Decay width of $d^*(2380) \to NN\pi\pi$ processes

Yubing Dong,[1, 2] Fei Huang,[3] Pengnian Shen,[4, 1, 2] and Zongye Zhang[1, 2]

[1] *Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*
[2] *Theoretical Physics Center for Science Facilities (TPCSF), CAS, Beijing 100049, China*
[3] *School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 101408, China*
[4] *College of Physics and Technology, Guangxi Normal University, Guilin 541004, China*

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The decay widths of four-body double-pion decays $d^* \to pn\pi^0\pi^0$, $d^* \to pn\pi^+\pi^-$, and iso-scalar parts of $d^* \to pp\pi^0\pi^-$ and $d^* \to nn\pi^+\pi^0$ are explicitly calculated with the help of the d^* wave function obtained in a chiral SU(3) quark model calculation. The effect of the dynamical structure on d^*'s width is analyzed both in the single $\Delta\Delta$ channel and coupled $\Delta\Delta$ and CC channel approximations. It is found that in the coupled-channel approximation, the obtained partial decay widths of $d^* \to pn\pi^0\pi^0$, $d^* \to pn\pi^+\pi^-$, and those of d^* to the iso-scalar parts of $pp\pi^0\pi^-$ and $nn\pi^+\pi^0$ are about 7.4MeV, 16.4MeV, 3.5MeV and 3.5MeV, respectively As a consequence, the total width is about 64.5MeV. These widths are consistent with those estimated by using the corresponding cross section data in our previous investigation and also the observed data. But in the single $\Delta\Delta$ channel approximation, the widths are still almost 2-times larger than the measured values. Apparently, the explicitly calculated width together with the evaluated mass of d^* in the coupled $\Delta\Delta$ and CC channel approximation can well explain the observed data, which again supports our assertion that the d^* resonance is a six-quark dominated exotic state.

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Since X(3872) was reported by the Belle and Babar Collaborations in 2003, many new exotic resonances were observed in Belle, Babar, BEPCII, LHCb and many other facilities. Those new resonances, like $X(3872)$, $Z_c(3900)$, $Z_b(10610)$, and $Z_b(10650)$ (or $\Lambda_c(2900)$, $p_c(4380)$, and $p'_c(4450)$) et al., cannot simply be understood by the well-established conventional q-$\bar{q}$ (or qqq) potential models. In particular, most of them are very near to the meson-meson (or meson-baryon) thresholds with rather narrow widths and some of them are even charged. Different interpretations, such as pentaquark states, molecule structures, triangle singularities, cusp and threshold effect, for those new resonances have been proposed.

Except for the possible multi-quark states with baryon number $\mathcal{B} = 0,\ 1$ mentioned above, the study of the 6-quark states (or dibaryons) also has a long history. In recent years, CELSIUS/WASA and WASA@COSY Collaborations have clearly observed a resonance-like structure in 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 dealing with the neutron-proton scattering data with newly measured analyzing power A_y. This possible resonance has a mass of about 2380MeV and a width of about 70MeV. [1–3]. Because the observed resonance cannot simply be explained by either the intermediate Roper excitation or the t-channel $\Delta\Delta$ process, they proposed a d^* hypothesis, in which its quantum number, mass, and width are $I(J^P) = 0(3^+)$, $M \approx 2370$ MeV and $\Gamma \approx 70$ MeV [1, 4] (in their recent paper [4], the averaged mass and width, from the elastic scattering and two-pion productions, are $M \approx 2375$ MeV and $\Gamma \approx 75$ MeV, respectively). Since its baryon number is 2, it would be regarded as a dibaryon, and could be either "an exotic compact particle or a hadronic molecule" [5]. Moreover, according to the experimental data, the mass of d^* is about 80 MeV smaller than the $\Delta\Delta$ threshold and about 70 MeV larger than the $\Delta\pi N$ threshold, so the threshold (or cusp) effect is expected to be not so important as that in the systems of XYZ particle cases, and therefore, the internal structure of d^* would be essentially significant.

