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Production spectra of the ΣNN quasibound states in ${}^3\text{He}(K^-, \pi^\mp)$ reactions

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Abstract We theoretically demonstrate the inclusive and semiexclusive spectra in the ${}^3\text{He}(K^-, \pi^\mp)$ reactions at 600 MeV/c (4°) within a distorted-wave impulse approximation, using a coupled $(2N-A)+(2N-\Sigma)$ model with a spreading potential. It is shown that a signal of a ${}^3_\Sigma\text{He}$ quasibound state is clearly observed near the Σ threshold in the π^- spectrum, whereas a peak of a ${}^3_\Sigma n$ quasibound state is relatively reduced in the π^+ spectrum. The mechanism of Σ production for these spectra is discussed.

Keywords Sigma hypernuclei · Quasibound states · Production

1 Introduction

One of the most important subjects on strangeness nuclear physics is to understand properties of a Σ hyperon in nuclei as well as the nature of ΣN interaction, e.g., the Σ^- hyperon is expected to play an essential role in the description of neutron stars [?]. Many efforts for Σ hypernuclear studies on s - and p -shell nuclei have been carried out in $(K^-, \pi^\mp)$ reactions at CERN, BNL and KEK. However, it has been known that there is no observation of a Σ nuclear state [?], except ${}^4_\Sigma\text{He}$, which is established to be a quasibound (or unstable bound) state experimentally [?,?], as predicted by Ref. [?]. Moreover, Saha *et al.* [?] reported that the Σ -nucleus potential has a strong repulsion in the real part with a sizable imaginary part, analyzing nuclear (π^-, K^+) spectra on C, Si, Ni, In and Bi targets. This repulsion originates from the $\Sigma N {}^3S_1$, $I=3/2$ channel that corresponds to a quark Pauli-forbidden state in the baryon-baryon system [?].

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Table 1 Hypernuclear final states in $(K^-, \pi^\mp)$ reactions on a ${}^3\text{He}$ target

Reactions	(a)	(b)	(c)	(d)
(K^-, π^-)	$pp\Lambda$	$d\Sigma^+$	$pn\Sigma^+$	$pp\Sigma^0$
(K^-, π^+)	$nn\Lambda$	$d\Sigma^-$	$pn\Sigma^-$	$nn\Sigma^0$

On the other hand, several theoretical predictions [?, ?, ?] have suggested a possible candidate of a ΣNN quasibound state: Koike and Harada [?] found that there are ΣNN quasibound states with $S=1/2$, $T=1$ (${}^3_\Sigma\text{He}$, ${}^3_\Sigma\text{H}$ and ${}^3_\Sigma\text{n}$) due to the coupling through the ΣN potential which strongly admixes 1S_0 , $I=1$ and 3S_1 , $I=0$ states in the NN pair. Recently, Garcilazo *et al.* [?] showed that a narrow ΣNN quasibound state exists near Σ threshold in the $S=1/2$, $T=1$ channel by ΛNN - ΣNN Faddeev calculations. However, it has long been recognized that there is no evidence of a narrow structure for the ΣNN quasibound state (${}^3_\Sigma\text{n}$) below the Σ threshold by the ${}^3\text{He}(K^-, \pi^+)$ reaction at BNL-E774 experiments [?]. These contradictory arguments are still not settled: Is there a quasibound state in ΣNN systems?

In this article, we theoretically demonstrate the inclusive and semiexclusive spectra in ${}^3\text{He}(K^-, \pi^\mp)$ reactions at 600 MeV/c (4°) within a distorted-wave impulse approximation (DWIA), using a coupled $(2N-\Lambda)+(2N-\Sigma)$ model with a spreading potential. Here we focus on behavior of a signal of the ΣNN quasibound state in the π^- and π^+ spectra in order to study the mechanism of Σ production for these spectra.

