Strong decays of the $\Xi_b(6227)$ as a $\Sigma_b \bar{K}$ molecule

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We study the strong decays of the newly observed $\Xi_b(6227)$ assuming that it is a pure $\Sigma_b \bar{K}$ molecular state. Considering four possible spin-parity assignments $J^P = 1/2^\pm$ and $3/2^\pm$, the partial decay widths of the $\Sigma_b \bar{K}$ molecular state into $\Lambda_b \bar{K}$, $\Xi_b \pi$, and $\Xi'_b \pi$ final states through hadronic loops are evaluated with the help of the effective Lagrangians. In comparison with the LHCb data, the spin-parity $1/2^-$ assignment is preferred while those of $J^P = 1/2^+$ and $J^P = 3/2^\pm$ are disfavored. In addition, we show that the two allowed decay modes $\Lambda_b \bar{K}$ and $\Xi_b \pi$ of the $\Xi_b(6227)$, being a S -wave $\Sigma_b \bar{K}$ molecular state, have almost equal branching ratios.

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I. INTRODUCTION

During the past decade, many new narrow baryon resonances containing a b quark, such as $\Lambda_b(5912)$, $\Lambda_b(5920)$, $\Sigma_b(5815)$, Σ_b^* , and Ξ_b , were discovered experimentally [1–3]. Very recently, a bottom baryon $\Xi_b(6227)$ was reported by the LHCb Collaboration in both the $\Lambda_b^0 K^-$ and $\Xi_b^0 \pi^-$ final states from pp collisions [4]. Its mass and width are, respectively,

$$M = 6226.9 \pm 2.0(\text{stat}) \pm 0.3(\text{syst}) \pm 0.2(\Lambda_b^0) \text{ MeV}$$

$$\Gamma = 18.1 \pm 5.4(\text{stat}) \pm 1.8(\text{syst}) \text{ MeV}. \quad (1)$$

Its spin-parity, however, remains unknown.

Before the discovery of the Ξ_b^* state, there were already a few theoretical studies on the existence of such a state.

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For instance, different quark models predicted that there exists a dsb three quark excited state with a mass about 6200 MeV [5–7]. The mass spectra of bottom baryons around 6200 MeV were investigated in a Faddeev equation approach [8]. A molecule Ξ_b state with a narrow width and a mass around 6200 MeV was predicted in the unitarized coupled channels approach [9]. In Ref. [10] the authors also found that the $\bar{K}\Sigma_b$ interaction is strong enough to form a bound state both in isospin 3/2 and 1/2.¹ The QCD sum rule predicted that there is a Ξ_b^* state with a mass around 6.14 ± 0.16 GeV [11].

Following the discovery of the Ξ_b^* , several theoretical studies have been performed [12–14]. In the heavy quark light diquark model, based on the analysis of the mass spectrum and the two-body Okubo-Zweig-Iizuka (OZI) allowed strong decays, the Ξ_b^* was suggested to be a $1P$ Ξ'_b state with spin-parity $J^P = 3/2^-$ or $J^P = 5/2^-$ [12]. In the chiral quark model, based on the two-body strong decays studied, Ref. [13] assigned the Ξ_b^* as a three-quark state with spin-parity $J^P = 3/2^-$ or $J^P = 5/2^-$. While in

¹We note that in Ref. [10], the predicted $\bar{K}\Sigma_b$ molecular state in isospin 1/2 is much lower than that in isospin 3/2, whose position is closer to that of the Ξ_b^* .

Ref. [14] the mass and two-body strong decays of the Ξ_b^* were studied in the QCD sum rules approach and it was shown that the $\Xi_b(6227)$ might be a $1P$ orbitally excited $\Xi_b(5955)$ state with $J^P = 3/2^-$.

Although the studies of Refs. [12–14] seem to indicate that this state is a conventional three-quark state, the Ξ_b^* might still be a $\bar{K}\Sigma_b$ hadronic molecule state, because the mass gap between the Ξ_b^* and the ground Ξ_b , about 440 MeV, is large enough to excite a light quark-antiquark pair to form a molecular state. Indeed, it is shown in Refs. [9,10] that the interaction between a $\bar{K}$ meson and a Σ_b baryon is strong enough to form a bound state with a mass about 6200 MeV. One way to distinguish the two scenarios is to study the two-body strong decay widths of the Ξ_b^* baryon. In the present paper we consider the following strong decay modes, $\Xi_b^* \rightarrow \Lambda_b^0 \bar{K}$, $\Xi_b^* \rightarrow \Xi_b \pi$, and $\Xi_b^* \rightarrow \Xi_b' \pi$, of the $\Xi_b(6227)$ with the following spin-parity assignments: $J^P = 1/2^\pm$ and $3/2^\pm$, using an effective Lagrangian approach and assuming that the $\Xi_b(6227)$ is a hadronic molecule state of $\bar{K}$ and Σ_b .

This work is organized as follows. The theoretical formalism is explained in Sec. II. The predicted partial decay widths are presented in Sec. III, followed by a short summary in the last section.

