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KEK東海キャンパス・東海1号館227号室

^{3}Heを標的にしたハイパー核の生成反応

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Outline

1. Introduction $^{3}_{Y}\mathrm{He}, ^{3}_{Y}\mathrm{H}, ^{3}_{Y}\mathrm{n}$
2. Calculations

   - Production in DWIA **(K^{-}, π^{-}), (K^{-}, π^{+}) reactions**

   - Coupled-channels Green's function calculations

   - Microscopic (2N)-Y folding-model potential

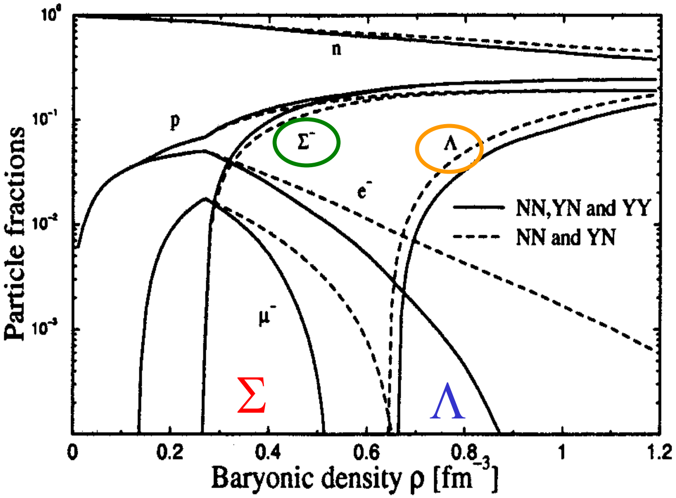
   - YN g-matrix calculation for D2'

3. Results and Discussion $^{3}_{Y}\mathrm{He}$, $^{3}_{Y}\mathrm{n}$
4. Summary

1. Introduction

Study of a Σ-hyperon in Nuclei

➢ Behavior of Σ^- interaction in nuclear medium



Neutron stars = An interesting hypernuclear system

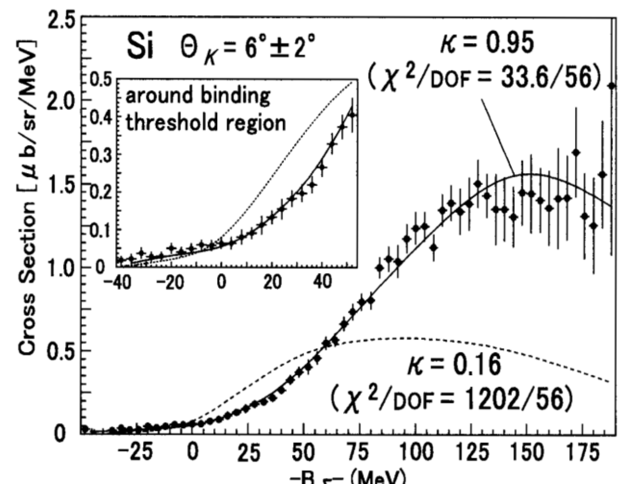
S. Balberg, A. Gal, NPA625(1997)435;
M.Baldo, et al., PRC61(2000)055801
S.Weissenbord, et al., NPA881(2012)62

Strongly related to the nature of Neutron stars core
Negative charged particle: Σ^-, Ξ^-,..
depending on the property of the s.p. potentials

➢ DWIA analysis of the (π^-,K^+) inclusive spectra

H.Noumi, et al. PRL89(2002)072301
P.K.Saha, et al., PRC70(2004)044613

C, Si, Ni, In, Bi



(V, W)=(+90 MeV, –40MeV)

Σ-nucleus potential has a repulsion with a sizable imaginary.

➢ Σ^- atomic data

Repulsion inside the nucleus and shallow attraction outside the nucleus - Batty-Friedman-Gal, PTP.Suppl.117(1994)227

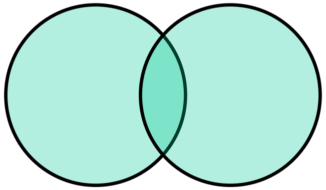
Short-range repulsive core in baryon-baryon intreaction

Quark Cluster Model

M.Oka,K.Shimizu,K.Yazaki, PLB130(1983)365; NPA464(1987)700

Spin-flavor SU(6) symmetry

Quark-exchange
(anti-symmetrized)



symmetric   antisymmetric

$$[3]\otimes[3]=[6]\oplus[42]\oplus[51]\oplus[33]$$

orbital x flavor-spin x color singlet ↓ L=0

Pauli forbidden state

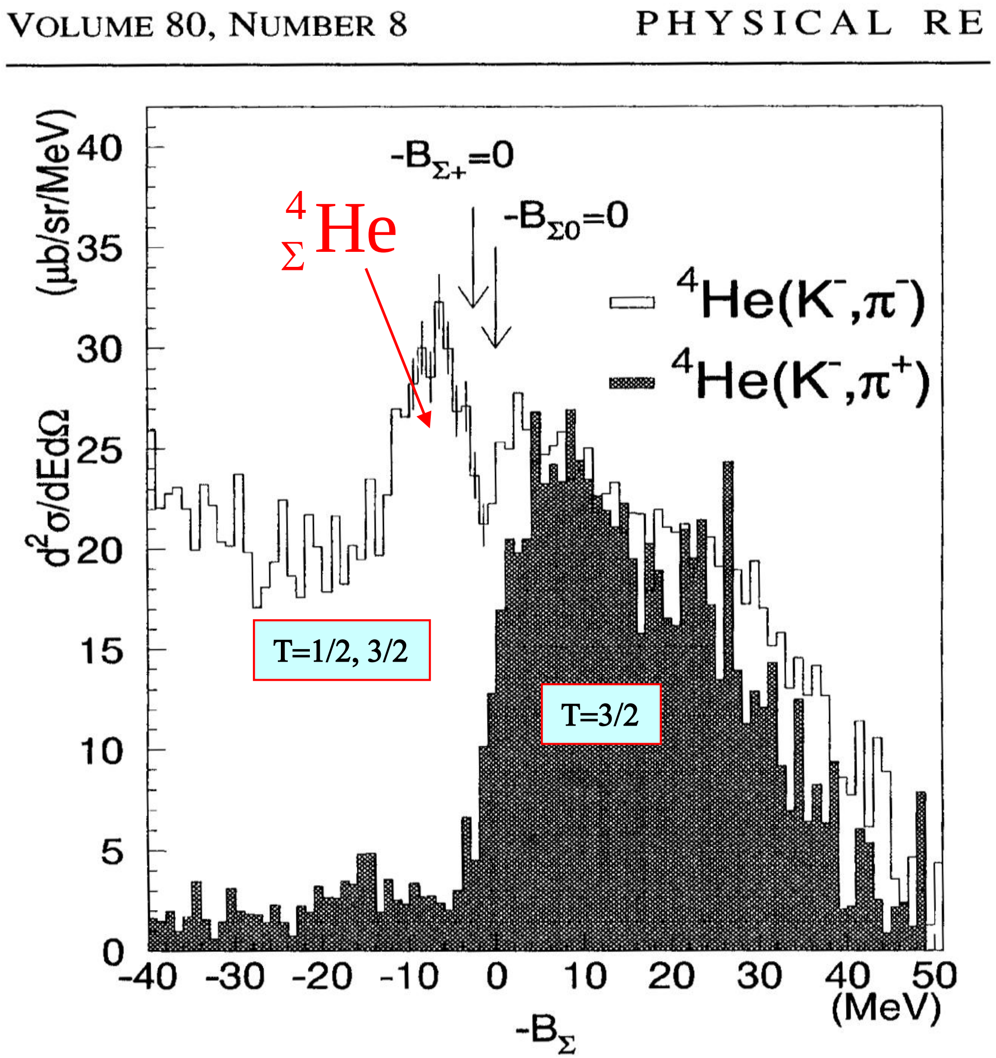
S = 0 state	**[51]**	**[33]**	
1			ΛΛ-ΞN-ΣΣ(I=0), H-dibaryon
$\mathbf{8_S}$	**1**		$\Sigma N(I=1/2,{}^1S_0)$ ***Pauli forbidden***
27	4/9	5/9	$NN({}^1S_0)$

