QCD Prediction for the Non-$D\bar{D}$ Annihilation Decay of $\psi(3770)$

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To clarify the marked difference between BES and CLEO measurements on the non-$D\bar{D}$ decays of the $\psi(3770)$, a 1^3D_1-dominated charmonium, we calculate the annihilation decay of $\psi(3770)$ in nonrelativistic QCD. By introducing the color-octet contributions, the results are free from infrared divergences. The color-octet matrix elements are estimated by solving the evolution equations. The S-D mixing effect is found to be very small. With $m_c = 1.5 \pm 0.1$ GeV, our result is $\Gamma(\psi(3770) \to \text{light hadrons}) = 467^{-187}_{+338}$ keV. For $m_c = 1.4$ GeV, together with the observed hadronic transitions and $E1$ transitions, the non-$D\bar{D}$ decay branching ratio of $\psi(3770)$ could reach about 5%. Our results do not favor the results of either the BES or the CLEO Collaborations, and further experimental tests are urged.

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Heavy quarkonia decays play an important role in understanding quantum chromodynamics (QCD) [1]. These include not only the determination of the running strong coupling constant α_s from S-wave decays $J/\psi \to ggg$ and $\Upsilon \to ggg$ but also the study of factorization from the P-wave annihilation decays, where infrared (IR) divergences appear in ${}^1P_1 \to ggg$ and ${}^3P_J \to gq\bar{q}$ [2,3]. A traditional way to treat the IR divergences was to use the quark binding energy or the gluon momentum as a cutoff to estimate these IR divergences, but this is model-dependent and breaks factorization of short- and long-distance processes. In Ref. [4], a new factorization scheme was proposed to absorb the IR logarithms by new nonperturbative parameters, the color-octet matrix elements. Based on the nonrelativistic nature of heavy quarkonia, an effective theory, nonrelativistic QCD (NRQCD), was developed [5], in which the inclusive annihilation decays can be calculated in a systematic way by double expansions in terms of α_s and v, the relative velocity of quarks in heavy quarkonium. In Refs. [6–8], the authors calculated QCD radiative corrections to the light hadron (LH) decays of P-wave charmonium in NRQCD and showed explicitly the cancellation of infrared divergences at the next-to-leading order (NLO). In Ref. [9], a more complete and precise NLO calculation for the P-wave decay perturbative coefficients in NRQCD is given (see also [10]). At NLO in α_s, the NRQCD predictions for the relative decay rates of $\chi_{cJ} \to \text{LH}$ are consistent with more updated data (see Chapter 4 of Ref. [1]). Moreover, the relativistic corrections of S- and P-wave electromagnetic quarkonium decays have been given at order v^7 [11]. As for the D wave, in Refs. [12,13] calculations of ${}^3D_J \to ggg$ decays were given but suffered from IR divergences, while in Ref. [8] only the leading order (LO) color-octet contribution to ${}^3D_J \to \text{LH}$ was given. So for the D wave a complete calculation for the IR cancellation and radiative correction in NRQCD is apparently needed.

Phenomenologically, for the ${}^3D_1$ ($J^{PC} = 1^{--}$) charmonium state $\psi(3770)$, there is a long-standing puzzle in its non-$D\bar{D}$ decays that the $\psi(3770)$ might have substantial decays not into $D^0\bar{D}^0$ and D^+D^-. BES earlier reported two results based on different analysis methods: $\text{Br}(\psi(3770) \to \text{non-}D\bar{D}) = (14.5 \pm 1.7 \pm 5.8)\%$ [14] and $\text{Br}(\psi(3770) \to \text{non-}D\bar{D}) = (16.4 \pm 7.3 \pm 4.2)\%$ [15]. In contrast, CLEO [16] measured the cross section $\sigma(e^+e^- \to \psi(3770) \to \text{non-}D\bar{D}) = -0.01 \pm 0.08^{+0.41}_{-0.30}$ nb. Very recently, with the first direct measurement on the non-$D\bar{D}$ decay, BES gives $\sigma(e^+e^- \to \psi(3770) \to \text{non-}D\bar{D}) = (0.95 \pm 0.35 \pm 0.29)$ nb and $\text{Br}(\psi(3770) \to \text{non-}D\bar{D}) = (13.4 \pm 5.0 \pm 3.6)\%$ [17]. Evidently, the two collaborations give very different results of the non-$D\bar{D}$ decay of $\psi(3770)$. Meanwhile, a number of experiments to search for the exclusive hadronic non-$D\bar{D}$ decays of $\psi(3770)$ have been done by BES [18] and CLEO [19], but no significant signals are found.

