections for $e^+e^- \to \gamma + \eta_c(1S/2S)(\chi_{c1,2}(1P/2P))$ processes at NLO in α_s within the framework of NRQCD factorization at the BESIII energy region of $\sqrt{s} = 4.04$-5.0 GeV. The factorization is verified at this order and the near threshold effects are partly recovered by using the modified phase space factors for the charmonium states. The cross sections are as large as 0.1-0.9 pb, which could be used to search for the missing $2P$ charmonium states or to estimate the continuum backgrounds in the resonance region.

Acknowledgments

This work is supported in part by the National Natural Science Foundation of China (No 11075002, No 11021092, No 10905001) and the Ministry of Education of China (20100001120013, RFDP). The work of Zhi-Guo He is supported in part by the German Federal Ministry for Education and Research BMBF through Grant No. 05H12GUE.

Note added. When this paper was being prepared, a similar calculation was made by Li *et al.* [18]. Differing from ours, they use $m_c = M_X/2$ to evaluate the short-distance amplitudes. Thus, the threshold singularities in the amplitudes, which have been analyzed in Sec. II, enhance their cross sections for $\chi_c(1P/2P)$ production by more than a factor of ten near the threshold region. As for the new BESIII measurement on $\gamma X(3872)$ at $\sqrt{s} = 4.229/4.260$ GeV [19], according to our calculation, the cross section of $e^+e^- \to \gamma X(3872)$ is only 0.15 pb, if the production of $X(3872)$ proceeds dominantly through its $\chi_{c1}(2P)$ component, of which the probability is 0.3-0.4 (see Table II and the context in the subsection III.C). The calculated cross section multiplied by the branching ratio $\mathrm{Br}(X(3872) \to J/\psi\pi^+\pi^-)$, which is estimated to be about 5% [13, 14], is much smaller than the experimental data at $\sqrt{s} = 4.229/4.260$ GeV [19]. This suggests that the observed cross section may mainly come from the resonance contributions through E1 transitions between chamonia [20] or some other exotic mechanisms [21].

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