The $\Lambda_b(6146)^0$ state newly observed by LHCb

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We study the bottom $\Lambda_b(6146)^0$ baryon, newly discovered by the LHCb Collaboration. By adopting an interpolating current of $(L_\rho, L_\lambda) = (0, 2)$ type and $D$-wave nature with spin-parity quantum numbers $J^P = \frac{3}{2}^-$ for this heavy bottom baryon, we calculate its mass and residue. The obtained mass, $m_{\Lambda_b} = (6144\pm68)$ MeV is in accord nicely with the experimental data. The obtained value of the residue of this state can be served as a main input in the investigation of various decays of this state. We calculate the spectroscopic parameters of the c-partner of this state, namely $\Lambda_c(2860)^+$, as well and compare the obtained results with the existing theoretical predictions as well as experimental data. The results indicate that the state $\Lambda_b(6146)^0$ and its charmed-partner $\Lambda_c(2860)^+$ can be considered as $1D$-wave baryons with $J^P = \frac{3}{2}^-$.

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I. INTRODUCTION

The heavy baryons containing a heavy quark play an important role in our understanding of the strong interaction. Their quark content makes them more attractive in point of studying the dynamics of light quarks when a heavy one is present. The studies on the heavy baryons with one heavy quark could improve our understanding of the confinement mechanism and provide us with test of the quark model and heavy quark symmetry. And also, the investigations on their different properties could help us test the predictions obtained by different theoretical assumptions on their internal organizations. Therefore, understanding the nature and properties of these baryons and their quantum numbers by means of theoretical and experimental studies are of great importance.

In the last decades, the advances in experimental facilities and techniques led to the observations of many new states. The new observations include the conventional hadrons and the exotic states. Some of the baryons with single heavy quark content are among these states. In the Particle Data Group (PDG) listing there exist seven $\Lambda_c$ states, which are $\Lambda_c^+, \Lambda_c(2595)^+, \Lambda_c(2625)^+, \Lambda_c(2765)^+$ (or $\Sigma_c(2765)$), $\Lambda_c(2860)^+$, $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$. On the other hand, there is a smaller number of listed $\Lambda_b$ states, which are $\Lambda_b^0, \Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$. Among these states, the $\Lambda_c(2860)^+$ was discovered in 2017 by the LHCb Collaboration. Besides the first observation of this resonance by means of an amplitude analysis of $\Lambda_b \to D^0 p \pi^-$ decay, the spin of $\Lambda_c(2880)^+$, which was firstly reported by the CLEO Collaboration, was also confirmed in this work. The quantum numbers of the $\Lambda_c(2860)^+$ state were reported as $J^P = 3/2^+$ and its measured mass and decay widths were presented as $m_{\Lambda_c(2860)^+} = 2856.1^{+2.0}_{-1.5}(\text{stat})\pm0.5(\text{syst})^{+1.1}_{-0.6}(\text{model})$ MeV and $\Gamma_{\Lambda_c(2860)^+} = 67.6^{+10.1}_{-8.2}(\text{stat})\pm1.4(\text{syst})^{+7.0}_{-5.9}(\text{model})$ MeV [2], respectively. Recently, the LHCb collaboration announced the observation of two bottom baryons with very close masses, which were reported as $m_{\Lambda_b(6146)^0} = 6146.17\pm0.33\pm0.22\pm0.16$ MeV and $m_{\Lambda_b(6152)^0} = 6152.51\pm0.26\pm0.16$ MeV. Their respective widths are $\Gamma_{\Lambda_b(6146)^0} = 2.9\pm1.3\pm0.3$ MeV and $\Gamma_{\Lambda_b(6152)^0} = 2.1\pm0.8\pm0.3$ MeV. According to their masses and widths, they were interpreted as a $\Lambda_b(1D)^0$ doublet [4].

The properties of the heavy baryons with single heavy quark were studied by different approaches in the literature. Among some of these studies, including analyses on their mass spectrum or decay mechanisms, are the various quark models, relativistic flux tube model, heavy hadron chiral perturbation theory, QCD sum rule method, light cone QCD sum rules, $3P_0$ model, Bethe-Salpeter formalism, lattice QCD and the bound state picture, etc. One may find more discussions about the related studies on the singly heavy baryons in the Refs. 71-76 and the references therein.

