A study of $d^*(2380) \to d\pi\pi$ decay width

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The decay widths of the $d^* \to d\pi^0\pi^0$ and $d^* \to d\pi^+\pi^-$ processes are explicitly calculated in terms of our chiral quark model. By using the experimental ratios of cross sections between various decay channels, the partial widths of the $d^* \to pnp^0\pi^0$, $d^* \to p\pi^+\pi^-$, $d^* \to pp\pi^0\pi^0$, and $d^* \to nn\pi^+\pi^0$ channels are also extracted. Further including the estimated partial width for the $d^* \to pn$ process, the total width of the $d^*$ resonance is obtained. In the first step of the practical calculation, the effect of the dynamical structure on the width of $d^*$ is studied in the single $\Delta\Delta$ channel approximation. It is found that the width is reduced by few tens of MeV, in comparison with the one obtained by considering the effect of the kinematics only. This presents the importance of such effect from the dynamical structure. However, the obtained width with the single $\Delta\Delta$ channel wave function is still too large to explain the data. It implies that the $d^*$ resonance will not consist of the $\Delta\Delta$ structure only, and instead there should be enough room for other structure such as the hidden-color (CC) component. Thus, in the second step, the width of $d^*$ is further evaluated by using a wave function obtained in the coupled $\Delta\Delta$ and CC channel calculation in the framework of the Resonating Group Method (RGM). It is shown that the resultant total width for $d^*$ is about 69 MeV, which is compatible with the experimental observation of about 75 MeV and justifies our assertion that the $d^*$ resonance is a hexaquark-dominated exotic state.

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I. INTRODUCTION

In recent years, the CELSIUS/WASA and WASA@COSY Collaborations successively reported the observation of a resonance-like structure in the double pionic fusion channels $pn \to d\pi^0\pi^0$ and $pn \to d\pi^+\pi^-$ when they studied the ABC effect and in the polarized neutron-proton scattering [1–3]. They mentioned that because the width of the $\Delta\Delta$ resonance is rather narrow, which is three more times smaller than $2 \Gamma_{\Delta\Delta}$ in the conventional $\Delta\Delta$ process, the observed data cannot be explained by the contribution from either the Roper excitation or the t-channel $\Delta\Delta$ process. Therefore, they proposed a $d^*$ hypothesis, in which its quantum number, mass and width are $I(J^P) = 0(3^+)$, $M \approx 2.36$ GeV and $\Gamma \approx 80$ MeV [1] (in their recent paper [4], they take averaged values over the results from elastic scattering and two-pion production, i.e. $M \approx 2.375$ GeV and $\Gamma \approx 75$ MeV), respectively, to accommodate the data. Because “the structure, containing six valence quarks, constitutes a dibaryon, and could be either an exotic compact particle or a hadronic molecule” [5], this result causes physicists’ special attention.

In fact, the existence of the non-trivial six-quark configuration with $I(J^P) = 0(3^+)$ (called $d^*$ lately) has intensively been studied since Dyson’s estimation [6]. A variety of methods or models, such as group theory [6], bag quark model [7], quark potential model [8,11], etc., have been employed to investigate the structure of $d^*$, among which even some investigations produced a mass close to the recent data, they are either not a dynamical calculation, or a calculation without the width prediction or with an incorrect width prediction. It should specially be noted that in one of those papers [10], one performed a coupled channel dynamical calculation in 1999 where a $\Delta\Delta$ channel and a hidden-color channel (denoted by CC) are included and the predicted mass is about $40 – 80$ MeV. This means that in this structure, there might exist a six-quark configuration, which coincides with COSY’s assertion. Nevertheless, in that paper, the width of the state has not been calculated.

After COSY reported their finding, many investigations have been devoted to this aspect. There are mainly three kinds of models on the structure of the $d^*$ resonance: a) It is a $\Delta\Delta$ resonance [11]. The authors in Ref. [11] performed a multi-channel scattering calculation and obtained a binding energy about 71 MeV with respect to the $\Delta\Delta$ threshold and a width about 150 MeV where $\Gamma_{NN} = 14$ MeV and $\Gamma_{med} = 136$ MeV. b) It is dominated by a “hidden-color” six-quark configuration. Bashkanov, Brodsky and Clement [12] argued in 2013 that this hidden-color structure is necessary for understanding the strong coupling of $d^*$ to $\Delta\Delta$. Later, Huang and his collaborators made an explicit dynamic calculation in the framework of the Resonating Group Method (RGM) [13] and showed a binding energy of about 84 MeV and almost 67% of “hidden-color” configuration in $d^*$. This implies that $d^*$ is probably a 6-quark dominated exotic state. c) It is a result of the $\Delta N\pi$ three body interaction [14]. In order to justify which one of
these three is more reasonable, a detailed calculation, especially the decay width, should be performed and further experimental investigation should be carried out.

