Contribution of the vector meson to the $\Upsilon(nS) \to \bar{d}^*(2380) + X$ decay channel

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$d^*(2380)$ was observed by WASA-at-COSY collaborations in the nuclear reaction recently. Its particularly narrow width may indicate the new QCD-allowed hadronic structure. To further confirm the existence of this peculiar particle in a totally different kind of reaction, $\Upsilon(nS) \to \bar{d}^*(2380) + X$, the contribution from the vector meson should also be considered. To this end, B^* meson as an intermediate state in the $\Upsilon(nS) + d^*(2380) \to \Upsilon(nS) + d^*(2380)$ scattering is studied within the same framework of the SU(3) chiral quark model. As a result, it is shown that $\bar{d}^*$ might be found in the momentum range of 0.3–0.9 GeV.

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I. INTRODUCTION

Research on the six quark system started more than 50 years ago when Dyson and Xuong proposed a $\Delta\Delta$ structure from a simple group classification without considering dynamical effects [1]. At that time, compared with the blank in experiment data, the relevant theoretical work went in advance. Recently, more and more XYZ zoos and kinds of exotic resonances are discovered. Tetraquarks, pentaquarks, molecular states, hybrid states, glueball, etc., all these hypothetical structures are allowed by quantum chromodynamics (QCD), which makes the research of these peculiar particles much attractive. Along with the flourish of this field these years, many efforts were put into experiments. The data was accumulated increasingly. As a consequence, a dibaryon-like exotic state came out from the theory, present in our front.

The signature of such a resonance was reported by WASA-at-COSY collaborations when they studied the ABC effect in $pn \to d\pi^0\pi^0$, $pn \to d\pi^+\pi^-$ reactions [2,3]. Further confirmation was done in a series of reactions, e.g., $pn \to pp\pi^-\pi^0$, $pn \to pn\pi^0\pi^0$, $pd \to {}^3\mathrm{He}\pi^-\pi^+$, $pd \to {}^3\mathrm{He}\pi^0\pi^0$, etc., [4–9]. After some analysis, it is shown that the quantum number of this resonance is $I(J^P) = 0(3^+)$ [10]. For the description of the observables, the collaboration obtained the mass and width of the s-channel resonance being $M = 2380$ MeV, $\Gamma = 70$ MeV, using the Breit-Wigner ansatz for the resonance amplitude. Facing its mass and extraordinarily narrow width, the conventional $\Delta\Delta$ picture does not work well. But on the other hand, the data clearly show a new dibaryon-like structure from the Dalitz plot [2,7]. All these messages together imply that there may exist a new structure in this particle.

The news from experimentalists spread around quickly and kindled the enthusiasm in theorists in a moment. Many hypotheses were proposed and various methods were employed to uncover the property of this particle [11–24]. However, up to now, $d^*(2380)$ has only shown up in the nuclear reaction process. Obviously, apart from the discussions on its structure, being observed in just one kind of reaction is far from enough. Further examination of its existence in totally different mechanism is extremely necessary. Relevant theoretical research on this topic is still scanty. For this reason, in the Ref. [18], we studied the decay widths of $\Upsilon(nS) \to \bar{d}^* + X$ in a phenomenological model. In that work, by virtue of the unitarity of S-matrix and crossing symmetry, the decay width was obtained through the imaginary part of the amplitude of the forward scattering between $\Upsilon(nS)$ and d^*, where the contribution of the pseudoscalar meson which is composed of a $\bar{b}$ and a u (or d) quarks in the s-channel is considered. However, it is a common sense that a $\bar{b}$ and a u (or d) quarks can also fuse to a vector meson B^*, and compared with the pseudoscalar meson, the vector meson plays a quite different role in the quark-meson interaction. Therefore, it is indispensable to discuss the contribution of vector meson to the decay

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widths in this work. The paper is organized as follows. In Sec. II, we present the brief formalism including both interaction and wave functions. The numerical results are discussed in Sec. III. Finally, Sec. IV is a summary.

