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What can we learn from the decay of $N_X(1625)$ in the molecule picture?

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Abstract. Considering two assumptions on the molecular state, i.e. the S-wave $\bar{\Lambda}$–K^- and S-wave $\bar{\Sigma}^0$–K^- molecular states, we study the possible decays of $\bar{N}_X(1625)$ that include $\bar{N}_X(1625) \to K^-\bar{\Lambda}, \pi^0\bar{p}, \eta\bar{p}, \pi^-\bar{n}$. Our results indicate that (1) if $\bar{N}_X(1625)$ is the $\bar{\Lambda}$–K^- molecular state, $K^-\bar{\Lambda}$ is the main decay mode of $\bar{N}_X(1625)$, and the branching ratios of the rest decay modes are tiny; (2) if $\bar{N}_X(1625)$ is the $\bar{\Sigma}^0$–K^- molecular state, the branching ratio of $\bar{N}_X(1625) \to K^-\bar{\Lambda}$ is one or two orders smaller than that of $\bar{N}_X(1625) \to \pi^0\bar{p}, \eta\bar{p}, \pi^-\bar{n}$. Thus the search for $\bar{N}_X(1625) \to \pi^0\bar{p}, \eta\bar{p}, \pi^-\bar{n}$ will be helpful to shed light on the nature of $\bar{N}_X(1625)$.

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1 Introduction

Two years ago, the BES Collaboration announced an enhancement $\bar{N}_X(1625)$ by studying the $K^-\bar{\Lambda}$ invariant mass spectrum in the $J/\psi \to pK^-\bar{\Lambda}$ channel [1–3]. The BES Collaboration gave the rough measurement result on the mass and width of $\bar{N}_X(1625)$ of $m = 1500$–1650 MeV and $\Gamma = 70$–110 MeV. Experiment also indicates that spin–parity favors $\frac{1}{2}^-$ for $N_X(1625)$, which denotes the antiparticle of $\bar{N}_X(1625)$.

Using the branching ratio $B(J/\psi \to p\bar{p}) = 2.17 \times 10^{-3}$ [4] as a reference, we can deduce $B[\bar{N}_X(1625) \to \bar{\Lambda}K^-] \sim 10\%$ if $\bar{N}_X(1625)$ is a regular baryon and the branching ratio of $J/\psi \to p\bar{N}_X(1625)$ should be comparable to that of $J/\psi \to p\bar{p}$, which shows that there exists a strong coupling between $\bar{N}_X(1625)$ and $K^-\bar{\Lambda}$.

This enhancement structure inspired several theoretical speculations on its underlying structure. The authors of [5] studied the S-wave ΛK and ΣK with isospin $I = 1/2$ within the framework of the chiral SU(3) quark model by solving a resonating group method (RGM) equation. Their results show a strong attraction between the Σ and K, and a ΣK quasibound state is thus formed as a consequence with a binding energy of about 17 MeV, whereas the ΛK is unbound. Considering the small mass difference of the ΛK and ΣK thresholds, the strong attraction between Σ and K, and the sizable off-diagonal matrix elements of ΛK and ΣK, they also investigated the coupled channel effect of ΛK and ΣK, and they found a sharp resonance with a mass $M = 1669$ MeV and a width $\Gamma = 5$ MeV [5].

Liu and Zou suggested that the enhancement structure $\bar{N}_X(1625)$ comes from the strong coupling between $\bar{N}(1535)$ and $K\Lambda$. Furthermore, $R = g_{\bar{N}(1535)K\Lambda}/g_{\bar{N}(1535)p\eta}$ is extracted by the branching ratios taken from BES experiments on $J/\psi \to \bar{p}p\eta$ [7–9] and $J/\psi \to pK^-\bar{\Lambda}$ [1]. The new obtained value of $g_{\bar{N}(1535)K^-\bar{\Lambda}}$ is shown to reproduce recent the $pp \to pK^-\bar{\Lambda}$ near-threshold cross section data as well [6].

At the recent Hadron 07 conference, the BES Collaboration reported the preliminary new experiment result of $\bar{N}_X(1625)$. Its mass and width are well determined as [10]

$$m = 1625^{+5+13}_{-7-23}\,\text{MeV}\,, \quad \Gamma = 43^{+10+28}_{-7\ -11}\,\text{MeV}\,,$$

respectively. The production rate of $\bar{N}_X(1625)$ is

$$\begin{aligned} &B[J/\psi \to p\bar{N}_X(1625)]B[\bar{N}_X(1625) \to K^-\bar{\Lambda}] \\ &\quad = 9.14^{+1.30+4.24}_{-1.25-8.28} \times 10^{-5}\,. \end{aligned}$$

The more accurate experimental information of $\bar{N}_X(1625)$ provides us with a good opportunity to further study the nature of $\bar{N}_X(1625)$.

