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Are the anticharmed and bottomed pentaquarks molecular heptaquarks?

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I study the charmed $uudd\bar{c}$ resonance $D^{*-}p(3100)$ very recently discovered by H1 Collaboration at HERA, using a standard quark model with a quark-antiquark annihilation constrained by chiral symmetry. I find that repulsion excludes the $D^{*-}p(3100)$ as a $uudd\bar{c}$ s-wave pentaquark. I explore the $D^{*-}p(3100)$ as a heptaquark, equivalent to a $N-\pi-D^*$ borromean linear molecule, with positive parity and total isospin $I=0$. I find that the $N-D$ repulsion is canceled by the attraction existing in the $N-\pi$ and $\pi-D$ channels. Multiquark molecules $N-\pi-D$, $N-\pi-B^*$, and $N-\pi-B$ are also predicted.

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I. INTRODUCTION

In this paper I study the anticharmed $uudd\bar{c}$ resonance $D^{*-}p(3100)$ using the heptaquark, or linear molecular perspective. The $D^{*-}p(3100)$ is a narrow hadron resonance of 3099 MeV decaying into a $D^{*-}p$, very recently discovered by H1 Collaboration at HERA [1]. It extends the SU(3) antidecuplet [2–5] which includes the $\Theta^+(1540)$ recently discovered at LEPS [6], and searched in many experiments [6–23], and the $\Xi^{--}(1860)$ observed at NA49 [24], and investigated by other collaborations [24–26]. Pentaquark structures have also been studied in the lattice [27–34]. The $\Theta^+(1540)$, $\Xi^{--}(1860)$, and $D^{*-}p(3100)$ are extremely exciting states, because they may be the first exotic hadrons to be discovered, with quantum numbers that cannot be interpreted as a quark and an antiquark meson or as a three-quark baryon. Multiquarks are expected since the works of Jaffe [35–38], and the SU(3) antidecuplet was predicted within the chiral soliton model [2–5]. However their isospin, parity [39,40], and angular momentum are yet to be observed.

In this communication it is shown that the pentaquarks cannot be in the ground state. The lowest excitation consists in including a light quark-antiquark pair in the system. This results in a heptaquark and in a linear molecular system. Recently this principle was used to propose that the $\Theta^+(1540)$ is a $K-\pi-N$ molecule with binding energy of 30 MeV [41–43], and the $\Xi^{--}(1862)$ is a $\bar{K}-N-\bar{K}$ molecule with a binding energy of 60 MeV [41,44]. I also find that the new positive parity scalar $D_s(2320)$ and axial $D_{s+}(2460)$ are $\bar{K}-D$ and $\bar{K}-D^*$ tetraquarks [45] with binding energies of 45 MeV.

In Ref. [41] we also suggest the existence of anticharmed $uudd\bar{c}$ and antibottomed exotic $uudd\bar{b}$ hadrons. The anticharmed pentaquark was widely expected [46], and the discovery of the H1 resonance motivates a detailed exploration of these new hadrons. In particular, the state $D^{*-}p(3100)$ may be similar to the Θ^+, with the antiquark $\bar{s}$ replaced by a $\bar{c}$. In this case it is natural to consider replacing the K meson with a D meson or with a D^* meson, because the D^* is also a narrow state [45]. The energy of the $D^{*-}p(3100)$ is consistent with a $D^*-\pi-N$ linear molecule with an energy of 14 ± 13 MeV above threshold. Nevertheless a system in which energy is located slightly above threshold is still a narrow state, and in this sense the $D^{*-}p(3100)$ remains in the same family of narrow flavor exotic pentaquarks of the Θ^+ and of the Ξ^{--}.

In Sec. II a standard quark model (QM) Hamiltonian is assumed, with a confining potential, a hyperfine term, and a quark-antiquark annihilation term which complies with spontaneous chiral symmetry breaking. Using the resonating group method (RGM) [47], I study the short range repulsion, and attraction, in multiquarks. I proceed in Sec. III with the study of the linear molecules or heptaquarks $D-\pi-N$, $D^*-\pi-N$, $B-\pi-N$, and $B^*-\pi-N$. In particular, the binding energy of these systems is discussed. Finally I conclude in Sec. IV.

