Charmed baryon $\Sigma_c(2800)$ as a $N\Delta$ hadronic molecule

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The isotriplet $\Sigma_c(2800)$ baryon with possible quantum numbers $J^P = \frac{1}{2}^\pm$ or $\frac{3}{2}^\pm$ is considered as a hadronic molecule composed of a nucleon and a $D$ meson. We determine the strong two–body decay widths $\Sigma_c \to \Lambda_c \pi$ which are shown to be consistent with current data for the $J^P = \frac{1}{2}^+$ and $J^P = \frac{3}{2}^+$ assignments.

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A few years ago the Belle Collaboration$^1$ observed an isotriplet of new baryon states with open charm $\Sigma_c(2800)$ decaying into $\Lambda_c \pi$. This resonance was fit by a D-wave Breit-Wigner distribution based on the measured mass of the state and the Belle Collaboration tentatively assigned the quantum numbers $J^P = \frac{3}{2}^-$. The same neutral state $\Sigma_c^0$ was possibly also observed in B decays by the BABAR Collaboration$^2$. Although the measured width of this resonance is consistent with the Belle value, the mass value is higher and somewhat inconsistent with the previous measurement. The BABAR Collaboration indicates that there is weak evidence that the excited $\Sigma_c^0$ they observe has $J = 1/2$. In the following we will assume that both collaborations observe the same baryon resonance, although the present mass discrepancy and the final assignment of quantum numbers remain to be resolved.

Earlier quark model predictions$^3$ for excited baryons containing one charmed quark lead to a possible identification of this state as a member of the $J^P = 3/2^-$ and $5/2^-$ doublet, where the light quark subsystem carries total angular momentum of 2 units. Further quark model studies on the mass spectrum of excited $\Sigma$ states were also performed$^3$. These later works also tend to identify the $\Sigma_c(2800)$ as one of the nearly degenerate orbital excitations with $J^P = 1/2^-, 3/2^- or 5/2^-$. The strong decays of excited charmed baryons have been considered in the framework of heavy hadron chiral perturbation theory (HHChPT)$^8$ and in quark models$^{9,10}$. The computed $\Lambda_c \pi$ decay widths$^8$ of various $J^P$ assignments for the $\Sigma_c(2800)$ in the context of the $3^P_0$ model are found to be inconsistent with observation. In the chiral model of $^{11}$ the $\Lambda_c \pi$ decay is consistent with a $J^P = 1/2^-$ assignment, while the HHChPT framework of$^8$ uses the total width of $\Sigma_c(2800)$ as an input. Hence from the theoretical side a unique interpretation of this resonance in terms of an orbital excitation of the charmed three-quark system is presently not available.

Alternatively, in Ref.$^{11}$ it was suggested that the $\Sigma_c(2800)$ is a so-called chiral excitation of open-charm baryons with $J^P = 3/2^-$ and $5/2^+$ sextet baryons with open charm. When including further pseudoscalar mesons like $D$ mesons in the coupled-channel dynamics the updated results of $^{11}$ resulted in $J^P = 3/2^-$ state, where the width is much too large to justify the identification with the $\Sigma_c(2800)$. The dynamical generation of charmed baryon resonances in the context of a unitarized meson-baryon coupled channel model was also pursued in Refs.$^{13,14}$. Both pseudoscalar and vector mesons are included in the S-wave coupled channel formalism as required by heavy quark symmetry. Now the $\Sigma_c(2800)$ is identified with a dynamically generated resonance in the $J^P = 1/2^-$ channel with a dominant $N\Delta$ configuration. But the resulting partial $\Lambda_c \pi$ decay width is much too small to justify this identification.

