Production of ΣNN quasibound states

Toru Harada

Osaka Electro-Communication University/
J-PARC Branch, KEK Theory Center, IPNS, KEK
Various effects on the hyperon mixing
Related to the 3BF in nuclei

Keyword: Hyperon-mixing
Important role of $\Sigma$ hyperons in nuclear matter

$\Lambda NN$ 3BF
There exist unstable bound (quasibound) states of $S=1/2$, $T=1$ ($\Sigma^3H$, $\Sigma^3He$, $\Sigma^3n$), due to the coupling through the $\Sigma N$ potential which strongly admixtures $^3S_1$, $T_{NN}=0$ and $^1S_0$, $T_{NN}=1$ states in the NN pair.

This suggests that a certain class of $\Lambda N-\Sigma N$ potentials we can form a $\Sigma$ hypertriton with a width of about 8 MeV.

There exist unstable bound (quasibound) states of $S=1/2$, $T=1$ ($\Sigma^3H$, $\Sigma^3He$, $\Sigma^3n$), due to the coupling through the $\Sigma N$ potential which strongly admixtures $^3S_1$, $T_{NN}=0$ and $^1S_0$, $T_{NN}=1$ states in the NN pair.

We find that the $\Sigma NN$ system has a quasibound state in the $(I,J)=(1,1/2)$ channel very near threshold with a width of about 2.1 MeV.
Our Purpose

• We demonstrate the inclusive and semi-exclusive spectra in the $^3\text{He}(K^-,\pi^\mp)$ reactions theoretically within a distorted-wave impulse approximation by using a coupled $(2N-\Lambda)+(2N-\Sigma)$ model with a spreading potential.

• *Is there a quasibound in $\Sigma NN$ systems?*

I will focus on
(1) the structure of the $\Sigma NN$ quasibound states,
(2) the $\Sigma NN$ signal appeared in the $\pi^-$ and $\pi^+$ spectra,
(3) an important role of the channel coupling in $\Sigma NN$.

*Keyword: Hyperon-mixing*
Outline

1. Σ hyperon in nuclei (Introduction)

2. Calculations
   - Microscopic Y-(2N) folding-model potential
   - ΣNN quasibound states $^3\Sigma\text{He}, \ ^3\Sigma\text{H}, \ ^3\Sigma\text{n}$
   - Production within DWIA $(K^-, \pi^-), (K^-, \pi^+)$ reactions

3. Results and Discussion
   - $\pi^-$ and $\pi^+$ spectra for the ΣNN quasibound states $^3\Sigma\text{He}, \ ^3\Sigma\text{n}$
   - no peak of the $\pi^+$ spectrum in BNL-E774 data

4. Summary
1. $\Sigma$ hyperon in nuclei
   (Introduction)
Study of a $\Sigma$-hyperon in Nuclei (1)

- Neutron star core
  = “An interesting neutron-rich hypernuclear system”


NS cooling processes
(Direct/Modified Uruca)

$\Lambda \rightarrow p + e^- + \bar{\nu}_e$
$\Sigma^- \rightarrow \Lambda + e^- + \bar{\nu}_e$

Behavior of $\Sigma^-$ hyperon in nuclear medium is very important to understand properties of Neutron star core.
Study of a $\Sigma$-hyperon in Nuclei (2)

- Batty-Gal-Toker, NPA402(1983)349: the earlier analysis
  Attractive in the real part of $\Sigma$-potential (−27 MeV)

Analysis of the shifts and widths of the $\Sigma^-$ atomic X-ray data

- Only 23 measurements !!

Repulsion inside the nucleus and shallow attraction outside the nucleus

Due to the insufficient quality of the these data, the potential is not so sensitive to the radial behavior of $U_\Sigma$ inside the nucleus.
Study of a $\Sigma$-hyperon in Nuclei (3)

- DWIA analysis of the ($\pi^-, K^+$) inclusive spectra


$28\text{Si}$

This analysis suggests that the $\Sigma$-nucleus potential has a repulsion with a sizable imaginary.