II. FRAMEWORK

Here I study multiquarks microscopically with a standard QM Hamiltonian. The energy of the multiquark state and the short range interaction of the mesonic or baryonic subclusters of the multiquark are computed with the multiquark matrix element of the QM Hamiltonian,

$$H = \sum_i T_i + \sum_{i<j} V_{ij} + \sum_{i\bar{j}} A_{i\bar{j}}, \qquad (1)$$

depicted in Fig. 1. Each quark or antiquark has a kinetic energy T_i. The color-dependent two-body interaction V_{ij} includes the standard confining and hyperfine terms,

$$V_{ij} = \frac{-3}{16}\vec{\lambda}_i \cdot \vec{\lambda}_j [V_{\rm conf}(r) + V_{\rm hyp}(r)\vec{S}_i \cdot \vec{S}_j]. \qquad (2)$$

The potential of Eq. (2) reproduces the meson and baryon spectrum with quark and antiquark bound states (from heavy quarkonium to the light pion mass). Moreover, the RGM [47] was applied by Ribeiro [48], Toki [49], and Oka [50] to show that in exotic $N+N$ scattering the quark two-body potential, together with the Pauli repulsion of quarks, explains the $N+N$ hard core repulsion. Recently, a break-

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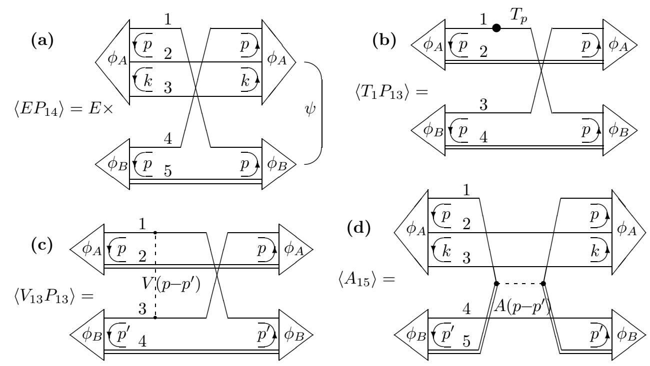

FIG. 1. Examples of RGM overlaps are depicted: in (a) the norm overlap for the meson-baryon interaction, in (b) a kinetic overlap for the meson-meson interaction, in (c) an interaction overlap for the meson-meson interaction, and in (d) the annihilation overlap for the meson-baryon interaction.

through was achieved [51–53] in quark models with a chiral invariant quark-antiquark interaction [54]. The Fock space is extended to include any number of $^3P_0$ quark-antiquark pairs, with a Bogoliubov-Valatin canonical transformation. The minimum condition for the vacuum energy results in the mass gap equation for quarks (equivalent to the Schwinger-Dyson equation for the quark propagator). The first result of this condensed vacuum solution is that the quarks acquire a finite, constituent mass. The second result, when one solves the pion Salpeter equation, is that the pion is massless in the chiral limit. The small but finite mass of the pion is recovered when finite current u and d quark masses are used from the onset. The third result, when one studies hadron-hadron effective interactions, is that the pion decouples in the chiral limit and for vanishing momentum, complying with the Adler Zero and with the Weinberg theorem. In the $^3P_0$ Fock space vacuum condensation, in the pion Salpeter equation, and in the pion-hadron couplings, the quark-antiquark annihilation $A_{i\bar{j}}$ plays a crucial role [51–53].

For the purpose of this paper, only the matrix elements of the potentials in Eq. (1) matter. The hadron spectrum constrains the hyperfine potential,

$$\langle V_{\rm hyp}\rangle \simeq \frac{4}{3}(M_\Delta - M_N) \simeq M_{K^*} - M_K. \tag{3}$$