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Given the sparse experimental information concerning the excited $\Sigma_c$ spectrum and decays, but also the somewhat contradictory theoretical interpretations it is intriguing to note that the observed $\Sigma_c(2800)$ states are very close to the respective ND thresholds. For example, the measured mass difference $\Delta m = m_{\Sigma^0_c(2800)} - m_{\Lambda^+_c} = (515 \pm 3\,^{+2}_{-1})$ MeV by the Belle Collaboration \cite{1} corresponds to an absolute mass of $m_{\Sigma^0_c(2800)} = (2802\,^{+1}_{-2})$ MeV \cite{12} which should be compared to the $nD^0$ threshold value of about 2804 MeV. The closeness of these thresholds could imply that the ND components play a dominant role in the $\Sigma_c(2800)$ configurations, either by coupling of the excited three-quark state to the ND channels or in a hadronic molecule configuration. Although a full dynamical calculation was not performed yet concerning binding in the ND channel both for $J = 1/2$ and $J = 3/2$ (values for $J$ as suggested by experiment) here we pursue a possible hadronic molecule interpretation of the $\Sigma_c(2800)$ – bound state of the nucleon and the charm $D$ meson. Our aim is to work out in a hadronic framework the resulting $\Sigma_c \rightarrow \Lambda_c \pi$ decay widths for possible quantum number assignments of $J^P = 1/2^\pm$ and $3/2^\pm$ which will be confronted with the experimental results. Note that while $J^P = 1/2^-$ corresponds to an S-wave ND configuration, the options $J^P = 1/2^+$ or $J^P = 3/2^+$ represent a P-wave and $J^P = 3/2^-$ a relative D-wave in the ND system. Although slight binding in the ND seems less likely for higher partial waves, especially for the D-wave, the possibility of such a weakly bound system is not excluded yet.

In Refs. \cite{10,20} we developed the formalism for the study of recently observed exotic meson states (like $D_{s0}^*(2317)$, $D_{s1}(2460)$, $X(3872)$, $Y(3940)$, $Y(4140)$, · · ·) as hadronic molecules. The extension of our formalism to baryonic molecules has been done in Refs. \cite{21,22}. A composite structure of these molecular states is defined by the compositeness condition $Z = 0$ \cite{22,23}. This condition implies that the renormalization constant of the hadron wave function is set equal to zero or that the hadron exists as a bound state of its constituents. The compositeness condition was originally applied to the study of the deuteron as a bound state of proton and neutron \cite{22}. Then it was extensively used in low-energy hadron phenomenology as the master equation for the treatment of mesons and baryons as bound states of light and heavy constituent quarks (see e.g. Refs. \cite{21,23}). By constructing a phenomenological Lagrangian including the couplings of the bound state to its constituents and the constituents with other particles we calculated one–loop meson diagrams describing different decays of the molecular states (see details in \cite{10,22}).

In the present paper we proceed as follows. First, we discuss the basic notions of our approach. We consider a choice for the effective meson Lagrangian for the treatment of the $\Sigma_c$ baryons as ND bound states: $\Sigma_c^{++} = (pD^+)$, $\Sigma_c^+ = (pD^0 + nD^+)/\sqrt{3}$, $\Sigma_c^0 = (nD^0)$, Second, we consider the two–body hadronic decays $\Sigma_c \rightarrow \Lambda_c + \pi$. Finally, we present our numerical results.

We consider the triplet ($\Sigma_c^{++}$, $\Sigma_c^+$, $\Sigma_c^0$) as molecular states composed of nucleons and $D$ mesons as:

$$
|\Sigma_c^{++}\rangle = |pD^+\rangle,
|\Sigma_c^+\rangle = \frac{1}{\sqrt{2}}|pD^0 + nD^+\rangle,
|\Sigma_c^0\rangle = |nD^0\rangle.
$$

Our approach is based on an effective interaction Lagrangian describing the couplings of the $\Sigma_c$ to its constituents. The molecular structure of the $\Sigma_c$ baryon with quantum numbers $J^P = \frac{3}{2}^\pm$ is described by the Lagrangian

$$
\mathcal{L}_{\Sigma_c}(x) = g_{\Sigma_c} \mathbf{\Sigma}_c(x) \mathbf{J}_{\Sigma_c}(x) + \text{H.c.}, \quad \mathbf{J}_{\Sigma_c}(x) = D(x) \mathbf{\tau} \Gamma \int d^4y \Phi(y^2) N(x + y)
$$