At least two kinds of non-$D\bar{D}$ decays of $\psi(3770)$ have been observed. The hadronic transitions $\psi(3770) \to \pi^+\pi^- J/\psi$ was first observed by BES with a branching ratio of $(0.34 \pm 0.14 \pm 0.09)\%$ [20] and was later confirmed by CLEO with a somewhat smaller branching ratio $\text{Br}(\psi(3770) \to \pi^+\pi^- J/\psi) = (0.189 \pm 0.020 \pm 0.020)\%$ [21], and the $\pi^0\pi^0 J/\psi$ and $\eta J/\psi$ modes were also seen with each having a branching ratio of about one-half that of $\pi^+\pi^- J/\psi$ [21]. These results are within the range of theoretical predictions based on the QCD multipole expansion for hadronic transitions [22]. With the total width of 23.0 ± 2.7 MeV for $\psi(3770)$ [23], the width of all hadronic transitions is about 100–150 keV. Another kind of non-$D\bar{D}$ decays of $\psi(3770)$ is the $E1$ transitions $\psi(3770) \to \gamma + \chi_{cJ}$ ($J = 0, 1, 2$), and their widths are measured by CLEO to be 172 ± 30, 70 ± 17, and <21 keV for $J = 0$, 1, and 2, respectively [24], which are in good agreement with predicted values 199, 72, and 3.0 keV in a QCD-inspired potential model calculation with relativistic corrections [25] (see also [26,27]). The width of all $E1$ transitions $\psi(3770) \to \gamma + \chi_{cJ}$ ($J = 0, 1, 2$) is about 250 ± 50 keV. The above-mentioned hadronic and $E1$ transitions contribute only 350–400 keV and

1.5%–1.8%, respectively, to the non-$D\bar{D}$ decay width and branching ratio of $\psi(3770)$.

To clarify the puzzle of $\psi(3770)$ non-$D\bar{D}$ decay, in this Letter we will give complete infrared safe NLO QCD corrections to the annihilation decay rate of the $\psi(3770)$ in the framework of NRQCD. Since $v^2 \sim \alpha_s(m_c) \approx 0.3$ in charmonium, the relativistic corrections are also important and should be considered in the future work.

The $\psi(3770)$ can be viewed as a 1^3D_1 dominated state with a small admixture of 2^3S_1 and expressed as (see, e.g., [25,26])

$$\begin{aligned} |\psi(3770)\rangle &= \cos\theta|1^3D_1\rangle + \sin\theta|2^3S_1\rangle, \\ |\psi(3686)\rangle &= -\sin\theta|1^3D_1\rangle + \cos\theta|2^3S_1\rangle, \end{aligned} \tag{1}$$

where θ is the S-D mixing angle and it is about $(12 \pm 2)°$ by fitting the leptonic decay widths of $\psi(3770)$ and $\psi(3686)$. Then the LH decay width of $\psi(3770)$ is

$$\begin{aligned} \Gamma(\psi(3770) \to \mathrm{LH}) = \cos^2\theta\Gamma(1^3D_1 \to \mathrm{LH}) \\ + \sin^2\theta\Gamma(2^3S_1 \to \mathrm{LH}) + \mathrm{IF}, \end{aligned} \tag{2}$$

where IF stands for the S-D interference term. The calculation of S-wave decay at order α_s^3 and leading order in v^2 is trivial, and it gives

