Identification of the newly observed $\Sigma_b(6097)^{\pm}$ baryons from their strong decays

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Two bottom $\Sigma_b(6097)^{\pm}$ baryons were observed in the final states $\Lambda_b^0\pi^-$ and $\Lambda_b^0\pi^+$ in pp collision by LHCb collaboration, whose masses and widths were measured. In a $^3P_0$ model, the strong decay widths of two ground S-wave and seven excited P-wave Σ_b baryons have been systematically computed. Numerical results indicate that the newly observed $\Sigma_b(6097)^{\pm}$ are very possibly $\Sigma_{b2}^1(\frac{3}{2}^-)$ with $J^P=\frac{3}{2}^-$ or $\Sigma_{b2}^1(\frac{5}{2}^-)$ with $J^P=\frac{5}{2}^-$. In particular, the ratios $\Gamma(\Sigma_b(6097)^{\pm}\to\Sigma_b^{\pm}\pi^0)/\Gamma(\Sigma_b(6097)^{\pm}\to\Sigma_b^{*\pm}\pi^0)$ are different in these two assignments. The ratios can be measured as an evidence of the two different assignments of $\Sigma_b(6097)^{\pm}$ in the future. In the meantime, our results support the assignments that $\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$ are the ground S-wave Σ_b baryons with $J^P=\frac{1}{2}^+$ and $J^P=\frac{3}{2}^+$, respectively.

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I. INTRODUCTION

There are two light u, d quarks and one heavy b quark in Σ_b baryons, and the two light quarks couple with isospin 1 inside. Four $\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$ have been observed by the CDF collaboration [1,2]. Their spins or parities have not been measured by experiment, they are assigned as the ground S-wave Σ_b with $J^P=\frac{1}{2}^+$ and $J^P=\frac{3}{2}^+$, respectively, in quark models. The assignments need confirmation in more ways. The widths of these baryons from Particle Data Group [3] are given in Table I. Recently, the data has been precisely improved by LHCb experiment [4].

In the same LHCb experiment, two bottom $\Sigma_b(6097)^{\pm}$ baryons were first observed in final states $\Lambda_b^0\pi^-$ and $\Lambda_b^0\pi^+$ in pp collision. The masses and widths of the $\Sigma_b(6097)^{\pm}$ are measured

$$m(\Sigma_b(6097)^-)=6098.0\pm1.7\pm0.5\ \mathrm{MeV},$$
$$\Gamma(\Sigma_b(6097)^-)=28.9\pm4.2\pm0.4\ \mathrm{MeV},$$
$$m(\Sigma_b(6097)^+)=6095.8\pm1.7\pm0.4\ \mathrm{MeV},$$
$$\Gamma(\Sigma_b(6097)^+)=31.0\pm5.5\pm0.7\ \mathrm{MeV}.$$

The identification of heavy baryons provides an excellent way to explore the structure and dynamics in baryons [5–9]. Therefore, the identification of $\Sigma_b(6097)^{\pm}$ is important in the quark model. In Ref. [10], $\Sigma_b(6097)^{\pm}$ were explained as P-wave baryons with $J^P=\frac{3}{2}^-$ or $J^P=\frac{5}{2}^-$ based on a mass spectra analysis and a calculation of the strong decay widths in a $^3P_0$ model with a diquark picture. In Ref. [11], $\Sigma_b(6097)^{\pm}$ were also explained as P-wave baryons with $J^P=\frac{3}{2}^-$ or $J^P=\frac{5}{2}^-$ based on their strong decay analysis in a chiral quark model.

As a phenomenological method, $^3P_0$ model has been employed to compute the Okubo-Zweig-Iizuka–allowed hadronic decay widths of hadrons after its appearance [12–15]. Though the bridge between the phenomenological $^3P_0$ model and QCD has not been established, some attempts have been made [16–18]. The $^3P_0$ model is also capable of exploring the dynamics and structure of baryons or multiquark systems. Recently, the approach has been employed to study of the structure of charmed baryons through their strong decays [19–23].

