The role of newly discovered $\Xi_b(6227)^-$ for constructing excited bottom baryon family

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Selecting the newly observed $\Xi_b(6227)^-$ by LHCb as a study example, we decode its inner structure by giving the mass spectrum analysis and the investigation of its two-body strong decay behaviors. Our result indicates that the $\Xi_b(6227)^-$ is a good candidate of $P$-wave $\Sigma_b^*$ state with $J^P = 3/2^-$ or $5/2^-$. In addition, we further provide the information of the properties of the partners of the $\Xi_b(6227)^-$. These predicted states include three $2S$ states and the remaining $1P$ states in bottom-strange baryon family. The calculated sizable OZI-allowed decay widths of those partners show that experimental search for them becomes possible via LHCb. We have a reason to believe that the present study can be treated as a start point for constructing the highly excited bottom baryon spectroscopy.

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I. INTRODUCTION

As an important part of the hadron spectrum, the heavy baryon family is being established step by step with the cooperative efforts from both experimentalist and theorist. A typical example is the charmed baryon group. In the past twenty years, there were about twenty candidates of charmed baryon have been announced by the different experimental collaborations [1]. However, searching for the bottom baryon states is not an easy task for experimentalist since production of the bottom baryons seems to be more difficult than that of the charmed baryon case.

![Diagram of discovered bottomed baryons and established 1S baryon multiplets](image)

FIG. 1: The discovered bottomed baryons and the established 1S baryon multiplets.

The first discovered bottom baryon state, $\Lambda_b(5620)^0$, was reported by CERN R415 in 1981 [2], while the first evidence of the $\Xi_b(5792)^0$ and the $\Xi_b(5795)^-$ with $I(J^P) = 1/2(1^-)$ was reported by DELPHI in 1995 [3]. In the following twelve years, almost no experimental progress on searching for the new bottom baryons had been made. This situation was changed in 2007 since the $\Xi_b(5815)^0$ and $\Sigma_b^*(5835)^-$ with $I(J^P) = 1(1^-)$ and $I(J^P) = 1(3^-)$ respectively were discovered by CDF [4]. After that, more bottom baryons were reported, especially with the running of LHCb [5–7]. We summarize all observed bottom baryons in Fig. 1. Until now, the $1S$ states of bottom baryon family almost have been established experimentally except the $\Sigma_b^0/\Xi_b^0$ with $J^P = 1/2^+$ and the $\Lambda_b^0/\Omega_b^-$ with $J^P = 3/2^+$. In addition, there were two observed $P$-wave $\Lambda_b^0$ states, i.e., the $\Lambda_b(5912)^0$ and the $\Lambda_b(5920)^0$ [7, 8]. Other excited bottom baryons are waiting for exploration. Obviously, it is time for LHCb.

Very recently, the LHCb brought us a surprise since a new bottom baryon state, the $\Xi_b(6227)^-$, was found in both $\Lambda_b^0K^-$ and $\Xi_b^0\pi^-$ channels [9], which has the resonance parameters

$$M = 6226.9 \pm 0.3$$(stat) $\pm 0.2$$(syst) MeV,$$
$$\Gamma = 18.1 \pm 5.4$$(stat) $\pm 1.8$$(syst) MeV.$$

We would like to emphasize none of excited bottom baryon states has been seen in its Okubo-Zweig-Iizuka (OZI)-allowed decay channels before the observation of the $\Xi_b(6227)^-$. Thus, the $\Xi_b(6227)^-$ is the first excited bottom baryon state which was identified by the OZI-allowed decay modes. In addition, the measured relative production rates indicate that two allowed decay modes, i.e., $\Lambda_b^0K^-$ and $\Xi_b^0\pi^-$, may have the nearly equal branching ratios for the $\Xi_b(6227)^-$. [9]

Obviously, the $\Xi_b(6227)^-$ is a key state when we begin to establish whole excited bottom baryon spectroscopy. In this work, the main task is to reveal the inner structure of this newly observed state by the analysis of mass spectrum and corresponding OZI-allowed decay behavior. We find that the $\Xi_b(6227)^-$ is most likely a $P$-wave $\Sigma_b^*$ state with $J^P = 3/2^-$ or $5/2^-$. Besides making such a conclusion, we also predict the properties of the partners of the $\Xi_b(6227)^-$, which

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include the $2S$ states and the remaining $1P$ states in bottom-strange baryon sector. Since these states have the sizable OZI-allowed decay modes, experimental searching for them will be an interesting research issue. We believe that treating the $\Xi_b(6227)^-$ as a $P$-wave bottom baryon is not only the start point of constructing the whole excited bottom baryons, but also can make the hadron spectroscopy become complete, which is helpful to further understand the non-perturbative behavior of Quantum Chromodynamics (QCD).

