特定領域研究「ストレンジネスで探るクォーク多体系」理論班主催
「ストレンジクォークを含むクォーク多体系分野の理論的将来を考える」研究会
2009年2月27-28日，熱海市

ハイパー核反応の今後

原田　融
Harada, Toru

大阪電気通信大学
Osaka Electro-Communication University
Neyagawa 572-8530, Osaka, Japan
harada@isc.osakac.ac.jp

-これまでにどういう新しい物理を明らかにしてきたか？

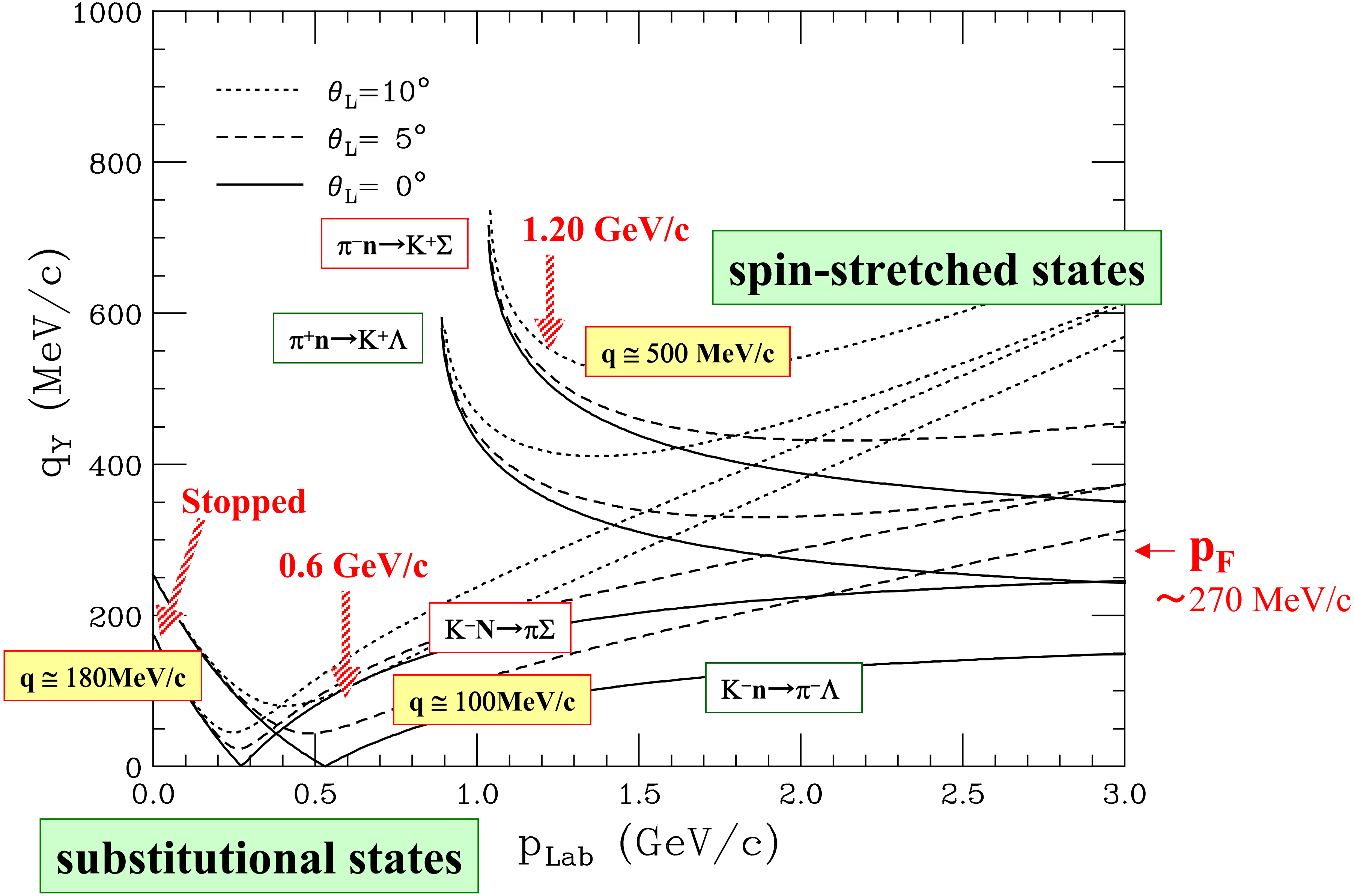
- 生成のメカニズムとDWIA計算の改良
- Σ–nucleus potentialの性質　Σ原子 v.s.(π⁻, K⁺)反応
- 中性子過剰ハイパー核生成　シグマ混合率

- 今後、どういう新しい展開が期待できるのか？

- ２重荷電交換反応によるハイパー核生成！

- J-PARCに対して、どういう実験を提案していくのか？

Momentum transfer to Λ, Σ-hyperons



spin-stretched states

1.20 GeV/c

q ≅ 500 MeV/c

Stopped

q ≅ 180MeV/c

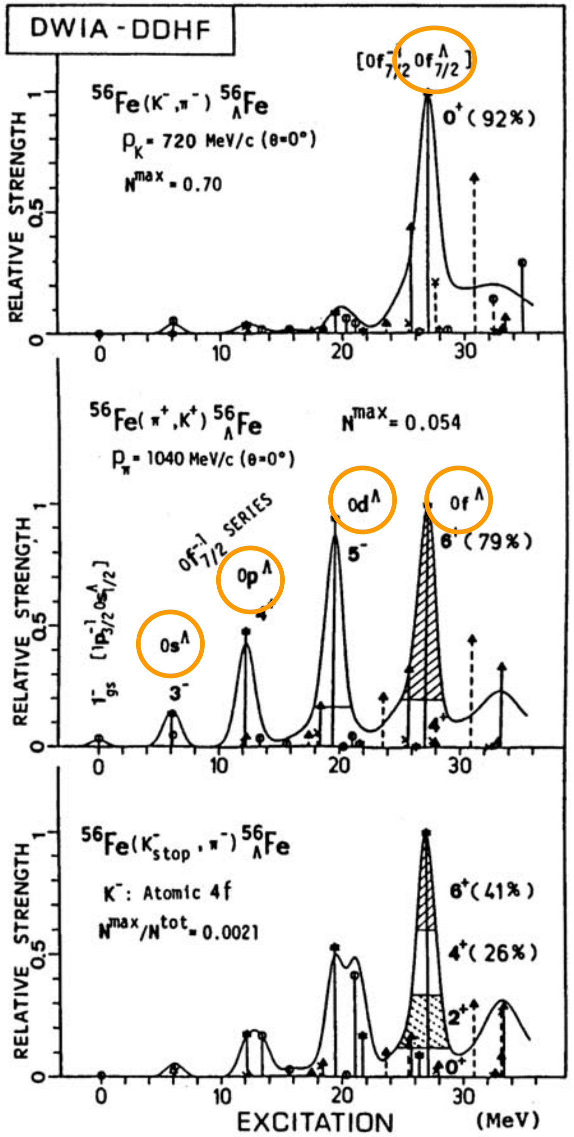
0.6 GeV/c

q ≅ 100MeV/c

← p_F ~270 MeV/c

substitutional states

Hypernuclear Production Reactions



(K⁻,π⁻)
720 MeV/c

$q_\Lambda \sim 60$MeV/c

"Substitutional"

$\Delta\ell \simeq 0$

(π⁺,K⁺)
1040 MeV/c

$q_\Lambda \sim 350$MeV/c

"Spin-Stretched''

$[(n\ell j)_N^{-1}(n\ell j)_\Lambda]_J$

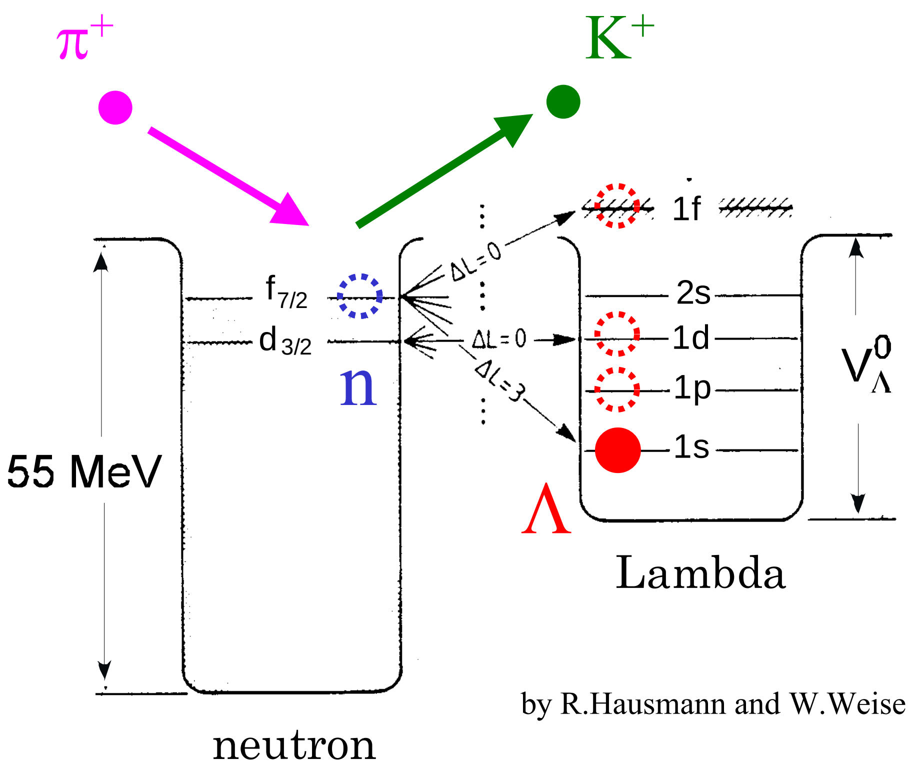
$[j_{N<}^{-1} j_{\Lambda>}]_{J=J\max}$

(K⁻,π⁻)
Stooped K-

$q_\Lambda \sim 300$MeV/c

・反応の特徴を生かす
・Λ状態を選択的に励起

(π⁺,K⁺) reactions

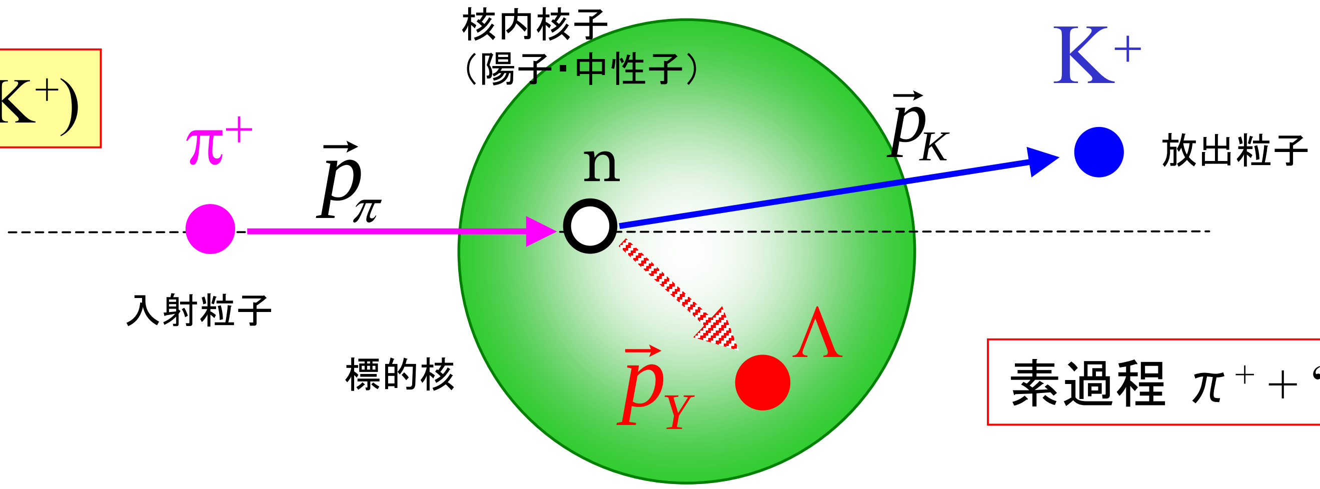


by R.Hausmann and W.Weise

H.Bando, T.Motoba, J.Zofka, Int.J.Mod.Phys. A5(1990)4021

Distorted wave impulse approximation（DWIA)

(π+, K+)



観測/測定

素過程 $\pi^+ + \text{“n”} \rightarrow K^+ + \Lambda$

Double-Differential Cross Sections

$$\frac{d^2\sigma}{dE_\pi d\Omega} = \beta \left[\frac{d\sigma}{d\Omega}\right]_{\pi^+ n\to K^+\Lambda} S(\omega,\mathbf{q})$$

Strength function

$$S(\omega,\mathbf{q}) = \sum_f \left|< f \,|\, \chi_{K+}^{(-)*} U_- \chi_{\pi+}^{(+)} \,|\, i >\right|^2 \delta(\omega + E_\pi - E_K)$$

Elementary cross sections (Fermi-averaging)

Meson distorted-wave functions (Eikonal approximation)

$$\chi_{K+}^{(-)*}(\mathbf{r})\chi_{\pi+}^{(+)}(\mathbf{r}) = \sum_L \sqrt{4\pi(2L+1)}\, i^L \boxed{\tilde{j}_{LM}^{(+)}(r)}\, Y_{LM}(\hat{\mathbf{r}})$$

$$\boxed{\tilde{j}_{LM}^{(+)}(r)} = \sum_{ll'} (-)^{\frac{l-l'-L}{2}} \sqrt{4\pi(2l'+1)}\, \frac{2l+1}{2L+1}\, \tilde{j}_l^{(+)}(k_\pi;r)\,\tilde{j}_{l'}^{(+)}(k_K;r)\,(l0l'M\,|\,LM)(l0l'0\,|\,L0)\,Y_{l'M}^*(\hat{k}_K)$$

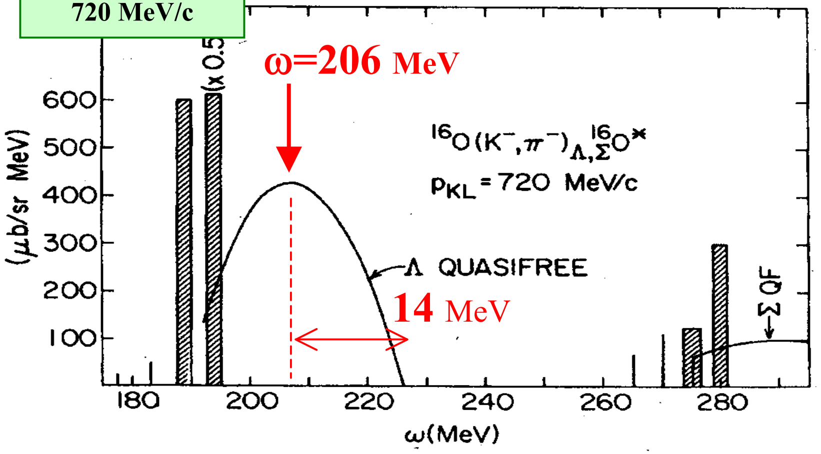
Optimal Fermi-averaging for the $\pi^+ + n \rightarrow K^+ + \Lambda$ t-matrix in Λ-hypernuclear production from (π^+, K^+) reactions

T.H and Y.Hirabayashi, NPA744(2004)323

Λ Quasi-free production spectrum

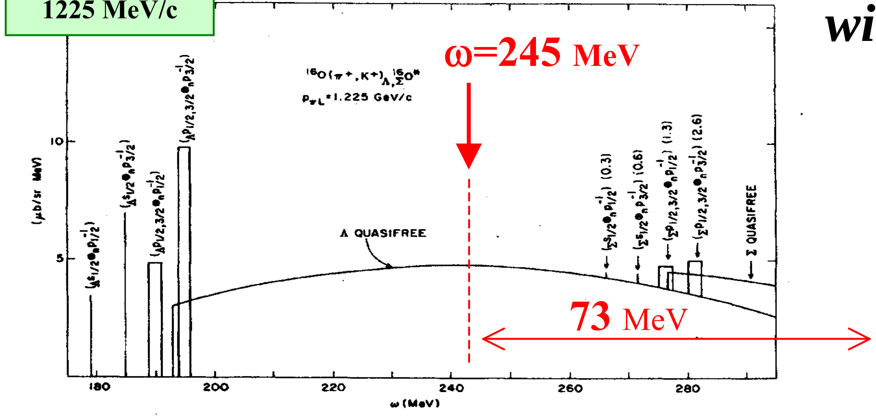
(K⁻,π⁻)
720 MeV/c

q_Λ～60MeV/c



(π⁺,K⁺)
1225 MeV/c

q_Λ～300MeV/c



C.B. Dover et al., PRC22 (1980) 2073.