So far, whether there is a diquark cluster in baryons is still unknown. It is necessary to study the strong decay of $\Sigma_b(6097)^{\pm}$ in the $^3P_0$ model with three-body picture in detail. In this paper, we will study the P-wave possibility of $\Sigma_b(6097)^{\pm}$ and find out any signal in different assignments.

TABLE I. Widths of the ground Σ_b (in MeV).

State	J^P	Width [3]	Width [4]	Decay modes
Σ_b^+	$\frac{1}{2}^+$	$9.7^{+4.0}_{-3.0}$	$4.83\pm0.31\pm0.37$	$\Lambda_b^0\pi$
Σ_b^-	$\frac{1}{2}^+$	$4.9^{+3.3}_{-2.4}$	$5.33\pm0.42\pm0.37$	$\Lambda_b^0\pi$
Σ_b^{*+}	$\frac{3}{2}^+$	11.5 ± 2.8	$9.34\pm0.47\pm0.26$	$\Lambda_b^0\pi$
Σ_b^{*-}	$\frac{3}{2}^+$	7.5 ± 2.3	$10.68\pm0.60\pm0.33$	$\Lambda_b^0\pi$

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Furthermore, we will explore whether there is any possible diquark evidence in P-wave Σ_b. By the way, the ground S-wave Σ_b possibility of Σ_b and Σ_b^* will be examined.

The work is organized as follows. In Sec. II, the $^3P_0$ model is briefly introduced, some notations of heavy baryons and related parameters are indicated. We present our numerical results and analyses in Sec. III. In the last section, we give our conclusions and discussions.

II. $^3P_0$ MODEL, SOME NOTATIONS AND PARAMETERS

$^3P_0$ model is also called a quark pair creation (QPC) model. It was first proposed by Micu [12] and further developed by Yaouanc *et al.* [13–15]. The basic idea of this model assumes that a pair of quark $q\bar{q}$ is created from the QCD vacuum with vacuum quantum numbers $J^{PC} = 0^{++}$, and then the quark and the antiquark regroup with the quarks from the initial hadron A to form two daughter hadrons B and C [12]. For a bottom baryon, there are three ways of regrouping shown in the following equations [19,23]:

$$\mathcal{A}(u_1,u_2,b_3)+\mathcal{P}(u_4,\bar{u}_5)\to\mathcal{B}(u_1,u_2,u_4)+\mathcal{C}(b_3,\bar{u}_5), \quad (1)$$

$$\mathcal{A}(u_1,u_2,b_3)+\mathcal{P}(u_4,\bar{u}_5)\to\mathcal{B}(u_1,b_3,u_4)+\mathcal{C}(u_2,\bar{u}_5), \quad (2)$$

$$\mathcal{A}(u_1,u_2,b_3)+\mathcal{P}(u_4,\bar{u}_5)\to\mathcal{B}(u_2,b_3,u_4)+\mathcal{C}(u_1,\bar{u}_5), \quad (3)$$

where uub (the constituent quark of initial baryon A) could be replaced by ddb, and the created quark pair $u\bar{u}$ could be replaced by $d\bar{d}$.

In the $^3P_0$ model, the strong decay width Γ of a process $A\to B+C$ follows [15]

$$\Gamma = \pi^2\frac{|\vec{p}|}{m_A^2}\sum_{JL}|\mathcal{M}^{JL}|^2, \quad (4)$$

where the partial wave amplitude $\mathcal{M}^{JL}$ is related to the helicity amplitude $\mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}}$ via the Jacob-Wick formula [24]

$$\mathcal{M}^{JL} = \frac{\sqrt{2L+1}}{2J_A+1}\sum_{M_{J_B}M_{J_C}}\langle L0JM_{J_A}|J_AM_{J_A}\rangle \times\langle J_BM_{J_B}J_CM_{J_C}|JM_{J_A}\rangle\mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}} \quad (5)$$

with $J=J_B+J_C$, $J_A=J_B+J_C+L$ and $M_{J_A}=M_{J_B}+M_{J_C}$. In Eq. (5), the conservation of the total angular momentum and the angular momentum of light quark freedom is indicated explicitly in the process, which is a natural result of the heavy quark effective theory.