This paper is organized as follows. After introduction, we decode the newly reported $\Xi_b(6227)^-$ as a $P$-wave bottom-strange baryon in Sec. II, where the analysis of mass spectrum and the calculation of strong decay behaviors can provide the direct support to this scenario. Finally, the paper ends with the discussion and conclusion in Sec. III.

II. DECODING THE PROPERTY OF THE $\Xi_b(6227)^-$

Since the $\Xi_b(6227)^-$ state was observed in the decay channels $\Lambda_b^0K^-$ and $\Xi_b^0\pi^-$, we conclude that it must contain $sbd$ quark component. To reveal its property, a mass spectrum analysis should be given. In the past years, the mass spectra of highly excited bottom baryons were investigated by several phenomenological models, which include the nonrelativistic quark model [10], the QCD-motivated relativistic quark model [11], the QCD motivated hypercentral quark model [12], the Faddeev formalism [13] or method [14], the relativistic flux tube model [15], the QCD sum rule [16], and the Regge phenomenology [17]. These studies of the mass spectrum of bottom baryon support the assignment of the $\Xi_b(6227)^-$ as a $2S$ or $1P$ state in the bottom-strange baryon sector.

As suggested in our former work [18, 19], the heavy-light baryon system can be treated as a quasi-two-body system in the heavy quark-light diquark picture\(^1\). Thus, the Cornell potential [20] is used to phenomenologically depict the confining interaction between a bottom quark and the light diquark. Under this treatment, we may construct the following the Schrödinger equation

$$\left( -\frac{\nabla^2}{2m_\mu} - \frac{4\alpha}{3r} + br + C + \frac{32\alpha\sigma^3}{9\sqrt{\pi}m_\mu m_b} \vec{S}_{d1} \cdot \vec{S}_b \right) \psi_{nl} = E\psi_{nl}. \tag{1}$$

Here, $\vec{S}_{d1}$ and $\vec{S}_b$ denote the spins of light diquark and the $b$ quark, respectively. The spin-spin contact hyperfine interaction in Eq. (1) is important for the $nS$ states. The reduced mass is defined as $m_{\mu} \equiv m_\mu/(m_{d1} + m_b)$. The parameters $\alpha$, $b$, and $C$ stand for the strength of the color Coulomb potential, the strength of linear confinement, and a mass-renormalized constant, respectively. By solving the Schrödinger equation, the spin averaged masses of these excited bottom baryons can be obtained. When the spin-orbit and tensor interactions are included, all masses of $P$-mode excited bottom-strange baryons can be calculated. All values of parameters used in our calculation are listed in Table I.

![Fig. 2: The obtained masses (blue and red solid lines) for the bottom-strange baryons. Here, we also listed the measured masses of the ground states [1] and the $\Xi_b(6227)^-$ [9], which are marked by “•”. We need to specify that these $\Xi_b$ states are composed of a good diquark ($S_{d1} = 0$) and a bottom quark while these $\Xi_b'$ states contain a bad diquark ($S_{d1} = 1$) and a bottom quark.](image)

Table I: Values of the parameters for the bottomed baryons in the nonrelativistic quark potential model where the mass of $b$ quark is taken as 4.96 GeV. $m_\mu$ refers to the mass of different diquark.

| Parameters | $m_\mu$ (GeV) | $\alpha$ | $b$ (GeV) | $C$ (GeV) |
|-----------|---------------|----------|----------|-----------|
| $\Lambda_b$ | 0.45 | 0.20 | 0.112 | - | 0.265 |
| $\Xi_b$ | 0.63 | 0.26 | 0.118 | - | 0.176 |
| $\Sigma_b$ | 0.66 | 0.22 | 0.116 | 1.20 | 0.185 |
| $\Xi_b'$ | 0.78 | 0.22 | 0.116 | 1.20 | 0.152 |
| $\Omega_b$ | 0.91 | 0.26 | 0.120 | 1.07 | 0.120 |

\(^1\) The basic consideration of why we can simplify a heavy-light baryon system as a quasi-two-body system in the heavy quark-light diquark picture and the details of calculation have been explained in Refs. [18, 19].