This newly observed d^* causes a great attention of theoreticians. 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]. Many phenomenological approaches, like the group classification method [6], the cloudy bag model [7], the quark potential model [8–10], etc., have been applied to the investigation of d^*'s structure in the past. The hidden dibaryons in one- and two-pion productions in NN collisions are also studied recently [11]. One of those calculations reported in 1999 should be specially mentioned. In such a calculation, a $\Delta\Delta$ channel and a hidden-color channel (denoted by CC afterward) were taken into account simultaneously, a binding energy of about $40 - 80$ MeV was predicted, which is consistent with the recently observed d^*, and the importance of the contribution from the CC channel was pointed out [10]. Unfortunately, the width of the state was not calculated in that paper.

Since COSY's discovery, there are mainly three types of explanations. Based on the SU(2) quark model, Ref. [12] considered it as a $\Delta\Delta$ resonance and performed a multi-channel scattering calculation. They obtained a binding energy of about 71 MeV with respect to the threshold of the $\Delta\Delta$ channel and a width of about 150 MeV where $\Gamma_{NN} = 14$ MeV and $\Gamma_{inel} = 136$ MeV, which is apparently much larger than the data. On the other hand, Ref. [13] studied a three-body system of $\Delta N\pi$ and found a resonance pole with a mass of 2363 ± 20MeV and a width of 65 ± 17MeV.

However, one mentioned that an additional factor of 2/3 should not be included in the estimation for comparing with the observed width [14]. An important view point, argued by Bashkanov, Brodsky and Clement [15] in 2013 is that a dominant hidden-color structure (or six-quark configure) of d^* is necessary for understanding its strong coupling. Sooner after, following our previous prediction [10], Huang and his collaborators made an explicit dynamic calculation by using a chiral SU(3) quark model in the framework of the Resonating Group Method (RGM), with which the ground state baryon properties, the baryon-baryon scattering and binding behaviors have been well reproduced [16–18], and showed that the d^* state has a mass of $2380-2414$MeV, which agrees with COSY's observation, and does have a "hidden-color" (CC) configuration of about $66-68\%$ in its wave function [19]. Based on the obtained wave functions of d^* and deuteron, Dong and his collaborators calculated the partial decay widths of the "Golden" decay channel (with emitted 2π) $d^* \to d + 2\pi^0(\pi^+\pi^-)$ recently [20]. In the calculation, both the single $\Delta\Delta$ channel and coupled $\Delta\Delta + CC$ channel are considered, and the dynamical effect on the d^*'s width is explicitly given. It is shown that the consideration of the hidden-color configuration inside d^* could greatly suppress its width and the resultant widths for both $d^* \to d\pi^0\pi^0$ and $d^* \to d\pi^+\pi^-$ are in good agreement with the experimental measurements. Then, by making use of the observed cross sections in other possible decay channels of d^*, they gave an estimate of the total d^*'s width of about 69MeV, which is fairly good in agreement with the data [20]. All of these outcomes imply that d^* is probably a six-quark dominated exotic state.

However, a blemish in our previous calculation is that the four-body $\pi\pi$ decays $d^* \to pn\pi^0\pi^0$, $d^* \to pn\pi^+\pi^-$, and iso-scalar parts of $d^* \to pp\pi^0\pi^-$ and $d^* \to nn\pi^+\pi^0$ were not explicitly calculated [20]. A naive conjecture from the $d^* \to \Delta\Delta \to np\pi\pi$ process showed a very large value [15], which does not fit the observed data [4]. Since in these four-body decays, the only difference with the corresponding three-body decays in our previous calculation is that the final proton and neutron are free particles rather than a weekly bound state of the deuteron, it is our purpose to check if the obtained d^* wave function with our conjectured structure of d^*, a six-quark dominated exotic state, can also reproduce the partial widths for these four-body double-pion decay processes.