In Eq. (4), $\vec{p}$ is the momentum of the daughter baryon in A's center of mass frame,

$$|\vec{p}| = \frac{\sqrt{[m_A^2-(m_B-m_C)^2][m_A^2-(m_B+m_C)^2]}}{2m_A}. \quad (6)$$

m_A and J_A are the mass and the total angular momentum of the initial baryon A, respectively. m_B and m_C are the masses of the final hadrons. $\mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}}$ is the helicity amplitude, which reads [19–21,23]

$$\begin{aligned}
&\delta^3(\vec{p}_B+\vec{p}_C-\vec{p}_A)\mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}}\\
&= -2\gamma\sqrt{8E_AE_BE_C}\sum_{M_{L_{\rho_A}}}\sum_{M_{L_A}}\sum_{M_{L_{\rho_B}}}\sum_{M_{L_B}}\sum_{M_{S_1},M_{S_3},M_{S_4},m}\langle J_{l_A}M_{J_{l_A}}S_3M_{S_3}|J_AM_{J_A}\rangle\langle L_{\rho_A}M_{L_{\rho_A}}L_{\lambda_A}M_{L_{\lambda_A}}|L_AM_{L_A}\rangle\\
&\times\langle L_AM_{L_A}S_{12}M_{S_{12}}|J_{l_A}M_{J_{l_A}}\rangle\langle S_1M_{S_1}S_2M_{S_2}|S_{12}M_{S_{12}}\rangle\langle J_{l_B}M_{J_{l_B}}S_3M_{S_3}|J_BM_{J_B}\rangle\langle L_{\rho_B}M_{L_{\rho_B}}L_{\lambda_B}M_{L_{\lambda_B}}|L_BM_{L_B}\rangle\\
&\times\langle L_BM_{L_B}S_{14}M_{S_{14}}|J_{l_B}M_{J_{l_B}}\rangle\langle S_1M_{S_1}S_4M_{S_4}|S_{14}M_{S_{14}}\rangle\langle 1m;1-m|00\rangle\langle S_4M_{S_4}S_5M_{S_5}|1-m\rangle\\
&\times\langle L_CM_{L_C}S_CM_{S_C}|J_CM_{J_C}\rangle\langle S_2M_{S_2}S_5M_{S_5}|S_CM_{S_C}\rangle\langle\varphi_B^{1,4,3}\varphi_C^{2,5}|\varphi_A^{1,2,3}\varphi_0^{4,5}\rangle I_{M_{L_B},M_{L_C}}^{M_{L_A},m}(\vec{p}).
\end{aligned} \quad (7)$$

The factor 2 in front of γ results from the fact that Eqs. (2) and (3) give the same final states.

In the equation above, the matrix $\langle\varphi_B^{1,4,3}\varphi_C^{2,5}|\varphi_A^{1,2,3}\varphi_0^{4,5}\rangle$ of the flavor wave functions φ_i $(i=A,B,C,0)$ can also be computed in terms of a matrix of the isospins as follows [15,20]

$$\langle\varphi_B^{1,4,3}\varphi_C^{2,5}|\varphi_A^{1,2,3}\varphi_0^{4,5}\rangle = \mathcal{F}^{(I_A;I_BI_C)}\langle I_BI_B^3I_CI_C^3|I_AI_A^3\rangle \quad (8)$$