II. FORMALISM AND INGREDIENTS

In this section, we explain how to calculate the strong decay widths $\Xi_b^* \rightarrow \Lambda_b \bar{K}$, $\Xi_b^* \rightarrow \Xi_b \pi$, and $\Xi_b^* \rightarrow \Xi_b' \pi$ in the molecular scenario with different spin-parity assignments for the Ξ_b^* . The molecular structure of the Ξ_b^* baryon with $J^P = 1/2^\pm$ is described by the following Lagrangian [15]

$$\mathcal{L}_{\Xi_b^*}(x) = g_{\Xi_b^* \bar{K} \Sigma_b} \int d^4 y \Phi(y^2) \times \bar{K}(x + \omega_{\Sigma_b} y) \Gamma \vec{\tau} \cdot \vec{\Sigma}_b(x - \omega_K y) \Xi_b^*(x), \quad (2)$$

while for $J^P = 3/2^\pm$ the Lagrangian contains a derivative $\bar{K}\Sigma_b$ coupling

$$\mathcal{L}_{\Xi_b^*}(x) = g_{\Xi_b^* \bar{K} \Sigma_b} \int d^4 y \Phi(y^2) \times \bar{K}(x + \omega_{\Sigma_b} y) \Gamma \vec{\tau} \cdot \partial_\mu \vec{\Sigma}_b(x - \omega_K y) \Xi_b^{*\mu}(x), \quad (3)$$

where $\omega_K = m_K/(m_K + m_{\Sigma_b})$, $\omega_{\Sigma_b} = m_{\Sigma_b}/(m_K + m_{\Sigma_b})$, and Γ is the corresponding Dirac matrix reflecting the spin-parity of Ξ_b^* . In particular, for $J^P = 1/2^+$ and $3/2^-$, $\Gamma = \gamma^5$, while for $J^P = 1/2^-$ and $3/2^+$, $\Gamma = 1$. In the Lagrangian, an effective correlation function $\Phi(y^2)$ is introduced to describe the distribution of the two constituents, the $\bar{K}$ and the Σ_b , in the hadronic molecular Ξ_b^* state. The introduced correlation function also makes the

FIG. 1. Self-energy of the Ξ_b^* state.

Feynman diagrams ultraviolet finite. Here we choose the Fourier transformation of the correlation to be a Gaussian form in the Euclidean space [15–31],

$$\Phi(p_E^2) \doteq \exp(-p_E^2/\Lambda^2) \quad (4)$$

with Λ being the size parameter which characterizes the distribution of the components inside the molecule. Though the value of Λ could not be determined from first principles, it is usually chosen to be about 1 GeV in the literature [15–31]. In this work, we vary Λ in a range of $0.9 \text{ GeV} \leq \Lambda \leq 1.10 \text{ GeV}$.

With the effective Lagrangian in Eq. (2) and Eq. (3) and the Feynman diagram shown in Fig 1, we can obtain the self energy of the Ξ_b^* ,

$$\begin{aligned} \Sigma_{\Xi_b^*}^{1/2}(k_0) &= g_{\Xi_b^* \Sigma_b \bar{K}}^2 \int \frac{d^4 k_1}{(2\pi)^4 i} \left\{ 2\Phi^2[(k_1 - k_0 \omega_{\Sigma_b^-})^2] \Gamma \frac{\not{k}_1 + m_{\Sigma_b^-}}{k_1^2 - m_{\Sigma_b^-}^2} \Gamma \right. \\ &\quad \times \frac{1}{(k_1 - k_0)^2 - m_{\bar{K}^0}^2} + \Phi^2[(k_1 - k_0 \omega_{\Sigma_b^0})^2] \Gamma \frac{\not{k}_1 + m_{\Sigma_b^0}}{k_1^2 - m_{\Sigma_b^0}^2} \Gamma \\ &\quad \left. \times \frac{1}{(k_1 - k_0)^2 - m_{\bar{K}^-}^2} \right\}, \end{aligned} \quad (5)$$

$$\begin{aligned} \Sigma_{\Xi_b^*}^{\mu\nu 3/2}(k_0) &= g_{\Xi_b^* \Sigma_b \bar{K}}^2 \int \frac{d^4 k_1}{(2\pi)^4 i} \left\{ 2\Phi^2[(k_1 - k_0 \omega_{\Sigma_b^-})^2] \Gamma \frac{\not{k}_1 + m_{\Sigma_b^-}}{k_1^2 - m_{\Sigma_b^-}^2} \Gamma \right. \\ &\quad \times \frac{1}{(k_1 - k_0)^2 - m_{\bar{K}^0}^2} + \Phi^2[(k_1 - k_0 \omega_{\Sigma_b^0})^2] \Gamma \frac{\not{k}_1 + m_{\Sigma_b^0}}{k_1^2 - m_{\Sigma_b^0}^2} \Gamma \\ &\quad \left. \times \frac{1}{(k_1 - k_0)^2 - m_{\bar{K}^-}^2} \right\} k_1^\mu k_1^\nu, \end{aligned} \quad (6)$$

where $k_0^2 = m_{\Xi_b^*}^2$ with k_0 , $m_{\Xi_b^*}$ denoting the four momenta and mass of the Ξ_b^* , respectively, k_1 , $m_{\bar{K}}$, and m_{Σ_b} are the four-momenta, the mass of the $\bar{K}$ meson, and the mass of the Σ_b baryon, respectively. The coupling constant $g_{\Xi_b^* \Sigma_b \bar{K}}$ is determined by the compositeness condition [15–31].

