Eur. Phys. J. C 51, 883–889 (2007)
DOI 10.1140/epjc/s10052-007-0347-y

THE EUROPEAN
PHYSICAL JOURNAL C

Regular Article – Theoretical Physics

$\Lambda_c(2940)^+$: a possible molecular state?

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Received: 11 February 2007 / Revised version: 29 May 2007 /
Published online: 13 July 2007 –

Abstract. A new baryonic state $\Lambda_c(2940)^+$ has recently been discovered by the Babar collaboration in the D^0p channel. Later Belle collaboration also observed this state in the $\Sigma_c(2455)^{0,++}\pi^\pm \to \Lambda_c^+\pi^+\pi^-$ channel. The mass of $\Lambda_c(2940)^+$ is just a few MeV below the sum of D^{*0} and p masses suggesting a possibility that this state may be a $D^{*0}p$ molecular state. In this paper we study whether such a molecular state can be consistent with data. We find that the molecular structure can explain data and that if $\Lambda_c(2940)^+$ is a $D^{*0}p$ molecular state it is likely a $1/2^-$ state. Several other decays modes are also suggested to further test the molecular structure of $\Lambda_c^+(2940)$.

PACS. 13.30.Eg; 14.20.Lg; 12.39.Pn

1 Introduction

Very recently, the Babar collaboration announced that a new charmed baryonic state $\Lambda_c(2940)^+$ has been observed in the mass spectrum of D^0p [1]. Its mass and width are, respectively,

$$m = 2939.8 \pm 1.3(\text{stat.}) \pm 1.0(\text{syst.})\ \text{MeV/c}^2$$

and

$$\Gamma = 17.5 \pm 5.2(\text{stat.}) \pm 5.9(\text{syst.})\ \text{MeV}\,.$$

Its spin and parity have not been determined by experimental measurement yet. Another charmed baryonic state, $\Lambda_c(2880)^+$, is also observed in the D^0p spectrum by the Babar collaboration. The state $\Lambda_c(2880)^+$ had already been observed before by the CLEO collaboration in the mass spectrum of $\Lambda_c^+\pi^+\pi^-$ [2] and the Belle collaboration has recently also observed $\Lambda_c(2940)^+$ in $\Lambda_c^+\pi^+\pi^-$ channel via $\Lambda_c(2940)^+ \to \Sigma_c(2455)^{0,++}\pi^\pm \to \Lambda_c^+\pi^+\pi^-$ [3].

As commonly believed, $\Lambda_c(2880)^+$ can be categorized as an excited charmed baryon [4–6]. It has large branching ratios into both D^0p and $\Lambda_c^+\pi^+\pi^-$ decay modes which can be realized via a subsequent process as shown in Fig. 1. The new $\Lambda_c(2940)^+$ might also be an excited state, but the sum of the masses of D^{*0} and p, ($m_{D^{*0}} + m_p = 2945$ MeV), is so close to the required 2940 MeV makes it very tempting to view it as a $D^{*0}p$ molecular state. The slight excess energy above the central value of $\Lambda_c(2940)^+$ mass can be attributed to the binding energy of the two constituents. If indeed $\Lambda_c(2940)$ is a molecular state, the decay pattern may be different. In the following we study if a $D^{*0}p$ molecular state is consistent with data.

2 $D^{*0}p$ molecular states

There is an abundant spectrum in charm-tau energy range, some of the charmed states are very close to each other in masses; their peaks even overlap. Some of them may be molecular states. The picture of molecular states was first proposed to interpret the behaviors of scalar mesons $f_0(980)$ and $a_0(980)$, which could be $K\bar{K}$ molecules [7–12]. This idea has now been widely adopted for explaining some experimental data. Rujula, Geogi and Glashow suggested that $\psi(4040)$ is a $D^*\bar{D}^*$ molecular state [13], Rosner and Tuan also studied the so-called C-exotic states [7–9]. In a recent work, it was suggested that $Y(4260)$ is a $\chi_c - \rho^0$ [14] or $\chi_c - \omega$ [15] molecule. For the dynamics, Okun and Volosin studied the interaction between charmed mesons and molecular states involving charmed quarks [16]. Following the previous studies it is not unrealistic to consider $\Lambda_c(2940)^+$ as a molecular state.

An immediate question one needs to answer, if interpreting $\Lambda_c(2940)^+$ as a $D^{*0}p$ molecular state, is that whether the correct binding energy of about 5 MeV can be realized. We find that one particle exchange model can indeed achieve this. In this model one deduces the effective potential of $D^{*0}p$ system by using the linear σ model [17]. Following the standard procedures [18], we calculated the transition matrix element of the elastic scattering $D^{*0} + p \to D^{*0} + p$ in the momentum space by regular quantum field theory method. Then setting $q_0 = 0$ where q^0 is the 0-th component of the momentum of the exchanged hadrons which pos-

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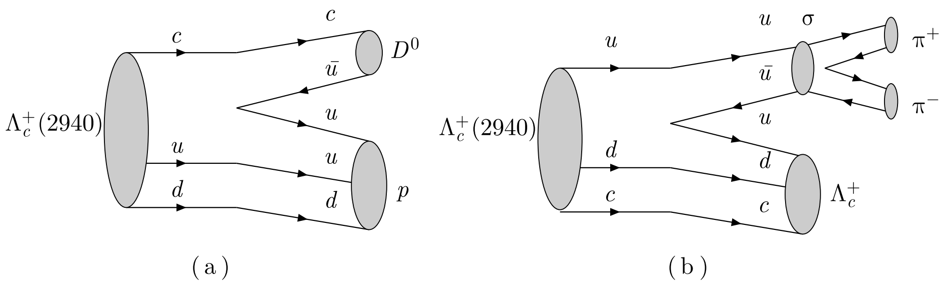

Fig. 1. Decays of excited charmed baryon Λ_c^+ to (**a**) D^0p, and (**b**) $\Lambda_c^+\pi^+\pi^-$

Table 1. The binding energies and the masses correspond to S-wave $D^{*0}p$ systems with spin 1/2 and spin 3/2, respectively

For case (**a**) $1/2^-$	For case (**b**) $3/2^-$
$\Lambda = 0.85 \sim 0.89$ GeV	$\Lambda = 0.90 \sim 0.95$ GeV
$E_{D^{*0}p} = -7.2 \sim -2.9$ MeV	$E_{D^{*0}p} = -7.4 \sim -3.6$ MeV
$m_{D^{*0}p} = 2.938 \sim 2.942$ GeV	$m_{D^{*0}p} = 2.938 \sim 2.941$ GeV

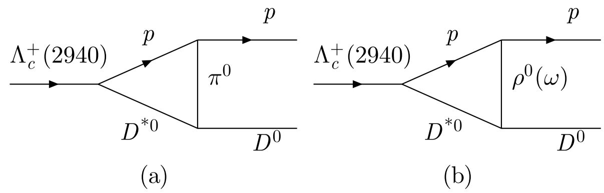

Fig. 2. The decay of $\Lambda_c(2940)^+ \to pD^0$ by intermediate states $D^{*0}p$. Here $D^{*0}p \to D^0p$ with exchanged mesons π^0 and $\rho^0(\omega)$

sess appropriate quantum numbers, we carry out a Fourier transformation from the momentum space to the configuration space to obtain the potential. This is the effective potential between the constituents D^{*0} and p. Substituting this effective potential into the Schrödinger equation, one can obtain the wave function and eigenenergy, which is identified to be the binding energy of the molecular state.