$$\Gamma(2^3S_1 \to \mathrm{LH}) = \frac{|R_{2S}(0)|^2}{4\pi}\frac{40\alpha_s^3(\pi^2 - 9)}{81m_c^2}, \tag{3}$$

where $R_{2S}(0)$ is the 2^3S_1 wave function at the origin. The S-D interference term IF in Eq. (2) is infrared finite at leading order in v^2 and α_s and can be obtained by combining the $1^3D_1 \to 3g$ with $2^3S_1 \to 3g$ amplitudes:

$$\mathrm{IF} = 2\sin\theta\cos\theta\frac{5(-240 + 71\pi^2)\alpha_s^3}{324m_c^4}\frac{R_{2S}(0)}{\sqrt{4\pi}}\sqrt{\frac{1}{8\pi}}R''_{1D}(0), \tag{4}$$

where $R''_D(0)$ is the second derivative of the 1^3D_1 wave function at the origin.

We now proceed with the calculation of the main part, the D-wave quarkonium LH decay. In NRQCD, the inclusive annihilation decay of $^3D_1$ at leading order in v^2 is factorized as

$$\begin{aligned} \Gamma(^3D_J \to \mathrm{LH}) = 2\mathrm{Im}f(^3D_J^{[1]})H_{D1} + \sum_{J=0}^{2} 2\mathrm{Im}f(^3P_J^{[8]})H_{P8J} \\ + 2\mathrm{Im}f(^3S_1^{[8]})H_{S8} + 2\mathrm{Im}f(^3S_1^{[1]})H_{S1}, \end{aligned} \tag{5}$$

where $\mathrm{Im}f(n)$ is the imaginary part of the $Q\bar{Q} \to Q\bar{Q}$ scattering amplitude and can be calculated perturbatively. The corresponding nonperturbative matrix elements are

$$\begin{aligned} H_{D1} &= \frac{\langle H|\mathcal{O}_1(^3D_1)|H\rangle}{m_c^6}, \qquad H_{P8J} = \frac{\langle H|\mathcal{O}_8(^3P_J)|H\rangle}{m_c^4}, \\ H_{S8} &= \frac{\langle H|\mathcal{O}_8(^3S_1)|H\rangle}{m_c^2}, \qquad H_{S1} = \frac{\langle H|\mathcal{O}_1(^3S_1)|H\rangle}{m_c^2}, \end{aligned} \tag{6}$$

where H is $\psi(1^3D_1)$. Those four-fermion operators of the S wave and the P wave are defined in Ref. [5], and here we give only the definition of the D-wave four-fermion operator (the normalization of the color singlet four-fermion operators agrees with those in Ref. [9]):

$$\mathcal{O}_1(^3D_1) = \frac{3}{10N_c}\psi^\dagger \boldsymbol{T}^i\chi\chi^\dagger \boldsymbol{T}^i\psi, \tag{7}$$

where $\boldsymbol{T}^i = \boldsymbol{\sigma}^j\boldsymbol{S}^{ij}$ and $\boldsymbol{S}^{kl} = (\frac{-i}{2})^2(\overleftrightarrow{D}^i\overleftrightarrow{D}^j - \frac{1}{3}\overleftrightarrow{D}^2\delta^{ij})$.

We calculate the short-distance coefficients at order α_s^3, and details of our calculation will be given elsewhere. The S-wave and P-wave short-distance coefficients have been calculated in Ref. [9], and our calculated results agree with theirs. The D-wave short-distance coefficients presented here are new, and they are

$$2\mathrm{Im}f(^3S_1^{[1]}) = \frac{40\alpha_s^3(\pi^2 - 9)}{81}, \tag{8a}$$

$$2\mathrm{Im}f(^3S_1^{[8]}) = \frac{\alpha_s^2}{108}\left(36N_f\pi + \alpha_s\left[5(-657 + 67\pi^2) + N_f(642 - 20N_f - 27\pi^2 + 72\ln 2) + 144\beta_0 N_f\ln\frac{\mu}{2m_c}\right]\right), \tag{8b}$$