S = 1 state	**[51]**	**[33]**	
$\mathbf{8_A}$	5/9	4/9	
10	**8/9**	1/9	$\Sigma N(I=3/2,{}^3S_1)$ ***almost Pauli forbidden***
10*	4/9	5/9	$NN({}^3S_1)$, ΛN-$\Sigma N(I=1/2,{}^3S_1)$

➢**SU(6) symm. → Strongly spin-isospin dependence**

Observation of a $^{4}_{\Sigma}$He Bound State

BNL-AGS (1995-)



T. Nagae, T. Miyachi, T. Fukuda, H. Outa, T. Tamagawa, J. Nakano, R.S.Hayano, H. Tamura, Y. Shimizu, K. Kubota, R. E. Chrien, R. Sutter, A. Rusek, W. J. Briscoe, R. Sawafta, E.V. Hungerford, A. Empl, W. Naing, C. Neerman, K. Johnston, M. Planinic,

Phys.Rev.Lett. 80(1998)1605.

$$B_{\Sigma^+} = 4.4 \pm 0.3 \text{ MeV}$$

$$\Gamma = 7 \pm 0.7 \text{ MeV}$$

$$T \simeq 1/2$$

$$J^{\pi} = 0^{+}$$

4.6 MeV

7.9 MeV

Theoretical Prediction

T.Harada, S.Shinmura, Y.Akaishi, H.Tanaka, NPA507(1990)715.

A=3, ΣNN

PHYSICAL REVIEW C 47, 1000 (1993)

Resonances in Λd scattering and the Σ hypertriton

I.R. Afnan, B.F. Gibson

Separable pot.+Faddeev calc.

"This suggests that a certain class of ΛN-ΣN potentials we can form a Σ hypertriton with a width of about 8 MeV."

Nuclear Physics A 611 (1996) 461–483

Structure of the $A = 3$ Σ-hypernuclei

Yoshimitsu H. Koike[a,1], Toru Harada[b,c,2]

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

PHYSICAL REVIEW C 76, 034001 (2007)

Λ*NN* and Σ*NN* systems at threshold. II. The effect of *D* waves

H. Garcilazo, A. Valcarce, T. Fernandez-Carames

Chiral constituent quark model pot+ Faddeev calc.

"We find that the ΣNN system has a quasibound state in the (I,J)=(1,1/2) channel very near threshold with a width of about 2.1 MeV. "

The binding energies and widths of ${}_{\Sigma}^{3}$H and ${}_{\Sigma}^{3}$n quasibound states

Y.H.Koike, T.Harada, NPA611(1996)461

$$|{}_{\Sigma}^{3}\mathrm{He}\rangle = \sqrt{0.213}\,|\{pn\}\otimes\Sigma^{+}\rangle + \sqrt{0.622}\,|[pn]\otimes\Sigma^{+}\rangle + \sqrt{0.165}\,|\{pp\}\otimes\Sigma^{0}\rangle$$

$$|{}_{\Sigma}^{3}\mathrm{n}\rangle = \sqrt{0.194}\,|\{nn\}\otimes\Sigma^{0}\rangle + \sqrt{0.522}\,|[pn]\otimes\Sigma^{-}\rangle + \sqrt{0.284}\,|\{pn\}\otimes\Sigma^{-}\rangle$$

	${}_{\Sigma}^{3}$He		${}_{\Sigma}^{3}$n	
$\mathrm{Im}(V^{\Sigma N})$	without	with	without	with
E (MeV)	−2.89	−0.46	−5.05	−3.04
E_{Σ} (MeV)	−0.67 [a]	+1.77 [a]	−1.46 [b]	+0.55 [b]
Γ (MeV)	–	7.58	–	9.05
k_{Σ} (fm^{-1}) [c]	$+0.158i$	$-0.333+0.213i$	$+0.234i$	$-0.309+0.274i$
$\langle\hat{T}\rangle$ (MeV)	25.32	27.91	28.20	29.89
$\mathrm{Re}\langle\hat{V}\rangle$ (MeV)	−28.45	−28.67	−32.20	−31.91
$\mathrm{Im}\langle\hat{V}\rangle$ (MeV)	-	−3.79	–	−4.52
$\langle\Delta\hat{Q}\rangle$ (MeV)	+0.23	+0.31	−1.06	−1.02
r_{NN} (fm)	3.4	3.5	3.4	3.4
$r_{N\Sigma}$ (fm)	4.9	4.3	3.7	3.7
$P_{T=1}$	0.998	0.997	0.986	0.990

[a] Σ-separation energy measured from the $d+\Sigma^{+}$ threshold.

[b] Σ-separation energy measured from the $n+n+\Sigma^{0}$ threshold.

[c] $k_{\Sigma} = \sqrt{2\mu(E_{\Sigma} - \frac{1}{2}i\Gamma)}/\hbar$, where μ is the reduced mass.

Purpose

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

"Is there a quasibound in ΣNN systems ?"

I will focus on

(1) structure of the ΣNN states,

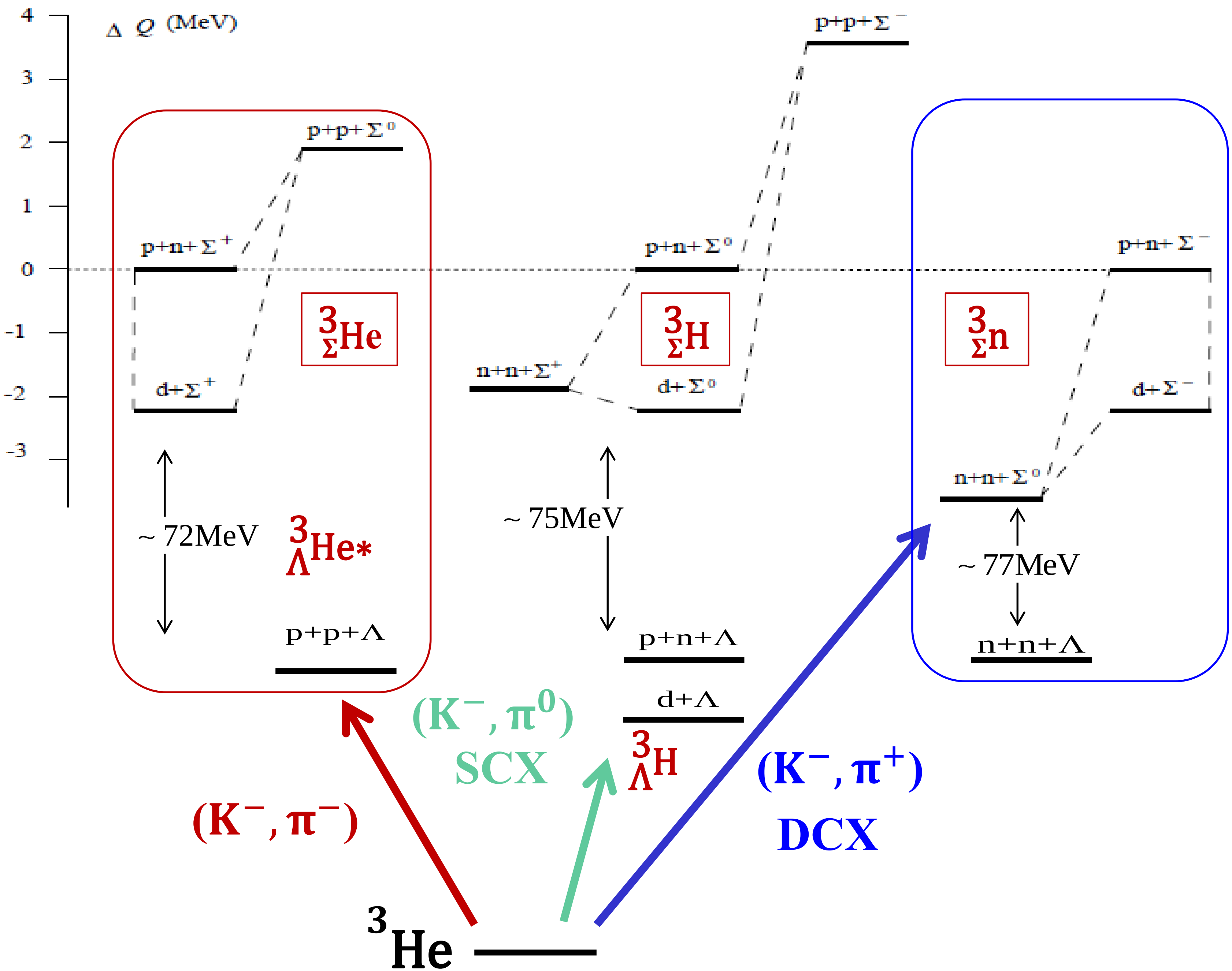
(2) the ΣNN signal appeared in the spectra, and

(3) an important role of Σ components in the ΣNN state.