Woods-Saxon form

$$U_\Sigma = \frac{V_\Sigma + iW_\Sigma}{1 + \exp[(r - R)/a]}$$

$(V, W) = (+90 \text{ MeV}, -40 \text{MeV})$
Inclusive spectrum in $^{28}\text{Si}(\pi^{-}, K^+)$ reaction at 1.2GeV/c


$(V_{\Sigma}, W_{\Sigma}) = (+30, -40)$ MeV by $\chi^2/N$-fitting

T.Harada, Y.Hirabayashi, NPA759 (2005) 143
Short-range repulsive core in baryon-baryon interaction


Spin-flavor SU(6) symmetry


orbital x flavor-spin x color singlet \( L=0 \)

Pauli forbidden state

<table>
<thead>
<tr>
<th>S = 0 state</th>
<th>[51]</th>
<th>[33]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>( \Lambda \Lambda - \Xi N - \Sigma \Sigma (I=0) ), H-dibaryon</td>
</tr>
<tr>
<td>8(_S)</td>
<td>1</td>
<td>( \Sigma N(I=1/2, {^1S_0}) ) Pauli forbidden</td>
</tr>
<tr>
<td>27</td>
<td>4/9</td>
<td>5/9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>S = 1 state</th>
<th>[51]</th>
<th>[33]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8(_A)</td>
<td>5/9</td>
<td>4/9</td>
</tr>
<tr>
<td>10</td>
<td>8/9</td>
<td>1/9</td>
</tr>
<tr>
<td>10(^*)</td>
<td>4/9</td>
<td>5/9</td>
</tr>
</tbody>
</table>

\( SU(6) \) symm. \( \Rightarrow \) Strongly spin-isospin dependence
\[ \Sigma N \text{ threshold cusp } (I=1/2, ^3S_1) \text{ in } K^-d \to \pi^-\Lambda p \text{ Reactions} \]

\[ \Sigma^+n \text{ threshold-cusp} \]

**In Flight**

```
ΣN \(^3S_1\) [10*]:
"Strangeness partner of deuteron"
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```
R.H. Dalitz, A. Deloff,
```

```
Y. Ichikawa et al.,
PTEP2014, 101D03
```

**At Rest**

```
T.H. Tan,
```

```
d(\pi^+, K^+) \n```

```
\Sigma^+n \n```

```
MM_d [GeV/c^2]
```

```
2.1 2.12 2.14 2.16
```
Two-body $\Sigma N$ potentials in free space

Effective Sigma-nucleon (absorptive) potential: SAP

S-matrix equivalent to Nijmegen model-D (model-F)

- $T=3/2$
  - Attractive $^3S_1$
  - Repulsive $^1S_0$

- $T=1/2$
  - Attractive $^3S_1$
  - Repulsive $^1S_0$

- Strong absorption $\Sigma N \rightarrow \Lambda N$ conv.

There is strong spin-isospin dependence in $\Sigma N$ potential.
Observation of a $^4\Sigma$ He Bound State

$B_{\Sigma^+} = 4.4 \pm 0.3$ MeV
$\Gamma = 7 \pm 0.7$ MeV
$J^\pi = 0^+\ T \simeq 1/2$


BBBB (T=1/2,S=0) [28*]:
“Strangeness partner of $\alpha$-particle”

$\Sigma$-3N potentials


Theoretical calculation
Baryon-Baryon force in SU(3) basis from lattice QCD


\[ [8] \otimes [8] = [27] \oplus [8_s] \oplus [1] \oplus [10^*] \oplus [10] \oplus [8_a] \]
2. Calculations
(ΣNN quasibound state and its production)
Y-2N folding-model potentials
**Microscopic (2N)-Y folding-model potentials**

\[
U_{\alpha\alpha'}(R) = \int \rho_{\alpha\alpha'}(r) \left( \bar{g}_{\alpha\alpha'}(r_1) + \bar{g}_{\alpha\alpha'}(r_2) \right) dr.
\]

**Nucleon or transition density for NN (CDCC)**

\[
\rho_{\alpha\alpha'}(r) = \langle \phi^{(2N)}_{\alpha} | \sum_i \delta(r - r_i) | \phi^{(2N)}_{\alpha'} \rangle
\]

**Coupled Bethe-Goldstone eq.**

\[
\begin{bmatrix}
\Psi_\Lambda \\
\Psi_\Sigma
\end{bmatrix} =
\begin{bmatrix}
\Phi_\Lambda \\
0
\end{bmatrix}
+ \frac{Q}{e} \nu
\begin{bmatrix}
\Psi_\Lambda \\
\Psi_\Sigma
\end{bmatrix}
\]
Microscopic Y-(2N) folding-model potentials

- The channel coupling is important to describe the YNN systems.

