Theoretical study of the $\Omega(2012)$ state in the $\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^- \rightarrow \pi^+ (\bar{K}\Xi)^-$ and $\pi^+ (\bar{K}\Xi\pi)^-$ decays

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We report on a theoretical study of the newly observed $\Omega(2012)$ resonance in the nonleptonic weak decays of $\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi^*(1530)(\eta\Omega) \rightarrow \pi^+ (\bar{K}\Xi)^-$ and $\pi^+ (\bar{K}\Xi\pi)^-$ via final-state interactions of the $\bar{K}\Xi^*(1530)$ and $\eta\Omega$ pairs. The weak interaction part is assumed to be dominated by the charm quark decay process: $c(ss) \rightarrow (s + u + \bar{d})(ss)$, while the hadronization part takes place between the sss cluster from the weak decay and a quark-antiquark pair with the quantum numbers $J^{PC} = 0^{++}$ of the vacuum, producing a pair of $\bar{K}\Xi^*(1530)$ and $\eta\Omega$. Accordingly, the final $\bar{K}\Xi^*(1530)$ and $\eta\Omega$ states are in pure isospin $I = 0$ combinations, and the $\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi^*(1530)(\eta\Omega) \rightarrow \pi^+ (\bar{K}\Xi)^-$ decay is an ideal process to study the $\Omega(2012)$ resonance. With the final-state interaction described in the chiral unitary approach, up to an arbitrary normalization, the invariant mass distributions of the final states are calculated, assuming that the $\Omega(2012)$ resonance with spin-parity $J^P = 3/2^-$ is dynamically generated from the coupled channels interactions of the $\bar{K}\Xi^*(1530)$ and $\eta\Omega$ in s -wave and $\bar{K}\Xi$ in d -wave. We also calculate the ratio $R_{\bar{K}\Xi}^{\bar{K}\Xi\pi} = \text{Br}[\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^- \rightarrow \pi^+ (\bar{K}\Xi\pi)^-] / \text{Br}[\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^- \rightarrow \pi^+ (\bar{K}\Xi)^-]$. The proposed mechanism can provide valuable information on the nature of the $\Omega(2012)$ and can in principle be tested by future experiments, such as LHCb, Belle, BelleII, and the planned facilities, such as the super tau charm facility and electron ion collider at China.

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I. INTRODUCTION

The study of baryon spectroscopy is one of the most important issues in hadron physics and is an essential tool to analyze baryon structure. Data on baryon masses and decay modes are compiled in the *Particle Data Group* (PDG) [1]. For the light flavor hyperons with strangeness -3 , not much is known about their properties [1]. In 2018, the Belle collaboration reported an Ω excited state, $\Omega(2012)$, in the $K^-\Xi^0$ and $K_S^0\Xi^-$ invariant mass distributions [2], with the measured mass $M = 2012.4 \pm 0.7 \pm 0.6$ MeV and width $\Gamma = 6.4^{+2.5}_{-2.0} \pm 1.6$ MeV. The $\Omega(2012)$ is the first Ω excited state with preferred negative parity [2] and it

is a PDG three-star state. Before this new observation, there is only one three-star Ω resonance, $\Omega(2250)$, with its spin-parity unknown. Further investigations about the Ω excited states are mostly welcome.

On the theoretical side, there exist several quark model studies of the Ω excited states before the Belle observation. A pioneer work was done in Ref. [3], where an Ω resonance was predicted with mass about 2020 MeV and spin-parity $J^P = 3/2^-$. The excitation spectrum for multi-strange baryons was investigated in Ref. [4] in a constituent quark model, where a $3/2^-$ Ω excited state was obtained with mass about 1953 MeV. Within the extended chiral quark model, the $\bar{K}\Xi$ and $\omega\Omega$ interactions were studied in Refs. [5,6], in which, the Ω excited states in the $\bar{K}\Xi$ system with $J^P = 1/2^-$ and $\omega\Omega$ system with $J^P = 3/2^-$ or $5/2^-$ were obtained. These Ω excited states with negative parity have also been studied by using an extended quark model in the five quark picture [7–9]. It was found that the lowest $3/2^-$ state has a mass around 1785 ± 25 MeV, which is lower than the one of the lowest $1/2^-$ state [9]. This indicates that five-quark components

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are dominant in the wave functions of those Ω resonances with lower masses [8,9].