Despite the two theoretical speculations proposed above, at present the study of the decays of $\bar{N}_X(1625)$, which play an important role to clarify the properties of $\bar{N}_X(1625)$, is missing. In this work, we firstly assume $\bar{N}_X(1625)$ to be a molecular state, and our work is dedicated to the study of the possible decays of $\bar{N}_X(1625)$. For the convenience of comparing with the BES experiment, one focuses on the study of decays of antiparticle $\bar{N}_X(1625)$ with the spin–parity $\frac{1}{2}^+$.

This paper is organized as follows. In Sect. 2, we present the formulation of the possible decays of $\bar{N}_X(1625)$.

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In Sect. 3, the numerical results are given. The last section is the conclusion and discussion.

2 Formulation

In this work we do not focus on whether $\bar{\Lambda}$–K^- or $\bar{\Sigma}^0$–K^- can form the S-wave molecular state; this is investigated in [5]. We are mainly devoted to the study of the possible decays of $\bar{N}_X(1625)$ in two different assumptions on the molecular states.

2.1 The possible decays assuming $\bar{N}_X(1625)$ to be the $\bar{\Lambda}$–K^- molecular state

In the assumption of the $\bar{\Lambda}$–K^- molecular state, the most direct decay mode of $\bar{N}_X(1625)$ is $\bar{N}_X(1625) \to \bar{\Lambda} + K^-$ depicted in Fig. 1a. Its decay amplitude is

$$\mathcal{M}[\bar{N}_X(1625) \to \bar{\Lambda} + K^-] = \mathrm{i}\mathcal{G}\bar{v}_N\gamma_5 v_{\bar{\Lambda}}\,, \tag{1}$$

where $\mathcal{G}$ is the coupling constant between $\bar{N}_X(1625)$ and $\bar{\Lambda}K^-$. $v_{\bar{\Lambda}}$ and v_N are the spinors.

Besides the direct decay, there are several subordinate decays depicted in Fig. 1c–e by the final state interaction (FSI) effect. For obtaining their decay amplitudes, one needs to use the Lagrangians [12, 13]

$$\mathcal{L}_{\mathcal{PPV}} = -\mathrm{i}g_{\mathcal{PPV}}\mathrm{Tr}\big([\mathcal{P}, \partial_\mu\mathcal{P}]\mathcal{V}^\mu\big)\,, \tag{2}$$

$$\mathcal{L}_{\mathcal{BBP}} = F_P\mathrm{Tr}\big(\mathcal{P}[\mathcal{B}, \bar{\mathcal{B}}]\big)\gamma_5 + D_P\mathrm{Tr}\big(\mathcal{P}\{\mathcal{B}, \bar{\mathcal{B}}\}\big)\gamma_5\,, \tag{3}$$

$$\mathcal{L}_{\mathcal{BBV}} = F_V\mathrm{Tr}\big(\mathcal{V}^\mu[\mathcal{B}, \bar{\mathcal{B}}]\big)\gamma_\mu + D_V\mathrm{Tr}\big(\mathcal{V}^\mu\{\mathcal{B}, \bar{\mathcal{B}}\}\big)\gamma_\mu\,, \tag{4}$$

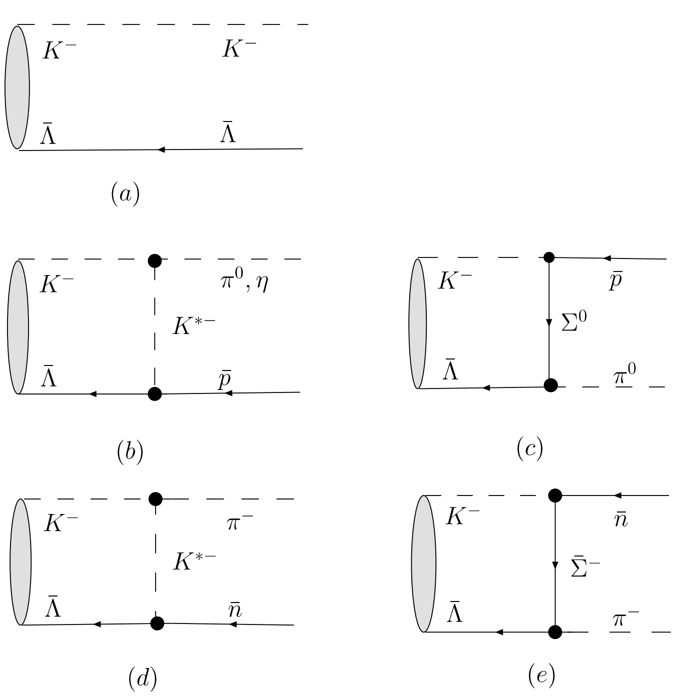

Fig. 1. The diagrams depicting the decays of $\bar{N}_X(1625)$ in the picture of the $\bar{\Lambda}$–K^- molecular state