In this work, we direct our attention to $1D$-wave charmed and bottom baryons with spin-$\frac{3}{2}$. Although our main focus is the bottom baryon $\Lambda_b(6146)^0$ that was recently observed by the LHCb Collaboration [4], we also consider its charmed counterpart, $\Lambda_c(2860)^+$. We represent these two states as $\Lambda_Q$ where $Q$ is used to represent either $b$ or $c$ quark. Considering the proper interpolating currents for the considered states with quantum numbers $(L_\rho, L_\lambda) = (0, 2)$, we
calculate the masses and the current coupling constants for these states using QCD sum rule approach. The QCD sum rule method is a powerful nonperturbative method, which has provided successful predictions for spectroscopic and decay properties of the hadrons, so far. The $D$-wave charmed baryons were analyzed via the QCD sum rules in Refs. [42, 44]. In Ref. [42], both the charmed baryons and the bottom ones were considered in the framework of heavy quark effective theory. Ref. [44] presented the mass results only for the charmed ones obtained in full QCD. In our case, we shall consider both the bottom and charmed baryons with light $u$ and $d$ quark content in full QCD. In the calculations, we adopt an interpolating current for the $\Lambda_b$ state considering the suggestion of the LHCb Collaboration as its possibly being one of $1D$ doublet of $\Lambda_b$ states. This suggestion was made considering the consistency of the mass of the observed $\Lambda_b$ states with the predictions presented by the constituent quark model [14, 15].

Such spectroscopic analyses improve our understanding of the nature and structure of this baryons and contribute to our understanding of the nonperturbative natures of the strong interaction. From the analyses, we may deduce information about the quantum numbers of these states, as well. Beside these, another issue in baryon physics is the so-called missing resonances problem. According to the quark model, three constituent quarks comprise the baryons and, as a result, theoretically there should be more states compared to experimentally observed ones. One suggestion to solve this problem is considering a heavy quark-light diquark picture, which reduces the number of excited states as a result of the reduction of the number of degrees of freedom. Considering this, we adopt an interpolating current in our calculation in the form of a heavy quark-light diquark with quantum numbers $J^P = 3/2^+$. This paper has the following organization. In Sec. II we give the details of the QCD sum rules calculations for the physical quantities. Section III is devoted to the numerical analyses and displaying of the results. The last section contains a summary of the results and conclusions.

II. QCD SUM RULE CALCULATIONS FOR THE $\Lambda_b$ AND $\Lambda_c$ STATES

After choosing a proper interpolating current that carries the same quantum numbers and same quark field operators in accordance with valance quark content, the following correlation function is chosen to calculate the spectroscopic parameters of the states under consideration:

$$\Pi_{\mu\nu}(q) = i \int d^4xe^{iq\cdot x} \langle 0 | T \{J_{\mu}(x)\bar{J}_{\nu}(0)\} | 0 \rangle,$$

(1)

where $T$ is time ordering operator and $J_{\mu}$ is the interpolating current with following explicit form [44]:

$$J_{\mu} = \epsilon^{abc}[\partial_\alpha \partial_\beta u^a_T C\gamma_5 d_b + \partial_\alpha u^a_T C\gamma_5 \partial_\beta d_b + \partial_\beta u^a_T C\gamma_5 \partial_\alpha d_b + u^a_T C\gamma_5 \partial_\alpha \partial_\beta d_b](g^{\alpha\mu}g^{\beta\delta} + g^{\alpha\delta}g^{\beta\mu} - \frac{1}{2}g^{\alpha\beta}g^{\mu\delta})\gamma^5 Q_c.$$  

(2)

In the above interpolating current, the $Q$ represents $b(c)$ quark field, $C$ is charge conjugation operator and the indices $a$, $b$ and $c$ display the colors.