while for the choice $J^P = \frac{3}{2}^-$ the Lagrangian contains a derivative ND coupling

$$
\mathcal{L}_{\Sigma_c}(x) = g_{\Sigma_c} \mathbf{\Sigma}_c(x) \mathbf{J}_{\Sigma_c,\mu}(x) + \text{H.c.}, \quad \mathbf{J}_{\Sigma_c,\mu}(x) = D(x) \mathbf{\tau} \Gamma \int d^4y \Phi(y^2) \partial_\mu N(x + y)
$$

where $g_{\Sigma_c}$ is the coupling constant of the isotriplet $\Sigma_c$ to the $N = (p, n)^T$ and $D = (D^0, D^+)^T$ constituents. Here $\Gamma$ is the corresponding Dirac matrix related to the spin–parity of the $\Sigma_c$. In particular, for $J^P = \frac{1}{2}^+$, $\frac{1}{2}^-$ we have $\Gamma = \gamma^5$ while for $J^P = \frac{3}{2}^+$, the Dirac structure $\Gamma = I$ should be inserted in the $\Sigma_c$ current.

We propose a picture for the $\Sigma_c$ in analogy to heavy quark–light antiquark mesons, i.e. the heavy $D$ meson is located at the center of mass of the $\Sigma_c$, while the light nucleon surrounds the $D$. We describe the distribution of the nucleon around the $D$ meson by the correlation function $\Phi(y^2)$ depending on the relative Jacobi coordinate $y$. A basic requirement for the choice of an explicit form of the correlation function $\Phi(y^2)$ is that its Fourier transform vanishes sufficiently fast in the ultraviolet region of Euclidean space to render the Feynman diagrams ultraviolet finite. We adopt a Gaussian form for the correlation function. The Fourier transform of this function is given by

$$
\tilde{\Phi}(p_E^2/\Lambda^2) = \exp(-p_E^2/\Lambda^2),
$$
where $p_E$ is the Euclidean Jacobi momentum. Here, $\Lambda \sim m_N \sim 1$ GeV is a size parameter, characterizing the distribution of the nucleon in the $\Sigma_c$ baryon, which is of order of the nucleon mass or 1 GeV. In the numerical analysis we therefore fix the mean value to $\Lambda = 1$ GeV.

The coupling constant $g_{\Sigma_c}$ is determined by the compositeness condition \cite{16, 23–25}. It implies that the renormalization constant of the hadron wave function is set equal to zero with:

$$Z_{\Sigma_c} = 1 - \Sigma'_{\Sigma_c}(m_{\Sigma_c}) = 0 .$$

(5)

Here, $\Sigma'_{\Sigma_c}(m_{\Sigma_c}) = g_{\Sigma_c}^2 \Pi'_{\Sigma}(m_{\Sigma_c})$ is the derivative of the mass operator for $J = \frac{3}{2}$. For $J = \frac{1}{2}$ the same relation holds but now $\Sigma'_{\Sigma_c}(m_{\Sigma_c})$ should be identified with the scalar function proportional to the Minkowski tensor $g^{\mu\nu}$ in the full mass operator $\Sigma_{\Sigma_c}^{\mu\nu}$. Note, that for $J = \frac{1}{2}$ the other possible Lorentz structures in the $\Sigma_c$ mass operator vanish due to the Rarita–Schwinger conditions. The mass operator of the $\Sigma_c$ baryon is described by the diagram of Fig.1. To clarify the physical meaning of the compositeness condition, we first want to remind the reader that the renormalization constant $Z_{\Sigma_c}^{1/2}$ can also be interpreted as the matrix element between the physical and the corresponding bare state — an elementary structureless field. For $Z_{\Sigma_c} = 0$ it then follows that the physical state does not contain the bare one and hence is described as a bound state. As a result of the interaction of the $\Sigma_c$ baryon with its constituents $N$ and $D$, the $\Sigma_c$ baryon is dressed, i.e. its mass and its wave function have to be renormalized. Note, in the present paper we only consider the contribution of a possible molecular $(ND)$ component to the structure of the $\Sigma_c$. An inclusion of a three–quark component is possible, but goes beyond the scope of the present paper.