We present the calculated masses of bottom-strange baryons in Fig. 2, and make a comparison of them with the experimental data. We also list several typical thresholds, which are denoted by the grey solid lines in Fig. 2. Obviously, the quark potential model adopted here has reproduced the masses of three observed ground states of the bottom-strange baryon family. And then, we may find that the newly observed state, the $\Xi_b(6227)^-$, could be a candidate of a $2S$ $\Xi_b$ state or a $1P$ $\Xi_b'$ state only by this mass spectrum analysis, where the theoretical value is close to the mass of the $\Xi_b(6227)^-$ under the $2S$ and $1P$ assignments. To give further constraints on its quantum number, we will investigate the strong decays in the following.

For carrying out the study of strong decay behaviors of the discussed bottom-strange baryons, we employ the quark pair creation (QPC) model [21–23] to calculate their two-body
OZI-allowed decays. The QPC model has been extensively used to study the strong decays of different kinds of hadrons. For a decay process of an excited $b$sq baryon state ($q$ designates a $u$ or $d$ quark), $A(q(1)s(2)b(3)) \rightarrow B(q(5)s(2)b(3)) + C(q(1)q(4))$, the transition matrix element in the QPC model is written as $\langle BC|\hat{T}|A\rangle = \delta^3(\mathbf{k}_B + \mathbf{k}_C)M_{1^{−,0,−};jB;C}^A(p)$, where the transition operator $\hat{T}$ reads as

$$\hat{T} = -3\gamma \sum_{m}(1, m; 1, -m)(0, 0) \int d^3k_3d^3k_5\delta^3(\mathbf{k}_4 + \mathbf{k}_5) \times Y^m_1(k_4 - k_5)\frac{\omega_0^{(4,5)}\varphi_0^{(4,5)}X_{1, m}^d(k_4)d_3^*(k_5)}{2}$$

(2)

in a non-relativistic limit. Here, the $\omega_0^{(4,5)}$ and $\varphi_0^{(4,5)}$ are the color and flavor wave functions of the $q_dq_s$ pair created from the vacuum, respectively. Therefore, $\omega_0^{(4,5)} = (RR + GG + BB)/\sqrt{3}$ and $\varphi_0^{(4,5)} = (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$ are color and flavor singlets. The $X_{1, m}^d(k)$ represents the pair production in a spin triplet state. The solid harmonic polynomial $Y^m_1(k) = |k|Y^m_1(\theta_k, \phi_k)$ reflects the momentum-space distribution of the $q_dq_s$. The dimensionless parameter $\gamma$ describes the strength of the quark-antiquark pair created from the vacuum.

The useful partial wave amplitude is related to the helicity amplitude $M_{1^{−,0,−};jB;C}^A(p)$ by

$$M_{1s}^{−B+C}(p) = \frac{\sqrt{2L + 1}}{2J_A + 1} \sum_{j_B, j_C} \langle L0j_A|J_Aj_A\rangle \times \langle J_BB|J_DC|J_J\rangle M_{1^{−,0,−};jB;C}^A(p)$$