II. BRIEF FORMALISM

The differential decay widths of $\Upsilon(nS) \to \bar{d} + X$ is given by the formula

$$\mathrm{d}\Gamma = \frac{1}{2m_\Upsilon}\left(\frac{\mathrm{d}\vec{p}_{\bar{d}}}{(2\pi)^3}\frac{1}{2E_{\bar{d}}}\right)\sum_{n-1}\left(\prod_f^{n-1}\int\frac{\mathrm{d}\vec{p}_{X_i}}{(2\pi)^3}\frac{1}{2E_{X_i}}\right) \times |\mathcal{M}(\Upsilon \to \bar{d} + X)|^2(2\pi)^4\delta^4\left(p_\Upsilon - p_{\bar{d}} - \sum p_{X_i}\right), \quad (1)$$

where we clearly separate the part related to $\bar{d}$ from others. The crossing symmetry tells us that

$$\mathcal{M}(\Upsilon \to \bar{d} + X) = \mathcal{M}(\Upsilon + d \to X), \quad (2)$$

with $p_d = -p_{\bar{d}}$. As a consequence of the unitarity of the S-matrix, when we insert $S = 1 + iT$ into $S^\dagger S = 1$, we have

$$-i(T - T^\dagger) = T^\dagger T. \quad (3)$$

Sandwiching the left- and right-hand side of Eq. (3) between the same initial and final states of $\Upsilon(nS)$ and deuteron, and inserting a complete set of intermediate states between $T^\dagger$ and T in the right-hand side to account for all possible physical processes, then we obtain

$$2\mathrm{Im}\mathcal{M}(\Upsilon + d \to \Upsilon + d) = \sum_n\left(\prod_{i=1}^n\int\frac{\mathrm{d}\vec{p}_{X_i}}{(2\pi)^3}\frac{1}{2E_{X_i}}\right) \times |\mathcal{M}(\Upsilon + d \to X)|^2\delta^4 \times \left(p_\Upsilon + p_d - \sum_i p_{X_i}\right), \quad (4)$$

which together with crossing symmetry relates the imaginary part of the forward scattering $\Upsilon(nS)+d\to\Upsilon(nS)+d$ to the differential decay width of $\Upsilon(nS) \to \bar{d} + X$. So the decay width can be converted into

$$\mathrm{d}\Gamma = \frac{1}{m_\Upsilon}\left(\frac{\mathrm{d}\vec{p}_d}{(2\pi)^3}\frac{1}{2E_d}\right) \times \mathrm{Im}\mathcal{M}(\Upsilon + d \to \Upsilon + d), \quad (5)$$

which is just the consequence of optical theorem. For the forward scattering processes $\Upsilon(nS) + d \to \Upsilon(nS) + d$, we approximately treat the fusion of the $\bar{b}$-quark and the light quark as the major mechanism, and the produced B and B^* mesons as the intermediate state in the s-channel. This is because that the quarks in Υ and deuteron are in different types, there is no meson exchange between them in the t-channel. In principle, both the pseudoscalar meson B and vector meson B^* should show up in this assumed scattering mechanism. Now, as an extreme case, we study the effect of the vector meson B^* in this semi-inclusive decay process. Similar as the usual treatment, we calculate the elementary process $\bar{b}+u(d)\to\bar{b}+u(d)$ by adopting the vector meson fusion mechanism in the constituent quark model. The corresponding Feynman diagram is shown in Fig. 1.

In the case where the vector meson B^* acts as the intermediate state in the s-channel, the effective Lagrangian among $\bar{b}$, light quark q and vector meson B^* is expressed as

$$\mathcal{L}_{q\bar{b}B^*} = g_v\bar{\Psi}_{\bar{b}}\gamma_\mu\Psi_q B^{*\mu} + \frac{f_v}{4M}\bar{\Psi}_{\bar{b}}\sigma_{\mu\nu}\Psi_q(\partial^\mu B^{*\nu} - \partial^\nu B^{*\mu}), \quad (6)$$

where g_v and f_v denote the coupling constants for vector and tensor components, and $\bar{\psi}_{\bar{b}}$, ψ_q and $B^{*\mu}$ describe the fields of the light flavor quark, $\bar{b}$-quark and B^* meson, respectively. M is a mass scale, which can be taken as the mass of Λ_b. To simplify the estimation, we temporarily ignore the tensor term because of its small contribution. With this Lagrangian, the contribution of the vector meson to the amplitude is expressed as