In Table I we display the results for the coupling $g_{\Sigma_c}^{+}$ of the single charged $\Sigma_c^+$ state for different spin–parity assignments and for a variation of the size parameter $\Lambda$ in the region of 0.75 – 1.25 GeV. Note, that an increase of the $\Lambda$ value leads to an enhancement of the couplings $g_{\Sigma_c}^{+}$. A final value for the cutoff model parameter $\Lambda$ can ultimately only be fixed when more decay data on $\Sigma_c$ are available.

The one–loop hadron diagrams contributing to the $\Sigma_c \to \Lambda_c + \pi$ transition are displayed in Fig.2(a) and 2(b). To evaluate these strong $\Sigma_c \to \Lambda_c + \pi$ decays we further need an effective Lagrangian including the couplings of the $\Sigma_c$ constituents to $\Lambda_c$ and $\pi$. The $\pi NN$ and $D^* D \pi$ couplings are constrained by data or by low–energy theorems. In particular, the $\pi NN$ coupling at leading order of the chiral expansion is expressed through the nucleon mass $m_N$, the
The couplings decay width for nucleons, In the evaluation of the diagrams in Figs. 1 and 2 we use the standard free propagators for the intermediate particles: \[ D \] for vector pion decay constant \( F_\pi = 92.4 \) MeV and the nucleon axial charge \( g_A = 1.2695 \) as:

\[ \mathcal{L}_{\pi NN} = g_{\pi NN} \bar{N} i \gamma_5 \pi \tau N, \quad g_{\pi NN} = \frac{m_N}{F_\pi} g_A. \]  

(6)

For the \( D^*D\pi \) coupling we take the central value of \( g_{D^*D\pi} = 17.9 \) extracted from the measured \( D^{*+} \to D^0 + \pi^+ \) decay width [26]

\[ \Gamma(D^{*+} \to D^0\pi^+) = \frac{g_{D^*D\pi}^2}{24 \pi m_{D^{*+}}^3} P^* \cdot \mathbf{3}, \]  

(7)

where \( P^* \) is the three–momentum of \( \pi^+ \) in the \( D^{*+} \) rest frame. Then the interaction \( D^*D\pi \) Lagrangian reads:

\[ \mathcal{L}_{D^*D\pi} = \frac{g_{D^*D\pi}}{\sqrt{2}} D_\mu D^{*\dagger}_\mu i \partial^\mu \pi \tau D + \text{H.c.} \]  

(8)

The couplings \( DN_A \) and \( D^*N_A \) are estimated by matching the flavor SU(4) effective Lagrangian to the SU(3) version, both describing the couplings of pseudoscalar and vector mesons to two baryons (see details in the Appendix):

\[ g_{DNA} = -g_{\pi NN}, \quad g_{D^*NA} = \frac{\sqrt{3}}{2} g_{\rho NN}. \]  

(9)

In the evaluation of the diagrams in Figs. 1 and 2 we use the standard free propagators for the intermediate particles:

\[ iS_N(x - y) = \langle 0|TN(x)\bar{N}(y)|0 \rangle = \int \frac{d^4k}{(2\pi)^4} \frac{1}{i} e^{-ik\cdot(x-y)}S_N(k), \quad S_N(k) = \frac{1}{m_N - \not{k} - i\epsilon} \]  

(10)

for nucleons,

\[ iS_D(x - y) = \langle 0|TD(x)D^\dagger(y)|0 \rangle = \int \frac{d^4k}{(2\pi)^4} \frac{1}{i} e^{-ik\cdot(x-y)}S_D(k), \quad S_D(k) = \frac{1}{m_D^2 - \not{k}^2 - i\epsilon} \]  

(11)

for pseudoscalar \( D \) mesons and

\[ iS_{D^*}^{\mu\nu}(x - y) = \langle 0|TD^*^{\mu}(x)D^{*\nu\dagger}(y)|0 \rangle = \int \frac{d^4k}{(2\pi)^4} e^{-ik\cdot(x-y)}S_{D^*}^{\mu\nu}(k), \quad S_{D^*}^{\mu\nu}(k) = -g^{\mu\nu} + k^\mu k^\nu/m_{D^*}^2 \]  

(12)

for vector \( D^* \) mesons.