with

$$\mathcal{F}^{(I_A;I_BI_C)} = f\cdot(-1)^{I_{13}+I_C+I_A+I_2}\times\left[\frac{1}{2}(2I_C+1)(2I_B+1)\right]^{1/2}\times\begin{Bmatrix} I_{13} & I_B & I_4\\ I_C & I_2 & I_A\end{Bmatrix} \quad (9)$$

where f takes a value $(\frac{2}{3})^{1/2}$ or $-(\frac{1}{3})^{1/2}$ due to the isospin $\frac{1}{2}$ or 0 of the created quarks, respectively. I_A, I_B and I_C represent the isospins of the initial baryon, the final baryon and the final meson. I_{12}, I_3 and I_4 denote the isospins of relevant quarks, respectively.

The space integral follows as,

$$
\begin{aligned}
I^{M_{L_A},m}_{M_{L_B},M_{L_C}}(\vec{p}) = \int & d\vec{p}_1 d\vec{p}_2 d\vec{p}_3 d\vec{p}_4 d\vec{p}_5 \\
& \times \delta^3(\vec{p}_1+\vec{p}_2+\vec{p}_3-\vec{p}_A)\delta^3(\vec{p}_4+\vec{p}_5) \\
& \times \delta^3(\vec{p}_1+\vec{p}_4+\vec{p}_3-\vec{p}_B)\delta^3(\vec{p}_2+\vec{p}_5-\vec{p}_C) \\
& \times \Psi^*_B(\vec{p}_1,\vec{p}_4,\vec{p}_3)\Psi^*_C(\vec{p}_2,\vec{p}_5) \\
& \times \Psi_A(\vec{p}_1,\vec{p}_2,\vec{p}_3) y_{1m}\left(\frac{\vec{p}_4-\vec{p}_5}{2}\right)
\end{aligned} \tag{10}
$$

with a simple harmonic oscillator (SHO) wave functions for the baryons [20,25,26]

$$
\Psi(\vec{p}) = N\Psi_{n_\rho L_\rho M_{L_\rho}}(\vec{p}_\rho)\Psi_{n_\lambda L_\lambda M_{L_\lambda}}(\vec{p}_\lambda), \tag{11}
$$

where $N = 3^{\frac{3}{4}}$ represents a normalization coefficient of the total wave function. Explicitly,

$$
\begin{aligned}
\Psi_{nLM_L}(\vec{p}) = & \frac{(-1)^n(-i)^L}{\beta^{3/2}}\sqrt{\frac{2n!}{\Gamma(n+L+\frac{3}{2})}}\left(\frac{\vec{p}}{\beta}\right)^L \exp\left(-\frac{\vec{p}^2}{2\beta^2}\right) \\
& \times L_n^{L+1/2}\left(\frac{\vec{p}^2}{\beta^2}\right) Y_{LM_L}(\Omega_p)
\end{aligned} \tag{12}
$$

where $L_n^{L+1/2}(\frac{\vec{p}^2}{\beta^2})$ denotes the Laguerre polynomial function, and $Y_{LM_L}(\Omega_p)$ is a spherical harmonic function. The relation between the solid harmonica polynomial $y_{1m}(\vec{p})$ and $Y_{LM_L}(\Omega_{\vec{p}})$ is $y_{1m}(\vec{p}) = |\vec{p}|^L Y_{LM_L}(\Omega_p)$. In the above equations, Jacobi coordinates $\vec{\rho}$ and $\vec{\lambda}$ [27] were employed.

Notations and internal structures of the heavy baryons in quark model are explained in Refs. [19,22,23,28,29]. In this model, there are two S-wave and seven P-wave Σ_b baryons through a symmetry analysis with color, flavor (or isospin), spin and space. In other quark model, the structure and dynamics in baryons may be different. In fact, the difference is an indication of the complexity of baryon. Accordingly, the numbers of P-wave Σ_b may be different in other models. For example, there are five P-wave Σ_b baryons in Refs. [10,11,30–32]. For a practical calculation's purpose, the quantum numbers of two $1S$-wave and seven $1P$-wave Σ_b baryons are presented in Table II.

