Towards the decays of $\bar{N}_X(1625)$ in the molecular picture *

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Abstract
In this talk, we firstly overview the experimental status of $\bar{N}_X(1625)$, which is an enhancement structure observed in $K^-\bar{\Lambda}$ invariant mass spectrum of $\psi$ process. Then we present the result of the decay of $\bar{N}_X(1625)$ under the two molecular assumptions, i.e. S-wave $\Lambda K^-$ and S-wave $\Sigma^0 K^-$ molecular states. Several experimental suggestions for $\bar{N}_X(1625)$ are proposed.

Key words molecular state, strong decay, rescattering mechanism

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1 Introduction

$\psi$ decay is an ideal platform for studying the excited baryons and hyperons. With the collected data, the BES experiment has carried out a series of investigations of hadron spectroscopy. Among the new observations of the hadron states, $\bar{N}_X(1625)$ is an enhancement near $K^-\bar{\Lambda}$ threshold, which was only reported in several conference proceedings \footnote{2,3} under the investigation of $K^-\bar{\Lambda}$ invariant mass spectrum in $\psi$ process. The rough measurement results about the mass and the width of $\bar{N}_X(1625)$ are $m = 1500 \sim 1650$ MeV and $\Gamma = 70 \sim 110$ MeV, respectively. The experiment also indicates that the spin-parity favors $\frac{1}{2}^-$ for $N_X(1625)$, which denotes the antiparticle of $\bar{N}_X(1625)$\footnote{3}. The $pK^-\bar{\Lambda}$ Dalitz plot and $K^-\bar{\Lambda}$ invariant mass spectrum are shown in figs. \textsuperscript{4} and \textsuperscript{2} $N_X(1625)$ enhancement structure was not observed in $\gamma p \rightarrow K^+\Lambda$ process at SAPHIR\footnote{4}.

At 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

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

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

\[ B[\bar{N}_X(1625) \rightarrow K^-\bar{\Lambda}] = (9.14^{+1.30+4.24}_{-1.25-8.28}) \times 10^{-5}. \]

These more accurate experimental information of $\bar{N}_X(1625)$ provides us good chance to study the nature of $\bar{N}_X(1625)$.

If $\bar{N}_X(1625)$ is a regular baryon, the branching ratio of $\psi \rightarrow \bar{p}\bar{N}_X(1625)$ should be comparable with that of $\psi \rightarrow \bar{p}\bar{p}$ considering the branching ratio $B(\psi \rightarrow \bar{p}\bar{p}) = 2.17 \times 10^{-3}\footnote{6}$. Thus, we can obtain

\[ B(\psi \rightarrow \bar{N}_X(1625) \rightarrow \bar{p}\bar{p}) = (9.14^{+1.30+4.24}_{-1.25-8.28}) \times 10^{-5}. \]
$B[\bar{N}_X(1625) \to \bar{\Lambda}K^-] \sim 10\%$, which indicates that there exists the strong coupling between $\bar{N}_X(1625)$ and $K^-\bar{\Lambda}$.

This peculiar property of $\bar{N}_X(1625)$ inspires our interest in exploring its structure, especially in its exotic component. In Ref. [7], we calculated the possible decay modes of $\bar{N}_X(1625)$ in the two different assumptions of the molecular states, i.e. $\bar{\Lambda} - K^-$ and $\Sigma^0 - K^-$. In the following, we will present the details of the calculation and the numerical result.

2 The decays under the assumptions of $\bar{\Lambda} - K^-$ and $\Sigma^0 - K^-$ molecular states

Since the mass of $\bar{N}_X(1625)$ is above the threshold of $\bar{\Lambda}$ and $K^-$ under the assumptions of $\bar{\Lambda} - K^-$ molecular state, thus $\bar{N}_X(1625)$ can directly decay into $\bar{\Lambda} + K^-$ (Fig. 3 (a)), which is depicted by the decay amplitude

$$\mathcal{M}[\bar{N}_X(1625) \to \bar{\Lambda} + K^-] = i\mathcal{G}\bar{v}_N\gamma_5v_X.$$  \hspace{1cm} (1)

Here $\mathcal{G}$ denotes the coupling constant between $\bar{\Lambda} - K^-$ molecular state.

