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$\Lambda_b \to \pi^-(D_s^-)\Lambda_c^*$ and $\Lambda_b \to \bar{\nu}_l l \Lambda_c^*$ decays in the molecular picture of $\Lambda_c(2595)$ and $\Lambda_c(2625)$

W. H. Liang[*†]
Department of Physics, Guangxi Normal University, Guilin 541004, China
E-mail: liangwh@gxnu.edu.cn

Z. S. Xie
Department of Physics, Guangxi Normal University, Guilin 541004, China

M. Bayar
Department of Physics, Kocaeli University, 41380, Izmit, Turkey

E. Oset
Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia - CSIC, Institutos de Investigación de Paterna, Aptdo. 22085, 46071 Valencia, Spain.

We have studied the nonleptonic $\Lambda_b \to \pi^-(D_s^-)\Lambda_c^*$ and the semileptonic $\Lambda_b \to \bar{\nu}_l l \Lambda_c^*$ decays, with $\Lambda_c^* \equiv \Lambda_c(2595), \Lambda_c(2625)$, from the perspective that the two Λ_c^* resonances are dynamically generated from the DN, D^*N interaction with coupled channels. We have developed a formalism to relate the $\Lambda_b \to \pi^- DN$ and $\Lambda_b \to \pi^- D^*N$ decays. We can evaluate the rates for these transitions, up to a global unknown factor. We find that the ratios of the rates obtained for these reactions are compatible with present experimental data and are very sensitive to the D^*N coupling, which becomes essential to obtain agreement with experiment. The results obtained with these reactions give support to the molecular picture for these two Λ_c^* resonances. Work with other models and checks for further experiments will help us gain further insight on the nature of these resonances, and new experiments producing these two resonances should be encouraged.

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1. Introduction

The interaction of mesons with baryons using the chiral unitary approach [1, 2] has brought light into the nature of some baryonic resonances. The prediction of two states for the $\Lambda(1405)$ [3, 4] has been one example of it, and is now supported by experiments [5]. Along this line, using a unitary scheme with coupled channels and the dynamics based on the local hidden gauge approach [6], the meson-baryon interactions in the sector with open or hidden heavy quark (charm or beauty) have been investigated [7, 8, 9, 10], and some experimentally observed baryon states, such as $\Lambda_b(5912)$, $\Lambda_b(5920)$, $\Lambda_c(2595)$ and $\Lambda_c(2625)$, are well reproduced with the molecular nature. In Ref. [9], the interaction of DN , D^*N and coupled channels has been considered, and the $\Lambda_c(2595)$ ($J^P = 1/2^-$) and $\Lambda_c(2625)$ ($J^P = 3/2^-$) are generated dynamically. It was found that the $\Lambda_c(2595)$ couples strongly to DN and D^*N in s-wave, and the $\Lambda_c(2625)$ couples strongly to D^*N in s-wave. In another unitary coupled channel approach, but with somewhat different dynamical input, similar conclusions are reached [11].

Support for the molecular picture of $\Lambda_c(2595)$ and $\Lambda_c(2625)$ should come from accumulation of experimental data which can be reproduced by the models. In this respect, here we report on the work of Refs. [12, 13], investigating the nonleptonic $\Lambda_b \to \pi^-(D_s^-)\Lambda_c^*$ and the semileptonic $\Lambda_b \to \bar{\nu}_l l \Lambda_c^*$ decays, with $\Lambda_c^* \equiv \Lambda_c(2595), \Lambda_c(2625)$. We develop the formalism that provides the width for these decays within the molecular picture of Ref. [9] and show that the ratios of the branching fractions for these reactions are compatible with present experimental data. It gives strong support to the molecular picture of the two Λ_c^* resonances.

