Single heavy baryons with chiral partner structure in a three-flavor chiral model

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We construct an effective hadronic model including single heavy baryons (SHBs) belonging to the \((3,3)\) representation under \(\text{SU}(3)_L \times \text{SU}(3)_R\) symmetry, respecting the chiral symmetry and heavy-quark spin-flavor symmetry. When the chiral symmetry is spontaneously broken, the SHBs are divided into the baryons with negative parity of \(3\) representation under \(\text{SU}(3)\) flavor symmetry which is the chiral partners to the ones with positive parity of \(6\) representation. We determine the model parameters from the available experimental data for the masses and strong decay widths of \(\Sigma_c^+(3000), \Lambda_c(2595), \Xi_c(2790),\) and \(\Xi_c(2815)\). Then, we predict the masses and strong decay widths of other baryons including \(\Sigma_b\) with negative parity. We also study radiative decays of SHBs including \(\Omega_b^+\) and \(\Omega_b^0\) with positive parity.

I. INTRODUCTION

The spontaneous chiral symmetry breaking, which is one of the most essential properties of QCD, is expected to generate a part of hadron masses and causes the mass difference between chiral partners. Investigation of chiral partner structure will provide some clues to understand the chiral symmetry. In particular, study of the chiral partner structure of hadrons including heavy quarks gives information which are not obtained from the hadrons including only light quarks.

There are several studies of hadrons including heavy quarks based on the chiral partner structure. The chiral partner structure of heavy-light mesons is studied in e.g., Refs. [1–3], that of doubly heavy baryons is in e.g., Refs. [4–8], and the single heavy baryons (SHBs) are studied in e.g., Refs. [9–13].

In Ref. Ref. [12], we proposed a new chiral partner structure for SHBs including a heavy quark and two light quarks. There, we considered the chiral partners of \(\Sigma_Q\) \((Q = c,b)\) baryons with positive parity as \(\Lambda_Q\) baryons with negative parity: a heavy quark doublet of \((\Lambda_c(2595; J^P = 1^-), \Lambda_c(2625; 3^-))\) is regarded as the chiral partners to the ones with positive parity of \(6\) representation. When the chiral symmetry is spontaneously broken, the SHBs are divided into the baryons with negative parity of \(3\) representation under \(\text{SU}(3)\) flavor symmetry which is the chiral partners to the ones with positive parity of \(6\) representation. We construct an effective Lagrangian including the interactions to light pseudo-scalar mesons. Determining the model parameters from existing experimental data, we give predictions on the masses and pionic decay widths which are not experimentally determined. We also study radiative decays by introducing the interactions with photon field in a chiral invariant way. The single heavy baryons have been studied experimentally (e.g., Refs. [14–18]), and theoretically based on chiral models (e.g., Refs. [17–19]), quark models (e.g., Refs. [20–26]), the sum rule (e.g., Refs. [27–29]), the Regge theory (e.g., Ref. [30]), lattice simulations (e.g., Refs. [31–32]), molecule models (e.g., Refs. [33–34]) (See for a review, e.g., Ref. [35] and references therein.).

In this paper, we make comparisons of our predictions with those in chiral effective models [17, 18], quark models [20–26], and lattice simulations [31, 32].

This paper is organized as follows: We construct an effective Lagrangian in section II. Sections III and IV are devoted to study the masses and the hadronic decays of SHBs. We also study the radiative decays of SHBs in section V. Finally, we give a summary and discussions in section VI.

II. EFFECTIVE LAGRANGIAN

In this section, we construct an effective model of single heavy baryons (SHBs) by extending the two-flavor model provided in the previous work [12], to three-flavor case.

We introduce a set of fields, \(S_Q\) \((Q = b,c)\), for SHBs in which the light-quark cloud carries the spin 1 and belongs to \((3,3)\) representation under \(\text{SU}(3)_L \times \text{SU}(3)_R\) symmetry. The field transforms as

\[
S_Q \rightarrow g_RS_Q^T g_{L,R}, \quad (Q = c,b),
\]

where \(g_{L,R} \in \text{SU}(3)_{L,R}\). When the chiral symmetry is spontaneously broken, \(S_Q\) is divided into two parts. One...
is for the positive parity SHBs belonging to 6 representation under SU(3)$_{\text{flavor}}$ symmetry, $\hat{B}^6_Q$, and another for the negative parity SHBs to 3, $\hat{B}^3_Q$:

$$S_Q^\mu = \hat{B}^{6\mu}_Q + \hat{B}^{3\mu}_Q .$$

We would like to stress that $\hat{B}^{6\mu}_Q$ and $\hat{B}^{3\mu}_Q$ are chiral partners to each other in the present model. The physical states are embedded as

$$\hat{B}^{6\mu}_Q = \left( \begin{array}{c} \frac{1}{\sqrt{2}} \bar{Q}_Q \left( \sigma^I \right)_{i=0}^{0} \frac{1}{\sqrt{2}} \bar{Q}_Q \left( \sigma^I \right)_{i=-1}^{1} \frac{1}{\sqrt{2}} \bar{Q}_Q \left( \sigma^I \right)_{i=-1}^{1} \frac{1}{\sqrt{2}} \bar{Q}_Q \left( \sigma^I \right)_{i=-1}^{1} \end{array} \right),$$

$$\hat{B}^{3\mu}_Q = \left( \begin{array}{c} \frac{1}{\sqrt{2}} \bar{Q}_Q \left( \sigma^I \right)_{i=0}^{0} \frac{1}{\sqrt{2}} \bar{Q}_Q \left( \sigma^I \right)_{i=-1}^{1} \frac{1}{\sqrt{2}} \bar{Q}_Q \left( \sigma^I \right)_{i=-1}^{1} \frac{1}{\sqrt{2}} \bar{Q}_Q \left( \sigma^I \right)_{i=-1}^{1} \end{array} \right).$$

These $\hat{B}^{6\mu}_Q$ and $\hat{B}^{3\mu}_Q$ are decomposed into spin-3/2 baryon fields and spin-1/2 fields as

$$B^{6\mu}_Q = B^{6\mu}_Q - \frac{1}{\sqrt{3}} (\gamma^\mu + v^\mu) \sigma^I B^6_Q,$$

$$B^{3\mu}_Q = B^{3\mu}_Q - \frac{1}{\sqrt{3}} (\gamma^\mu + v^\mu) \sigma^I B^3_Q,$$

where $B^{6\mu}_Q$ and $B^{3\mu}_Q$ denote the spin-3/2 baryon fields, and $B^6_Q$ and $B^3_Q$ the spin-1/2 fields, respectively. We note that the parity transformation of the $S^\mu_0$ field is given by

$$S^\mu_0 \rightarrow -\gamma^0 S^\mu_0 ,$$

where $T$ denotes the transposition of the $3 \times 3$ matrix in the light-quark flavor space, and that the Dirac conjugate is defined as

$$\bar{S}^\mu_0 = S^\mu_0 \gamma^0 .$$

We introduce a $3 \times 3$ matrix field $M$ for scalar and pseudoscalar mesons made from a light quark and a light anti-quark, which belongs to the $(3, 3)$ representation under the chiral SU(3)$_L \times$ SU(3)$_R$ symmetry. The transformation properties of $M$ under the chiral symmetry and the parity are given by