(3)

where the $J_i$ and $j_i$ ($i = A, B,$ and $C$) denote the total angular momentum and their projection of initial and final hadron states, respectively. $L$ denotes the orbital angular momenta between the final states $B$ and $C$. Finally, the partial width of $A \rightarrow BC$ is written in terms of the partial wave amplitudes as

$$\Gamma(A \rightarrow BC) = 2\pi \frac{E_BE_C}{M_A} p \sum_{LS} |M_{LS}(p)|^2$$

(4)

in the $A$ rest frame. To obtain the concrete expressions of $M_{1^{−,0,−};jB;C}^A(p)$, an integral $I_{1, m}^{A,B}(p)$ should be performed, which describes the overlap of the spatial functions of the initial state ($A$), the created pair from the vacuum, and two final states ($B$ and $C$). Usually, the simple harmonic oscillator (SHO) wave function $\psi_{n, l}^m(k) = R_{n, l}(\beta, k)Y_{n}^m(k)$ is taken to construct the spatial wave function of a hadron state. In this way, the analytical $I_{1, m}^{A,B}(p)$ can be extracted. In our calculations, all values of the SHO wave function scale (denoted as “$\beta$”), which reflect the distances between the light diquark and the $b$ quark in the bottomed baryons, are obtained by reproducing the realistic root mean square radius via the Eq. (1). The results are collected in Table II. The values of $\beta$s for light diquark and other related hadrons are taken from our previous work [18]. In this work, the value of $\gamma$ is taken as 1.296 since the measured widths of 2S and 1P states of charmed and charmed-strange baryons have been reproduced in Ref. [18].

With the preparation above, we firstly test our method by calculating the partial widths of these observed 1S bottom baryon states. At present, only the 1S bottomed baryons have been reported by experiments in their OZI-allowed decay channels. In Table III, we make a comparison between theoretical and experimental results of partial decay widths, which shows that the measured decay behaviors of the $\Sigma_b(5815)^−$, $\Sigma_b(5835)^−$, $\Xi_b(5935)^−$, and $\Xi_b′(5955)^−$ can well explained. Thus, the reliability of our method is tested due to this success, which makes us to apply it to study the strong decay behaviors of these discussed 1P and 2S $b$sq states.

### Table II: The effective $\beta$ values for the different bottomed baryon states (in GeV).

| States     | $\beta_0$ | $\beta_1$ | $\beta_2$ | $\beta_3$ |
|------------|-----------|-----------|-----------|-----------|
| $1S(1/2^−)$ | 0.288     | 0.341     | 0.345     | 0.367     | 0.404     |
| $1S(3/2^−)$ | 0.334     | 0.355     | 0.390     |           |
| $2S$       | 0.157     | 0.181     | 0.181     | 0.191     | 0.206     |
| $3S$       | 0.115     | 0.131     | 0.132     | 0.139     | 0.148     |
| $1P$       | 0.198     | 0.227     | 0.228     | 0.241     | 0.258     |
| $2P$       | 0.131     | 0.149     | 0.150     | 0.158     | 0.169     |
| $1D$       | 0.157     | 0.179     | 0.179     | 0.189     | 0.201     |

### Table III: The calculated and measured decays of the 1S $\Sigma_b$ and $\Xi_b$ baryons (in MeV).

| Decay channels | Prediction | Experiments [1] |
|----------------|------------|-----------------|
| $\Sigma_b(5815)^− \rightarrow \Lambda_b^0\pi^−$ | 5.12 | 4.9$^{+3.1}_{−2.4}$ |
| $\Sigma_b(5835)^− \rightarrow \Lambda_b^0\pi^−$ | 9.13 | 7.5$^{±2.3}$ |
| $\Xi_b(5935)^− \rightarrow \Xi_b^0\pi$ | 0.05 | $<0.08, CL=95\%$ |
| $\Xi_b(5955)^− \rightarrow \Xi_b^0\pi$ | 1.09 | 1.65$±0.33$ |

#### A. 2S states

As shown in Fig. 2, there are three 2S states of bottom-strange baryons, i.e., the $\Xi_b(6255)$, $\Xi_b^0(6365)$, and $\Xi_b'(6376)$, where we use the theoretical values to distinguish these three states. Their decay properties are collected in Table IV.

The predicted $\Xi_b(6255)$ cannot decay into $\Lambda_bK$ and $\Xi_b\pi$ since these decay modes are forbidden for the 2S $\Xi_b$ state due to the requirement of the heavy quark symmetry. Our result indicates that the $\Xi_b'(5935)^−$ and $\Xi_b'(5955)^−$ are the two dominant decay channels for the 2S $\Xi_b$ state. And then, its total decay width is 16.5 MeV. If comparing the above information with experimental data of the observed $\Xi_b′(6227)^−$, we may fully exclude the possibility of the $\Xi_b′(6227)^−$ as a 2S $\Xi_b$ state, which is composed of a good diquark and a bottom quark. If experimentally establishing the predicted $\Xi_b(6255)$, we suggest to search for it via the decay channels $\Xi_b'(5935)^−$ and $\Xi_b'(5955)^−$.