2. Formalism

2.1 The nonleptonic $\Lambda_b \to \pi^-(D_s^-)\Lambda_c^*$ decay

The basic diagram for the $\Lambda_b \to \pi^-\Lambda_c^*$ decay is shown in Fig. 1. The weak transition occurs on the b quark, which turns into a c quark, and a π^- is produced through the mechanism of external emission [14]. Since we will have a $1/2^-$ or $3/2^-$ state at the end, and the u, d quarks are spectators, the final c quark must carry negative parity and hence must be in an $L = 1$ level. Since the $\Lambda_c(2595)$ and $\Lambda_c(2625)$ come from meson-baryon interaction in our picture, we must hadronize the final state including a $\bar{q}q$ pair with the quantum numbers of the vacuum. Following the work of Ref. [12], the hadronization gives rise to

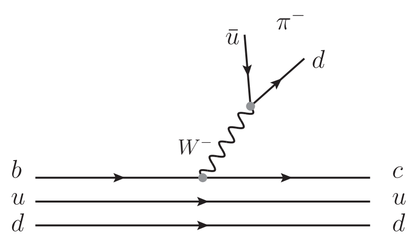

Figure 1: Basic diagram for $\Lambda_b \to \pi^-\Lambda_c(2595)$. The u and d quarks are spectators and in isospin and strangeness $I = 0$, $S = 0$.

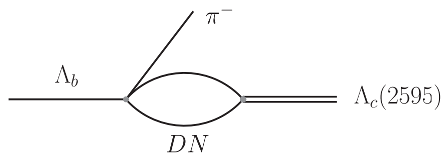

Figure 2: Diagram to produce the $\Lambda_c(2595)$ through an intermediate propagation of the DN state.

$$|H'\rangle = |D^0 p + D^+ n + \sqrt{\frac{2}{3}} D_s^+ \Lambda\rangle \simeq \sqrt{2}|DN, I=0\rangle, \tag{2.1}$$

where we neglect the $D_s^+\Lambda$ that has a much higher mass than the DN and does not play a role in the generation of the $\Lambda_c(2595)$. The isospin $I = 0$ in Eq. (2.1) comes from the implicit phase convention in our approach, with the doublets $(D^+,\ -D^0)$ and $(\bar{D}^0,\ D^-)$.

The production of the resonance is done after the produced DN in the first step merges into the resonance, as shown in Fig. 2. The transition matrix for the mechanism of Fig. 2 gives us

$$t_R = V_P\, \sqrt{2}\, G_{DN} \cdot g_{R,DN}, \tag{2.2}$$

where G_{DN} is the loop function for the DN propagation [9], $g_{R,DN}$ is the coupling of the Λ_c^* resonance to the DN channel in $I = 0$ [9], V_P is a factor that includes the dynamics of $\Lambda_b \to \pi^- DN$, involving the weak matrix elements.

The arguments used above can be equally used for the production of D^*N. The V_p factor would now be different. If we wish to relate the DN and D^*N production, we need to consider the spin and angular dependence of the created pair, and we also need to evaluate the weak matrix elements related to the $W^- \to \pi^-$ production. According to the detailed evaluation in Ref. [12], the weak vertex transition, at the macroscopic level of the Λ_b and Λ_c^* baryons, can be written as

$$V_P \sim \left[(iq + i\frac{w_\pi}{q}\, \vec{\sigma}\cdot\vec{q})\ \delta_{J,\frac{1}{2}} + (-i\frac{w_\pi}{q}\, \sqrt{3}\,\vec{S}^+ \cdot \vec{q})\ \delta_{J,\frac{3}{2}} \right] \mathrm{ME}(q), \tag{2.3}$$

with $w_\pi = q^0$ and $\vec{q}$ the energy and momentum of the pion, and $\vec{\sigma}$ the Pauli spin matrix. $\vec{S}^+$ is the spin transition operator from spin $1/2$ to $3/2$, defined as

$$\langle \frac{3}{2} M' | S_\mu^+ | \frac{1}{2} M \rangle = \mathscr{C}(\frac{1}{2} 1 \frac{3}{2};\ M \mu M'), \tag{2.4}$$

where $\mathscr{C}(\frac{1}{2} 1 \frac{3}{2};\ M\mu M')$ is the Clebsch-Gordan coefficient. $\mathrm{ME}(q)$ is a common factor for $\Lambda_b \to \pi^-\Lambda_c(2595)$ and $\Lambda_b \to \pi^-\Lambda_c(2625)$ decays,