In this table, L_ρ denotes an orbital angular momentum between the two light quarks, L_λ denotes the orbital angular momentum between the bottom quark and the two light quark system, and L is the total orbital angular momentum of L_ρ and L_λ ($L = L_\rho + L_\lambda$). S_ρ denotes the total spin of the two light quarks, J_l is the total angular momentum of L and S_ρ ($J_l = L + S_\rho$), and J is the total angular momentum of the baryons ($J = J_l + \frac{1}{2}$). For $\tilde{\Sigma}^L_{bJ_l}$, a superscript L is specialized to denote different total angular momentum. The tilde indicates $L_\rho = 1$, and the blank indicates $L_\rho = 0$.

TABLE II. Quantum numbers of $1S$-wave and $1P$-wave excitations of Σ_b baryons.

N	Assignments	J	J_l	L_ρ	L_λ	L	S_ρ
1	$\Sigma^0_{b1}(\frac{1}{2}^+)$	$\frac{1}{2}$	1	0	0	0	1
2	$\Sigma^0_{b1}(\frac{3}{2}^+)$	$\frac{3}{2}$	1	0	0	0	1
3	$\Sigma^1_{b0}(\frac{1}{2}^-)$	$\frac{1}{2}$	0	0	1	1	1
4	$\Sigma^1_{b1}(\frac{1}{2}^-)$	$\frac{1}{2}$	1	0	1	1	1
5	$\Sigma^1_{b1}(\frac{3}{2}^-)$	$\frac{3}{2}$	1	0	1	1	1
6	$\Sigma^1_{b2}(\frac{3}{2}^-)$	$\frac{3}{2}$	2	0	1	1	1
7	$\Sigma^1_{b2}(\frac{5}{2}^-)$	$\frac{5}{2}$	2	0	1	1	1
8	$\tilde{\Sigma}^1_{b1}(\frac{1}{2}^-)$	$\frac{1}{2}$	1	1	0	1	0
9	$\tilde{\Sigma}^1_{b1}(\frac{3}{2}^-)$	$\frac{3}{2}$	1	1	0	1	0

TABLE III. Masses of mesons and baryons involved in the decays [3].

State	Mass (MeV)	State	Mass (MeV)
$\pi^\pm$	139.570	Σ_b^-	5815.64
π^0	134.977	Σ_b^+	5810.55
Λ_b^0	5619.58	Σ_b^{*-}	5834.73
$\Lambda_b^0(5912)$	5912.2	Σ_b^{*+}	5830.28
$\Lambda_b^0(5920)$	5919.92	$\Sigma_b^+(6097)$	6095.8
-	-	$\Sigma_b^-(6097)$	6098.0

Masses of relevant mesons and baryons involved in our calculation are presented in Table III [3,4].

Some parameters are chosen as follows. The dimensionless pair-creation strength $\gamma = 13.4$. The $\beta_{\lambda,\rho} = 600$ MeV in the S-wave baryon wave functions are fixed through the measured data of the ground Σ_b and Σ_b^*. The $\beta_{\lambda,\rho} = 400$ MeV in the P-wave baryon wave functions are chosen as those in Refs. [19,20,33–35]. The $R = 2.5\ \mathrm{GeV}^{-1}$ in π wave functions. To account for the uncertainties from β, the results from $\beta_{\lambda,\rho} = 400 \pm 100$ MeV in the P-wave baryon wave functions are also calculated and presented.