We have carried out a calculation similar to that in [17] by taking exchanges of π, ω and ρ mesons as the leading interaction of D^{*0} and p, which eventually binds D^{*0} and p into a molecular state, to obtain the binding energy. In the derivation of the effective interaction in the momentum space, to compensate the off-shell effects for the exchanging mesons, one usually phenomenologically introduces a form factor at each effective vertex. A commonly used form factor is taken as [19, 20] $(\Lambda^2 - M_m^2)/(\Lambda^2 - q^2)$, which we also use in this work. Here Λ is a phenomenological parameter whose value is near 1 GeV [21], and q is the four-momentum of the exchanged meson.

Since the spin of $\Lambda_c(2940)^+$ is not determined by experiment yet, we consider two possible cases for the spin of $\Lambda_c(2940)^+$ in the S-wave state. In this case one obtains two J^P states: (a) $1/2^-$, and (b) $3/2^-$. We display the allowed ranges for the masses of the molecular states and their binding energies in Table 1. We see that the binding energies are in the right ranges. From the spectrum we cannot distinguish whether the spin is 1/2 or 3/2. Adjusting parameters in the form factors, we find that P-wave states with the right binding energy are also possible. In that case one would have $1/2^+$ and $3/2^+$ states. To get more information, one needs to invoke the decay rates measured recently by the Babar and Belle collaborations.

3 $\Lambda_c(2940)^+ \to D^0p, \Lambda_c^+\pi^+\pi^-$

To have more information about the $D^{*0}p$ molecular state, we now consider the decay of this state to D^0p and $\Lambda_c^+\pi^+\pi^-$. Since $\Lambda_c(2940)^+$ is just below the threshold of $D^{*0}p$, it can fall apart into $D^{*0}p$ through threshold effects due to finite width. More specifically, we assume that the dominant decays of $\Lambda_c(2940)^+$ occur via two steps shown in Fig. 2 (3, 4). The molecular state $\Lambda_c(2940)^+$ first dissolves into D^{*0} and p due to the threshold effect, that is, the finite width of $\Lambda_c^+(2940)$ about 20 MeV allows on-shell final D^* and p with small three momenta. Thus D^{*0} and p are treated as on-mass-shell real particles, and then D^{*0} and p re-scatter into D^0p or $\Lambda_c^+\pi^+\pi^-$ by exchanging intermediate states. If $\Lambda_c(2940)^+$ is a $1/2^+$ or $3/2^+$ state, it must be a P-wave molecule of D^* and p, and its dissociation into D^*p (or derivative of the wave function $\Psi'(0)$) is further suppressed by small three momentum. Thus the transition rate would be very small. In this picture, $\Lambda_c(2940)^+$ is disfavored to be P-wave or higher wave bound states. We then left with S-wave $1/2^-$ and $3/2^-$ to study.

We now proceed to calculate $\Lambda_c(2940)^+ \to D^0p$ and $\Lambda_c(2940)^+ \to \Lambda_c^+\pi^+\pi^-$ decays by the diagrams in Fig. 2 (3, 4) with on-shell D^{*0} and p, and then D^{*0} and p re-scatter in to the desired final states. For the $\Lambda_c(2940)^+$ coupling to D^{*0} and p, we write as [23]

$$L_{\text{bound}} = g_{ND^{*0}\Lambda_c^+(2940)} \bar{N} A_\mu \epsilon^\mu_{D^{*0}} , \tag{1}$$

and

$$A_\mu = \begin{cases} \gamma_\mu\gamma^5\Lambda_c(2940)^+, J^P(2940) = \frac{1}{2}^- , \\ \Lambda_{c\mu}^+(2940), \qquad J^P(2940) = \frac{3}{2}^- , \end{cases}$$

where $\Lambda_{c\mu}^+$ is the Rarita–Schwinger vector-spinor for a spin-3/2 particle. For $\Lambda_c^+(2940)$ to be $1/2^-$ and $3/2^-$, A_μ are given by: $\gamma_\mu\Lambda_c^+(2940)$ and $\gamma^5\Lambda_{c\mu}^+(2940)$, respectively. In the above $g_{ND^*\Lambda_c^+(2940)}$ parameterizes the bound state effect which is not known. Since we will be concerned with relative strength of $\Lambda_c^+(2940) \to D^0p$ and $\Lambda_c^+(2940) \to \Lambda_c^+\pi^+\pi^-$, the specific value of $g_{ND^*\Lambda_c^+(2940)}$ is not important for our purpose.

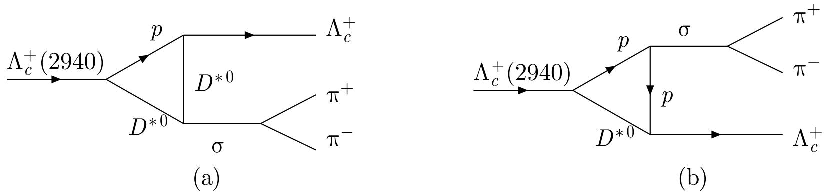

Fig. 3. The decay of $\Lambda_c(2940)^+ \to \Lambda_c^+\pi^+\pi^-$ by intermediate states pD^{*0}. Here $D^{*0}p \to D^0 p$ with exchanged mesons D^{*0} and p