$$\mathrm{ME}(q) \equiv \int r^2 dr\ j_1(qr)\ \varphi_{\rm in}(r)\ \varphi^*_{\rm fin}(r), \tag{2.5}$$

where $\varphi_{\rm in}(r)$ and $\varphi_{\rm fin}(r)$ are the radial wave functions of the b and c quarks, and $j_1(qr)$ is a spherical Bessel function. Given the fact that we only want to evaluate ratios of rates, that the momenta q involved in the different transitions are very similar and that $\varphi_{\rm in}$, $\varphi_{\rm fin}$ are the same for all of them, we shall assume $\mathrm{ME}(q)$ to be the same for all these transitions.

We finally have a full transition t matrix given, up to an arbitrary common factor, by

$$t_R = C\{(iq + i\frac{w_\pi}{q}\vec{\sigma}\cdot\vec{q})(\frac{1}{2}G_{DN}\, g_{R,DN} + \frac{1}{2\sqrt{3}}G_{D^*N}\, g_{R,D^*N})\delta_{J,\frac{1}{2}} - (i\frac{w_\pi}{q}\sqrt{3}\vec{S}^+\cdot\vec{q})\frac{1}{\sqrt{3}}G_{D^*N}\, g_{R,D^*N}\,\delta_{J,\frac{3}{2}}\}, \tag{2.6}$$

where C contains the matrix element ME(q) and the weak interaction constants and can be assumed to be constant, and factors $G_{D^{(*)}N}\, g_{R,D^{(*)}N}$ are taken from Ref. [9] (see also Table 2 in Ref. [12]).

The partial decay width for $\Lambda_b \to \pi^-\Lambda_c^*$ is given by

$$\Gamma_R = \frac{C^2}{2\pi}\frac{M_{\Lambda_c^*}}{M_{\Lambda_b}}\, p_{\pi^-}\,\overline{\sum}\sum|t_R|^2, \tag{2.7}$$

where p_{π^-} is the momentum of the pion, $p_{\pi^-} = \lambda^{1/2}(M^2_{\Lambda_b}, m^2_\pi, M^2_R)/2M_{\Lambda_b}$, and

$$\left[\overline{\sum}\sum|t_R|^2\right]_1 = (q^2 + w_\pi^2)\left|\frac{1}{2}G_{DN}\, g_{R,DN} + \frac{1}{2\sqrt{3}}G_{D^*N}\, g_{R,D^*N}\right|^2, \text{ for } J = \frac{1}{2}, \tag{2.8}$$

$$\left[\overline{\sum}\sum|t_R|^2\right]_2 = 2w_\pi^2\left|\frac{1}{\sqrt{3}}G_{D^*N}\, g_{R,D^*N}\right|^2, \text{ for } J = \frac{3}{2}. \tag{2.9}$$

2.2 The semileptonic $\Lambda_b \to \bar{\nu}_l l \Lambda_c^*$ decay

Comparing to the nonleptonic $\Lambda_b \to \pi^-\Lambda_c^*$ decay, now we have $\bar{\nu}_l l$ production, instead of a π^-. The transition matrix T' involves the leptonic operator L^α, the quark operator Q_α and a factor $V_{\rm had}$ accounting for the hadronic interaction [15, 13],

$$T' \propto L^\alpha\, Q_\alpha\, V_{\rm had}, \qquad L^\alpha \equiv \bar{u}_l\gamma^\alpha(1-\gamma_5)v_\nu, \qquad Q_\alpha \equiv \bar{u}_c\gamma_\alpha(1-\gamma_5)u_b. \tag{2.10}$$