2 Calculations

Now we consider hypernuclear final states in $(K^-, \pi^\mp)$ reactions on a ${}^3\text{He}$ target, as shown in Table ???. The model wavefunctions of $2N$ - Y systems are assumed to be written as

$$\Psi({}^3_Y\text{He}) = \phi(\{pp\})\varphi_\Lambda + \phi([pn])\varphi_{\Sigma^+}^{(t)} + \phi(\{pn\})\varphi_{\Sigma^+}^{(s)} + \phi(\{pp\})\varphi_{\Sigma^0}, \quad (1)$$

for the π^- spectrum, and those as

$$\Psi({}^3_Y\text{n}) = \phi(\{nn\})\varphi_\Lambda + \phi([pn])\varphi_{\Sigma^-}^{(t)} + \phi(\{pn\})\varphi_{\Sigma^-}^{(s)} + \phi(\{nn\})\varphi_{\Sigma^0}, \quad (2)$$

for the π^+ spectrum. Here $\phi(\{N_1 N_2\})$ and $\phi([N_1 N_2])$ denote the $2N$ wavefunctions with 1S_0 , $I=1$ and 3S_1 , $I=0$ state, respectively, and φ_Λ , $\varphi_{\Sigma^\pm}^{(t,s)}$ and φ_{Σ^0} denote relative wavefunctions between $2N$ and Y ($=\Lambda$, $\Sigma^\pm$ or Σ^0), respectively.

According to the KAT theory [?], we calculate the effective $2N$ - Y potential which is derived from a two-body YN potential microscopically. The effective $2N$ - Y potential is written by

$$\hat{U}_{cc'} = \langle \phi(c) | \hat{V}^{\text{ex}} \hat{F}^{\text{ex}} | \phi(c') \rangle, \quad (3)$$

where $\hat{V}^{\text{ex}} \hat{F}^{\text{ex}}$ is an external operator which is constructed from the multiple-scattering operators with YN g-matrices and on/off-shell correlation functions in nuclei [?]. In order to estimate them, we solve the Bethe-Goldstone equation for the YN system in nuclear medium, taking appropriate values of E_s and k_f parameters, so that we can reproduce the binding energies of $B_\Lambda^{\text{exp}}({}^3_\Lambda\text{H}) = 0.13$ MeV in experimental data

Fig. 1 Real parts of the effective $2N$ - Y potential $\hat{U}_{cc'}(R)$ for ${}^3_Y\text{He}$ ($J^\pi = 1/2^+$) at $E_\Lambda = 70$ MeV which corresponds to the Σ threshold region, as a function of a relative distance R between $2N$ and Y .

and $B_\Sigma^{\text{cal}}({}^3_Y\text{He})$ obtained in three-body calculations [?]. For a spreading (imaginary) potential that describes $2N$ -breakup processes due to the $\Sigma N \rightarrow \Lambda N$ conversion, we determine the strength of its potential to reproduce the width of $\Gamma_\Sigma^{\text{cal}}({}^3_Y\text{He})$ [?].

Figure ?? displays real parts of the effective $2N$ - Y potential $\hat{U}_{cc'}(R)$ for ${}^3_Y\text{He}$ ($J^\pi = 1/2^+$) at $E_\Lambda = 70$ MeV which corresponds to the Σ threshold region, as a function of a relative distance R between $2N$ and Y . Here we used the Nijmegen model F simulated (NF_S) for YN [?], which was often used in full few-body calculations of $A = 2$ -6 hypernuclei [?]. We find that the coupling components of $\{pn\}\Sigma^+ - \{pp\}\Sigma^0$, $[pn]\Sigma^+ - [pn]\Sigma^+$ and $[pn]\Sigma^+ - \{pp\}\Sigma^0$ are quite large. This nature originates from the fact that the ΣN potential has a strong spin-isospin dependence, as suggested by recent YN potential models [?].

Let us consider the production spectra of the ΣNN quasibound states in ${}^3\text{He}(K^-, \pi^\mp)$ reactions. The inclusive spectrum of the double-differential cross section within the DWIA [?] is rewritten as

$$\frac{d^2\sigma}{d\Omega_\pi dE_\pi} = \beta \left(-\frac{1}{\pi}\right) \text{Im} \sum_{c'c} \langle F_{c'} | \hat{G}(\omega) | F_c \rangle, \quad (4)$$

where $\hat{G}(\omega)$ is the complete Green's function for the $2N$ - Y system, and β is a kinematical factor for the translation from K^- - N to K^- - ${}^3\text{He}$ systems. The production function is written by $F_c = \bar{f}_{\pi Y}(\chi_\pi^{(-)})^* \chi_{K^-}^{(+)} \langle \phi(c) | \Psi_A \rangle$, where $\bar{f}_{\pi Y}$ is a Fermi-averaged amplitude for $K^- N \rightarrow \pi Y$ in nuclear medium, which is obtained from the elementary amplitude by Gopal *et al.* [?], $\chi_\pi^{(-)}$ and $\chi_{K^-}^{(+)}$ are meson distorted waves obtained with