The channel coupling is important to describe the YNN systems.
ΣNN quasibound states

\[ \Sigma^3 \text{He}, \Sigma^3 \text{H}, \Sigma^3 \text{n} \]

\( (T = 1, S = 1/2) \)

\( (T = 1, S = \frac{3}{2}) \quad (T = 0, 2, S = \frac{1}{2}, \frac{3}{2}) \) repulsive

Energies and widths of $\Sigma NN$ ($S=1/2$, $T=1$)

\[ T = 1, T_Z = +1, S = 1/2 \]

\[ (T = 1, T_Z = -1, S = 1/2) \]

\[ \exp(ik_{\Sigma^+}R) = \exp(\text{i}Re k_{\Sigma^+}R) \exp(-\text{Im} k_{\Sigma^+}R) \rightarrow 0 \] (quasibound state)

<table>
<thead>
<tr>
<th>$(J^\pi, T)$</th>
<th>$E_\Lambda$ (MeV)</th>
<th>$E_{\Sigma^\pm}$ (MeV)</th>
<th>$E_{\Sigma^0}$ (MeV)</th>
<th>$\Gamma_{\Sigma}$ (MeV)</th>
<th>$k_{\Sigma^\pm}$ (fm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3\Sigma\text{He}$ $(1/2^+, 1)$</td>
<td>73.7</td>
<td>0.96$^a$</td>
<td>-3.24</td>
<td>9.0</td>
<td>-0.322 + i0.260</td>
</tr>
<tr>
<td>$^3\Sigma n$ $(1/2^+, 1)$</td>
<td>76.4</td>
<td>-1.87$^b$</td>
<td>-0.58</td>
<td>10.5</td>
<td>-0.263 + i0.374</td>
</tr>
</tbody>
</table>
Hyperon mixing probabilities of the $\Sigma$NN states

<table>
<thead>
<tr>
<th>States</th>
<th>Components</th>
<th>Probabilities (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3\Sigma$He</td>
<td>${pp}\Lambda\ (T = 1)$</td>
<td>2.07</td>
</tr>
<tr>
<td></td>
<td>$[pn]\Sigma^+$</td>
<td>54.9</td>
</tr>
<tr>
<td></td>
<td>${pn}\Sigma^+$</td>
<td>24.7</td>
</tr>
<tr>
<td></td>
<td>${pp}\Sigma^0$</td>
<td>18.3</td>
</tr>
<tr>
<td>${N_1,N_2} = N_1N_2 + N_2N_1 : ^1S_0$</td>
<td>$T = 1\ (I_2 = 0, S_2 = 1)$</td>
<td>54.9</td>
</tr>
<tr>
<td>$[N_1,N_2] = N_1N_2 - N_2N_1 : ^3S_1$</td>
<td>$T = 1\ (I_2 = 1, S_2 = 0)$</td>
<td>42.5</td>
</tr>
<tr>
<td></td>
<td>$T = 2$</td>
<td>0.45</td>
</tr>
<tr>
<td>$^3\Sigma n$</td>
<td>${nn}\Lambda\ (T = 1)$</td>
<td>2.42</td>
</tr>
<tr>
<td></td>
<td>$[pn]\Sigma^-$</td>
<td>39.5</td>
</tr>
<tr>
<td></td>
<td>${pn}\Sigma^-$</td>
<td>20.9</td>
</tr>
<tr>
<td></td>
<td>${nn}\Sigma^0$</td>
<td>37.2</td>
</tr>
<tr>
<td></td>
<td>$T = 1\ (I_2 = 0, S_2 = 1)$</td>
<td>39.5</td>
</tr>
<tr>
<td></td>
<td>$T = 1\ (I_2 = 1, S_2 = 0)$</td>
<td>56.0</td>
</tr>
<tr>
<td></td>
<td>$T = 2$</td>
<td>2.10</td>
</tr>
</tbody>
</table>
Production by $K^-$ beam from $^3$He targets