The partial decay width for the $\Lambda_b \to \bar{\nu}_l l \Lambda_c^*$, as a function of the invariant mass $M_{\rm inv}$ of the $(\bar{\nu} l)$ pair, is given by [13],

$$\frac{d\Gamma}{dM_{\rm inv}} = 2M_{\Lambda_b}2M_{\Lambda_c^*}2m_\nu 2m_l\frac{1}{4M^2_{\Lambda_b}}\frac{1}{(2\pi)^3}p_{\Lambda_c^*}\tilde{p}_l\overline{\sum}\sum|T'|^2, \tag{2.11}$$

with

$$\overline{\sum}\sum|T'|^2 = \frac{8C'^2}{M^2_{\Lambda_b}m_\nu m_l}\frac{M^2_{\rm inv}}{4}(\tilde{E}^2_{\Lambda_b} - \frac{1}{3}\tilde{\vec{p}}^{\,2}_{\Lambda_b})\begin{cases}\left|\frac{1}{2}G_{DN}\cdot g_{R,DN} + \frac{1}{2\sqrt{3}}G_{D^*N}\cdot g_{R,D^*N}\right|^2, & \text{for } J = 1/2\\ 2\left|\frac{1}{\sqrt{3}}G_{D^*N}\cdot g_{R,D^*N}\right|^2, & \text{for } J = 3/2\end{cases} \tag{2.12}$$

where the factor C' has the similar meaning of C in Eq. (2.7), and energies and momenta of the particles are given by

$$\tilde{E}_{\Lambda_b} = \frac{M^2_{\Lambda_b} + M^2_{\rm inv} - M^2_{\Lambda_c^*}}{2M_{\rm inv}}, \qquad |\tilde{\vec{p}}_{\Lambda_b}| = \frac{\lambda^{1/2}(M^2_{\Lambda_b}, M^2_{\rm inv}, M^2_{\Lambda_c^*})}{2M_{\rm inv}},$$

$$p_{\Lambda_c^*} = \frac{\lambda^{1/2}(M^2_{\Lambda_b}, M^2_{\rm inv}, M^2_{\Lambda_c^*})}{2M_{\Lambda_b}}, \qquad |\tilde{p}_l| = \frac{\lambda^{1/2}(M^2_{\rm inv}, m_l^2, m_\nu^2)}{2M_{\rm inv}} \equiv \frac{M_{\rm inv}}{2}.$$

3. Results

Using Eq. (2.7) and the $G_{D^{(*)}N}\, g_{R,D^{(*)}N}$ factors given in Table 2 of Ref. [12], we can evaluate the ratio of Γ for $\Lambda_c(2595)$ and $\Lambda_c(2625)$ production,

$$\frac{\Gamma[\Lambda_b \to \pi^- \Lambda_c(2595)]}{\Gamma[\Lambda_b \to \pi^- \Lambda_c(2625)]} = 0.76\ . \tag{3.1}$$

Experimentally we have [5, 12]

$$\left.\frac{\Gamma[\Lambda_b \to \pi^- \Lambda_c(2595)]}{\Gamma[\Lambda_b \to \pi^- \Lambda_c(2625)]}\right|_{\text{Exp.}} = 1.03 \pm 0.60. \tag{3.2}$$

The value that we get in Eq. (3.1) is compatible within errors.

We should call the attention to the fact that the DN and D^*N contributions are about the same for the $\Lambda_c(2595)$ case and sum constructively. Should the sign be opposite then there would be a near cancellation of the rate for the case of $\Lambda_c(2595)$ and there would have been massive disagreement with experiment. This point is worth mentioning because in Ref. [9] the signs for the D^*N couplings are opposite to those in Table 1 in Ref. [12]. The reason for the change of sign here is that in Ref. [9] a full box diagram with π exchange on each side was evaluated. This provided the value of V_{eff}^2 to be used in coupled channels of DN and D^*N and, since the sign did not matter for the spectra discussed in Ref. [9] the positive sign of V_{eff} was chosen by default. The sign here is crucial and hence, taking the negative sign for V_{eff}, is the correct choice.