It implies that the renormalization constant of the hadron wave function is set to zero, i.e.,

$$Z_{\Xi_b^*} = 1 - \frac{d\Sigma_{\Xi_b^*}^{1/2(3/2-T)}}{dk_0} \Big|_{k_0=m_{\Xi_b^*}} = 0, \quad (7)$$

where the $\Sigma_{\Xi_b^*}^{3/2-T}$ is the transverse part of the self-energy operator $\Sigma_{\Xi_b^*}^{\mu\nu 3/2}$, related to $\Sigma_{\Xi_b^*}^{3/2}$ via

$$\Sigma_{\Xi_b^*}^{\mu\nu 3/2}(k_0) = \left(g_{\mu\nu} - \frac{k_0^\mu k_0^\nu}{k_0^2} \right) \Sigma_{\Xi_b^*}^{3/2-T} + \dots \quad (8)$$

The strong decay modes of the Ξ_b^* are $\Xi_b^* \rightarrow \Lambda_b^{(')0} K^-$, $\Xi_b^* \rightarrow \Lambda_b^{(')0} \bar{K}^0$, $\Xi_b^* \rightarrow \Xi_b^{(')0} \pi^-$, $\Xi_b^* \rightarrow \Xi_b^{(')-} \pi^0$, and $\Xi_b^* \rightarrow \Xi_b^{(')0} \pi^0$. Here, we only calculate the decay widths in the channels $\Xi_b^* \rightarrow \Lambda_b^0 K^-$ and $\Xi_b^* \rightarrow \Xi_b^{(')0} \pi^-$. The decay widths in the other channels can be obtained by isospin symmetry as $\Gamma(\Xi_b^* \rightarrow \Lambda_b^0 \bar{K}^0) = \Gamma(\Xi_b^* \rightarrow \Lambda_b^0 K^-)$ and $\Gamma(\Xi_b^* \rightarrow \Xi_b^{(')0} \pi^0) = \Gamma(\Xi_b^* \rightarrow \Xi_b^{(')-} \pi^0) = \frac{1}{2} \Gamma(\Xi_b^* \rightarrow \Xi_b^{(')0} \pi^-)$. The sum of these partial decay widths is the total decay width of the Ξ_b^* .

Figure 2 shows the hadronic decay of the $\Sigma_b \bar{K}$ molecular state into $\Lambda_b^0 K^-$, $\Xi_b^0 \pi^-$, and $\Xi_b^{0(-)} \pi^-$ mediated by the exchange of the ρ and $\bar{K}^*$ mesons. In Refs. [32,33], the couplings of the vector meson with the charm baryons are obtained using the hidden-gauge formalism and assuming SU(4) flavor symmetry:

$$\mathcal{L}_{VBB} = \frac{g}{2} \sum_{i,j,k,l=1}^4 \bar{B}_{ijk} \gamma^\mu (V_{\mu,l}^K B^{ijl} + 2V_{\mu,l}^j B^{ilk}), \quad (9)$$

where the coupling constant $g = 6.6$ is taken from Ref. [32]. The symbol V_μ represents the vector fields of the 16-plet of the ρ meson,

FIG. 2. Feynman diagrams for the $\Xi_b^* \rightarrow \Lambda_b^0 K^-$, $\Xi_b^0 \pi^-$, and $\Xi_b^{0(-)} \pi^-$ decay processes. We also show the definitions of the kinematics (k_0, k_1, k_2, p_1, p_2 , and q) used in the calculation.

$$V_\mu = \begin{pmatrix} \frac{1}{\sqrt{2}}(\rho^0 + \omega) & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & \frac{1}{\sqrt{2}}(-\rho^0 + \omega) & K^{*0} & D^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}_\mu, \quad (10)$$