$$M^\text{Ch} \rightarrow g_L M g_R^\dagger ,$$

$$M^P \rightarrow M^T.$$

We assume that the potential terms for $M$ in the model are constructed in such a way that the $M$ has a vacuum expectation value (VEV) which breaks the chiral symmetry spontaneously:

$$\langle M \rangle = \left( \begin{array}{c} f_\pi & 0 & 0 \\ 0 & f_\pi & 0 \\ 0 & 0 & \sigma_s \end{array} \right) ,$$

where $f_\pi$ is the pion decay constant and $\sigma_s$ is written as $\sigma_s = 2f_K - f_\pi$ with the Kaon decay constant $f_K$. In the following, for studying the decays of the SHBs with emitting pions, we parameterize the field $M$ as

$$M = \xi \left( \begin{array}{ccc} f_\pi & 0 & 0 \\ 0 & f_\pi & 0 \\ 0 & 0 & \sigma_s \end{array} \right) \xi^{-1} ,$$

where

$$\xi = e^{i\pi/f_\pi} ,$$

with $\pi$ being the $3 \times 3$ matrix field including pions as

$$\pi = \frac{1}{2} \left( \begin{array}{ccc} \pi^0 & \sqrt{2}\pi^0 & 0 \\ \sqrt{2}\pi^0 & -\pi^0 & 0 \\ 0 & 0 & 0 \end{array} \right) .$$

In addition, we introduce two fields, one belonging to $(3, 1)$ representation under SU(3)$_L \times$ SU(3)$_R$ symmetry and another to $(1, 3)$ representation. It is convenient to use anti-symmetric $3 \times 3$ matrix fields which transform as

$$S_{QLL} \rightarrow g_L S_{QLL} g_L^T , \quad S_{QRR} \rightarrow g_R S_{QRR} g_R^T ,$$

where $S_{QLL}$ and $S_{QRR}$ denote the fields of $(3, 1)$ and $(1, 3)$ representations, respectively. They are related to each other by parity transformation as

$$S_{QLL} \rightarrow -\gamma^0 S_{QRR} .$$

We introduce the parity eigenstates as

$$S_{QLL} \rightarrow \tilde{A}_Q^3 - \tilde{C}_Q^3 , \quad S_{QRR} \rightarrow \tilde{A}_Q^3 + \tilde{C}_Q^3 ,$$

where $\tilde{A}_Q^3$ and $\tilde{C}_Q^3$ carry the negative and positive parities, respectively. They include the flavor anti-symmetric fields as

$$\tilde{A}_Q^3 = \left( \begin{array}{ccc} 0 & \Lambda^\mu_1 & \Xi^1 \mu \\ -\Lambda^\mu_2 & 0 & \Xi^2 \mu \\ -\Xi^1 \mu & \Xi^2 \mu & 0 \end{array} \right) ,$$

$$\tilde{C}_Q^3 = \left( \begin{array}{ccc} 0 & \Lambda^\mu_1 & \Xi^3 \mu \\ -\Lambda^\mu_2 & 0 & \Xi^3 \mu \\ -\Xi^3 \mu & \Xi^3 \mu & 0 \end{array} \right) .$$

These $\tilde{A}_Q^3$ and $\tilde{C}_Q^3$ express spin-1/2 fields respectively. Since the particles which are expressed by $\tilde{A}_Q^3$ are still undiscovered, we neglect $\tilde{A}_Q^3$ in the following discussion.

Now, let us write down an effective Lagrangian including the baryon fields $S^\mu_0$, $S_{QLL}$, and $S_{QRR}$ together with the meson field $M$, based on the heavy-quark spin-flavor symmetry and the chiral symmetry. We do not consider the terms including more than square of $M$ field or more than two derivatives. A possible Lagrangian is given by
\[ \mathcal{L}_Q = - \text{tr} \tilde{S}_Q^\mu (v \cdot i D - \Delta) S_{Q\mu} + \tilde{S}_{QLL}^\mu (v \cdot i D) S_{QLL} + \tilde{S}_{QRR}^\mu (v \cdot i D) S_{QRR} \]

\[ + \frac{g_1}{2f_\pi} \text{tr} \left( \tilde{S}_Q^\mu M^1 M S_{Q\mu} + \tilde{S}_Q^T \mu M M^1 S_{Q\mu}^T \right) \]

\[ - \frac{g_2}{2f_\pi} \text{tr} \tilde{S}_Q^\mu M'^1 S_{Q\mu}' M^T - \frac{g_2^*_c}{2m_{\Lambda c}} \text{tr} \tilde{S}_Q^\mu M^1 S_{Q\mu}' M^T \]

\[ + \frac{\kappa_1}{4f_\pi} \text{tr} \left( \tilde{S}_Q^\mu M^1 M S_{Q\mu} + \tilde{S}_Q^\mu M'^1 M S_{Q\mu}' + \tilde{S}_Q^T \mu M M^1 S_{Q\mu}^T + \tilde{S}_Q^T \mu M M^1 S_{Q\mu}^T \right) \]

\[ - \frac{\kappa_2}{2f_\pi} \text{tr} \left( \tilde{S}_Q^\mu M^1 S_{Q\mu}' M^T + \tilde{S}_Q^\mu M^1 S_{Q\mu}' M^T \right) \]

\[ - \frac{h_1^1 - ih_1^R}{4f_\pi^2} \text{tr} \left( S_Q^\mu v \cdot \partial MS_{Q\mu} + S_{Q\mu}^T M v \cdot \partial M^1 S_{Q\mu}^T \right) \]

\[ - \frac{h_2^1 - ih_2^R}{4f_\pi^2} \text{tr} \left( S_Q^\mu v \cdot \partial M^1 S_{Q\mu} + S_{Q\mu}^T v \cdot \partial M^1 S_{Q\mu}^T \right) \]

\[ + \frac{h_3^1}{2f_\pi} \text{tr} \left( \tilde{S}_{QLL}^\mu \partial MS_{Q\mu} + \tilde{S}_{Q\mu}^\mu \partial M^1 S_{QLL} + \tilde{S}_{QRR}^\mu \partial M^1 S_{QRR} + \tilde{S}_{Q\mu}^\mu \partial M S_{QRR} \right) , \quad (18) \]

where \( m_{\Lambda c} (Q = c, b) \) are the masses of \( \Lambda_c (2286) \) and \( \Lambda_b \) in the ground state, \( \Delta \) provides the difference between the chiral invariant mass of \( S_Q \) and that of \( S_{QLL} \) and \( S_{QRR} \). \( g_i (i = 1, 2, 3) \), \( g_2^* \), \( \kappa_i (i = 1, 2) \), \( h_1^1 \), \( h_1^R \), \( h_2 \) are dimensionless coupling constants. We note that we include \( g_2^* \)-term to incorporate the heavy-flavor violation needed for explaining the mass differences of charm and bottom sectors (See Ref. [12]). Although we can add heavy-quark flavor violation terms corresponding to \( g_i \)-term, such contributions are absorbed into the definition of \( \Delta \). We expect that heavy-quark flavor violating contributions to terms other than \( g_2^* \) are small. Since thresholds of \( B_{Q^*} \to B_{Q'} \pi \) are not open, the related terms are not included here. We note that the above chiral partner may not be necessarily a three-quark state but can be also a molecular state such as the one in Ref. [34].