When a light quark is replaced by a heavy quark, say a charmed quark, the hyperfine interaction is decreased, and it must also be replaced by $\langle V_{{\rm hyp}D}\rangle \simeq M_{D^*} - M_D$. The quark-antiquark annihilation potential $A_{i\bar{j}}$ is also constrained when the quark model produces spontaneous chiral symmetry breaking [55,56]. The annihilation potential A is present in the π Salpeter equation,

$$\begin{bmatrix} 2T+V & A \\ A & 2T+V \end{bmatrix}\begin{pmatrix} \phi^+ \\ \phi^- \end{pmatrix} = M_\pi \begin{pmatrix} \phi^+ \\ -\phi^- \end{pmatrix} \tag{4}$$

where the π is the only hadron with a large negative energy wave function, $\phi^- \simeq \phi^+$. In Eq. (4) the annihilation potential A cancels most of the kinetic energy and confining potential $2T + V$. This is the reason why the pion has a very small mass. From the hadron spectrum and using Eq. (4) the matrix elements of the annihilation potential are determined,

$$\langle A\rangle \simeq -\langle 2T + V\rangle \simeq -\frac{2}{3}(2M_N - M_\Delta), \tag{5}$$

where this result is correct for the annihilation of u or d quarks. In heavier systems, like the D meson, the negative energy wave function vanishes. In what concerns the K, our calculations find that the negative energy component of the Kaon is at most 30% of the positive energy. Therefore the K is much closer in nature to a normal meson, like the D or the ρ, than the pion. In our framework we can neglect the negative energy component of the K, and the annihilation of s quarks, for the RGM computation of the energy of the multiquarks. While the SU(2) chiral symmetry is weakly broken, here we do not implement SU(3) chiral symmetry.

The annihilation potential only shows up in nonexotic channels, and it is clear from Eq. (5) that the annihilation potential provides an attractive (negative) interaction. The quark-quark (antiquark) potential is dominated by the interplay of the hyperfine interaction of Eq. (3) and the Pauli quark exchange. In s-wave systems with low spin this results in a repulsive interaction. Therefore, I arrive at the *attraction/repulsion criterion* for ground-state hadrons: (i) whenever the two interacting hadrons have quarks (or antiquarks) with a common flavor, the repulsion is increased by the Pauli principle; (ii) when the two interacting hadrons have a quark and an antiquark with the same flavor, the attraction is enhanced by the quark-antiquark annihilation. For instance, $uud - s\bar{u}$ is attractive, and $uud - u\bar{s}$ is repulsive.

The attraction/repulsion criterion shows clearly that the exotic ground-state pentaquarks, containing five quarks only, are repelled. For instance, if the pentaquark $uudd\bar{s}$ could be somehow forced to remain in the ground state, this repulsion would provide a mass of 1535 MeV, close to the Θ^+ mass. There is evidence of such a negative parity state both in quark-model calculations and in lattice computations. However the existence of this ground state can only appear as an artefact in simulations that deny the decay into the $K - N$ channel. Actually the ground state is completely open to a strong decay into the $K - N$ channel, and this decay is further enhanced by the repulsion. In the particular case of one nucleon interacting with D or B mesons, the criterion implies that the short range exotic $D - N$ and $B - N$ interactions are repulsive. The $I = 0$ s-wave pentaquarks $uudd\bar{c}$ and $uudd\bar{b}$ are certainly quite unstable for the decay to $D - N$ and $B - N$ channels.

It is indeed well known that any narrow pentaquark must contain an excitation to prevent a decay width of hundreds of MeV to a meson-baryon channel. This is understood in the diquark and string model of Jaffe and Wiczek [57] and Karliner and Lipkin [58], and in the Skyrme model of Diakonov, Petrov, and Polyakov [5]. These authors suggest that the pentaquarks include a p-wave, or rotational excitation. However, in the spectrum of hadrons, p-wave excitations produce large energy shifts. For instance p-wave baryons suffer an excitation of 500 MeV. In charmonium the p-wave excitation increases the energy by 400 MeV. Moreover, in compact pentaquarks one has to account for the repulsion due to the quark-quark hyperfine interaction. I checked that with RGM computations, and this is confirmed by recent quark-model studies of the five quarks attached by strings and by recent lattice simulations, where the p-wave pentaquarks are indeed much heavier than the observed pentaquarks.

Although the diquark and the chiral soliton models are quite appealing, and their authors have been advocating pentaquarks for a long time, here I propose a different mechanism, which is more plausible in a standard quark-model approach. In this paper I consider that an s-wave flavor-singlet light quark-antiquark pair $u\bar{u} + d\bar{d}$ is added to the pentaquark M. The resulting heptaquark M' is a state with parity opposite of the original M [59]. The ground state of M' is also naturally rearranged in a linear system with an s-wave baryon and two s-wave mesons, where the two outer hadrons are repelled, while the central hadron provides stability. Indeed a quark-antiquark excitation, when it rearranges into a pion, only costs 140 MeV. Thus, starting with a quark-model approach, at the same token consistent with chiral symmetry, I conclude that the Fock space excitations are energetically more favorable than the Hilbert space excitations. Actually, this does not contradict the Skyrmion model. In nuclear physics, the pion exchange and the double pion exchange also dominate the attractive part of the $N-N$ interaction.