$$2\mathrm{Im}f(^3P_0^{[8]}) = \frac{5\alpha_s^2}{1296}\left[648\pi + \alpha_s\left(9096 - 464N_f + 63\pi^2 + 2520\ln 2 + 2592\beta_0\ln\frac{\mu}{2m_c} + 96N_f\ln\frac{2m_c}{\mu_\Lambda}\right)\right], \tag{8c}$$

$$2\mathrm{Im}f(^3P_1^{[8]}) = \frac{5\alpha_s^3(4107 - 64N_f - 414\pi^2 + 48N_f\ln\frac{2m_c}{\mu_\Lambda})}{648}, \tag{8d}$$

$$2\mathrm{Im}f(^3P_2^{[8]}) = \frac{\alpha_s^2}{648}\left[432\pi + \alpha_s\left(12\,561 - 464N_f - 774\pi^2 + 1008\ln 2 + 1728\beta_0\ln\frac{\mu}{2m_c} + 240N_f\ln\frac{2m_c}{\mu_\Lambda}\right)\right], \tag{8e}$$

$$2\mathrm{Im}f(^3D_1^{[1]}) = \frac{(321\pi^2 - 8032 - 29\,184\ln\frac{\mu_\Lambda}{2m_c})\alpha_s^3}{5832}, \tag{8f}$$

where $\beta_0 = \frac{11N_c - 2N_f}{6}$, $N_c = 3$, and N_f is the number of flavors of light quarks. μ and μ_Λ are renormalization and factorization scales, respectively. We consider ten processes to get the short-distance coefficients in Eq. (8), including gg, ggg, $q\bar{q}$, and $q\bar{q}g$ final states. The contributions of $q\bar{q}$ and $q\bar{q}g$ processes are labeled by the powers of N_f.

After calculating the short-distance coefficients, we come to determine the long-distance matrix elements. In the P-wave charmonium decay, at leading order in v^2 there are two four-fermion operators $H1$ and $H8$ [4], while in the case of the D-wave decay, there are four independent matrix elements under the heavy-quark spin symmetry. They are H_{D1}, H_{P8}, H_{S8}, and H_{S1}, where $H_{P8} = \frac{\langle H|\mathcal{O}_8(^3P_0)|H\rangle}{m_c^4} = \frac{4\langle H|\mathcal{O}_8(^3P_1)|H\rangle}{3m_c^4} = \frac{20\langle H|\mathcal{O}_8(^3P_2)|H\rangle}{m_c^4}$, and these relations can be derived by considering the $E1$ transition from $^3D_1$ to ^3P_J. In NRQCD, H_{D1} is related to the wave function's second derivative at the origin, while for the other three, in the absence of lattice simulations and phenomenological inputs, we will resort to the operator evolution equation method suggested in Ref. [5], where the authors give the result of the matrix elements in the P-wave decay. Here we derive the following matrix elements in the D-wave case:

$$H_{P8} = \frac{5}{9}\frac{8C_F}{3\beta_0}\ln\left(\frac{\alpha_s(\mu_{\Lambda_0})}{\alpha_s(\mu_\Lambda)}\right)H_{D1}, \tag{9a}$$

$$H_{S8} = \frac{C_F B_F}{2}\left(\frac{8}{3\beta_0}\right)^2\ln^2\left(\frac{\alpha_s(\mu_{\Lambda_0})}{\alpha_s(\mu_\Lambda)}\right)H_{D1}, \tag{9b}$$

$$H_{S1} = \frac{C_F}{4N_c}\left(\frac{8}{3\beta_0}\right)^2\ln^2\left(\frac{\alpha_s(\mu_{\Lambda_0})}{\alpha_s(\mu_\Lambda)}\right)H_{D1}, \tag{9c}$$

where $C_F = \frac{4}{3}$ and $B_F = \frac{5}{12}$. We choose the region of validity of the evolution equation: the lower limit $\mu_{\Lambda_0} = m_c v$ and the upper limit μ_Λ of order m_c.