and B represents the 20-plet of the proton,

$$\begin{aligned} B^{121} &= p, & B^{122} &= n, & B^{132} &= \frac{1}{\sqrt{2}}\Sigma^0 - \frac{1}{\sqrt{6}}\Lambda, \\ B^{213} &= \sqrt{\frac{2}{3}}\Lambda, & B^{231} &= \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda, & B^{232} &= \Sigma^-, \\ B^{233} &= \Xi^-, & B^{311} &= \Sigma^+, & B^{313} &= \Xi^0, & B^{141} &= -\Sigma_c^{++}, \\ B^{142} &= \frac{1}{\sqrt{2}}\Sigma_c^+ + \frac{1}{\sqrt{6}}\Lambda_c, & B^{143} &= \frac{1}{\sqrt{2}}\Xi_c'^+ - \frac{1}{\sqrt{6}}\Xi_c^+, \\ B^{241} &= \frac{1}{\sqrt{2}}\Sigma_c^+ - \frac{1}{\sqrt{6}}\Lambda_c, & B^{242} &= \Sigma_c^0, \\ B^{243} &= \frac{1}{\sqrt{2}}\Xi_c'^0 + \frac{1}{\sqrt{6}}\Xi_c^0, & B^{341} &= \frac{1}{\sqrt{2}}\Xi_c'^+ + \frac{1}{\sqrt{6}}\Xi_c^+, \\ B^{124} &= \sqrt{\frac{2}{3}}\Lambda_c, & B^{234} &= \sqrt{\frac{2}{3}}\Xi_c^0, & B^{314} &= \sqrt{\frac{2}{3}}\Xi_c^+, \\ B^{342} &= \frac{1}{\sqrt{2}}\Xi_c'^0 - \frac{1}{\sqrt{6}}\Xi_c^0, & B^{343} &= \Omega_c^0, \\ B^{144} &= \Xi_{cc}^{++}, & B^{244} &= -\Xi_{cc}^+, & B^{344} &= \Omega_{cc}, \end{aligned} \quad (11)$$

where the indices i, j, k of B^{ijk} denote the quark content of the baryon fields with the identification $1 \leftrightarrow u, 2 \leftrightarrow d, 3 \leftrightarrow s$, and $4 \leftrightarrow c$. Following the strategy of Ref. [33], the Lagrangian for the bottom hadrons can be easily obtained by replacing the charm baryons in Eq. (11) with the bottom ones. And the couplings of the vector meson with the beauty baryons are also obtained as $g_{BBV} = g = 6.6$ [33].

To compute the ρKK and πKK^* vertices, we also need the following effective Lagrangians

$$\mathcal{L}_{KK\rho} = ig_{KK\rho} [\bar{K}(\partial_\mu K) - (\partial_\mu \bar{K})K] \vec{\tau} \cdot \vec{\rho}^\mu, \quad (12)$$

$$\mathcal{L}_{K^*K\pi} = i \frac{g_{K^*K\pi}}{\sqrt{2}} K_\mu^{*\dagger} [(\vec{\tau} \cdot \vec{\pi}) \partial^\mu K - \partial^\mu (\vec{\tau} \cdot \vec{\pi}) K], \quad (13)$$

where

$$K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix}, \quad \bar{K} = \begin{pmatrix} \bar{K}^0 \\ -K^- \end{pmatrix} \quad (14)$$

with $\vec{\tau}$ being the usual Pauli matrices and $\vec{\rho}^\mu$ the field operators of the ρ meson. In the $SU(3)_f$ limit, the coupling constant satisfies $g_{KK\rho} = 2.9$, which is determined by the Kawarabayashi-Suzuki-Riazuddin-Fayyazuddin relation [34]. The coupling $g_{K^*K\pi}$ is fixed from the strong

TABLE I. Masses of the particles needed in the present work (in units of MeV).

Σ_b	Λ_b^0	Ξ_b^0	$\Xi_b^{\prime 0}$
5815.5	5619.6	5791.9	5935.02
ρ	K^*	K^-	$\pi^\pm$
775.26	891.76	493.68	139.57

decay width of $K^* \rightarrow K\pi$. With the help of Eq. (13), the two-body decay width $\Gamma(K^{*+} \rightarrow K^0\pi^+)$ is related to $g_{K^*K\pi}$ as

$$\Gamma(K^{*+} \rightarrow K^0\pi^+) = \frac{g_{K^*K\pi}^2}{6\pi m_{K^{*+}}^2} \mathcal{P}_{\pi K^*}, \quad (15)$$

where $\mathcal{P}_{\pi K^*}$ is the three-momentum of the π in the rest frame of the K^* . Using the experimental strong decay width and the masses of the particles needed in the present work are listed in Table I we obtain $g_{K^*K\pi} = 4.61$ [35].

Putting all the pieces together, we obtain the following amplitudes,

$$\begin{aligned} \mathcal{M}_a^{1/2}(\Xi_b^{*-} \rightarrow \Lambda_b^0 K^-) \\ = \sqrt{3} g_{\Xi_b^* \Sigma_b \bar{K}} g_{KK\rho} g_{\Sigma_b \Lambda_b \rho} \int \frac{d^4 k_1}{(2\pi)^4 i} \\ \times \Phi[(k_1 \omega_{\bar{K}^0} - k_2 \omega_{\Sigma_b^-})^2] \bar{u}(p_1) \gamma_\mu \frac{\not{k}_1 + m_{\Sigma_b^-}}{k_1^2 - m_{\Sigma_b^-}^2} \Gamma u(k_0) \\ \times \frac{1}{k_2^2 - m_{\bar{K}^0}^2} (k_2^\nu + p_2^\nu) \frac{-g^{\mu\nu} + q^\mu q^\nu / m_{\rho^-}^2}{q^2 - m_{\rho^-}^2}, \end{aligned} \quad (16)$$