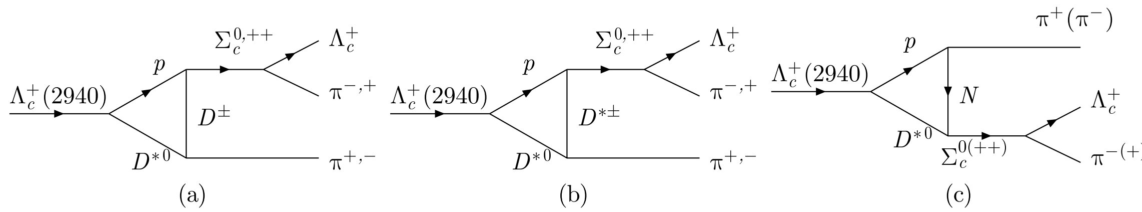

Fig. 4. The decay of $\Lambda_c(2940)^+ \to \Lambda_c^+\pi^+\pi^-$ by intermediate states pD^{*0}. Here $D^{*0}p \to D^0 p$ with exchanged mesons $D^{*\pm}$ and N

For the couplings of the other vertices in Fig. 2 (3, 4), we write the relevant Lagrangian as

$$
\begin{aligned}
L = {} & g_{NN\pi}\bar{\psi}(\sigma + i\gamma_5\tau\cdot\pi)\psi + g_{NN\rho}\bar{\psi}\gamma_\mu\tau\psi\cdot\rho^\mu \\
& + g_{VV\pi}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu V_\nu^\dagger\tau\partial_\alpha V_\beta\cdot\pi \\
& + g_{VV\sigma}\left[\partial^\mu V^{\dagger\nu}\partial_\mu V_\nu - \partial^\mu V^{\dagger\nu}\partial_\nu V_\mu\right]\sigma \\
& + g_{VV\rho}\left[\left(\partial_\mu V^{\dagger\nu}\tau V_\nu - \partial^\nu V_\mu^\dagger\tau V_\nu\right)\cdot\rho^\mu\right. \\
& + \left(V^{\dagger\nu}\tau\cdot\partial_\mu\rho_\nu - \partial_\mu V^{\dagger\nu}\tau\cdot\rho\right)V^\mu \\
& \left. + V^{\dagger\mu}(\tau\cdot\rho\partial_\mu V_\nu - \tau\cdot\partial_\mu\rho V_\nu)\right] \\
& + \left[g_{VP\pi}V^{\dagger\mu}\tau\cdot(P\partial_\mu\pi - \partial_\mu P\pi) + \text{h.c.}\right] \\
& + g_{VP\rho}\varepsilon^{\mu\nu\alpha\beta}\left[\partial_\mu\rho_\nu\partial_\alpha V_\beta^\dagger\cdot\tau P + \partial_\mu V_\nu^\dagger\tau\cdot\partial_\alpha\rho_\beta P\right] \\
& + g_{ND^*\Lambda_c^+(2285)}\bar{N}\gamma_\mu\Lambda_c^+(2285)D^{*\mu} \\
& + g_{\Sigma_c^+(2455)D^*N}\bar{N}\gamma_\mu\Sigma_c^+(2455)D^{*\mu} \\
& + g_{\Sigma_c^+(2520)D^*N}\bar{N}\gamma_5\Sigma_c^{+\mu}(2520)D^{*\mu} \\
& + g_{\Sigma_c^+(2455)DN}\bar{N}\gamma_5\Sigma_c^+(2455)D \\
& + \frac{g_{\Sigma_c^+(2520)DN}}{m_D}\bar{\Sigma}_c^{+\mu}(2520)N(\partial_\mu D)\,,
\end{aligned}
\tag{2}
$$

where P, V are pseudoscalar and vector mesons D, D^*. The known couplings are given by $g_{NN\pi} = 13.5$, $g_{NN\rho} = 3.25$, $g_{D^*D^*\rho} = 2.9$, $g_{D^*D\pi} = 18$, $g_{D^*D\rho} = 4.71\,\text{GeV}^{-1}$ and $g_{D^*D^*\pi} = g_{D^*D^*\sigma} = 3.5$ [17, 22]. The values of the couplings $g_{ND^*\Lambda_c^+(2285)}$, $g_{ND\Sigma_c(2455)}$, $g_{ND^*\Sigma_c(2455)}$, $g_{ND\Sigma_c(2520)}$ and $g_{ND^*\Sigma_c(2520)}$ are not known. We keep them here and discuss their effects later.

From the above effective Lagrangian, we can construct decay amplitudes for $\Lambda_c^+(2940) \to D^0p, \Lambda_c^+\pi^+\pi^-$ through the triangle diagrams shown in Fig. 2 (3, 4). These amplitudes are given in the Appendix.

Once the decay amplitudes are obtained, the partial decay width can be derived. We give three typical examples in the following

$$
\begin{aligned}
& \Gamma\left(\Lambda_c(2940)^+ \to D^0p\right) \\
& = \frac{1}{2M}\int\frac{\mathrm{d}^3P_{D^0}}{(2\pi)^3}\frac{1}{2E_{D^0}}\frac{\mathrm{d}^3P_p}{(2\pi)^3}\frac{2m_p}{2E_p}(2\pi)^4\delta^4 \\
& \times(M - P_{D^0} - P_p) \\
& \times\left|\mathcal{M}\left(\Lambda_c(2940)^+ \to D^0p\right)\right|^2, \\
& \Gamma(\Lambda_c(2940)^+ \to \Lambda_c^+\sigma \to \Lambda_c^+\pi^+\pi^-)_\sigma \\
& = \frac{1}{2M}\int\frac{\mathrm{d}^3P_{\Lambda_c^+}}{(2\pi)^3}\frac{2m_{\Lambda_c^+}}{2E_{\Lambda_c^+}}\frac{\mathrm{d}^3P_\sigma}{(2\pi)^3}\frac{1}{2E_\sigma}(2\pi)^4\delta^4 \\
& \times(M - P_{\Lambda_c^+} - P_\sigma) \\
& \times\left|\mathcal{M}\left(\Lambda_c(2940)^+ \to \Lambda_c^+\sigma\right)\right|^2 \times B(\sigma \to \pi^+\pi^-), \\
& \Gamma(\Lambda_c(2940)^+ \to \Sigma_c\pi \to \Lambda_c^+\pi^+\pi^-)_{\Sigma_c} \\
& = \frac{1}{2M}\int\frac{\mathrm{d}^3P_{\Sigma_c}}{(2\pi)^3}\frac{2m_{\Sigma_c}}{2E_{\Sigma_c}}\frac{\mathrm{d}^3P_\pi}{(2\pi)^3}\frac{1}{2E_\pi}(2\pi)^4\delta^4 \\
& \times(M - P_{\Sigma_c} - P_\pi) \\
& \times\left|\mathcal{M}\left(\Lambda_c(2940)^+ \to \Sigma_c\pi\right)\right|^2 \times B\left(\Sigma_c \to \Lambda_c^+\pi\right)\,.
\end{aligned}
$$

Numerically the branching ratio $B(\sigma \to \pi^+\pi^-)$ is about 0.6∼ 0.7 and the branching radio $B(\Sigma_c \to \Lambda_c^+\pi)$ is about 1. [24]. Note that since $g_{ND^*\Lambda_c^+(2940)}$ is not known, we will not be able to obtain the absolute value. However, we can obtain the relative strength of each diagram which can still give information about the decay pattern of $\Lambda_c^+(2940)$.