Fermi gas model

R.H.Dalitz, A.Gal, PL64B(1976)154

$$\frac{d\sigma}{d\Omega_L dE} = \alpha \left[\frac{d\sigma}{d\Omega_L}\right]^{\text{elem}} R(\omega,\theta)$$

peak position

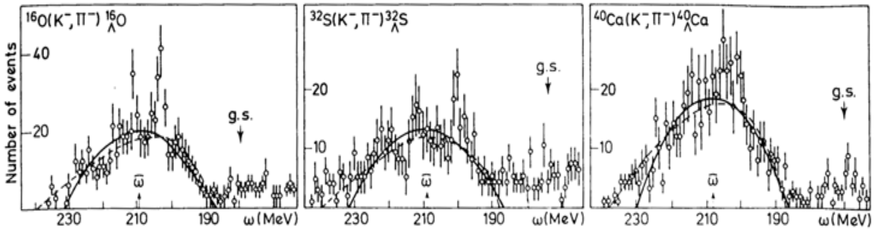
$$\bar{\omega} = \underbrace{(M_\Lambda - M_N)\left(1 - \frac{\overset{270\text{ MeV /c}}{k_F^2}}{4M_\Lambda M_N}\right)}_{174\text{ MeV}} + \underbrace{(\overset{-28\text{ MeV}}{U_\Lambda} - \overset{-58\text{ MeV}}{U_N})}_{30\text{ MeV}} + \boxed{\frac{q^2}{2M_\Lambda}}$$

(K-,π): 2 MeV
(π,K+,): 56 MeV

width

$$\bar{\omega} - \boxed{\frac{k_F q}{M_\Lambda}} \le \omega \le \bar{\omega} + \boxed{\frac{k_F q}{M_\Lambda}}$$

(K-,π): 14 MeV
(π,K+,): 73 MeV

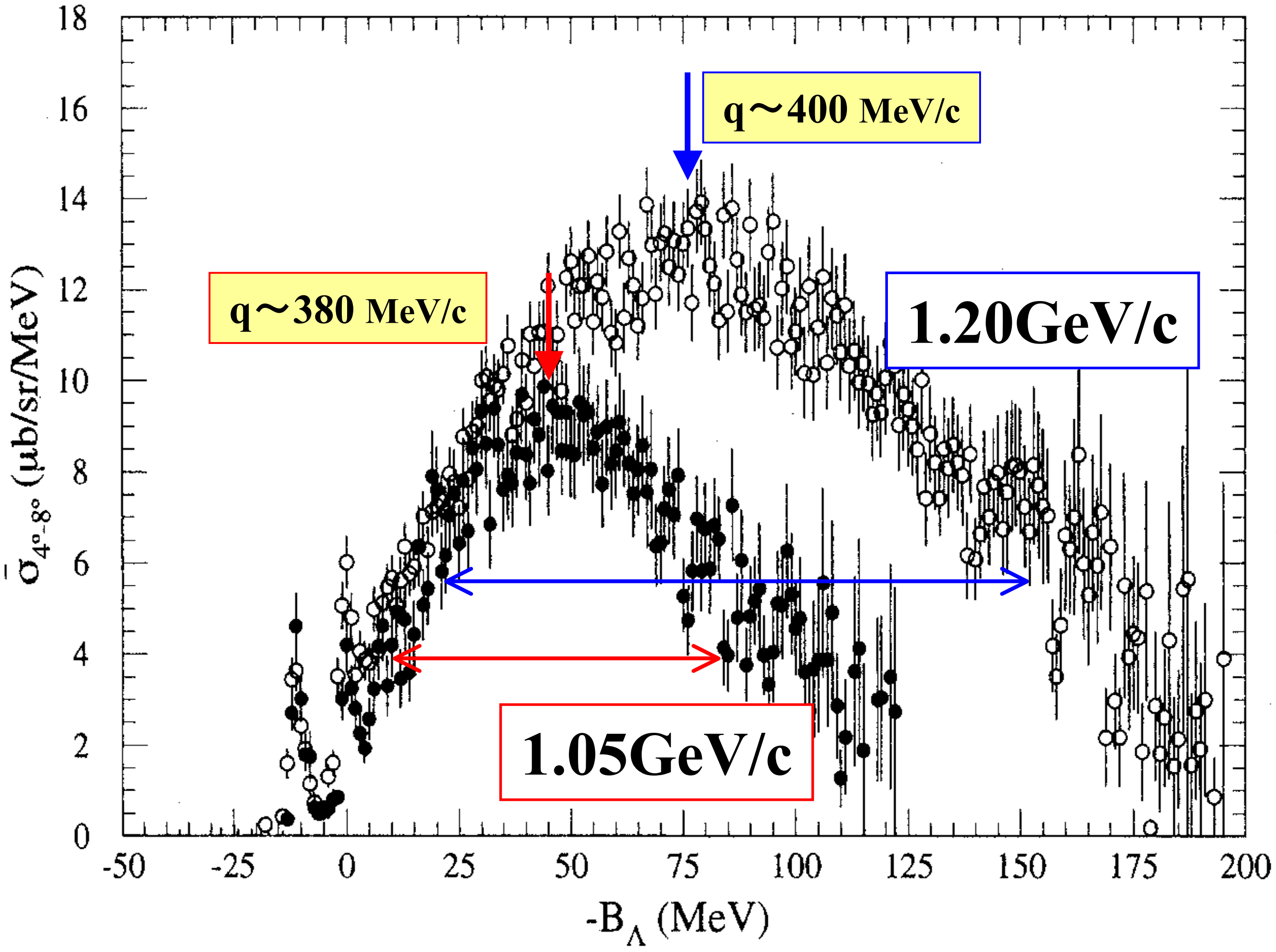


Λ spectrum by (π^+,K^+) reaction at 1.20, 1.05GeV/c

^{12}C

(π⁺,K⁺)反応によるΛ−QF生成

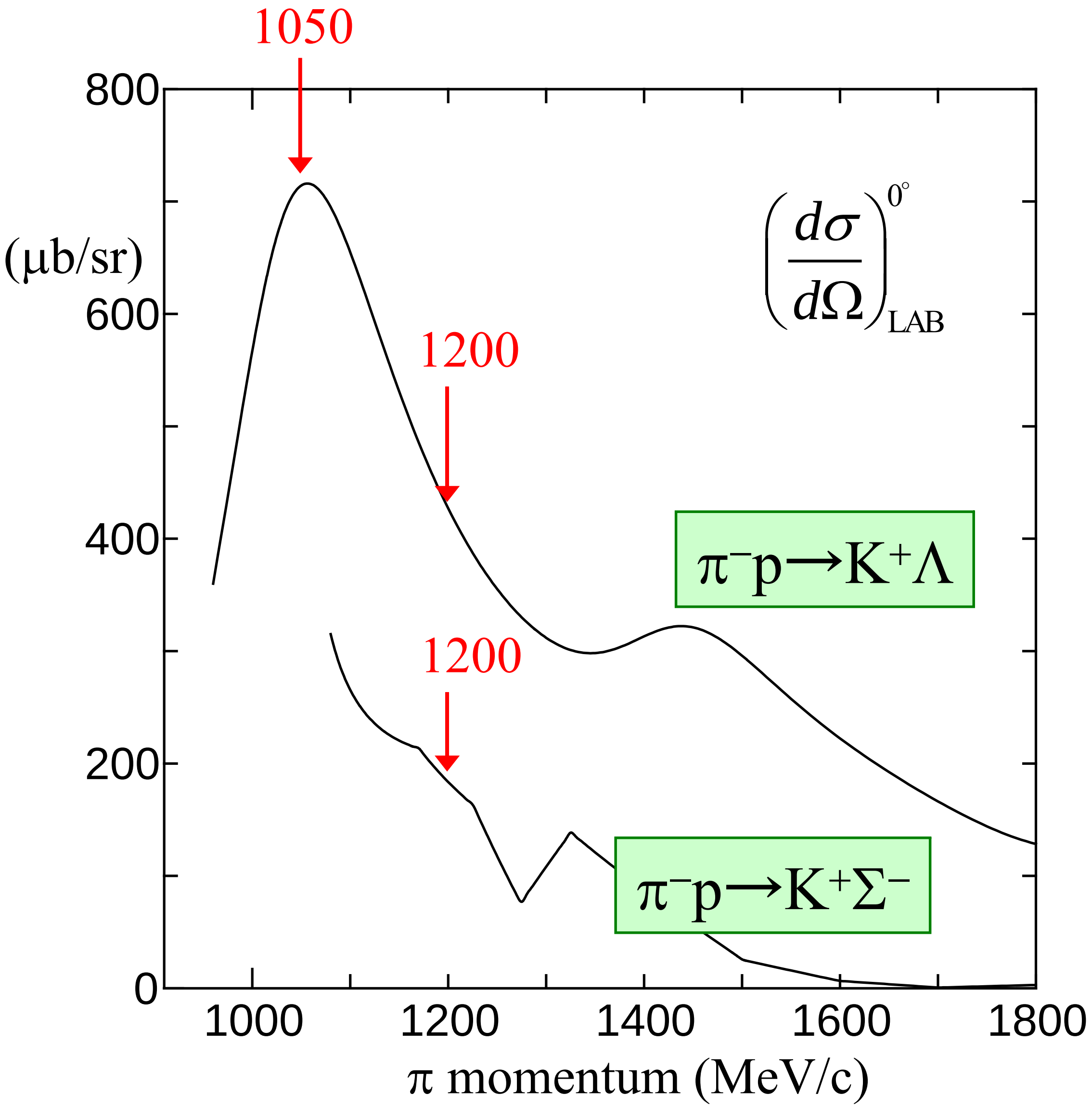
P.K.Saha et al., KEK-E438, E521



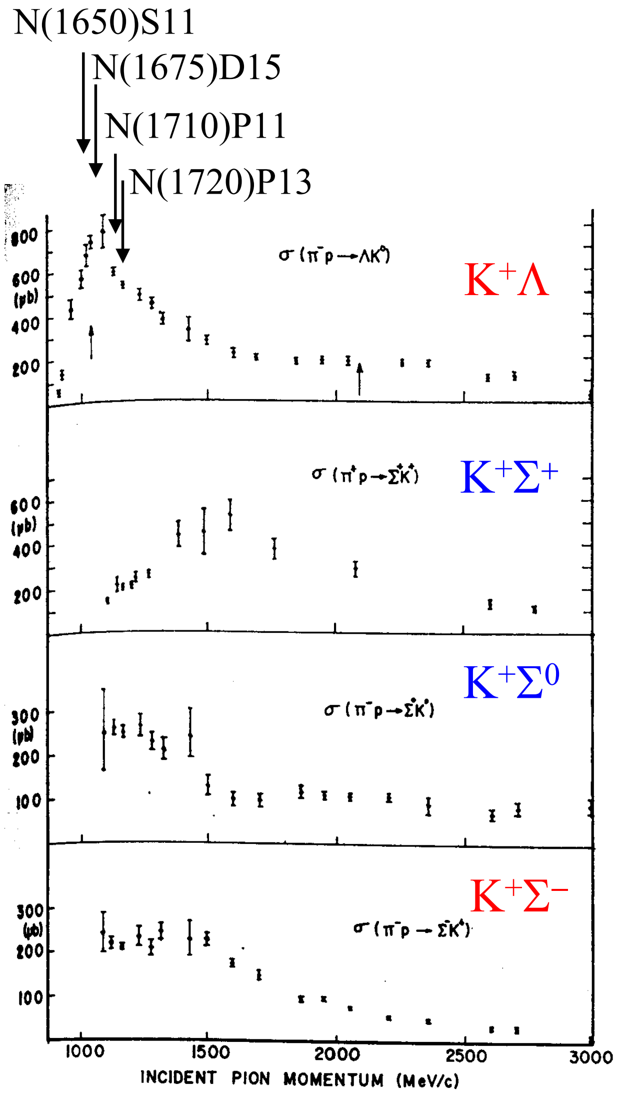
σ(1.20) > σ(1.05)

peak (MeV)	width (MeV)	
～80	～140	1.20GeV/c
～50	～80	1.05GeV/c

Elementary cross sections of $\pi N \rightarrow K^+\Lambda$, $K^+\Sigma^-$ reactions



T.O.Binford, et al. PR183(1969)1134

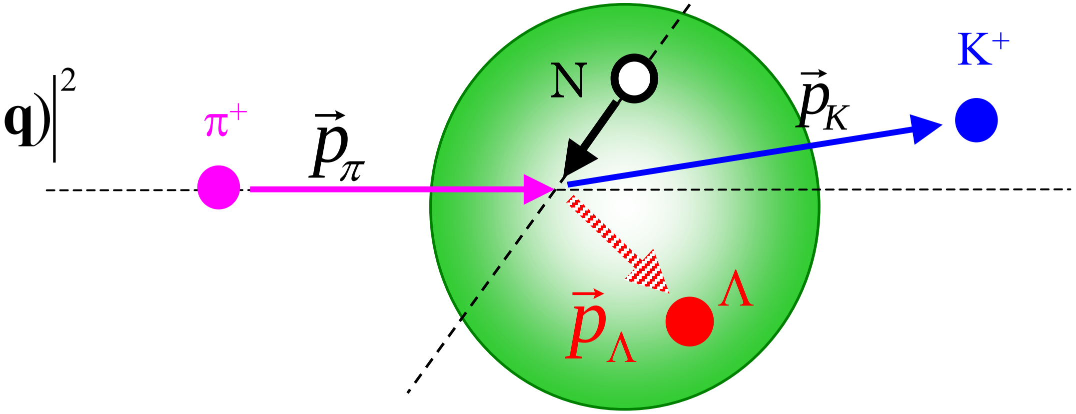


Optimal Fermi-averaging for an elementary t-matrix

T. Harada and Y.Hirabayashi, NPA744 (2004) 323.

"Optimal" cross section

$$\left[\frac{d\sigma}{d\Omega}\right]^{\mathrm{opt}}_{\pi^+ p\to K^+\Lambda}=\frac{k_K E_K}{(2\pi)^2 v_\pi}\left|\hat{t}^{\mathrm{opt}}(p_\pi;\omega,\mathbf{q})\right|^2$$



Optimal Fermi-averaged t-Matrix

On-shell T-matrix

$$\hat{t}^{\mathrm{opt}}(p_\pi;\omega,\mathbf{q})=\left.\frac{\int_0^\pi \sin\theta d\theta\int_0^\infty p_N^2 dp_N \hat{t}_{Lab}(E_{\pi N};p_\pi,p_N)\rho(p_N)}{\int_0^\pi \sin\theta d\theta\int_0^\infty p_N^2 dp_N\rho(p_N)}\right|_{\mathbf{p}_N=\mathbf{p}_N^*}$$

given

"On-energy-shell'' equation $\omega=E_{\mathrm{f}}-E_{\mathrm{i}}=\sqrt{(\mathbf{p}_N^*+\mathbf{q})^2+m_\Lambda}-\sqrt{\mathbf{p}_N^{*\,2}+m_N}$