$$\mathcal{M} = |g_v|^2\Psi^*_\Upsilon\Psi^*_d\bar{u}(p_u)\gamma_\mu v(p_{\bar{b}})\frac{g^{\mu\nu} - q^\mu q^\nu/q^2}{q^2 - m^2_{B^*} + im_{B^*}\Gamma} \times \bar{v}(p_{\bar{b}})\gamma_\nu u(p_u)\Psi_d\Psi_\Upsilon, \quad (7)$$

where Ψ_Υ and Ψ_d are the wave functions of $\Upsilon(nS)$ and deuteron, respectively. $u(p_u)$, $\bar{u}(p_u)$, $\bar{v}(p_{\bar{b}})$ and $v(p_{\bar{b}})$ represent the spinors of the $u(d)$-quark and $\bar{b}$-quark in the initial and final states, respectively, q is the momentum of the B^* meson, and m_{B^*} and Γ denote the mass and width of the vector meson B^*, respectively. The formula for the process $\Upsilon(nS) \to \bar{d}^* + X$ is the same as that for deuteron case except the wave function of deuteron is replaced by the wave function of d^*.

The realistic wave function of $\Upsilon(nS)$ is obtained by solving the Schrödinger equation with the well-known Cornell potential $V(r) = -\frac{4\alpha}{3r} + \lambda r + c$, where the values of the strong coupling constant α, confining strength λ and zero-point energy c are taken from Refs. [25–27]. The wave functions of deuteron and d^* are taken from the previous

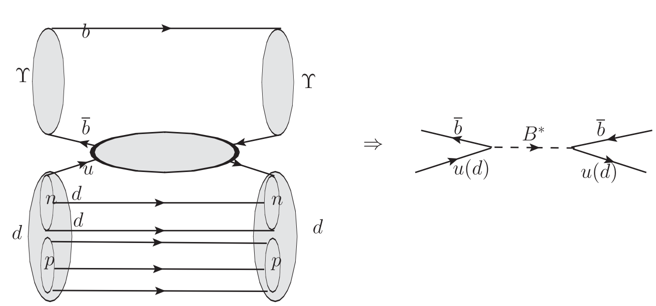

FIG. 1. The Feynman diagram of $\Upsilon + d \to \Upsilon + d$ forward scattering.

works [24], which are obtained by solving the Schrödinger equation for the six-quark system in the framework of the resonating group method (RGM). Then, on the quark degrees of freedom, the wave function of d^* can approximately be written as

$$\Psi_{d^*} \cong [\phi_\Delta(\vec{\rho}_1,\vec{\lambda}_1)\phi_\Delta(\vec{\rho}_2,\vec{\lambda}_2)\chi^{\mathrm{eff},l=0}_{\Delta\Delta}(\vec{R})\zeta_{\Delta\Delta} + \phi_{C_8}(\vec{\rho}_1,\vec{\lambda}_1)\phi_{C_8}(\vec{\rho}_2,\vec{\lambda}_2)\chi^{\mathrm{eff},l=0}_{C_8C_8}(\vec{R})\zeta_{C_8C_8}]_{(SI)=(30)}, \tag{8}$$

where $\phi_\Delta(\vec{\rho}_i,\vec{\lambda}_i)$ and $\phi_{C_8}(\vec{\rho}_i,\vec{\lambda}_i)$ ($i=1,2$) are the internal wave functions of Δ and C_8 clusters, respectively. It should be particularly mentioned that the resultant effective wave function maintains all the effect of total antisymmetrization of the wave function of d^*. For the sake of convenience, we further expand the effective wave function between $\Delta\Delta$, $\chi^{\mathrm{eff},l=0}_{\Delta\Delta}(\vec{R})$, by the sum of four Gaussian functions

$$\chi^{\mathrm{eff},l=0}_{\Delta\Delta}(\vec{R}) = \sum_{i=1}^{4} c_i \exp\left(-\frac{\vec{R}^2}{2b_i^2}\right), \tag{9}$$

but express the effective wave function between C_8C_8, $\chi^{\mathrm{eff},l=0}_{C_8C_8}(\vec{R})$, as a single Gaussian function

$$\chi^{\mathrm{eff},l=0}_{C_8C_8}(\vec{R}) = c_{C_8} \exp\left(-\frac{\vec{R}^2}{2b_{C_8}^2}\right), \tag{10}$$

only due to its special shape. More details about the wave functions can be found in Ref. [24].