The decay widths of the strong two–body transitions \( \Sigma_c \to \Lambda_c + \pi \) are then calculated according to the following expressions for the different spin–parity assignments \( \Sigma_c[J^P] \):

\[ \Gamma(\Sigma_c[1/2^+] \to \Lambda_c + \pi) = \frac{\delta_{\Sigma_c\Lambda_c\pi}^2}{16\pi m_{\Sigma_c}^3} \lambda^{1/2}(m_{\Sigma_c}^2, m_{\Lambda_c}^2, m_{\pi}^2)(m_{\Sigma_c} - m_{\Lambda_c})^2 - m_{\pi}^2, \]  

(13a)

\[ \Gamma(\Sigma_c[1/2^-] \to \Lambda_c + \pi) = \frac{\bar{h}_{\Sigma_c\Lambda_c\pi}^2}{16\pi m_{\Sigma_c}^3} \lambda^{1/2}(m_{\Sigma_c}^2, m_{\Lambda_c}^2, m_{\pi}^2)(m_{\Sigma_c} + m_{\Lambda_c})^2 - m_{\pi}^2, \]  

(13b)

\[ \Gamma(\Sigma_c[3/2^+] \to \Lambda_c + \pi) = \frac{f_{\Sigma_c\Lambda_c\pi}^2}{192\pi m_{\Sigma_c}^3} \lambda^{3/2}(m_{\Sigma_c}^2, m_{\Lambda_c}^2, m_{\pi}^2)(m_{\Sigma_c} - m_{\Lambda_c})^2 - m_{\pi}^2, \]  

(13c)

\[ \Gamma(\Sigma_c[3/2^-] \to \Lambda_c + \pi) = \frac{g_{\Sigma_c\Lambda_c\pi}^2}{192\pi m_{\Sigma_c}^3} \lambda^{3/2}(m_{\Sigma_c}^2, m_{\Lambda_c}^2, m_{\pi}^2)(m_{\Sigma_c} + m_{\Lambda_c})^2 - m_{\pi}^2, \]  

(13d)

Table I. Coupling constants \( g_{\Sigma_c^+} \) for different \( J^P \) assignments.

| \( J^P = 1/2^+ \) | \( J^P = 1/2^- \) | \( J^P = 3/2^+ \) | \( J^P = 3/2^- \) |
|-----------|-----------|-----------|-----------|
| 7 ± 1.9   | 0.6 ± 0.2 | 4.2 ± 1.4 GeV⁻¹ | 35.3 ± 1.8 GeV⁻¹ |
Table II. Effective couplings $d_{\Sigma_c \Lambda_c \pi}$, $h_{\Sigma_c \Lambda_c \pi}$, $f_{\Sigma_c \Lambda_c \pi}$ and $g_{\Sigma_c \Lambda_c \pi}$.
Error reflects variation in $\Lambda$ from 0.75 to 1.25 GeV.

| Mode | $d_{\Sigma_c \Lambda_c \pi}$ | $h_{\Sigma_c \Lambda_c \pi}$ | $f_{\Sigma_c \Lambda_c \pi}$ | $g_{\Sigma_c \Lambda_c \pi}$ |
|------|-----------------|-----------------|-----------------|-----------------|
| $\Sigma_c^{++} \rightarrow \Lambda_c^+ \pi^+$ | $-8.15 \pm 2.72$ | $1.63 \pm 0.54$ | $1.95 \pm 0.97$ GeV$^{-1}$ | $-3.35 \pm 1.61$ GeV$^{-1}$ |
| $\Sigma_c^+ \rightarrow \Lambda_c^0 \pi^0$ | $-7.78 \pm 2.60$ | $1.48 \pm 0.47$ | $1.90 \pm 0.95$ GeV$^{-1}$ | $-3.24 \pm 1.59$ GeV$^{-1}$ |
| $\Sigma_c^0 \rightarrow \Lambda_c^- \pi^-$ | $-7.52 \pm 2.54$ | $1.43 \pm 0.45$ | $1.87 \pm 0.94$ GeV$^{-1}$ | $-3.16 \pm 1.58$ GeV$^{-1}$ |