The phenomenological effective Hamiltonian for the pseudo-scalar interaction among quark, pion, and quark in the non-relativistic approximation reads

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

where $g_{qq\pi}$ is the coupling constant, ϕ stands for the π meson field, ω_π and $\vec{k}_\pi$ are the energy and three-momentum of the π meson, respectively, and $\sigma(\tau)$ represents the spin (isospin) operator of a single quark. In the conventional constituent quark model, the wave functions are

$$| N >= \frac{1}{\sqrt{2}}\Big[\chi_\rho\psi_\rho + \chi_\lambda\psi_\lambda\Big]\Phi_N(\vec{\rho},\vec{\lambda}) \tag{2}$$

for the nucleon and

$$| \Delta >= \chi_s\psi_s\Phi_\Delta(\vec{\rho},\vec{\lambda}) \tag{3}$$

for the $\Delta(1232)$ resonance. In Eqs. (2-3), χ and ψ stand for their spin and isospin wave functions, $\Phi_N(\vec{\rho},\vec{\lambda})$ and Φ_Δ are the spatial wave functions of the nucleon and Δ resonance, respectively, and $\vec{\rho} = \frac{1}{\sqrt{2}}(\vec{r}_1 - \vec{r}_2)$ and $\vec{\lambda} = \frac{1}{\sqrt{6}}(\vec{r}_1 + \vec{r}_2 - 2\vec{r}_3)$ are the conventional Jacobi coordinates for the internal motion. Then, in terms of the measured decay width of the $\Delta \to \pi N$ process, for example $\Gamma_{\Delta^+\to\pi^0 p} \sim 117\ MeV$), one can easily extract the coupling constant $g_{qq\pi}$ by calculating $\Gamma_{\Delta\to N\pi} = \langle\Delta|\mathcal{H}|N\rangle$ [21] (the details can be found in Ref. [20]).

As mentioned in Ref.[19, 20], our model wave function is obtained by dynamically solving the bound-state RGM equation of the six quark system in the framework of the extended chiral $SU(3)$ quark model, where the binding energy of d^* is $\epsilon \approx 62$ MeV in the single $\Delta\Delta$ channel approximation and $\epsilon \approx 84$ MeV if the CC channel is further considered, and consequently, the mass of d^* is $M_{d^*} = 2M_\Delta - \epsilon$. Further projecting the wave function in the quark level onto the two-cluster wave function in the baryon level, namely the physical state, we end up a wave function of d^*

$$\Psi_{d^*} \;=\; [\;\phi_\Delta(\vec{\xi}_1,\vec{\xi}_2)\;\phi_\Delta(\vec{\xi}_4,\vec{\xi}_5)\;\chi_{\Delta\Delta}(\vec{R})\;\zeta_{\Delta\Delta} \;+\; \phi_C(\vec{\xi}_1,\vec{\xi}_2)\;\phi_C(\vec{\xi}_4,\vec{\xi}_5)\;\chi_{CC}(\vec{R}))\;\zeta_{CC}\;]_{(SI)=(30)}, \tag{4}$$

where ϕ_Δ, and ϕ_C denote the internal wave functions of Δ and C (color-octet particle) in the coordinate space, $\chi_{\Delta\Delta}$ and χ_{CC} represent the relative wave functions between Δs and Cs (in the single $\Delta\Delta$ channel case, the CC component is absent), and $\zeta_{\Delta\Delta}$ and ζ_{CC} stand for the spin-isospin wave functions in the $\Delta\Delta$ and CC channels, respectively [19]. It should be specially mentioned that in such a wave function, normally called channel wave function, these two components are orthogonal to each other, and the totally anti-symmetric effect is implicitly included in the resultant relative wave function through above mentioned two steps [19]. To simplify the calculation without missing the major character, the D-wave contribution in the following calculations would be ignored due to its relatively smaller contribution, although both the S- and D-wave functions exist in our resultant wave functions. For convenience, the relative S- wave function is expanded as

$$\chi(R) = \sum_{i=1}^{4} c_i \exp\left(-\frac{R^2}{2b_i^2}\right). \tag{5}$$

In terms of obtained wave function of d^*, we are able to calculate the four-body decay width of $d^* \to pn\pi^0\pi^0$

$$\Gamma_{d^*\to pn\pi^0\pi^0} = \frac{1}{2!2!}\int d^3k_1 d^3k_2 d^3p_1 (2\pi)\delta(\Delta E) \mid \overline{\mathcal{M}(k_1,k_2;p_1)} \mid^2, \tag{6}$$

where $\mid \overline{\mathcal{M}(k_1,k_2;p_1)} \mid^2$ stands for the squared transition matrix element with a sum over the final four body state and an average of the polarizations of the initial state d^*, the factor of $2! \times 2!$ is due to the identical particles of $\pi^0\pi^0$ and pn, respectively, and $\delta(\Delta E)$ denotes the energy conservation with $\Delta E = M_{d^*} - \omega_\pi(k_1) - \omega_\pi(k_2) - E_N(p_1) - E_N(-p_1 - k_1 - k_2)$, ω_π and E_N being the the energies of the outgoing pion and nucleon, respectively.