With both the obtained short-distance coefficients and long-distance matrix elements, we predict the LH decay width of $^3D_1$. The renormalization proceeds by using the $\overline{MS}$ scheme for the coupling constant α_s and the on-shell scheme for the charm quark mass. For convenience, we take the factorization scale μ_Λ to be the same as the renormalization scale μ of order m_c. We choose the pole mass $m_c = 1.5$ GeV, $v^2 = 0.3$, $\mu_{\Lambda_0} = m_c v$, $\mu_\Lambda = 2m_c$, $\alpha_s(2m_c) = 0.249$, $N_f = 3$, $\Lambda_{\text{QCD}} = 390$ MeV, and $H_{D1} = \frac{15|R_D''(0)|^2}{8\pi m_c^6} = 0.786 \times 10^{-3}$ GeV [28]. At $\mathcal{O}(\alpha_s^2)$, the LH decay involves three subprocesses $(^3P_0)_8 \to gg$, $(^3P_2)_8 \to gg$, and $(^3S_1)_8 \to q\bar{q}$, and the decay width is estimated to be

$$\Gamma(^3D_1 \to \text{LH}) = 0.205 \text{ MeV}. \tag{10}$$

At $\mathcal{O}(\alpha_s^3)$, there will be seven more subprocesses $(^3S_1)_{1,8} \to ggg$, $(^3P_1)_8 \to ggg$, $(^3P_J)_8 \to q\bar{q}g$, $(^3D_1)_1 \to ggg$ involved, and the result turns to be

TABLE I. Subprocess decay rates of $^3D_1$ charmonium, where $v^2 = 0.3$, $\mu_\Lambda = 2m_c$, and $\alpha_s(2m_c) = 0.249$.

Subprocess	LO (keV)	NLO (keV)
$(^3S_1)_1 \to$ LH	0	0.24
$(^3S_1)_8 \to$ LH	18	33
$(^3P_0)_8 \to$ LH	184	410
$(^3P_1)_8 \to$ LH	0	−5.8
$(^3P_2)_8 \to$ LH	2.5	4.4
$(^3D_1)_1 \to$ LH	0	−10

$$\Gamma(^3D_1 \to \text{LH}) = 0.436 \text{ MeV}. \tag{11}$$

Our result shows that in NRQCD factorization the NLO QCD correction is even larger than the LO result. The numerical values for all subprocesses are listed in Table I. If we choose $\mu_\Lambda = m_c$, $\alpha_s(m_c) = 0.369$, the values of LO and NLO (the sum of the LO contribution plus the NLO correction) become 0.28 and 0.68 MeV, respectively. The renormalization scale μ dependence of the decay rate is shown in Fig. 1. We see that the μ dependence at $\mathcal{O}(\alpha_s^3)$ is rather mild when $\mu > 0.9m_c$. For simplicity, we take $\mu = 2m_c$, where the logarithm term $\ln\frac{\mu}{2m_c} = 0$.

With the pole mass $m_c = 1.5$ GeV, $\alpha_s(2m_c) = 0.249$, $|R_{1D}''(0)|^2 = 0.015$ GeV^7, $|R_{2S}(0)|^2 = 0.529$ GeV^3, and $\theta = 12°$, we find that the three terms on the right-hand side of Eq. (2) contribute 417, 5.3, and 44 keV, respectively, to the LH decay of $\psi(3770)$ and result in

$$\Gamma(\psi(3770) \to \text{LH}) = 467 \text{ keV}. \tag{12}$$

Our result shows that the D-wave LH decay is dominant, and the S-D mixing has only a very small effect on the $\psi(3770)$ LH decay. One important uncertainty of our prediction is associated with the long-distance matrix ele-