where the concrete values of the coupling constants will be given in detail in the following section. $\bar{B}$ is the Hermitian conjugate of B. $\mathcal{P}$, $\mathcal{V}$ and B respectively denote the octet pseudoscalar meson, the nonet vector meson and baryon matrices:

$$\mathcal{P} = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{3}\eta \end{pmatrix},$$

$$\mathcal{V} = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix},$$

$$\mathcal{B} = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^{*-} & \Xi^{*0} & \frac{-2\Lambda}{\sqrt{6}} \end{pmatrix}.$$

Because $M_{\bar{\Lambda}} + M_{K^-}$ is about 1610 MeV, which is less than the mass of $\bar{N}_X(1625)$, the intermediate states $\bar{\Lambda}$ and K^- in Fig. 1b–d can be on-shell. By the Cutkosky cutting rules, one writes out the general expression for the amplitude corresponding to Fig. 1b and d as follows:

$$\begin{aligned}\mathcal{M}_1^{(\mathcal{A}_1,\mathcal{C}_1)} &= \frac{1}{2}\int\frac{\mathrm{d}^3p_1}{(2\pi)^3 2E_1}\frac{\mathrm{d}^3p_2}{(2\pi)^3 2E_2} \\ &\times (2\pi)^4\delta^4(M_N - p_1 - p_2)[\mathrm{i}\mathcal{G}\bar{v}_N\gamma_5 v_{\bar{\Lambda}}] \\ &\times [\mathrm{i}g_1\bar{v}_{\bar{\Lambda}}\gamma_\mu v_{\mathcal{A}_1}][\mathrm{i}g_2(p_1+p_3)_\nu]\frac{\mathrm{i}}{q^2 - M^2_{\mathcal{C}_1}} \\ &\times \left[-g^{\mu\nu} + \frac{q^\mu q^\nu}{M^2_{\mathcal{C}_1}}\right]\mathcal{F}^2\left(M_{\mathcal{C}_1}, q^2\right).\end{aligned} \tag{5}$$

For Fig. 1c and e, the general expression for the amplitude is

$$\begin{aligned}\mathcal{M}_1^{(\mathcal{A}_2,\mathcal{C}_2)} &= \frac{1}{2}\int\frac{\mathrm{d}^3p_1}{(2\pi)^3 2E_1}\frac{\mathrm{d}^3p_2}{(2\pi)^3 2E_2} \\ &\times (2\pi)^4\delta^4(M_N - p_1 - p_2)[\mathrm{i}\mathcal{G}\bar{v}_N\gamma_5 v_{\bar{\Lambda}}] \\ &\times [\mathrm{i}g_2'\bar{v}_{\bar{\Lambda}}\gamma_5]\frac{\mathrm{i}(\not{q} + M_{\mathcal{C}_2})}{q^2 - M^2_{\mathcal{C}_2}}[\mathrm{i}g_1'\gamma_5 v_{\mathcal{A}_2}]\mathcal{F}^2\left(M_{\mathcal{C}_2}, q^2\right).\end{aligned} \tag{6}$$

In the above expressions, $\mathcal{C}_i$ and $\mathcal{A}_i$ denote the exchanged particle and the final state baryon, respectively. p_1 and p_2 are respectively the four momenta of K^- and $\bar{\Lambda}$. The $\mathcal{F}^2(m_i, q^2)$ etc. denote the form factors that compensate the off-shell effects of hadrons at the vertices. In this work, one takes $\mathcal{F}^2(m_i, q^2)$ as the monopole form [16, 17]

$$\mathcal{F}^2(m_i, q^2) = \left(\frac{\xi^2 - m_i^2}{\xi^2 - q^2}\right)^2, \tag{7}$$

where ξ is a phenomenological parameter. As $q^2 \to 0$ the form factor becomes a number. If $\xi \gg m_i$, it becomes unity. As $q^2 \to \infty$, the form factor approaches zero. As the distance becomes very small, the inner structure would manifest itself and the whole picture of the hadron interaction is no longer valid. Hence the form factor vanishes and plays the role of a cut-off in the end effect. The expression for ξ is [17]

$$\xi(m_i) = m_i + \alpha \Lambda_{\rm QCD}, \tag{8}$$

where m_i denotes the mass of the exchanged meson. $\Lambda_{\rm QCD} = 220\,\text{MeV}$. α is a phenomenological parameter and is of order unity.