One follows two paths to calculate the correlation function. In the first one, it is computed in terms of hadronic degrees of freedom. This is done by saturation of the correlation function by a complete set of hadronic states with the same quantum numbers of the interpolating current. After that the results emerge in terms of hadronic degrees of freedom such as the current coupling constant and mass of the considered hadron. This procedure leads to

$$\Pi_{\mu\nu}^{\text{Had}}(q) = \frac{\langle 0 | J_{\mu} | \Lambda_Q(q,s) \rangle \langle \Lambda_Q(q,s) | \bar{J}_{\nu} | 0 \rangle}{m_{\Lambda_Q}^2 - q^2} + \cdots.$$  

(3)

The \cdots represents the contributions of the higher states and continuum. The matrix element $\langle 0 | J_{\mu} | \Lambda_Q(q,s) \rangle$ in the last result is parameterized in terms of the current coupling constant, $\lambda_{\Lambda_Q}$, and spin vector in Rarit-Schwinger representation, $u_{\mu}(q,s)$, as

$$\langle 0 | J_{\mu} | \Lambda_Q(q,s) \rangle = \lambda_{\Lambda_Q} u_{\mu}(q,s).$$  

(4)

When this matrix element is used in Eq. (3) we need to perform the following summation over spin $s$:

$$\sum_{s} u_{\mu}(q,s)\bar{u}_{\nu}(q,s) = (\not{g} + m)(-g_{\mu\nu} + \frac{\gamma_{\mu}\gamma_{\nu}}{3} + \frac{2g_{\nu}q_{\nu}}{3m_{\Lambda_Q}^2} - \frac{q_{\mu}q_{\nu} - q_{\nu}q_{\mu}}{3m_{\Lambda_Q}^2}),$$  

(5)

which recasts the result into the form

$$\Pi_{\mu\nu}^{\text{Had}}(q) = \frac{\lambda_Q^2 (\not{g} + m_{\Lambda_Q})}{m_{\Lambda_Q}^2 - q^2}(-g_{\mu\nu} + \frac{\gamma_{\mu}\gamma_{\nu}}{3} + \frac{2g_{\nu}q_{\nu}}{3m_{\Lambda_Q}^2} - \frac{q_{\mu}q_{\nu} - q_{\nu}q_{\mu}}{3m_{\Lambda_Q}^2}) + \cdots.$$  

(6)
The interpolating current used in the calculations couples not only with spin-$\frac{1}{2}$ states but also spin-$\frac{1}{2}$ states. Therefore to refrain from the contributions of spin-$\frac{1}{2}$ states and isolate the terms related only to spin-$\frac{1}{2}$ states, we choose a proper Lorentz structure free from spin-$\frac{1}{2}$ contribution. To this end, we consider the following matrix element showing the coupling of the chosen current to spin-$\frac{1}{2}$ states:

$$
\langle 0| J_{\mu}^{1+} \frac{1}{2} (q) \rangle = C_{\frac{1}{2}} \left( \gamma_{\mu} + \frac{4q_{\mu}}{m} \right) \gamma_{5} u(q, s).
$$

(7)

This matrix element indicates that the terms containing $\gamma_{\mu}$ and $q_{\mu}$ in the Lorentz structures take also contributions from spin-$\frac{1}{2}$ states due to the coupling of the current with them. To isolate the spin-$\frac{1}{2}$ states we make our analyses with the Lorentz structure $\not q g_{\mu\nu}$. Finally, the hadronic side results in

$$
\hat{\Pi}_{\mu\nu}^{\text{Had}}(q) = \lambda_{A_Q}^{2} e^{-\frac{m}{T}} \not q g_{\mu\nu} + \cdots,
$$

(8)

after the Borel transformation. $\hat{\Pi}_{\mu\nu}^{\text{Had}}(q)$ represents the Borel transformed correlation function obtained for hadronic side, the $\cdots$ in the last result stands for both the contributions coming from the other Lorentz structures and from higher states and continuum.