In this paper, we focus on $d^*$ width study. We would firstly examine the effect of the dynamical structures of the $d^*$ and deuteron bound states on the decay width of $d^*$, and consequently fetch out the contribution from the $\Delta\Delta$ structure of $d^*$ with $J^P = 3^+$. Then, we would estimate the total width of $d^*$ by including the contributions from other possible decay channels. At the beginning, we temporarily assume that $d^*$ is composed of the $\Delta\Delta$ structure only. In the calculation, the extended chiral SU(3) quark model is employed, because this constituent quark potential model can successfully reproduce the spectra of baryon ground states, the binding energy of the deuteron, the nucleon-nucleon (NN), Kaon-nucleon (KN) scattering phase shifts, and the hyperon-nucleon (YN) cross sections (for details see Refs. [13–17]). With the same set of model parameters fixed in explaining the above mentioned data, the bound state problem of the $\Delta\Delta$ system is solved and the realistic wave functions of other possible decay channels such as $NN$, $\pi N$, etc., the total width of $d^*$ is estimated, and the role of dynamical structures to the decay width is analyzed. The result with the single $\Delta\Delta$ channel assumption exhibits the importance of the dynamical structure effect which reduces the decay width by about few tens of MeV. However, the width is still larger than the experimentally observed value, so that the other structure in $d^*$ could not be neglected. In the next section, the formulism is briefly given. The numerical results and discussion are presented in the final section.

II. BRIEF FORMULISM

Referring to Ref. [18], the phenomenological effective Hamiltonian for the quark-quark-pion interaction in the non-relativistic approximation is

$$\mathcal{H}_{qq\pi} = g_{qq\pi} d \cdot k_\pi \tau \cdot \phi \times \frac{1}{(2\pi)^{3/2} \sqrt{2\omega_\pi}},$$

where $g_{qq\pi}$ is the coupling constant, $\phi$ stands for the pion meson field, $\omega_\pi$ and $k_\pi$ are the energy and three-momentum of the pion meson, respectively, and $\sigma(\tau)$ represents the spin (isospin) operator of a single quark. The wave functions are

$$|N\rangle = \frac{1}{\sqrt{2}} \left[ \chi_\rho \psi_\rho + \chi_\lambda \psi_\lambda \right] \Phi_N(\bar{\rho}, \bar{\lambda})$$

for the nucleon and

$$|\Delta\rangle = \chi_\rho \psi_\rho \Phi_\Delta(\bar{\rho}, \bar{\lambda})$$

for the $\Delta$(1232) resonance. In Eqs. (2-3), $\chi$ and $\psi$ stand for their spin and isospin wave functions, $\Phi_N(\bar{\rho}, \bar{\lambda})$ and $\Phi_\Delta$ are the spatial wave functions of the nucleon and $\Delta$ resonance, respectively, and $\rho$ and $\lambda$ are the Jacobi coordinates for the internal motion. Then, the decay width for $\Delta \rightarrow \pi N$ reads

$$\Gamma_{\Delta \rightarrow \pi N} = \frac{4}{3\pi} k_\pi^3 (g_{qq\pi} I_o)^2 \frac{\omega_N}{M_\Delta},$$

where $\omega_{\pi,N} = \sqrt{M_{\pi,N}^2 + k_\pi^2}$ are the energies of the pion and nucleon, respectively, $k_\pi \sim 0.229$ GeV, and $I_o$ denotes the spatial overlap integral of the internal motion of the nucleon and the $\Delta$ resonance. By fitting the measured width of 117 MeV for $\Delta_{3/2}(1232)$ [13], one gets $G = g_{qq\pi} I_o \sim 5.41$ GeV$^{-1}$ which is the product of the coupling constant $g_{qq\pi}$ and the spatial integral $I_o$.