2.2 The decay modes assuming $\bar{N}_X(1625)$ to be a $\bar{\Sigma}^0$–K^- molecular state

Because of having not enough phase space, $\bar{N}_X(1625)$ cannot decay to $\bar{\Sigma}^0$ and K^-.

The isospin violation effect can result in the mixing of Σ with Λ^0 [11]. Thus the decay $\bar{N}_X(1625) \to \bar{\Lambda} + K^-$ occurs, which is depicted by Fig. 2a. Using the Lagrangian

$$\mathcal{L}_{\rm mixing} = g_{\rm mixing}\left(\bar{\psi}_{\Sigma^0}\psi_{\Lambda} + \bar{\psi}_{\Lambda}\psi_{\Sigma^0}\right),$$

with the coupling constant $\theta = 0.5 \pm 0.1\,\text{MeV}$ obtained by QCD sum rules [11], one obtains the decay amplitude

$$\mathcal{M}\left[\bar{N}_X(1625) \to \bar{\Sigma}^0 + K^-\right] = \mathcal{G}\, g_{\rm mixing}\, \bar{v}_N \gamma_5 \frac{\mathrm{i}}{\not{p} - M_{\Lambda}} v_{\bar{\Lambda}}, \tag{9}$$

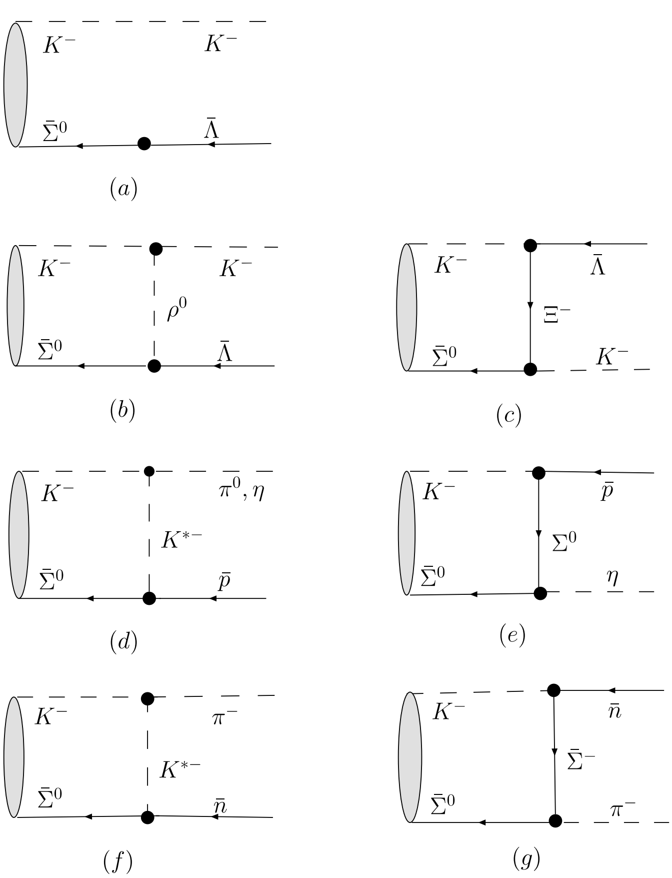

Fig. 2. The diagrams depicting the decays of $\bar{N}_X(1625)$ in the assumption of the $\bar{\Sigma}^0$–K^- molecular state for $\bar{N}_X(1625)$

where p and M_Λ are the four momentum and mass carried by $\bar{\Lambda}$.

For the decays depicted in Fig. 2b–g, $\bar{\Sigma}^0$ and K^- are off-shell. Thus the general expression of Fig. 2b, d and f is expressed as

$$\begin{aligned}\mathcal{M}_3^{(\mathcal{A}_3,\mathcal{C}_3)} &= \int \frac{\mathrm{d}^4 q}{(2\pi)^4}[i\mathcal{G}\bar{v}_N\gamma_5]\frac{\mathrm{i}}{-\not{p}_2 - M_{\bar{\Sigma}^0}}[\mathrm{i}g_3\gamma_\mu v_{\mathcal{A}_3}] \\ &\quad\times [\mathrm{i}g_4(p_1+p_3)_\nu]\frac{-\mathrm{i}g^{\mu\nu}}{q^2 - M^2_{\mathcal{C}_3}}\frac{\mathrm{i}}{p_1^2 - M_K^2} \\ &\quad\times \mathcal{F}^2\left(M_{\mathcal{C}_3}, q^2\right),\end{aligned} \tag{10}$$