III. NUMERICAL RESULTS

A. Decays of Σ_b and Σ_b^*

$\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ were first observed in the final states $\Lambda_b^0\pi^\pm$ in $p\bar{p}$ collision by the CDF collaboration [1], and were interpreted as the lowest-lying $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ baryons with $J^P = \frac{1}{2}^+$ and $\frac{3}{2}^+$, respectively, according to their decay widths and masses. $\Lambda_b^0\pi^+$ is the only decay mode of Σ_b^+ and Σ_b^{*+}, and $\Lambda_b^0\pi^-$ is the only decay mode of Σ_b^- and Σ_b^{*-}. In the $^3P_0$ model, the hadronic decay widths of these four observed $\Sigma_b^\pm$ into $\Lambda_b^0\pi^\pm$ in two S-wave and seven P-wave assignments are computed and presented in Table IV, where

TABLE IV. Decay widths (MeV) of $\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$ into $\Lambda_b^0\pi^{\pm}$ as $1S$-wave states or $1P$-wave excitations.

N	$\Sigma_{bJ_l}(J^P)$	Σ_b^+	Σ_b^-	Σ_b^{*+}	Σ_b^{*-}
1	$\Sigma_{b1}^0(\frac{1}{2}^+)$	4.54	5.29	8.95	9.74
2	$\Sigma_{b1}^0(\frac{3}{2}^+)$	4.54	5.29	8.95	9.74
3	$\Sigma_{b0}^1(\frac{1}{2}^-)$	81.99	88.00	105.09	110.23
4	$\Sigma_{b1}^1(\frac{1}{2}^-)$	0	0	0	0
5	$\Sigma_{b1}^1(\frac{3}{2}^-)$	0	0	0	0
6	$\Sigma_{b2}^1(\frac{3}{2}^-)$	0.02	0.02	0.03	0.03
7	$\Sigma_{b2}^1(\frac{5}{2}^-)$	0.02	0.02	0.03	0.03
8	$\tilde{\Sigma}_{b1}^1(\frac{1}{2}^-)$	0	0	0	0
9	$\tilde{\Sigma}_{b1}^1(\frac{3}{2}^-)$	0	0	0	0
	Expt [3]	$9.7^{+3.8+1.2}_{-2.8-1.1}$	$4.9^{+3.1}_{-2.1}\pm 1.1$	$11.5^{+2.7+1.0}_{-2.2-1.5}$	$7.5^{+2.2+0.9}_{-1.8-1.4}$

a "0" indicates a vanish decay channel. In comparison with experimental results (see Table I), our numerical results support the assignments that $\Sigma_b^{\pm}$ and Σ_b^* are $\Sigma_{b1}^0(\frac{1}{2}^+)$ and $\Sigma_{b1}^0(\frac{3}{2}^+)$, respectively. Σ_b and Σ_b^* are very possibly the ground S-wave Σ_b, where there is no λ or ρ excitation inside.

B. Decays of $\Sigma_b(6097)$

As pointed out in the second section, there are seven P-wave Σ_b baryons. The masses of low-lying bottom baryons have been systemically predicted in many references such as [29–32]. If $\Sigma_b(6097)^{\pm}$ are P-wave Σ_b baryons, there exist five possible Okubo-Zweig-Iizuka–allowed hadronic decay modes. The five channels are : $\Lambda_b^0\pi^{\pm}$, $\Sigma_b^{\pm}\pi^0$, $\Sigma_b^{*\pm}\pi^0$, $\Lambda_b^0(5912)\pi^{\pm}$, and $\Lambda_b^0(5920)\pi^{\pm}$. The strong decay widths of $\Sigma_b(6097)^-$ into these five channels are calculated in seven different P-wave assignments, and presented in Table V. The results of $\Sigma_b(6097)^+$ are similar to those for $\Sigma_b(6097)^-$. In the table, the decay widths from $\beta_{\lambda,\rho} = 300$ MeV to $\beta_{\lambda,\rho} = 500$ MeV are given, while the ratios in the final volume are given at a centered $\beta_{\lambda,\rho} = 400$ MeV.