3 The decay modes if $\bar{N}_X(1625)$ is $\bar{\Lambda} - K^-$ molecular state.

In the rescattering mechanism, the subordinate decays $\bar{N}_X(1625) \to \pi^0\bar{p}, \eta\bar{p}, \pi^-\bar{n}$ occur, which are depicted in Fig. 3 (c)-(e). The effective Lagrangians relevant to the calculation are [2]:

$$\mathcal{L}_{PPP} = -ig_{PPP}Tr([\bar{P},\partial_\mu P]V^\mu),$$  \hspace{1cm} (2)

$$\mathcal{L}_{BBP} = F_\pi Tr(\bar{P}[B,\bar{B}])\gamma_5 + D_\pi Tr(\bar{P}[B,\bar{B}])\gamma_5,$$  \hspace{1cm} (3)

$$\mathcal{L}_{BBV} = F_\pi Tr(V^\mu[B,\bar{B}])\gamma_\mu + D_\pi Tr(V^\mu[B,\bar{B}])\gamma_\mu.$$  \hspace{1cm} (4)

where $\bar{B}$ is the Hermitian conjugate of $B$. $P$, $V$ and $B$ respectively denote the octet pseudoscalar meson, the nonet vector meson and the baryon matrixes. $F_P$ and $D_P$ in eq. (2) and $F_V$ and $D_V$ in eq. (4) satisfy the relations $F_P/D_P = 0.6$ [16] and $F_V/(F_V + D_V) = 1/3$. In the limit of SU(3) symmetry, by $g_{NKN} = 13.5$ and $g_{NKN} = 3.25$ [12], one obtains the meson-baryon coupling constants relevant to our calculation: $g_{PPV} = 6.1, F_P = 13.5, D_P = 0, F_V = 1.2, D_V = 2.0$.

Since the intermediate states $\bar{\Lambda}$ and $K^-$ in Fig. 3 (b)-(d) are on-shell, one writes out the general amplitude expression corresponding to Fig. 3 (b) and (d) by Cutkosky cutting rules

$$\mathcal{M}_1^{(A_1,c_1)} = \frac{1}{2} \int \frac{d^4p_1}{(2\pi)^4E_1} \frac{d^4p_2}{(2\pi)^4E_2} \times (2\pi)^4\delta^4(M_N - p_1 - p_2)\bar{G}\bar{v}_N\gamma_5v_X \times \left[ i\bar{q}_1\gamma_\mu\gamma_5v_{A_1}\right] i\left[ q_1\gamma_\mu\gamma_5v_{A_1}\right] - M_{c_1}^2 \times \left[ -g^{\mu\nu} + \frac{g^{\mu\nu}}{M_{c_1}^2} \right] \mathcal{F}^2(M_{c_1},q^2).$$  \hspace{1cm} (5)

For Fig. 3 (c) and (e), the general amplitude expression is

$$\mathcal{M}_1^{(A_2,c_2)} = \frac{1}{2} \int \frac{d^4p_1}{(2\pi)^4E_1} \frac{d^4p_2}{(2\pi)^4E_2} \times (2\pi)^4\delta^4(M_N - p_1 - p_2)\bar{G}\bar{v}_N\gamma_5v_X \times \left[ i\bar{q}_2\gamma_\mu\gamma_5v_{A_2}\right] i\left[ q_2\gamma_\mu\gamma_5v_{A_2}\right] - M_{c_2}^2 \times \mathcal{F}^2(M_{c_2},q^2).$$  \hspace{1cm} (6)

In the above expressions, $c_1$ and $c_2$ denote the exchanged particle and the final state baryon, respectively. $p_1$ and $p_2$ are respectively the four momenta of $K^-$ and $\bar{\Lambda}$. $\mathcal{F}^2(m_i, q^2)$ denotes the form factor which compensates the off-shell effects of the hadrons at the vertices. In this work, one takes $\mathcal{F}^2(m_i, q^2)$ as the monopole form [14, 15] $\mathcal{F}^2(m_i, q^2) = \left( \frac{E^2 - m_i^2}{E^2 - q^2} \right)^2$, which plays the role to cut off the end effect. Phenomenological parameter $\xi$ is parameterized as $\xi = m_i + \alpha \Lambda_{QCD}$, where $m_i$ denotes the mass of exchanged meson [14] and $\Lambda_{QCD} = 220$ MeV. $\alpha$ is a phenomenological parameter and is of order unity.

In the $\Sigma^0 - K^-$ molecular picture, $\bar{N}_X(1625)$ does not decay into $\Sigma^0$ and $K^-$ because of having not enough phase space. However, decay $\bar{N}_X(1625) \to \bar{\Lambda} + K^-$ occurs by the isospin violation effect, which results in the mixing of $\Sigma^0$ with $\Lambda_{[2]}$ (see Fig. 3 (a)). By the Lagrangian

$$\mathcal{L}_{\text{mixing}} = g_{\text{mixing}}(\bar{\psi}_{\Sigma^0}\psi_X + \bar{\psi}_X\psi_{\Sigma^0})$$
with the coupling constant $g_{\text{mixing}} = 0.5 \pm 0.1$ MeV determined by QCD sum rule, one writes out the decay amplitude

$$\mathcal{M}[\bar{N}_X(1625) \rightarrow \Sigma^0 + K^-] = \mathcal{G} g_{\text{mixing}} \bar{v}_N \gamma_\mu \frac{i}{p - M_\Lambda} v_\Lambda,$$

where $p$ and $M_\Lambda$ are the four momentum and the mass of $\Lambda$, respectively.