and for Fig. 2c, e and g the general expression for the amplitude reads

$$\begin{aligned}\mathcal{M}_4^{(\mathcal{A}_4,\mathcal{C}_4)} &= \int \frac{\mathrm{d}^4 q}{(2\pi)^4}[\mathrm{i}\mathcal{G}\bar{v}_N\gamma_5]\frac{\mathrm{i}(\not{p}_2 - M_{\bar{\Sigma}^0})}{-p_2^2 - M^2_{\bar{\Sigma}^0}}[\mathrm{i}g_4'\gamma_5] \\ &\quad\times \frac{\mathrm{i}(\not{q} + M_{\mathcal{C}_4})}{q^2 - M^2_{\mathcal{C}_4}}[\mathrm{i}g_3'\gamma_5 v_{\mathcal{A}_4}]\frac{\mathrm{i}}{p_1^2 - M_K^2}\mathcal{F}^2(M_{\mathcal{C}_4}, q^2),\end{aligned} \tag{11}$$

where p_1 and p_2 denote the four momenta carried by K^- and $\bar{\Sigma}^0$, respectively. We have $q = p_1 - p_3 = p_4 - p_2$. The definition of $\mathcal{F}^2(m_i, q^2)$ is given in (7). Moreover, the form factor may provide a convergent behavior for the triangle loop integration. That is very similar to the case of the Pauli–Villars renormalization scheme [18, 19].

Using the same treatment in [20], we obtain the further expressions of (10) and (11), which are listed in the appendix.

3 Numerical results

In the QCD sum rule approach, the ratios of the coupling constants in (3) and (4) are given by $F_P/D_P = 0.6$ [21] and the ratio $F_V/(F_V + D_V) = 1$ [22]. In the limit of SU(3) symmetry, by $g_{NN\pi} = 13.5$ and $g_{NN\rho} = 3.25$ [23–25], one obtains the meson–baryon coupling constants relevant to our calculation: $g_{PPV} = 6.1$, $F_P = 13.5$, $D_P = 0$, $F_V = 1.2$ and $D_V = 2.0$.

Using the above parameters as input, we get the ratios of the decay widths of $\bar{N}_X(1625) \to \pi^0\bar{p}, \eta\bar{p}, \pi^-\bar{n}$ to the decay width of $\bar{N}_X(1625) \to \bar{\Lambda}K^-$ in the assumptions of the $\bar{\Lambda}$–K^- molecular state and the $\bar{\Sigma}^0$–K^- molecular state for $\bar{N}_X(1625)$, which are shown in Figs. 3 and 4, respectively. Here α in the form factor is taken in the range 1–3 [17].

Table 1. The ratios of the decay width of $\bar{N}_X(1625) \to \pi^0\bar{p}, \eta\bar{p}, \pi^-\bar{n}$ to the decay width of $\bar{N}_X(1625) \to \bar{\Lambda}K^-$ in different molecular assumptions with $\alpha = 1.5$

	$\frac{\Gamma(\pi^0\bar{p})}{\Gamma(K^-\bar{\Lambda})}$	$\frac{\Gamma(\eta\bar{p})}{\Gamma(K^-\bar{\Lambda})}$	$\frac{\Gamma(\pi^-\bar{n})}{\Gamma(K^-\bar{\Lambda})}$
$\bar{\Lambda}$–K^-	1×10^{-4}	5×10^{-7}	2×10^{-4}
$\bar{\Sigma}^0$–K^-	9	70	18

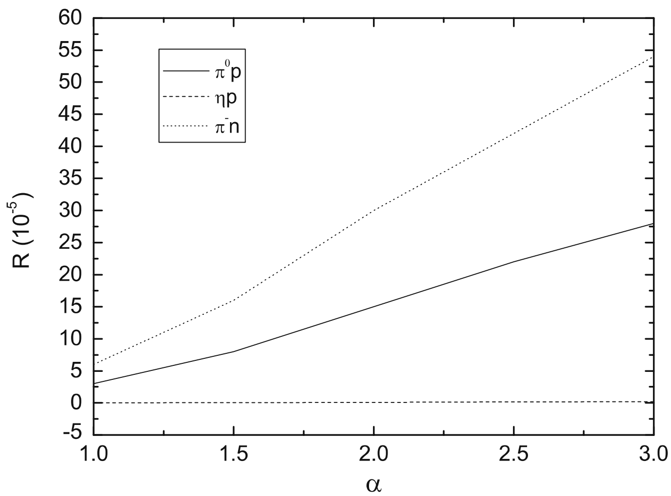

Fig. 3. The ratios of the $\bar{N}_X(1625) \to \pi^0\bar{p}, \eta\bar{p}, \pi^-\bar{n}$ decay widths to the $\bar{N}_X(1625) \to \bar{\Lambda}K^-$ decay width in the picture of the $\bar{\Lambda}$–K^- molecular state