4 Results and discussions

We now discuss contributions from each diagram to $\Lambda_c^+(2940) \to D^0p$ and $\Lambda_c^+(2940) \to \Lambda_c^+\pi^+\pi^-$. Here we have omitted (and will omit) to indicate the intermediate stage D^*p in the decay chain. Since the spin of $\Lambda_c(2940)^+$ has not been determined, we discuss both $J^P = 1/2^-$ and $J^P = 3/2^-$.

(1) $J^P(\Lambda_c^+) = \frac{1}{2}^-$.

For $\mathcal{M}(\Lambda_c(2940)^+ \to D^0 p)$ with π and ρ^0 exchange, we have

$$|\mathcal{M}(\Lambda_c(2940)^+ \to D^0 p)_{\pi^0}|^2 : |\mathcal{M}(\Lambda_c(2940)^+ \to D^0 p)_{\rho^0}|^2 = 1.0 \times 10^3 : 1 .$$

Since the $\Lambda_c^+(2940)$ wave function is not known (in our notation the coupling $g_{ND^*\Lambda_c^+(2940)}$ is not known), it is not possible to calculate the absolute value for each of the partial decay width. However, we are able to obtain the relative widths which can also provide us with useful information. For convenience of discussion, in the above we have normalized $|\mathcal{M}(\Lambda_c(2940)^+ \to D^0 p)_{\rho^0}|^2 = 1$. The matrix element squared listed below are all evaluated according to the same normalization.

The contribution to the amplitude from ω exchange is close to that from ρ exchange, that is, $\mathcal{M}(\Lambda_c(2940)^+ \to D^0 p)_{\rho^0} \simeq \mathcal{M}(\Lambda_c(2940)^+ \to D^0 p)_\omega$. So when we consider the decay of $\mathcal{M}(\Lambda_c(2940)^+ \to D^0 p)$, we can almost ignore the influence of ρ and ω exchange and consider π^0 exchange only.

For $\mathcal{M}(\Lambda_c^+(2940) \to \Lambda_c^+\pi^+\pi^-)$, we have considered several contributions coming from $\Lambda_c(2940)^+ \to \Lambda_c^+\sigma \to \Lambda_c^+\pi^+\pi^-$, $\Lambda_c^+(2940) \to \Sigma_c(2455)\pi \to \Lambda_c^+\pi^+\pi^-$ and $\Lambda_c^+(2940) \to \Sigma_c(2520)\pi \to \Lambda_c^+\pi^+\pi^-$ with exchanges of different intermediate states in various triangle diagrams. For $\mathcal{M}(\Lambda_c(2940)^+ \to \Lambda_c^+\sigma \to \Lambda_c^+\pi^+\pi^-)$, we have

$$\left|\mathcal{M}\left(\Lambda_c(2940)^+ \to \Lambda_c^+\sigma\right)_{D^*}\right|^2 : \left|\mathcal{M}\left(\Lambda_c(2940)^+ \to \Lambda_c^+\sigma\right)_N\right|^2 = 2.0 \times 10^{-4} : 0.015 .$$

In this case N exchange is more important. The resulting branching ratio for $\Lambda_c^+(2940) \to \Lambda_c^+\pi^+\pi^-$ will be much smaller than that for $\Lambda_c^+(2940) \to D^0 p$.

For $\mathcal{M}(\Lambda_c^+(2940) \to \Sigma_c(2455)\pi \to \Lambda_c^+\pi^+\pi^-)$, we have

$$\begin{aligned} &\left|\mathcal{M}\left(\Lambda_c(2940)^+ \to \Sigma_c(2455)\pi\right)_D\right|^2 \\ &: \left|\mathcal{M}\left(\Lambda_c(2940)^+ \to \Sigma_c(2455)\pi\right)_{D^*}\right|^2 \\ &: \left|\mathcal{M}\left(\Lambda_c(2940)^+ \to \Sigma_c(2455)\pi\right)_N\right|^2 \\ &= 0.02 g^2_{ND\Sigma_c^+(2455)} : 1.5 \times 10^{-3} g^2_{ND^*\Sigma_c^+(2455)} \\ &: 9.3 g^2_{ND^*\Sigma_c^+(2455)} . \end{aligned}$$

Since the couplings are not determined, the numbers cannot be determined. If the couplings are similar in order of magnitude, the N exchange is most likely to dominate. We will come back to discuss this later.

For $\mathcal{M}(\Lambda_c^+(2940) \to \Sigma_c(2520)\pi \to \Lambda_c^+\pi^+\pi^-)$, we have

$$\begin{aligned} &\left|\mathcal{M}\left(\Lambda_c(2940)^+ \to \Sigma_c(2520)\pi\right)_D\right|^2 \\ &: \left|\mathcal{M}\left(\Lambda_c(2940)^+ \to \Sigma_c(2520)\pi\right)_{D^{*0}}\right|^2 \\ &: \left|\mathcal{M}\left(\Lambda_c(2940)^+ \to \Sigma_c(2520)\pi\right)_N\right|^2 \\ &= 4.2 \times 10^{-2} g^2_{ND\Sigma_c^+(2520)} : 1.8 \times 10^{-4} g^2_{ND^*\Sigma_c^+(2520)} \\ &: 9.4 \times 10^{-5} g^2_{ND^*\Sigma_c^+(2520)} . \end{aligned}$$

Here D exchange is most likely to dominate.