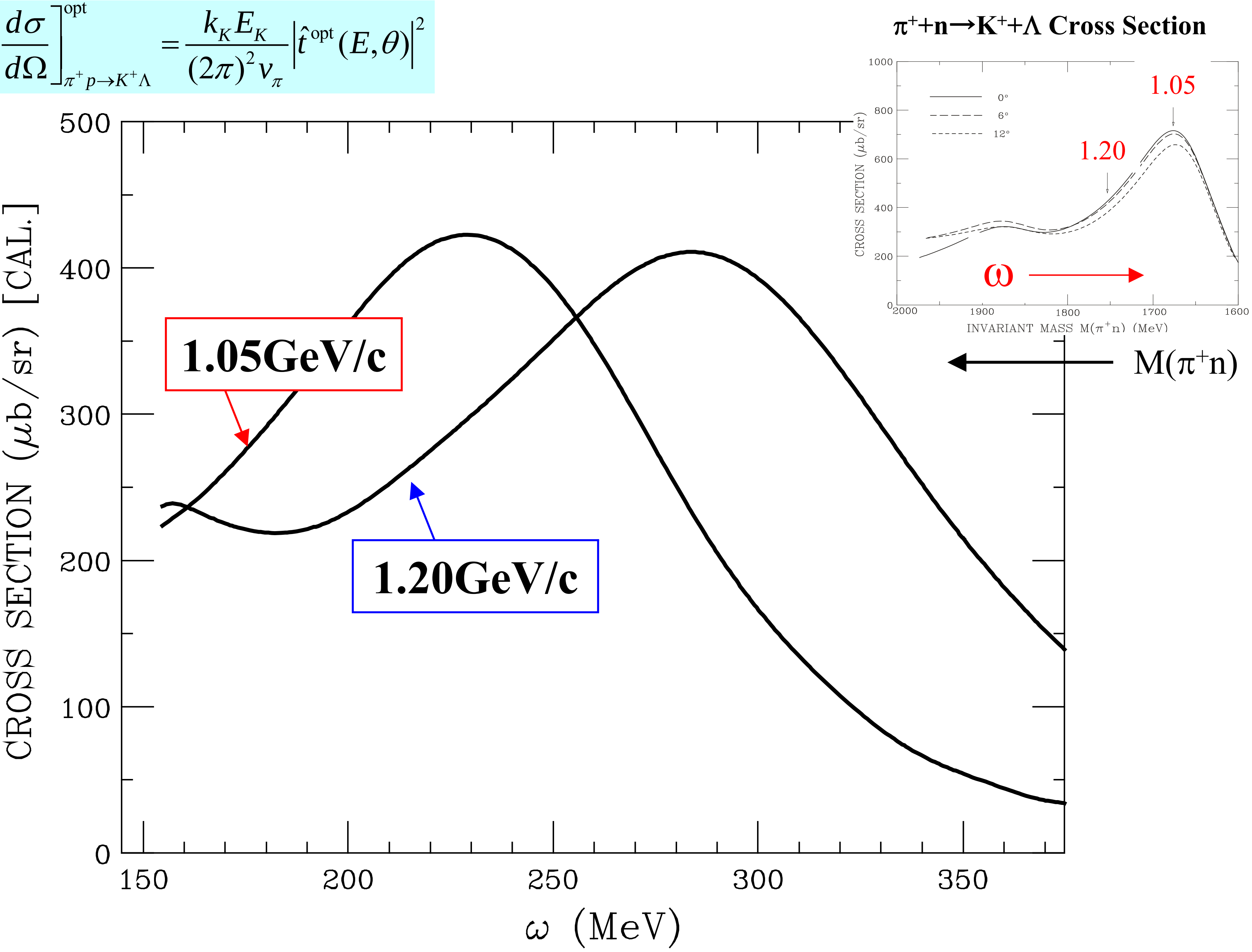
given

$$\mathbf{p}_\pi+\mathbf{p}_{\mathrm{N}}^*=\mathbf{p}_{\mathrm{K}}+\mathbf{p}_\Lambda$$

S,A.Gurvitz, PRC33(1986)422: Optimal factorization

Optimal cross section of the $\pi^+ + n \rightarrow K^+ + \Lambda$ reaction in nuclei

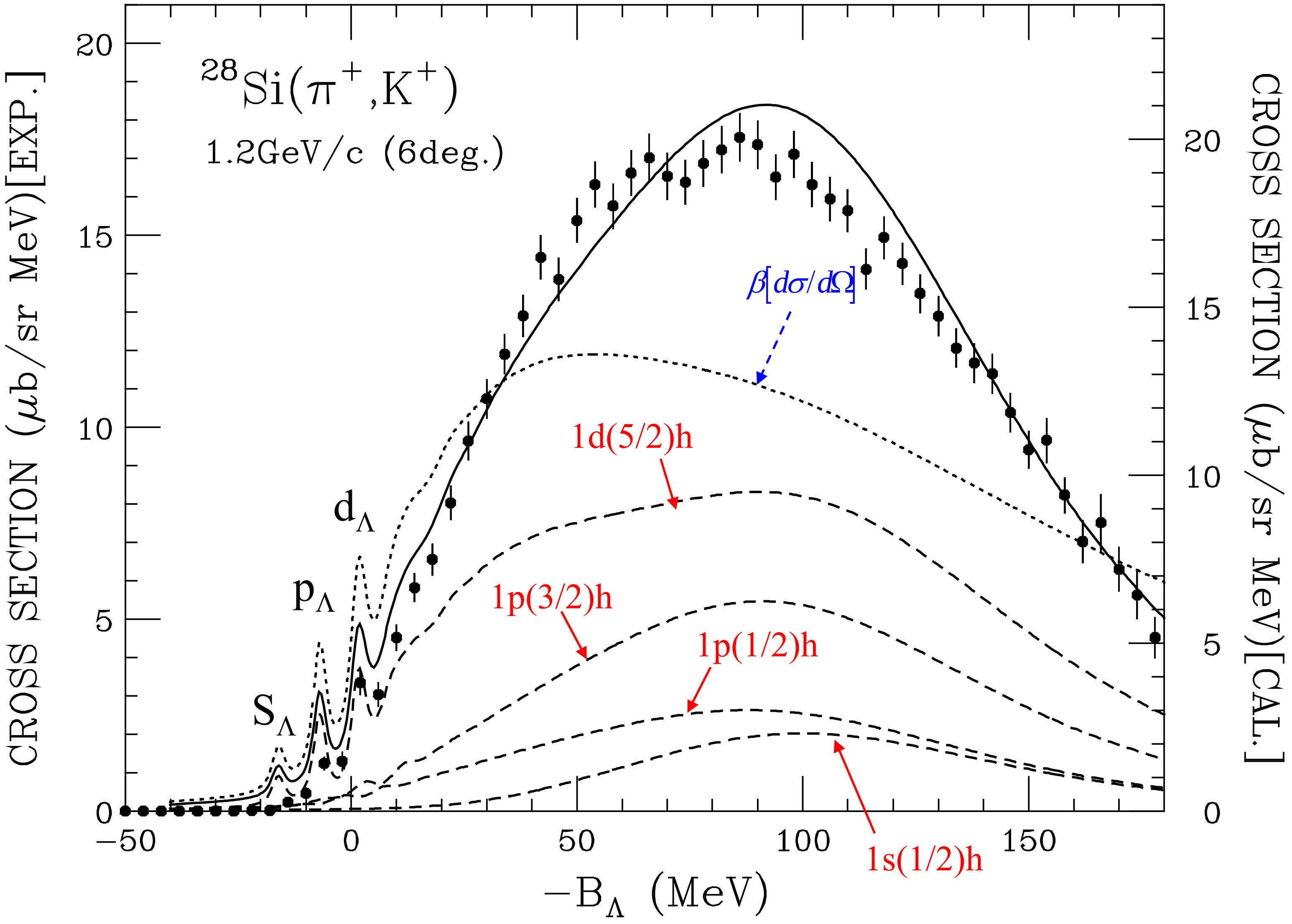
$$\left[\frac{d\sigma}{d\Omega}\right]^{\mathrm{opt}}_{\pi^+ p \rightarrow K^+ \Lambda} = \frac{k_K E_K}{(2\pi)^2 v_\pi} \left|\hat{t}^{\mathrm{opt}}(E,\theta)\right|^2$$



Λ spectrum by (π^+,K^+) reaction at 1.2GeV/c

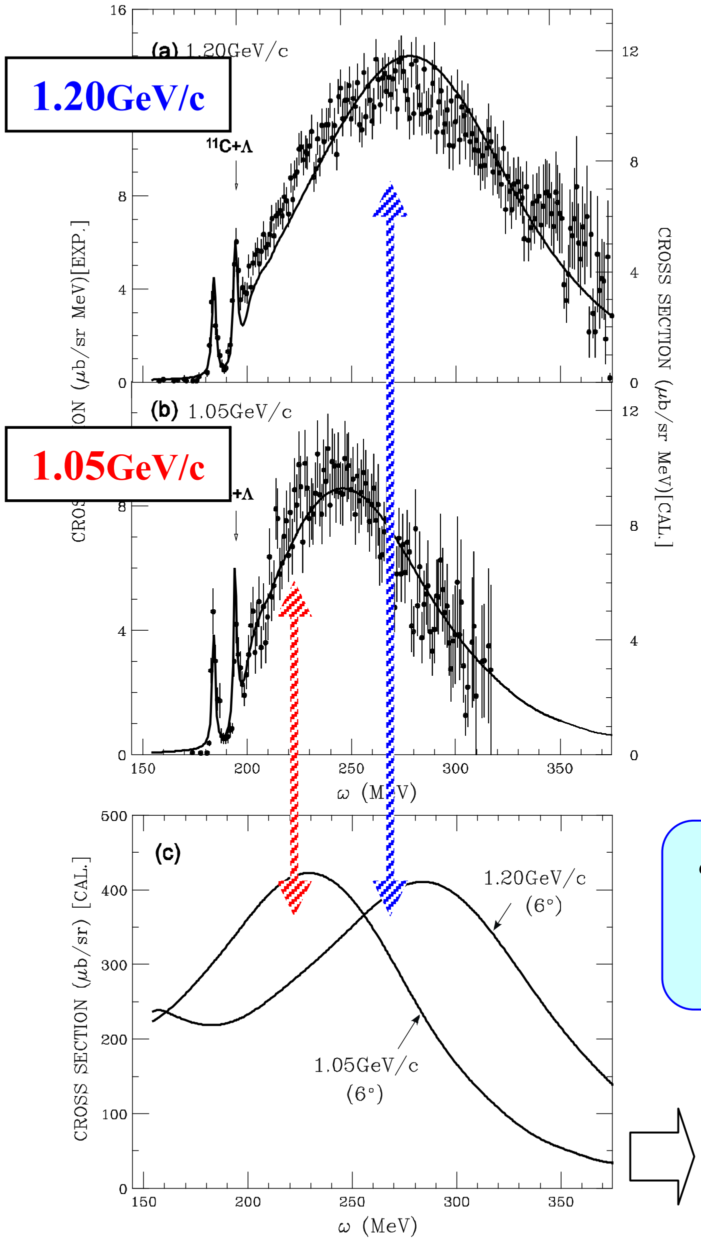
^{28}Si

KEK-E438



The contribution of deep hole-states is important !

^{12}C(π^+,K$^+$) Reactions



- The calculated spectra in QF region can explain the experimental data at 1.20 and 1.05GeV/c.
- The ω energy-dependence originates from the nature of the "optimal Fermi-averaging" t-matrix.

make the width look narrow

$$\frac{d^2\sigma}{dE_\pi d\Omega} = \left[\frac{d\sigma}{d\Omega}\right]^{\mathrm{opt}}_{\pi^+ n \to K^+ \Lambda} S(\omega,\mathbf{q})$$

"Optimal Fermi-averaging" t-matrix $\hat{t}^{\mathrm{opt}}(p_\pi;\omega,\mathbf{q})$

Strength function

well-known

Λ-nucleus potential

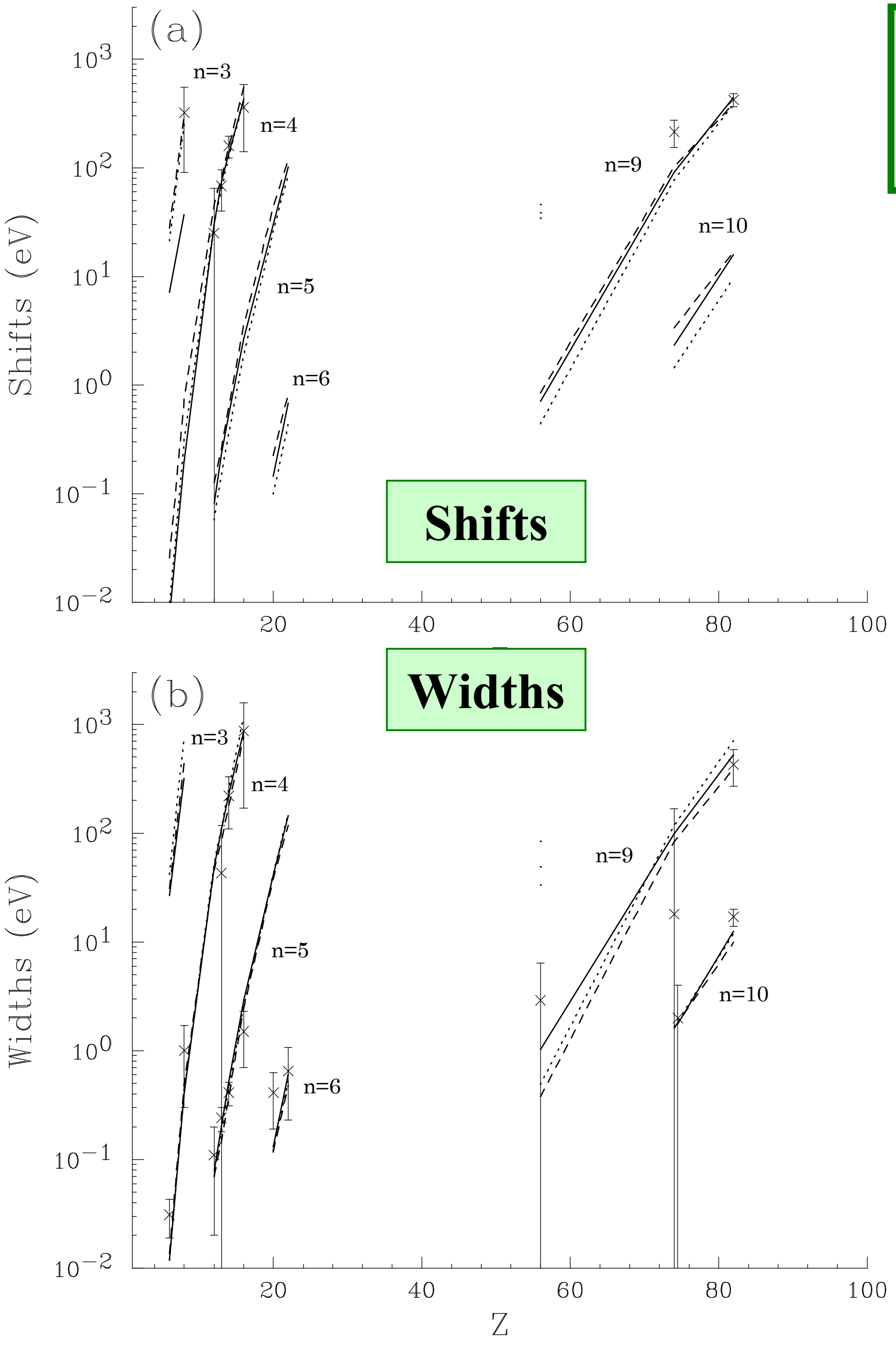
Need careful consideration for energy-dependent of the elementary cross section.