Now using the knowledge of $M_{\Delta \rightarrow \pi N}$ obtained above, we can estimate the decay width in the $d^* \rightarrow d\pi\pi$ process. The transition matrix element between the initial state $d^*$ and the final state $d\pi^0\pi^0$ can be written as

$$M_{ij}^{\pi^0\pi^0} = \frac{1}{\sqrt{3}} \sum F_{1} F_{2} k_{1,\mu} k_{2,\nu} I_o \int_{\tau} C_{1,\sigma_{1}}^{m_{1,\mu}} C_{3,\sigma_{2}}^{m_{2,\rho}} C_{3,\sigma_{2}}^{m_{2,\rho}}$$

$$\times \int d^3 q \left[ \frac{\chi_\rho^*(\bar{q} - \frac{2}{\sqrt{3}} k_{12})^2}{E_\Delta(q) - E_N(q - k_1) - \omega_1} + \frac{\chi_\rho^*(\bar{q} + \frac{2}{\sqrt{3}} k_{12})^2}{E_\Delta(q) - E_N(q - k_1) - \omega_2} \right] \chi_{d^*}(\bar{q}), \quad (5)$$
where \( i \) and \( f \) stand for the initial \( d^* \) state with quantum numbers \(((S_mS) = (3m_d^*) \) and the final deuteron state with \(((S_mS) = (1m_d) \), respectively, \( I^0 \) is the spin (isospin) factor shown in the appendix, \( F_{1,2} = F(k_{1,2}^2) = \frac{4G}{(2\pi)^3 \sqrt{\omega_{1,2}}} \), \( \vec{k}_{1,2} = \vec{k}_1 - \vec{k}_2 \), \( \omega_{1,2} = \sqrt{m_N^2 + k_{1,2}^2} \). \( \chi_{d}(\vec{q}) \) and \( \chi_{d^*}(\vec{q}) \) are, respectively, the relative wave functions of the final deuteron (between the two nucleons) and the initial \( d^* \) (between the two \( \Delta s \)) where \( \vec{q} = \frac{1}{2}(\vec{p}_1 + \vec{p}_2 + \vec{p}_3 - \vec{p}_4 - \vec{p}_5 - \vec{p}_6) \) with \( \vec{p}_i \) being the momentum of the \( i \)-th quark. Four terms in the bracket of Eq. (5) are related to the propagators of four sub-diagrams in Fig. 1.

\[ \Psi_d = [ \phi_N(\xi_1, \xi_2) \phi_N(\xi_4, \xi_5) \chi_d(R) ] \chi_{d^*}(\xi_{SI}) = (10), \]
\[ \Psi_d^* = [ \phi_\Delta(\xi_1, \xi_2) \phi_\Delta(\xi_4, \xi_5) \chi_{\Delta\Delta}(R) + \phi_C(\xi_1, \xi_2) \phi_C(\xi_4, \xi_5) \chi_{CC}(R) ] \chi_{d^*}(\xi_{SI}) = (30), \]

where \( \phi_N, \phi_\Delta, \phi_C \) denote the internal wave functions of \( N, \Delta, C \) (color-octet particle) in the coordinate space, \( \chi_d \) describes the relative wave function of the deuteron, \( \chi_{\Delta\Delta} \) and \( \chi_{CC} \) represent the relative wave functions between \( \Delta s \) and \( Cs \) (in the single \( \Delta\Delta \) channel case, the CC component is absent), and \( \chi_{d^*} \) stands for the spin-isospin wave function of the corresponding system. It should be specially mentioned that in the form of such a wave function, normally called channel wave function [13], the totally anti-symmetric effect is implicitly included in the resultant relative wave function by solving the RGM equation and then projecting to the physical states. The channel wave functions of relevant systems are plotted in Fig. 2.

FIG. 1: Four possible emission ways in the decay of the \( d^* \) resonance composed of the \( \Delta\Delta \) structure only. Two pions with momenta of \( \vec{k}_{1,2} \) are emitted from one of the three quarks in 2 \( \Delta s \), respectively.