The second step in the calculations is computation of the correlation function in terms of QCD degrees of freedom such as QCD condensates, quark masses and QCD coupling. To accomplish this part of the calculations, the interpolating current is used explicitly in the correlator and possible contractions between the quark fields are carried out using Wick’s theorem. This turns the result into a form containing heavy and light quark propagators:

$$
\Pi_{\mu\nu}^{\text{QCD}} = -i \int d^{4}x e^{i q x} e_{abc} e_{a'b'c'} \left\{ \text{Tr} \left[ \left[ \not \partial_x \gamma_{\mu} \gamma_{\nu} \not S_{u}^{a'}(x-y) \right] \gamma_{5} C S_{d}^{T,b'b'}(x-y) C_{5} \right] \right. \\
+ \left. \text{Tr} \left[ \left[ \not \partial_x \gamma_{\mu} \gamma_{\nu} \not S_{u}^{a'}(x-y) \right] \gamma_{5} C \left[ \not \partial_y \gamma_{5} S_{d}^{T,b'b'}(x-y) C_{5} \right] \right] + \text{Tr} \left[ \left[ \not \partial_x \gamma_{5} \not S_{u}^{a'}(x-y) \right] \gamma_{5} C \left[ \not \partial_y \gamma_{5} S_{d}^{T,b'b'}(x-y) C_{5} \right] \right] \\
+ \left. \text{Tr} \left[ \left[ \not \partial_x \gamma_{5} \not S_{u}^{a'}(x-y) \right] \gamma_{5} C \left[ \not \partial_y \gamma_{5} S_{d}^{T,b'b'}(x-y) C_{5} \right] \right] \right\} T_{\alpha\beta\mu}^{c_{Q}}(x-y) T_{\alpha'\beta'\nu},
$$

(9)

where $\not \partial_x = \frac{\partial}{\partial x}$, $\not \partial_y = \frac{\partial}{\partial y}$, and $S_{q}(x-y)$ and $S_{Q}(x-y)$ are the light and heavy quark propagators, respectively. We have also used the short-hand notation,

$$
T_{\alpha\beta\mu} = (g_{\alpha\mu} g_{\beta\delta} + g_{\alpha\delta} g_{\beta\mu} - \frac{1}{2} g_{\alpha\beta} g_{\mu\delta}) \gamma^{5} \gamma_{5}.
$$

(10)

In the last equation, after taking the derivatives we set $y$ to zero. The propagators in Eq. (9) are used explicitly in the calculations to obtain the QCD side of the sum rules. Their explicit forms are

$$
S_{q,ab}(x) = i \delta_{ab} \frac{x}{2 \pi^{2} x^{3}} - \delta_{ab} \frac{m_{q}}{4 \pi^{2} x^{2}} - \delta_{ab} \frac{\langle \bar{q}q \rangle}{12} + i \delta_{ab} \frac{x^{2} f_{q}(q)}{48} - \delta_{ab} \frac{x^{2}}{192} \frac{m_{q}}{g_{q} \sigma G_{q}} + i \delta_{ab} \frac{x^{2} f_{q}(q)}{1152} \\
- i \frac{g_{q}}{32 \pi^{2} x^{2}} \left[ \sigma_{\alpha\beta} + \sigma_{\alpha\beta} \not q \right] - i \delta_{ab} \frac{x^{2} \not q g_{q}(\not q)^{2}}{7776},
$$

(11)
and

\[ S_{Q,ab}(x) = i \int \frac{d^4 k}{(2\pi)^4} e^{-ikx} \left\{ \frac{\delta_{ab}(k + m_Q)}{k^2 - m_Q^2} \frac{g_s G^\alpha_3}{4} \sigma_{\alpha\beta} \frac{(k + m_Q) + (k + m_Q)\sigma_{\alpha\beta}}{(k^2 - m_Q^2)^2} + \frac{g_s^2 G^2}{12} \delta_{ab} m_Q \frac{k^2 + m_Q k}{(k^2 - m_Q^2)^4} \right\}, \]

(12)

for the light and the heavy quark propagators in the coordinate space, respectively. The following notations are also used in Eqs. (11) and (12):

\[ G^\alpha_3 = G^A_3 \tau^A, \quad G^2 = G^A G^A, \quad G^3 = f^{ABC} G^A_{\mu\nu} G^B_{\nu\lambda} G^C_{\mu\sigma}, \]