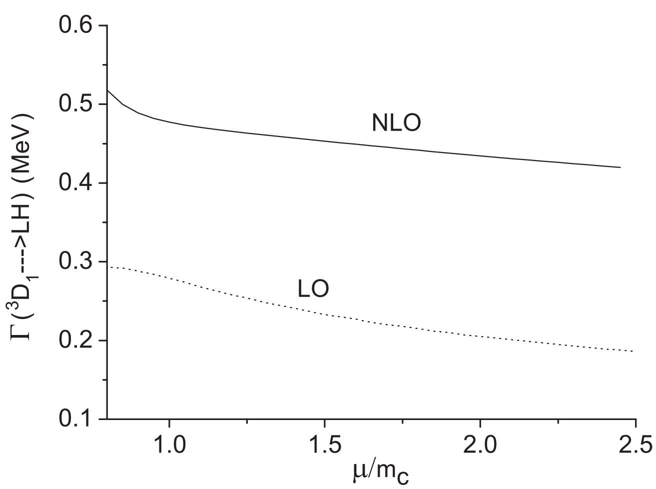

FIG. 1. Renormalization scale μ dependence of the decay width of charmonium $^3D_1$ to light hadrons. Here NLO means LO contribution + NLO correction.

ments, especially the color-octet matrix elements. Using the same evolution equation method in χ_{cJ} decays, we find the ratio of color octet to color singlet P-wave decay matrix elements agrees with the lattice calculation [29] to within about 20% and with the phenomenological values [7,10] to within about 30%. This might indicate, though not compellingly, that the uncertainty related to the matrix elements calculated using the evolution equation in the D-wave decays are also about (20–30)% or (with more confidence) less than 50%. Other uncertainties such as the relativistic corrections and higher order QCD radiative corrections are beyond the scope of the present study. On the other hand, however, we find the decay rate to be sensitive to the value of the charm quark mass. If we choose the pole mass $m_c = 1.5 \pm 0.1$ GeV, $\alpha_s(\mu) = \alpha_s(2m_c)$, and fix other parameters as before, then our prediction becomes

$$\Gamma(\psi(3770) \to \mathrm{LH}) = 467^{-187}_{+338}\ \mathrm{keV}(\pm 50\%), \tag{13}$$

$$\mathrm{Br}\,(\psi(3770) \to \mathrm{LH}) = (2.0^{-0.80}_{+1.50})\%(\pm 50\%). \tag{14}$$

For a small mass $m_c = 1.4$ GeV, the LH decay width and branching ratio of $\psi(3770)$ can reach 805 keV($\pm 50\%$) and 3.5%($\pm 50\%$), respectively, and this could be viewed as the maximum value for the LH decay of $\psi(3770)$ in our estimation based on the calculation at leading order in v^2 and next-to-leading order in α_s in NRQCD.

Together with the partial decay width of 350–400 keV observed for hadronic transitions and $E1$ transitions of the $\psi(3770)$, the predicted annihilation (LH) decay width in Eq. (13) will make the total non-$D\bar{D}$ decay width of $\psi(3770)$ to be about 820–870 keV for $m_c = 1.5$ GeV and 1.15–1.20 MeV for $m_c = 1.4$ GeV. The latter may be viewed as the maximum value obtained in our approach for the total non-$D\bar{D}$ decay width, corresponding to a branching ratio of about 5% of the $\psi(3770)$ decay.

In summary, we have given a rigorous theoretical prediction for the LH decay of $\psi(3770)$, based on NRQCD factorization at NLO in α_s and LO in v^2. By introducing the color-octet contributions, the results are free from infrared divergences. We find that for the $\psi(3770)$ the D-wave contribution is dominant, and the effect of S-D mixing is very small. Numerically, our results do not favor either of the two experimental results measured by the BES and CLEO Collaborations. We hope that our theoretical result can serve as a clue to clarify the long-standing puzzle of the $\psi(3770)$ non-$D\bar{D}$ decay. We urge doing more precise measurements on both inclusive and exclusive non-$D\bar{D}$ decays of $\psi(3770)$ in the future. If their total branching ratio can be as large as 10%, it will be a real challenge to our current understanding of QCD, and new decay mechanisms have to be considered.

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