Fig. 2 Calculated spectrum of the ${}^3\text{He}(K^-, \pi^-)$ reaction at 600 MeV/c (4°) near the $d+\Sigma^+$ threshold, together with the contributions of $NN\Lambda$, $NN\Sigma$ and Λ - Σ conversion.

the help of the eikonal approximation, and $\langle\phi(c)|\Psi_A\rangle$ is a wave function for a struck nucleon in the ${}^3\text{He}$ target. The recoil effects are taken into account.

The complete Green's function $\hat{G}(\omega)$ describes all information concerning $(2N-\Lambda)+(2N-\Sigma)$ coupled-channel dynamics. We obtain it as a numerical solution of the multichannels radial coupled equations with the $2N$ - Y potential $\hat{U}$, which is written as

$$\hat{G}(\omega) = \hat{G}^{(0)}(\omega) + \hat{G}^{(0)}(\omega)\hat{U}\hat{G}(\omega), \quad (5)$$

where $\hat{G}^{(0)}(\omega)$ is a free Green's function. Therefore, we evaluate the inclusive π^- spectrum from Eq. (??), and also the semiexclusive spectra of (a)-(d) in Table ?? with the identity

$$\begin{aligned} \text{Im}\hat{G}(\omega) = & \hat{\Omega}^{(-)\dagger}\{\text{Im}\hat{G}_\Lambda^{(0)}(\omega)\}\hat{\Omega}^{(-)} + \hat{\Omega}^{(-)\dagger}\{\text{Im}\hat{G}_{\Sigma^\pm}^{(0)}(\omega)\}\hat{\Omega}^{(-)} \\ & + \hat{\Omega}^{(-)\dagger}\{\text{Im}\hat{G}_{\Sigma^0}^{(0)}(\omega)\}\hat{\Omega}^{(-)} + \hat{G}(\omega)\{\text{Im}\hat{U}\}\hat{G}(\omega), \end{aligned} \quad (6)$$

where $\hat{\Omega}^{(-)} = 1 + \hat{U}\hat{G}(\omega)$ is the Möller wave operator, and $\hat{G}_Y^{(0)}(\omega)$ denotes the free Green's function for the $2N$ - Y channel [?].

3 Results and discussion

Figures ?? shows the calculated spectrum of the ${}^3\text{He}(K^-, \pi^-)$ reaction at 600 MeV/c (4°) near the $d+\Sigma^+$ threshold, together with the components of $pp\Lambda$, $d\Sigma^+$, $pn\Sigma^+$, $pp\Sigma^0$ and Λ - Σ conversion, which will be carried out at forthcoming J-PARC facilities. It is recognized that a clear enhancement just below the $d+\Sigma^+$ threshold in the π^- spectrum is connected with dominance of the secondary process $[{}^3\text{He}] \rightarrow pp\Lambda$, where

Fig. 3 Calculated spectrum of the ${}^3\text{He}(K^-, \pi^+)$ reaction at 600 MeV/c (4°) near the Σ threshold, together with the experimental data from BNL-E774 [?]. The dashed line denotes the contribution of the Λ - Σ conversion via the ${}^3_\Sigma n$ quasibound state.

the produced Σ hyperon in the real or virtual ${}^3_\Sigma\text{He}$ state subsequently interacts with a second nucleon, and it is converted to a Λ via the $\Sigma N \rightarrow \Lambda N$ processes inducing $2N$ -nuclear breakup due to the mass difference $m_\Sigma - m_\Lambda \simeq 70$ MeV. We confirm that a pole of the quasibound state ${}^3_\Sigma\text{He}$ with $S=1/2$, $T=1$ resides on the second Riemann sheet in the Σ channel, and gives rise to a resonance in the Λ channel. The pole position corresponds to a complex eigenvalue of the $2N$ - Y system on the complex energy plane. This complex eigenvalue represents

$$E_{\Sigma^+}^{(pole)}({}^3_\Sigma\text{He}) = +1.2 - i 3.1 \text{ MeV} \quad (7)$$

for NF_S , where the real part of $E_{\Sigma^+}^{(pole)}$ is measured from the $d+\Sigma^+$ threshold, and its width becomes $\Gamma = 6.2$ MeV.