Collecting the above results, we obtain the leading contributions to the radio of $B(\Lambda_c(2940)^+ \to D^0 p)$ and $B(\Lambda_c^+(2940) \to \Lambda_c^+\pi^+\pi^-)$,

$$\begin{aligned} &B\left(\Lambda_c(2940)^+ \to D^0 p\right) : B\left(\Lambda_c(2940)^+ \to \Lambda_c^+\pi^+\pi^-\right) \\ &= 429 : \Big(5.0 \times 10^{-3} g^2_{ND^*\Lambda_c^+(2285)} + 4.0 g^2_{ND^*\Sigma_c^+(2455)} \\ &\quad + 1.7 \times 10^{-2} g^2_{ND\Sigma_c^+(2520)}\Big) . \end{aligned} \tag{3}$$

There are no data available to determine unknown effective coupling parameters appearing in the Lagrangian (2). A rough idea about the relative strength of these couplings can be obtained from the use of SU(3) for the light quarks, and the heavy quark symmetry for the heavy c-quark, since D, D^*, Λ_c and Σ_c all contain a relatively heavy c-quark. In the heavy quark limit the spin of heavy quark is decoupled [25–27], so that the dimensionless coupling constants for spin 1/2 and 3/2 heavy baryons and spin 0 and 1 heavy mesons are approximately equal. If applicable, one would approximately have, $g_{ND^*\Lambda_c^+(2285)} \simeq g_{ND\Sigma_c(2455)} \simeq g_{ND^*\Sigma_c(2455)} \simeq g_{ND\Sigma_c(2520)} \simeq g_{ND^*\Sigma_c(2520)} = \mathfrak{g}$.

This approximation is, of course, very rough, but as an estimation of the order of magnitude, they should work. Using this approximation, we find that the contribution to $\Lambda_c(2940)^+ \to \Lambda_c^+\pi^+\pi^-$ is dominated by the second term in (3), that is dominated by $\mathcal{M}(\Lambda_c^+(2940) \to D^{*0}p \to \Sigma_c(2455)\pi \to \Lambda_c^+\pi^+\pi^-)$. We then obtain the radio of $\Lambda_c(2940)^+ \to D^0 p)$ and $\Lambda_c(2940)^+ \to \Lambda_c^+\pi^+\pi^-$ branching radios as:

$$\begin{aligned} &B(\Lambda_c(2940)^+ \to D^0 p) : B(\Lambda_c(2940)^+ \to \Lambda_c^+\pi^+\pi^-) \\ &= 429 : 4.0 \mathfrak{g}^2 . \end{aligned} \tag{4}$$

One expects that the coupling $\mathfrak{g}$ involves two baryons and a meson is similar to the couplings to $NN\pi$ and $NN\rho$ in some way. If it is comparable in size with $g_{NN\rho} = 3.5$, the ratio $R = B(\Lambda_c(2940)^+ \to \Lambda_c^+\pi^+\pi^-)/B(\Lambda_c(2940)^+ \to D^0 p)$ is at order one level, and can be near to one if $\mathfrak{g}$ is close to $g_{NN\pi} = 13.5$.

(2) $J^P(\Lambda_c^+) = \frac{3}{2}^-$.

For the various ratios similar to the case with $J^P(\Lambda_c^+) = 1/2^-$ discussed earlier, we have

$$\begin{aligned} &\left|\mathcal{M}\left(\Lambda_c(2940)^+ \to D^0 p\right)_{\pi^0}\right|^2 : \left|\mathcal{M}\left(\Lambda_c(2940)^+ \to D^0 p\right)_{\rho^0}\right|^2 \\ &= 2.0 \times 10^3 : 1 , \\ &\left|\mathcal{M}\left(\Lambda_c(2940)^+ \to \Lambda_c^+\sigma\right)_{D^*}\right|^2 \\ &: \left|\mathcal{M}\left(\Lambda_c(2940)^+ \to \Lambda_c^+\sigma\right)_N\right|^2 \\ &= 3.6 \times 10^{-2} : 3.4 , \\ &\left|\mathcal{M}\left(\Lambda_c(2940)^+ \to \Sigma_c(2455)\pi\right)_D\right|^2 \\ &: \left|\mathcal{M}\left(\Lambda_c(2940)^+ \to \Sigma_c(2455)\pi\right)_{D^*}\right|^2 \\ &: \left|\mathcal{M}\left(\Lambda_c(2940)^+ \to \Sigma_c(2455)\pi\right)_N\right|^2 \\ &= 4.1 \times 10^{-2} g^2_{ND\Sigma_c^+(2455)} : 6.2 \times 10^{-3} g^2_{ND^*\Sigma_c^+(2455)} \\ &: 5.4 \times 10^{-2} g^2_{ND^*\Sigma_c^+(2455)} , \end{aligned}$$

$$
\begin{aligned}
&\left|\mathcal{M}\left(\Lambda_c(2940)^+ \to \Sigma_c(2520)\pi\right)_D\right|^2 \\
&\quad : \left|\mathcal{M}\left(\Lambda_c(2940)^+ \to \Sigma_c(2520)\pi\right)_{D^*}\right|^2 \\
&\quad : \left|\mathcal{M}\left(\Lambda_c(2940)^+ \to \Sigma_c(2520)\pi\right)_N\right|^2 \\
&= 8.7\times 10^{-2} g^2_{ND\Sigma_c^+(2520)} : 9.0\times 10^{-4} g^2_{ND^*\Sigma_c^+(2520)} \\
&\quad : 3.3 g^2_{ND^*\Sigma_c^+(2520)}\,.
\end{aligned}
$$

The leading contributions in the above lead to

$$
\begin{aligned}
&B\left(\Lambda_c(2940)^+ \to D^0 p\right) : B\left(\Lambda_c(2940)^+ \to \Lambda_c^+\pi^+\pi^-\right) \\
&= 859 : \Big(0.66 g^2_{ND^*\Lambda_c^+(2285)} + 0.04 g^2_{ND^*\Sigma_c^+(2455)} \\
&\quad + 1.25 g^2_{ND^*\Sigma_c^+(2520)}\Big) \\
&= 859 : 1.95\mathfrak{g}^2\,. \qquad (5)
\end{aligned}
$$

We find that in this case the dominant contribution to $\Lambda_c^+(2940) \to \Lambda_c^+\pi^+\pi^-$ is from $\Lambda_c(2940)^+ \to \Sigma_c(2520)\pi \to \Lambda_c^+\pi^+\pi^-$.