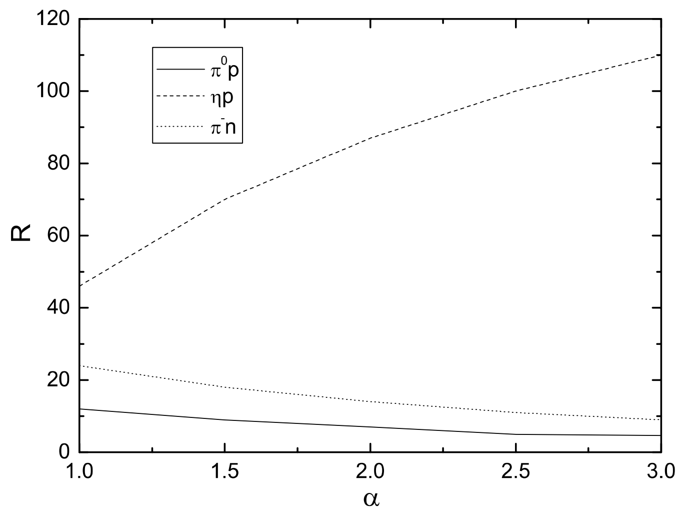

Fig. 4. The ratios of the $\bar{N}_X(1625) \to \pi^0\bar{p}, \eta\bar{p}, \pi^-\bar{n}$ decay width to the $\bar{N}_X(1625) \to \bar{\Lambda}K^-$ decay width in the $\bar{\Sigma}^0$–K^- molecular state picture

Table 2. The branching ratios of subordinate decays of $\bar{N}_X(1625)$ in two different molecular state pictures

	$\bar{\Lambda}$–K^- system	$\bar{\Sigma}^0$–K^- system
$J/\psi \to p\bar{N}_X(1625) \to p(\pi^0\bar{p})$	$1\times10^{-8} \sim 3\times10^{-8}$	$\sim 1\times10^{-3}$
$J/\psi \to p\bar{N}_X(1625) \to p(\eta\bar{p})$	$4\times10^{-11} \sim 2\times10^{-10}$	$\sim 7\times10^{-3}$
$J/\psi \to p\bar{N}_X(1625) \to p(\pi^-\bar{n})$	$2\times10^{-8} \sim 5\times10^{-8}$	$\sim 2\times10^{-3}$

Figures 3 and 4 show that these ratios do not strongly depend on α. By taking the typical value $\alpha = 1.5$, one further finds the ratios listed in Table 1.

By using the ratios shown in Figs. 3 and 4 and the branching ratio $B[J/\psi \to p\bar{N}_X(1625)]B[\bar{N}_X(1625) \to K^-\bar{\Lambda}] = 9.14^{+1.30+4.24}_{-1.25-8.28} \times 10^{-5}$ given by BES [10], one estimates the branching ratio of the subordinate decays of $\bar{N}_X(1625)$ in J/ψ decay shown in Table 2. Due to the uncertainty of α, we give the possible ranges for these branching ratios.

If $\bar{N}_X(1625)$ is the $\bar{\Lambda}$–K^- molecular state, the $\bar{N}_X(1625)$ mainly decay to $K^-\bar{\Lambda}$. The branching ratios of the subordinate decays $\bar{N}_X(1625) \to \pi^0\bar{p}, \eta\bar{p}, \pi^-\bar{n}$ are far less than that of $\bar{N}_X(1625) \to K^-\bar{\Lambda}$, which can explain why $\bar{N}_X(1625)$ was firstly observed in the mass spectrum of $K^-\bar{\Lambda}$. In the Particle Data Book [4], the smallest branching ratios that have been measured for J/ψ decays are larger than 10^{-5}. Thus the rest decays of $\bar{N}_X(1625)$ is hardly measured in further experiments.

If $\bar{N}_X(1625)$ is the S-wave $\bar{\Sigma}^0$–K^- molecular state, $\bar{N}_X(1625)$ cannot decay to $\bar{\Sigma}^0K^-$ due to having not enough phase space. Because of the Λ–Σ^0 mixing mechanism and final state interaction effect, $\bar{N}_X(1625)$ can decay to $\bar{\Lambda}K^-$. Our calculations indicate that the branching ratio of $\bar{N}_X(1625) \to \bar{\Lambda}K^-$ is about one or two orders smaller than that of $\bar{N}_X(1625) \to \pi^0\bar{p}, \eta\bar{p}, \pi^-\bar{n}$. Although the neutral particles in the decay modes $\pi^0\bar{p}, \eta\bar{p}, \pi^-\bar{n}$ increase the difficulty of searching these decay modes in experiment, future experiments still have the potential to find $\bar{N}_X(1625) \to \pi^0\bar{p}, \eta\bar{p}, \pi^-\bar{n}$.