T. Harada, Y. Hirabayashi, Few Body Syst. 54 (2013) 1205

T. Harada, Y. Hirabayashi, to be submitted to PRC (2014), Update!!

Production by K^- beam from ^{3}He targets



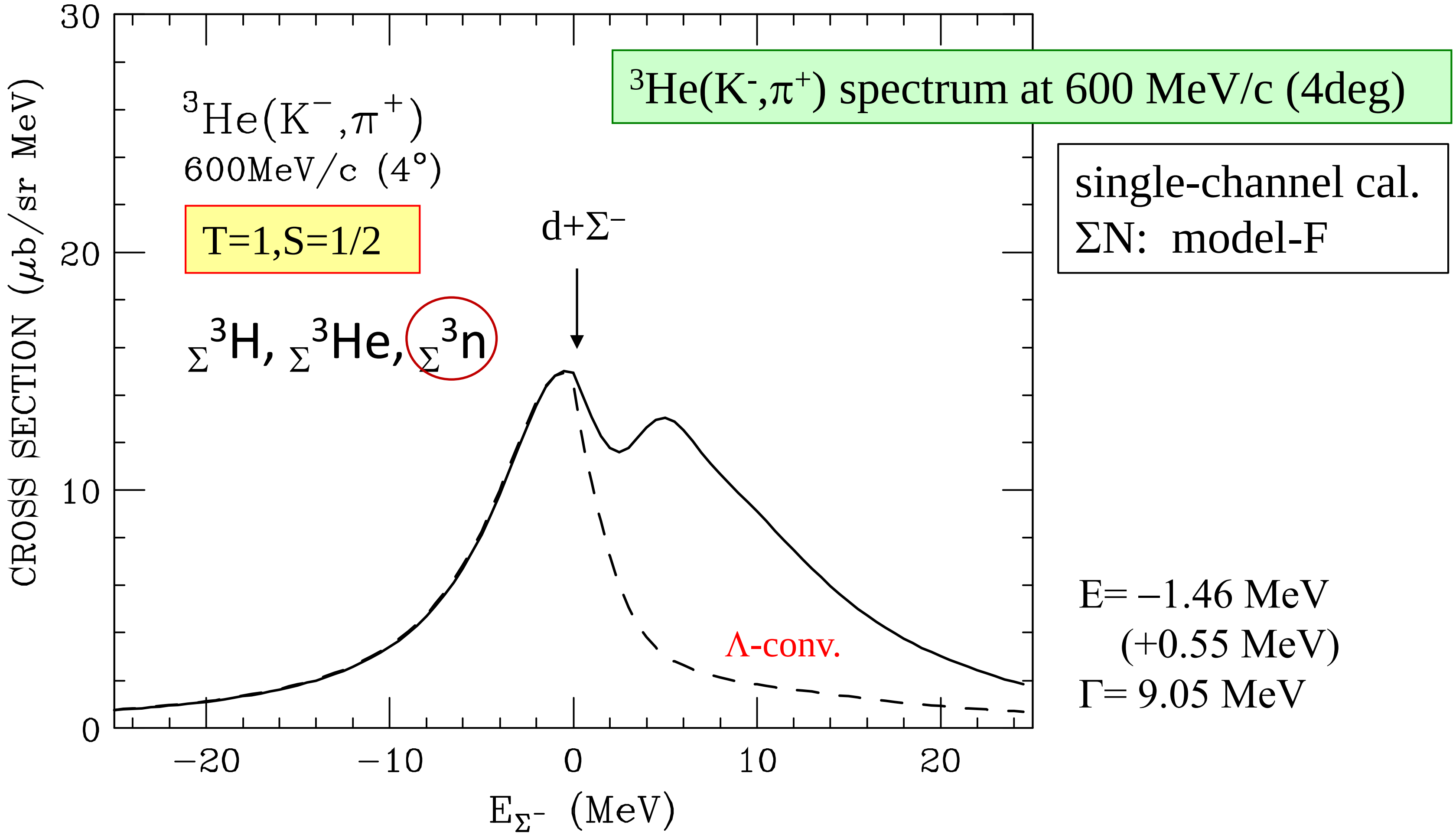
Advantage reaction to search a bound state

For this purpose, we often propose the reaction which has

magic-mom.

(1) a small recoil momentum → incident K^- beam at 600 MeV/c

(2) no background production → DCX (K^-,π^+) (no Λ production)

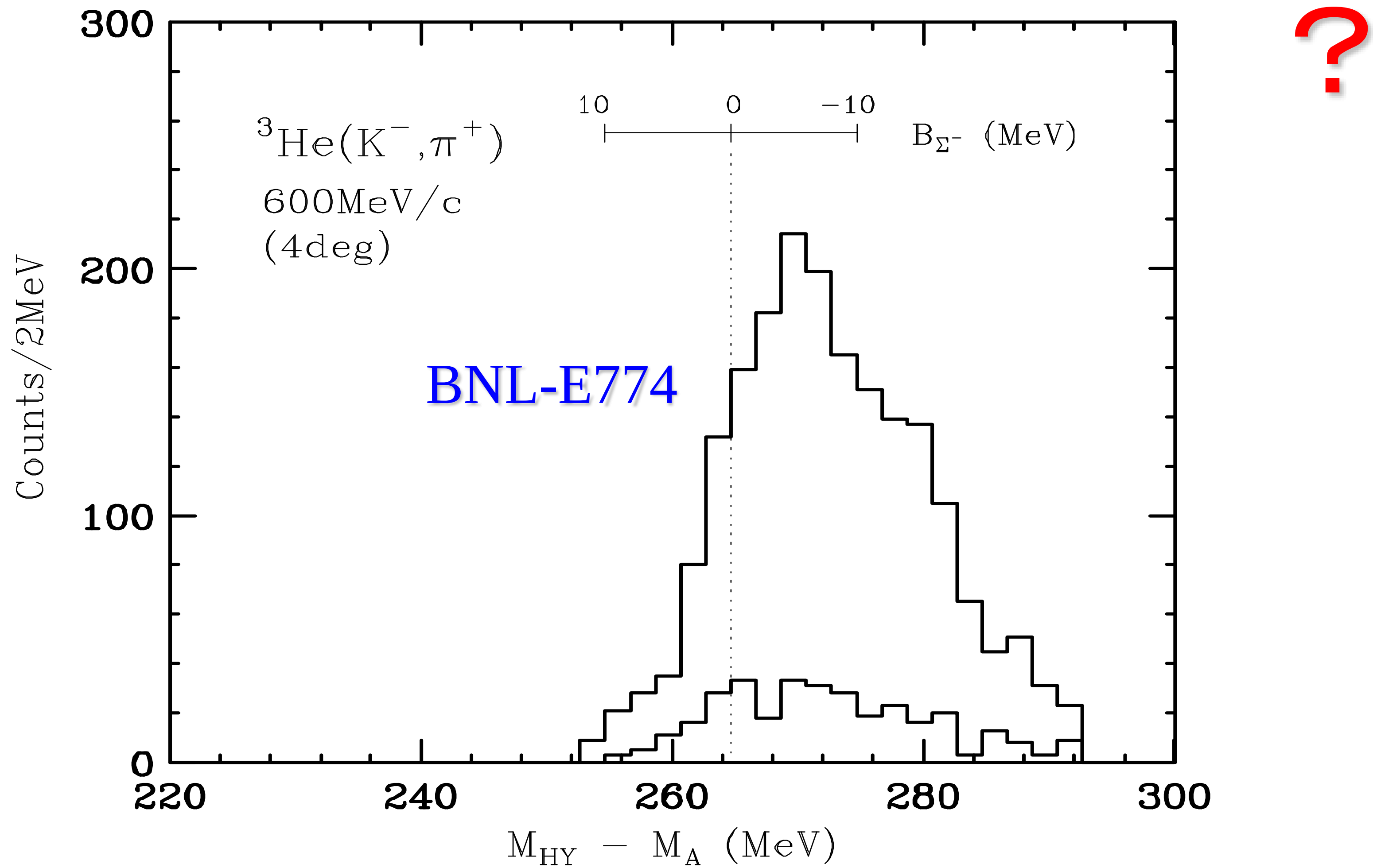


E= −1.46 MeV
(+0.55 MeV)
Γ= 9.05 MeV

Inclusive spectrum by ^{3}He(K^-,π^+) reactions at 600MeV/c

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

- *"There is no evidence for a state below Σ-d threshold."*



2. Calculations

Double differential cross sections within the DWIA

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

Production operators with zero-range interaction

$$\hat{F} = \int d\boldsymbol{r}\, \chi_\pi^{(-)*}(\boldsymbol{p}_\pi, \boldsymbol{r}) \chi_K^{(+)}(\boldsymbol{p}_K, \boldsymbol{r}) \sum_{j=1}^{A} \bar{f}_{(Y\pi)}(\omega_{\bar{K}N}) \delta(\boldsymbol{r} - \boldsymbol{r}_j) \hat{O}_j$$