(13)

with \(A, B, C = 1, 2 \ldots 8\) and \(\tau^A = \lambda^A/2\). \(\lambda^A\) are the Gell-Mann matrices, and the \(G^A_{\mu\nu}\) represent the gluon field strength tensors. Insertion of the propagators into the correlation function is followed by Fourier and Borel transformations. Finally, continuum subtraction is applied and the following result is achieved:

\[ \tilde{\Pi}^{\text{QCD}} = \int_{(m_Q + m_a + m_b)^2}^{s_0} dse^{-\frac{m_s^2}{sL^2}} \rho(s) + \Gamma. \]

(14)

where \(s_0\) is the continuum threshold and \(\rho(s)\) is the spectral density obtained from the imaginary part of the correlation function, viz \(\text{Im}\tilde{\Pi}^{\text{QCD}}\). In the analyses, as it was stated, to isolate the contribution coming only from the spin-1/2 states the Lorentz structure is chosen as \(qg_{\mu\nu}\). The standard calculations lead to the following results for \(\rho(s)\) and \(\Gamma\) corresponding to this Lorentz structure:

\[ \rho(s) = \rho_{\text{Pert}}(s) + \rho_{\text{Dim3}}(s) + \rho_{\text{Dim4}}(s) + \rho_{\text{Dim6}}(s), \]

(15)

where

\[ \rho_{\text{Pert}}(s) = - \int_0^1 dx \frac{1}{256\pi^4(x-1)^2} \left( m_Q^2 + s(x-1) \right)^3 \left[ m_Q^3 (8x - 3) + s(3 - 19x + 16x^2) \right] \theta[L(s, x)], \]

\[ \rho_{\text{Dim3}}(s) = - \int_0^1 dx \frac{1}{16\pi^2} \left[ m_u (\bar{u}u - 2\bar{d}d) + m_d (\bar{d}d - 2\bar{u}u) \right] x^2 \left[ m_Q^3 (8x - 1) + s^2 (x - 1)^2 (12x - 1) \right] \theta[L(s, x)], \]

\[ \rho_{\text{Dim4}}(s) = - \int_0^1 dx \frac{1}{384\pi^2(x-1)^2} \left( \frac{\alpha_s}{\pi} G^2 \right)^2 \left[ 3s^2 (x - 1)^4 (12x - 1) + m_Q^4 (-3 + 30x - 57x^2 + 40x^3) \right] \theta[L(s, x)], \]

\[ \rho_{\text{Dim5}}(s) = 0, \]

\[ \rho_{\text{Dim6}}(s) = \int_0^1 dx \frac{1}{12288\pi^4(x-1)^2} \left( g_s^3 G^3 \right)^2 x^5 \left[ 7s (1 - 10x + 21x^2 - 12x^3) - 4m_Q^2 (-6 + 5x + 12x^2) \right] \theta[L(s, x)], \]

(16)

and

\[ \Gamma = \int_0^1 dx e^{-\frac{m^2}{s(x-1)^2}} \frac{1}{2048\pi^4(x-1)^4} \left( g_s^3 G^3 \right)^2 m_Q^4 (x - 8) x^5. \]

(17)

Here \(\theta[\ldots]\) is the usual unit-step function and

\[ L(s, x) = sx(1 - x) - m_Q^2 x. \]

(18)

After completing the calculations for both the hadronic and QCD sides, the next stage is equating the coefficient of the same Lorentz structure obtained from each side, that is \(qg_{\mu\nu}\), as a result we get

\[ \lambda^2 e^{-\frac{m^2}{s(1-x)}} = \tilde{\Pi}^{\text{QCD}}. \]