$\Delta Q$ (MeV)

- $p+p+\Sigma^0$
- $p+n+\Sigma^0$
- $d+\Sigma^+$
- $n+n+\Sigma^+$
- $d+\Sigma^0$
- $n+n+\Sigma^0$
- $d+\Sigma^-$
- $n+n+\Sigma^0$
- $d+\Sigma^-$

$^3\Sigma_{He}$

$^3\Sigma_{He}^*$

$^3\Sigma_{H}$

$^3\Sigma_{n}$

$\sim 72$ MeV

$\sim 75$ MeV

$\sim 77$ MeV

$(K^-, \pi^0)$

$(K^-, \pi^-)$

$(K^-, \pi^+)$

SCX

DCX

$^3$He

$72$ MeV

$75$ MeV

$77$ MeV
Distorted-wave impulse approximation (DWIA)

$^3\text{He} \rightarrow (K^-, \pi^-)$
Double differential cross sections within the DWIA

\[
\frac{d^2\sigma}{dE_\pi d\Omega_\pi} = \beta \frac{1}{[J_A]} \sum_{M_A} \sum_{B} |\langle \Psi_B | \hat{F} | \Psi_A \rangle|^2 \delta(E_\pi + E_B - E_K - E_A)
\]

Production operators with zero-range interaction

\[
\hat{F} = \int dr \chi_{\pi}^{(-)*}(p_\pi, r)\chi_K^{(+)}(p_K, r) \sum_{j=1}^{A} \tilde{f}(Y_\pi)(\omega_{KN})\delta(r - r_j) \hat{O}_j
\]

Mesons distorted-waves

Momentum and energy transfer

\[
q = p_K - p_\pi, \quad \omega = E_K - E_\pi,
\]

Kinematical factor

\[
\beta = \left(1 + \frac{E_\pi^{(0)}}{E_Y^{(0)}} \frac{p_\pi^{(0)}}{p_K^{(0)}} \cos \theta_{lab} \right) \frac{p_\pi E_\pi}{p_\pi^{(0)} E_\pi^{(0)}}
\]

Transition-amplitude for $K^-N \rightarrow \pi Y$. 
Wavefunction of the initial state for a 3He target nucleus

\[ |\Psi_A\rangle = \hat{A} \left[ \left[ \phi_0^{(2N)} \otimes \varphi_0^{(N)} \right]_{L_A} \otimes X^A_{T_A,S_A} \right]_{J_A}^{M_A}, \]

\[ X^A_{T_A,S_A} = [\chi_{I_2,S_2}^{(2N)} \otimes \chi_{1/2,1/2}^{(N)}]_{1/2,1/2}, \]

Wavefunctions of final states for ppY

\[ |\Psi_B\rangle = \sum_{\alpha} \left[ \left[ \phi_\alpha^{(2N)} \otimes \varphi_Y^{(Y)} \right]_{L_B} \otimes X^B_{Y_\alpha,S_\alpha} \right]_{J_B}^{M_B}, \]

\[ X^B_{Y_\alpha,S_\alpha} = [\chi_{I_2,S_2}^{(2N)} \otimes \chi_{I_Y,1/2}^{(Y)}]_{Y_\alpha,S_\alpha}, \]

Continuum-discretized coupled-channel (CDCC) w.f.

\[ \tilde{\phi}_{\alpha,i}^{(2N)}(r) = \frac{1}{\sqrt{\Delta k}} \int_{k_i}^{k_{i+1}} \phi_\alpha^{(2N)}(k, r) \, dk, \]

The momentum bin method for the pp-systems

\[ (T_\alpha + v_{\alpha}^{(NN)}(r) - \varepsilon_\alpha) \phi_\alpha^{(2N)}(k, r) = 0 \]
Fermi-averaged amplitude for $K^- N \rightarrow \pi Y$ elementary processes.