### III. Masses and One-Pion Decays

In this section, we determine the coupling constants \( g_2 \), \( g_2^* \), and \( \kappa_2 \) from masses of relevant SHBs, and \( g_3 \) from \( \Sigma_{Q^*} \to \Lambda_c \pi \) decays. Then we make predictions of the one-pion decay widths of other members of the flavor \( 6 \) representation.

When the chiral symmetry is spontaneously broken, the light meson field \( M \) acquires its vacuum expectation value as in Eq. (4). Then the masses of the particles included in the model are expressed as

\[ M(\Sigma_Q) = M_{\Lambda Q} + \Delta + g_1 f_\pi - \frac{g_Q^1}{2} f_\pi + \tilde{\kappa}_1 - \tilde{\kappa}_2 \]

\[ M(\Sigma_Q^l) = M_{\Lambda Q} + \Delta + g_1 f_\pi + \frac{\sigma_2^2}{2f_\pi} - \frac{g_Q^2}{2} \sigma_s + \tilde{\kappa}_1 f_\pi + \frac{\sigma_s m}{m} - \tilde{\kappa}_2 \frac{f_\pi m}{m} + \sigma_s \]

\[ M(\Omega_Q) = M_{\Lambda Q} + \Delta + g_1 \sigma_2 f_\pi - \frac{\sigma_2^2}{2f_\pi} + \frac{g_Q^2}{2} \sigma_s f_\pi + \frac{\sigma_s m}{m} f_\pi - \tilde{\kappa}_1 m \frac{\sigma_s}{m} - \tilde{\kappa}_2 \frac{m f_\pi}{m} \]

\[ M(\Lambda_{Q1}) = M_{\Lambda Q} + \Delta + g_1 f_\pi + \frac{g_Q^2}{2} f_\pi + \tilde{\kappa}_1 + \tilde{\kappa}_2 \]

\[ M(\Xi_{Q1}) = M_{\Lambda Q} + \Delta + g_1 \frac{f_\pi^2 + \sigma_2^2}{2f_\pi} + \frac{g_Q^2}{2} \sigma_s f_\pi + \frac{\sigma_s m}{m} f_\pi + \tilde{\kappa}_1 \frac{f_\pi m}{m} + \tilde{\kappa}_2 \frac{f_\pi m}{m} + \sigma_s . \]

\[ \text{Here we adopt the normalization of } f_\pi = 92.4 \text{ MeV and } f_K = 1.197 f_\pi. \]
where $\bar{\kappa}_i = \kappa_i m$, and $g_2^Q$ is defined as

$$g_2^Q = g_2 + g_v f_\pi \frac{m_{\lambda Q}}{2m}. \tag{24}$$

We determine the fraction of strange quark mass $m_s$ and up or down quark mass $\bar{m}$ from the masses of the pion and kaon as $m_s/\bar{m} = 25.9$ using

$$\frac{m_{K}^2}{m_{\pi}^2} = \frac{m_s + \bar{m}}{2\bar{m}}. \tag{25}$$

In the present analysis, we assign the following physical states to the flavor 3 representation:

$$(\Lambda_c, \Lambda_c^*) = (\Lambda_c(2595; J^P = 1/2^-), \Lambda_c(2625; 3/2^-)), \tag{26}$$

$$(\Xi_c, \Xi_c^*) = (\Xi_c(2790; J^P = 1/2^-), \Lambda_c(2815; 3/2^-))$$

and are the chiral partner to the flavor 6 representation:

$$(\Xi_c, \Xi_c^*) = (\Xi_c(2455; 1/2^+), \Sigma_c(2520; 3/2^+)), \tag{27}$$

$$(\Omega_c, \Omega_c^*) = (\Xi_c(1/2^+), \Xi_c(3/2^+))$$

and in the bottom sector, 3 includes

$$(\Lambda_b, \Lambda_b^*) = (\Lambda_b(5912; J^P = 1/2^-), \Lambda_b(5920; 3/2^-)), \tag{28}$$

$$(\Xi_b, \Xi_b^*) = (\Xi_b(1/2^-), \Xi_b(3/2^-))$$

and 6 includes

$$(\Xi_b, \Xi_b^*) = (\Xi_b(1/2^+), \Sigma_b(3/2^-)), \tag{29}$$

$$(\Omega_b, \Omega_b^*) = (\Omega_b(1/2^+), \Omega_b(3/2^-)).$$

We list experimental data of their masses and full decay widths [33] in Table II.

Here, we cannot determine the values of $\Delta$, $g_1$, and $\kappa_1$, separately. Instead, we introduce

$$\bar{\Delta} = \Delta + g_1 f_\pi + \bar{\kappa}_1$$

$$\Delta_s = \Delta + g_1 f_\pi^s \sigma_s^2 + \bar{\kappa}_1 f_\pi + \sigma_s \frac{m_{\mu}}{f_\pi}$$

$$\Delta_Q = \Delta + g_1 \frac{\sigma^2}{f_\pi} + \bar{\kappa}_1 \frac{m_{\mu} \sigma_s}{m f_\pi}, \tag{30}$$

to rewrite mass formulas as

$$M(\Sigma_Q) = M_{\lambda \Omega} + \bar{\Delta} - \frac{g_2^Q}{2} f_\pi - \bar{\kappa}_2,$$

$$M(\Xi_Q') = M_{\lambda \Omega} + \Delta_s - \frac{g_2^Q}{2} \sigma_s - \bar{\kappa}_2 \frac{f_\pi m_{\mu} + \sigma_s}{2f_\pi},$$

$$M(\Omega_Q) = M_{\lambda \Omega} + \Delta_Q - \frac{g_2^Q}{2} \frac{\sigma^2}{f_\pi} - \bar{\kappa}_2 \frac{m_{\mu} \sigma_s}{m f_\pi},$$

$$M(\Lambda_Q) = M_{\lambda \Omega} + \bar{\Delta} + \frac{g_2^Q}{2} f_\pi + \bar{\kappa}_2,$$

$$M(\Xi_Q) = M_{\lambda \Omega} + \Delta_s + \frac{g_2^Q}{2} \sigma_s + \bar{\kappa}_2 \frac{f_\pi m_{\mu} + \sigma_s}{2f_\pi}. \tag{31}$$

We estimate the values of mass parameters and coupling constants in charm sector from experimental data in a way explained in Ref. [12]. We calculate the spin-averaged mass of SHBs in a heavy-quark multiplet with including errors to include the masses of members belonging to the multiplet as shown in Table II.