Is the Σ-nucleus potential for Σ^- atoms consistent with the (π^-, K^+) data?

^{28}Si T.H and Y.Hirabayashi, NPA759(2005)143

Isospin dependence of Σ-nucleus potentials for N > Z

^{209}Bi T.H and Y.Hirabayashi, NPA767(2006)206



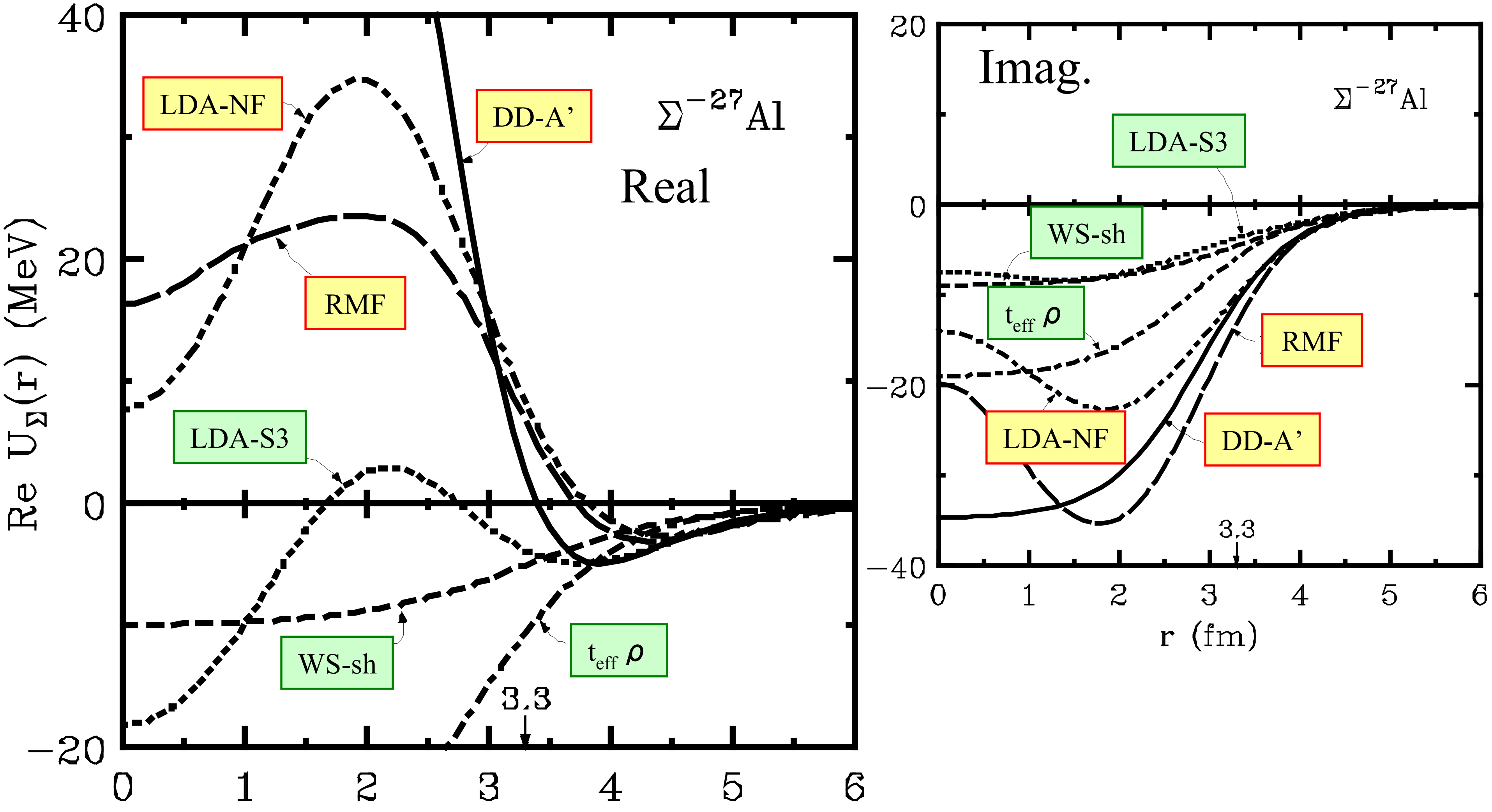
Observation of Σ^- atomic X-ray

G. Backenstoss, et al., Z. Phys. A273(1975)137
C.J. Batty, et al.,Phys.Lett.B 74 (1978) 27
R.J. Powers, et al.,PRC47(1993)1263

C	4→3	Γu
O	4→3	ε, Γu
Mg	5→4	ε, Γu
Al	5→4	ε, Γ, Γu
Si	5→4	ε, Γ, Γu
S	5→4	ε, Γ, Γu
Ca	6→5	Γu
Ti	6→5	Γu
Ba	9→8	Γu
W	10→9	ε, Γ, Γu
Pb	10→9	ε, Γ, Γu

Only 23 measurements !!

Σ^--nucleus optical potentials in ^{27}Al+Σ^-



	Real part	Imag. part		Real part	Imag. part
Type I	repulsive	strong (30-40MeV)	**Type II**	(weak) attractive	weak (< 10MeV)

Σ^--nucleus potentials fitted to the Σ^--atomic data

DD-A' **Density-dependent (DD) potential** C.J.Batty et al., Phys.Rep.287(1997)385

$\chi^2/N=20.1/23$

$$2\mu U_\Sigma = -4\pi\left(1+\frac{\mu}{m}\right)\left\{\left[b_0+B_0\left(\frac{\rho(r)}{\rho(0)}\right)^\alpha\right]\rho(r)+\left[b_1+B_1\left(\frac{\rho(r)}{\rho(0)}\right)^\alpha\right]\delta\rho(r)\right\}$$

$$\rho(r)=\rho_p(r)+\rho_n(r) \qquad \delta\rho(r)=\rho_n(r)-\rho_p(r)$$

RMF **Relativistic mean-field (RMF) potential** J. Mares et al., NPA594(1995)311

$\chi^2/N=18.1/23$

LDA-NF **Local density approximation (LDA) with YNG-NF**

$\chi^2/N=20.4/23$

D. Halderson, Phys. Rev. C40(1989)2173

T.Yamada and Y.Yamamoto, PTP. Suppl. 117(1994)241

J. Dabrowski, Acta Phys. Pol. B31(2001)2179

Repulsive

Attractive

LDA-S3 **Local density approximation (LDA) with SAP3 (simulates ND)**

T.Harada, in: Proceedings of the 23nd INS Symp. 1995, p.211

WS-sh **Shallow Woods-Saxon potential**: $(V_0,W_0)=(-10,-9)$ MeV

R.S.Hayano, NPA478(1988)113c

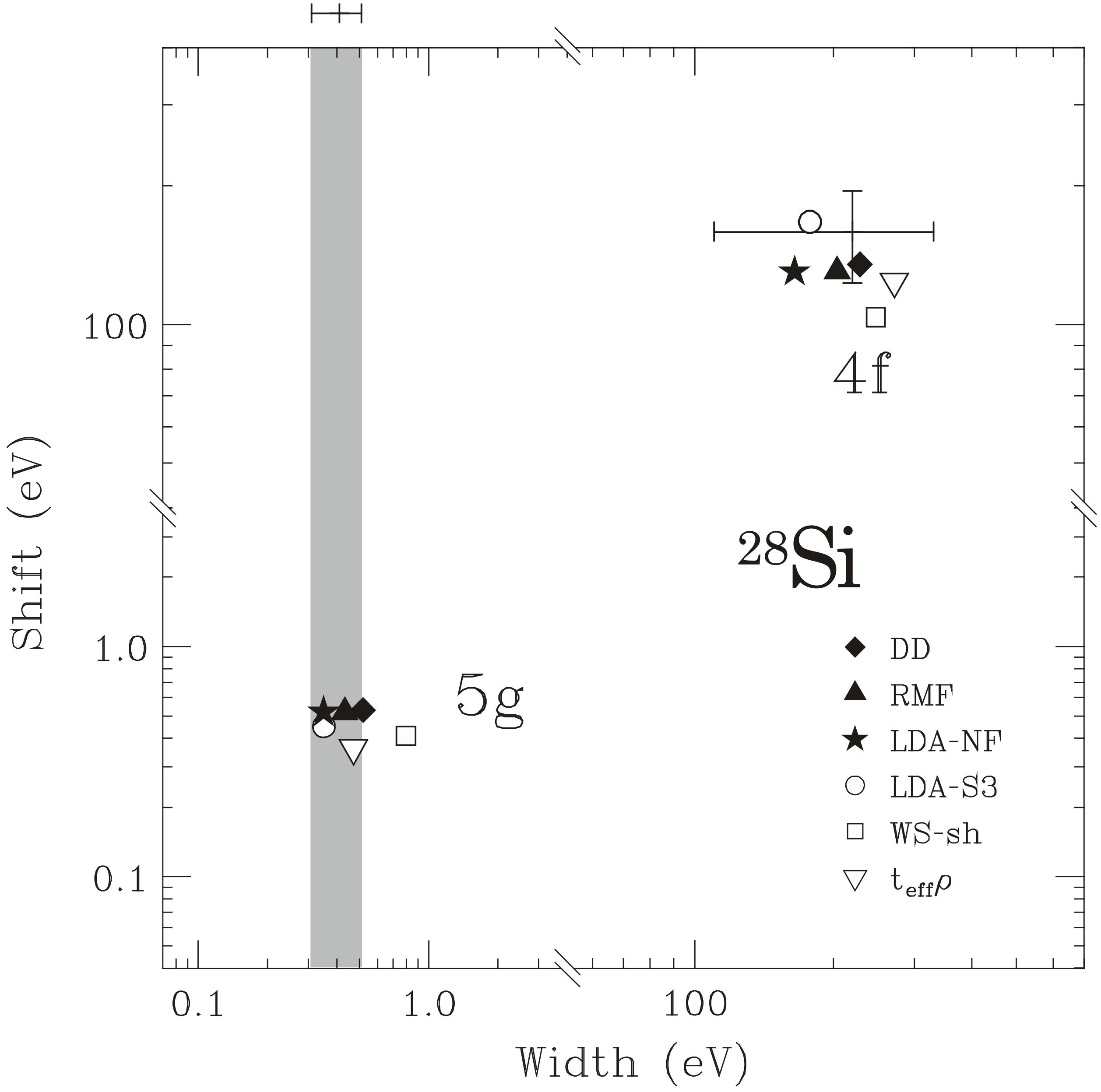
$t_{eff}\,\rho$ **$t_{eff}\,\rho$–type potential ($B_0=B_1=0$):** $a_0=0.36+i0.20$ fm