Since we study the contribution of the vector meson alone, and the width of B^* meson is very narrow, the Breit-Wigner form of the propagator can be approximated as a δ-function in this extreme condition

$$\frac{1}{q^2-m_{B^*}^2+im_{B^*}\Gamma} \simeq \frac{1}{q^2-m_{B^*}^2+i\epsilon} \to -2\pi i\delta(q^2-m_{B^*}^2), \tag{11}$$

when we only focus on the imaginary part of the amplitude.

The remained work is to simplify the spinors with the numerator in propagator to the kinematic variables. The sum over quark spins can be easily performed by using the completeness relations. After contracting the indices and evaluating the trace, we arrive at

$$S_V = |g_v|^2\Big(-4E_{\bar{b}}E_q - 12m_{\bar{b}}m_q - \frac{8}{m_B^2}\Big(m_{\bar{b}}^2m_q^2 + \Big(m_{\bar{b}}^2+m_q^2\Big)E_{\bar{b}}E_q + E_{\bar{b}}^2E_q^2 + (\vec{p}_{\bar{b}}\cdot\vec{p}_q)^2\Big)\Big), \tag{12}$$

where $\vec{p}_{\bar{b}}$ and $\vec{p}_q$ are momenta of the $\bar{b}$-quark and light quark, respectively. $E_{\bar{b}}$ and E_q are energies of the $\bar{b}$-quark and light quark. The terms odd in $\vec{p}_{\bar{b}}$ do not contribute to the integral and they are not shown in the above expression. The expression is quite different from S_{PS} for the pseudoscalar case, where S_{PS} only has the first two terms in the bracket of Eq. (12).

The momentum of d or d^* is related to the particles X generated from the Υ decay. Because of the lack of the information on X in the final state, we simply insert a phenomenological form factor to describe the momentum distribution of deuteron and d^*. For example, for the deuteron case, the form factor $F(p_d)$ is assumed to be

$$F(p_d) = \mathcal{N}\exp\left[-\frac{(p_d-p_0^d)^2}{(\Lambda^d)^2}\right], \tag{13}$$

where $\mathcal{N}$ is the normalization factor. p_0^d and Λ^d together with the coupling constant g_v can be determined by the experimental momentum distribution of antideuteron in the $\Upsilon(nS)$ semi-inclusive decay and the corresponding partial width of the decay by a least squares fit. Referring these values, we can proceed the $\Upsilon(nS)\to\bar{d}^*+X$ calculation in the same way.

III. NUMERICAL RESULTS

In this section, we will show the numerical results. In our numerical calculation, the masses of light quark and $\bar{b}$ quark are chosen as $m_q=0.313$ GeV and $m_{\bar{b}}=4.96$ GeV. The mass of vector meson B^* is taken as 5.32 GeV. Three parameters g_v, p_0^d and Λ^d should be determined first. We fix them with the experimental momentum distribution of $\bar{d}$ in the $\Upsilon(nS)\to\bar{d}+X$ decay and their decay widths [28,29] through a least squares fitting procedure. The obtained p_0^d (Λ^d) for $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ are 0.58 GeV (0.57 GeV), 0.24 GeV (0.73 GeV) and 0.24 GeV (0.71 GeV), respectively. The differential partial width with respect to the momentum of $\bar{d}$ are plotted in Fig. 2. It shows that the experimental distribution can be reasonably fitted. The momentum of the generated $\bar{d}$ in the $\Upsilon(nS)$ decays are all peaked around 0.9 GeV, and the position of the peak moves downward slightly as the mass of $\Upsilon(nS)$ increases. With $g_v=0.78\times10^{-3}$, we get a decay width of 155×10^{-5} keV for the $\Upsilon(1S)$ decay. The effective coupling constant g_v becomes smaller for $\Upsilon(2S)$ and $\Upsilon(3S)$. They are 0.7×10^{-3} and 0.55×10^{-3}, respectively. The corresponding decay widths are 78×10^{-5} keV and 44×10^{-5} keV. We should mention that although we do not include the momentum dependence in the effective coupling constant g_v explicitly, but the determined coupling constants for different $\Upsilon(nS)$ states by fitting their own decay widths imply the momentum dependence in g_v.