Table III. $\Sigma_c \rightarrow \Lambda_c \pi$ decay widths (in MeV) for different spin–parity assignments of the $\Sigma_c$.
Error reflects variation in $\Lambda$ from 0.75 to 1.25 GeV. Results for preferred value of $\Lambda = 1$ GeV are given in brackets.

| Mode | $J^P = \frac{1}{2}^+$ | $J^P = \frac{3}{2}^-$ | $J^P = \frac{1}{2}^+$ | $J^P = \frac{3}{2}^-$ |
|------|-----------------|-----------------|-----------------|-----------------|
| $\Sigma_c^{++} \rightarrow \Lambda_c^+ \pi^+$ | $41.1 \pm 24.7$ | $173.6 \pm 103.6$ | $0.176 \pm 0.140$ | $0.141$ |
| $\Sigma_c^+ \rightarrow \Lambda_c^0 \pi^0$ | $37.6 \pm 22.6$ | $142.3 \pm 82.1$ | $0.171 \pm 0.137$ | $0.137$ |
| $\Sigma_c^0 \rightarrow \Lambda_c^- \pi^-$ | $35.1 \pm 21.3$ | $132.3 \pm 75.8$ | $0.164 \pm 0.132$ | $0.131$ |

where $\lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2xz$ is the Källen function; $m_{\Sigma_c}$, $m_{\Lambda_c}$ and $m_\pi$ are the masses of $\Sigma_c$, $\Lambda_c$ baryons and the pion. We also introduce the effective coupling constants $d_{\Sigma_c \Lambda_c \pi}$, $h_{\Sigma_c \Lambda_c \pi}$, $f_{\Sigma_c \Lambda_c \pi}$ and $g_{\Sigma_c \Lambda_c \pi}$ defining the interaction of the $\Sigma_c$ of definite spin–parity with $\Lambda_c$ and $\pi$ as a result of the processes in Fig. 2 with:

$$\mathcal{L}_{\Sigma_c(1/2^+)} = \frac{d_{\Sigma_c \Lambda_c \pi}}{\Lambda_c} \gamma_5 \pi \Sigma_c + \text{H.c.},$$

$$\mathcal{L}_{\Sigma_c(1/2^-)} = \frac{h_{\Sigma_c \Lambda_c \pi}}{\Lambda_c} \pi \Sigma_c + \text{H.c.},$$

$$\mathcal{L}_{\Sigma_c(3/2^+)} = \frac{f_{\Sigma_c \Lambda_c \pi}}{\Lambda_c} \partial_\mu \pi \Sigma_c^\mu + \text{H.c.},$$

$$\mathcal{L}_{\Sigma_c(3/2^-)} = \frac{g_{\Sigma_c \Lambda_c \pi}}{\Lambda_c} \gamma_5 \partial_\mu \pi \Sigma_c^\mu + \text{H.c.}.$$ (14a, 14b, 14c, 14d)

In Table II we present our results for these effective couplings $d_{\Sigma_c \Lambda_c \pi}$, $h_{\Sigma_c \Lambda_c \pi}$, $f_{\Sigma_c \Lambda_c \pi}$ and $g_{\Sigma_c \Lambda_c \pi}$ including a variation of the cutoff parameter from 0.75 to 1.25 GeV.