III. BINDING FLAVOR $uudd\bar{Q}$ MULTIQUARKS

Again, the simplest pentaquarks are not expected to bind due to the attraction/repulsion criterion. Nevertheless the $\bar{c}$ pentaquarks are more subtle than the ones with an $\bar{s}$, because the D^* is quite stable, and close to the D when compared with the K^* and the K. Therefore one should also consider exciting the spin in the $l\bar{c}$ cluster, and this amounts to studying $D^* - N$ bound states. Indeed the effective potential of Eq. (6) is attractive in this case. However this state is coupled to the $D - N$ case also in Eq. (6). Once the coupled channel Hamiltonian is diagonalized, we find that the energy of the $D^* - N$ is lifted and the attraction is essentially lost.

On the other hand, a pion can be attracted both by the N baryon and by the D or D^* meson to produce a $N - \pi - D$ or $N - \pi - D^*$ linear molecule. For instance the flavor includes combinations of terms like $uud - d\bar{u} - u\bar{c}$ where the antiquark $\bar{u}$ in the pion can be annihilated both by the u present in the N and by the u present in the D. According to the attraction/repulsion criterion this produces an attractive interaction. Incidentally the pion-nucleon $I = 1/2$ attraction is fixed by chiral symmetry; see Ref. [53].

This motivates the study of a linear molecule with an N, a π, and a D, or a D^*, or a B, or a B^*. Quantitatively [41,45,52,53], the effective potentials computed for the different channels are the separable potentials,

$$
\begin{aligned}
V_{D-N} &= \frac{1}{2}\frac{\frac{1}{2}+\frac{1}{3}\vec{\tau}_D\cdot\vec{\tau}_N}{\frac{3}{4}-\frac{1}{3}\vec{\tau}_D\cdot\vec{\tau}_N}\langle V_{\rm hyp}\rangle|\phi_{\mathbf{0}}^{\alpha}\rangle\langle\phi_{\mathbf{0}}^{\alpha}| + \frac{1}{2}\frac{\frac{1}{2}+\frac{1}{3}\vec{\tau}_D\cdot\vec{\tau}_N}{\frac{3}{4}-\frac{1}{3}\vec{\tau}_D\cdot\vec{\tau}_N}\langle V_{{\rm hyp}D}\rangle|\phi_{\mathbf{0}}^{\alpha}\rangle\langle\phi_{\mathbf{0}}^{\alpha}|,\\
V_{\substack{D-N\\ \to D^*-N}} &= \frac{\frac{1+2\sqrt{3}}{8}+\frac{1+\sqrt{3}}{3}\vec{\tau}_D\cdot\vec{\tau}_N}{\sqrt{3}+\frac{1}{4}+\frac{5}{3}\vec{\tau}_D\cdot\vec{\tau}_N}\langle V_{\rm hyp}\rangle|\phi_{\mathbf{0}}^{\alpha}\rangle\langle\phi_{\mathbf{0}}^{\alpha}| + \frac{-\frac{1}{8}-\frac{4}{3}\vec{\tau}_D\cdot\vec{\tau}_N}{\sqrt{3}+\frac{1}{4}+\frac{5}{3}\vec{\tau}_D\cdot\vec{\tau}_N}\langle V_{{\rm hyp}D}\rangle|\phi_{\mathbf{0}}^{\alpha}\rangle\langle\phi_{\mathbf{0}}^{\alpha}|,\\
V_{D^*-N} &= \frac{1}{2}\frac{2+\frac{7}{3}\vec{\tau}_D\cdot\vec{\tau}_N}{\frac{11}{4}+\frac{7}{3}\vec{\tau}_D\cdot\vec{\tau}_N}\langle V_{\rm hyp}\rangle|\phi_{\mathbf{0}}^{\alpha}\rangle\langle\phi_{\mathbf{0}}^{\alpha}| + \frac{1}{2}\frac{\frac{-1}{2}+\frac{5}{3}\vec{\tau}_D\cdot\vec{\tau}_N}{\frac{11}{4}+\frac{7}{3}\vec{\tau}_D\cdot\vec{\tau}_N}\langle V_{{\rm hyp}D}\rangle|\phi_{\mathbf{0}}^{\alpha}\rangle\langle\phi_{\mathbf{0}}^{\alpha}|, \qquad V_{\pi-N} = -\frac{1}{3}\vec{\tau}_\pi\cdot\vec{\tau}_N\langle A\rangle|\phi_{\mathbf{0}}^{\alpha}\rangle\langle\phi_{\mathbf{0}}^{\alpha}|,\\
V_{\pi-D} &= -\frac{4}{9}\vec{\tau}_\pi\cdot\vec{\tau}_D\langle A\rangle|\phi_{\mathbf{0}}^{\alpha}\rangle\langle\phi_{\mathbf{0}}^{\alpha}|, \qquad V_{\pi-D^*} = -\frac{4}{9}\vec{\tau}_\pi\cdot\vec{\tau}_D\langle A\rangle|\phi_{\mathbf{0}}^{\alpha}\rangle\langle\phi_{\mathbf{0}}^{\alpha}|,
\end{aligned}
\tag{6}
$$