For $\Sigma^0 - K^-$ molecular state assumption, $\bar{N}_X(1625)$ still can decay into $\pi^0 \bar{p}, \eta \bar{p}, \pi^- \bar{n}$, which are described in Fig. 4(b)-(g). The general expression of Fig. 4 (b)-(g) is expressed as

$$\mathcal{M}^{(A_4, c_3)} = \int \frac{d^4q}{(2\pi)^4} \frac{i}{q^2 - M_{\Sigma^0}} [i g_\Lambda(p_1 + p_3) v_{A_3}]$$

$$\times [i g_\Lambda(p_1 + p_3) v_{A_3}] - i g_\Lambda v_{A_3}$$

$$\times \mathcal{F}^2(M_{c_3}, q^2),$$

for Fig. 4(c), (e), (g) the general amplitude expression reads as

$$\mathcal{M}^{(A_4, c_4)} = \int \frac{d^4q}{(2\pi)^4} \frac{i}{q^2 - M_{\Sigma^0}} [i g_\Lambda(p_1 + p_3) v_{A_3}]$$

$$\times [i g_\Lambda(p_1 + p_3) v_{A_3}] - i g_\Lambda v_{A_3}$$

$$\times \frac{i}{p_1^2 - M_K^2} \mathcal{F}^2(M_{c_4}, q^2),$$

where $p_1$ and $p_2$ denote the four momenta carried by $K^-$ and $\Sigma^0$, respectively. $q = p_1 - p_3 = p_3 - p_2$. For the decays depicted in Fig. 4(b)-(g), $\Sigma^0$ and $K^-$ are off-shell. The form factor may provide a convergent behavior for the triangle loop integration, which is very similar to the case of the Pauli-Villas renormalization scheme.

3 Numerical result

In Figs. 5 and 6 we show the ratios of the decay widths of $\bar{N}_X(1625) \rightarrow \pi^0 \bar{p}, \eta \bar{p}, \pi^- \bar{n}$ to the decay width of $\bar{N}_X(1625) \rightarrow \Lambda K^-$ under the assumptions of $\Lambda - K^-$ and $\Sigma^0 - K^-$ molecular states when taking $\alpha = 1 \sim 3$. Fig. 5 and Fig. 6 illustrate that these ratios do not strongly depend on the $\alpha$. One further obtains the typical values of these ratios taking $\alpha = 1.5$, which are listed in Table 1. Combining these ratios shown in Figs. 5 and 6 with the branching ratio $B[J/\psi \rightarrow p \bar{N}_X(1625)]B[\bar{N}_X(1625) \rightarrow K^+ \Lambda] = (9.14^{+1.30+1.24}_{-1.25-1.28}) \times 10^{-5}$ given by BES, one estimates the branching ratio of the subordinate decays of $J/\psi \rightarrow p \bar{N}_X(1625) \rightarrow p(\pi^0 \bar{p}), p(\eta \bar{p}), p(\pi^- \bar{n})$, which are shown in Table 2.
4 Discussion and conclusion

Assuming \( \bar{N}_X(1625) \) as \( \Lambda - K^- \) molecular state, \( K^- \Lambda \) is the dominant decay mode of \( \bar{N}_X(1625) \). The branching ratio of \( \bar{N}_X(1625) \rightarrow K^- \Lambda \) is far larger than the branching ratios of \( \bar{N}_X(1625) \rightarrow \pi^0 \bar{p},\eta \bar{p},\pi^- \bar{n}, \) which can explain why \( \bar{N}_X(1625) \) was firstly observed in the mass spectrum of \( K^- \Lambda \). And we notice that the smallest measurable branching ratio for \( J/\psi \) decay listed in the Particle Data Book[9] is about 10\(^{-5}\). Thus, it is difficult to measure \( J/\psi \rightarrow p\bar{N}_X(1625) \rightarrow p(\pi^0 \bar{p}), p(\eta \bar{p}), p(\pi^- \bar{n}) \) in further experiments.