After its discovery the $\Omega(2012)$ resonance was studied in the framework of QCD sum rules in Refs. [10,11], where the $\Omega(2012)$ can be interpreted as a $1P$ orbital excitation of the ground Ω baryon with $J^P = 3/2^-$. The two body strong decays of $\Omega(2012)$ resonance were also studied in Refs. [12–14], within a nonrelativistic constituent quark potential model, in which it was found that the strong decay of $\Omega(2012)$ is predominated by $\bar{K}\Xi$ mode.

Furthermore, the topic of the hadronic molecular states, with mesons and baryons bound by strong interactions in s -wave, has been well developed by the combination of the chiral Lagrangians with nonperturbative unitary techniques in coupled channels, which has been a very fruitful scheme to study the nature of many baryon resonances [15–18]. The analysis of meson-baryon scattering amplitudes shows poles, which can be identified with existing baryon resonances or new ones. In this way the Ω resonances are dynamically generated [19–22] from the coupled channels interactions of the $\bar{K}\Xi^*(1530)$ and $\eta\Omega$ in s -wave.

Indeed, there is growing evidence that the newly observed $\Omega(2012)$ can be interpreted as a hadronic molecular state, with $J^P = 3/2^-$, as discussed in Refs. [23–28]. However, the large decay width for $\Omega(2012) \rightarrow \bar{K}\Xi^* \rightarrow \bar{K}\pi\Xi$, predicted by the molecular nature [23–25], is in disagreement with the very recent Belle measurement [29]. The measured ratio of the three body decay width to the one of the two body decay, $R_{\bar{K}\Xi}^{\bar{K}\pi\Xi} = \Gamma_{\Omega(2012) \rightarrow \bar{K}\pi\Xi} / \Gamma_{\Omega(2012) \rightarrow \bar{K}\Xi}$, is less than 11.9% at the 90% confidence level [29]. Based on this recent measurement, Refs. [30,31] claimed a reasonable reproduction of the experimental data of the Belle collaboration [2,29], and concluded that the experimental data on the $\Omega(2012)$ are compatible with the molecular picture and the theoretical results are rather stable with different sets of model parameters of natural size.

The nonleptonic weak decays of charmed baryons can be useful tools to study hadron resonances [32–39]. The double strange baryon $\Xi^*(1620)^0$ was first observed in its decay mode to $\pi^+\Xi^-$ via $\Xi_c^+ \rightarrow \pi^+\pi^+\Xi^-$ process, measured by the Belle collaboration [40]. In Ref. [41] the role of the $\Lambda_c^+ \rightarrow \pi^+n\bar{K}^0$ decay in testing $SU(3)$ flavor symmetry and final state interactions was investigated. Taking the advantage of these ideas and the previous works of Refs. [30,31], we study the $\Omega(2012)$ resonance in the $\Omega_c^0 \rightarrow \pi^+\bar{K}\Xi^*(1530)(\eta\Omega) \rightarrow \pi^+(\bar{K}\Xi)^-$ and $\pi^+(\bar{K}\Xi\pi)^-$ decays, showing that they provide a good filter for $I = 0$ and strangeness $S = -3$ resonances, which can be used to probe the nature of the Ω excited states.

Before ending the Introduction, we want to mention that, in this work, the $\Omega(2012)$ is a dynamically generated state with $J^P = 3/2^-$ from the coupled channels

interactions of the $\bar{K}\Xi^*(1530)$ and $\eta\Omega$ in s -wave and $\bar{K}\Xi$ in d -wave [30,31].

The paper is organized as follows. In the next section, we revisit the experimental measurements of $\Omega(2012)$ resonance and the theoretical $3q$ description of it. In Sec. III we present the formalism and ingredients of the decay amplitudes of the three and four-body decays of Ω_c^0 . Numerical results are given in Sec. IV, followed by a short summary in the last section.

II. THE $\Omega(2012)$

The $\Omega(2012)$ was first observed by the Belle collaboration in the $K^-\Xi^0$ and $K_S^0\Xi^-$ invariant mass spectra [2], where the measured ratio of $R_{\bar{K}^0\Xi^-}^{K^-\Xi^0} = \Gamma_{\Omega(2012) \rightarrow K^-\Xi^0} / \Gamma_{\Omega(2012) \rightarrow \bar{K}^0\Xi^-}$ is 1.2 ± 0.3 . It is the first Ω excited state with favored negative parity. Later, its existence was confirmed by the same collaboration in Ref. [29] where the upper limit of the ratio $R_{\bar{K}\Xi}^{\bar{K}\pi\Xi}$, as mentioned above, was obtained. In the PDG [1], though the $\Omega(2012)$ is a three-star resonance, its spin is unknown.