In the calculation, Σ_b and Σ_b^* are set to the ground S-wave $\Sigma_{b1}^0(\frac{1}{2}^+)$ and $\Sigma_{b1}^0(\frac{3}{2}^+)$ as indicated in previous subsection. $\Lambda_b^0(5912)$ and $\Lambda_b^0(5920)$ were observed in $\Lambda_b^0\pi^+\pi^-$ in pp collision by LHCb [36], and interpreted as the orbitally excited $\Lambda_b^{*0}(5912)$ and $\Lambda_b^{*0}(5920)$ though their exact assignment as the P-wave Λ_b has not been made. For simplicity, $\Lambda_b^0(5912)$ and $\Lambda_b^0(5920)$ are set to $\Lambda_b(\frac{1}{2}^-)$ and $\Lambda_b(\frac{3}{2}^-)$, respectively.

Based on numerical results, $\Sigma_b(6097)^{\pm}$ are very possibly $\Sigma_{b2}^1(\frac{3}{2}^-)$ or $\Sigma_{b2}^1(\frac{5}{2}^-)$ where there is no ρ-mode excitation inside. Under theoretical uncertainties, the total decay widths ($\Gamma \approx 17$–21 MeV) are consistent with the experimentally measured ones by LHCb. In both assignments, $\Lambda_b^0\pi^{\pm}$ are their dominant decay channels with branching fraction ratios ≈48–76%.

The decay widths into $\Sigma_b^{\pm}\pi^0$ or $\Sigma_b^{*\pm}\pi^0$ are small in $\Sigma_{b2}^1(\frac{3}{2}^-)$ or $\Sigma_{b2}^1(\frac{5}{2}^-)$ assignment. However, the branching fraction ratios $R = \frac{\Gamma(\Sigma_b(6097)^{\pm}\to\Sigma_b^{\pm}\pi^0)}{\Gamma(\Sigma_b(6097)^{\pm}\to\Sigma_b^{*\pm}\pi^0)}$ are largely different in these two different assignments. If $\Sigma_b(6097)^{\pm}$ are $\Sigma_{b2}^1(\frac{3}{2}^-)$, the branching fraction ratios $R = \frac{\Gamma(\Sigma_b(6097)^{\pm}\to\Sigma_b^{\pm}\pi^0)}{\Gamma(\Sigma_b(6097)^{\pm}\to\Sigma_b^{*\pm}\pi^0)} \approx 1.7$; If $\Sigma_b(6097)^{\pm}$ are $\Sigma_{b2}^1(\frac{5}{2}^-)$, the branching fraction ratios $R = \frac{\Gamma_{\Sigma_b(6097)^{\pm}\to\Sigma_b^{\pm}\pi^0}}{\Gamma_{\Sigma_b(6097)^{\pm}\to\Sigma_b^{*\pm}\pi^0}} \approx 0.5$. In particular, these ratios depend weakly on the parameters in the $^3P_0$ model and can be employed by experiment to distinguish $\Sigma_{b2}^1(\frac{3}{2}^-)$ from $\Sigma_{b2}^1(\frac{5}{2}^-)$.

Through Tables II and V, only $\tilde{\Sigma}_{b1}^1(\frac{1}{2}^-)$ or $\tilde{\Sigma}_{b1}^1(\frac{3}{2}^-)$ has vanish $\Lambda_b\pi$ mode. Obviously, the observation of $\Lambda_b\pi$ mode is an indication that the two light quarks in the $\Sigma_b(6097)^{\pm}$ state may couple with spin $S_\rho = 1$. That is to say, a bad diquark is possibly located in Σ_b baryons.

IV. CONCLUSIONS AND DISCUSSIONS

There are two ground S-wave and seven excited P-wave Σ_b baryons. The Okubo-Zweig-Iizuka–allowed strong decay channels of these Σ_b baryons have been given, and their widths have been systematically computed in the $^3P_0$ model.

$\Lambda_b^0\pi^{\pm}$ is the only strong decay channel of $\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$. In comparison with experimental data, our theoretical results support the assignments that $\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$ are the ground S-wave Σ_b baryons with $J^P = \frac{1}{2}^+$ and $J^P = \frac{3}{2}^+$, respectively.