With the transition matrix element \( M^{\pi\pi\pi}_{if} \), the decay width of \( d^* \) in the \( d^* \rightarrow d\pi\pi \) channel can be evaluated by

\[
\Gamma_{d^* \rightarrow d\pi\pi} = \frac{1}{2!} \int d^3k_1 d^3k_2 d^3p_\pi (2\pi)^3 \delta^3(k_1 + k_2 + p_\pi) \delta(\omega_k + \omega_{k_2} + E_{p_\pi} - M_{d^*}) | M^{\pi\pi\pi}_{if} |^2,
\]

where \( \omega_{k_1, k_2} \) are the energies of the two outgoing pions, \( E_{p_\pi} \) is the energy of the outgoing deuteron with momentum \( p_\pi \), and the bar on the top of the transition matrix \( M^{\pi\pi\pi}_{if} \) means that this matrix element is averaged over the initial states and the summed over the final states. The factor of \( 2! \) is due to the two identical pions in the final states.

In the practical decay width calculation, one needs the explicit deuteron and \( d^* \) (2380) relative wave functions. These wave functions can usually be taken from the realistic solutions of the system considered. In this work, we obtain them by dynamically solving the RGM equation in the extended chiral \( SU(3) \) quark model [13] where the binding energy of deuteron is \( \epsilon = 2.2 \text{ MeV} \) and the binding energy of \( d^* \) is \( \epsilon \approx 62 \text{ MeV} \) in the single \( \Delta\Delta \) channel approximation and \( \epsilon \approx 84 \text{ MeV} \) if the CC channel is further considered, and consequently, the mass of \( d^* \) is \( M_{d^*} = 2M_\Delta - \epsilon \). In the coordinate space, the wave functions of the deuteron and \( d^* \) systems can also be expressed, respectively, as

\[ \Psi_d = [ \phi_N(\xi_1, \xi_2) \phi_N(\xi_4, \xi_5) \chi_d(R) ] \chi_{d^*}(\xi_{SI}) = (10), \]
\[ \Psi_{d^*} = [ \phi_\Delta(\xi_1, \xi_2) \phi_\Delta(\xi_4, \xi_5) \chi_{\Delta\Delta}(R) + \phi_C(\xi_1, \xi_2) \phi_C(\xi_4, \xi_5) \chi_{CC}(R) ] \chi_{d^*}(\xi_{SI}) = (30), \]
by using Eq. (6).

that the calculation can be much more simplified without losing the major characters of such a process. Based on resultant decay widths for all the possible channels in Table I. In order to consider the effect of isospin symmetry breaking of pions, namely the mass difference between constituent if they were assumed to be free particles. And even more, deeper binding would cause narrower width. This feature is reasonable, because the width is not only related to the phase space, but also depends on the overlap interaction between constituents, the decay width of the system is much smaller than the total decay widths of its constituents if they were assumed to be free particles. Moreover, the experimental data \[1, 2, 20, 21\] and one of the theoretical calculations \[22\] showed that for the \[^*\]\(d^+\) resonance at \(\sqrt{s} = 2.37\) GeV, the decay cross section in the \(d^+ \rightarrow p\pi^+\pi^-\) process is about 0.20 mb which is comparable with that of 0.24 mb in the \(d^+ \rightarrow d\pi^0\pi^0\) process, and the decay cross section in the \(d^+ \rightarrow ppm^0\pi^-\) process (also its mirrored channel \(d^+ \rightarrow nnn\pi^0\pi^0\)) has a visible value of about 0.10 mb as well. Therefore, contributions in these processes should also be accounted for in the \(d^+\) width estimation. Using Breit-Wigner formulism and those cross section data, one estimated the branching ratios of various decay modes \[4, 23\]. For reference, we tabulate them in the second last column in Table I. In order to consider the effect of isospin symmetry breaking of pions, namely the mass difference between \(\pi^\pm\) and \(\pi^0\), we calculate the cross section in the \(d^+ \rightarrow d\pi^+\pi^-\) process explicitly. The obtained cross section in this calculation is 1.83 times that in the \(d^+ \rightarrow d\pi^0\pi^0\) process, which is slightly larger than the multiple of 1.6 estimated in Ref. \[4, 23\]. Based on resultant decay widths for \(d^+ \rightarrow d\pi^0\pi^0\) and \(d^+ \rightarrow d\pi^+\pi^-\) and cross sections mentioned above, we get the branching ratios, and consequently the partial decay widths, for all possible decay modes.