We can now make prediction for the reactions $\Lambda_b \to D_s^- \Lambda_c(2595)$ and $\Lambda_b \to D_s^- \Lambda_c(2625)$. The reactions are analogous. The formulae for the widths are identical changing the kinematics to account for the larger D_s^- mass. We find

$$\frac{\Gamma[\Lambda_b \to D_s^- \Lambda_c(2595)]}{\Gamma[\Lambda_b \to D_s^- \Lambda_c(2625)]} = 0.54\ . \tag{3.3}$$

This is a good prediction that relies upon the ME(q) being about the same for the decay into $\Lambda_c(2595)$ and $\Lambda_c(2625)$. Assuming that ME(q) is the same for $\Lambda_b \to D_s^- \Lambda_c(2595)$ and $\Lambda_b \to \pi^- \Lambda_c(2595)$, we can make another prediction but with larger error,

$$BR[\Lambda_b \to D_s^- \Lambda_c(2595)] \sim (2.22 \pm 0.97) \times 10^{-4}, \tag{3.4}$$

$$BR[\Lambda_b \to D_s^- \Lambda_c(2625)] \sim (3.03 \pm 1.70) \times 10^{-4}. \tag{3.5}$$

For the semileptonic $\Lambda_b \to \bar{\nu}_l l \Lambda_c^*$ decay, by integrating the $\frac{d\Gamma}{dM_{\text{inv}}}$ in Eq. (2.11) over the dM_{inv}, we evaluate $\Gamma[\Lambda_b \to \bar{\nu}_l l \Lambda_c(2595)]$ and $\Gamma[\Lambda_b \to \bar{\nu}_l l \Lambda_c(2625)]$, and find

$$\frac{\Gamma[\Lambda_b \to \bar{\nu}_l l \Lambda_c(2595)]}{\Gamma[\Lambda_b \to \bar{\nu}_l l \Lambda_c(2625)]} = 0.39. \tag{3.6}$$

The experimental value from the PDG is [5]

$$\left.\frac{\Gamma[\Lambda_b \to \bar{\nu}_l l \Lambda_c(2595)]}{\Gamma[\Lambda_b \to \bar{\nu}_l l \Lambda_c(2625)]}\right|_{\text{Exp.}} = 0.6^{+0.4}_{-0.3}. \tag{3.7}$$

We can see that there is agreement between theory and experiment within errors.

The agreement obtained is not trivial and essentially tied to the D^*N component of the $\Lambda_c^*(2595)$ resonance. Should there be no coupling to D^*N, we would have obtained a ratio for Eq. (3.6) of the order of 0.1, clearly in contradiction with experiment, even within the large errors. On the other hand, should the relative sign between g_{R,D^*N} and $g_{R,DN}$ be the opposite, we would have obtained a ratio for Eq. (3.6) of 0.02 in shear contradiction with experiment.

4. Conclusions

We have studied the $\Lambda_b \to \pi^-(D_s^-)\Lambda_c^*$ and $\Lambda_b \to \bar{\nu}_l l \Lambda_c^*$ decays, with $\Lambda_c^* \equiv \Lambda_c(2595), \Lambda_c(2625)$, from the perspective that the two Λ_c^* resonances are dynamically generated from the DN, D^*N interaction with coupled channels. We have developed a formalism to relate the $\Lambda_b \to \pi^- DN$ and $\Lambda_b \to \pi^- D^*N$ decays. With the input for the DN, D^*N couplings to Λ_c^* obtained in Ref. [9] we can evaluate the rates for these transitions, up to a common factor involving radial matrix elements of the b and c wave functions. The ratios of rates are then predictions of the theory and are in good agreement with experiment within experimental uncertainties.

One of the important findings of the work was the relevance of the D^*N component in the $\Lambda_c(2595)$, which was overlooked in early works studying these resonances. We found that the D^*N had a strength similar to that of the DN component and was essential to have good agreement with experiment. Also, the relative sign of the coupling of the $\Lambda_c(2595)$ to DN and D^*N was of crucial importance.

The results obtained with these reactions give support to the molecular picture for these two Λ_c^* resonances. Work with other models and checks for further experiments will help us gain further insight on the nature of these resonances, and new experiments producing these two resonances should be encouraged.

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