It is important to remark that (i) the $\Omega(2012)$ resonance was only observed by the Belle collaboration and (ii) most of its properties, such as decay fractions and spin, are not determined yet.

It should be noted that quark models predict two $1P$ -wave states with mass around 2012 MeV. Although the $\Omega(2012)$ can be understood as one of them with $J^P = 1/2^-$, which provides the reasonable total decay width and the ratio $R_{\bar{K}^0\Xi^-}^{K^-\Xi^0}$ as discussed in Refs. [12–14], it remains a puzzle why the other broader one with $J^P = 1/2^-$ has not been observed in the $K^-\Xi^0$ and $K_S^0\Xi^-$ channels as well, if it really exists.

On the other hand, the $\Omega(2012)$ is naturally accommodated as a dynamically generated state from the coupled channels interactions of the $\bar{K}\Xi^*(1530)$ and $\eta\Omega$ in s -wave. In this picture, its spin-parity are $3/2^-$, and the ratio $R_{\bar{K}\Xi}^{\bar{K}\pi\Xi}$ could be well reproduced with different sets of model parameters [30,31]. Further work and more precise experimental data may be used to pin down those model parameters and then the decay properties of $\Omega(2012)$ resonance could be determined in the future. In this context it is worth to investigate the $\Omega(2012)$ resonance in other processes, for example, the $\Omega_c^0 \rightarrow \pi^+\Omega^-(2012) \rightarrow \pi^+(\bar{K}\Xi)^-$ and $\pi^+(\bar{K}\Xi\pi)^-$ decays studied in this work.

III. FORMALISM AND INGREDIENTS

Following Refs. [34,35], the Cabibbo favored process of Ω_c^0 into a π^+ plus a pair of ground state pseudoscalar mesons and decuplet baryons (MB) is as follows: in the first step the charm quark in Ω_c^0 turns into a strange quark with a π^+ ($u\bar{d}$ pair) by the weak decay as shown in Fig. 1. Then the sss cluster hadronizes with a new $\bar{q}q$ pair with the quantum

FIG. 1. Dominant quark-line schematic diagram for $\Omega_c^0 \rightarrow \pi^+ \text{MB}$ decay.

numbers $J^{PC} = 0^{++}$ of the vacuum, to form a pair of meson and baryon. Finally, the final-state interactions of the MB leads to the dynamical generation of the $\Omega(2012)$.

It is worth to mention that our following results are based on the dominance of the mechanism shown in Fig. 1. In the weak decay of charmed baryons the diagrams in the quark level are classified into six different topologies [42,43]: the external W -emission tree diagram T , internal W -emission diagrams C and C' , W -exchange diagrams E_1 , E_2 , and E' . In principle, the contribution from the external W -emission diagram is larger than these other diagrams. As discussed in Refs. [34,35,44], we will only consider the tree diagram T as the dominant contribution for the $\Omega_c^0 \rightarrow \pi^+ \text{MB}$ decays.

A. Decay amplitudes

As in Refs. [34,35], one can easily obtain the final meson-baryon states as

$$\begin{aligned} |\text{MB}\rangle &= |s(\bar{u}u + \bar{d}d + \bar{s}s)ss\rangle \\ &= \frac{1}{\sqrt{3}}(|K^-\Xi^{*0}\rangle + |\bar{K}^0\Xi^{*-}\rangle) - \frac{1}{\sqrt{3}}|\eta\Omega\rangle, \\ &= \sqrt{\frac{2}{3}}|\bar{K}\Xi^*\rangle_{I=0} - \frac{1}{\sqrt{3}}|\eta\Omega\rangle, \end{aligned} \quad (1)$$

where the last step is obtained in the isospin basis using the convention of Ref. [45]: $|K^-\rangle = -|\frac{1}{2} - \frac{1}{2}\rangle$, and the flavor states of the baryons and η meson are as follows [23,34]:

$$|\Xi^{*0}\rangle = \frac{1}{\sqrt{3}}|uss + sus + ssu\rangle, \quad (2)$$

$$|\Xi^{*-}\rangle = \frac{1}{\sqrt{3}}|dss + sds + ssd\rangle, \quad (3)$$

$$|\Omega\rangle = |sss\rangle, \quad (4)$$

$$|\eta\rangle = \frac{1}{\sqrt{3}}|\bar{u}u + \bar{d}d - \bar{s}s\rangle. \quad (5)$$

FIG. 2. Diagram for the meson-baryon final-state interaction for the $\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^- \rightarrow \pi^+ (\bar{K}\Xi)^-$ decay.