4 Discussion and conclusion

In this work, we focus on different results of the decay mode of $\bar{N}_X(1625)$ resulting from two assumptions on the molecular state, i.e. the S-wave $\bar{\Lambda}$–K^- and the S-wave $\bar{\Sigma}^0$–K^- systems. Basing on these two pictures, we estimate the possible decay modes of $\bar{N}_X(1625)$, which include $K^-\bar{\Lambda}$, $\pi^0\bar{p}$, $\eta\bar{p}$ and $\pi^-\bar{n}$. Our result indicates that the search for $\bar{N}_X(1625) \to \pi^0\bar{p}, \eta\bar{p}, \pi^-\bar{n}$ will shed light on the nature of $\bar{N}_X(1625)$.

At present the experimental information indicates that $\bar{N}_X(1625)$ has a very strong coupling with $\bar{\Lambda}K^-$, and other modes are still missing [10]. Thus the assumption of the S-wave $\bar{\Lambda}$–K^- molecular state is more favorable than that of the S-wave $\bar{\Sigma}^0$–K^- molecular state for $\bar{N}_X(1625)$. However, the result of [5] indicates that it is difficult to form a ΛK bound state. In fact, in the molecule picture, in general such an S-wave $\bar{\Lambda}K^-$ system should be of very wide width, which contradicts the experimental information on $\bar{N}_X(1625)$ ($\Gamma_{\bar{N}_X(1625)} = 43\,\mathrm{MeV}$). Although the above analysis shows that the S-wave $\bar{\Lambda}$–K^- molecule assignment as $\bar{N}_X(1625)$ is not suitable, we still try to study the decay of $\bar{N}_X(1625)$ in the S-wave $\bar{\Lambda}$–K^- molecule picture.

In the assumption of the S-wave $\bar{\Sigma}^0$–K^- molecular state, the sum of the branching ratios of $\bar{N}_X(1625) \to \pi^0\bar{p}, \eta\bar{p}, \pi^-\bar{n}$ listed in Table 2 is about 10^{-2}. Such a large branching ratio is unreasonable for J/ψ decay. The BES Collaboration has already studied $J/\psi \to p\pi^-\bar{n}$ in [8] and $J/\psi \to p(\eta\bar{p})$ in [9]. The branching ratios respectively corresponding to $J/\psi \to p\pi^-\bar{n}$ and $J/\psi \to p\eta\bar{p}$ are 2.4×10^{-3} and 2.1×10^{-3} [8,9]. Although these experimental values are comparable with our numerical result of the corresponding channel, experiments did not find a structure consistent with $\bar{N}_X(1625)$, which seems to show that evidence against the S-wave $\bar{\Sigma}^0$–K^- molecular picture is gradually accumulating. However, we still urge our experimental colleagues to carefully analyze the $J/\psi \to p\pi^-\bar{n}$ and $J/\psi \to p\eta\bar{p}$ channels in further experiments, especially the forthcoming BESIII.

Thus the above analysis shows that the pure molecular state structure seems to be very difficult to explain $N_X(1625)$.

We note that there exist the two well established states $N^*(1535)$ and $N^*(1650)$, with $J^P = 1/2^-$, close to the mass of $N_X(1625)$. In PDG [4], the branching ratio of $N^*(1650) \to K\Lambda$ is about 3%–11%. The authors of [6] indicated that $N^*(1535)$ should have a large $s\bar{s}$ component in its wave function, which shows the large $N^*(1535)K\Lambda$ coupling. $N^*(1535)$ and $N^*(1650)$ can strongly couple to $K\Lambda$. Thus, before confirming $N_X(1625)$ to be a new resonance, theorists and experimentalists of high energy physics need to cooperate to answer whether $N_X(1625)$ enhancement is related to $N^*(1535)$ and $N^*(1650)$. Forthcoming BESIII and HIRFL-CSR will provide a good place to further come to understand the $N_X(1625)$ structure.