$600 \text{ MeV/c}$
Multichannel Green’s function \((N \times N)\)

\[
\sum_B |\Psi_B\rangle \langle \Psi_B| \delta(E - E_B) = -\frac{1}{\pi} \text{Im}\hat{G}(E).
\]

Inclusive spectra for the production cross sections

\[
\frac{d^2\sigma}{dE_\pi d\Omega_\pi} = \beta \frac{1}{[J_A]} \sum_{M_A} S_{\pi}, \quad S_{\pi} = -\frac{1}{\pi} \text{Im}\langle F|\hat{G}(E)|F\rangle,
\]

For \(3\text{He}(K^-,\pi^-)\) reactions

\[
\text{Im}\hat{G} = \hat{\Omega}^{(-)\dagger}(\text{Im}\hat{G}^{(0)})\hat{\Omega}^{(-)} + \hat{G}^{\dagger}(\text{Im}\hat{U})\hat{G},
\]

\[
S_{\pi-} = S_{\pi-}^{\{pp\}A} + S_{\pi-}^{[pn]\Sigma^+} + S_{\pi-}^{\{pn\}\Sigma^+} + S_{\pi-}^{\{pp\}\Sigma^0} + S_{\pi-}^{(\text{Conv})} \quad (4 \times 4)
\]

\[
S_{\pi}^\alpha = -\frac{1}{\pi} \langle F|\hat{\Omega}^{(-)\dagger}(\text{Im}\hat{G}_\alpha^{(0)})\hat{\Omega}^{(-)}|F\rangle
\]

\[
S_{\pi}^{(\text{Conv})} = -\frac{1}{\pi} \sum_{\alpha'\alpha} \langle F|\hat{G}_\alpha^{\dagger}W_{\alpha\alpha'}\hat{G}_{\alpha'}|F\rangle
\]

For \(3\text{He}(K^-,\pi^+)\) reactions

\[
S_{\pi^+} = S_{\pi^+}^{[pn]\Sigma^-} + S_{\pi^+}^{\{pn\}\Sigma^-} + S_{\pi^+}^{\{nn\}\Sigma^0} + S_{\pi^+}^{(\text{Conv})} \quad (4 \times 4)
\]
**Multichannels Green’s functions**

**Complete Green’s function**

\[
\hat{G}(E_f) = \hat{G}^{(0)}(E_f) + \hat{G}^{(0)}(E_f)\hat{U}\hat{G}(E_f)
\]

\[
\hat{G}^{(0)}(E_f) = \begin{bmatrix}
G_{\lambda_0}^{(0)} \\
G_{\lambda_1}^{(0)} \\
\vdots \\
G_{\lambda_N}^{(0)}
\end{bmatrix}, \quad \hat{U} = \begin{bmatrix}
U_{0,0} & U_{0,1} & \cdots & U_{0,N} \\
U_{1,0} & U_{1,1} & \cdots & \vdots \\
\vdots & \vdots & \ddots & \vdots \\
U_{N,0} & \cdots & \cdots & U_{N,N}
\end{bmatrix}
\]

**Green’s function method**

\[\sum_B |\Psi_B\rangle \langle \Psi_B| \delta(E - E_B) = -\frac{1}{\pi} \text{Im} \hat{G}(E)\]

**Strength function**

\[S(E_B) = \sum_B \left| \langle \Psi_B| \hat{F}|\Psi_A\rangle \right|^2 \delta(E_\pi + E_B - E_K - E_A)\]

\[= (-)^{1/\pi} \text{Im} \sum_{\alpha\alpha'} \int d\mathbf{R}d\mathbf{R}' F^\dagger_\alpha(\mathbf{R}) G_{\alpha\alpha'}(E_B; \mathbf{R}, \mathbf{R}') F^\_\alpha(\mathbf{R}')\]

T. Harada, NPA672(2000)181

Morimatsu, Yazaki, NPA483(1988)493
3. Results and Discussion
Inclusive spectrum in $^3\text{He}(K^-,\pi^-)$ reactions at 600MeV/c
Inclusive spectrum in $^3$He($K^-,\pi^-$) reactions at 600MeV/c
Inclusive spectrum in $^3\text{He}(K^-,\pi^+)$ reactions at 600MeV/c

Graph showing cross section in units of $\mu\text{b}/\text{sr} \text{ MeV}$ vs $E_{\Sigma^-}$ (MeV)