In the above equation, the matrix element includes the contributions from four sub-diagrams plotted in Fig. 1.

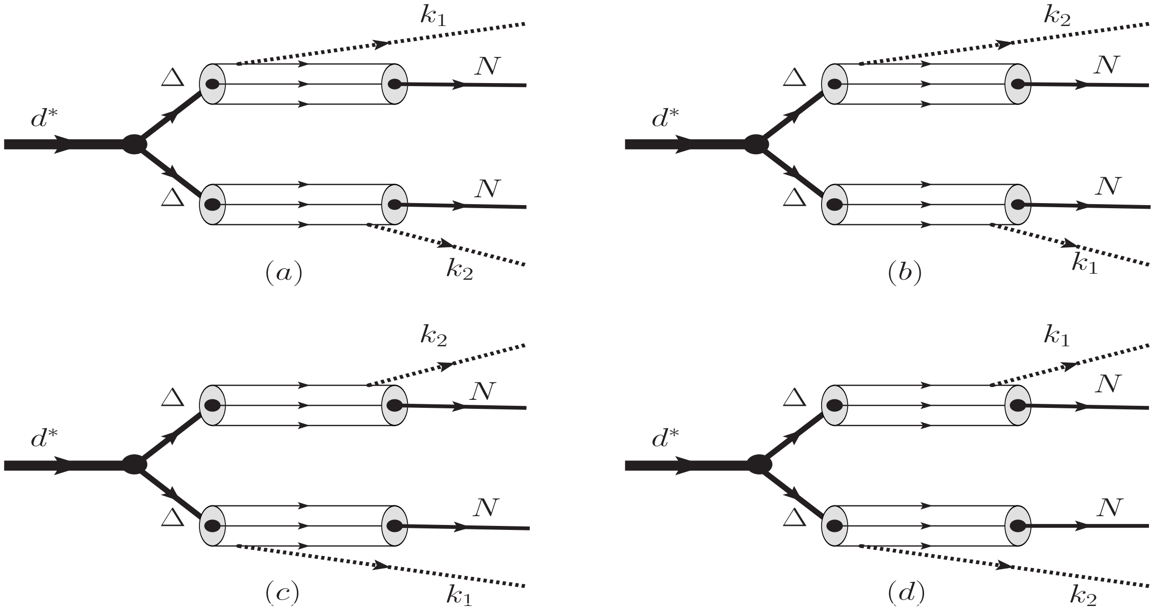

FIG. 1: Four possible emission ways in the decay of the d^* resonance composed of the $\Delta\Delta$ structure only. Two pions with momenta of $\vec{k}_{1,2}$ are emitted from one of the three quarks in 2 Δs, respectively.

The explicit expression, for example Fig. 1a, reads

$$\begin{aligned} \mathcal{M}^a(k_1,k_2;p_1) &= \int d^3p_2 d^3q \Big[\mathcal{H}\mathcal{S}_f\mathcal{H}\Big]\Psi_{d^*}(q)\delta^3(\vec{p_1}+\vec{k}_1-\vec{q})\delta(\vec{p}_2+\vec{k}_2+\vec{q}) \\ &= \int d^3p_2\delta^3(\vec{p_1}+\vec{p_2}+\vec{k}_1+\vec{k}_2)\Big[\mathcal{H}\mathcal{S}_f\mathcal{H}\Big]\psi_{d^*}(-\vec{p}_2-\vec{k}_2), \end{aligned} \tag{7}$$

where $\mathcal{S}_f$ is the propagator of the intermediate state. Ψ_{d^*} represents the d^* wave function in the momentum space which can be obtained by Fourier transforming the d^* wave functions in the coordinate space in both single $\Delta\Delta$ channel and coupled $\Delta\Delta + CC$ channel approximations.