On the other hand, the (K^-, π^+) reaction on a nuclear target seems to be appropriate to search a bound state in the Σ bound region. The reason is because (1) this reaction can only populate a Σ^- configuration in final states by the double-charge exchange reaction, so that the contribution of a Λ can be removed out from the π^+ spectrum, and (2) it has a substitutional mechanism under the near-recoilless condition so as to produce ${}^3_\Sigma n$ which belongs to a $S=1/2$ isotriplet state from the ${}^3\text{He}$ target, as well as ${}^3_\Sigma\text{He}$. Therefore, we often expect that a signal of the corresponding peak can be clearly observed in the π^+ spectrum, rather than the π^- one.

Figure ?? shows the calculated spectrum of the ${}^3\text{He}(K^-, \pi^+)$ reaction at 600 MeV/c (4°), together with the experimental data from BNL-E774 [?]. However, we find that no enhancement below the $d+\Sigma^-$ threshold is observed in the π^+ spectrum although there exists a quasibound state in ${}^3_\Sigma n$. The shape of the calculated spectrum seems to agree with that of the E774 data [?].

In order to understand the behavior of the π^+ spectrum, we discuss interference effects among configurations of the NN core states in the Σ production amplitude, because the $2N$ - Y potential should admix 1S_0 and 3S_1 states in the NN pair [?],

depending on the nature of the ΣN potential. We get the production amplitude as

$$\begin{aligned} & \langle (\Sigma NN)^0 \pi^+ | T | {}^3\text{He} K^- \rangle \\ & \simeq \bar{f}_{\pi^+ \Sigma^-} \left(\frac{1}{2} \langle T = 2 | {}^3\text{He} \rangle + \frac{2\sqrt{3} - \sqrt{2}}{4} \langle {}^3_{\Sigma} n | {}^3\text{He} \rangle + \frac{2\sqrt{3} + \sqrt{2}}{4} \langle {}^3_{\Sigma} n^* | {}^3\text{He} \rangle \right), \quad (8) \end{aligned}$$

where $|{}^3_{\Sigma} n\rangle = \alpha |T = 1^{(s)}\rangle + \beta |T = 1^{(t)}\rangle$ as a ground state of $(\Sigma NN)^0$. Here we assumed $\alpha = -\beta = 1/\sqrt{2}$ for simplicity [?]. We find that a cross section for ${}^3_{\Sigma} n$ as a ground state is relatively reduced by a factor $(2\sqrt{3} - \sqrt{2})/4 = 0.51$, whereas that for ${}^3_{\Sigma} n^*$ as an excited state is enhanced by a factor $(2\sqrt{3} + \sqrt{2})/4 = 1.22$. This mechanism is inevitable whenever we consider the ${}^3\text{He}(K^-, \pi^+)$ reaction, and it gives a similar spectrum to the E774 data, as seen in Fig. ??.

4 Summary

We theoretically have demonstrated the inclusive and semiexclusive spectra in the ${}^3\text{He}(K^-, \pi^\mp)$ reactions at 600 MeV/c (4°) within the DWIA, using the coupled $(2N-\Lambda) + (2N-\Sigma)$ model with the spreading potential. The effective $2N-Y$ potential derived from the KAT theory has a strong spin-isospin dependence, and gives us quasibound states with $S=1/2$, $T=1$ (${}^3_{\Sigma}\text{He}$, ${}^3_{\Sigma}\text{H}$, ${}^3_{\Sigma}n$). Our result shows that a signal of the ${}^3_{\Sigma}\text{He}$ quasibound state is clearly observed near the Σ threshold in the π^- spectrum, whereas a peak of the ${}^3_{\Sigma}n$ quasibound state is relatively reduced in the π^+ spectrum because of the admixture of the 1S_0 and 3S_1 states in the NN pair, as seen in the BNL-E774 data. We believe that the π^- and π^+ spectra on the ${}^3\text{He}$ target provide valuable information on properties of ΣNN quasibound states so as to study ΣN interaction. This investigation is in progress.

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