Our final numerical results for the decay widths are summarized in Table III. For the $\Sigma_c$ masses we use the measured values [1] of the Belle Collaboration. The predictions for the decay widths differ sizably depending on the $J^P$ assignment for the $\Sigma_c(2800)$. These predictions are to be compared to the measured total widths of the $\Sigma_c(2800)$ baryons [12] with:

$$\Gamma(\Sigma_c^{++}) = 75^{+18+12}_{-13-11} \text{ MeV},$$

$$\Gamma(\Sigma_c^+) = 62^{+37+52}_{-23-38} \text{ MeV},$$

$$\Gamma(\Sigma_c^0) = 61^{+18+22}_{-13-13} \text{ MeV}.$$ (15)

Since the observed $\Lambda_c \pi$ decay modes of the $\Sigma_c(2800)$ states are assumed to be dominant present results favor, at least in the context of the $ND$ molecule interpretation, either the $J^P = 1/2^+$ or the $J^P = 3/2^-$ assignment. Note, the $J^P = 3/2^-$ assignment was originally assumed by the Belle Collaboration [1]. The alternative scenario for $\Sigma_c$ with $J^P = 3/2^+$ is clearly excluded by the predictions of Table III. For small values of the dimensional parameter $\Lambda$ the scenario for $\Sigma_c$ with $J^P = 1/2^-$ becomes compatible with data.

In conclusion, we estimated the strong $\Lambda_c \pi$ decays of the $\Sigma_c(2800)$ baryon for different spin–parity assignments assuming a dominant molecular $ND$ structure of this state. Judging from the decay widths of the order of 40 MeV we find that the original scenario where the $\Sigma_c$ has spin–parity $J^P = \frac{3}{2}^-$ is excluded by the data. The option $J^P = \frac{3}{2}^+$ leads to strongly suppressed partial decay widths of the order of a hundred keV, while $J^P = \frac{1}{2}^+$ leads to enhanced partial decay widths and only becomes compatible with data for relatively small values of the $\Lambda$ parameter. Although weak binding in the $ND$ system for $J^P = 1/2^+$ and $J^P = 3/2^-$ remains to be studied, present evaluation of the $\Lambda_c \pi$ decay widths point to a possibly sizable role of the $ND$ configuration in the $\Sigma_c(2800)$. 
Appendix A: Matching of the phenomenological SU(3) and SU(4) $PBB$ and $VBB$ interaction Lagrangians

First we consider the $PBB$ interaction that is the coupling of a pseudoscalar ($P$) meson to two baryons ($BB$). In flavor SU(3) the couplings are generated from the $O(p)$ term of chiral perturbation theory (ChPT) \[27\] describing the coupling of baryon fields with the chiral fields:

$$\mathcal{L}_{PBB}^{SU_3} = \frac{D}{F_P \sqrt{2}}(m_B + m_P)\text{tr}(\bar{B}i\gamma^5PB) - \frac{F}{F_P \sqrt{2}}(m_B + m_P)\text{tr}(\bar{B}i\gamma^5PB).$$  \hspace{1cm} (A1)

Here $F_P = F_\pi = 92.4$ MeV is the leptonic decay constant; $D$ and $F$ are the baryon axial coupling constants (we restrict to the SU(3) symmetric limit, where $D = 3F/2 = 3g_A/5$ with $g_A = 1.2695$ being the nucleon axial charge) the symbols $\text{tr}$, $\{\ldots\}$ and $[\ldots]$ denote the trace over flavor matrices, anticommutator and commutator, respectively. We replace the pseudoscalar coupling by the pseudoscalar one considering on-mass-shell baryons. The SU(3) baryon $B$ and pseudoscalar meson $P$ matrices read as:

$$B = \begin{pmatrix}
\Sigma^0/\sqrt{2} + \Lambda/\sqrt{6} & \Sigma^+ & p \\
\Sigma^- & -\Sigma^0/\sqrt{2} + \Lambda/\sqrt{6} & n \\
\Xi^- & \Xi^0 & -2\Lambda/\sqrt{6}
\end{pmatrix},$$  \hspace{1cm} (A2)

$$P = \begin{pmatrix}
\pi^0/\sqrt{2} + \eta/\sqrt{6} & \pi^+ & K^+ \\
\pi^- & -\pi^0/\sqrt{2} + \eta/\sqrt{6} & K^0 \\
K^- & K^0 & -2\eta/\sqrt{6}
\end{pmatrix}.$$  \hspace{1cm} (A3)