To include the heavy quark flavor symmetry violation, we determined the value of $g_2^b$ from the mass difference between spin-averaged masses of $\Lambda_b^{(*)}$ and $\Sigma_b^{(*)}$. In addition, we use the weighted average of $\Sigma_0^+ \to
We show the estimated values of model parameters in Table III. Spin averaged masses and widths used as inputs to determine the model parameters.

| parameter     | value (MeV) | value (MeV) |
|---------------|-------------|-------------|
| \( \Delta \)  | 270^{+30}_{-20} \text{MeV} | 180^{+30}_{-20} \text{MeV} |
| \( \Delta_s \) | 300^{+10}_{-10} \text{MeV} | 290^{+10}_{-10} \text{MeV} |
| \( \Delta_\Omega \) | 600^{+100}_{-100} \text{MeV} | 600^{+100}_{-100} \text{MeV} |
| \( g_s \)     | 12.89^{+0.20}_{-0.20} | 12.89^{+0.20}_{-0.20} |
| \( g_2 \)     | 0.890^{+0.020}_{-0.020} | 0.890^{+0.020}_{-0.020} |
| \( \delta_2 \) | 0.897^{+0.020}_{-0.020} | 0.897^{+0.020}_{-0.020} |
| \( g_3 \)     | 0.688^{+0.020}_{-0.020} | 0.688^{+0.020}_{-0.020} |

Using the estimated value of \( g_3 \), we predict the decay widths of \( \Sigma_Q^{(*)} \to \Lambda_Q \pi \) and \( \Xi_Q^{(*)} \to \Xi_Q \pi \) as shown in Table IV. These predictions are consistent with experimental data because light flavor symmetry violation and heavy quark symmetry violation are small for the \( g_3 \)-term.

### Table III. Estimated values of model parameters

| input          | value (MeV) |
|----------------|-------------|
| \( M(\Lambda_c) \) | 2286.46 |
| \( M(\Sigma_c^{(*)}) \) | 2496.6^{+21.5}_{-43.6} |
| \( M(\Xi^{(*)}) \) | 2623.3^{+22.6}_{-45.2} |
| \( M(\Lambda^{(*)}) \) | 2742.3^{+23.6}_{-47.3} |
| \( M(\Xi^{(*)}) \) | 2617.6^{+10.95}_{-21.91} |
| \( \Gamma(\Sigma^{(*)} \to \Lambda_c \pi) \) | 10.6^{+4.9}_{-9.0} |
| \( M(\Lambda_b) \) | 5619.58 |
| \( M(\Lambda_b^{(*)}) - M(\Sigma_b^{(*)}) \) | 90.5^{+8.3}_{-4.2} |

### Table IV. Decay widths \( \Sigma_Q^{(*)} \to \Lambda_Q \pi \) predicted in our model.

| decay modes | our model [MeV] | expt. [MeV] |
|-------------|-----------------|-------------|
| \( \Sigma_Q^{(*)} \to \Lambda_Q \pi \) | 1.96^{+0.04}_{-0.04} | 1.89^{+0.04}_{-0.18} |
| \( \Xi_Q^{(*)} \to \Xi_Q \pi \) | 2.28^{+0.09}_{-0.12} | < 4.6 |
| \( \Sigma_Q^{(*)} \to \Lambda_Q \pi \) | 1.94^{+0.04}_{-0.04} | 1.83^{+0.04}_{-0.18} |
| \( \Sigma_Q^{(*)} \to \Lambda_Q \pi \) | 14.7^{+0.8}_{-0.0} | 14.78^{+0.0}_{-0.40} |
| \( \Sigma_Q^{(*)} \to \Lambda_Q \pi \) | 15.3^{+0.8}_{-0.11} | < 17 |
| \( \Sigma_Q^{(*)} \to \Lambda_Q \pi \) | 15.7^{+0.6}_{-0.0} | 15.3^{+0.4}_{-0.0} |
| \( \Sigma_Q^{(*)} \to \Lambda_Q \pi \) | 6.14^{+0.25}_{-0.43} | 9.7^{+3.2}_{-2.8} |
| \( \Sigma_Q^{(*)} \to \Lambda_Q \pi \) | 7.2^{+0.27}_{-0.41} | ... |
| \( \Sigma_Q^{(*)} \to \Lambda_Q \pi \) | 7.09^{+0.27}_{-0.41} | 4.9^{+3.1}_{-2.2} |
| \( \Sigma_Q^{(*)} \to \Lambda_Q \pi \) | 11.0^{+0.4}_{-0.0} | 11.5^{+2.2}_{-1.5} |
| \( \Sigma_Q^{(*)} \to \Lambda_Q \pi \) | 12.3^{+0.4}_{-0.0} | ... |
| \( \Sigma_Q^{(*)} \to \Lambda_Q \pi \) | 11.9^{+0.4}_{-0.0} | 7.5^{+2.2}_{-1.4} |

We can estimate the masses of bottom baryons included in our model using the parameters in Table III. In the present analysis, we assume heavy quark spin symmetry, so that we predict the spin-averaged masses which are shown in Table IV. Here, we show the result in Ref. [12] and experimental values for comparison. We note that, in Table IV, we just put the minimum and maximum values predicted for the members in a multiplet in Ref. [30]. This table shows that our predictions are consistent with those in Ref. [30].

We can see that our predictions for \( \Sigma_Q^{(*)} \), \( \Xi_Q^{(*)} \) and \( \Lambda_Q^{(*)} \) are consistent with the spin-averaged masses of experimentally observed masses. For \( \Omega_b \), only the mass of the spin-1/2 member is known experimentally. Although our prediction of the spin-average is slightly larger than the observed mass of the spin-1/2 member, we expect that the spin-3/2 member is slightly heavier which makes the spin-averaged larger and consistent with our prediction. Future experimental observation of spin-3/2 member as
TABLE V. Predicted values of the spin-averaged masses of bottom baryons. For comparison we list the spin-averages of experimentally observed masses and the predicted values in Ref. \[30, 36\].

| particle our model | \[30\] | \[36\] | expt. (spin averaged) |
|--------------------|-------|-------|-----------------------|
| Σ\(_{(b)}^{(*)}\) | 5843\(_{+20}^{-37}\) | 5811 – 5835 | ... | 5826.9 |
| Ξ\(_{(b)}^{(*)}\) | 5975\(_{+18}^{-37}\) | ... | ... | 5946.7 |
| Ω\(_{(b)}^{(*)}\) | 6102\(_{+16}^{-36}\) | 6048 – 6086 | ... | 6046.1 (spin-1/2) |
| Λ\(_{(b)}^{(*)}\) | 5936\(_{+20}^{-36}\) | 5980 – 6000 | ... | 5917.33 |
| Ξ\(_{(b)}^{(*)}\) | 6124\(_{+20}^{-34}\) | 6129 – 6151 | 6096, 6102 | ... |

IV. PION DECAYS OF SINGLE HEAVY BARYONS WITH NEGATIVE PARITY

In this section, we consider decays of \(B_{Q}^{(s)}\), the negative parity excited SHBs belonging to the flavor 3 representation. The main modes of \(\Lambda_{Q1}^{(*)}\) are three body decay, \(\Lambda_{Q1} \rightarrow \Lambda_{Q} \pi \pi\) because \(\Lambda_{Q1}^{(*)} \rightarrow \Sigma_{Q}^{(*)} \pi\) decay thresholds are closed in most cases. In the decays of \(\Xi_{c}^{(*)}\), the decay thresholds of \(\Xi_{c}^{(*)} \rightarrow \Xi_{c}^{(*)} \pi\) are completely open, so the main mode is the two body decay.