After the production of $\bar{K}\Xi^*(1530)$ and $\eta\Omega$ pairs, the final-state interactions between the mesons ($\bar{K}$, η) and the baryons [$\Xi^*(1530)$, Ω] take place, which can be parametrized by the rescattering shown in Fig. 2 at the hadronic level for the production of $\Omega(2012)$, and then it decays into $\bar{K}\Xi$ in d -wave.

According to Eq. (1), we can write down the $\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi$ decay amplitude of Fig. 2 as,

$$\begin{aligned} \mathcal{M}_{\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi} &= V_p \left(\sqrt{\frac{2}{3}} G_{\bar{K}\Xi^*}(M_{\text{inv}}) t_{\bar{K}\Xi^* \rightarrow \bar{K}\Xi}(M_{\text{inv}}) \right. \\ &\quad \left. - \sqrt{\frac{1}{3}} G_{\eta\Omega}(M_{\text{inv}}) t_{\eta\Omega \rightarrow \bar{K}\Xi}(M_{\text{inv}}) \right), \end{aligned} \quad (6)$$

with M_{inv} the invariant mass of $\bar{K}\Xi$. Similarly, one can obtain the decay amplitude for $\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi^*(1530)$ as,

$$\begin{aligned} \mathcal{M}_{\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi^*} &= V_p \left(\sqrt{\frac{2}{3}} [1 + G_{\bar{K}\Xi^*}(M_{\text{inv}}) t_{\bar{K}\Xi^* \rightarrow \bar{K}\Xi^*}(M_{\text{inv}})] \right. \\ &\quad \left. - \sqrt{\frac{1}{3}} G_{\eta\Omega}(M_{\text{inv}}) t_{\eta\Omega \rightarrow \bar{K}\Xi^*}(M_{\text{inv}}) \right). \end{aligned} \quad (7)$$

where the factor V_p is assumed to be constant in the relevant energy region [34,46,47], and its actual value should be determined from the experimental measurements for a certain decay channel. The loop functions $G_{\bar{K}\Xi^*}$ and $G_{\eta\Omega}$ depend on the invariant mass, M_{inv} , of the final $\bar{K}\Xi$ or $\bar{K}\Xi^*(1530)$ system. The two body scattering amplitudes $t_{\bar{K}\Xi^* \rightarrow \bar{K}\Xi(\Xi^*)}$ and $t_{\eta\Omega \rightarrow \bar{K}\Xi(\Xi^*)}$ are those obtained in the chiral unitary approach, which depend also on M_{inv} , and we take them as,

$$t_{\bar{K}\Xi^* \rightarrow \bar{K}\Xi^*} = \frac{g_{\Omega^* \bar{K}\Xi^*} g_{\Omega^* \bar{K}\Xi^*}}{M_{\text{inv}} - M_{\Omega^*} + i\Gamma_{\Omega^*}/2}, \quad (8)$$

$$t_{\eta\Omega \rightarrow \bar{K}\Xi^*} = \frac{g_{\Omega^* \eta\Omega} g_{\Omega^* \bar{K}\Xi^*}}{M_{\text{inv}} - M_{\Omega^*} + i\Gamma_{\Omega^*}/2}, \quad (9)$$

TABLE I. Pole positions ($M_{\Omega^*}, \Gamma_{\Omega^*}$) of the $\Omega(2012)$ and the couplings to different channels obtained with $q_{\max}$ (see more details in Ref. [30]).

Model	$\Lambda = q_{\max}$ (MeV)	M_{Ω^*} (MeV)	Γ_{Ω^*} (MeV)	$g_{\Omega^* \bar{K}\Xi^*}$	$g_{\Omega^* \eta\Omega}$	$g_{\Omega^* \bar{K}\Xi}$
I	735	2012.3	8.3	(1.826, -0.064)	(3.350, 0.159)	(-0.419, -0.040)
II	750	2012.2	7.8	(1.796, -0.128)	(3.448, 0.298)	(-0.399, -0.109)
III	800	2012.4	6.4	(1.574, 0.188)	(3.590, -0.313)	(-0.307, 0.201)
IV	850	2012.4	6.4	(1.386, 0.090)	(3.777, -0.151)	(-0.353, 0.109)
V	900	2012.4	6.4	(1.251, 0.063)	(3.853, -0.111)	(-0.363, 0.082)