Finally, we achieve the total width of \(d^+\).

In order to see the effect of the dynamical structure on the decay width, we calculate the width in the single \(\Delta\Delta\) channel case with \(\epsilon = 80\) or 90 MeV (the corresponding mass of \(d^+\) is about 2384 MeV or 2374 MeV, respectively) to compare with the result reported by Bashkanov et al. \[12\], where the decay width is reduced by the phase space effect only. We tabulate resultant decay widths for all the possible channels in Table II. From this table, one sees that in the single \(\Delta\Delta\) channel calculation, no matter in which case (\(M_{d^+} = 2384\) MeV or \(M_{d^+} = 2374\) MeV), the resultant total width of \(d^+\) justifies the fact that in a composite system, due to the binding behavior, namely the attractive interaction between constituents, the decay width of the system is much smaller than the total decay widths of its constituents if they were assumed to be free particles. And even more, deeper binding would cause narrower width. This feature is reasonable, because the width is not only related to the phase space, but also depends on the overlap.

For the sake of convenience, we expand the relative wave function in the following:

\[
\chi(R) = \sum_{i=1}^{4} c_i \exp\left(-\frac{R^2}{2b_i^2}\right). \tag{8}
\]

We would also mention that the \(D\)-wave contribution is omitted due to its relevant smaller contribution, although both the \(S\)- and \(D\)-wave functions exist in our resultant wave functions.

III. NUMERICAL RESULTS AND DISCUSSION

In the calculation, the masses of deuteron, \(\Delta\), nucleon and pion are taken from Particle Data Group \[19\]. The mass of \(d^+\) is \(M_{d^+} = 2M_\Delta - \epsilon\) with \(\epsilon\) being 80 - 90 MeV for the single \(\Delta\Delta\) channel case and \(\sim 84\) MeV for the coupled \(\Delta\Delta\) and CC channel case, respectively. The value of \(G\) is already fixed by using the \(\Delta \rightarrow pN\) decay data. The decay width in the \(d^+ \rightarrow d\pi\pi\) process with realistic wave functions from the RGM calculation can numerically be obtained by using Eq. (8).

Moreover, the experimental data \[1\] \[2\] \[21\] and one of theoretical calculations \[22\] showed that for the \(d^+\) resonance at \(\sqrt{s} = 2.37\) GeV, the decay cross section in the \(d^+ \rightarrow p\pi^+\pi^-\) process is about 0.20 mb which is comparable with that of 0.24 mb in the \(d^+ \rightarrow d\pi^0\pi^0\) process, and the decay cross section in the \(d^+ \rightarrow ppm^0\pi^-\) process (also its mirrored channel \(d^+ \rightarrow nnn\pi^0\pi^0\)) has a visible value of about 0.10 mb as well. Therefore, contributions in these processes should also be accounted for in the \(d^+\) width estimation. Using Breit-Wigner formulism and those cross section data, one estimated the branching ratios of various decay modes \[4\] \[23\]. For reference, we tabulate them in the second last column in Table I. In order to consider the effect of isospin symmetry breaking of pions, namely the mass difference between \(\pi^\pm\) and \(\pi^0\), we calculate the cross section in the \(d^+ \rightarrow d\pi^+\pi^-\) process explicitly. The obtained cross section in this calculation is 1.83 times that in the \(d^+ \rightarrow d\pi^0\pi^0\) process, which is slightly larger than the multiple of 1.6 estimated in Ref. \[23\]. Based on resultant decay widths for \(d^+ \rightarrow d\pi^0\pi^0\) and \(d^+ \rightarrow d\pi^+\pi^-\) and cross sections mentioned above, we get the branching ratios, and consequently the partial decay widths, for all possible decay modes. Finally, we achieve the total width of \(d^+\).

