\[ \Lambda_b \rightarrow \pi^- \Lambda_c^* \text{ and } \Lambda_b \rightarrow D_s^- \Lambda_c^* \text{ Decays} \]

in the molecular picture of \( \Lambda_c(2595) \) and \( \Lambda_c(2625) \)

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Outline

• Introduction and motivation
• Formalism
• Results and discussions
• Summary
**Introduction and motivation**

- $\Lambda_c(2595)$ and $\Lambda_c(2625)$ are excited states of $\Lambda_b$, with narrow width.

In PDG:

$$\Lambda_c(2595)^+$$

- $I(J^P) = 0(\frac{1}{2}^-)$ Status: ***
- $\Gamma_{\Lambda_c(2595)} = 2.59 \pm 0.30 \pm 0.47$ MeV

$$\Lambda_c(2625)^+$$

- $I(J^P) = 0(\frac{3}{2}^-)$ Status: /***
- $\Gamma_{\Lambda_c(2625)} < 0.97$ MeV

- **Open question:** Are $\Lambda_c(2595)$ and $\Lambda_c(2625)$ normal $qqq$ states or exotic states?
Introduction and motivation

- Theroretical results from a study on baryon states with open charm in the extended local hidden gauge approach


- Considering both pseudoscalar-baryon and vector-baryon interactions.

  Pseudoscalar-baryon coupled channels ($I=0$): $DN$, $\pi \Sigma_c$, $\eta \Lambda_c$

  Vector-baryon coupled channels ($I=0$): $D^*N$, $\rho \Sigma_c$, $\omega \Lambda_c$, $\phi \Lambda_c$

- Both $\Lambda_c(2595)$ and $\Lambda_c(2625)$ are generated dynamically from meson – baryon interaction.

  $\Lambda_c(2595)$ couples mostly to $DN$ and $D^*N$. $\Lambda_c(2625)$ couples mostly to $D^*N$.

- This work, to test the molecular picture of $\Lambda_c(2595)$ and $\Lambda_c(2625)$ in $\Lambda_b \to \pi^- \Lambda_c^*$ and $\Lambda_b \to D_s^- \Lambda_c^*$ decays.
**Formalism**

$\Lambda_b \rightarrow \pi^- \Lambda_c^*$ decay:

$I = 0, S = 0 \{u, d\} \text{spectators}$

*Fig. 1* Basic diagram for $\Lambda_b \rightarrow \pi^- \Lambda_c(2595)$.  

$\bar{u}u + \bar{d}d + \bar{s}s$ (with the quantum numbers of the vacuum)

*Fig. 2* Hadronization creating $\bar{q}q$ pairs
Formalism

• Flavour aspect of the hadronization

Original state $|\Lambda_b\rangle = \frac{1}{\sqrt{2}} |b(ud - du)\rangle$  

weak process $\Rightarrow |H\rangle = \frac{1}{\sqrt{2}} |c(ud - du)\rangle$

$|H'\rangle = \frac{1}{\sqrt{2}} |c(\bar{u}u + \bar{d}d + \bar{s}s)(ud - du)\rangle$  

hadronization in term of hadrons $\Rightarrow |H'\rangle = \left| D^0 p + D^+ n + \sqrt{\frac{2}{3}} D_s^+ \Lambda \right|$  

Neglect $D_s^+ \Lambda$, for its much higher mass than $DN$. (Its contribution will be considered later.)

$|H'\rangle \simeq \sqrt{2} |DN, I = 0\rangle$
**Formalism**

- **Production of \( \Lambda_c^* \) resonance**

The transition matrix for Fig. 3:

\[
t_R = V_P \sqrt{2} \ G_{DN} \cdot g_{R,DN},
\]

**Fig. 3** Diagram to produce \( \Lambda_c(2595) \) through an intermediate propagation of \( DN \) state.

- **\( V_P \)** — a factor that includes the dynamics of \( \Lambda_b \rightarrow \pi^-DN \), involving the weak matrix elements;

- **\( G_{DN} \)** — loop function for the \( DN \) propagation;

- **\( g_{R,DN} \)** — coupling of the resonance to DN channel in \( I = 0 \).