Momentum and energy transfer

$$\boldsymbol{q} = \boldsymbol{p}_K - \boldsymbol{p}_\pi, \qquad \omega = E_K - E_\pi,$$

Kinematical factor

$$\beta = \left(1 + \frac{E_\pi^{(0)}}{E_Y^{(0)}} \frac{p_\pi^{(0)} - p_K^{(0)} \cos\theta_{\rm lab}}{p_\pi^{(0)}}\right) \frac{p_\pi E_\pi}{p_\pi^{(0)} E_\pi^{(0)}},$$

Coupled-channel Green's function

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

Inclusive spectra for the production cross sections

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

For 3He(K-,π-) reactions

$$\mathrm{Im}\hat{G} = \hat{\Omega}^{(-)\dagger}(\mathrm{Im}\hat{G}^{(0)})\hat{\Omega}^{(-)} + \hat{G}^\dagger(\mathrm{Im}\hat{U})\hat{G},$$

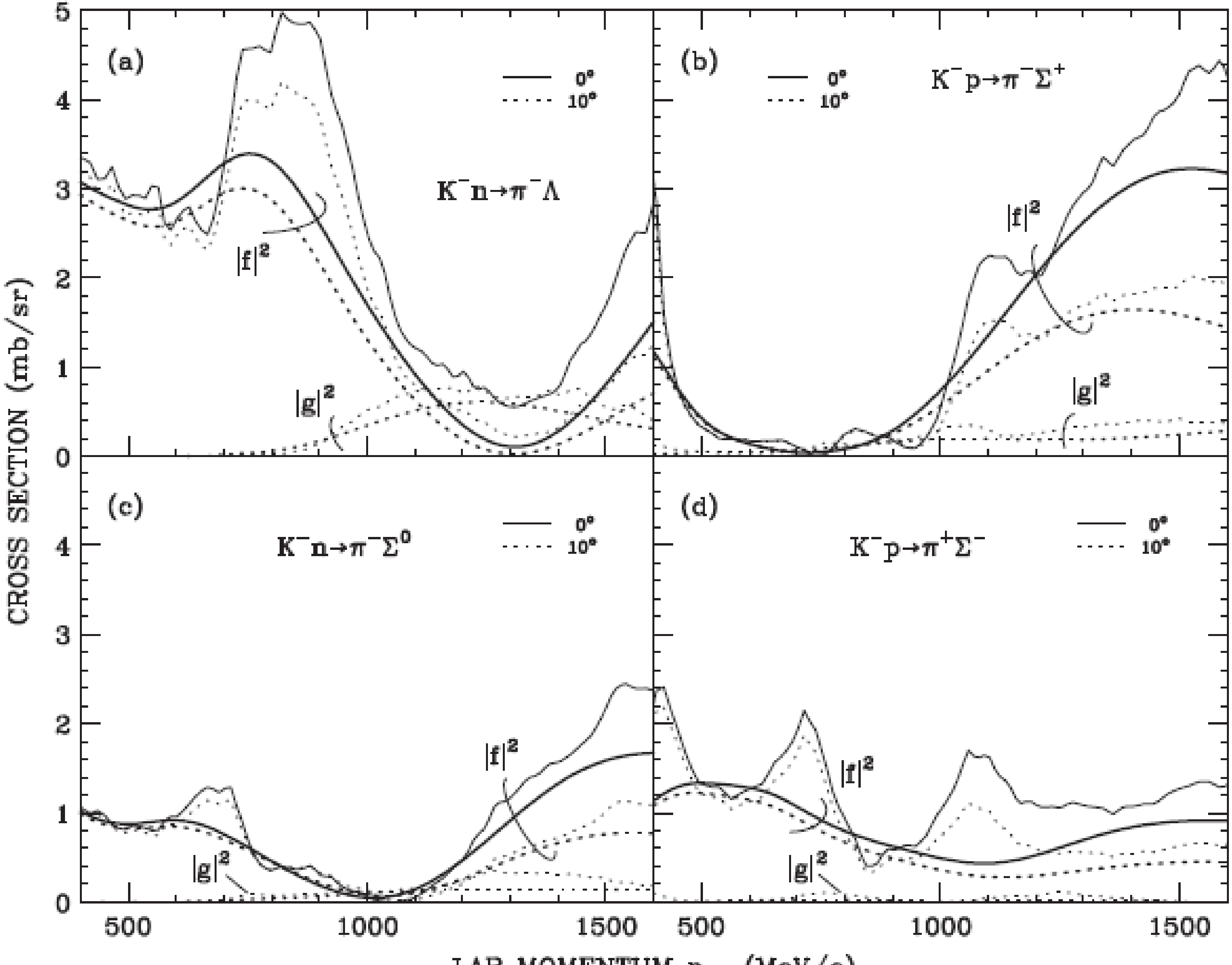
$$S_{\pi^-} = S_{\pi^-}^{\{pp\}\Lambda} + S_{\pi^-}^{[pn]\Sigma^+} + S_{\pi^-}^{\{pn\}\Sigma^+} + S_{\pi^-}^{\{pp\}\Sigma^0} + S_{\pi^-}^{(\mathrm{Conv})}$$

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

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

For 3He(K-,π+) reactions

$$S_{\pi^+} = S_{\pi^+}^{[pn]\Sigma^-} + S_{\pi^+}^{\{pn\}\Sigma^-} + S_{\pi^+}^{\{nn\}\Sigma^0} + S_{\pi^+}^{(\mathrm{Conv})}$$

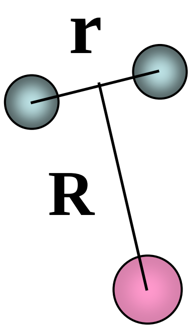


(a)
0°
10°
$K^- n \to \pi^- \Lambda$
$|f|^2$
$|g|^2$
(b)
0°
10°
$K^- p \to \pi^- \Sigma^+$
$|f|^2$
$|g|^2$
(c)
0°
10°
$K^- n \to \pi^- \Sigma^0$
$|f|^2$
$|g|^2$
(d)
0°
10°
$K^- p \to \pi^+ \Sigma^-$
$|f|^2$
$|g|^2$
CROSS SECTION (mb/sr)
LAB MOMENTUM p_{K^-} (MeV/c)
0
1
2
3
4
5
500
1000
1500

Wavefunction of the initial state for a 3He target nucleus

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

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



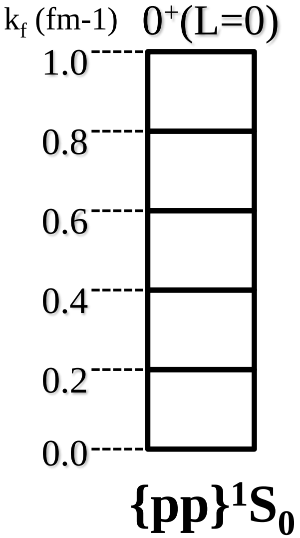
Wavefunctions of final states for ppY

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

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

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

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



The momentum bin method for the pp-systems

$$\left(T_\alpha + v_\alpha^{(NN)}(\boldsymbol{r}) - \varepsilon_\alpha\right)\phi_\alpha^{(2N)}(k,\boldsymbol{r}) = 0$$