In the coupled channel case, we found that there are 31.5% $\Delta\Delta$ component and 68.5% CC component in the d^* wave function shown in Eq.(4) [19]. Since the pion itself is colorless, emission of pion would not change the color structure of the parent particle. On the other hand, the final proton and neutron are, of course, colorless. Therefore, although the pion can be emitted both from the colorless particle and from the colored particle, in the leading approximation, the parent particle should be colorless, as an estimation, the contribution from the CC component can be neglected although such a component is the dominant component in d^*. In other words, the quark-rearrangement effect is in the higher order and thus can be ignored here. Then, the major contribution to the decay width comes merely from the $\Delta\Delta$ component.

In the $d^* \to pn\pi^0\pi^0$ process, the obtained partial widths are about 15.2MeV and 7.4MeV in the single channel and coupled channel approximations, respectively, they are tabulated in Tab.I.

TABLE I: Calculated partial decay widths and corresponding branching ratios of d^* in the two-body, three-body and four-body decay channels and the total width of d^*. Case I and Case II denote the single channel and coupled channel cases, respectively.

	This work			Ref. [20][a]		Expt. [2, 4, 22–24]	
	Case I	Case II					
Wave Function	$(100\%)\Delta\Delta$	$(31.5\%)\Delta\Delta + (68.5\%)CC$		$(31.5\%)\Delta\Delta + (68.5\%)CC$			
$M_{d^*}(MeV)$	2374	2380		2380		2375	
Decay Channel	$\Gamma(MeV)$	$\Gamma(MeV)$	$Br(\%)$	$\Gamma(MeV)$	$Br(\%)$	$\Gamma(MeV)$	$Br(\%)$
$d^* \to d\pi^0\pi^0$	17.0	9.2	14.3	9.2	13.3	10.2	14(1)
$d^* \to d\pi^+\pi^-$	30.8	16.8	26.0	16.8	24.3	16.7	23(2)
$d^* \to pn\pi^0\pi^0$	15.2	7.4	11.5	7.8	11.3	8.7	12(2)
$d^* \to pn\pi^+\pi^-$	33.5	16.4	25.4	19.2	27.8	21.8	30(4)
$d^* \to pp\pi^0\pi^-$	7.2	3.5	5.4	3.9	5.65	4.4	6(1)
$d^* \to nn\pi^+\pi^0$	7.2	3.5	5.4	3.9	5.65	4.4	6(1)
$d^* \to pn$	8.2	7.7	11.9	8.3	12.0	8.7	12(3)
Total	119.1	64.5	99.9	69.1	100.0	74.9	103

[a] Results in this column are obtained by using the ratios of cross section data between relevant decay channels.

It should be mentioned that in the $d^* \to pn\pi^+\pi^-$ process, both the (pn) pair and $(\pi^+\pi^-)$ pair can be either iso-scalar simultaneously or iso-vector simultaneously, namely $[(pn)_{I_{pn}=0}(\pi^+\pi^-)_{I_{\pi\pi}=0}]_{I=0}$ or $[(pn)_{I_{pn}=1}(\pi^+\pi^-)_{I_{\pi\pi}=1}]_{I=0}$ [4]. According to the isospin relation, the contribution from the former configuration ($I_{pn} = I_{\pi\pi} = 0$) should be twice of that from the $d^* \to pn\pi^0\pi^0$ configuration. But due to the isospin violation of pion, our explicit calculation shows that the partial widths of the first iso-scalar coupling part are 26.3MeV and 12.9MeV in the single channel and coupled channel cases, respectively, which are somewhat smaller than the expected value from the isospin relation, just like in the $d^* \to d\pi\pi$ case. The ratios of the iso-scalar coupling part of the charged pion decay to the chargeless pion decay are 1.73 and 1.74, which is similar to the values of 1.81 and 1.83 in the $d^* \to d\pi\pi$ case, respectively. The later iso-vector coupling part would also have some contribution. Since both components in this part have an isospin 1 ($I_{pn} = I_{\pi^+\pi^-} = 1$), its contribution would be the same as that from the iso-scalar part of the $d^* \to pp\pi^0\pi^-$ process, which will be discussed in the next paragraph. Our calculation gives a partial width of 7.2MeV and 3.5MeV for the $d^* \to pp\pi^0\pi^-$ process in the single channel and coupled channel case. Adding all these isospin caused effects together, the resultant partial width of the $d^* \to pn\pi^+\pi^-$ process is about 33.5MeV and 16.4MeV, respectively, in the single $\Delta\Delta$ and coupled $\Delta\Delta+CC$ channel approximations, which are also tabulated in Tab.I. The calculated partial width in the coupled channel approximation is close to our previous estimation of 19.2MeV [20] by using the experimental data, and compatible with the experimental data of 21.8MeV. If we define the ratio of the partial decay widths between the charged and chargeless double-pion decays as