The predicted $\Xi_b^0(6365)$ and $\Xi_b'(6376)$ are bottom-strange baryons with a bad diquark and a bottom quark. Their calculated total decay widths in Table IV are far larger than the
measured width of the $\Xi_b(6227)^-$. According to this point, we may conclude that the $\Xi_b(6227)^-$ does not favor the $2S$ $\Xi_b^-$ assignments. Moreover, the predicted masses of two $2S$ $\Xi_b^-$ are higher than the measurement of $\Xi_b(6227)^-$ (see Fig. 2), which also enforces the above conclusion.

Since two $2S$ $\Xi_b^-$ states are still missing at experiment, we provide the whole information of their strong decays in Table IV. Obviously, the $\Lambda_bK$ and $\Xi_b\pi\pi$ channels can be applied to reconstruct the signals of the predicted $\Xi_b'(6365)$ and $\Xi_b''(6376)$.

### Table IV: The partial and total decay widths of the $2S$ $\Xi_b^-$ and $\Xi_b'$ states (in MeV).

| Decay modes | $\Xi_b(6255)$ | $\Xi'_b(6365)$ | $\Xi''_b(6376)$ |
|-------------|---------------|----------------|-----------------|
| $\Lambda_bK$ | ×             | 15.6           | 16.1            |
| $\Sigma_b(5815)K$ | –             | 4.4            | 1.6             |
| $\Sigma_b(5835)K$ | –             | 0.8            | 3.3             |
| $\Xi_b\pi$       | ×             | 16.0           | 16.4            |
| $\Xi'_b(5935)\pi$ | 6.3          | 7.2            | 1.9             |
| $\Xi''_b(5955)\pi$ | 10.2         | 3.4            | 9.4             |
| $\Xi_b(6096)\pi$     | ×             | 5.9            | 1.7             |
| $\Xi_b(6102)\pi$     | ×             | 2.5            | 7.4             |
| **Total**          | 16.5          | 55.8           | 57.8            |

#### 1P states

There are five $1P$ $\Xi_b'$ states. For distinguishing them, we introduce the notation $\Xi_{b(6)}^{J}\ J_{P_D}$, where $J_{P_D}$ is defined as the total angular momentum of the light diquark. With our predicted masses as input, the partial widths of the strong decays of these five $\Xi_b'$ states are obtained (see Table V). Although the $\Xi_{b(6)}^0$ state can decay into both $\Lambda_bK$ and $\Xi_b\pi$ channels, the partial decay width of the $\Xi_b\pi$ mode is much smaller than that of the $\Lambda_bK$ mode. This fact contradicts with experimental result of the $\Xi_b(6227)^-$, where the ratio of the partial decay widths of the $\Xi_b(6227)^-$ into $\Lambda_bK$ and $\Xi_b\pi$ is about 1 [9]. Thus, the possibility of the $\Xi_b(6227)^-$ as the $\Xi_{b(6)}^0$ state can be excluded.

Two $\Xi_{b(1)}^0$ state with $J^P = 1/2^-$ and $J^P = 3/2^-$ cannot decay into $\Lambda_bK$ and $\Xi_b\pi$, which implies that the explanation of the $\Xi_b(6227)^-$ as the $\Xi_{b(1)}^0$ state with $J^P = 1/2^-$ or $J^P = 3/2^-$ can be also killed. We further illustrate that the main decay mode of the $\Xi_{b(1)}^0$ state with $J^P = 1/2^-$ is $\Xi_{b(1)}'(5935)\pi$ while the $\Xi_{b(1)}^0$ state with $J^P = 3/2^-$ mainly decays into $\Xi_{b(1)}''(5955)\pi$. This information is crucial to experimental exploration on these two missing bottom-strange baryons.