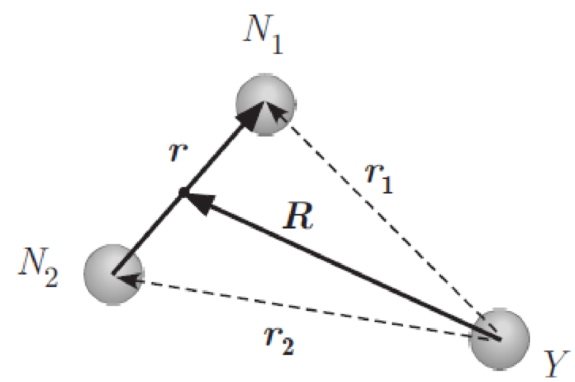
Microscopic (2N)-Y folding-model potentials

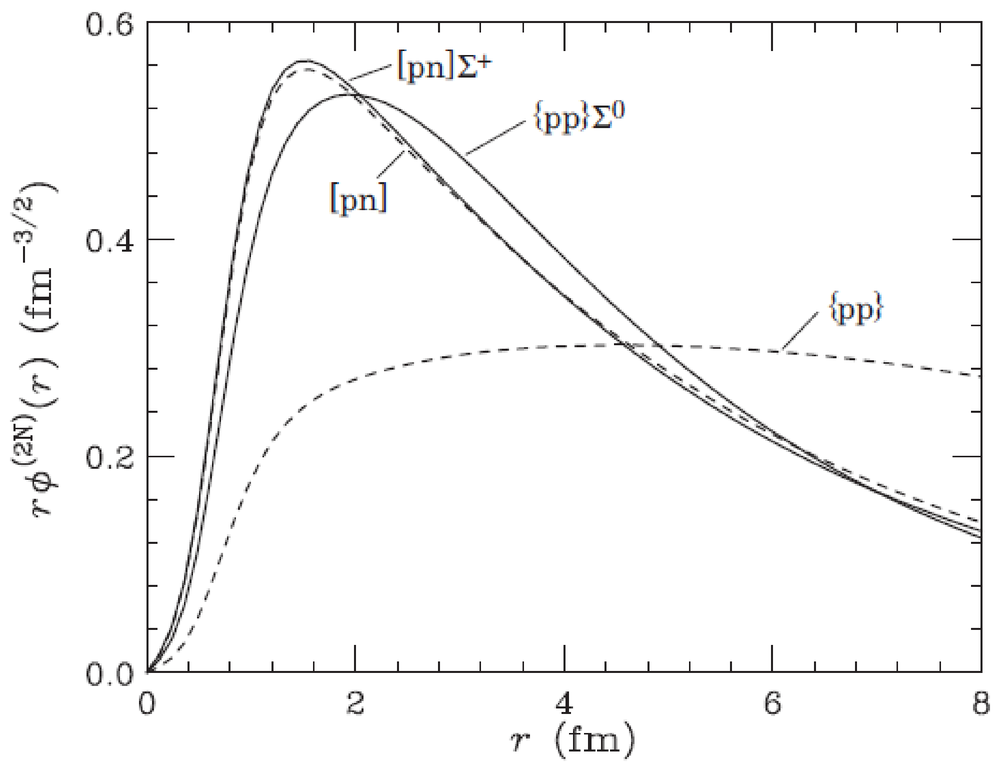
$$U_{\alpha\alpha'}(\boldsymbol{R}) = \int \rho_{\alpha\alpha'}(\boldsymbol{r})\left(\overline{g}_{\alpha\alpha'}(\boldsymbol{r}_1) + \overline{g}_{\alpha\alpha'}(\boldsymbol{r}_2)\right) d\boldsymbol{r},$$

YN g-matrices obtained by D2'

Nucleon or transition density for NN

$$\rho_{\alpha\alpha'}(\boldsymbol{r}) = \langle \phi_{\alpha}^{(2N)} | \sum_i \delta(\boldsymbol{r} - \boldsymbol{r}_i) | \phi_{\alpha'}^{(2N)} \rangle$$

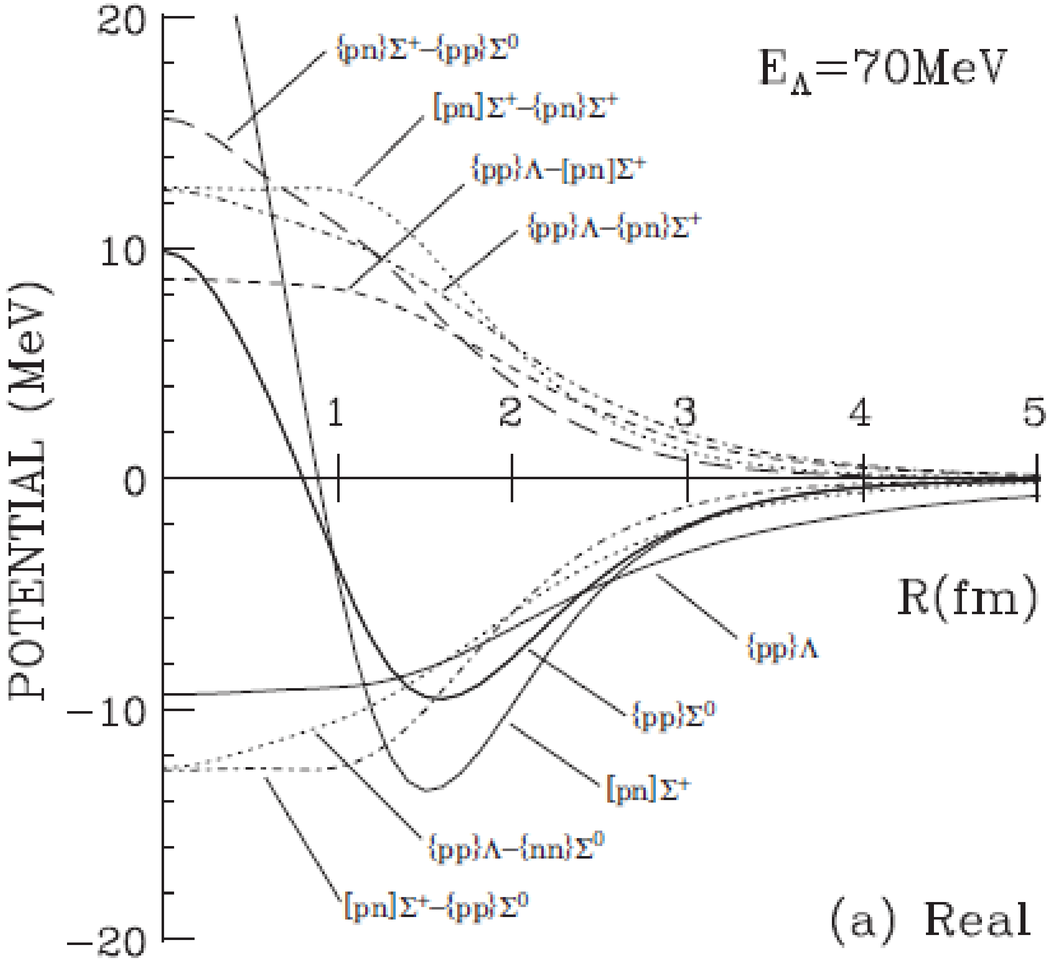


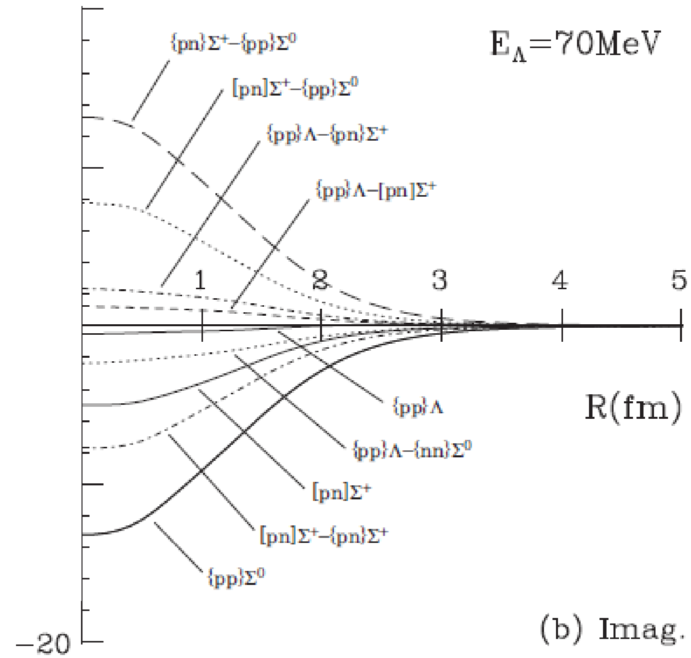


Coupled Bethe-Goldstone eq.