In Ref. \[12\], we used the two-pion decay width of \(\Lambda_{c}(2595)\) to determine the values of derivative coupling constants, \(h_{1}^{l}\) and \(h_{2}\). Here, we also include the decay widths of \(\Xi_{c}(2790)\) and \(\Xi_{c}(2815)\). There exists violation of the heavy quark spin symmetry between the decay widths of \(\Xi_{c}(2790)\) and \(\Xi_{c}(2815)\). Instead of treating this violation precisely, we include the violation as systematic errors of the model. Therefore, we use values of a decay width of \(\Lambda_{c}(2595)\) and, a spin averaged decay width between \(\Xi_{c}(2790)\) and \(\Xi_{c}(2815)\) as inputs to determine \(h_{1}^{l}\) and \(h_{2}\). The region colored by dark purple in Fig. 1 shows the allowed values of \(h_{1}^{l}\) and \(h_{2}\) determined from the decay width of \(\Lambda_{c}(2595)\) where the errors of \(g_{2}^{c}\), \(g_{3}\) and the total width with \(\Lambda(2595)\) are taken into account. The region by light purple are obtained from the spin averaged width of \(\Xi_{c}(2790)\) and \(\Xi_{c}(2815)\) with the errors of model parameters included.

![FIG. 1. Allowed range of \(h_{1}^{l}\) and \(h_{2}\).](image)
TABLE VI. Predicted widths of excited SHBs. We used the spin and isospin averaged value of the decay widths of $\Xi^0(2790)$, $\Xi^+_b(2790)$, $\Xi^{*+}(2815)$ and $\Xi^{*0}(2815)$ in addition to the decay width of $\Lambda_c(2995)$ as inputs.

| Initial | Mode | Our model | Ref. 36 | Ref. 25 | Expt. |
|---------|------|-----------|----------|---------|-------|
| $\Lambda_c(2995)$ | $\Lambda_c^-\pi^+$ | 0.562-1.09 | | | |
| | $\Lambda_c^-\pi^0$ | 1.23-2.31 | | | |
| | sum (input) | 1.82-3.36 | | | |
| $\Lambda_c(2625)$ | $\Lambda_c^-\pi^+$ | 0.0618-0.507 | | | |
| | $\Lambda_c^-\pi^0$ | 0.0431-0.226 | | | |
| | sum (input) | 0.106-0.733 | | | |
| $\Lambda_b(5912)$ | $\Lambda_b^-\pi^+$ | $(0.67-4.4) \times 10^{-3}$ | 0.66 | | |
| | $\Lambda_b^-\pi^0$ | $(1.4-6.0) \times 10^{-3}$ | | | |
| | sum (input) | $(2.1-10) \times 10^{-3}$ | | | |
| $\Xi^+(2790)$ | $\Xi^{+0}(2790)$ | 0.94 - 0.15 | 0.63 | | |
| | sum (input) | 3.61 | 8.9 ± 0.6 | |
| $\Xi^+(2815)$ | $\Xi^{+0}(2815)$ | 0.94 - 0.15 | 0.63 | | |
| | sum (input) | 3.61 | 10.0 ± 0.7 | |
| $\Xi^{*+}(2815)$ | $\Xi^{*+0}(2815)$ | 0.94 - 0.15 | 0.63 | | |
| | sum (input) | 1.80 | 2.43 ± 0.20 | |
| $\Xi^{01}_1$ | $\Xi^{01}_1$ | 0.0415-0.15 | 0.63 | | |
| | sum (input) | 1.80 | 2.54 ± 0.18 | |
| $\Xi^{01}_2$ | $\Xi^{01}_2$ | 0.0415-0.15 | 0.63 | | |
| | sum (input) | 1.80 | 2.54 ± 0.18 | |
| $\Xi^{01}_3$ | $\Xi^{01}_3$ | 0.0415-0.15 | 0.63 | | |
| | sum (input) | 1.80 | 2.54 ± 0.18 | |
| $\Xi^{01}_4$ | $\Xi^{01}_4$ | 0.0415-0.15 | 0.63 | | |
| | sum (input) | 1.80 | 2.54 ± 0.18 | |

We note that we use the predicted masses of $\Xi_b$ with negative parity shown in Table V with including their errors. So the predicted decay widths take a wide range of values, which includes predictions in Refs. [25, 30]. In particular, since the minimum value shown in Table V is very close to the threshold of the relevant decays, the minimum values of the predictions of one-pion decays of $\Xi^{01}_1$ in Table VI are very small, and three-body decays such as $\Xi^{01}_1 \rightarrow \Xi_b \pi \pi$ become dominant. Here, we study the contributions of possible intermediate states of three-body decays and show the results in Table VII where we set the parameters as $g_2^0 = 0.980$, $\bar{\kappa}_2 = 0.807$, $g_3 = 0.688$, $h_1^l = -0.40$, and $h_2 = 0$, and set the masses of $\Xi^{01}_1$ to be their minimum of the predicted values shown in Table VI and $\Xi^{*0}_1$ to be the central mass values in Table IV.

We note that, unlikely to the decays of $\Lambda_b(5912)$ and $\Lambda_b(5920)$, the decays of $\Xi^{01}_1$ and $\Xi^{*0}_1$ are not dominated by the non-resonant contribution.
TABLE VII. Estimated values of the decay widths of bottom baryons.

| initial state | decay mode | intermediate state | width [keV] |
|---------------|------------|-------------------|-------------|
| $\Xi_{b}^{+}$ | $\Xi_{b}^{-} \pi^{0}$ | non-resonant | 0.688 |
| $\Xi_{b}^{-}$ | $\Xi_{b}^{0} \pi^{-}$ | NR & $\Xi_{b}^{\ast 0}$ | 2.97 |
| $\Xi_{b}^{0} \pi^{+} \pi^{-}$ | NR | 0.432 |
| $\Xi_{b}^{-}$ | $\Xi_{b}^{0} \pi^{+}$ | 8.67 |
| $\Xi_{b}^{0}$ | $\Xi_{b}^{-} \pi^{0}$ | NR & $\Xi_{b}^{\ast 0}$ | 2.59 |
| $\Xi_{b}^{+} \pi^{+} \pi^{-}$ | NR | 0.510 |
| $\Xi_{b}^{-}$ | $\Xi_{b}^{0} \pi^{-}$ | 53.6 |
| $\Xi_{b}^{0}$ | $\Xi_{b}^{-} \pi^{0}$ | NR & $\Xi_{b}^{\ast 0}$ | 5.02 |
| $\Xi_{b}^{+} \pi^{-}$ | NR | 0.275 |
| $\Xi_{b}^{-}$ | $\Xi_{b}^{0}$ | 194 |
| $\Xi_{b}^{0}$ | $\Xi_{b}^{-}$ | NR & $\Xi_{b}^{\ast 0}$ | 4.55 |
| $\Xi_{b}^{0} \pi^{0}$ | $\Xi_{b}^{0}$ | 386 |
| $\Xi_{b}^{-}$ | $\Xi_{b}^{0}$ | 1.40 x 10^3 |
| $\Xi_{b}^{0}$ & $\Xi_{b}^{\ast 0}$ | 5.39 |