Indeed, our theoretical results support the possibility of the observed $\Xi_b(6227)^-$ as a $P$-wave $\Xi_b'$ state with $J^P = 3/2^-$ or $J^P = 5/2^-$ due to three evidences: (1) These two bottom-strange baryons have the comparable partial widths for the decay modes $\Lambda_bK$ and $\Xi_b\pi$. And, the ratio of the partial widths of $\Lambda_bK$ and $\Xi_b\pi$ for these two bottom-strange baryons is around 1, which is consistent with the measurement of $\Xi_b(6227)^-$ from LHCb [9]; (2) The predicted total widths of these two states are also comparable with the experimental data. (3) The large partial widths of the $\Lambda_bK$ and $\Xi_b\pi$ decay channels can also explain why the $\Xi_b(6227)^-$ was firstly observed in these two decay modes [9]. The results listed in Table V show the similarity of the decay behaviors of the $\Xi_{b(1)}^0$ state with $J^P = 3/2^-$ and $J^P = 5/2^-$. It results in the difficult situation of how to further distinguish these two assignments to the observed $\Xi_b(6227)^-$ according to the present experimental information.

Besides the above five discussed states, there are two $1P$ $\Xi_b$ states predicted in this work, i.e., the $\Xi_b(6096)$ and $\Xi_b(6102)$. If adopting the theoretical mass as input, the predicted $\Xi_b(6096)$ and $\Xi_b(6102)$ only decay into $\Xi_{b(1)}'(5935)\pi$ and $\Xi_{b(1)}''(5955)\pi$. Here, the dominant decay mode of the $\Xi_b(6096)$ is $\Xi_{b(1)}'(5935)\pi$, while the $\Xi_{b(1)}''(5955)\pi$ has dominant contribution to the total decay width of the predicted $\Xi_b(6102)$.

### Table V: The partial and total decay widths of the $1P$ $\Xi_b'$ states (in MeV).

| Decay modes | $1/2^-$ | $3/2^-$ | $5/2^-$ |
|-------------|---------|---------|---------|
| $\Xi_{b(1)}'(6249)$ | 9.1     | ×       | 10.2    |
| $\Xi_{b(1)}'(6239)$ | ×       | 9.4     | 1.6     |
| $\Xi_{b(1)}'(6244)$ | ×       | 0.8     | 3.3     |
| $\Xi_{b(1)}'(6213)$ | ×       | 15.1    | 0.9     |
| $\Xi_{b(1)}''(6217)$ | 2.0     | 23.7    | 1.0     |
| Theory      | 9.9     | 17.2    | 24.8    |
| Expt. [9]   | 24.8    | 23.6    | 24.9    |

| Expt. [9]   | 18.1 ± 5.4 ± 1.8 |

#### III. DISCUSSION AND CONCLUSION

Very recently, LHCb discovered a new bottom-strange baryon state, the $\Xi_b(6227)^-$, by studying the $\Lambda_bK$ and $\Xi_b\pi$ invariant mass spectra [9]. Stimulated by this new state, we carry out a phenomenological analysis of the $2S$ and $1P$ $b\bar{b}q\bar{q}$ states by performing the mass spectrum analysis and two-body OZI-allowed strong decay investigation. Finally, two assignments of the $\Xi_b(6227)^-$ become possible, i.e., the $\Xi_b(6227)^-$ can be explained as a $1P$ $\Xi_b^-$ state with either $J^P = 3/2^-$ or $J^P = 5/2^-$ quantum number. Our study also shows that the decay property of the $P$-wave $\Xi_b^-$ state with $J^P = 3/2^-$ is very similar to the state with $J^P = 5/2^-$. So
distinguishing these two possible assignments becomes difficult only by the present experimental data.

Besides decoding the inner structure of the $\Xi_b(6227)^-$, we also predict the existence of its partners by illustrating their mass spectrum and decay behaviors. Surely, this information is helpful to find more excited bottom-strange baryons in future experiment like LHCb.

We also believe that the newly observed $\Xi_b(6227)^-$ is only a good start point when we are constructing the excited bottom baryon family. With the running of LHCb in Run II, more and more data will be accumulated. In near future, theorist and experimentalist should pay more attentions to this interesting research issue.

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