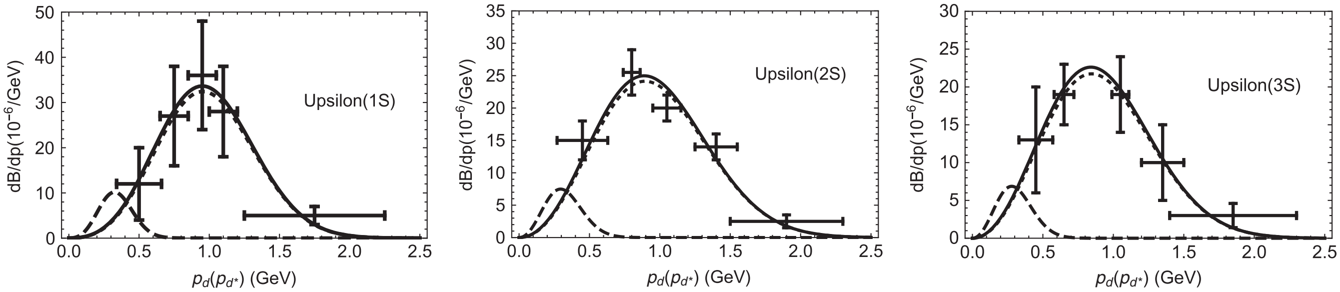

FIG. 2. The differential decay widths for the processes $\Upsilon(nS) \to \bar{d}(\bar{d}^*) + X$. The subfigures from left to right are for decay of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$, respectively. The dots with error bars are the experimental data [28,29]. The solid line is obtained by the data fitting in the $\Upsilon(nS) \to \bar{d} + X$ case, and the dotted line denotes the prediction of the partial decay width with respect to the momentum of $\bar{d}^*$ in the $\Upsilon(nS) \to \bar{d}^* + X$ case. The dashed line on the left in each subfigure represents the lowest limit where the decay width can be distinguished in the experiment.

Now we are ready to study the production of $\bar{d}^*$ in the $\Upsilon(nS) \to \bar{d}^*(2380) + X$ decay. It is straightforward to use the same parameters and replace the wave function of deuteron with the wave function of d^*. The obtained momentum distributions of $\bar{d}^*$ are also shown in Fig. 2 with the dotted lines, and the resultant partial decay widths are tabulated in Table I. It can be seen that with the same parameters, the momentum distributions of $\bar{d}$ and $\bar{d}^*$ are close to each other. Both of them are peaked around 0.9 GeV. The difference of the d^* wave function leads to a small physical effect. For example, compared with the widths of 155×10^{-5} keV, 78×10^{-5} keV and 43×10^{-5} keV in the $\Upsilon(nS) \to \bar{d} + X$ decays for $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$, the maximal decay widths in the $\Upsilon(nS) \to \bar{d}^* + X$ decays are 150×10^{-5} keV, 75×10^{-5} keV and 41×10^{-5} keV for $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$, respectively.