$$\begin{aligned} \mathcal{M}_b^{1/2}(\Xi_b^{*-} \rightarrow \Lambda_b^0 K^-) \\ = \frac{\sqrt{3}}{2} g_{\Xi_b^* \Sigma_b \bar{K}} g_{KK\rho} g_{\Sigma_b \Lambda_b \rho} \int \frac{d^4 k_1}{(2\pi)^4 i} \\ \times \Phi[(k_1 \omega_{K^-} - k_2 \omega_{\Sigma_b^0})^2] \bar{u}(p_1) \gamma_\mu \frac{\not{k}_1 + m_{\Sigma_b^0}}{k_1^2 - m_{\Sigma_b^0}^2} \Gamma u(k_0) \\ \times \frac{1}{k_2^2 - m_{K^-}^2} (k_2^\nu + p_2^\nu) \frac{-g^{\mu\nu} + q^\mu q^\nu / m_{\rho^0}^2}{q^2 - m_{\rho^0}^2}, \end{aligned} \quad (17)$$

$$\begin{aligned} \mathcal{M}_c^{1/2}(\Xi_b^{*-} \rightarrow \Xi_b^{0(\prime)} \pi^-) \\ = \mathcal{K} g_{\Xi_b^* \Sigma_b \bar{K}} g_{K^* K \pi} g_{\Sigma_b \Xi_b^{0(\prime)} \bar{K}^*} \int \frac{d^4 k_1}{(2\pi)^4 i} \\ \times \Phi[(k_1 \omega_{\bar{K}^0} - k_2 \omega_{\Sigma_b^-})^2] \bar{u}(p_1) \gamma_\mu \frac{\not{k}_1 + m_{\Sigma_b^-}}{k_1^2 - m_{\Sigma_b^-}^2} \Gamma u(k_0) \\ \times \frac{1}{k_2^2 - m_{\bar{K}^0}^2} (k_2^\nu + p_2^\nu) \frac{-g^{\mu\nu} + q^\mu q^\nu / m_{K^{*-}}^2}{q^2 - m_{K^{*-}}^2}, \end{aligned} \quad (18)$$

$$\begin{aligned} \mathcal{M}_d^{1/2}(\Xi_b^{*-} \rightarrow \Xi_b^{0(\prime)} \pi^-) \\ = -\mathcal{H} g_{\Xi_b^* \Sigma_b \bar{K}} g_{K^* K \pi} g_{\Sigma_b \Xi_b^{0(\prime)} \bar{K}^*} \int \frac{d^4 k_1}{(2\pi)^4 i} \\ \times \Phi[(k_1 \omega_{K^-} - k_2 \omega_{\Sigma_b^0})^2] \bar{u}(p_1) \gamma_\mu \frac{\not{k}_1 + m_{\Sigma_b^0}}{k_1^2 - m_{\Sigma_b^0}^2} \Gamma u(k_0) \\ \times \frac{1}{k_2^2 - m_{K^-}^2} (k_2^\nu + p_2^\nu) \frac{-g^{\mu\nu} + q^\mu q^\nu / m_{K^{*0}}^2}{q^2 - m_{K^{*0}}^2}, \end{aligned} \quad (19)$$

$$\begin{aligned} \mathcal{M}_a^{3/2}(\Xi_b^{*-} \rightarrow \Lambda_b^0 K^-) \\ = -i\sqrt{3} g_{\Xi_b^* \Sigma_b \bar{K}} g_{KK\rho} g_{\Sigma_b \Lambda_b \rho} \int \frac{d^4 k_1}{(2\pi)^4 i} \\ \times \Phi[(k_1 \omega_{\bar{K}^0} - k_2 \omega_{\Sigma_b^-})^2] \bar{u}(p_1) \gamma_\mu \frac{\not{k}_1 + m_{\Sigma_b^-}}{k_1^2 - m_{\Sigma_b^-}^2} \Gamma u^\eta(k_0) \\ \times \frac{1}{k_2^2 - m_{\bar{K}^0}^2} (k_2^\nu + p_2^\nu) \frac{-g^{\mu\nu} + q^\mu q^\nu / m_{\rho^-}^2}{q^2 - m_{\rho^-}^2} k_1^\eta, \end{aligned} \quad (20)$$