V. RADIATIVE DECAYS

In this section, we study radiative decays of the SHBs. The relevant Lagrangian is given by

$$L_{\text{rad}} = \frac{r_{1}}{F} \text{tr} \left( \bar{S}_{Q} \mathcal{Q}_{Q} S_{\pi}^{\mu} + \bar{S}_{Q}^{T} \mathcal{Q}_{Q} S_{\pi}^{\mu} \right) F_{\mu\nu}$$

$$+ \frac{r_{2}}{F} \text{tr} \left( \bar{S}_{Q} \mathcal{Q}_{Q} S_{\pi}^{\mu} - \bar{S}_{Q}^{T} \mathcal{Q}_{Q} S_{\pi}^{\mu} \right) \tilde{F}_{\mu\nu}$$

$$+ \frac{r_{3}}{F^{2}} \text{tr} \left( \bar{S}_{Q} \mathcal{Q}_{Q} S_{\pi}^{\mu} \mathcal{Q}_{Q} \mathcal{Q}_{Q} \mathcal{Q}_{Q} S_{\pi}^{\mu} \right) F_{\mu\nu}$$

$$+ \text{h.c.}$$

$$+ \frac{r_{4}}{F^{2}} \text{tr} \left( \bar{S}_{Q} \mathcal{Q}_{Q} S_{\pi}^{\mu} \mathcal{Q}_{Q} \mathcal{Q}_{Q} \mathcal{Q}_{Q} S_{\pi}^{\mu} \right) \tilde{F}_{\mu\nu}$$

$$+ \text{h.c. ,}$$ (32)

where $F_{\mu\nu}$ is the field strength of the photon and $\tilde{F}_{\mu\nu}$ is its dual tensor: $\tilde{F}_{\mu\nu} = (1/2)F_{\rho\sigma\nu\mu}F^{\rho\sigma}$, $r_{i}$ ($i = 1, ..., 4$) are dimensionless constants, and $F$ is a constant with dimension one. In this analysis, we take $F = 350$ MeV following Ref. [17]. We note that the values of the constants $r_{i}$ are of order one based on quark models [17].

Let us first study the electromagnetic intramultiplet transitions governed by the $r_{1}$-term in Eq. (32). Let $B^{*}$ denotes the decaying baryon with spin-3/2 ($B^{*} = \Lambda_{Q}, \Xi_{Q1}, \Xi_{Q}^{0}, \Xi_{Q}, \Omega_{Q}$), and $B$, the daughter baryon with spin-1/2 ($\Lambda_{Q}, \Xi_{Q1}, \Xi_{Q}, \Xi_{Q}^{0}, \Omega_{Q}$). Then the radiative decay width is given by

$$\Gamma_{B^{*} \rightarrow B \gamma} = C_{B^{*} B \gamma}^{2} \frac{16\alpha r_{1}^{2}}{9F^{2}} m_{B^{*}} E_{\gamma}^{3}$$ (33)

where $\alpha$ is the electromagnetic fine structure constant, $E_{\gamma}$ is the photon energy and $C_{B^{*} B \gamma}$ is the Clebsh-Gordon constants given by

$$C_{\Sigma_{c}^{+} + \Sigma_{c}^{+} \gamma} = \frac{2}{3},$$

$$C_{\Sigma_{c}^{+} + \Sigma_{c}^{+} \gamma} = \frac{1}{6},$$

$$C_{\Sigma_{c}^{0} + \Sigma_{c}^{0} \gamma} = \frac{1}{6},$$

$$C_{\Xi_{c}^{+} + \Xi_{c}^{+} \gamma} = \frac{1}{3},$$

$$C_{\Xi_{c}^{0} + \Xi_{c}^{0} \gamma} = \frac{1}{3},$$

$$C_{\Lambda_{c}^{+} + \Lambda_{c}^{+} \gamma} = \frac{1}{3},$$

$$C_{\Xi_{c}^{+} + \Xi_{c}^{+} \gamma} = \frac{1}{3},$$

$$C_{\Xi_{c}^{0} + \Xi_{c}^{0} \gamma} = \frac{1}{3},$$ (34)

Here we would like to stress that the radiative decay widths of positive parity SHBs ($\Sigma_{Q}, \Xi_{Q}, \Omega_{Q}$) and those of negative parity SHBs ($\Lambda_{Q1}, \Xi_{Q1}$) are determined by just one coupling constant $r_{1}$, reflecting the chiral partner structure. We think that checking the relation among these radiative decays will be one of the crucial tests of the chiral partner structure.

TABLE VIII. Predicted widths of radiative decays between heavy quark multiplets of charm baryons. We also show the predictions in Refs. [18, 32] for comparison.

| decay mode | predicted width [keV] | [18] keV | [32] keV |
|------------|----------------------|----------|----------|
| $\Sigma_{c}^{+} \rightarrow \Sigma_{c}^{+} \gamma$ | 11.8r_{1}^{2} | 11.6 | ... |
| $\Sigma_{c}^{+} \rightarrow \Sigma_{c}^{+} \gamma$ | 0.743r_{1}^{2} | 0.85 | ... |
| $\Sigma_{c}^{0} \rightarrow \Sigma_{c}^{0} \gamma$ | 2.99r_{1}^{2} | 2.92 | ... |
| $\Xi_{c}^{+} \rightarrow \Xi_{c}^{+} \gamma$ | 0.872r_{1}^{2} | 1.10 | ... |
| $\Xi_{c}^{0} \rightarrow \Xi_{c}^{0} \gamma$ | 3.40r_{1}^{2} | 3.83 | ... |
| $\Omega_{c}^{0} \rightarrow \Omega_{c}^{0} \gamma$ | 3.90r_{1}^{2} | 4.82 | 0.096(14) |
| $\Lambda_{c}^{+} \rightarrow \Lambda_{c}^{+} \gamma$ | 0.131r_{1}^{2} | ... | ... |
| $\Xi_{c}^{+} \rightarrow \Xi_{c}^{+} \gamma$ | 0.0432r_{1}^{2} | ... | ... |
| $\Xi_{c}^{0} \rightarrow \Xi_{c}^{0} \gamma$ | 0.237r_{1}^{2} | ... | ... |
TABLE IX. Predicted widths of radiative decays between heavy quark multiplets of bottom baryons. We also show the predictions in Ref. [18] for comparison.

| decay mode                  | predicted width [18] | predicted width [keV] |
|-----------------------------|----------------------|------------------------|
| \( \Sigma_q^+ \to \Sigma_q^+ \gamma \) | 0.420 \( r_1^2 \)   | 0.60                   |
| \( \Sigma_q^0 \to \Sigma_q^0 \gamma \) | 0.0240 \( r_1^2 \)  | 0.05                   |
| \( \Sigma_q^+ \to \Sigma_q^+ \gamma \) | 0.0879 \( r_1^2 \)  | 0.08                   |
| \( \Xi_b^0 \to \Xi_b^0 \gamma \) | 0.00944 \( r_1^2 \) | ···                     |
| \( \Xi_b^+ \to \Xi_b^+ \gamma \) | 0.0977 \( r_1^2 \)  | ···                     |
| \( \Omega_b^0 \to \Omega_b^0 \gamma \) | 0.0920 − 4.07 \( r_1^2 \) | ···                     |
| \( \Lambda_b^1 \to \Lambda_b^1 \gamma \) | 0.00135 \( r_1^2 \) | ···                     |
| \( \Xi_b^0 \to \Xi_b^0 \gamma \) | < 0.453 \( r_1^2 \)  | ···                     |
| \( \Xi_b^+ \to \Xi_b^+ \gamma \) | < 1.81 \( r_1^2 \)   | ···                     |