$\chi^2/N=23.1/23$

C.J.Batty, E.Friedman, A.Gal, PTP. Suppl. 117(1994)227

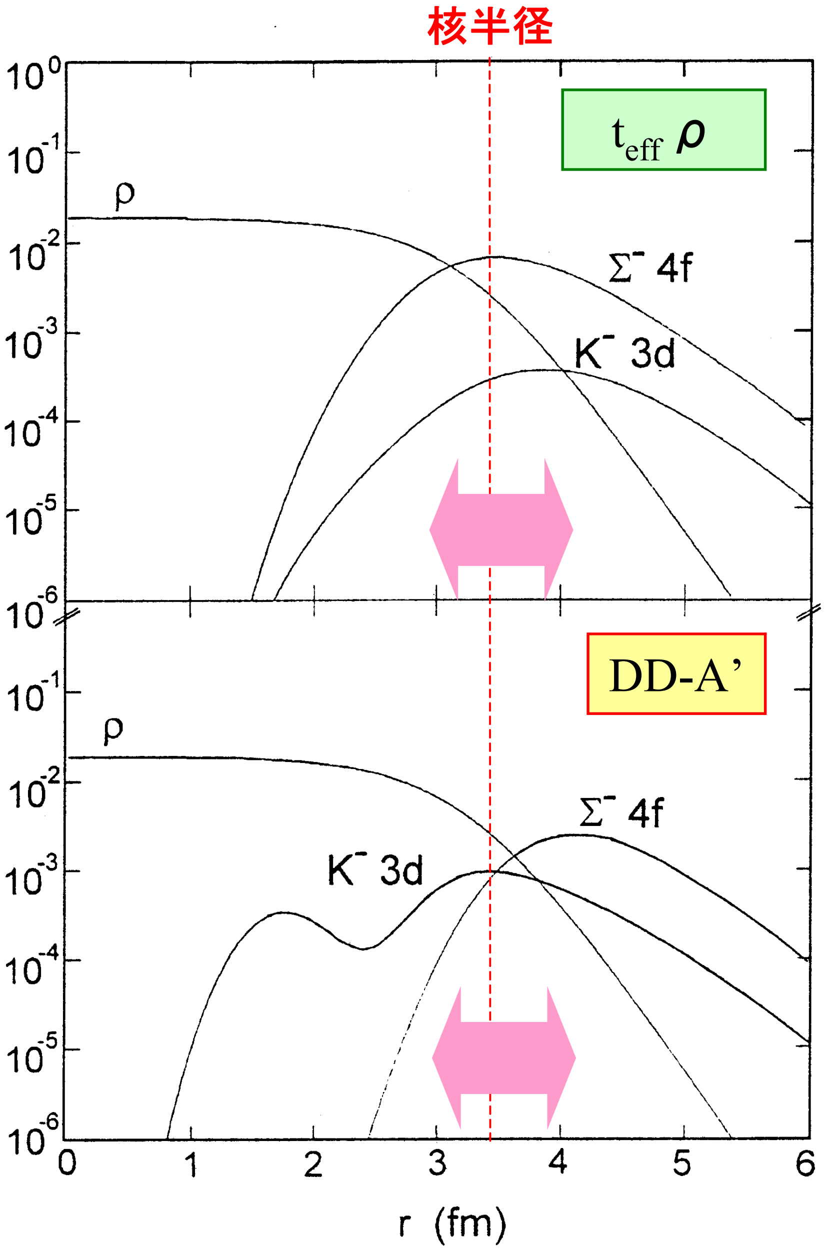
Strong-shifts and widths on Σ^- atoms

$\Sigma^{-28}Si$



Σ^-原子のX線データは核のどの領域をみているのか？

^{32}S



C.J. Batty et al.,
Phys.Rep.287(1997)385

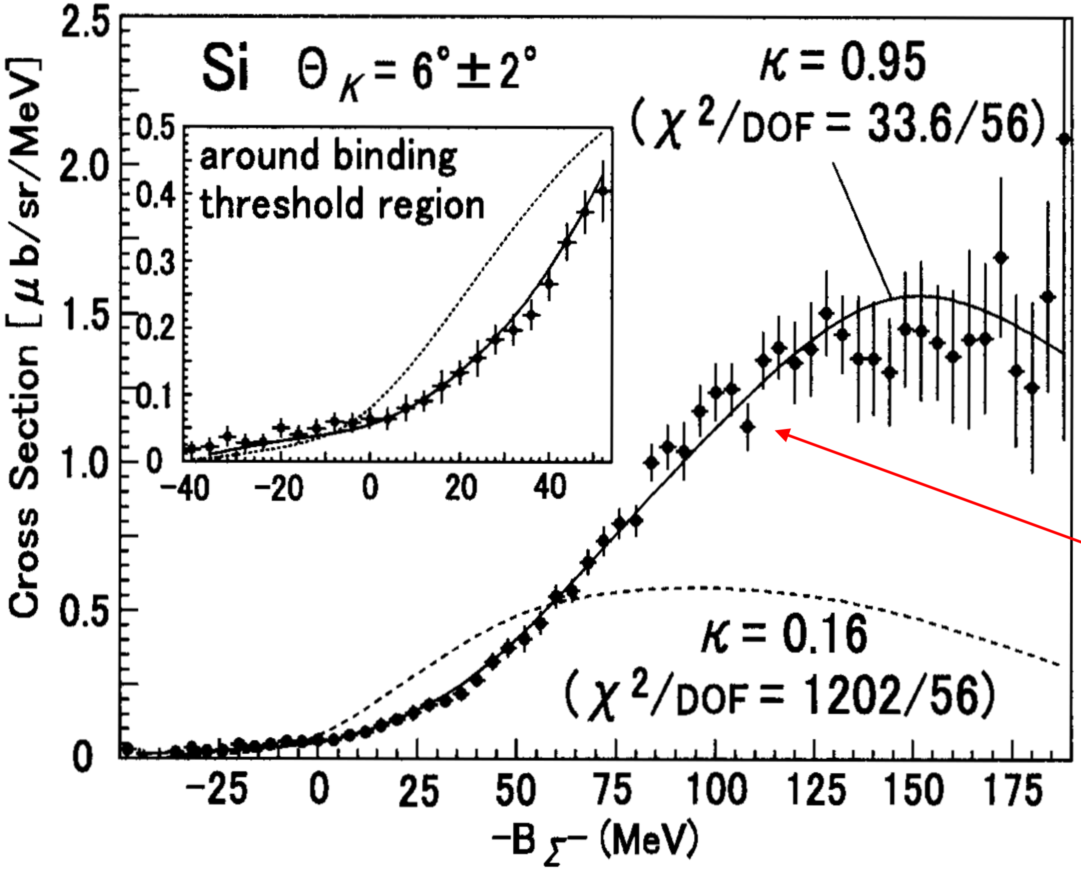
Cf.（stopped K^-,π^+）

Σ^- spectrum by (π^-,K^+) reaction at 1.2GeV/c

(π^-,K^+)反応による生成 原子核内部からΣ粒子を生成 標的: ^{28}Si, ^{58}Ni, ^{115}In, ^{209}Bi

^{28}Si

H.Noumi, et al. PRL89(2002)072301



Woods-Saxon form

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

$$R = r_0(A-1)^{1/3}\text{fm}$$

$$a = 0.67\ \text{fm} \quad r_0 = 1.1\text{fm}$$

$V_\Sigma = +150$ MeV

$W_\Sigma = -15$ MeV

+90 MeV

−40 MeV

(NEW)

P.K.Saha, et al., PRC70(2004)044613

Calculations for Hypernuclear Production

Distorted-wave Impulse Approximation (DWIA)

Double-Differential Cross Sections

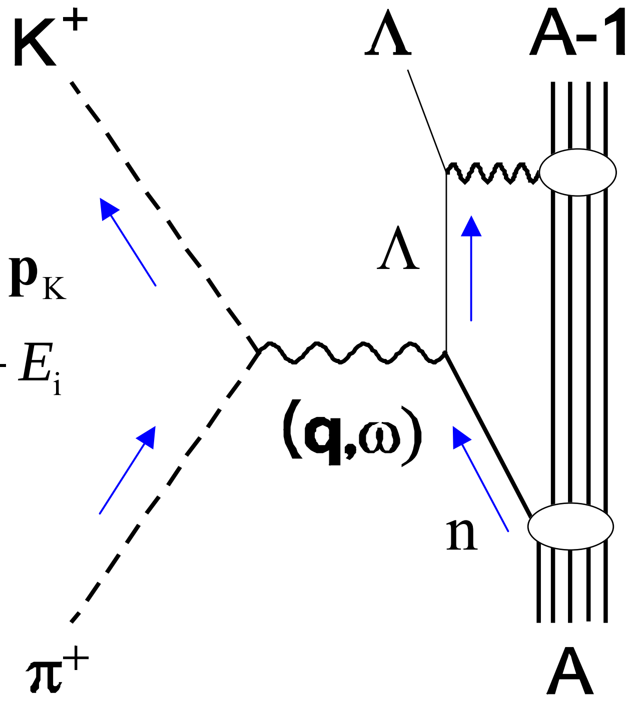
"Optimal" elementary cross sections

Strength function

$$\frac{d^2\sigma}{dE_\pi d\Omega} = \left[\frac{d\sigma}{d\Omega}\right]^{\text{opt}}_{\pi^+ n \to K^+\Lambda} S(\omega,\mathbf{q})$$

$$\mathbf{q} = \mathbf{p}_\pi - \mathbf{p}_{\mathrm{K}}$$

$$\omega = E_{\mathrm{f}} - E_{\mathrm{i}}$$



Strength function

$$S(\omega,\mathbf{q}) = \sum_f \left| < f \,|\, \chi^{(-)*}_{K+} U\_\chi^{(+)}_{\pi+} \,|\, i > \right|^2 \delta(\omega + E_\pi - E_K)$$

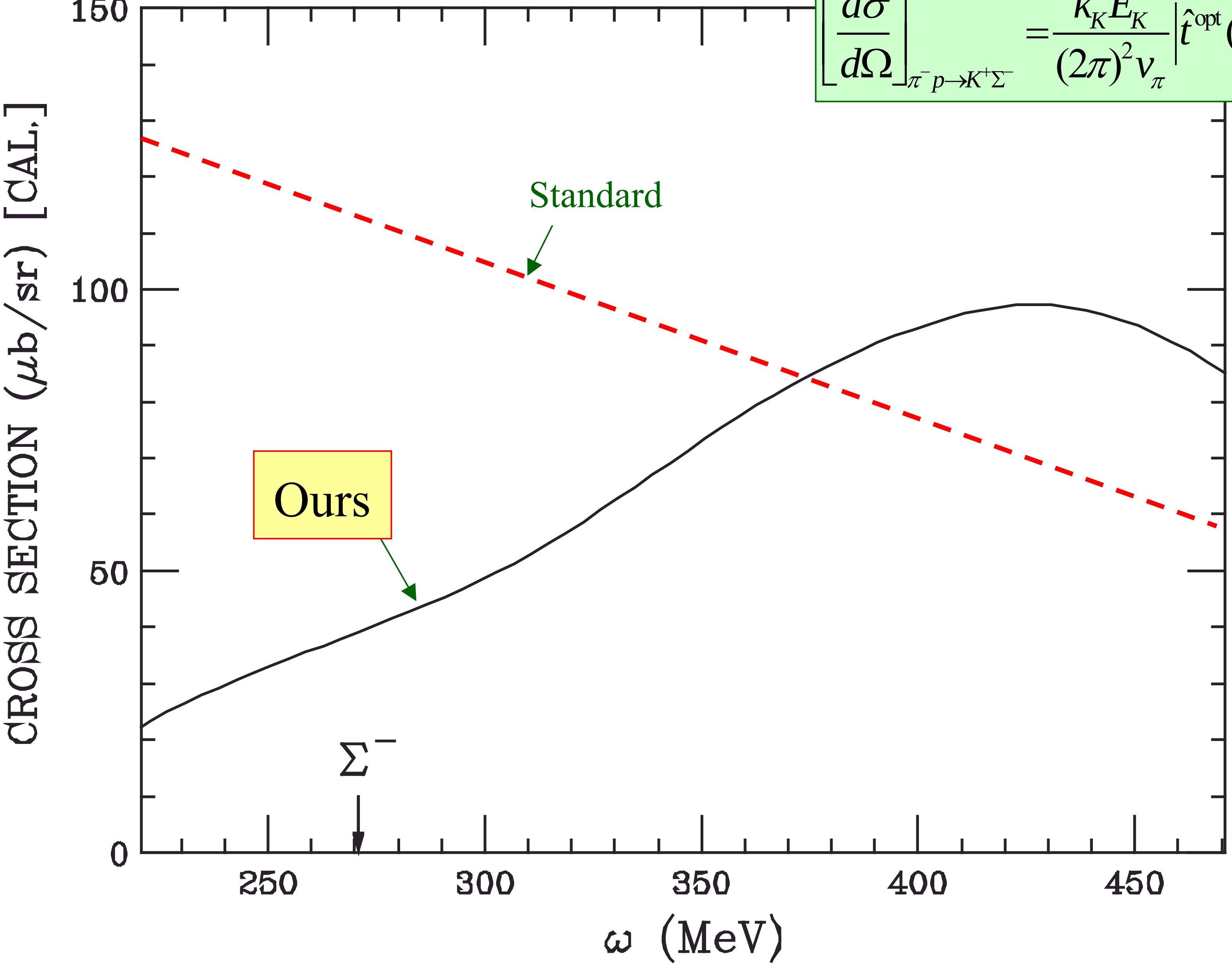
Meson distorted-wave functions **(Eikonal or Full optical model approximation)**

$$\chi^{(-)*}_{K+}(\mathbf{r})\chi^{(+)}_{\pi+}(\mathbf{r}) = \sum_L \sqrt{4\pi(2L+1)}\, i^L \boxed{\tilde{j}^{(+)}_{LM}(r)}\, Y_{LM}(\hat{\mathbf{r}})$$

$$\boxed{\tilde{j}^{(+)}_{LM}(r)} = \sum_{ll'} (-)^{\frac{l-l'-L}{2}} \sqrt{4\pi(2l'+1)}\, \frac{2l+1}{2L+1}\, \tilde{j}^{(+)}_{l}(k_\pi;r)\, \tilde{j}^{(+)}_{l'}(k_K;r)$$
$$\times (l0l'M \,|\, LM)(l0l'0 \,|\, L0) Y^{*}_{l'M}(\hat{\mathrm{k}}_K)$$

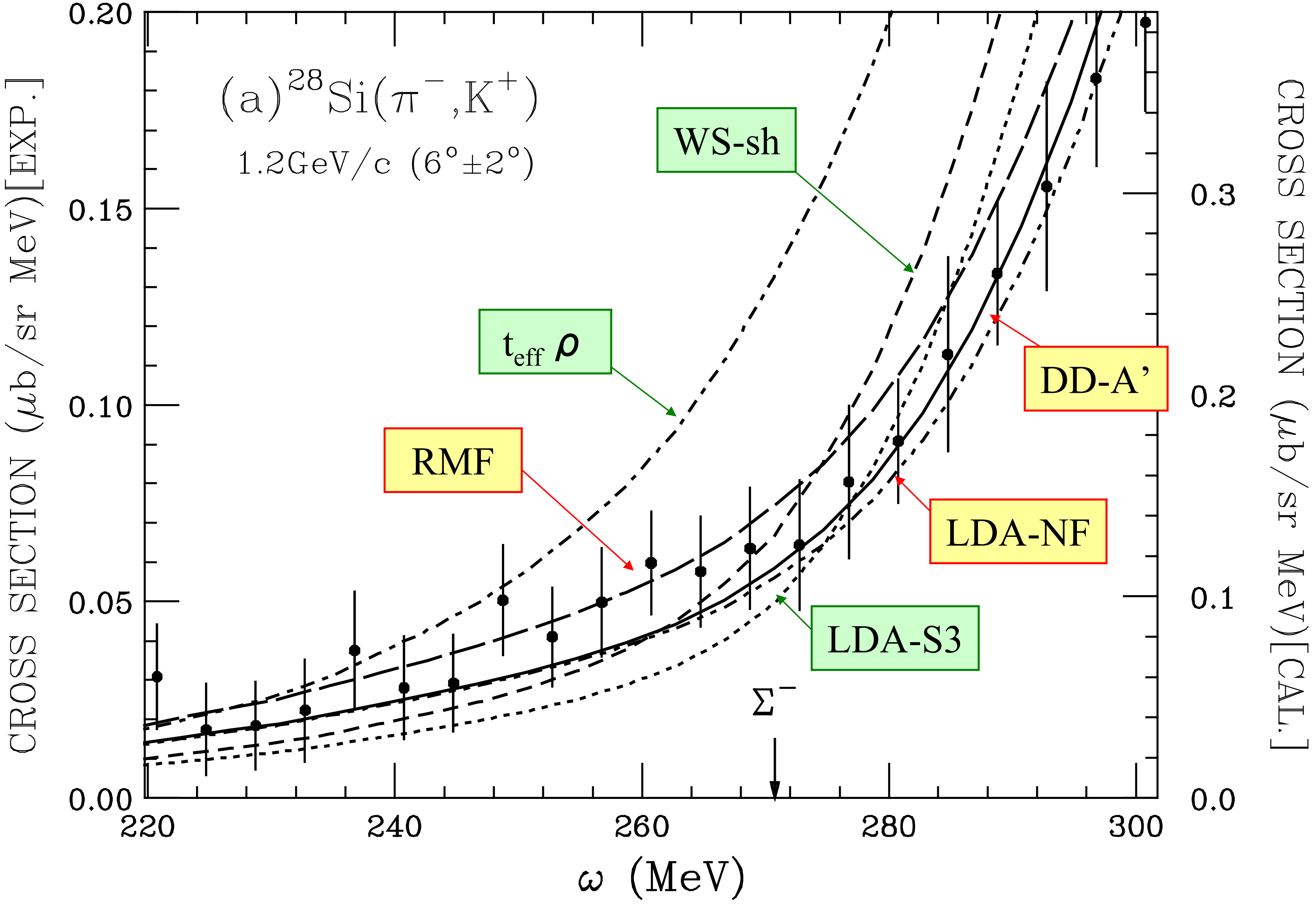
“Optimal” cross section of $\pi^- p \to K^+\Sigma^-$ reactions in nuclei

$$\left[\frac{d\sigma}{d\Omega}\right]^{\mathrm{opt}}_{\pi^- p\to K^+\Sigma^-} = \frac{k_K E_K}{(2\pi)^2 v_\pi}\left|\hat{t}^{\mathrm{opt}}(p_\pi;\omega,\mathbf{q})\right|^2$$