$$t_{\bar{K}\Xi^* \rightarrow \bar{K}\Xi} = \frac{g_{\Omega^* \bar{K}\Xi^*} g_{\Omega^* \bar{K}\Xi}}{M_{\text{inv}} - M_{\Omega^*} + i\Gamma_{\Omega^*}/2}, \quad (10)$$

$$t_{\eta\Omega \rightarrow \bar{K}\Xi} = \frac{g_{\Omega^* \eta\Omega} g_{\Omega^* \bar{K}\Xi}}{M_{\text{inv}} - M_{\Omega^*} + i\Gamma_{\Omega^*}/2}, \quad (11)$$

where these coupling constants, the mass and width of the $\Omega(2012)$ are obtained in Ref. [30] with different sets of parameters as shown in Table I.

The $\Omega(2012) \rightarrow \bar{K}\Xi$ decay is in d -wave, thus $t_{\bar{K}\Xi^* \rightarrow \bar{K}\Xi}$ and $t_{\eta\Omega \rightarrow \bar{K}\Xi}$ should go with $q_{\bar{K}}^2$, which is the relative momentum between $\bar{K}$ and Ξ in the rest frame of $\bar{K}\Xi$. However, the transition potentials $V_{\bar{K}\Xi^* \rightarrow \bar{K}\Xi}$ and $V_{\eta\Omega \rightarrow \bar{K}\Xi}$ incorporate the $q_{\bar{K}}^2$. For more details we refer to Refs. [23,30,48,49] for the case of the $\Lambda(1520)$ resonance where the interaction of $\bar{K}N$ and $\pi\Sigma$ in d -wave are included.

Next we consider the $\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^- \rightarrow \pi^+ [\bar{K}\Xi^*(1530)]^- \rightarrow \pi^+ (\bar{K}\Xi\pi)^-$ decay, where the $\Omega(2012)$ is produced by the final state interactions of $\bar{K}\Xi^*(1530)$ and $\eta\Omega$ in coupled channels. The decay amplitude of $\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi\pi$ decay can be written as

$$\mathcal{M}_{\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi\pi} = \frac{g_{\Xi^* \Xi\pi} \bar{p}_\pi \mathcal{M}_{\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi^*}}{M_{\Xi\pi} - M_{\Xi^*} + i\Gamma_{\Xi^*}/2}, \quad (12)$$

where $M_{\Xi\pi}$ is the invariant mass of $\Xi\pi$ system, and Γ_{Ξ^*} is energy dependent, and its explicit form is given by¹

$$\Gamma_{\Xi^*} = \frac{1}{2\pi} \frac{M_{\Xi}}{M_{\Xi\pi}} \bar{p}_\pi (g_{\Xi^* \Xi\pi} \bar{p}_\pi)^2 = \Gamma_{\Xi^*}^{\text{on}} \frac{M_{\Xi^*}}{M_{\Xi\pi}} \left(\frac{\bar{p}_\pi}{\bar{p}_\pi^{\text{on}}} \right)^3, \quad (13)$$

where

$$\bar{p}_\pi = \frac{\sqrt{[M_{\Xi\pi}^2 - (M_{\Xi} + m_\pi)^2][M_{\Xi\pi}^2 - (M_{\Xi} - m_\pi)^2]}}{2M_{\Xi\pi}},$$

$$\bar{p}_\pi^{\text{on}} = \frac{\sqrt{[M_{\Xi^*}^2 - (M_{\Xi} + m_\pi)^2][M_{\Xi^*}^2 - (M_{\Xi} - m_\pi)^2]}}{2M_{\Xi^*}}.$$

On the other hand, the coupling constant $g_{\Xi^* \Xi\pi} = 4.4 \times 10^{-3} \text{ MeV}^{-1}$ can be easily obtained from Eq. (13)

¹The p -wave $\Xi^*(1530) \rightarrow \Xi\pi$ decay is considered.

with the values of $m_\pi = 138.04$, $M_{\Xi^*} = 1533.4$, $M_{\Xi} = 1318.29 \text{ MeV}$, and $\Gamma_{\Xi^*}^{\text{on}} = 9.5 \text{ MeV}$.