In order to see the effect of the dynamical structure on the decay width, we calculate the width in the single \(\Delta\Delta\) channel case with \(\epsilon = 80\) or 90 MeV (the corresponding mass of \(d^+\) is about 2384 MeV or 2374 MeV, respectively) to compare with the result reported by Bashkanov et al. \[12\], where the decay width is reduced by the phase space effect only. We tabulate resultant decay widths for all the possible channels in Table II. From this table, one sees that in the single \(\Delta\Delta\) channel calculation, no matter in which case (\(M_{d^+} = 2384\) MeV or \(M_{d^+} = 2374\) MeV), the resultant total width of \(d^+\) justifies the fact that in a composite system, due to the binding behavior, namely the attractive interaction between constituents, the decay width of the system is much smaller than the total decay widths of its constituents if they were assumed to be free particles. And even more, deeper binding would cause narrower width. This feature is reasonable, because the width is not only related to the phase space, but also depends on the overlap.
of the wave functions of the bound states $d^*$ and deuteron. In comparison with the estimated width of about 160 MeV with the binding energy of 90 MeV by Bashkanov et al. [12], where the effect of the phase space is considered only, the contribution to the width from the dynamical structure of the system is about few tens of MeV. This tells us how important the effect of the dynamics on the width of an unstable composite system is, namely, the decay width is not only dependent on the phase space, but also depended on the dynamical structure of the system. It also shows that the width of $d^*$ in the single $\Delta\Delta$ channel case where the mass of $d^*$ coincides the experimental data of 2384 MeV still far exceeds the experimental value of 75 MeV. This means that the $\Delta\Delta$ structure alone cannot provide a reasonable width of $d^*$.

With the same scenario, we further exam the width contributed by the $\Delta\Delta$ component in $d^*$ if $d^*$ has the $\Delta\Delta$+ CC structure proposed in Refs. [10, 13]. The results are also tabulated in Table I. It shows that with the wave function of the $\Delta\Delta$ component in Ref. [12], the decay widths for the $d^* \rightarrow d\pi^0\pi^0$ and $d^* \rightarrow d\pi^+\pi^-$ modes are about 9 MeV and 17 MeV, respectively. If we further consider the $d^* \rightarrow pn\pi\pi$, $pp\pi^0\pi^-$, $nn\pi^+\pi^0$, and $NN$ modes, the total width would be about 69.1 MeV.

Here we would like to mention that in the RGM calculation, the trial wave function of the $d^*$ system is assumed to have two major components, $\Delta\Delta$ and CC, which are totally anti-symmetrized. Solving the RGM equation, one obtains the relative wave functions of the system. By projecting the resultant wave function onto the cluster internal wave function in each component, we get the inter-cluster relative wave function, namely the channel wave function, for corresponding channel. Now, the contribution from the CC channel via the quark exchange is included in the projected wave function (or channel wave function) $\chi_{\Delta\Delta}(R)$ already [13]. We should specially emphasis that the channel wave functions obtained in Eq. (7) are orthogonal to each other. Therefore, in the lowest order, by using this channel wave function, there is no quark exchange between the two physical particles and thus the colored clusters (color octet) cannot turn into the un-colored clusters (color singlet). As a consequence, the width contributed by the projected CC component would almost be zero. Combining this point with the contribution from the $\Delta\Delta$ component, one sees that total width of $d^*$ in our $\Delta\Delta$+ CC model is about 69.1 MeV, which is compatible with the experimental data of 75 MeV. Apparently, because the fraction of the wave function of the CC component in our $\Delta\Delta$+ CC model is about 67%, the resultant width of $d^*$ justifies our assertion that the $d^*$ resonance is a hexaquark-dominated exotic state.

Finally, it also should be mentioned that the existence of $d^*$ should further be checked in other experimental processes. Now, except the $\gamma(\text{or } e)\ell$ reaction and $pp$ collision, the strong decay of the hidden heavy flavor meson, such $bb$ meson and $cc$ meson, is also a place to hunt for $d^*$. In particular, searching for its anti-particle $\bar{d}^*$ in these processes is even plausible, because the anti-deuteron $\bar{d}$ and consequently $\bar{d}^*$ can only be created from quark-pair productions, so that the background would be very clean [24]. Now, at $\sqrt{s} \approx 10.6$ GeV, the integrated luminosity is about 470 $fb^{-1}$ at BaBar, and about 3 $fb^{-1}$ at CLEO. And both Collaborations have observed $d\bar{d}$ production at $\sqrt{s} \approx 10.6$ GeV [25, 26]. Thus, one might search for $d^*$ in the $\Upsilon(nS) \rightarrow d^* + p + n$ process. Moreover, the Belle Collaboration has collected even more data of about 1000 $fb^{-1}$ around $\sqrt{s} \approx 10.6$ GeV, and they might have the chance to observe the $\bar{d}$ and $d^*$ productions in the similar process. Also, BEPCII/BESIII has reached an integrated luminosity of 1 $fb^{-1}$ at $\sqrt{s} = 4.42$ GeV and 0.57 $fb^{-1}$ at $\sqrt{s} = 4.6$ GeV. It might be possible to detect $d^*$ in the $e^+e^- \rightarrow d^* + p + n$ process as well. If one could observe $d^*$ in the data set accumulated by BaBar, Belle, CLEO, and BEPCII/BESIII, it would definitely be helpful in confirming the existence of $d^*(2380)$ and its structure.