It should be specially mentioned that in the semi-inclusive decay, theoretically, we do not know exactly the momentum distributions of $\bar{d}$ and $\bar{d}^*$, because of lacking the information of X. Since d^* mass is about 500 MeV larger than the deuteron mass, the momentum of the emitted $\bar{d}^*$ in the final states could be smaller than that of deuteron. In other words, $p_0^{d^*}$ and Λ^{d^*} might be smaller than p_0^d and Λ^d, and as a result, $\bar{d}^*$ might be peaked at a smaller momentum. For this reason, when we make a prediction for the production of $\bar{d}^*$, we let the values of $p_0^{d^*}$ and Λ^{d^*} vary in relatively broad ranges, such as about one third of p_0^d and Λ^d for their lower bounds. For example, the lower limit of $p_0^{d^*}$ and Λ^{d^*} are chosen to be 0.2 and 0.2 GeV for $\Upsilon(1S)$ decay. With this choice, the obtained decay width is 16×10^{-5} keV which is about one magnitude smaller than that in the deuteron case. Meanwhile, the peak of the momentum distribution of the produced $\bar{d}^*$ is shifted to a lower momentum place around 0.3 GeV, which is shown by the dashed curve on the left in the subfigure in Fig. 2. The similar shifts are also occurred in the $\Upsilon(2S)$ and $\Upsilon(3S)$ cases. Therefore, in d^* case, with the relatively broad ranges of parameters, the obtained widths are ranged in $(16-150)\times 10^{-5}$ keV, $(8-75) \times 10^{-5}$ keV and $(4-41)\times 10^{-5}$ keV for the $\Upsilon(nS) \to \bar{d}^* + X, (n = 1, 2, 3)$ decays, respectively. It is shown that even at the lower limit, $\bar{d}^*$ can still be measured at the current experimental facility. This means it is possible to find $\bar{d}^*$ with momentum 0.3–0.9 GeV in the semi-inclusive decay of $\Upsilon(nS)$.

Compared with the case with the pseudoscalar meson B as the intermediate state only, the results in the case with the vector meson B^* only are close to those in the former case, except the coupling constants. The parameters and the corresponding results for both cases are listed in Table I. The first three lines and the second three lines are for the

TABLE I. Partial decay widths and parameters in the $\Upsilon(nS) \to \bar{d} + X$ and $\Upsilon(nS) \to \bar{d}^* + X$ semi-inclusive decays. The first three lines and the second three lines are for the cases with the pseudoscalar meson B only and the vector meson B^* only, respectively. The mass parameters are: $m_{\bar{b}} = 4.5$ GeV, $m_{B^*} = 5.32$ GeV, $m_q = 0.313$ GeV.

State	g_v/g_{ps}	p_0^d (GeV)	Λ^d (GeV)	$\Gamma_{\bar{d}}$ (10^{-5} keV)	$p_0^{d^*}$ (GeV)	Λ^{d^*} (GeV)	$\Gamma_{\bar{d}^*}$ (10^{-5} keV)
$1S$	0.78×10^{-3}	0.58	0.57	155	0.2–0.58	0.2–0.57	16–150
$2S$	0.7×10^{-3}	0.24	0.73	78	0.08–0.24	0.25–0.73	8–75
$3S$	0.55×10^{-3}	0.20	0.71	43	0.07–0.2	0.24–0.71	4–41
$1S$	1.1×10^{-3}	0.59	0.57	144	0.2–0.59	0.2–0.57	15–137
$2S$	1.0×10^{-3}	0.29	0.72	79	0.1–0.29	0.24–0.72	8–75
$3S$	0.8×10^{-3}	0.22	0.71	46	0.07–0.22	0.24–0.71	4–41

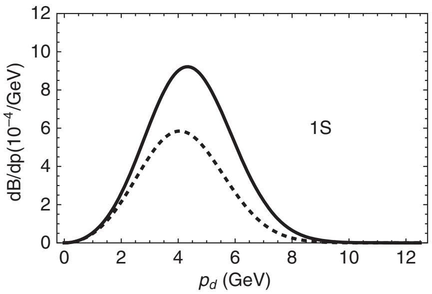

FIG. 3. The differential widths in the case with intermediate pseudoscalar and vector mesons without adding momentum distribution function. The solid and dashed lines denote the contributions from the pseudoscalar meson and vector meson, respectively.