B. Invariant mass distributions

With all the ingredients obtained above, one can write down the invariant mass distributions for the $\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^- \rightarrow \pi^+ \bar{K}\Xi$ decay as [1]

$$\frac{d\Gamma_{\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi}}{dM_{\bar{K}\Xi}} = \frac{1}{16\pi^3} \frac{M_{\Xi}}{M_{\Omega_c^0}} p_\pi^3 p_{\bar{K}} \sum |\mathcal{M}_{\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi}|^2, \quad (14)$$

where we have only considered $L = 1$ for the π^+ in the $\Omega_c^0(1/2^+) \rightarrow \pi^+(0^-) \Omega(2012)^-(3/2^-)$ transition to match angular momentum conservation,² and

$$p_\pi = \frac{\sqrt{[M_{\Omega_c^0}^2 - (m_\pi + M_{\bar{K}\Xi})^2][M_{\Omega_c^0}^2 - (m_\pi - M_{\bar{K}\Xi})^2]}}{2M_{\Omega_c^0}},$$

$$p_{\bar{K}} = \frac{\sqrt{[M_{\bar{K}\Xi}^2 - (m_{\bar{K}} + M_{\Xi})^2][M_{\bar{K}\Xi}^2 - (m_{\bar{K}} - M_{\Xi})^2]}}{2M_{\bar{K}\Xi}}.$$

Similarly, the $d\Gamma_{\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi^*}/dM_{\bar{K}\Xi^*}$ can be easily obtained by applying the substitution to $d\Gamma_{\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi}/dM_{\bar{K}\Xi}$ with $M_{\Xi} \rightarrow M_{\Xi^*}$, $M_{\bar{K}\Xi} \rightarrow M_{\bar{K}\Xi^*}$, and $\mathcal{M}_{\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi} \rightarrow \mathcal{M}_{\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi^*}$.

For the $\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^- \rightarrow \pi^+ \bar{K}\Xi\pi$ decay, the $\bar{K}\Xi\pi$ invariant mass distribution is given by [50,51],

$$\frac{d\Gamma_{\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi\pi}}{dM_{\bar{K}\Xi\pi} dM_{\Xi\pi}} = \frac{M_{\Xi} p'_\pi \bar{p}_\pi \bar{p}_\pi}{64\pi^5 M_{\Omega_c^0}} \sum |\mathcal{M}_{\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi\pi}|^2, \quad (15)$$

with

²Since the transition of $\Omega_c^0(1/2^+) \rightarrow \pi^+(0^-) \Omega(2012)^-(3/2^-)$ is weak decay, in general, the d -wave term also gives contribution. In the narrow energy region around the mass of $\Omega(2012)$ we considered here, the d -wave contribution will not change the spectral shape and the relative fraction which we focus on, and its contribution is small, if we take the same strength as the p -wave. Hence, we will leave the d -wave contributions to future studies when the resolution of the analysis is sufficient and the experimental data become available.

FIG. 3. $\bar{K}\Xi$ invariant mass distributions of the $\Omega_c^0 \rightarrow \pi^+(\bar{K}\Xi)^-$ decay.

$$p'_\pi = \frac{\sqrt{[M_{\Omega_c^0}^2 - (m_\pi + M_{\bar{K}\Xi\pi})^2][M_{\Omega_c^0}^2 - (m_\pi - M_{\bar{K}\Xi\pi})^2]}}{2M_{\Omega_c^0}},$$

$$\tilde{p}_{\bar{K}} = \frac{\sqrt{[M_{\bar{K}\Xi\pi}^2 - (m_{\bar{K}} + M_{\Xi\pi})^2][M_{\bar{K}\Xi\pi}^2 - (m_{\bar{K}} - M_{\Xi\pi})^2]}}{2M_{\bar{K}\Xi\pi}}.$$

After the integration of $M_{\pi\Xi}$, we can obtain

$$\frac{d\Gamma_{\Omega_c^0 \rightarrow \pi \bar{K} \Xi \pi}}{dM_{\bar{K} \Xi \pi}} = \int_{M_{\Xi} + m_\pi}^{M_{\bar{K} \Xi \pi} - m_{\bar{K}}} \frac{d\Gamma_{\Omega_c^0 \rightarrow \pi \bar{K} \Xi \pi}}{dM_{\Xi \pi} dM_{\bar{K} \Xi \pi}} dM_{\Xi \pi}. \quad (16)$$

IV. NUMERICAL RESULTS

In this section, we show our theoretical predictions for the production of $\Omega(2012)$ in different final states in the Ω_c^0 decay. Note that the physical masses of the involved particles are taken from PDG [1] and we take the isospin averaged values for $m_K = 495.64$, $m_\eta = 547.86$, $m_\Omega = 1672.45$, and $M_{\Omega_c^0} = 2695.2$ MeV. In addition, the following numerical results are obtained with $V_P = 1$.