**For the case of \( D^*N \) production, the \( V_P \) factor would be different.**
Formalism

- Evaluation of the weak matrix elements (\(V_p\) factor)

(Detail can be seen in [WHL, M. Bayar, E. Oset, Eur. Phys. J. C 77 (2017) 39])

\[
V_p \sim \left(i \frac{w_\pi}{q} \frac{\vec{\sigma} \cdot \vec{q}}{q} \right) \delta_{J, \frac{1}{2}} + \left(-i \frac{w_\pi}{q} \sqrt{3} \vec{S}^+ \cdot \vec{q} \right) \delta_{J, \frac{3}{2}},
\]

with \(q^0, \vec{q}\) the energy and momentum of the pion, \(\vec{\sigma}\) the Pauli spin matrix.

\(\vec{S}^+\) is the spin transition operator from spin 1/2 to 3/2, defined as

\[
\left\langle \frac{3}{2} M' \right| \vec{S}^+ \cdot \vec{q} \left| \frac{1}{2} M \right\rangle = C \left( \frac{1}{2} \frac{1}{2} \frac{3}{2} ; M_\mu M' \right)
\]

There is a common factor for \(\Lambda_b \rightarrow \pi^- \Lambda_c (2595)\) and \(\Lambda_b \rightarrow \pi^- \Lambda_c (2625)\),

\[
\text{ME}(q) \equiv \int r^2 dr \ j_1(qr) \ \varphi_{\text{in}}(r) \ \varphi_{\text{fin}}^*(r).
\]

\(\varphi_{\text{in}}\) and \(\varphi_{\text{fin}}\) are the radial wave functions of \(b\) and \(c\) quarks.
Formalism

• Decay width for $\Lambda_b \rightarrow \pi^- \Lambda_c$

The full transition $t$ matrix for $\Lambda_b \rightarrow \pi^- \Lambda_c$

$$t_R = \left( iq + i \frac{w_\pi}{q} \vec{\sigma} \cdot \vec{q} \right) \left( \frac{1}{2} G_{DN} g_{R,DU} + \frac{1}{2\sqrt{3}} G_{D^*N} g_{R,D^*U} \right) \delta_{J, \frac{1}{2}}$$

$$- \left( +i \frac{w_\pi}{q} \sqrt{3} \vec{S}^+ \cdot \vec{q} \right) \frac{1}{\sqrt{3}} G_{D^*N} g_{R,D^*U} \delta_{J, \frac{3}{2}}.$$  \hspace{1cm} (40)

Factors $G_{D^{(*)}N} g_{R,D^{(*)}N}$ are taken from


The decay width for $\Lambda_b \rightarrow \pi^- \Lambda_c$

$$\Gamma_R = \frac{1}{2\pi} \frac{M_{\Lambda_c^*}}{M_{\Lambda_b}} \sum \sum |t_R|^2 p_{\pi^-},$$
where $\sum \sum$ stands for the sum and average over polarization.

$$\left[ \sum \sum |t_R|^2 \right]_1 = (q^2 + w_{\pi}^2) \left| \frac{1}{2} G_{DN} g_{R, DN} + \frac{1}{2\sqrt{3}} G_{D^* N} g_{R, D^* N} \right|^2,$$

for $J = \frac{1}{2}$; \hspace{1cm} (41)

and

$$\left[ \sum \sum |t_R|^2 \right]_2 = 2w_{\pi}^2 \left| \frac{1}{\sqrt{3}} G_{D^* N} g_{R, D^* N} \right|^2,$$

for $J = \frac{3}{2}$. \hspace{1cm} (42)
Results and discussions

- The ratio of $\Gamma$ for $\Lambda_c(2595)$ and $\Lambda_c(2625)$ production

\[
\frac{\Gamma[\Lambda_b \to \pi^- \Lambda_c(2595)]}{\Gamma[\Lambda_b \to \pi^- \Lambda_c(2625)]} = 0.76 .
\]

\[
\Gamma[\Lambda_b \to \pi^- \Lambda_c(2595)] \bigg|_{\text{Exp.}} \left( \frac{1}{\Gamma[\Lambda_b \to \pi^- \Lambda_c(2625)]} \right) = 1.03 \pm 0.60. \]

Compatible within errors!

\[
\frac{\Gamma[\Lambda_b \to D_s^- \Lambda_c(2595)]}{\Gamma[\Lambda_b \to D_s^- \Lambda_c(2625)]} = 0.54 .
\]
◆ Results and discussions

- The relative sign of the coupling of $\Lambda_c(2595)$ to $DN$ and $D^*N$

$$\left[ \sum \sum |t_R|^2 \right]_1 = \left( q^2 + \omega^2 \right) \left[ \frac{1}{2} G_{DN} g_{R,DN} + \frac{1}{2\sqrt{3}} G_{D^*N} g_{R,D^*N} \right]^2,$$

for $J = \frac{1}{2}$;

$DN$ and $D^*N$ contributions are about the same for the $\Lambda_c(2595)$ case.