We next study the radiative decays between the SHBs with negative parity in the flavor 3 representations and the SHBs with positive parity in the flavor 6 representations, which concern the \( r_2 \)-term. The decay widths are expressed as

\[
\Gamma_{\Lambda_{Q1} \to \Sigma_{Q1} \gamma} = \frac{16\alpha r_2^2 m_{\Sigma_{Q1}} E^3}{9F^2 m_{\Lambda_{Q1}}} ,
\]

\[
\Gamma_{\Lambda_{Q1} \to \Sigma_{Q1} \gamma} = \frac{8\alpha r_2^2 m_{\Sigma_{Q1}}}{9F^2 m_{\Lambda_{Q1}}} E^3 ,
\]

\[
\Gamma_{\Lambda_{Q1} \to \Sigma_{Q1} \gamma} = \frac{4\alpha r_2^2 m_{\Sigma_{Q1}} E^3}{9F^2 m_{\Lambda_{Q1}}} ,
\]

\[
\Gamma_{\Lambda_{Q1} \to \Sigma_{Q1} \gamma} = \frac{20\alpha r_2^2 m_{\Sigma_{Q1}} E^3}{9F^2 m_{\Lambda_{Q1}}} ,
\]

\[
\Gamma_{\Xi_{Q1} \to \Xi_{Q1} \gamma} = \frac{16\alpha r_2^2 m_{\Xi_{Q1}} E^3}{9F^2 m_{\Xi_{Q1}}} ,
\]

\[
\Gamma_{\Xi_{Q1} \to \Xi_{Q1} \gamma} = \frac{8\alpha r_2^2 m_{\Xi_{Q1}} E^3}{9F^2 m_{\Xi_{Q1}}} ,
\]

\[
\Gamma_{\Xi_{Q1} \to \Xi_{Q1} \gamma} = \frac{4\alpha r_2^2 m_{\Xi_{Q1}} E^3}{9F^2 m_{\Xi_{Q1}}} ,
\]

\[
\Gamma_{\Xi_{Q1} \to \Xi_{Q1} \gamma} = \frac{20\alpha r_2^2 m_{\Xi_{Q1}} E^3}{9F^2 m_{\Xi_{Q1}}} .
\]

(35)

In Table X and XI we show our predictions comparing with those in Ref. [17] and Ref. [20]. Our results are consistent with those in Ref. [17] when \( r_2 \sim c_{RS}/\sqrt{2} \), and with those in Ref. [20] when \( r_2 \sim 1/2 \).

The \( r_3 \)-term generates the radiative decays between the negative parity SHBs in the flavor 3 representations and the positive parity SHBs in the flavor 3 representations and the positive parity bottom baryons in the flavor 6 representations, which concern the \( r_2 \)-term. The decay widths are expressed as

\[
\Gamma_{\Lambda_{Q1} \to \Sigma_{Q1} \gamma} = \frac{8\alpha r_2^2 f_\pi^2 m_{\Lambda_{Q1}} E^3}{27F^4 m_{\Lambda_{Q1}}} ,
\]

\[
\Gamma_{\Xi_{Q1} \to \Xi_{Q1} \gamma} = \frac{8\alpha r_2^2 (f_\pi - 2\sigma_\pi)^2 m_{\Xi_{Q1}} E^3}{27F^4 m_{\Xi_{Q1}}} ,
\]

\[
\Gamma_{\Xi_{Q1} \to \Xi_{Q1} \gamma} = \frac{8\alpha r_2^2 (f_\pi + \sigma_\pi)^2 m_{\Xi_{Q1}} E^3}{27F^4 m_{\Xi_{Q1}}} .
\]

In Table XII and XIII we show our predictions together with the ones in Ref. [17] and Ref. [20]. We think that the differences between our predictions and those in Ref. [20] are from the value of \( \sigma_\pi \); we use \( \sigma_\pi = 2f_K - f_\pi \) while \( \sigma_\pi = f_\pi \) is used in Ref. [20].

The widths of radiative decays between the positive parity SHBs in the flavor 6 representations and the positive parity bottom baryons in the flavor 3 representations via the
TABLE XII. Predicted widths of radiative decays between negative parity charm baryons in the flavor 3 representations and positive parity charm baryons in the flavor 3 representations. We also show the predictions in Ref. [17, 20].

| decay mode | predicted width [keV] |
|------------|-----------------------|
| $\Lambda_{c^+} \to \Lambda_c \gamma$ | 25.9r<sub>3</sub> |
| $\Lambda_{c^+} \to \Lambda_c \gamma$ | 34.9r<sub>3</sub> |
| $\Xi_{c^+} \to \Xi_c \gamma$ | 98.9r<sub>3</sub> |
| $\Xi_{c^+} \to \Xi_c \gamma$ | 121r<sub>3</sub> |
| $\Xi_{c^+} \to \Xi_c \gamma$ | 174r<sub>3</sub> |
| $\Xi_{c^+} \to \Xi_c \gamma$ | 217r<sub>3</sub> |

TABLE XIII. Predicted widths of radiative decays between positive parity bottom baryons in the flavor 3 representations and positive parity bottom baryons in the flavor 3 representations.

| decay mode | predicted width [keV] |
|------------|-----------------------|
| $\Lambda_b \to \Lambda_b \gamma$ | 27.2r<sub>3</sub> |
| $\Xi_b \to \Xi_b \gamma$ | 92.0 - 148r<sub>3</sub> |
| $\Xi_b \to \Xi_b \gamma$ | 92.0 - 148r<sub>3</sub> |
| $\Xi_b \to \Xi_b \gamma$ | 161 - 260r<sub>3</sub> |
| $\Xi_b \to \Xi_b \gamma$ | 161 - 260r<sub>3</sub> |

$r_4$-term are given by

\[ \Gamma_{\Sigma^{(*)}_{Q} \to \Lambda_{Q} \gamma} = \frac{8 \sigma_3^2 f_3^2 m_{\Lambda_{Q}} E_\gamma^3}{3 F_4^2 m_{\Sigma^{(*)}_{Q}}^3} \]

\[ \Gamma_{\Xi^{(*)}_{Q} \to \Xi_{Q} \gamma} = \frac{8 \sigma_3^2 (f_3 + 2 \sigma_3)^2 m_{\Xi^{(*)}_{Q}} E_\gamma^3}{27 F_4^2 m_{\Xi^{(*)}_{Q}}^3} \]

\[ \Gamma_{\Xi^{(*)}_{Q} \to \Xi_{Q} \gamma} = \frac{8 \sigma_3^2 (f_3 - \sigma_3)^2 m_{\Xi^{(*)}_{Q}} E_\gamma^3}{27 F_4^2 m_{\Xi^{(*)}_{Q}}^3} \]

and the predicted values are shown in Table XIV and XV with the ones in Ref. [18, 31]. Our results are consistent with the lattice results in Ref. [31] if $r_4 \sim 0.1$. On the other hand, comparison with the results in Ref. [18] indicates that the chiral loop may be important.