Σ^- spectrum by (π^-,K^+) reaction at 1.2GeV/c

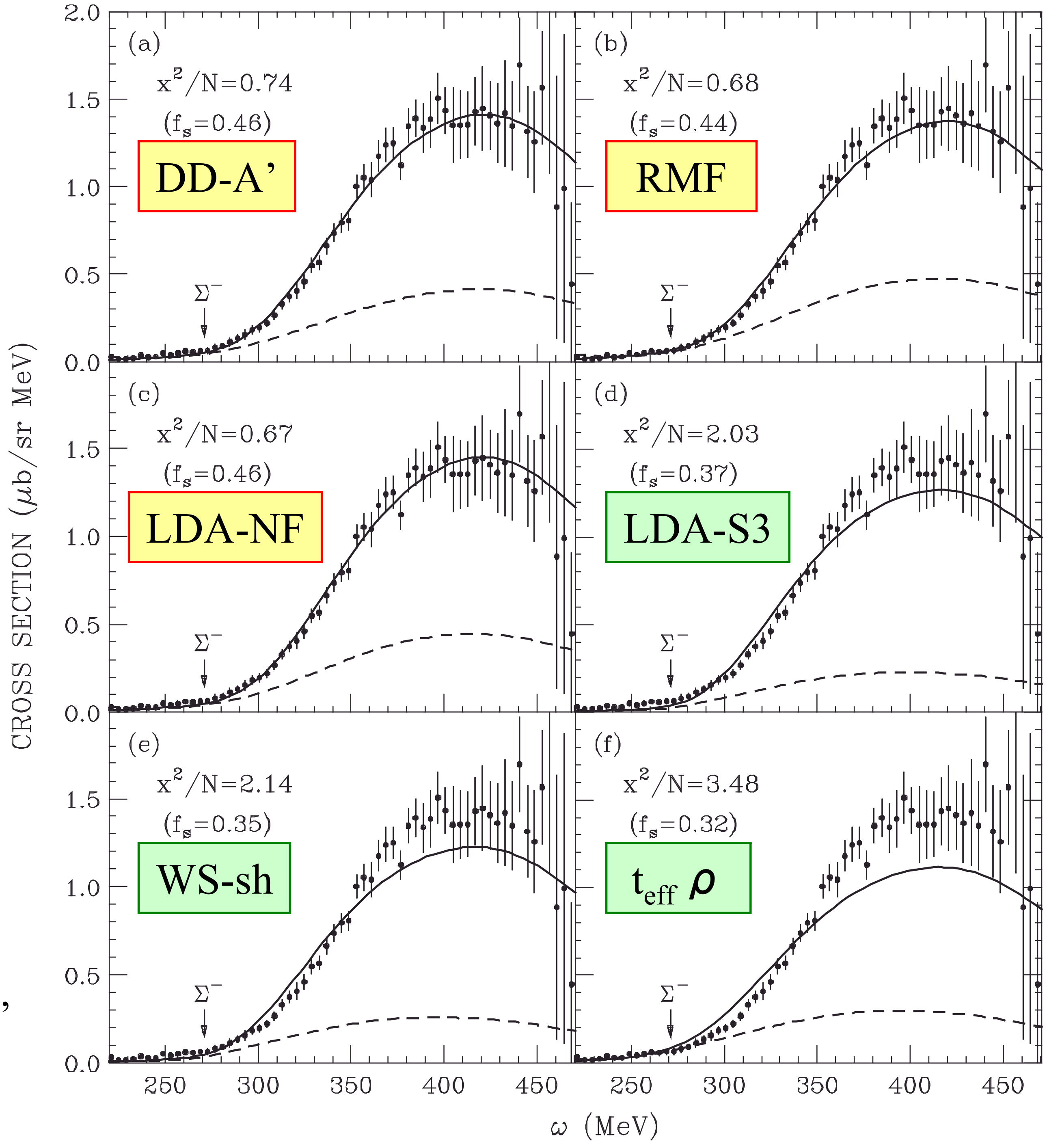
T.Harada, Y.Hirabayashi, NPA759 (2005) 143



(π^-,K^+) reaction at 1.2GeV/c

^{28}Si

Σ^-



T.Harada, Y.Hirabayashi,
NPA759 (2005) 143

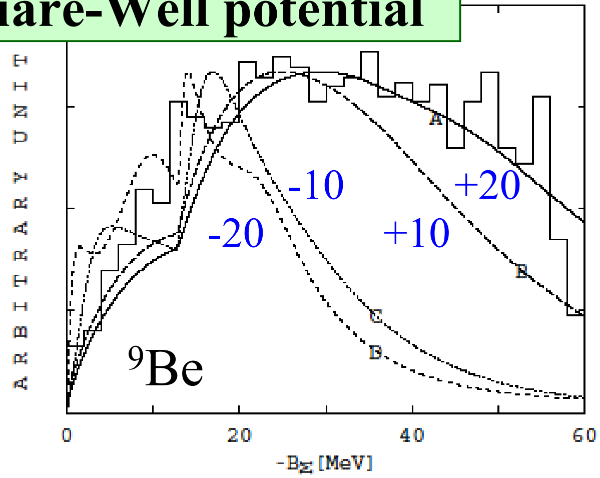
Comparison with resent studies

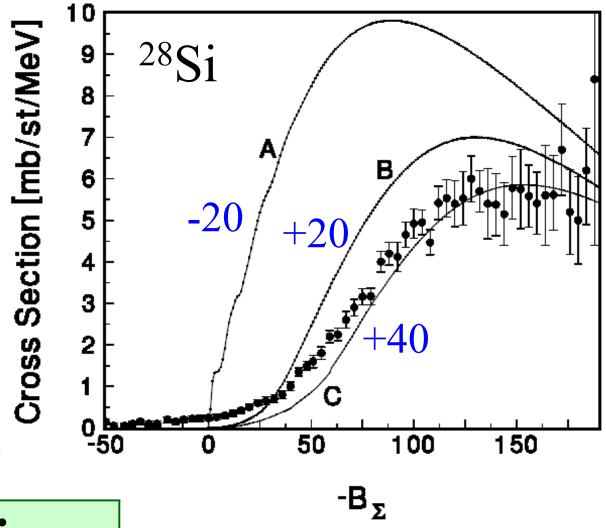
PWIA Analysis with the Square-Well potential

J. Dabrowski, PRC60 (1999) 025205.

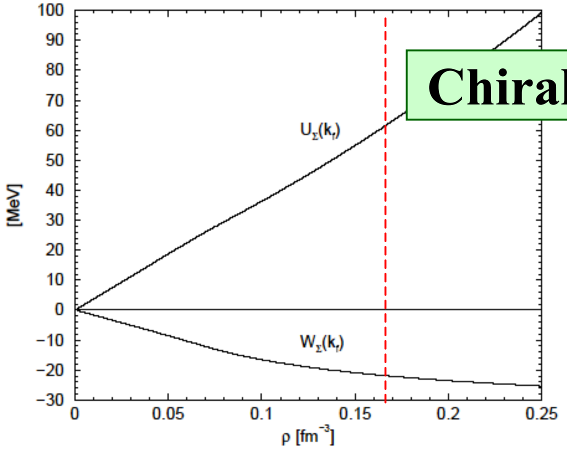
J. Dabrowski, J. Rozynek, Acta. Phys.
Pol. B35 (2004) 2303.

"The Σ s.p. potential is repulsive inside nucleus. Only NHC-F is acceptable."





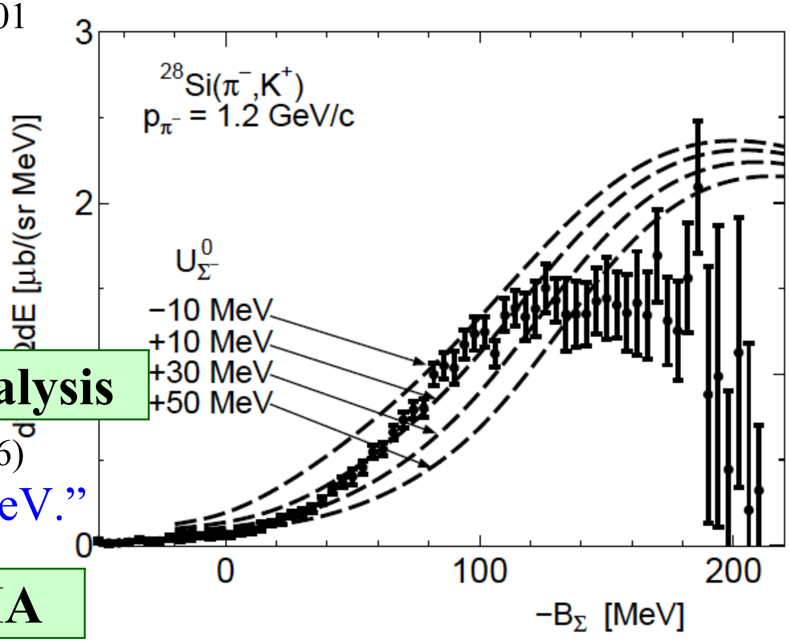
Chiral dynamics in the nuclear medium



N. Kaiser, PRC71 (2005) 068201

$U_\Sigma(\rho_0)$ ~ 59MeV
repulsive

$W_\Sigma(\rho_0)$~ –21MeV



Semi-Classical Distorted Wave Model Analysis

M. Kohno, Y. Fujiwara, et al., nucl-th/0611080 (2006)

"The repulsive Σ potential is not so strong as ~100MeV."

Local Optimal Fermi-averaged t-matrix DWIA

H. Maekawa, A.Ohnishi, et al., Eur.Phys.J.A33(2007)269.

Feasibility of extracting a Σ^- admixture probability in the neutron-rich $^{10}_{\Lambda}$Li hypernucleus

T.H, A.Umeya, Y. Hirabayashi, PRC79(200)014603

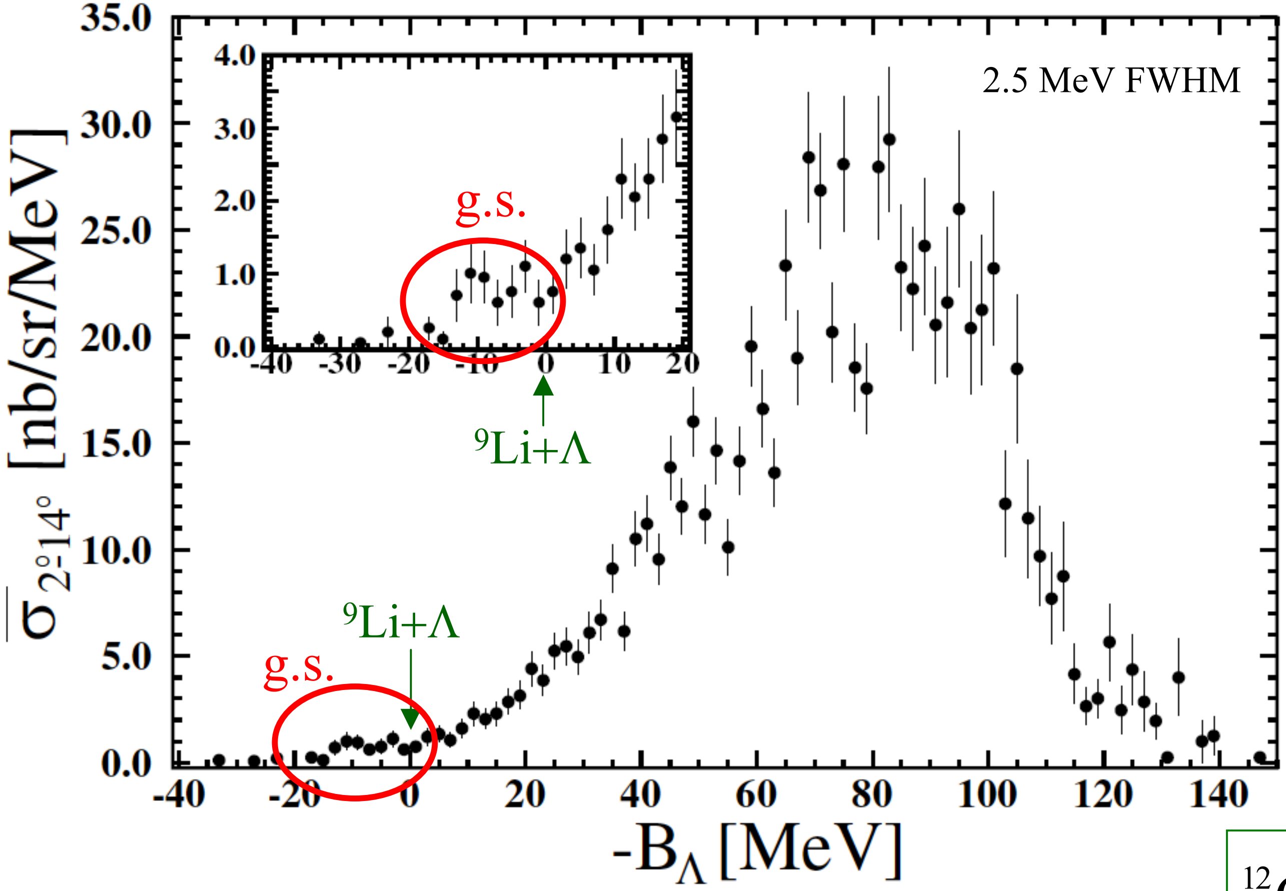
Λ spectrum by DCX (π^-,K^+) reaction at 1.2GeV/c