$$R = \frac{\Gamma_{d^*\to pn\pi^+\pi^-}}{\Gamma_{d^*\to pn\pi^0\pi^0}}, \tag{8}$$

the resultant R value is about 2.20 in the single $\Delta\Delta$ approximation and 2.22 in the coupled channel approximation. Comparing with the value of 2.5 from the isospin relation and the similar value of 1.83 in the $d^* \to d\pi\pi$ case, this ratio is somehow relatively smaller. This is because that the pion isospin breaking effect caused phase space reduction in the non-fusion double-pion production process plays a relatively weaker role.

The partial widths of the iso-scalar parts of $d^* \to pp\pi^0\pi^-$ and $d^* \to nn\pi^+\pi^0$ processes can also be calculated in terms of our wave function of d^* in the same framework. Since these two processes are mirror states, the widths of these decays should be same. As shown in Tab.I, the calculated partial width of 3.5MeV in the coupled channel approximation is again compatible with our previous estimated value of 3.9MeV and the data of 4.4MeV.

From this table, one also sees that in the coupled $\Delta\Delta + CC$ channel approximation, the total width of d^* is about 64.5MeV, which is close to our previous estimated value of 69.1MeV and the observed value of 74.9MeV. Moreover, the calculated branching ratios for the decay processes shown in Tab.I are all close to our previous estimations and are all in acceptable ranges in comparison with the data.

In short, from this table, we have following observations:

- All the partial widths of the three-body and four-body double-pion decays of d^* are explicitly calculated in the same

framework by using our model wave function in the extended chiral SU(3) quark model in a unified way. The obtain widths are close to the estimations by using corresponding cross section data in our previous paper [20].
• Four-body decay width of d^* in the coupled channel approximation is much smaller than that in the single channel approximation. This decay width suppression is mainly due to the suppression of $\Delta\Delta$ component in the d^* wave function, and the large CC component does not contribute in the lowest order approximation.
• The partial decay width of the chargeless pion process $d^* \to pn\pi^0\pi^0$ is close to the estimated value in our previous paper but slightly smaller than the data due to the approximation in the calculation. However, the corresponding branching ratio is close to the data and our previous estimation, because the total width is somewhat smaller than the data.
• The partial decay width of the $d^* \to pp\pi^-\pi^0$ process is also slightly smaller than the value of the data. Consequently, the partial decay width of the $d^* \to pn\pi^+\pi^-$ process is even smaller than the data although it is still acceptable for a crude theoretical calculation. But, the branching ratios do not contradict the data.
• The R value shows an isospin-symmetry breaking effect due to the mass difference between π^0 and $\pi^\pm$. The explicitly calculated R value of 2.22 in the coupled channel approximation is slightly smaller than the value of 2.46 extracted in terms of the cross section data in our previous paper and the value of 2.5 from the theoretical isospin relation.
• The total width of d^* is about 64.5MeV, which is still not incompatible with the value of 69.1MeV in our previous estimation and the data of 75MeV.

From this calculation, one again sees that the single $\Delta\Delta$ structure cannot explain the observed data of d^*, but if a CC component is involved, the partial decay widths of the three-body and four-body double pion decays can be reasonably obtained and the mass and width data of d^* can be well-understood. All these results support our assertion that one may assign the observed d^* state as a $\Delta\Delta$ bound state with a dominant CC component, namely the d^* state is a six-quark dominated exotic state. The real structure of d^* should further be checked in other decay modes, for instance the non-fusion triple-pion production process [25].

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