$$\begin{bmatrix} \Psi_\Lambda \\ \Psi_\Sigma \end{bmatrix} = \begin{bmatrix} \Phi_\Lambda \\ 0 \end{bmatrix} + \frac{Q}{e} v \begin{bmatrix} \Psi_\Lambda \\ \Psi_\Sigma \end{bmatrix}$$

Microscopic (2N)-Y folding-model potentials



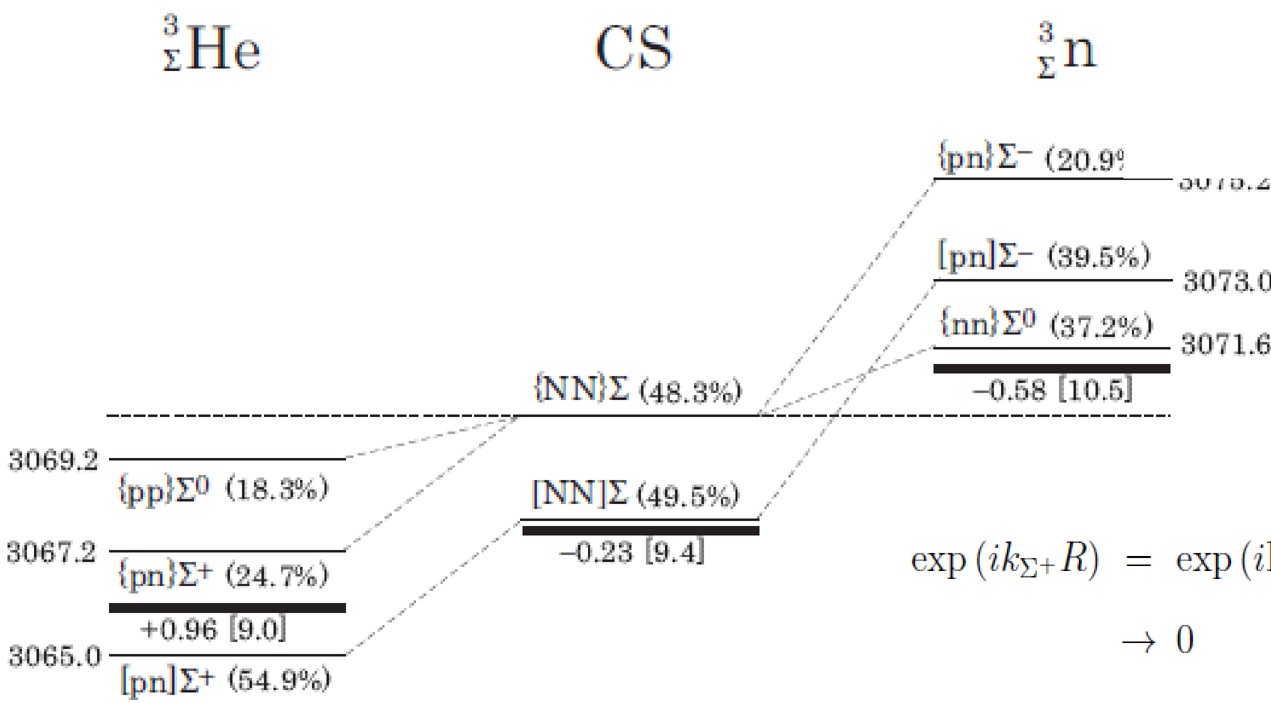


3. Results and Discussion

Energies and widths of SNN (S=1/2, T=1) predicted by D2'

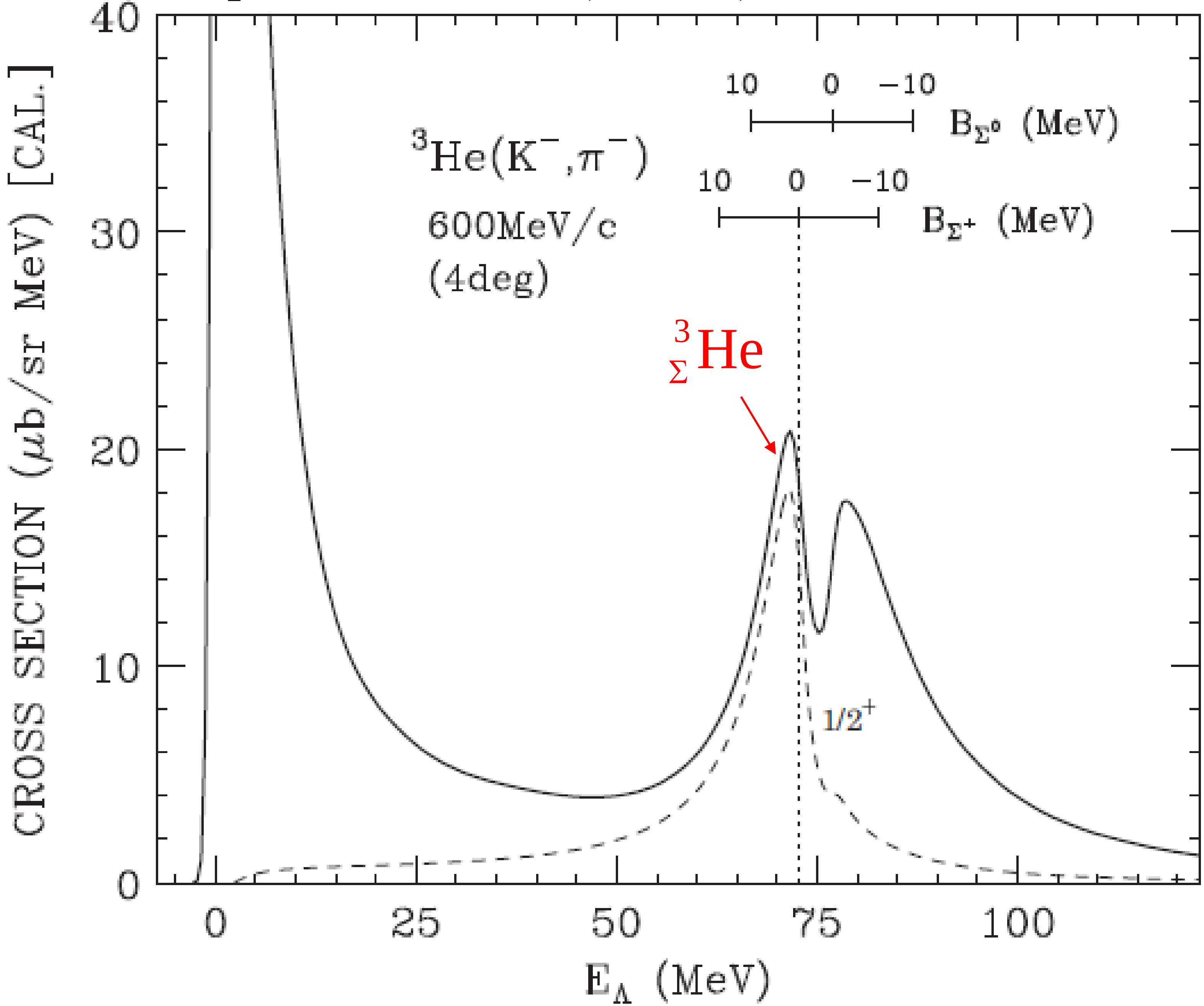
TABLE IV: Energies and widths of $2N$–Y systems in complex E plane.