| $M_{d^*}(\text{MeV})$ | $\Delta\Delta$ | $\text{two channels } \Delta\Delta + \text{CC}$ | $\text{Expt.}$ |
|------------------------|----------------|---------------------------------|----------------|
|                        | $\Gamma(\text{MeV})$ | $B_r$ | $\Gamma(\text{MeV})$ | $B_r$ | $\Gamma(\text{MeV})$ |
| $d^* \rightarrow d\pi^0\pi^0$ | 22.6 | 17.0 | 13.3% | 9.2 | 14(1)% | 10.2 |
| $d^* \rightarrow d\pi^+\pi^-$ | 41.5 | 30.8 | 24.3% | 16.8 | 23(2)% | 16.7 |
| $d^* \rightarrow pn\pi\pi^0$ | 18.8 | 14.2 | 11.3% | 7.8 | 12(2)% | 8.7 |
| $d^* \rightarrow pn\pi^+\pi^-$ | 47.1 | 35.4 | 27.8% | 19.2 | 30(4)% | 21.8 |
| $d^* \rightarrow pp\pi^0\pi^-$ | 9.4 | 7.1 | 5.65% | 3.9 | 6(1)% | 4.4 |
| $d^* \rightarrow nn\pi^+\pi^0$ | 9.4 | 7.1 | 5.66% | 3.9 | 6(1)% | 4.4 |
| Total                | 167.6 | 125.8 | 99.9% | 69.1 | 103(14)% | 74.9 |
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Appendix A: Spin-isospin part

The spin matrix element in the calculation is

\[ I_S = \sum C_{S_{A}m_{A},S_{B}m_{B}} C_{S_{A}m_{A}^{'},S_{B}m_{B}^{'}} C_{S_{A}m_{A},1} C_{S_{B}m_{B},1} \]

\[ = \sum (-)^{S_{A}^{'}} S_{A} + S_{B} - S_{A}^{'}, - S_{B} S_{A}^{'}, S_{B} \frac{\gamma_{2}}{2j} \frac{1}{\nu} \left\{ \begin{array}{ccc} 1 & S_{A} & S_{A}' \\ S_{B} & S_{A}' \end{array} \right\} \left\{ \begin{array}{ccc} 1 & S_{B} & S_{B}' \\ j_{23} & S_{AB} \end{array} \right\} \]

\[ \times \left\{ \begin{array}{ccc} S_{AB} & 1 & j_{23} \\ 1 & S_{AB}' & j \end{array} \right\} \gamma^{\mu} \frac{1}{\nu} \gamma^{\mu} \left\{ \begin{array}{ccc} C_{S_{A}m_{A}^{'},S_{B}m_{B}'} \nu & j_{23} \\ 1 & j_{23} & j_{23} \end{array} \right\} \]

\[ = \gamma^{\mu} \frac{1}{\nu} \gamma^{\mu} C_{S_{A}m_{A}^{'},S_{B}m_{B}'} \]

where \( \hat{a} = \sqrt{2a + 1} \). For the present process, the initial \( d^* \) and final deuteron have \( S_{AB} = 3 \) and \( S_{AB}' = 1 \), respectively. Moreover, \( \Delta \) and nucleon have \( S_{A} = S_{B} = 3/2 \) and \( S_{A}' = S_{B}' = 1/2 \), respectively. Therefore, in the present case \( j_{23} = j = 2 \) is restricted.

Moreover, one can deal with the isospin matrix element similarly. The isospins of \( \Delta \), nucleon, \( d^* \), and deuteron are \( 3/2, 1/2, 0, \) and \( 0 \), respectively. Then \( j = 0 \) and \( j_{23} = 1 \) are constraint for isospin part.

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