We first show in Figs. 3 and 4 the theoretical predictions for the invariant mass distribution $d\Gamma/dM_{\bar{K}\Xi}$ and $d\Gamma/dM_{\bar{K}\Xi^*(1530)}$. From Fig. 3 one can see clearly the shape of the $\Omega(2012)$, while from the invariant mass distribution of $\bar{K}\Xi^*(1530)$ as shown in Fig. 4, there is no signal of the $\Omega(2012)$ resonance. This is because its mass is below the $\bar{K}\Xi^*$ mass threshold, and its width is narrow. The interference between the tree level contribution and the final state interactions of $\bar{K}\Xi^*(1530)$ and $\eta\Omega$ makes the production of $\Omega(2012)$ in the $\bar{K}\Xi^*(1530)$ channel even worse. In other words, the first term in Eq. (7) contributes at the tree level to the $\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi^*(1530)$ decay, but does not contribute to the production of $\Omega(2012)$, followed by decaying into $\bar{K}\Xi^*(1530)$.

FIG. 4. $\bar{K}\Xi^*$ invariant mass distribution of the $\Omega_c^0 \rightarrow \pi^+(\bar{K}\Xi^*)^-$ decay.

Next we consider the $\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi^*(1530) \rightarrow \pi^+ \bar{K}\Xi\pi$ decay. The invariant mass distribution $d\Gamma/dM_{\bar{K}\Xi\pi}$ is shown in Fig. 5, where one can see that the tree level contributions provide a very big background, and, hence, the signal of the $\Omega(2012)$ is rather weak. However, the $\Omega(2012)$ may give significant contribution to the invariant mass distributions of $\bar{K}\Xi\pi$ close to threshold, as shown in the subfigure of Fig. 5, especially for the Models I, II, and III.

In general we cannot fix the value of V_P , which should be determined by experimental measurements. Therefore, it would be interesting to remove the uncertainties arising from the introduction of V_P by investigating the ratios between different partial decay widths, where the effect of the V_P factor is canceled, and which only reflect the production of $\Omega(2012)$ through the final state interactions of $\bar{K}\Xi^*(1530)$ and $\eta\Omega$. For such a purpose, we define

FIG. 5. $\bar{K}\Xi\pi$ invariant mass distributions of the $\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi^*(1530) \rightarrow \pi^+ \bar{K}\Xi\pi$ decay.

TABLE II. Predicted ratio $R_{\bar{K}\Xi}^{\bar{K}\Xi\pi}$ for different cutoffs.

$\Lambda = q_{\max}(\text{MeV})$	735	750	800	850	900
$R_{\bar{K}\Xi}^{\bar{K}\Xi\pi}(\%)$	13.9	13.8	13.5	10.0	7.3

$$R_{\bar{K}\Xi}^{\bar{K}\Xi\pi} = \frac{\Gamma[\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^- \rightarrow \pi^+ \bar{K}\Xi\pi]}{\Gamma[\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^- \rightarrow \pi^+ \bar{K}\Xi]} \quad (17)$$

$$= \frac{\int_{M_{\Omega^*} - 2\Gamma_{\Omega^*}}^{M_{\Omega^*} + 2\Gamma_{\Omega^*}} \frac{d\Gamma_{\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi\pi}}{dM_{\bar{K}\Xi\pi}} dM_{\bar{K}\Xi\pi}}{\int_{M_{\Omega^*} - 2\Gamma_{\Omega^*}}^{M_{\Omega^*} + 2\Gamma_{\Omega^*}} \frac{d\Gamma_{\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi}}{dM_{\bar{K}\Xi}} dM_{\bar{K}\Xi}}.$$

As discussed before, the main contribution to the $\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi\pi$ decay comes from the tree level production of $\bar{K}\Xi^*(1530)$. In order to consider the contribution from the $\Omega(2012)$ resonance, we need to switch off the first term in Eq. (7), which means that we have to change $\mathcal{M}_{\Omega_c^0 \rightarrow \pi \bar{K}\Xi^*}$ in the following way

$$\mathcal{M}_{\Omega_c^0 \rightarrow \pi \bar{K}\Xi^*} \rightarrow \tilde{\mathcal{M}}_{\Omega_c^0 \rightarrow \pi \bar{K}\Xi^*}$$

$$= V_p \left(\sqrt{\frac{2}{3}} G_{\bar{K}\Xi^*} t_{\bar{K}\Xi^* \rightarrow \bar{K}\Xi} - \sqrt{\frac{1}{3}} G_{\eta\Omega} t_{\eta\Omega \rightarrow \bar{K}\Xi} \right). \quad (18)$$