<table>
<thead>
<tr>
<th></th>
<th>$G_{DN} \cdot g_{R,DN}$</th>
<th>$G_{D^*N} \cdot g_{R,D^*N}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_c(2595)$ $(J = \frac{1}{2})$</td>
<td>$13.88 - 1.06i$</td>
<td>$26.51 + 2.1i$</td>
</tr>
<tr>
<td>$\Lambda_c(2625)$ $(J = \frac{3}{2})$</td>
<td>$0$</td>
<td>$29.10$</td>
</tr>
</tbody>
</table>

The $D^*N$ component in $\Lambda_c(2595)$ is relevant;

The relative sign of the coupling of $\Lambda_c(2595)$ to $DN$ and $D^*N$ is of crucial importance.
◆ Results and discussions

- Contributions from $D_s \Lambda$ and $D_s^* \Lambda$ channels

\[
G_{DN} \cdot g_{R, DN} \rightarrow G_{DN} \cdot g_{R, DN} + \frac{1}{\sqrt{2}} \sqrt{\frac{2}{3}} G_{D_s \Lambda} \cdot g_{R, D_s \Lambda},
\]

\[
G_{D^*N} \cdot g_{R, D^*N} \rightarrow G_{D^*N} \cdot g_{R, D^*N} + \frac{1}{\sqrt{2}} \sqrt{\frac{2}{3}} G_{D_s^* \Lambda} \cdot g_{R, D_s^* \Lambda}.
\]

Table 3  The values of $G_{D_s \Lambda} \cdot g_{R, D_s \Lambda}$ and $G_{D_s^* \Lambda} \cdot g_{R, D_s^* \Lambda}$ from Ref. [43]

<table>
<thead>
<tr>
<th></th>
<th>$G_{D_s \Lambda} \cdot g_{R, D_s \Lambda}$</th>
<th>$G_{D_s^* \Lambda} \cdot g_{R, D_s^* \Lambda}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_c(2595)(J = \frac{1}{2})$</td>
<td>$2.76 - 0.068i$</td>
<td>$4.62 - 0.12i$</td>
</tr>
<tr>
<td>$\Lambda_c(2625)(J = \frac{3}{2})$</td>
<td>$0$</td>
<td>$-0.065 + 0.91i$</td>
</tr>
</tbody>
</table>
Results and discussions

The ratios with corrections from $D_s \Lambda$ and $D_s^* \Lambda$ channels

$$\frac{\Gamma[\Lambda_b \rightarrow \pi^- \Lambda_c(2595)]}{\Gamma[\Lambda_b \rightarrow \pi^- \Lambda_c(2625)]} = 0.76 \sim 0.91,$$

PDG:

$$\frac{\Gamma[\Lambda_b \rightarrow \pi^- \Lambda_c(2595)]}{\Gamma[\Lambda_b \rightarrow \pi^- \Lambda_c(2625)]} \bigg|_{\text{Exp.}} = 1.03 \pm 0.60.$$  

$$\frac{\Gamma[\Lambda_b \rightarrow D_s^- \Lambda_c(2595)]}{\Gamma[\Lambda_b \rightarrow D_s^- \Lambda_c(2625)]} = 0.54 \sim 0.65.$$  

The inclusion of $D_s \Lambda, D_s^* \Lambda$ channels improves the agreement with experiment.
In the picture that the $\Lambda_c(2595)$ and $\Lambda_c(2625)$ are dynamically generated resonances from the interaction of $DN$, $D^*N$ with coupled channels, we studied $\Lambda_b \rightarrow \pi^-(D_s^-)\Lambda_c(2595)$ and $\Lambda_b \rightarrow \pi^-(D_s^-)\Lambda_c(2625)$ decays. Ratios of decay widths were predicted.

The predicted ratio $\Gamma(\Lambda_b \rightarrow \pi^-\Lambda_c(2595))/\Gamma(\Lambda_b \rightarrow \pi^-\Lambda_c(2625))$ is in good agreement with the experimental data, showing that the molecular picture of $\Lambda_c(2595)$ and $\Lambda_c(2625)$ is reasonable.

The relative sign of the coupling of $\Lambda_c(2595)$ to $DN$ and $D^*N$ is important to have good agreement with exp.
Thank you for your attention!