- $\Sigma^0$ (MeV)
- $\Sigma^-$ (MeV)
- $^3\text{n}$
- $\{nn\}\Sigma^0$
- $\{pn\}\Sigma^-$
- $\{pn\}\Sigma^-$
- $\text{(No peak)}$

Legend: $\pi^+$
Remarks

There is a quasibound in $\Sigma NN$ systems with $J^p = 1/2^+, L = 0, S = 1/2$ state. $\frac{3}{2}^+ \text{He}, \frac{3}{2}^+ \text{H}, \frac{3}{2}^- \text{n}$

The pole is located as

$$\mathcal{E}^{(\text{pole})}_{\Sigma^+} \left( \frac{3}{2} \Sigma \text{He} \right) = +0.96 - i 4.5 \text{ MeV} \quad (K^-, \pi^-)$$

$$\mathcal{E}^{(\text{pole})}_{\Sigma^0} \left( \frac{3}{2} \Sigma \text{n} \right) = -0.58 - i 5.3 \text{ MeV} \quad (K^-, \pi^+)$$

measured from the $d + \Sigma^+$ threshold.

The pole positions reside on the second Riemann sheet $[-+++]$ on the complex $E$ plane.

$$[\text{Im}k_{\{pp\} \Lambda}, \text{Im}k_{\{pn\} \Sigma^+}, \text{Im}k_{\{pn\} \Sigma^+}, \text{Im}k_{\{nn\} \Sigma^0}]$$
**Inclusive spectrum by \(^3\text{He}(K^-,\pi^+)\) reactions at 600MeV/c**

BNL-E774: Barakat, Hungerford, NPA547(1992)157c

"There is no evidence for a state below \(\Sigma\)-d threshold."

- Why can we see no peak of the \(^3\Sigma n\) quasibound state?
Production cross sections on $^3\text{He}(K^-,\pi^\pm)$ reactions

Dover and Gal, PLB110(1982)433

Table 2
Production cross sections on $^3\text{He}$ and width quenching factors $Q$ for states in $^3\Sigma$He and $^3\Sigma$ of spin $S$, isospin $I$ and core isospin $T$ ($I = 0$ production is forbidden, since $I_3 = \pm 1$).

<table>
<thead>
<tr>
<th>$I(T)$</th>
<th>$S$</th>
<th>$Q$</th>
<th>$\sigma(K^-,\pi^-)$</th>
<th>$\pi^-$</th>
<th>$\sigma(K^-,\pi^+)$</th>
<th>$\pi^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0(1)</td>
<td>1/2</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\Sigma[\text{pn}]$ →</td>
<td>1(0)</td>
<td>1/2</td>
<td>1/3 $3/2</td>
<td>f_p \rightarrow \Sigma^+$</td>
<td></td>
<td>$3/2</td>
</tr>
<tr>
<td>1(0)</td>
<td>3/2</td>
<td>4/3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\Sigma{\text{pn}}$ →</td>
<td>1(1)</td>
<td>1/2</td>
<td>2 $1/2</td>
<td>f_n \rightarrow \Sigma^0 + 1/\sqrt{2} f_p \rightarrow \Sigma^+$</td>
<td></td>
<td>$1/4</td>
</tr>
<tr>
<td>2(1)</td>
<td>1/2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Because $\Sigma[\text{pn}]$ and $\Sigma\{\text{pn}\}$ states couple each other, we must take into account the coupling effects in the $^3\text{He}(K^-,\pi^+)$ reaction.
Interference between $K^-N-\pi Y$ amplitudes in the spectra (I)