	(J^π, T)	E_Λ (MeV)	$E_{\Sigma^\pm}$ (MeV)	E_{Σ^0} (MeV)	Γ_Σ (MeV)	$k_{\Sigma^\pm}$ (fm^{-1})
${}^3_\Sigma$He	$(\frac{1}{2}^+, 1)$	+73.7	+0.96[a]	−3.24	9.0	−0.322+i0.260
${}^3_\Sigma$n	$(\frac{1}{2}^+, 1)$	+76.4	−1.87[b]	−0.58	10.5	−0.263+i0.374

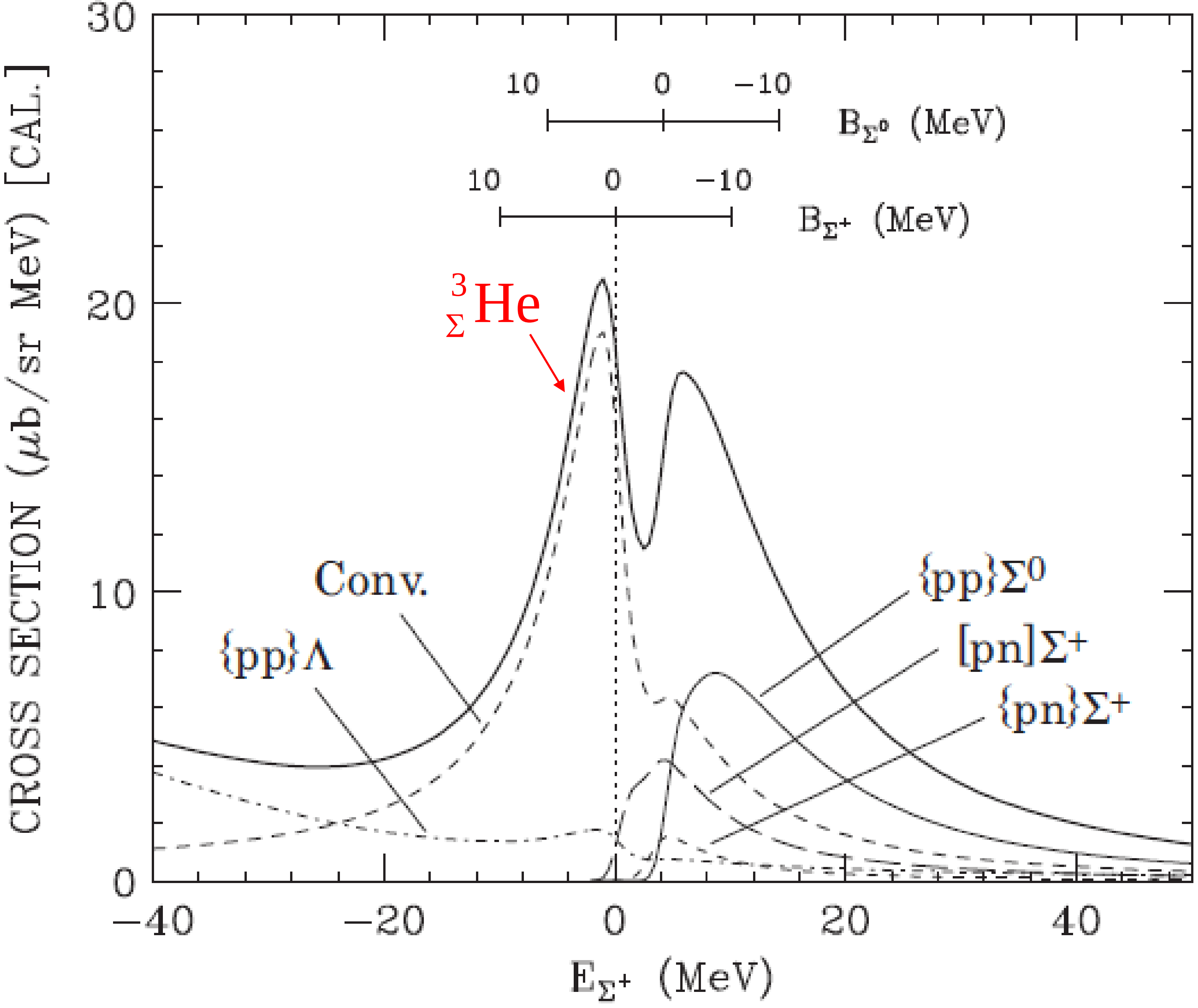


$$\exp(ik_{\Sigma^+}R) = \exp(i\mathrm{Re}k_{\Sigma^+}R)\exp(-\mathrm{Im}k_{\Sigma^+}R)$$
$$\to 0$$

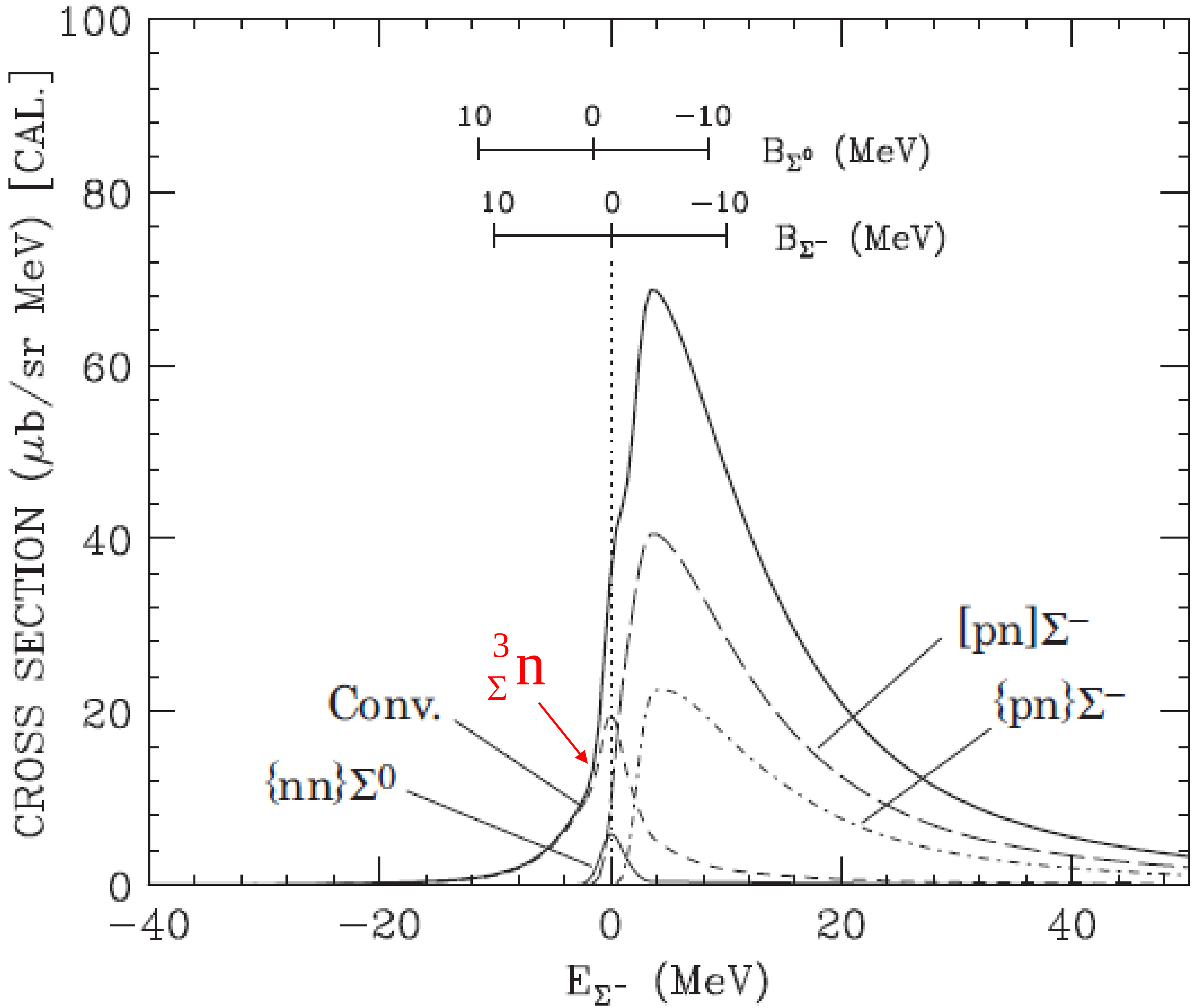
Inclusive spectrum in $^3He(K^-,\pi^-)$ reactions at 600MeV/c