where $\vec{\tau}$ are the isospin matrices, normalized with $\vec{\tau}^2 = \tau(\tau+1)$. The wave-function $|\phi_0^\alpha\rangle$ in the separable interaction is the ground-state harmonic oscillator wave function. Equations (6) result from the calculation of RGM overlaps of Fig. 1.

Qualitatively, the proposed systems $N - \pi - D$ and $N - \pi - D^*$ are similar to the model for $\Theta^+(1540)$ advocated in Ref. [41], when the antiquark $\bar{s}$ is replaced by a heavy $\bar{c}$ or $\bar{b}$. The increase of the quark mass does not directly affect the attraction, where the $\bar{Q}$ is just a spectator. However the size $1/\alpha$ of the hadronic wave functions is affected. For instance, in a harmonic oscillator potential, α is proportional to $\sqrt[4]{\mu}$, and the reduced mass μ doubles when one changes from a light-light meson to a heavy-light meson. This amounts to an increase of nearly 20% of the α in the D or B meson. Because the α parameter is increased only in one of the Jacobi coordinates, the average α in $\pi - D$ or $\pi - D^*$ or $\pi - B$ or $\pi - B^*$ is only expected to suffer a 10% increase. This increase of α will effectively decrease the attractive interaction. Similar results are obtained in different models of confinement, say in the funnel interaction which is more adequate for heavy quarks. In what concerns the repulsive $D - N$ potential the strength of the hyperfine potential is decreased because

$\langle V_{\text{hyp}D}\rangle < < \langle V_{\text{hyp}}\rangle$. The α decrease further reduces the repulsive interaction. Moreover the kinetic energy of the $N-D$ is much smaller than the kinetic energy of the $N-K$ system. Essentially the $N-\pi-D$ has 20% less attraction and 50% less repulsion than the $N-\pi-K$.

However a quantitative study of binding is necessary because the π is very light. I now use an adiabatic Hartree method to study the stability of the linear $N-\pi-D$ molecule and related molecules with a D^*, a B, or a B^*. Essentially the wave function of the pion is centered between the nucleon and the D, where the nucleon and the D do not overlap with each other. This results in a linear molecule. For simplicity I use an averaged mass for the N and the D. I solve a Schrödinger equation for the nucleon in the potential produced by a pion placed at the origin and by the other heavy-light meson placed at a distance $-\mathbf{a}$ of the pion. The potential of the pion is produced by the D meson at the point $-\mathbf{a}$ and the nucleon at the point $+\mathbf{a}$. This produces three binding energies E_D, E_π, E_N, and three wave functions. In the Hartree method the total energy is the sum of these energies minus the matrix elements of the potential energies, and this is easily computed once the two Schrödinger equations are solved. The total energy is a function of the distance $\mathbf{a}$, and I minimize it as a function of $\mathbf{a}$. The same steps are repeated for the $N-\pi-D^*$, $N-\pi-B$, and $N-\pi-B^*$ systems. At this point I am not yet able to bind these linear molecular systems, with a negative binding energy, because the attraction is lost, when finally the matrix elements of the potential energies are subtracted. Comparing with the $N-\pi-K$ [41] system, the $N-\pi-D$ is slightly harder to bind, due to the reduction in the $\pi-D$ attraction, when compared with the $\pi-K$ attraction [41].