cases with the vector meson B^* only and the pseudoscalar meson B only, respectively. In Fig. 3, we plot the resultant differential widths for $\Upsilon(1S)$ without the additional phenomenological momentum distribution $F(p_d)$ in Eq. (13). The solid and dashed lines represent the results in the cases with the pseudoscalar and vector mesons only, respectively. As we can see, the difference of the differential widths in the case of pseudoscalar and vector meson is obvious, especially at large momentum of deuteron. However, because the observed momentum of $\bar{d}$ is mainly distributed in the small momentum region, we have to include a phenomenological form factor $F(p_d)$ to account for the effect from the unknown X, which also suppresses the result in the high momentum region. As a result, the calculated difference between the results in the vector and pseudoscalar meson cases is very small. In practice, both pseudoscalar and vector mesons should exist as the intermediate state in the elementary s-channel interaction and consequently in the $\bar{d}^*$ production in the Υ semi-inclusive decay. In other words, pseudoscalar and vector mesons each give a certain proportion of contribution. However, according to the above deduction, no matter what ratio between the contributions from the pseudoscalar meson and vector meson is, the partial decay width will not change much. Therefore, the conclusion to find $\bar{d}^*$ in the $\Upsilon(nS)$ semi-inclusive decay does not change with the inclusion of the intermediate vector meson.

We have made a more complete analysis of the possibility to find $\bar{d}^*$ in the semi-inclusive $\Upsilon(nS)$ decay. Based on the mechanism used in Ref. [18], the vector B^* meson should also be allowed as an intermediate state. Therefore, for completeness, both the pseudoscalar B meson and vector B^* meson should be included. In the case of the vector meson, besides the analytic expression for the amplitude of the $\Upsilon(nS)$-$d(d^*)$ scattering, and consequently the differential width of the semi-inclusive process $\Upsilon(nS) \to \bar{d}(\bar{d}^*) + X$, are different from those in the case of the pseudoscalar meson, the maximal differential width of $\bar{d}(\bar{d}^*)$ is located at the lower p_d (p_{d^*}) region, due to the mass difference between B and B^*. However, after including the form factor $F(p_d)$ ($F(p_{d^*})$) constrained by the experimental data, the momentum distribution of $\bar{d}$ ($\bar{d}^*$) produced in the $\Upsilon(nS)$ decay moves to the smaller momentum region. As a result, the difference between the cases of B meson only and both B and B^* meson is highly suppressed and the final results are close to each other with the coupling constants predetermined from the data in the $\Upsilon(nS) \to \bar{d} + X$ process.

IV. SUMMARY

The possibility to find $\bar{d}^*(2380)$ in the $\Upsilon(nS)$ ($n = 1$, 2, 3) decays is studied in the framework of SU(3) chiral quark model. Utilizing the unitarity of S-matrix and crossing symmetry, the expression of the partial decay width can be obtained in terms of the imaginary part of the amplitude of the forward scattering between $d(d^*)$ and $\Upsilon(nS)$, where both the pseudoscalar meson and the vector meson contribute in the s-channel interaction. In this paper, we focus on the contribution of the vector meson B^* in the production of $\bar{d}^*$ in the semi-inclusive decay of $\Upsilon(nS)$. We start from the determination of the unknown parameters by fitting the data of the $\Upsilon(nS) \to \bar{d} + X$ decays. The wave functions of deuteron and d^* obtained in our previous work are used. The realistic wave functions of $\Upsilon(nS)$ are obtained by solving the Schrödinger equation with a Cornell potential. Because of the lack of information on the particles other than $\bar{d}$ in the final state, we have to insert a phenomenological form factor to describe the momentum distribution of $\bar{d}$. With fitted values of unknown parameters, we predict the partial decay width of the $\Upsilon(nS) \to \bar{d}^* + X$ in a relatively broad ranges of parameters accordingly. Our results show that it is likely to find $\bar{d}^*$ in the momentum region (0.3–0.9) GeV in the semi-inclusive decays of $\Upsilon(nS)$. It is found that the contributions from the intermediate vector and pseudoscalar mesons are very close due to the suppression of the high momentum of $\bar{d}$ and $\bar{d}^*$. The partial widths of the semi-inclusive decay $\Upsilon(nS) \to \bar{d}^* + X$ are about $(16 - 169) \times 10^{-5}$ keV, $(9 - 96) \times 10^{-5}$ keV and $(5 - 48) \times 10^{-5}$ keV for the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ states, respectively. We should mention that our results are based on the relevant available data fitting, so the results give the main partial widths and should be reliable. Of course, inclusion of other mechanisms, for example through the gluon processes either perturbatively or nonperturbatively, might vary the result in some extent.

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