Although both decay modes $\Lambda_c^+(2940) \to D^0 p$ and $\Lambda_c^+(2940) \to \Lambda_c^+\pi^+\pi^-$ have been observed experimentally, no detailed information for $B(\Lambda_c(2940)^+ \to D^0 p)$: $B(\Lambda_c(2940)^+ \to \Lambda_c^+\pi^+\pi^-)$ is available. But the fact that the Belle collaboration observed $\Lambda_c^+(2940) \to \Lambda_c^+\pi^+\pi^-$ via the intermediate $\Sigma_c^{++}(2455)$ already can tell us interesting information about the property of $\Lambda_c^+(2940)$. We note that with a reasonable size of $\mathfrak{g}$ between $g_{NN\rho}$ and $g_{NN\pi}$, if $\Lambda_c^+(2940)$ is a $1/2^-$ $D^{*0}p$ molecular state, there is a sizable contribution to $\Lambda_c(2940)^+ \to \Lambda_c^+\pi^+\pi^-$ via the intermediate $\Sigma_c(2455)$ state, but not for $3/2^-$ $D^{*0}p$ molecular state. For a $3/2^-$ state, $\Lambda_c(2940)^+ \to \Lambda_c^+\pi^+\pi^-$ would be dominated by $\Sigma_c(2520)$ intermediate state with a smaller branching ratio for a similar strength for the coupling $\mathfrak{g}$. Therefore present data support that $\Lambda_c^+(2940)$ to be a $1/2^-$ D^*p molecular state.

We now discuss some other decay properties of $\Lambda_c^+(2940)$. If $\Lambda_c(2940)^+$ is an S-wave molecular state of $D^{*0}p$, the binding is loose. $\Lambda_c(2940)^+$ may decay into D^{*0} and p via the threshold effect. We have considered the sequential decay of $D^{*0} \to D^0\pi^0$ with the π^0 playing the role of a exchanged particle. The π^0 can also become a particle in the final state. Also D^{*0} can decay into $D^0\gamma$. Thus $\Lambda_c(2940)^+$ may have other two decay modes: $D^0\pi^0 p$ and $D^0\gamma p$ with sizable branching ratios because $B(D^{*0} \to D^0\pi^0) = 61.9\%$ and $B(D^{*0} \to D^0\gamma) = 38.1\%$ are large. These decay modes should be searched in future experiments.

If exchanged particles π^0 and ρ^0 in Fig. 2 are replaced by π^- and ρ^- respectively, we can get other decay modes of $\Lambda_c(2940)^+$, i.e., $\Lambda_c(2940)^+ \to D^+ n$, $D^{*+}n$. Since n is only about 1.3 MeV heavier than p, $\Lambda_c^+(2940) \to D^0 p$ and $\Lambda_c^+(2940) \to D^+ n$ should have comparable widths although the threshold suppression factor is more sever for the latter. Search for $\Lambda_c(2940)^+ \to D^+ n$ in future experiments should also be carried out to understand the property of $\Lambda_c^+(2940)$.

Since $\Lambda_c(2940)^+$ in $\Lambda_c(2940)^+ \to \Lambda_c^+\pi^+\pi^-$ has been observed, the $\Lambda_c(2940)^+$ in $\Lambda_c(2940)^+ \to \Lambda_c^+\pi^0\pi^0$ should also occur. We suggest to look for $\Lambda_c(2940)^+$ in this channel. From our previous discussion, this decay is likely to go through $\Lambda_c(2940)^+ \to \Sigma_c(2455)^+\pi^\pm \to \Lambda_c^+\pi^0\pi^0$ than $\Lambda_c(2940)^+ \to \Sigma_c(2520)^+\pi^\pm \to \Lambda_c^+\pi^0\pi^0$.

In this paper we have suggested that the newly observed baryonic state $\Lambda_c(2940)^+$ to be a $D^{*0}p$ molecular state. The molecular structure can naturally explain why the mass is a few MeV below the threshold, and explain the observations of $\Lambda_c^+(2940) \to D^0 p$ and $\Lambda_c^+(2940) \to \Lambda_c^+\pi^+\pi^-$. Observation of $\Lambda_c^+(2940) \to \Lambda_c^+\pi^+\pi^-$ via $\Sigma_c^+ +$ (2455) suggests that the molecular state is a $1/2^-$ sate. Several other decay modes of $\Lambda_c(2940)^+$ with final products as D^+n, $D^0\pi^0 p$, $D^0\gamma p$ and $\Lambda_c^+\pi^0\pi^0$ can be used to further test the molecular structure. We urge our experimental colleagues to carry out such analyses.

Acknowledgements. This work is partly supported by NNSFC and NSC. XGH is also partially supported by NCTS.

Appendix

In this appendix we give the absorptive decay amplitude for each diagram in Fig. 2 (3, 4). Since $\Lambda_c^+(2940)$ is very close to the threshold of $D^{*0}+p$, the three momenta k for p is very small in the rest from of $\Lambda_c(2940)$.

1) $J^P(2940) = \frac{1}{2}^-$

In the following , q is the momenta of the exchange particle and $q^2 = (k-p_3)^2 = m_N^2 + m_3^2 - 2m_N p_3^0$, where m_3 is the mass of the particle with momentum p_3.

(1)$\mathcal{M}(\Lambda_c(2940)^+ \to D^{*0}p \to D^0 p)$

$$
\begin{aligned}
&\mathcal{M}\left(\Lambda_c(2940)^+(p_c) \to D^{*0}(k-p_c)p(k) \right.\\
&\quad \left.\to D^0(p_4)p(p_3)\right)_{\pi^0} \text{ (Fig. 2a)} \\
&= \left[\frac{|\mathbf{k}|}{8\pi M}\frac{g_{ND^*\Lambda_c^+(2940)}\, g_{D^*D\pi}\, g_{NN\pi}}{q^2 - m_\pi^2}(4kp_3 - 4m_N m_N)\right]\bar{p}\Lambda_c^+ \\
&\mathcal{M}\left(\Lambda_c(2940)^+ \to D^{*0}(k-p_c)p(k) \right.\\
&\quad \left.\to D^0(p_4)p(p_3)\right)_{\rho^0} \text{ (Fig. 2b)} \\
&= \left[\frac{|\mathbf{k}|}{8\pi M}\frac{2m_N m_{D^{*0}}}{M}\frac{g_{ND^*\Lambda_c^+(2940)}\, g_{D^*D\rho}\, g_{NN\rho}}{q^2 - m_\rho^2}\right]\bar{p}\gamma^\mu\gamma^\nu\gamma^5 \\
&\quad \times \Lambda_c^+ \epsilon_{\mu\nu\alpha\beta} p_3^\alpha p_c^\beta\,,
\end{aligned}
$$