TABLE V. Decay widths (MeV) of $\Sigma_b^-(6097)$ as $1P$-wave excitations. $\mathcal{B} = \Gamma(\Sigma_b^-(6097) \to \Lambda_b^0\pi^-)/\Gamma_{\text{total}}$.

$\Sigma_{bJ_l}(J^P)$	$\Lambda_b^0\pi^-$	$\Sigma_b^-\pi^0$	$\Sigma_b^{*-}\pi^0$	$\Lambda_b^0(5912)\pi^-$	$\Lambda_b^0(5920)\pi^-$	Γ_{total}	$\mathcal{B}$
$\Sigma_{b0}^1(\frac{1}{2}^-)$	132–317	0	0	2.02–5.48	2.92–7.98	145–321.93	$97.0\%^{+1\%}_{-6\%}$
$\Sigma_{b1}^1(\frac{1}{2}^-)$	0	67–129	0.20–0.30	3.98–9.96	1.43–3.61	81–135	0
$\Sigma_{b1}^1(\frac{3}{2}^-)$	0	0.16–0.4	61–115	0.99–2.49	3.58–9.02	72–119	0
$\Sigma_{b2}^1(\frac{3}{2}^-)$	9.43–14.60	0.30–0.50	0.18–0.30	3.11–7.49	0.45–1.09	17.28–20.95	$69\%^{+7\%}_{-19\%}$
$\Sigma_{b2}^1(\frac{5}{2}^-)$	9.43–14.60	0.15–0.2	0.28–0.40	1.70–3.08	2.69–6.53	18.02–19.5	$75\%^{+0\%}_{-27\%}$
$\tilde{\Sigma}_{b1}^1(\frac{1}{2}^-)$	0	101–193	1.20–1.70	0	0	191–235	0
$\tilde{\Sigma}_{b1}^1(\frac{3}{2}^-)$	0	0.99–1.6	91–173	0	0	168–213	0

Channels $\Lambda_b^0\pi^\pm$, $\Sigma_b^\pm\pi^0$, $\Sigma_b^{*\pm}\pi^0$, $\Lambda_b^0(5912)\pi^\pm$, and $\Lambda_b^0(5920)\pi^\pm$ are five possible strong decays for $\Sigma_b(6097)^\pm$. The observation of $\Lambda_b\pi$ mode is an obvious indication that the two light quarks in P-wave bottom baryons couple with spin $S_\rho = 1$. Numerical results indicate that $\Sigma_b(6097)^\pm$ are very possibly $\Sigma_{b2}^1(\frac{3}{2}^-)$ or $\Sigma_{b2}^1(\frac{5}{2}^-)$. In these assignments, the decay widths $\Gamma \approx 17$–21 MeV, which are consistent with experimental measurements under theoretical uncertainties. $\Lambda_b^0\pi^\pm$ are their dominant decay channels with branching fraction ratios ≈48–76%.

The ratios $R = \frac{\Gamma(\Sigma_b(6097)^\pm \to \Sigma_b^\pm\pi^0)}{\Gamma(\Sigma_b(6097)^\pm \to \Sigma_b^{*\pm}\pi^0)}$ are different in $\Sigma_{b2}^1(\frac{3}{2}^-)$ or $\Sigma_{b2}^1(\frac{5}{2}^-)$ assignment. The measurement of these ratios by experiments is possible to distinguish $\Sigma_{b2}^1(\frac{3}{2}^-)$ from $\Sigma_{b2}^1(\frac{5}{2}^-)$ in the future.

There are some uncertainties in the $^3P_0$ model. In addition to the masses of the hadrons involved in the decays, the strong decay widths depend on some parameters such as γ and β. These uncertainties may result in some large uncertainties of the predicted decay widths. However, these uncertainties can be reduced largely through the prediction of some branching fraction ratios.

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