Under the assumption of S-wave \( \Sigma^0 - K^- \) molecular state for \( \bar{N}_X(1625) \), \( \bar{N}_X(1625) \) can not decay to \( \Sigma^0 K^- \) due to having not enough phase space. The \( \Lambda - \Sigma^0 \) mixing mechanism and final state interaction effect result in the decay \( \bar{N}_X(1625) \rightarrow \Lambda K^- \). The branching ratio of \( \bar{N}_X(1625) \rightarrow \Lambda K^- \) is about one or two order smaller than that of \( \bar{N}_X(1625) \rightarrow \pi^0 \bar{p},\eta \bar{p},\pi^- \bar{n} \). The sum of the branching ratios of \( \bar{N}_X(1625) \rightarrow \pi^0 \bar{p},\eta \bar{p},\pi^- \bar{n} \) listed in Table 2 is about 10\(^{-2}\). Such a large branching ratio is unreasonable for \( J/\psi \) decay. The BES collaboration has already studied \( J/\psi \rightarrow p\pi^- \bar{n} \) in Ref. [20] and \( J/\psi \rightarrow p(\eta \bar{p}) \) in Ref. [21]. The branching ratios respectively corresponding to \( J/\psi \rightarrow p\pi^- \bar{n} \) and \( J/\psi \rightarrow p\eta \bar{p} \) are 2.4 \times 10^{-3} and 2.1 \times 10^{-3}[20,21]. Although these experimental values are comparable with our numerical result of the corresponding channel, the former experiments did not find the structure consistent with \( \bar{N}_X(1625) \), which seems to show that the evidence against S-wave \( \Sigma^0 - K^- \) molecular picture is gradually accumulating[1].

As indicated in Ref. [3], there exists very strong coupling between \( \bar{N}_X(1625) \) and \( \Lambda K^- \). At present other decay modes of \( \bar{N}_X(1625) \) are still missing[1]. Thus the assumption of S-wave \( \Lambda - K^- \) molecular state is more favorable than that of S-wave \( \Sigma^0 - K^- \) molecular state for \( \bar{N}_X(1625) \). The result of Ref. [22], which is from the calculation within the framework of the chiral SU(3) quark model by solving a resonating group method (RGM) equation, indicates that the \( \Lambda K \) system is unbound. Whether there exists the S-wave \( \Lambda - K^- \) molecular state is still an open issue. The dynamics study of S-wave \( \Lambda - K^- \) system by other phenomenological models is encouraged. If it is problematic to explain \( \bar{N}_X(1625) \) as the pure molecular state structure, we have to again ask what is the underlying structure of \( \bar{N}_X(1625) \). We notice that there exist two well established states \( N^*(1535) \) and \( N^*(1650) \) with \( J^P = 1/2^- \) nearby the mass of \( N_X(1625) \). In PDG[6], the branching ratio of

| Decays | \( \Lambda - K^- \) system | \( \Sigma^0 - K^- \) system |
|--------|----------------|----------------|
| \( J/\psi \rightarrow p\pi^- \bar{n} \) | 10\(^{-5}\) \( \sim 3 \times 10^{-8} \) | \( \sim 1 \times 10^{-3} \) |
| \( J/\psi \rightarrow p(\eta \bar{p}) \) | 4 \times 10\(^{-11}\) \( \sim 2 \times 10^{-10} \) | \( \sim 7 \times 10^{-3} \) |
| \( J/\psi \rightarrow p\bar{N}_X(1625) \rightarrow p(\pi^- \bar{n}) \) | 2 \times 10^{-8} \( \sim 5 \times 10^{-8} \) | \( \sim 2 \times 10^{-3} \) |
$N^*(1650) \rightarrow KA$ is about $3 \sim 11\%$. The authors of Ref. [23] indicated that $N^*(1535)$ should have large $s\bar{s}$ component in its wave function which shows the large $N^*(1535)KA$ coupling. $N^*(1535)$ and $N^*(1650)$ can strongly couple to $KA$. Thus, whether $N_X(1625)$ enhancement is related to $N^*(1535)$ and $N^*(1650)$ is also an interesting topic.

Finally, we want to propose several suggestions for future experiment:

- Until now, the experimental information of $\bar{N}_X(1625)$ only appeared in the proceeding of conference [24, 25, 26]. We are expecting the formal publication of this enhancement, which will be helpful to stimulate more experimentalists and theorists to pay attention to this issue.

- Searching for $\bar{N}_X(1625) \rightarrow \pi^0\bar{p}, \eta\bar{p}, \pi^-\bar{n}$ modes in future experiment can shed light on the nature of $N_X(1625)$. We urge our experimental colleague carefully analyze $J/\psi \rightarrow p\pi^-\bar{n}$ and $J/\psi \rightarrow p\eta\bar{p}$ channel in further experiments, especially in the forthcoming BESIII.

- Confirming $N_X(1625)$ by the other experiments is encouraged. At present, Lanzhou CSR is a good platform to study the baryon spectroscopy. Analyzing the invariant mass spectrum of $K^+\Lambda$, which comes from the $p\alpha$ reaction, will be an important approach to investigate the $N_X(1625)$ enhancement structure.

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