$^{10}\mathrm{B}(\pi^-,K^+)^{10}_{\Lambda}\mathrm{Li}$

neutron-rich Λ hypernucleus

First successful measurements

KEK-PS-E521 P. K. Saha, et al., PRL94(2005)052502



Cross sections

- p_π=1.20 GeV/c

$$\frac{d\sigma}{d\Omega_L} \approx 11.3 \pm 1.9 \text{ nb/sr}$$

- p_π=1.05 GeV/c

$$\frac{d\sigma}{d\Omega_L} \approx 5.8 \pm 2.2 \text{ nb/sr}$$

～1/1000

$^{12}\mathrm{C}(\pi^+,K^+)^{12}_{\Lambda}\mathrm{C}$ at 1.20 GeV/c

17.5±0.6 μb/sr

(π^-, K^+) —Double Charge Exchange (DCX) Reaction

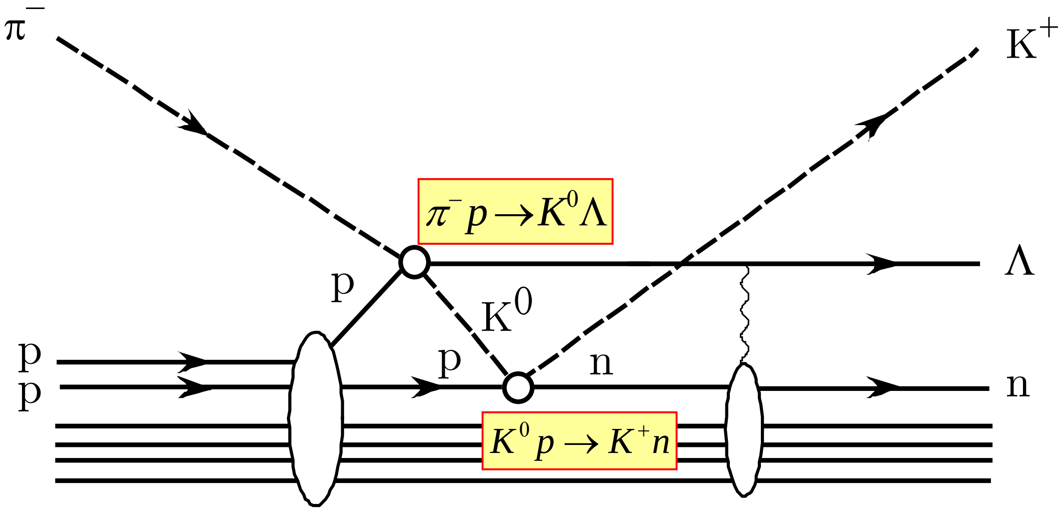
- ***Two-step process:***

$$\pi^- p \rightarrow K^0 \Lambda$$

$$K^0 p \rightarrow K^+ n$$

$$\pi^- p \rightarrow \pi^0 n$$

$$\pi^0 p \rightarrow K^+ \Lambda$$

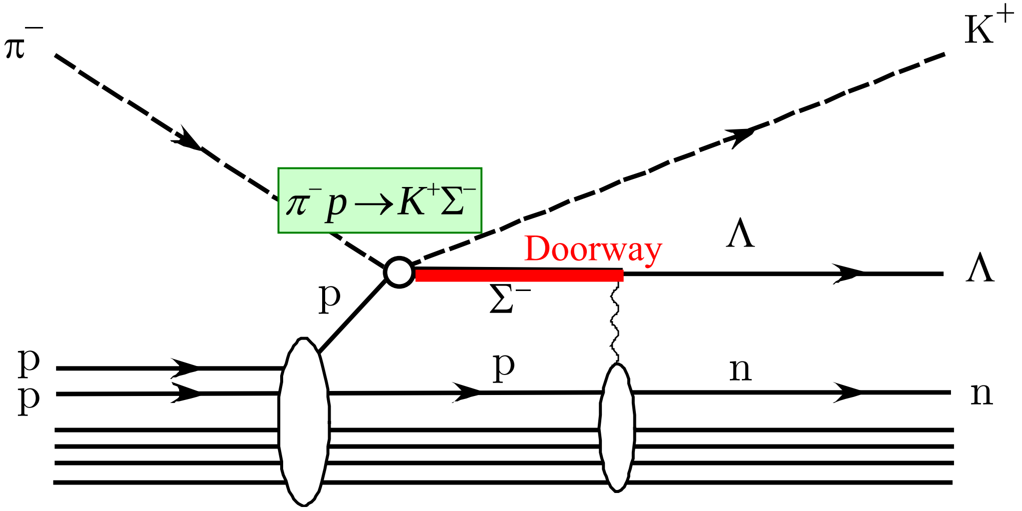


- ***One-step process:***

$$\pi^- p \rightarrow K^+ \Sigma^-$$

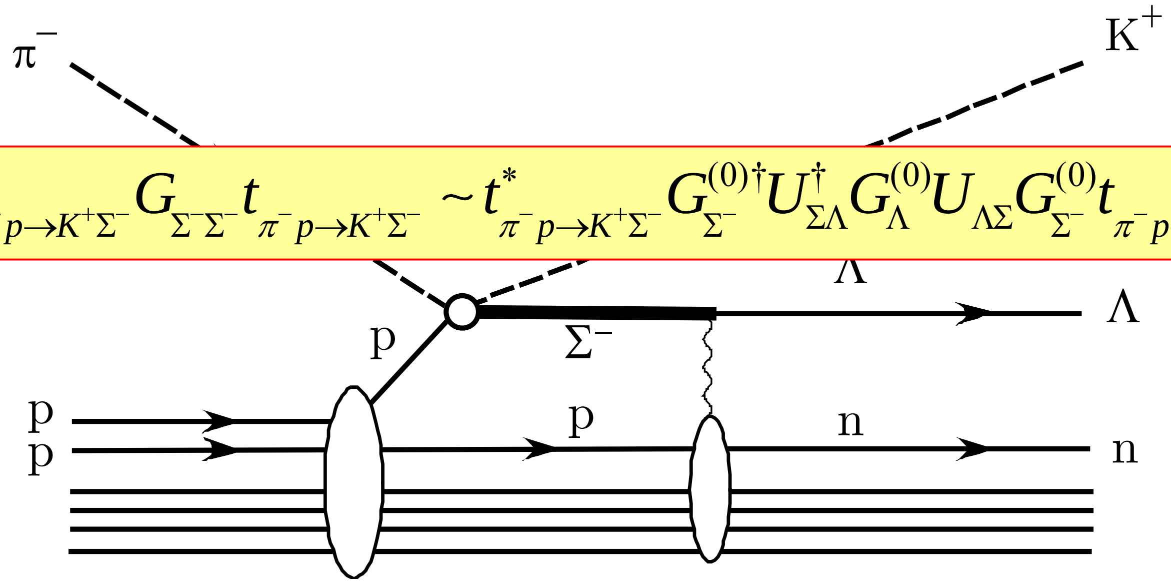
$$\Sigma^- p \leftrightarrow \Lambda n$$

Σ-Λ coupling

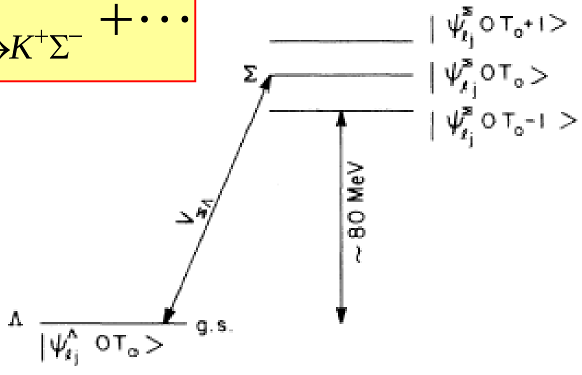


Coupled-channel DWIA calculations

T.Harada, NPA672(2000)181



$$t^*_{\pi^- p\to K^+\Sigma^-} G_{\Sigma^-\Sigma^-} t_{\pi^- p\to K^+\Sigma^-} \sim t^*_{\pi^- p\to K^+\Sigma^-} G^{(0)\dagger}_{\Sigma^-} U^\dagger_{\Sigma\Lambda} G^{(0)}_{\Lambda} U_{\Lambda\Sigma} G^{(0)}_{\Sigma^-} t_{\pi^- p\to K^+\Sigma^-} + \cdots$$



Coupled-channel Green's function

$$\hat{\mathbf{G}}(\omega) = \hat{\mathbf{G}}^{(0)}(\omega) + \hat{\mathbf{G}}^{(0)}(\omega)\hat{\mathbf{U}}\hat{\mathbf{G}}(\omega)$$

$$\hat{\mathbf{G}}^{(0)}(\omega) = \begin{bmatrix} G^{(0)}_{\Lambda} & \\ & G^{(0)}_{\Sigma^-} \end{bmatrix} \quad \hat{\mathbf{U}} = \begin{bmatrix} U_\Lambda & U_X \\ U_X & U_\Sigma \end{bmatrix}$$

$$\mathrm{Im}\hat{G} = \underbrace{\hat{\Omega}^{(-)\dagger}\{\mathrm{Im}\hat{G}^{(0)}_{\Lambda}\}\hat{\Omega}^{(-)}}_{\Lambda\text{ escape}} + \underbrace{\hat{\Omega}^{(-)\dagger}\{\mathrm{Im}\hat{G}^{(0)}_{\Sigma^-}\}\hat{\Omega}^{(-)}}_{\Sigma^-\text{ escape}} + \underbrace{\hat{G}^{\dagger}\{W_{Y,T}\}\hat{G}}_{\substack{\text{Spreading (nuclear-core breakup)} \\ = \text{Complicated excited states}}}$$

Strength function

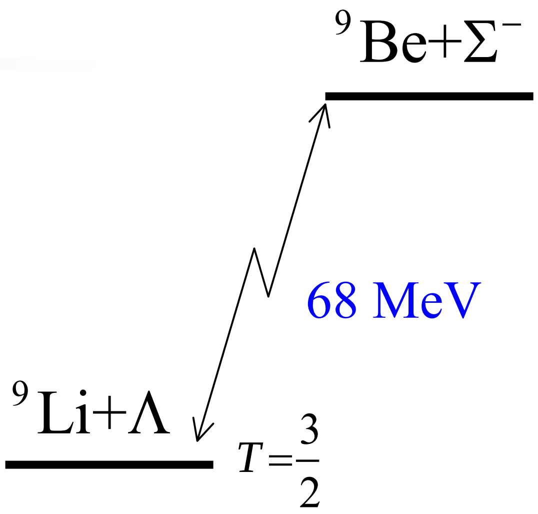
Green's function method

Morimatsu, Yazaki, NPA483(1988)493

$$S(\omega) = \sum_f |< f\,|\hat{O}|\,i>|^2\,\delta(\omega + E_K - E_\pi) = -\frac{1}{\pi}\mathrm{Im}\int \mathrm{d}\mathbf{r}\mathrm{d}\mathbf{r}' F^\dagger(\mathbf{r}) \boxed{\mathrm{G}(\omega + i\varepsilon;\mathbf{r},\mathbf{r}')} F(\mathbf{r}')$$

Green's function

Model for calculations



Single-particle shell model wf.

$$\left|{}^{10}_{\Lambda}\mathrm{Li}\right\rangle = \alpha\left|{}^{9}\mathrm{Li}\otimes\Lambda\right\rangle + \beta\left|{}^{9}\mathrm{Be}\otimes\Sigma^-\right\rangle$$

$$\alpha^2+\beta^2=1$$

Hyperon-nucleus potentials

Woods-Saxon form $R=r_0(A-1)^{1/3}\mathrm{fm}$ $r_0=1.128+0.439A^{-2/3}\mathrm{fm}$ $a=0.6\ \mathrm{fm}$

$$U_{Y=\Lambda,\Sigma}=-(V_Y+iW_Y)/(1+\exp[(r-R)/a])$$

30 MeV for Λ

spreading potential : energy-dependent = excited states

$$U_X=\left\langle {}^{9}\text{Li-}\Lambda\right|\sum_j\frac{1}{\sqrt{3}}v_{\Lambda\Sigma}\vec{\tau}_j\cdot\vec{\phi}\left|{}^{9}\text{Be-}\Sigma^-\right\rangle=V_X/(1+\exp[(r-R)/a])$$

Λ-Σ coupling pot.

Distorted waves for mesons

Eikonal distortion: $\bar{\sigma}=(\sigma_\pi+\sigma_K)/2=20\ \mathrm{mb},\ \ \alpha_\pi=\alpha_K=0$

Elementary cross section : $\pi^- p\to K^+\Sigma^-$

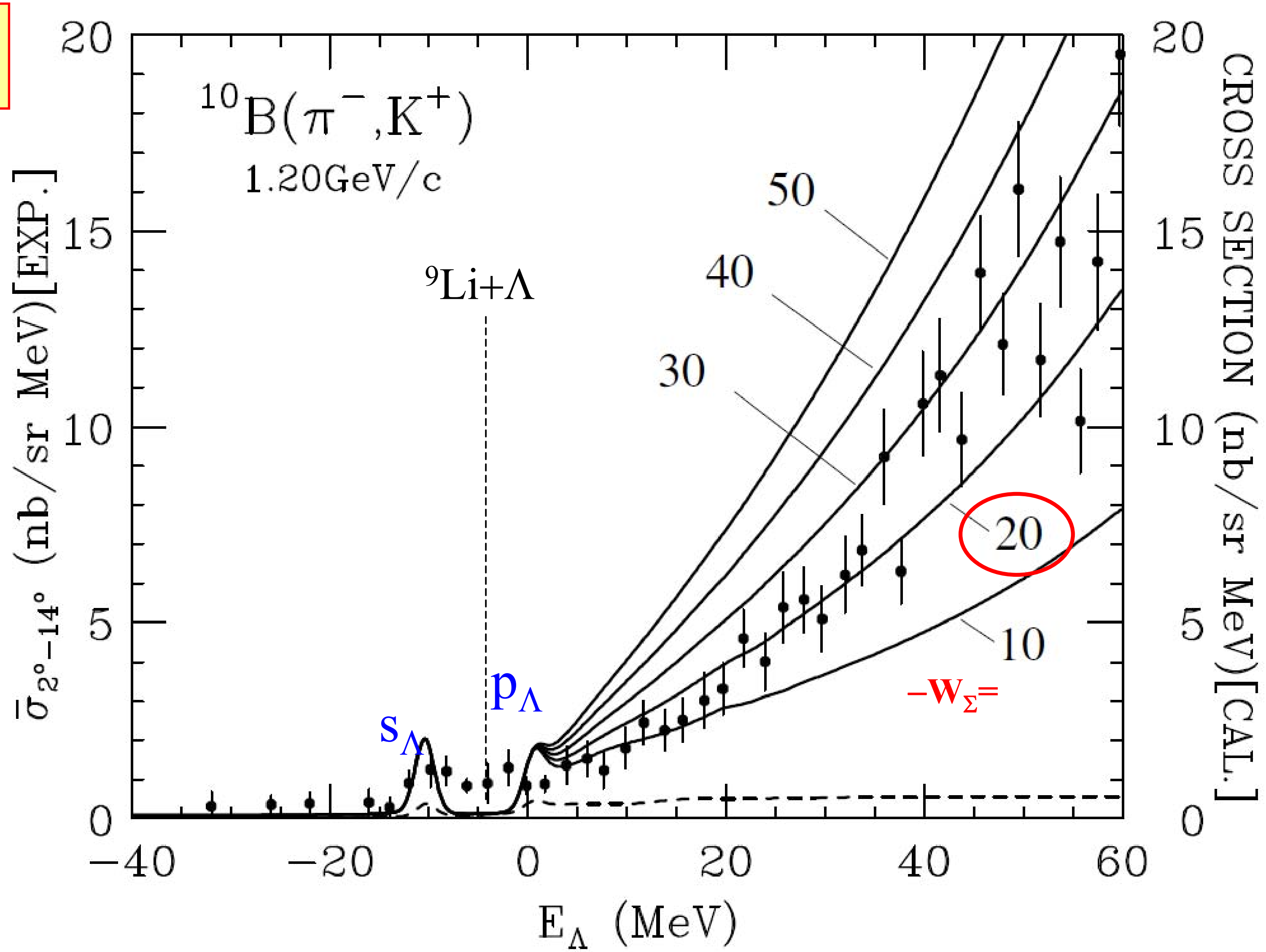
$\beta[\mathrm{d}\sigma/\mathrm{d}\Omega]$ Optimal Fermi-averaging ～10-20 μb/sr (p_π=1.2GeV/c)

Λ spectrum by DCX (π^-,K^+) reaction at 1.2GeV/c

Spreading potential dep.

U_X =11 MeV is fixed. $P_{\Sigma-}$=0.57%

^{10}B



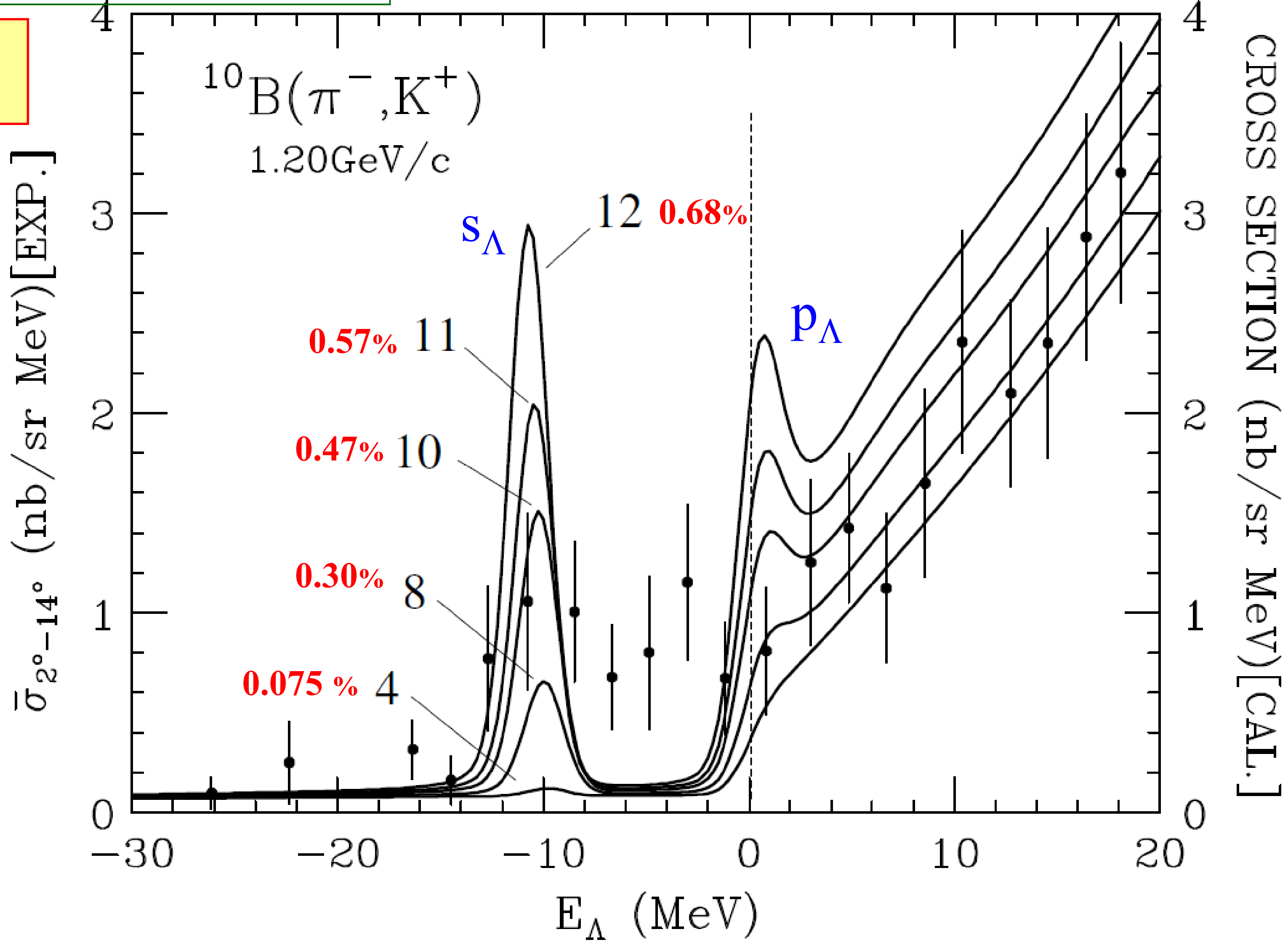
⇨ $-W_\Sigma$ = 20-30 MeV はΣ⁻生成の解析と矛盾しない。

Λ spectrum by DCX (π^-,K^+) reaction at 1.2GeV/c

Coherent Λ-Σ coupling dep.