VI. A SUMMARY AND DISCUSSIONS

We constructed an effective hadronic model regarding negative parity 3 representations as chiral partners to positive parity 6 representations, based on the chiral symmetry and heavy-quark spin-flavor symmetry. We determine the model parameters from the experimental data for relevant masses and decay widths of $\Sigma_c(2455, 1/2^+)$, $\Sigma_c(2520, 3/2^+)$, $\Lambda_c(2595, 1/2^-)$, $\Xi_c(2790, 1/2^-)$, and $\Xi_c(2815, 1/2^-)$.

Then, we studied the decay widths of $\Lambda_c(2625)$, $\Lambda_b(5912)$, $\Lambda_b(5920)$, and negative parity $\Xi_c^{(*)}$ which have not been yet discovered in any experiments. We think that $\Xi_c^{(*)}$ here is unlikely to be $\Xi_b(6227)$ reported in Ref. [37], which may be explained as e.g., a molecule state in Ref. [38]. Using the model parameters, we predict the values for masses and decay widths of negative parity excited $\Xi_b$.

As shown in our previous work Ref. [12], the chiral partner structure is reflected in the direct decay processes in three-body decays of negative parity 3 representations. Our results for the three-body decays of $\Xi_{c(3)} \to \Xi_b \pi \pi$ are dominated by the resonant decay modes unlikely to the decays of $\Lambda_c(2625)$, $\Lambda_b(5912)$ and $\Lambda_b(5920)$ shown in Ref. [12]. However, the Dalitz analysis, which was performed in Ref. [13] for the decays of $\Lambda_c$ and $\Lambda_b$, may give an information of the direct decays of $\Xi_b$. Therefore, we would like to stress that future investigations of detailed three-body decay processes of negative parity SHBs will provide some clues to understand the chiral partner structure.

We also studied the radiative decays of the SHBs included in the present model using the effective interaction Lagrangians in Eq. (32). We showed that there is a relation among the radiative decay widths of positive parity SHBs ($\Sigma^*_Q$, $\Xi^*_Q$, $\Omega^*_Q$) and those of negative parity SHBs ($\Lambda^*_Q$, $\Xi^*_Q$, $\Omega^*_Q$), reflecting the chiral partner structure. Since the masses of negative parity SHBs in the bottom sector...
are close to the threshold of hadronic decays, the radiative decay widths can be comparable with the strong decay widths depending on the precise values of the masses. We summarize the decays of bottom SHBs with negative parity in Table XVI.

We expect that experimental study of these radiative decays will provide a clue to understand the chiral partner structure. In addition, we predict the \( \Omega^* \rightarrow \Omega Q \gamma \) decay which is the sole decay mode of \( \Omega^* \). Experimental observation of this in future will be a check of the present framework based on the effective model respecting the chiral symmetry and the heavy-quark spin-flavor symmetry. In addition, we expect that the future lattice simulations for the radiative decay of negative parity SHBs also provide some clues to the chiral partner structure.

While we are writing this manuscript, we are informed of Ref. [10], in which the chiral partner structure of SHBs is studied based on the mirror assignment of parity doublet structure including three chiral representations, i.e., \((3,3), (3,1) + (1,3)\) and \((6,1) + (1,6)\).

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**TABLE XVI.** Pionic and radiative decays of bottom SHBs with negative parity.

| SHB   | \( J^{P} \) | decay modes | Our model \([\text{MeV}]\) | exp. \([\text{MeV}]\) |
|-------|-------------|-------------|-----------------------------|------------------------|
| \( \Lambda_{b1} \) | 1/2 | \( \Lambda_b \pi^+ \pi^- \) | \((0.67-4.4) \times 10^{-4}\) |  |
|       |       | \( \Lambda_b \pi^- \pi^0 \) | \((1.4-6.0) \times 10^{-3}\) |  |
|       |       | \( \Sigma_b^0 \gamma \) | 0.098 \( r_2^2 \) | < 0.66 |
|       |       | \( \Sigma_b^0 \gamma \) | 0.025 \( r_2^2 \) |  |
|       |       | \( \Lambda_b \gamma \) | 0.027 \( r_2^2 \) |  |
| \( \Lambda_{b1} \) | 3/2 | \( \Lambda_b \pi^+ \pi^- \) | \((0.75-13) \times 10^{-4}\) |  |
|       |       | \( \Lambda_b \pi^- \pi^0 \) | \((2.2-12) \times 10^{-3}\) |  |
|       |       | \( \Lambda_{b1} \gamma \) | 0.0013 \( r_2^2 \) | < 0.63 |
|       |       | \( \Sigma_b^0 \gamma \) | 0.031 \( r_2^2 \) |  |
|       |       | \( \Sigma_b^0 \gamma \) | 0.081 \( r_2^2 \) |  |
|       |       | \( \Lambda_b \gamma \) | 0.029 \( r_2^2 \) |  |
| \( \Xi_{b1} \) | 1/2 | \( \Xi_b \pi^- \) | 0.0415 - 15.3 |  |
|       |       | \( \Xi_b^0 \gamma \) | 0.370 - 0.887 \( r_2^2 \) |  |
|       |       | \( \Xi_b^0 \gamma \) | 0.138 - 0.358 \( r_2^2 \) |  |
|       |       | \( \Xi_b^0 \gamma \) | 0.0288 - 0.0464 \( r_2^2 \) |  |
| \( \Xi_{b1} \) | 1/2 | \( \Xi_b \pi^- \) | 0.0415 - 15.3 |  |
|       |       | \( \Xi_b^0 \gamma \) | 0.370 - 0.887 \( r_2^2 \) |  |
|       |       | \( \Xi_b^0 \gamma \) | 0.138 - 0.358 \( r_2^2 \) |  |
|       |       | \( \Xi_b^0 \gamma \) | 0.0288 - 0.0464 \( r_2^2 \) |  |
| \( \Xi_{b1} \) | 3/2 | \( \Xi_b \pi^- \) | 0.326 - 11.5 |  |
|       |       | \( \Xi_b^0 \gamma \) | < 4.53 \( r_2^2 \) × 10^{-4} |  |
|       |       | \( \Xi_b^0 \gamma \) | 0.0924 - 0.222 \( r_2^2 \) |  |
|       |       | \( \Xi_b^0 \gamma \) | 0.344 - 0.895 \( r_2^2 \) |  |
|       |       | \( \Xi_b^0 \gamma \) | 0.0288 - 0.0464 \( r_2^2 \) |  |
| \( \Xi_{b1} \) | 3/2 | \( \Xi_b \pi^- \) | 0.326 - 11.5 |  |
|       |       | \( \Xi_b^0 \gamma \) | < 1.81 \( r_2^2 \) × 10^{-3} |  |
|       |       | \( \Xi_b^0 \gamma \) | 0.344 - 0.895 \( r_2^2 \) |  |
|       |       | \( \Xi_b^0 \gamma \) | 0.0288 - 0.0464 \( r_2^2 \) |  |
|       |       | \( \Xi_b^0 \gamma \) | 0.112 - 0.182 \( r_2^2 \) |  |
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