Nevertheless, because several attractive effects remain to be included, and because the linear heptaquark picture also complies with the experiment, binding remains plausible. This will be discussed in Sec. IV. Assuming that there is binding, with a very small binding energy, I arrive at a precise estimate of the energy of the charmed and bottomed heptaquarks. Comparing with the $N-\pi-K$ model for the Θ^+, an energy of 14 ± 13 MeV above threshold for the $N-\pi-D^*$, corresponding to a $uudd\bar{c}$ mass of 3.10 GeV, as observed by H1 Collaboration, is plausible. The corresponding mass of the heptaquark $N-\pi-B^*$ with flavor $uudd\bar{b}$ is then of the order of 6.42 GeV. In what concerns the ground-state $N-\pi-D$ and $N-\pi-B$, these states should have an energy some MeV larger than, respectively, 2.94 GeV and 6.36 GeV.

IV. CONCLUSION AND OUTLOOK

I find that $N-\pi-D$, $N-\pi-D^*$, $N-\pi-B$, and $N-\pi-B^*$ nearly bound linear s-wave molecules, with $I=0$ and positive parity, are plausible. The mass of the linear heptaquarks is also in good agreement with all the presently observed exotic flavor pentaquarks Θ^+, Ξ^{--}, and $D^{*-}p$. Moreover the absorption of a low energy pion, producing a low energy p-wave $N-D(D^*, B, B^*)$, results in a narrow decay width. The $N-\pi-D^*$ and $N-\pi-B^*$ can also decay, respectively, into the three-body systems $N-\pi-D$ and $N-\pi-D$, but this is again narrow since the $N-D^*$ and $N-B^*$ overlaps are suppressed. The heptaquark picture also explains why most lattice simulations (except for the work of Chiu) [27–34] fail to reproduce the Θ^+, the Ξ^{--}, and the $D^{*-}p$ with pentaquark operators.

The numerical study of the $uudd\bar{c}(\bar{b})$ multiquarks is performed with a state-of-the-art RGM computation of five-quark and seven-quark systems. I show that these multiquark systems are equivalent to simpler meson-baryon and meson-meson-baryon systems with short range interactions. I, respectively, find strong repulsion (ruling out the pentaquark configuration), and combined attraction with repulsion, leading to a heptaquark linear configuration. This simple heptaquark picture is quite effective because it provides an ansatz with lower energy than the rotationally excited models. Although many other Fock space, spin, angular, and radial excitations can in principle couple to the dominant component, it is well know that in coupled channel equations (with controlled couplings) the energy of the system is led by the lowest energy component. The coupling to a wider basis will only lower the energy of the crypto-heptaquark, further binding it. Moreover the binding energy only contributes to less than 1% of the total mass of the system. Therefore more complete computations are not expected to change the total mass significantly.

However the exotic pentaquarks are not yet fully understood in chiral consistent quark models. The RGM computation with a fixed number of seven quarks only produces the short range part of the interaction, which is not sufficient to bind the seven-quark linear system. To progress in the binding of the linear heptaquark, the Fock space ansatz should be enlarged with more pions. In the chiral limit one should consider all many-pion Fock space components. In the actual case of 140 MeV pions, the states with few pions are expected to dominate. For instance, in the $N-N$ interaction, the long range one-pion-exchange and the medium range two-pion-exchange interactions are crucial to bind the deuteron. While this is naturally achieved in effective meson theories, in quark-model calculations this amounts to having four more quarks, adding to a total of at least 11 quarks. Moreover, other effects contributing to binding are the full overlaps of at least seven quarks, the negative energy of the kaon, the exact solution of the three, four or five hadron systems, and the coupling to p-wave pentaquarks. In the case of the charmed and bottomed pentaquarks one also has to be concerned with the mixing of $D-N$ and of D^*-N channels, and the effect of the $D^*-\pi-N$ threshold. A detailed account of the possibility to compute these several effects at the microscopic level of quarks is under preparation.

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