(2)$\mathcal{M}(\Lambda_c(2940)^+ \to D^{*0}p \to \Lambda_c^+\sigma \to \Lambda_c^+\pi^+\pi^-)$

$$
\begin{aligned}
&\mathcal{M}\left(\Lambda_c(2940)^+ \to D^{*0}(k-p_c)p(k) \right.\\
&\quad \left.\to \Lambda_c^+(p_3)\sigma(p_4)\right)_{D^*} \text{ (Fig. 3a)} \\
&= \left[\frac{|\mathbf{k}|}{8\pi M}\frac{g_{ND^*\Lambda_c^+(2940)}\, g_{D^*D^*\sigma}\, g_{ND^*\Lambda_c^+(2285)}}{q^2 - m_\pi^2} 2m_{D^{*0}} \right.\\
&\quad \left.\times (3m_N m_N - 2kp_3 + m_N m_{\Lambda_c^+})\right]\bar{\Lambda}_c\gamma^5\Lambda_c^+ \\
&\mathcal{M}\left(\Lambda_c(2940)^+ \to D^{*0}(k-p_c)p(k) \right.\\
&\quad \left.\to \Lambda_c^+(p_4)\sigma(p_3)\right)_N \text{(Fig. 3b)}
\end{aligned}
$$

$$= \left[\frac{|\mathbf{k}|}{8\pi M}\frac{g_{ND^*\Lambda_c^+(2940)}g_{NN\sigma}g_{ND^*\Lambda_c^+(2285)}}{q^2-m_\rho^2}\right.$$
$$\left.\times\left(6m_N^2-6m_NM+4kp_4-2m_Nm_{\Lambda_c^+}+6m_Nm_N\right)\right]$$
$$\times\bar{\Lambda}_c\gamma^5\Lambda_c^+\,,$$

(3)$\mathcal{M}(\Lambda_c^+(2940)\to D^{*0}p\to\Sigma_c(2455)\pi\to\Lambda_c^+\pi^+\pi^-)$

$$\mathcal{M}\big(\Lambda_c(2940)^+\to D^{*0}(k-p_c)p(k)\to\Sigma_c(2455)(p_3)\pi(p_4)\big)_D(\text{Fig. 4a})$$
$$=\left[\frac{|\mathbf{k}|}{8\pi M}\frac{g_{ND^*\Lambda_c^+(2940)}g_{D^*D\pi}g_{N\Sigma_c(2455)D}}{q^2-m_D^2}\times(4kp_3-4m_Nm_{\Sigma_c})\right]\bar{\Sigma}_c\Lambda_c^+$$

$$\mathcal{M}\big(\Lambda_c(2940)^+\to D^{*0}(k-p_c)p(k)\to\Sigma_c(2455)(p_3)\pi(p_4)\big)_{D^*}(\text{Fig. 4b})$$
$$=\left[\frac{|\mathbf{k}|}{8\pi M}\frac{2m_Nm_{D^{*0}}}{M}\frac{g_{ND^*\Lambda_c^+(2940)}g_{D^*D^*\pi}g_{N\Sigma_c(2455)D^*}}{q^2-m_{D^*}^2}\right]$$
$$\times\bar{\Sigma}_c\gamma^\mu\gamma^\nu\Lambda_c^+\epsilon_{\mu\nu\alpha\beta}p_3^\alpha p_c^\beta$$

$$\mathcal{M}\big(\Lambda_c(2940)^+\to D^{*0}(k-p_c)p(k)\to\Sigma_c(2455)(p_4)\pi(p_3)\big)_N(\text{Fig. 4c})$$
$$=\left[\frac{|\mathbf{k}|}{8\pi M}\frac{g_{ND^*\Lambda_c^+(2940)}g_{NN\pi}g_{N\Sigma_c(2455)D^*}}{q^2-m_N^2}\times\left(6m_N^2-6m_NM+4kp_4+2m_Nm_{\Sigma_c^+}-6m_Nm_N\right)\right]$$
$$\times\bar{\Sigma}_c\Lambda_c^+\,,$$

(4)$\mathcal{M}(\Lambda_c(2940)^+\to D^{*0}p\to\Sigma_c(2520)\pi\to\Lambda_c^+\pi^+\pi^-)$

$$\mathcal{M}\big(\Lambda_c(2940)^+\to D^{*0}(k-p_c)p(k)\to\Sigma_c(2520)(p_3)\pi(p_4)\big)_D(\text{Fig. 4a})$$
$$=\left[\frac{|\mathbf{k}|}{8\pi Mm_D}\frac{g_{ND^*\Lambda_c^+(2940)}g_{D^*D\pi}g_{N\Sigma_c(2520)D}}{q^2-m_D^2}\times(4kp_3+4m_Nm_{\Sigma_c})\right]\bar{\Sigma}_c^\mu k_\mu\gamma^5\Lambda_c^+$$

$$\mathcal{M}\big(\Lambda_c(2940)^+\to D^{*0}(k-p_c)p(k)\to\Sigma_c(2520)(p_3)\pi(p_4)\big)_{D^*}(\text{Fig. 4b})$$
$$=\left[\frac{|\mathbf{k}|}{8\pi M}\frac{2m_Nm_{D^{*0}}}{M}\frac{g_{ND^*\Lambda_c^+(2940)}g_{D^*D^*\pi}g_{N\Sigma_c(2520)D^*}}{q^2-m_{D^*}^2}\right]$$
$$\times\bar{\Sigma}_c^\mu\gamma^\nu\Lambda_c^+\epsilon_{\mu\nu\alpha\beta}p_3^\alpha p_c^\beta$$

$$\mathcal{M}\big(\Lambda_c(2940)^+\to D^{*0}(k-p_c)p(k)\to\Sigma_c(2520)(p_4)\pi(p_3)\big)_N(\text{Fig. 4c})$$
$$=\left[\frac{|\mathbf{k}|}{8\pi M}\frac{g_{ND^*\Lambda_c^+(2940)}g_{NN\pi}g_{N\Sigma_c(2520)D^*}}{q^2-m_N^2}\times\left(6m_N^2-6m_NM+4kp_4+2m_Nm_{\Sigma_c^+}-6m_Nm_N\right)\right]$$
$$\times\bar{\Sigma}_c^\mu k_\mu\gamma^5\Lambda_c^+\,.$$

2) $J^P(2940)=\frac{3}{2}^-$

(1)$\mathcal{M}(\Lambda_c(2940)^+\to D^{*0}p\to D^0p)$

$$\mathcal{M}\big(\Lambda_c(2940)^+\to D^{*0}(k-p_c)p(k)\to D^0(p_3)p(p_4)\big)_{\pi^0}(\text{Fig. 2a})$$
$$=\left[\frac{|\mathbf{k}|}{8\pi M}\frac{g_{ND^*\Lambda_c^+(2940)}g_{D^*D\pi}g_{NN\pi}}{q^2-m_\pi^2}4m_N\right]\bar{P}\gamma^5\Lambda_c^{+\mu}p_{3\mu}$$

$$\mathcal{M}\big(\Lambda_c(2940)^+\to D^{*0}(k-p_c)p(k)\to D^0(p_3)p(p_4)\big)_{\rho^0}(\text{Fig. 2b})$$
$$=\left[\frac{|\mathbf{k}|}{8\pi M}\frac{2m_Nm_{D^{*0}}}{M}\frac{g_{ND^*\Lambda_c^+(2940)}g_{D^*D\rho}g_{NN\rho}}{q^2-m_\rho^2}\right]$$
$$\times\bar{P}\gamma^\mu\Lambda_c^{+\nu}\epsilon_{\mu\nu\alpha\beta}p_3^\alpha p_c^\beta\,,$$

