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# Production spectra of the $\Sigma NN$ 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  $(2N \cdot A) + (2N \cdot \Sigma)$  model with a spreading potential. It is shown that a signal of a  ${}^{3}_{\Sigma}\text{He}$  quasibound state is clearly observed near the  $\Sigma$  threshold in the  $\pi^{-}$  spectrum, whereas a peak of a  ${}^{3}_{\Sigma}$ n quasibound state is relatively reduced in the  $\pi^{+}$  spectrum. The mechanism of  $\Sigma$  production for these spectra is discussed.

Keywords Sigma hypernuclei  $\cdot$  Quasibound states  $\cdot$  Production

### 1 Introduction

One of the most important subjects on strangeness nuclear physics is to understand properties of a  $\Sigma$  hyperon in nuclei as well as the nature of  $\Sigma N$  interaction, e.g., the  $\Sigma^-$  hyperon is expected to play an essential role in the description of neutron stars [?]. Many efforts for  $\Sigma$  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  $\Sigma$  nuclear state [?], except  ${}^4_{\Sigma}$ He, which is established to be a quasibound (or unstable bound) state experimentally [?,?], as predicted by Ref. [?]. Moreover, Saha *et al.* [?] reported that the  $\Sigma$ -nucleus potential has a strong repulsion in the real part with a sizable imaginary part, analyzing nuclear  $(\pi^-, K^+)$  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 <sup>3</sup>He target

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

On the other hand, several theoretical predictions [?,?,?] have suggested a possible candidate of a  $\Sigma NN$  quasibound state: Koike and Harada [?] found that there are  $\Sigma NN$  quasibound states with S=1/2, T=1 ( ${}_{\Sigma}^{3}$ He,  ${}_{\Sigma}^{3}$ H and  ${}_{\Sigma}^{3}$ n) due to the coupling through the  $\Sigma N$  potential which strongly admixes  ${}^{1}S_{0}$ , I=1 and  ${}^{3}S_{1}$ , I=0 states in the NN pair. Recently, Garcilazo *et al.* [?] showed that a narrow  $\Sigma NN$  quasibound state exists near  $\Sigma$  threshold in the S=1/2, T=1 channel by  $ANN-\Sigma NN$  Faddeev calculations. However, it has long been recognized that there is no evidence of a narrow structure for the  $\Sigma NN$  quasibound state ( ${}_{\Sigma}^{3}$ n) below the  $\Sigma$  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  $\Sigma NN$  systems?

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

## 2 Calculations

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

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

for the  $\pi^-$  spectrum, and those as

$$\Psi({}^{3}_{Y}\mathbf{n}) = \phi(\{nn\})\varphi_{\Lambda} + \phi([pn])\varphi_{\Sigma^{-}}^{(t)} + \phi(\{pn\})\varphi_{\Sigma^{-}}^{(s)} + \phi(\{nn\})\varphi_{\Sigma^{0}}, \qquad (2)$$

for the  $\pi^+$  spectrum. Here  $\phi(\{N_1N_2\})$  and  $\phi([N_1N_2])$  denote the 2N wavefunctions with  ${}^1S_0$ , I=1 and  ${}^3S_1$ , I=0 state, respectively, and  $\varphi_A$ ,  $\varphi_{\Sigma^{\pm}}^{(t,s)}$  and  $\varphi_{\Sigma^0}$  denote relative wavefunctions between 2N and Y (= $\Lambda$ ,  $\Sigma^{\pm}$  or  $\Sigma^0$ ), 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

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

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 Es and  $k_f$  parameters, so that we can reproduce the binding energies of  $B_A^{\text{exp}}(^3_A\text{H}) = 0.13$  MeV in experimental data



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

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

Figure ?? displays real parts of the effective 2N-Y potential  $\hat{U}_{cc'}(R)$  for  ${}^{3}_{Y}$ He $(J^{\pi} = 1/2^{+})$  at  $E_{A} = 70$  MeV which corresponds to the  $\Sigma$  threshold region, as a function of a relative distance R between 2N and Y. Here we used the Nijmegen model F simulated (NF<sub>S</sub>) 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  $\Sigma N$  potential has a strong spin-isospin dependence, as suggested by recent YN potential models [?].