$$\begin{aligned} \mathcal{M}_b^{3/2}(\Xi_b^{*-} \rightarrow \Lambda_b^0 K^-) \\ = i\frac{\sqrt{3}}{2} g_{\Xi_b^* \Sigma_b \bar{K}} g_{KK\rho} g_{\Sigma_b \Lambda_b \rho} \int \frac{d^4 k_1}{(2\pi)^4 i} \\ \times \Phi[(k_1 \omega_{K^-} - k_2 \omega_{\Sigma_b^0})^2] \bar{u}(p_1) \gamma_\mu \frac{\not{k}_1 + m_{\Sigma_b^0}}{k_1^2 - m_{\Sigma_b^0}^2} \Gamma u^\eta(k_0) \\ \times \frac{1}{k_2^2 - m_{K^-}^2} (k_2^\nu + p_2^\nu) \frac{-g^{\mu\nu} + q^\mu q^\nu / m_{\rho^0}^2}{q^2 - m_{\rho^0}^2} k_1^\eta, \end{aligned} \quad (21)$$

$$\begin{aligned} \mathcal{M}_c^{3/2}(\Xi_b^{*-} \rightarrow \Xi_b^{0(\prime)} \pi^-) \\ = i\mathcal{K} g_{\Xi_b^* \Sigma_b \bar{K}} g_{K^* K \pi} g_{\Sigma_b \Xi_b^{0(\prime)} \bar{K}^*} \int \frac{d^4 k_1}{(2\pi)^4 i} \\ \times \Phi[(k_1 \omega_{\bar{K}^0} - k_2 \omega_{\Sigma_b^-})^2] \bar{u}(p_1) \gamma_\mu \frac{\not{k}_1 + m_{\Sigma_b^-}}{k_1^2 - m_{\Sigma_b^-}^2} \Gamma u^\eta(k_0) \\ \times \frac{1}{k_2^2 - m_{\bar{K}^0}^2} (k_2^\nu + p_2^\nu) \frac{-g^{\mu\nu} + q^\mu q^\nu / m_{K^{*-}}^2}{q^2 - m_{K^{*-}}^2} k_1^\eta, \end{aligned} \quad (22)$$

$$\begin{aligned} \mathcal{M}_d^{3/2}(\Xi_b^{*-} \rightarrow \Xi_b^{0(\prime)} \pi^-) \\ = -i\mathcal{H} g_{\Xi_b^* \Sigma_b \bar{K}} g_{K^* K \pi} g_{\Sigma_b \Xi_b^{0(\prime)} \bar{K}^*} \int \frac{d^4 k_1}{(2\pi)^4 i} \\ \times \Phi[(k_1 \omega_{K^-} - k_2 \omega_{\Sigma_b^0})^2] \bar{u}(p_1) \gamma_\mu \frac{\not{k}_1 + m_{\Sigma_b^0}}{k_1^2 - m_{\Sigma_b^0}^2} \Gamma u^\eta(k_0) \\ \times \frac{1}{k_2^2 - m_{K^-}^2} (k_2^\nu + p_2^\nu) \frac{-g^{\mu\nu} + q^\mu q^\nu / m_{K^{*0}}^2}{q^2 - m_{K^{*0}}^2} k_1^\eta, \end{aligned} \quad (23)$$

where $\mathcal{K} = (\sqrt{3}, \sqrt{2})$ and $\mathcal{H} = (\frac{\sqrt{6}}{2}, 1)$ for amplitude $\mathcal{M}(\Xi_b^{*-} \rightarrow \Xi_b^0 \pi^-)$ and $\mathcal{M}(\Xi_b^{*-} \rightarrow \Xi_b^{\prime 0} \pi^-)$, respectively.

Once the amplitudes are determined, the corresponding partial decay widths can be obtained, which read,

$$\Gamma(\Xi_b^* \rightarrow MB) = \frac{1}{2J+1} \frac{2}{8\pi} \frac{|\vec{p}_1|}{m_{\Xi_b^*}^2} |\overline{\mathcal{M}}|^2, \quad (24)$$

where J is the total angular momentum of the Ξ_b^* state, the $|\vec{p}_1|$ is the three-momenta of the decay products in the center of mass frame, the overline indicates the sum over the polarization vectors of the final hadrons, and MB denotes the decay channel of MB , i.e., $\Lambda_b \bar{K}$, $\Xi_b \pi$, $\Xi_b' \pi$.

III. RESULTS AND DISCUSSIONS

In this work, we study the strong decays of the Ξ_b^* to the two-body final states $\Lambda_b \bar{K}$, $\Xi_b \pi$, and $\Xi_b' \pi$ assuming that it is a $\bar{K}\Sigma_b$ molecular state. In order to obtain the two body decay width through the triangle diagrams shown in Fig. 2, we first compute the coupling constant $g_{\Xi_b^* \Sigma_b \bar{K}}$.

With a value of the cutoff $\Lambda = 0.9$ – 1.1 GeV, the corresponding coupling constants are listed in Table II. The Λ dependence of these coupling constants are shown in Fig. 3. We note that they decrease slowly with the increase of the cutoff, and the coupling constant is almost independent of Λ for the $J^P = 1/2^-$ case, where the Ξ_b^* is an S -wave $\bar{K}\Sigma_b$ molecular state. It is consistent with the conclusion in Refs. [15–31] that for an S -wave loosely bound state the effective coupling strength of the bound state to its components is insensitive to its inner structure.