(2)$\mathcal{M}(\Lambda_c(2940)^+\to D^{*0}p\to\Lambda_c^+\sigma\to\Lambda_c^+\pi^+\pi^-)$

$$\mathcal{M}\big(\Lambda_c(2940)^+\to D^{*0}(k-p_c)p(k)\to\Lambda_c^+(p_3)\sigma(p_4)\big)_{D^*}(\text{Fig. 3a})$$
$$=\left[\frac{|\mathbf{k}|}{8\pi M}\frac{g_{ND^*\Lambda_c^+(2940)}g_{D^*D^*\sigma}g_{ND^*\Lambda_c^+(2285)}}{q^2-m_{D^*}^2}2m_Nm_{D^{*0}}\right]$$
$$\times\bar{\Lambda}_c\Lambda_c^{+\mu}p_{3\mu}$$

$$\mathcal{M}\big(\Lambda_c(2940)^+\to D^{*0}(k-p_c)p(k)\to\Lambda_c^+(p_4)\sigma(p_3)\big)_N(\text{Fig. 3b})$$
$$=\left[\frac{|\mathbf{k}|}{8\pi M}\frac{g_{ND^*\Lambda_c^+(2940)}g_{NN\sigma}g_{ND^*\Lambda_c^+(2285)}}{q^2-m_N^2}4m_N\right]\bar{\Lambda}_c\Lambda_c^{+\mu}p_{4\mu}\,,$$

(3)$\mathcal{M}(\Lambda_c^+(2940)\to D^{*0}p\to\Sigma_c(2455)\pi\to\Lambda_c^+\pi^+\pi^-)$

$$\mathcal{M}\big(\Lambda_c(2940)^+\to D^{*0}(k-p_c)p(k)\to\Sigma_c(2455)(p_3)\pi(p_4)\big)_D(\text{Fig. 4a})$$
$$=\left[\frac{|\mathbf{k}|}{8\pi M}\frac{g_{ND^*\Lambda_c^+(2940)}g_{D^*D\pi}g_{N\Sigma_c(2455)D}}{q^2-m_D^2}4m_N\right]$$
$$\times\bar{\Sigma}_c\gamma^5\Lambda_c^{+\mu}p_{3\mu}$$

$$\mathcal{M}\big(\Lambda_c(2940)^+\to D^{*0}(k-p_c)p(k)\to\Sigma_c(2455)(p_3)\pi(p_4)\big)_{D^*}(\text{Fig. 4b})$$
$$=\left[\frac{|\mathbf{k}|}{8\pi M}\frac{2m_Nm_{D^{*0}}}{M}\frac{g_{ND^*\Lambda_c^+(2940)}g_{D^*D^*\pi}g_{N\Sigma_c(2455)D^*}}{q^2-m_{D^*}^2}\right]$$
$$\times\bar{\Sigma}_c\gamma^\mu\Lambda_c^{+\nu}\epsilon_{\mu\nu\alpha\beta}p_3^\alpha p_c^\beta$$

$$\mathcal{M}\big(\Lambda_c(2940)^+\to D^{*0}(k-p_c)p(k)\to\Sigma_c(2455)(p_4)\pi(p_3)\big)_N(\text{Fig. 4c})$$
$$=\left[\frac{|\mathbf{k}|}{8\pi M}\frac{g_{ND^*\Lambda_c^+(2940)}g_{NN\pi}g_{N\Sigma_c(2455)D^*}}{q^2-m_N^2}4m_N\right]$$
$$\times\bar{\Sigma}_c\gamma^5\Lambda_c^{+\mu}p_{3\mu}\,,$$

$$(4)\mathcal{M}(\Lambda_c(2940)^+ \to D^{*0}p \to \Sigma_c(2520)\pi \to \Lambda_c^+\pi^+\pi^-)$$

$$\begin{aligned}
&\mathcal{M}\big(\Lambda_c(2940)^+ \to D^{*0}(k-p_c)p(k) \\
&\quad \to \Sigma_c(2520)(p_3)\pi(p_4)\big)_D (\text{Fig. 4a}) \\
&= \left[\frac{|\mathbf{k}|}{8\pi M m_D} \frac{g_{ND^*\Lambda_c^+(2940)}\, g_{D^*D\pi}\, g_{N\Sigma_c(2520)D}}{q^2-m_D^2} 4m_N\right] \\
&\quad \times \bar{\Sigma}_c^\mu k_\mu \Lambda_c^{+\nu} p_{3\nu} \\
&\mathcal{M}\big(\Lambda_c(2940)^+ \to D^{*0}(k-p_c)p(k) \\
&\quad \to \Sigma_c(2520)(p_3)\pi(p_4)\big)_{D^*} (\text{Fig. 4b}) \\
&= \left[\frac{|\mathbf{k}|}{8\pi M} \frac{2m_N m_{D^{*0}}}{M} \frac{g_{ND^*\Lambda_c^+(2940)}\, g_{D^*D^*\pi}\, g_{N\Sigma_c(2520)D^*}}{q^2-m_{D^*}^2}\right] \\
&\quad \times \bar{\Sigma}_c^\mu \gamma^5 \Lambda_c^{+\nu} \epsilon_{\mu\nu\alpha\beta} p_3^\alpha p_c^\beta \\
&\mathcal{M}\big(\Lambda_c(2940)^+ \to D^{*0}(k-p_c)p(k) \\
&\quad \to \Sigma_c(2520)(p_4)\pi(p_3)\big)_N (\text{Fig. 4c}) \\
&= \left[\frac{|\mathbf{k}|}{8\pi M} \frac{g_{ND^*\Lambda_c^+(2940)}\, g_{NN\pi}\, g_{N\Sigma_c(2520)D^{*0}}}{q^2-m_N^2} \right. \\
&\qquad \left. \times 2m_N(M-m_{\Sigma_c^+})\right] \bar{\Sigma}_c^\mu \Lambda_{c\ \mu}^+ .
\end{aligned}$$

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