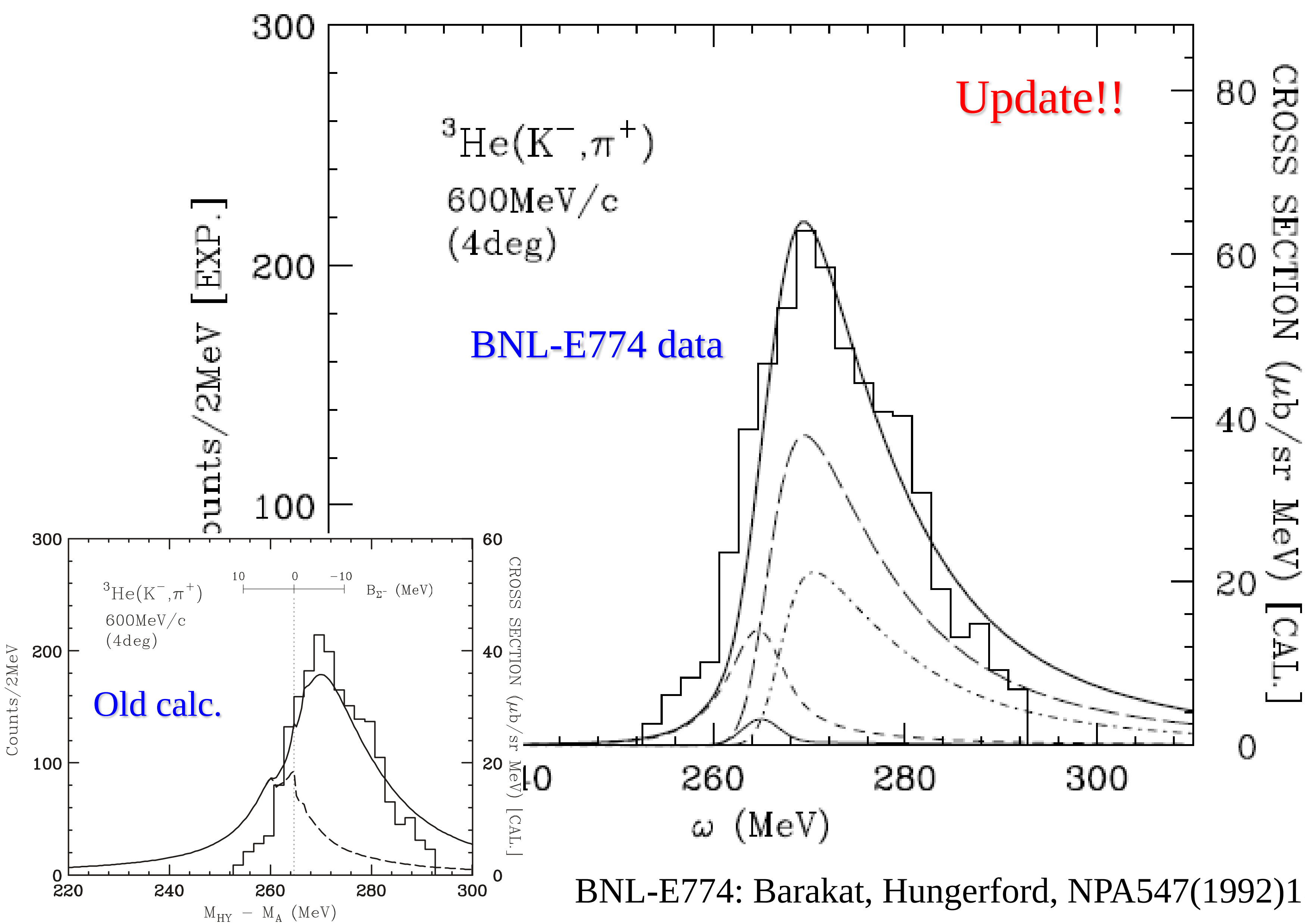
Inclusive spectrum in $^3He(K^-,\pi^-)$ reactions at 600MeV/c



Inclusive spectrum in $^3He(K^-,\pi^+)$ reactions at 600MeV/c



Conparison with the data in ^{3}He(K$^-$,π^+) reactions at 600MeV/c



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

Production cross sections on $^3He(K^-,\pi^{-/+})$ reactions

Dover and Gal, PLB110(1982)433

Table 2

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

	$I(T)$	S	Q	$\sigma(K^-, \pi^-)$	$\sigma(K^-, \pi^+)$
	0(1)	1/2	3	–	–
Σ[pn] →	1(0)	1/2	1/3	$3/2\,\lvert f_{p\to\Sigma^+}\rvert^2$	$3/2\,\lvert f_{p\to\Sigma^-}\rvert^2$
	1(0)	3/2	4/3	0	0
Σ{pn} →	1(1)	1/2	2	$1/2\,\lvert f_{n\to\Sigma^\circ} + 1/\sqrt{2} f_{p\to\Sigma^+}\rvert^2$	$1/4\,\lvert f_{p\to\Sigma^-}\rvert^2$
	2(1)	1/2	0	$1/2\,\lvert f_{n\to\Sigma^\circ} - 1/\sqrt{2} f_{p\to\Sigma^+}\rvert^2$	$1/4\,\lvert f_{p\to\Sigma^-}\rvert^2$

Interference between K$^-$N-πY amplitudes in the spectra (I)

For ^{3}He(K$^-$,π^-) reactions

$$
\begin{aligned}
T^{(K^-,\pi^-)} &\simeq f_{\Sigma^0}\langle\{pp\}\Sigma^0|^3\mathrm{He}\rangle + f_{\Sigma^+}\langle\{pn\}\Sigma^+|^3\mathrm{He}\rangle + f_{\Sigma^+}\langle[pn]\Sigma^+|^3\mathrm{He}\rangle \\
&= \sqrt{\frac{1}{2}}f^{(3/2)}\langle T=2|^3\mathrm{He}\rangle + \sqrt{\frac{1}{2}}f_s^{(1/2)}\langle T=1_s|^3\mathrm{He}\rangle + \sqrt{\frac{1}{2}}f_t^{(1/2)}\langle T=1_t|^3\mathrm{He}\rangle
\end{aligned}
$$

dynamically admixtures
due to the ΣN potential

$$
= \sqrt{\frac{1}{2}}\left\{\sqrt{\frac{1}{2}}f_{\Sigma^+} - f_{\Sigma^0}\right\}\langle T=2|^3\mathrm{He}\rangle + \left\{\left(\frac{\sqrt{3}+1}{2}\right)f_{\Sigma^+} + \frac{1}{2}f_{\Sigma^0}\right\}\langle T=1^{(-)}|^3\mathrm{He}\rangle \quad {}^3_\Sigma\mathrm{He}_{g.s.}
$$

most attractive

$$
+\left\{\left(\frac{\sqrt{3}-1}{2}\right)f_{\Sigma^+} - \frac{1}{2}f_{\Sigma^0}\right\}\langle T=1^{(+)}|^3\mathrm{He}\rangle \quad {}^3_\Sigma\mathrm{He}^*
$$

interference between
K$^-$p→$\pi^-\Sigma$+ and K$^-$n→$\pi^-\Sigma$0 production amplitudes

Interference between K⁻N-πY amplitudes in the spectra (II)

For ^{3}He(K$^-$,π^+) reactions

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

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

dynamically admixtures

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

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

most attractive

Reduced 0.51

Enhanced

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

1.219

➢ **This reduction mechanism must appear in ^{3}He(K$^-$,π^+) reactions !**

Summary

There is a quasibound in ΣNN systems !!

- The coupled-channel framework is very important for calculating the spectra of the $^3He(K^-,\pi^{\mp})$ reactions.
  taking into account K^-N-πY amplitudes and threshold-differences .
- The effective "2N"-Y potential is constructed from YN g-matix from D2'.
- The calculated spectra of the $^3He(K^-,\pi^+)$ reaction may be consistent with the E774 data due to the admixture of the NN core states. depending the ΣNN structure obtained by the 2N-Y potential.
- Both the π^- and π^+ spectra provide valuable information to understand the nature of the ΣNN quasibound states and also the YN (ΣN) interactions.

To determine a quasibound state [+ −] or cusp state [− +].