Furthermore, as shown in Eq. (17), to get the partial decay widths of $\Gamma[\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^- \rightarrow \pi^+ \bar{K}\Xi\pi]$ and $\Gamma[\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^- \rightarrow \pi^+ \bar{K}\Xi]$, we have integrated $dM_{\bar{K}\Xi\pi}$ and $dM_{\bar{K}\Xi}$ over the range of $[M_{\Omega^*} - 2\Gamma_{\Omega^*}, M_{\Omega^*} + 2\Gamma_{\Omega^*}]$, in which the contributions from $\Omega(2012)$ resonance are covered.

The numerical results for the ratio $R_{\bar{K}\Xi}^{\bar{K}\Xi\pi}$ are listed in Table II. One can see that these predictions are in agreement with the measurements reported by the Belle collaboration [29], as expected. This ratio is relevant because it is obtained with no free parameters (all the model parameters are fixed by previous works) and, thus, it is a prediction of the model. We expect that these numerical results could be tested by future experimental measurements, which may be used to pin down the model parameters and then the properties of the $\Omega(2012)$ resonance could be determined.

V. SUMMARY

In summary, we have investigated the nonleptonic weak decays of $\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi^*(1530)(\eta\Omega) \rightarrow \pi^+(\bar{K}\Xi)^-$ as a tool to study the newly observed $\Omega(2012)$ resonance via the final-state interactions of the $\bar{K}\Xi^*(1530)$ and $\eta\Omega$ pairs. We assume that the weak interaction part is dominated by the Cabibbo favored charm quark decay process: $c(ss) \rightarrow (s + u + \bar{d})(ss)$, then the sss cluster and a

quark-antiquark pair from the vacuum hadronize into the intermediate meson-baryon states, in this case, the $\bar{K}\Xi^*(1530)$ and $\eta\Omega$. Accordingly, the final $\bar{K}\Xi^*(1530)$ and $\eta\Omega$ states are in pure isospin $I = 0$ combinations, and the final state interaction of $\bar{K}\Xi^*(1530)$ and $\eta\Omega$ can produce the $\Omega(2012)$ state by using the chiral unitary approach. After the $\Omega(2012)$ is dynamically generated in the above process, it will decay into $\bar{K}\Xi$ and $\bar{K}\Xi\pi$, and shows a peak or bump structure in the $\bar{K}\Xi$ and $\bar{K}\Xi\pi$ invariant mass distributions. Thus, we have calculated the invariant mass distributions of $d\Gamma_{\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi}/dM_{\bar{K}\Xi}$ and $d\Gamma_{\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi\pi}/dM_{\bar{K}\Xi\pi}$. We have seen that the $\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi\pi$ decay is not well suited to study the $\Omega(2012)$ resonance because the dominant contribution is from the $\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi^*(1530)$ decay at tree level, which will not contribute to the production of $\Omega(2012)$. However, the $\Omega(2012)$ peak can be clearly seen in the $\bar{K}\Xi$ invariant mass distribution of the $\Omega_c^0 \rightarrow \pi^+ \bar{K}\Xi$ decay.

We have also calculated the ratio, $R_{\bar{K}\Xi}^{\bar{K}\Xi\pi} = \text{Br}[\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^- \rightarrow \pi^+(\bar{K}\Xi\pi)^-]/\text{Br}[\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^- \rightarrow \pi^+(\bar{K}\Xi)^-]$. The numerical results are in agreement with the Belle measurements [29]. The good agreement with experimental data of the chiral unitary approach as shown by us here, provides extra support to the picture of the $\Omega(2012)$ as a dynamically generated resonance.

Finally, we would like to stress that the predictions here are very qualitative, since the contributions from other resonances are neglected. We hope that the theoretical calculations presented in this work may stimulate experimental interest in exploring the $\Omega(2012)$ resonance or other Ω excited states through the Ω_c^0 decays. The proposed mechanism can provide valuable information on the nature of the $\Omega(2012)$ and can in principle be tested by future experiments, such as LHCb, Belle, and BelleII or the planned super tau charm facility [52,53] and electron ion collider in China [54,55].

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