We show the dependence of the total decay width on the cutoff Λ in Fig. 4. In the present calculation, we vary Λ from 0.9 to 1.1 GeV. In this Λ range, the total decay width increases for the cases of $J^P = 1/2^\pm$ and $J^P = 3/2^+$, while decreases for the $J^P = 3/2^-$ case. For the case of $J^P = 1/2^+$, the predicted total decay width is much smaller than the experimental total width, which disfavors such a spin-parity assignment for the Ξ_b^* in the $\bar{K}\Sigma_b$ molecular picture. The $J^P = 3/2^+$ assignment is not favored by our study as well. In this case the $\bar{K}\Sigma_b$ molecular state should be in P -wave. Hence, the $J^P = 3/2^+$ assumption for $\Xi_b^*(6227)$ can be excluded. The $J^P = 3/2^-$ case is disfavored due to the smallest width predicted, and a D -wave $\bar{K}\Sigma_b$ molecular with $J^P = 3/2^-$ is difficult to form through long range meson exchanges. In other words, the $J^P = 1/2^+$ and $J^P = 3/2^\pm$ $\Sigma_b \bar{K}$ molecular assumptions for the Ξ_b^* are excluded. Hence, only the assignment as an S -wave $\bar{K}\Sigma_b$ molecular state is possible for the Ξ_b^* based on the total decay width experimentally measured.

TABLE II. The coupling constant $g_{\Xi_b^* \Sigma_b \bar{K}}$ for different J^P assignments with $\Lambda = 0.9$ – 1.1 GeV.

$J^P = \frac{1}{2}^-$	$J^P = \frac{1}{2}^+$	$J^P = \frac{3}{2}^-$ (GeV $^{-1}$)	$J^P = \frac{3}{2}^+$ (GeV $^{-1}$)
1.84–1.71	12.01–10.39	4.50–3.37	3.87–2.95

FIG. 3. The coupling constants of the Ξ_b^* state with different J^P assignments as a function of the parameter Λ .

In Fig. 4, we show the partial decay widths of the $\Xi_b^* \rightarrow \Lambda_b \bar{K}$, $\Xi_b \pi$, and $\Xi_b' \pi$ as a function of the cutoff parameter Λ . The two-body decays in the $\Xi_b^* \rightarrow \bar{K}\Lambda_b$, $\Xi_b \pi$, and $\Xi_b' \pi$ channels are insensitive to the cutoff parameter Λ . The transition $\Xi_b^* \rightarrow \bar{K}\Lambda_b$ and $\Xi_b^* \rightarrow \Xi_b \pi$ are the main decay channels in the $J^P = 1/2^\pm$ case, the sum of which almost saturates the total width. For the $J^P = 3/2^\pm$ assignment, the transition $\Xi_b^* \rightarrow \Lambda_b \pi$ provides an dominant contribution to the total decay width. Since the phase space is small compared with the other two channels, the $\Xi_b' \pi$ two-body decay width is the smallest in the four spin-parity assignments.

In Table III, we list the decay widths of the $\Xi_b^*(6227)$ for the $J^P = 1/2$ assignment with $\Lambda = 0.9$ – 1.1 GeV. The ratio of the partial decay widths in the $\Lambda_b \bar{K}$ and $\Xi_b \pi$ channels is shown in the eleventh line. For comparison, we show the results of the quark models [12–14] as well.

FIG. 4. Partial decay widths of the $\Xi_b^* \rightarrow \Lambda_b \bar{K}$ (blue dashed lines), $\Xi_b^* \rightarrow \Xi_b \pi$ (red dotted lines), $\Xi_b^* \rightarrow \Xi_b' \pi$ (green dash-dotted lines), and the total decay width (black solid lines) with different spin-parity assignments for the Ξ_b^* as a function of the parameter Λ . The cyan bands denote the experimental total width [4].

TABLE III. Partial decay widths of $\Xi_b^* \rightarrow \Lambda_b \bar{K}$, $\Xi_b \pi$, $\Xi_b' \pi$, and the total decay width Γ_{total} with $\Lambda = 0.9\text{--}1.1$ MeV, in comparison with the results of the quark model [12–14] and the total width obtained from the LHCb experiments [4]. The relative decay ratio of the $\Lambda_b \bar{K}$ and $\Xi_b \pi$ channels are also shown in the eleventh row. All masses and widths are in units of MeV.