The SU(4) $PBB$ Lagrangian is given by \[28\]:

$$\mathcal{L}_{PBB}^{SU_4} = g_1 \bar{B}^{kmn} i\gamma_5 P^l_k B_{lmn} + g_2 \bar{B}^{kmn} i\gamma_5 P^l_k B_{lmn},$$  \hspace{1cm} (A4)

where the indices $l, m, n$ of the tensor $B_{lmn}$ run from 1 to 4, representing the 20–plet of baryons (see details in Refs. \[28\]); $P^l_k$ is the matrix representing the 15–plet of pseudoscalar fields. The baryon tensor satisfies the conditions

$$B_{lmn} + B_{mnl} + B_{nml} = 0,$$  \hspace{1cm} (A5)

The full list of physical states in terms of SU(4) tensors is given in Ref. \[28\]. Here we only display a few of them:

$$p = B_{112} = -2B_{121} = -2B_{211}, \quad n = -B_{221} = 2B_{212} = 2B_{122},$$
$$\Sigma^{++} = B_{114} = -2B_{141} = -2B_{411}, \quad \Sigma^0 = -B_{224} = 2B_{242} = 2B_{422},$$
$$\pi^+ = P^1_2, \quad \pi^- = P^2_1, \quad D^0 = P^4_1, \quad D^{++} = V^2_1, \quad D^{*0} = V^4_1.$$

(E6)

Evaluating the $\pi NN$ couplings in both versions we fix the SU(4) couplings $g_1$ and $g_2$ as (in the SU(3) Lagrangian we restrict to the mass degenerate case $m_B = m_P = 938.27$ MeV):

$$g_{\pi NN} = g_1 - \frac{5}{4}g_2, \quad g_{\pi NN} \frac{D - F}{D + F} = -\frac{g_1 + g_2}{4\sqrt{2}}.$$  \hspace{1cm} (A7)

Considering the SU(3) symmetric ratio of $F$ and $D$ couplings $F/D = 2/3$ we get

$$g_1 = 0, \quad g_2 = -\frac{4}{5}\sqrt{2}g_{\pi NN}.$$  \hspace{1cm} (A8)
Finally the $g_{DN\Lambda_c}$ coupling is fixed as

$$g_{DN\Lambda_c} = -g_{\pi NN}.$$  \hfill (A9)

In complete analogy we fix the vector meson $V_{BB}$ couplings. The SU(3) $V_{BB}$ Lagrangian can be expressed in terms of the $\rho NN$ coupling constant as:

$$L_{SU^3 V_{BB}} = g_{\rho NN} \frac{1}{\sqrt{2}} \text{tr} \left( \overline{B} \gamma^\mu \{V_\mu B \} \right) + g_{\rho NN} \frac{1}{\sqrt{2}} \text{tr} \left( \overline{B} \gamma^\mu B \right) \text{tr} V_\mu$$  \hfill (A10)

where

$$V = \begin{pmatrix} \rho^0 / \sqrt{2} + \omega / \sqrt{2} & \rho^+ & K^{*+} \\ \rho^- & -\rho^0 / \sqrt{2} + \omega / \sqrt{2} & K^{*0} \\ K^{-} & K^{0} & -\phi \end{pmatrix}.$$  \hfill (A11)

The SU(4) $V_{BB}$ Lagrangian is given by \cite{28}:

$$L_{SU^4 V_{BB}} = h_1 \overline{B}_{kmn} \gamma^\mu V_{l\mu,k} B_{lmn} + h_2 \overline{B}_{kmn} \gamma^\mu V_{l\mu,k} B_{lnm}.$$  \hfill (A12)

Evaluating the $\rho NN$ couplings in both versions we fix the SU(4) couplings $h_1$ and $h_2$ as:

$$h_1 = 2h_2 = \frac{8}{3\sqrt{2}} g_{\rho NN}.$$  \hfill (A13)

Finally, the $D^* N\Lambda_c$ coupling is fixed as

$$g_{D^* N\Lambda_c} = -\sqrt{3} \frac{1}{2} g_{\rho NN}.$$  \hfill (A14)

where for the $g_{\rho NN}$ coupling we take the SU(3) prediction of $g_{\rho NN} = 6$.

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