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

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

where  $\hat{G}(\omega)$  is the complete Green's function for the 2N-Y system, and  $\beta$  is a kinematical factor for the translation from  $K^-$ -N to  $K^-$ - $^3$ He systems. The production function is written by  $F_c = \overline{f}_{\pi Y}(\chi_{\pi}^{(-)})^* \chi_{K^-}^{(+)} \langle \phi(c) | \Psi_A \rangle$ , where  $\overline{f}_{\pi Y}$  is a Fermi-averaged amplitude for  $K^- N \to \pi Y$  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 *NNA*, *NN* $\Sigma$  and *A*- $\Sigma$  conversion.

the help of the eikonal approximation, and  $\langle \phi(c) | \Psi_A \rangle$  is a wave function for a struck nucleon in the <sup>3</sup>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

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

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

$$Im\hat{G}(\omega) = \hat{\Omega}^{(-)\dagger} \{ Im\hat{G}_{\Lambda}^{(0)}(\omega) \} \hat{\Omega}^{(-)} + \hat{\Omega}^{(-)\dagger} \{ Im\hat{G}_{\Sigma^{\pm}}^{(0)}(\omega) \} \hat{\Omega}^{(-)} + \hat{\Omega}^{(-)\dagger} \{ Im\hat{G}_{\Sigma^{0}}^{(0)}(\omega) \} \hat{\Omega}^{(-)} + \hat{G}(\omega) \{ Im\hat{U} \} \hat{G}(\omega),$$
(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 ppA,  $d\Sigma^{+}$ ,  $pn\Sigma^{+}$ ,  $pp\Sigma^{0}$  and  $\Lambda$ - $\Sigma$  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  $\pi^{-}$  spectrum is connected with dominance of the secondary process  $[{}^{3}_{\Sigma}\text{He}] \rightarrow ppA$ , where



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

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

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

for NF<sub>S</sub>, 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  $(K^-, \pi^+)$  reaction on a nuclear target seems to be appropriate to search a bound state in the  $\Sigma$  bound region. The reason is because (1) this reaction can only populate a  $\Sigma^-$  configuration in final states by the double-charge exchange reaction, so that the contribution of a  $\Lambda$  can be removed out from the  $\pi^+$  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 <sup>3</sup>He target, as well as  $^3_{\Sigma}$ He. Therefore, we often expect that a signal of the corresponding peak can be clearly observed in the  $\pi^+$  spectrum, rather than the  $\pi^-$  one.

Figure ?? shows the calculated spectrum of the  ${}^{3}\text{He}(K^{-}, \pi^{+})$  reaction at 600 MeV/c (4°), together with the experimental data form BNL-E774 [?]. However, we find that no enhancement below the  $d+\Sigma^{-}$  threshold is observed in the  $\pi^{+}$  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  $\pi^+$  spectrum, we discuss interference effects among configurations of the NN core states in the  $\Sigma$  production amplitude, because the 2N-Y potential should admix  ${}^{1}S_{0}$  and  ${}^{3}S_{1}$  states in the NN pair [?],

depending on the nature of the  $\Sigma N$  potential. We get the production amplitude as

$$\langle (\Sigma NN)^0 \pi^+ |T|^3 \mathrm{He}K^- \rangle$$

$$\simeq \overline{f}_{\pi^+ \Sigma^-} \Big( \frac{1}{2} \langle T = 2|^3 \mathrm{He} \rangle + \frac{2\sqrt{3} - \sqrt{2}}{4} \langle_{\Sigma}^3 n|^3 \mathrm{He} \rangle + \frac{2\sqrt{3} + \sqrt{2}}{4} \langle_{\Sigma}^3 n^*|^3 \mathrm{He} \rangle \Big), \quad (8)$$

where  $|_{\Sigma}^{3}n\rangle = \alpha |T = 1^{(s)}\rangle + \beta |T = 1^{(t)}\rangle$  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  $\frac{3}{\Sigma}n$  as a ground state is relatively reduced by a factor  $(2\sqrt{3} - \sqrt{2})/4 = 0.51$ , whereas that for  ${}_{\Sigma}^{3}n^{*}$  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 ( ${}^{3}_{\Sigma}$ He,  ${}^{3}_{\Sigma}$ H,  ${}^{3}_{\Sigma}$ n). Our result shows that a signal of the  ${}^{3}_{\Sigma}$ He quasibound state is clearly observed near the  $\varSigma$  threshold in the  $\pi^-$  spectrum, whereas a peak of the  $\frac{3}{\Sigma}$ n quasibound state is relatively reduced in the  $\pi^+$  spectrum because of the admixture of the  ${}^{1}S_{0}$  and  ${}^{3}S_{1}$  states in the NN pair, as seen in the BNL-E774 data. We believe that the  $\pi^-$  and  $\pi^+$  spectra on the <sup>3</sup>He target provide valuable information on properties of  $\varSigma NN$  quasibound states so as to study  $\varSigma N$  interaction. This investigation is in progress.

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