Decay models	This work	Reference [13]		Reference [12]		Reference [14]	Exp. [4]
	$J^P = 1/2^-$	$J^P = 3/2^-$	$J^P = 5/2^-$	$J^P = 3/2^-$	$J^P = 5/2^-$	$J^P = 3/2^-$	
Ξ_b^*	Ξ_b^*	$\Xi_b'(6224)$	$\Xi_b'(6226)$	$\Xi_{b2}'(6213)$	$\Xi_{b2}'(6217)$	Ξ_b^*	Ξ_b^*
$\Lambda_b \bar{K}$	5.76–6.87	5.9	4.2	10.2	11.0	1.58 ± 0.45	
$\Xi_b \pi$	4.45–5.26	16.0	16.4	11.4	11.7	15.21 ± 2.52	
$\Xi_b' \pi$	1.76–2.16	1.3	0.6	1.0	0.5		
$\Xi_b^* \pi$				1.0	1.7		
$\Xi_b'(5945)\pi$		1.0	3.2				
$\Xi_b(6096)\pi$				...	...		
$\Xi_b(6102)\pi$				...	...		
Ratio	1.29–1.30	0.37	0.26	0.89	0.94	0.10	0.5–1.5
Total	11.97–14.28	24.2	24.4	23.6	24.9	16.79 ± 2.57	$18.1 \pm 5.4 \pm 1.8$

In Refs. [13,14], although the Ξ_b^* state can decay into both $\bar{K}\Lambda_b$ and $\pi\Xi_b$, the partial decay width of the $\bar{K}\Lambda_b$ mode is much smaller than that of the $\pi\Xi_b$ mode. The ratio of the partial decay widths of the Ξ_b^* into $\bar{K}\Lambda_b$ and $\pi\Xi_b$ is about 0.37 for the $J^P = 3/2^-$ assignment or 0.26 for the $J^P = 5/2^-$ assignment in Ref. [13] and is a mere 0.1 in Ref. [14]. In Ref. [12] the new Ξ_b^* state can be well interpreted as a conventional three quark state in comparison with the experimental total width, while the ratio of the partial decay widths of the Ξ_b^* into $\bar{K}\Lambda_b$ and $\pi\Xi_b$ is about 0.89 and 0.94 for the case of $J^P = 3/2^-$ and the case of $J^P = 5/2^-$, respectively. One should note that the difference between the results of Refs. [12–14] mainly originates from the different choices on fixing some of the parameters accounting for the strength of the quark-meson couplings and/or the harmonic oscillator (SHO) wave functions.

In Fig. 5, we show the ratios of the partial decay widths into $\Lambda_b \bar{K}$ and $\Xi_b \pi$ for different spin-parity

assignments. The cyan bands correspond to the experimental value of Ref. [4]. One should note that because the ratio of branching fractions is of the order of 1 with sizable uncertainty (of the order of ± 0.5) due to theoretical assumptions and the values of experimental inputs, one should not interpret too much this constraint. For the $J^P = 1/2^+$ case, the ratio is about 1.06 but the total decay width is much smaller than the experimental value. The ratio for the $J^P = 3/2^\pm$ cases are obviously inconsistent with the ratio 1.0 ± 0.5 . We note that the two allowed decay modes $\Lambda_b \bar{K}$ and $\Xi_b \pi$ of the $\Xi_b(6227)$, being a S -wave $\Sigma_b \bar{K}$ molecular state, have almost equal branching ratios and the ratio is about 1.29–1.30.

To sum up, the S -wave $\bar{K}\Sigma_b$ assignment for $\Xi_b^*(6227)$ is supported by our study, while the P - and D - wave $\bar{K}\Sigma_b$ assignments are excluded. It should be noted that the $\Xi_b^*(6227)$ can also be considered as a conventional three quark state [12–14]. Theoretical investigations on other decay modes and further experimental information on its spin parities and partial decay widths will be very helpful to pin down the nature of the $\Xi_b^*(6227)$ state.

IV. SUMMARY

We studied the strong decays of the newly observed Ξ_b^* baryon into $\bar{K}\Lambda_b^0$, $\Xi_b \pi$, and $\pi\Xi_b'$ with different spin-parity assignments and assuming that it is a $\bar{K}\Sigma_b$ molecular structure. With the couplings constants between the Ξ_b^* and its components determined by the composition condition, we calculated the partial decay widths into $\bar{K}\Lambda_b^0$, $\Xi_b \pi$, and $\pi\Xi_b'$ final states through triangle diagrams in an effective Lagrangian approach. In such a picture, the decays $\Xi_b^* \rightarrow \bar{K}\Lambda_b^0$, $\Xi_b^* \rightarrow \pi\Xi_b$, and $\Xi_b^* \rightarrow \pi\Xi_b'$ occur by exchanging ρ and K^* mesons. We found that the total decay width can be reproduced with the assumption that the Ξ_b^* is an S -wave $\bar{K}\Sigma_b$ bound

FIG. 5. Ratio of the partial decay widths $B(\Xi_b^* \rightarrow \Lambda_b \bar{K}) / B(\Xi_b^* \rightarrow \Xi_b \pi)$ for different spin-parity assignments. The cyan band denotes that the ratio is about 0.5–1.5 and is cited from Ref. [4].

state with $J^P = 1/2^-$, while the P - and D -wave $\bar{K}\Sigma_b$ assignments are excluded. Our study shows that the experimental measurement of the spin-parity of the Ξ_b^* will be able to tell whether it is a molecular state or a conventional three-quark state.

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