For $^3\text{He}(K^-,\pi^-)$ reactions

\[ T^{(K^-,\pi^-)} \simeq f_{\Sigma^0} \langle \{pp\} \Sigma^0 | ^3\text{He} \rangle + f_{\Sigma^+} \langle \{pn\} \Sigma^+ | ^3\text{He} \rangle + f_{\Sigma^+} \langle [pn] \Sigma^+ | ^3\text{He} \rangle \]

\[ = \sqrt{\frac{1}{2}} f^{(3/2)} (T = 2 | ^3\text{He} \rangle + \sqrt{\frac{1}{2}} f_s^{(1/2)} (T = 1_s | ^3\text{He} \rangle + \sqrt{\frac{1}{2}} f_t^{(1/2)} (T = 1_t | ^3\text{He} \rangle \]

\[ = \sqrt{\frac{1}{2}} \left\{ \sqrt{\frac{1}{2}} f_{\Sigma^+} - f_{\Sigma^0} \right\} \langle T = 2 | ^3\text{He} \rangle + \left\{ \left( \frac{\sqrt{3} + 1}{2} \right) f_{\Sigma^+} + \frac{1}{2} f_{\Sigma^0} \right\} \langle T = 1^- | ^3\text{He} \rangle \]

most attractive

$^3\Sigma\text{He}$ g.s.

\[ + \left\{ \left( \frac{\sqrt{3} - 1}{2} \right) f_{\Sigma^+} - \frac{1}{2} f_{\Sigma^0} \right\} \langle T = 1^+ | ^3\text{He} \rangle \]

$^3\Sigma\text{He}^*$

interference between $K^-p \rightarrow \pi^-\Sigma^+$ and $K^-n \rightarrow \pi^-\Sigma^0$ production amplitudes
Interference between K⁻N-πY amplitudes in the spectra (II)

For $^3\text{He}(K^-,\pi^+)$ reactions

$$T^{(K^-,\pi^+)} \simeq f_0 \langle \{nn\} \Sigma^0 | ^3\text{He}\rangle + f_{\Sigma-} \langle \{pn\} \Sigma^- | ^3\text{He}\rangle + f_{\Sigma-} \langle [pn] \Sigma^- | ^3\text{He}\rangle$$

$$= f_{\Sigma-} \left( \frac{1}{2} \langle T = 2 | ^3\text{He}\rangle + \frac{1}{2} \langle T = 1_s | ^3\text{He}\rangle + \sqrt{\frac{3}{2}} \langle T = 1_t | ^3\text{He}\rangle \right)$$

We assume $\langle T = 1^{(-)} \rangle = \frac{1}{\sqrt{2}} \langle T = 1_s \rangle - \frac{1}{\sqrt{2}} \langle T = 1_t \rangle$, but it depends on (2N)-Y pot.

$$= f_{\Sigma-} \left( \frac{1}{2} \langle T = 2 | ^3\text{He}\rangle + \frac{2\sqrt{3}}{4} - \frac{\sqrt{2}}{4} \langle T = 1^{(-)} | ^3\text{He}\rangle \right) \Sigma n_{\text{g.s.}}$$

$$+ \frac{2\sqrt{3}}{4} + \frac{\sqrt{2}}{4} \langle T = 1^{(+)} | ^3\text{He}\rangle \right) \Sigma n^*$$

$\Rightarrow$ This reduction mechanism must appear in $^3\text{He}(K^-,\pi^+)$ reactions!
“There is no evidence for a state below $\Sigma$-d threshold.”

$^3\text{He}(K^-,\pi^+)$ reactions at 600MeV/c

The calculated spectrum is in good agreement with the BNL-E774 data.
Remarks

- The calculated inclusive spectrum of the $^3\text{He}(K^-, \pi^+)$ reaction shows no peak of the $^3\Sigma n$ quasibound state that is located near the $\Sigma$-threshold with the width of 10.5 MeV.

- This spectrum is consistent with the BNL-E774 data.

- The reason is because the interference effects caused by $^3S_1-^1S_0$ admixture in the NN pair for $^3\Sigma n$ and properties of the $\Sigma N$ interactions.
Summary

There is a quasibound in $\Sigma NN$ systems!!

- The coupled-channel framework is very important for calculating the spectra of the $^3$He($K^-,\pi^\mp$) reactions.

  *Keyword: Hyperon-mixing*

- The calculated spectra of the $^3$He($K^-,\pi^+$) reaction may be consistent with the E774 data due to the admixture of the NN core states.

- Both the $\pi^-$ and $\pi^+$ spectra provide valuable information to understand the nature of the $\Sigma NN$ quasibound states and also the $YN$ ($\Sigma N$) interactions.

  To determine a quasibound state [+ −] or cusp state [− +].
Thank you very much for your attention.