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Appendix

The further expressions of (10) and (11) are

$$
\begin{aligned}
&\mathcal{M}_3^{(\mathcal{A}_3,\mathcal{C}_3)} \\
&= -g_3 g_4 \mathcal{G}\int_0^1 \mathrm{d}x \int_0^{1-x}\mathrm{d}y \left\{\left[\frac{\left(\xi^2-M_{\mathcal{C}_3}^2\right)y}{16\pi^2\Delta^2(M_K,M_{\bar{\Sigma}^0},\xi)}\right.\right.\\
&\left.-\frac{1}{16\pi^2\Delta(M_K,M_{\bar{\Sigma}^0},M_{\mathcal{C}_3})}+\frac{1}{16\pi^2\Delta(M_K,M_{\bar{\Sigma}^0},\xi)}\right]\\
&\times \bar{v}_N\gamma_5\big[\not{p}_4\not{p}_3[2-2x-(1-x-y)+(1-x-y)x]\\
&+\not{p}_3\not{p}_3\left[2(1-x-y)-(1-x-y)^2\right]+\not{p}_4\not{p}_4\left(x-x^2\right)\\
&+\not{p}_3\not{p}_4(1-x-y)x\\
&\left.+\not{p}_3[2M_{\bar{\Sigma}^0}-(1-x-y)M_{\bar{\Sigma}^0}]+\not{p}_4 x M_{\bar{\Sigma}^0}\big]\bar{v}_{\mathcal{A}3}\right\}\\
&-g_3 g_4\mathcal{G}\int_0^1\mathrm{d}x\int_0^{1-x}\mathrm{d}y\\
&\times\left\{\left[\frac{2}{(4\pi)^2}\log\left(\frac{\Delta(M_K,M_{\bar{\Sigma}^0},\xi)}{\Delta(M_K,M_{\bar{\Sigma}^0},M_{\mathcal{C}_3})}\right)\right.\right.\\
&\left.\left.-\frac{(\xi^2-M_{\mathcal{C}_3}^2)y}{8\pi^2\Delta(M_K,M_{\bar{\Sigma}^0},\xi)}\right]\left[\bar{v}_N\gamma_5\left(-\frac{1}{4}\right)\gamma_\mu\gamma^\mu v_{\mathcal{A}3}\right]\right\},
\end{aligned}
\tag{A.1}
$$

$$
\begin{aligned}
\mathcal{M}_4^{(\mathcal{A}_4,\mathcal{C}_4)} &= -g_3'g_4'\mathcal{G}\int_0^1\mathrm{d}x\int_0^{1-x}\mathrm{d}y\\
&\times\left\{\left[\frac{(\xi^2-M_{\mathcal{C}_4}^2)y}{16\pi^2\Delta^2(M_K,M_{\bar{\Sigma}^0},\xi)}-\frac{1}{16\pi^2\Delta(M_K,M_{\bar{\Sigma}^0},M_{\mathcal{C}_4})}\right.\right.\\
&\left.+\frac{1}{16\pi^2\Delta(M_K,M_{\bar{\Sigma}^0},\xi)}\right]\bar{v}_N\gamma_5\\
&\times[\not{p}_4\not{p}_3[(1-x-y)-(1-x-y)x]\\
&+\not{p}_3\not{p}_3(1-x-y)^2+\not{p}_4\not{p}_4(x^2-x)\\
&-\not{p}_3\not{p}_4(1-x-y)x\\
&+\not{p}_3[-M_{\bar{\Sigma}^0}(1-x-y)+(1-x-y)M_{\mathcal{C}_4}]\\
&\left.-\not{p}_4 x(M_{\mathcal{C}_4}-M_{\bar{\Sigma}^0})+\not{p}_4 M_{\mathcal{C}_4}-M_{\bar{\Sigma}^0}M_{\mathcal{C}_4}]v_{\mathcal{A}_4}\right\}\\
&-g_3'g_4'\mathcal{G}\int_0^1\mathrm{d}x\int_0^{1-x}\mathrm{d}y\\
&\times\left\{\left[\frac{2}{(4\pi)^2}\log\left(\frac{\Delta(M_K,M_{\bar{\Sigma}^0},\xi)}{\Delta(M_K,M_{\bar{\Sigma}^0},M_{\mathcal{C}_4})}\right)\right.\right.\\
&\left.\left.-\frac{\left(\xi^2-M_{\mathcal{C}_4}^2\right)y}{8\pi^2\Delta(M_K,M_{\bar{\Sigma}^0},\xi)}\right]\left[\bar{v}_N\gamma_5\frac{1}{4}\gamma_\mu\gamma^\mu v_{\mathcal{A}_4}\right]\right\},
\end{aligned}
\tag{A.2}
$$

where

$$
\begin{aligned}
\Delta(a,b,c) &= m_3^2(1-x-y)^2-2\,(p_3p_4)\,(1-x-y)x\\
&+m_4^2x^2-\left(m_3^2-a^2\right)(1-x-y)\\
&-\left(m_4^2-b^2\right)x+yc^2\,,
\end{aligned}
$$

$m_3(m_4)$ and $p_3(p_4)$ are the masses and four- momenta of the final states.

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