(19)
| Parameters | Values |
|-----------|--------|
| $m_c$     | $1.27 \pm 0.02$ GeV [80] |
| $m_b$     | $4.18^{+0.02}_{-0.01}$ GeV [80] |
| $m_u$     | $2.16^{+0.28}_{-0.24}$ MeV [80] |
| $m_d$     | $4.67^{+0.47}_{-0.17}$ MeV [80] |
| $(\bar{q}q) (1 \text{GeV})$ | $(-0.24 \pm 0.01)^3$ GeV$^3$ [81] |
| $m_{\Xi_0}^2$ | $(0.8 \pm 0.1)$ GeV$^2$ [81] |
| $\langle \frac{G^2}{2G^2} \rangle$ | $(0.012 \pm 0.004)$ GeV$^4$ [82] |
| $\langle g_3^2 G^3 \rangle$ | $(0.57 \pm 0.29)$ GeV$^6$ [83] |

**TABLE I:** Some input parameters used in the calculations of the masses and current coupling constants.

Using this relation we obtain the masses of the considered hadrons and their current coupling constants. Thus, for the mass we obtain

$$m_{\Lambda_Q}^2 = \frac{\frac{d}{ds} \left[ \int_{(m_Q+m_u+m_d)^2}^{s_0} ds e^{-\frac{s}{M^2}} \rho(s) + \Gamma \right]}{\int_{(m_Q+m_u+m_d)^2}^{s_0} ds e^{-\frac{s}{M^2}} \rho(s) + \Gamma}, \quad (20)$$

and the current coupling constant is obtained as

$$\lambda_{\Lambda_Q}^2 = e^{-\frac{m_{\Lambda_Q}^2}{M^2}} \left[ \int_{(m_Q+m_u+m_d)^2}^{s_0} ds e^{-\frac{s}{M^2}} \rho(s) + \Gamma \right]. \quad (21)$$

### III. NUMERICAL ANALYSES

The results obtained in the previous section are numerically analyzed using the input parameters given in Table I and the working windows of auxiliary parameters such as threshold parameter $s_0$ and Borel parameter $M^2$. Although our main focus in the present work is the mass and current coupling constant of $\Lambda_b(6146)^0$ state, for completeness we also calculate the mass and current coupling constant for $\Lambda_c(2860)^+$ state.

To determine the working intervals for the auxiliary parameters we consider the criteria of the QCD sum rule method such as the convergence of OPE and dominance of the pole contribution. Beside these requirements, the dependencies of the results on these parameters are demanded to be relatively weak. As an asymptotic expansion, the dominant contribution to the OPE side should come from perturbative contribution and the terms with higher dimensions contribute less and less. To fix the lower limit of the Borel parameter we consider the convergence ratio, $CR(M^2)$, that is the ratio of the contribution of the highest dimensional term in the OPE side to the total one and it is given as

$$CR(M^2) = \frac{\Pi_{\text{Dime}}(M^2, s_0)}{\Pi(M^2, s_0)}. \quad (22)$$

To determine the lower limit of Borel parameter we consider this ratio to be less than 5% for $\Lambda_Q$ state. The pole contribution, $PC(M^2)$ is considered to be larger or at least equal to the 10% for the D-wave state,

$$PC(M^2) = \frac{\Pi(M^2, s_0)}{\Pi(M^2, \infty)} \geq 0.10. \quad (23)$$

Our analyses result in the following intervals of the Borel parameters:

- For $\Lambda_b$ state and
  $$5.2 \text{ GeV}^2 \leq M^2 \leq 6.2 \text{ GeV}^2,$$
  (24)

- for $\Lambda_c$ state. In the analyses, the working windows of the threshold parameters, $s_0$ are decided as
  $$41.5 \text{ GeV}^2 \leq s_0 \leq 43.3 \text{ GeV}^2,$$
  (26)
| The state | Mass (MeV) | Current coupling constant $\lambda$ (GeV$^2$) |
|-----------|------------|------------------------------------------|
| $\Lambda_b$ | 6144 ± 68  | 0.264 ± 0.039                          |
| $\Lambda_c$ | 2855 ± 66  | 0.080 ± 0.012                          |

TABLE II: The results of the masses and current coupling constants obtained for 1D wave $\Lambda_b$ and $\Lambda_c$ states with $J^P = \frac{3}{2}^+$. for $\Lambda_b$ state and

$$10.8 \text{ GeV}^2 \leq s_0 \leq 11.6 \text{ GeV}^2,$$

for $\Lambda_c$ state. In these intervals the variations of the physical quantities with respect to the changes of $s_0$ are weak. The weak dependencies of the results on the auxiliary parameters form the main parts of the errors present in predictions of the QCD sum rules method. With these errors and the errors coming from the other input parameters used in the analyses our results are presented in Table II. To display the dependencies of our results on $M^2$ and $s_0$ we also present Fig. 1 showing the variations of mass and current coupling constant of $\Lambda_b$ state as functions of $M^2$ and $s_0$. This figure shows mild dependencies of the results on these parameters, as expected. Note that, as the interpolating currents for the $D$-wave baryons contain second order derivatives their residues or current coupling constants are obtained in GeV$^5$ against the usual $S$-wave and $P$-wave baryonic states that these quantities are in GeV$^3$.

![Figure 1](image_url)

**FIG. 1:** **Left:** The variation of the mass $m_{\Lambda_b}$ as a function of Borel parameter $M^2$ and threshold parameters $s_0$. **Right:** The variation of the current coupling constant $\lambda_{\Lambda_b}$ as a function of Borel parameter $M^2$ and threshold parameters $s_0$.

### IV. DISCUSSION AND CONCLUSION

We calculated the mass and the current coupling constant of the recently observed $\Lambda_b(6146)^0$ state assigning its quantum numbers as $J^P = \frac{3}{2}^+$. This state together with the $\Lambda_b(6152)^0$ (probably a 1D-wave state with $J^P = \frac{5}{2}^+$) form a $\Lambda_b(1D)^0$ doublet. Based on the provided information by recent experimental results, we choose a $D$-wave type interpolating current for $\Lambda_b(6146)^0$ state. For completeness, we also calculated the spectroscopic parameters of its charmed partner $\Lambda_c$ state with the same quantum numbers. The result for the mass of the $\Lambda_b$ state was obtained to be $m_{\Lambda_b} = (6144 \pm 68)$ MeV, which is in a good consistency with other theoretical predictions: $m_{\Lambda_b} = 6147$ MeV [33], $m_{\Lambda_b} = 6190$ MeV [18], $m_{\Lambda_b} = 6181$ MeV [17], $m_{\Lambda_b} = 6195$ MeV [7], $m_{\Lambda_b} = 6149$ MeV [84], and $6.01^{+0.29}_{-0.12}$ GeV [42]. Our result on the mass of the $\Lambda_b$ is in accord with the experimental data of the LHCb Collaboration, as well. This supports the $\Lambda_b(6146)^0$ state to be a 1D-wave resonance with quantum numbers $J^P = \frac{3}{2}^+$. The mass result obtained for 1D wave $\Lambda_c$ state with $J^P = \frac{3}{2}^+$ is $m_{\Lambda_c} = (2855 \pm 66)$ MeV, which is also consistent, within the errors, with the predictions of Refs. [8, 17, 18, 25, 33, 42] given as $m_{\Lambda_c} = 2857$ MeV, $m_{\Lambda_c} = 2874$ MeV, $m_{\Lambda_c} = 2887$ MeV, $m_{\Lambda_c} = 2910$ MeV, $m_{\Lambda_c} = 2843$ MeV, $m_{\Lambda_c} = 2.81^{+0.18}_{-0.18}$ GeV, and $m_{\Lambda_c} = 2.83^{+0.15}_{-0.24}$ GeV, respectively. Our result is also in agreement with experimentally observed mass value for $\Lambda_c(2860)^+$ state which is $m_{\Lambda_c(2860)^+} = 2856.1^{+2.3}_{-6.0}$ MeV. This can be considered as another support to assign these states as resonances in $b$ and $c$ 1D-wave channels with spin-parity $J^P = \frac{3}{2}^+$. 
The results obtained for the spectroscopic parameters and the nature and quantum numbers of the states under study may be supported by further analyses on the electromagnetic, strong or weak decay processes of these states. We plan to make such analyses using the same interpolating currents in a future study. Such investigations will complete our knowledge on the new resonances of heavy baryons. The results obtained for the residues or current coupling constants of these states can be used as the main inputs in investigation of various decay properties of these states.

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