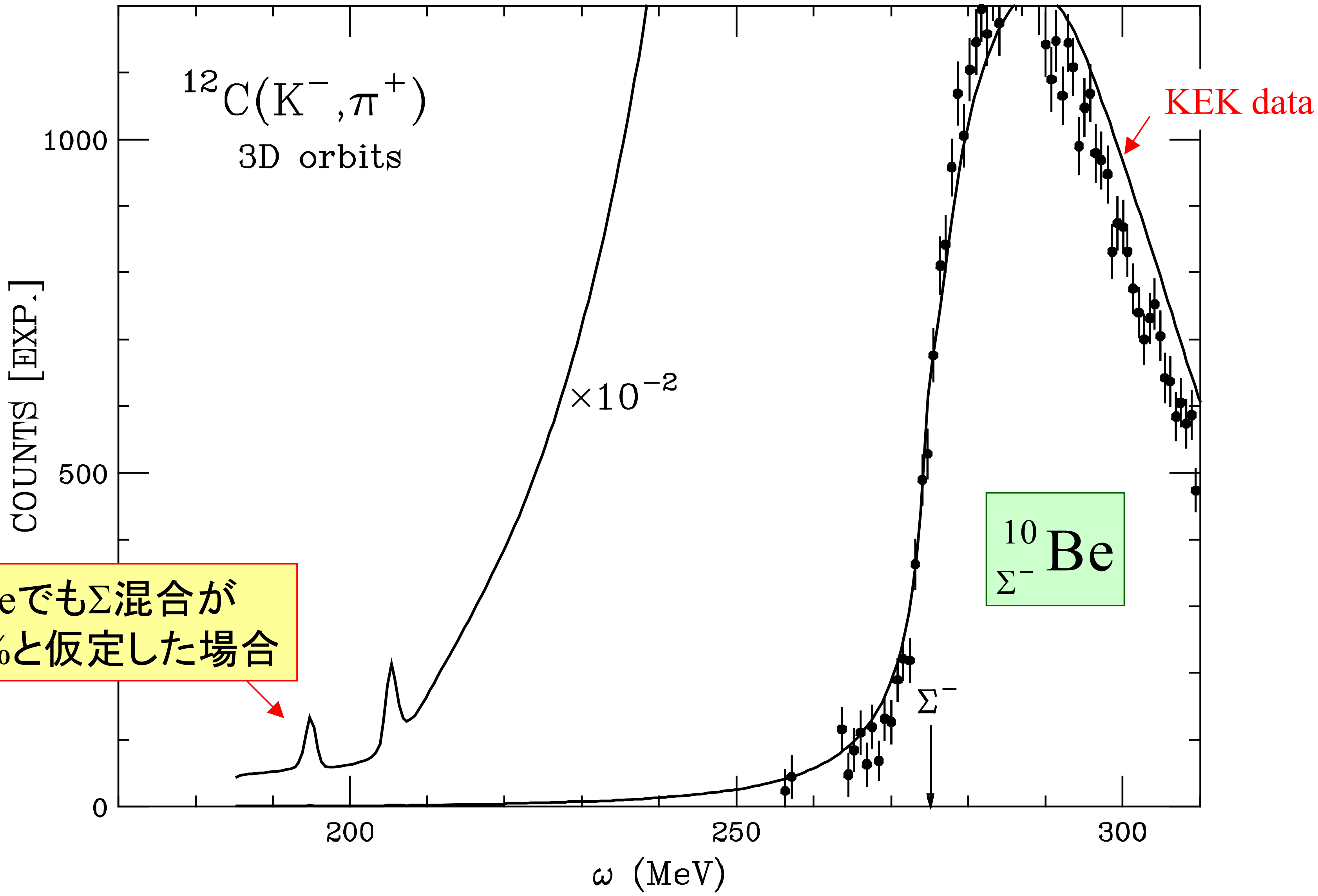
$-W_\Sigma = 20$ MeV is fixed.

^{10}B



⇨ $P_{\Sigma-}$～0.4-0.6% ($U_{\Sigma\Lambda}$ ～10 MeV) でΛスペクトルの一致が良い。

Λ spectrum by DCX (stopped K^{-}, π^{+}) reaction



$^{12}{}_{\Lambda}$BeでもΣ混合が
0.7%と仮定した場合

Summary

DCX (π^-,K^+)反応による中性子過剰Λハイパー核の生成スペクトルのDWIA計算を行い、理論的考察を行った。

- ${}^{10}\mathrm{B}(\pi^-,K^+){}^{10}\mathrm{Li}_\Lambda$において、One-step 過程: $\pi^- p \rightarrow K^+\Sigma^-$, $\Sigma^- p \rightarrow \Lambda n$ 反応による中性子過剰ハイパー核の生成メカニズムとその効果を調べた。

$$\left|{}^{10}_{\Lambda}\mathrm{Li}\right\rangle = a\left|{}^{9}\mathrm{Li}\otimes\Lambda\right\rangle + b\left|{}^{9}\mathrm{Be}\otimes\Sigma^-\right\rangle$$

生成スペクトルは波動関数の性質に強く影響を受ける。

- ${}^{10}\mathrm{B}(\pi^-,K^+){}^{10}\mathrm{Li}_\Lambda$の実験データとの比較から、One-step 過程によって実験スペクトルを説明できる可能性があることが分かった。

$-W_\Sigma = 20\text{-}30$ MeV, U_x ～10 MeV, P_Σ ～1 % 未満
$\beta[d\sigma/d\Omega]$ ～10-20 μb/sr

これまでの解析との矛盾しない。

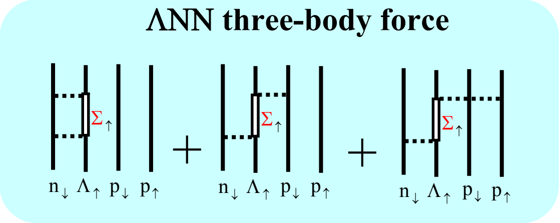
- (π^-,K^+)反応はΣ^- admixtureの割合などハイパー核の波動関数の詳細な情報を得る可能性がある。

Λ-Σ coupling effect in the neutron-rich Λ hypernucleus $^{10}_{\Lambda}\mathrm{Li}$ in a microscopic shell-model calculation

A.Umeya, T.H, PRC79(200)014603

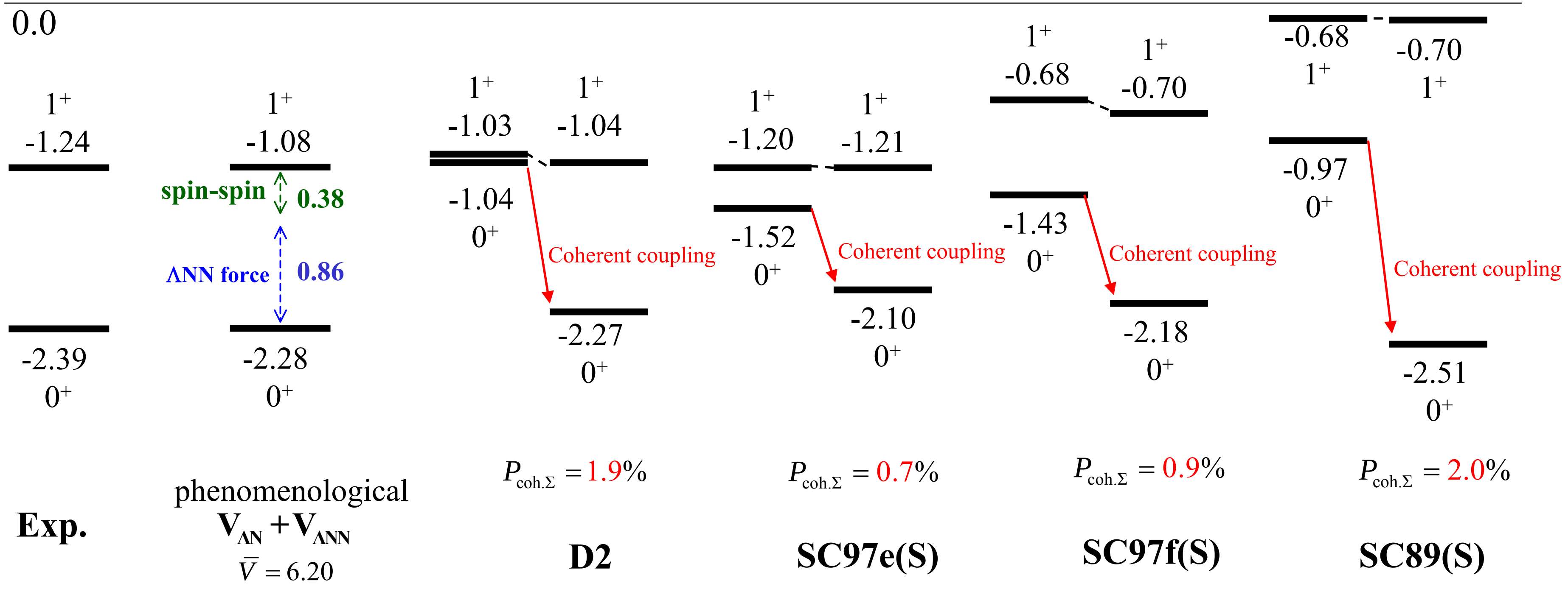
“The 0^+-1^+ difference is not a measure of ΛN spin-spin interaction.”

by B.F. Gibson


ΛNN three-body force

$^4_\Lambda$He

(unit in MeV) ($^4_\Lambda$H)



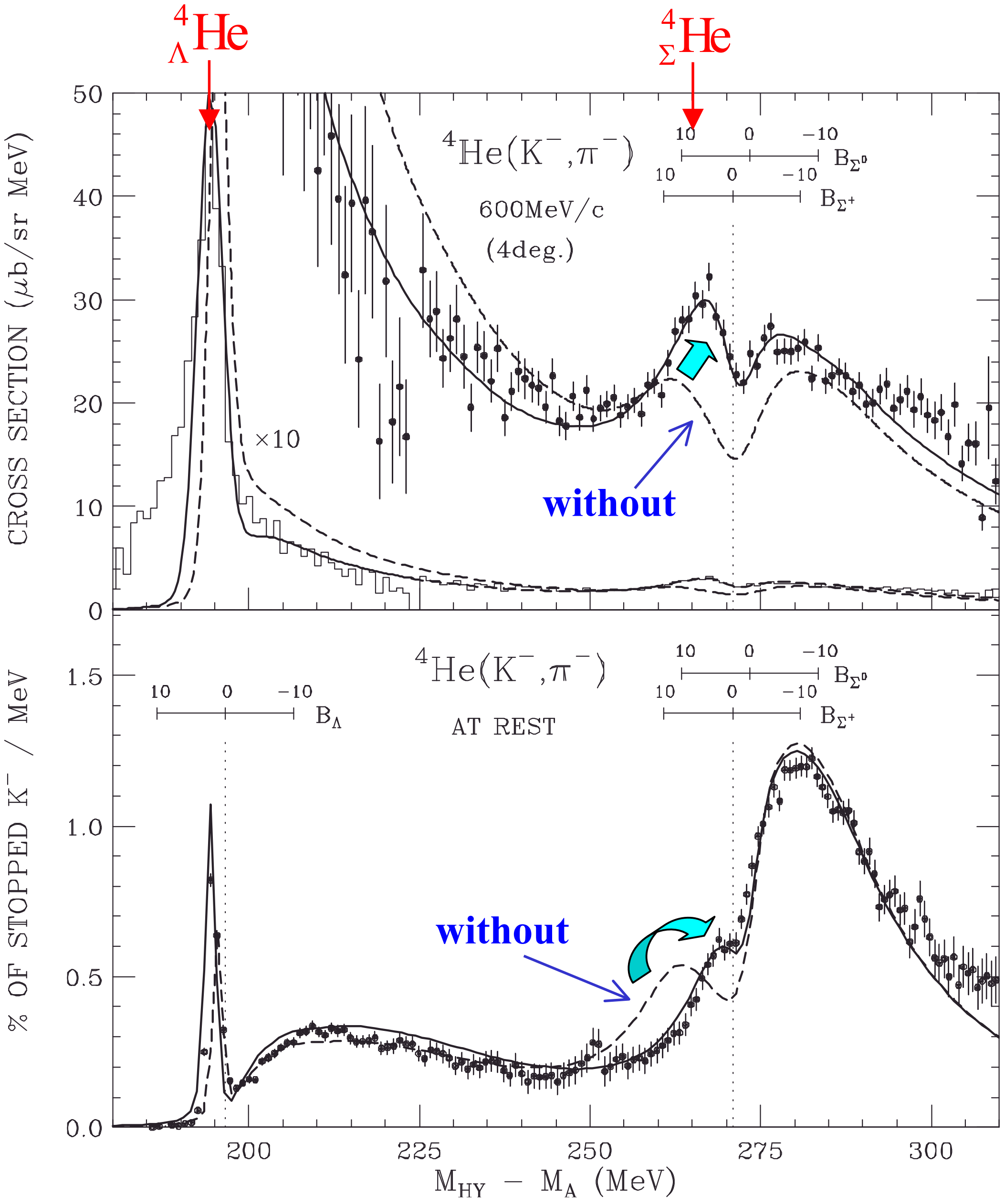
VMC

R. Sinha, Q.N.Usmani,
NPA684(2001)586c

Breuckner-Hartree-Fock

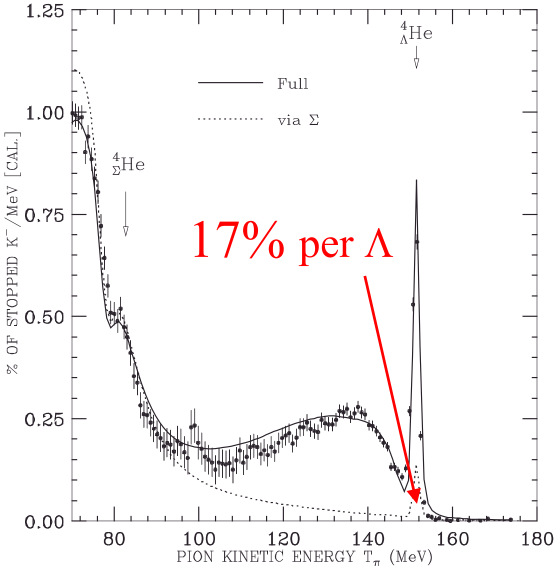
Y. Akaishi, T.Harada, S.Shinmura, Khin Swe Myint,
PRL84(2000)3539

Λ-Σ coupling effects on the π^- spectrum



- Λ–Σ couplingの効果はスペクトルの再現に重要
- Σを経由したΛハイパー核生成

Λ production via Σ



Calculated energy levels of the Λ hypernucleus

by the shell-model calculation with Λ-Σ coupling

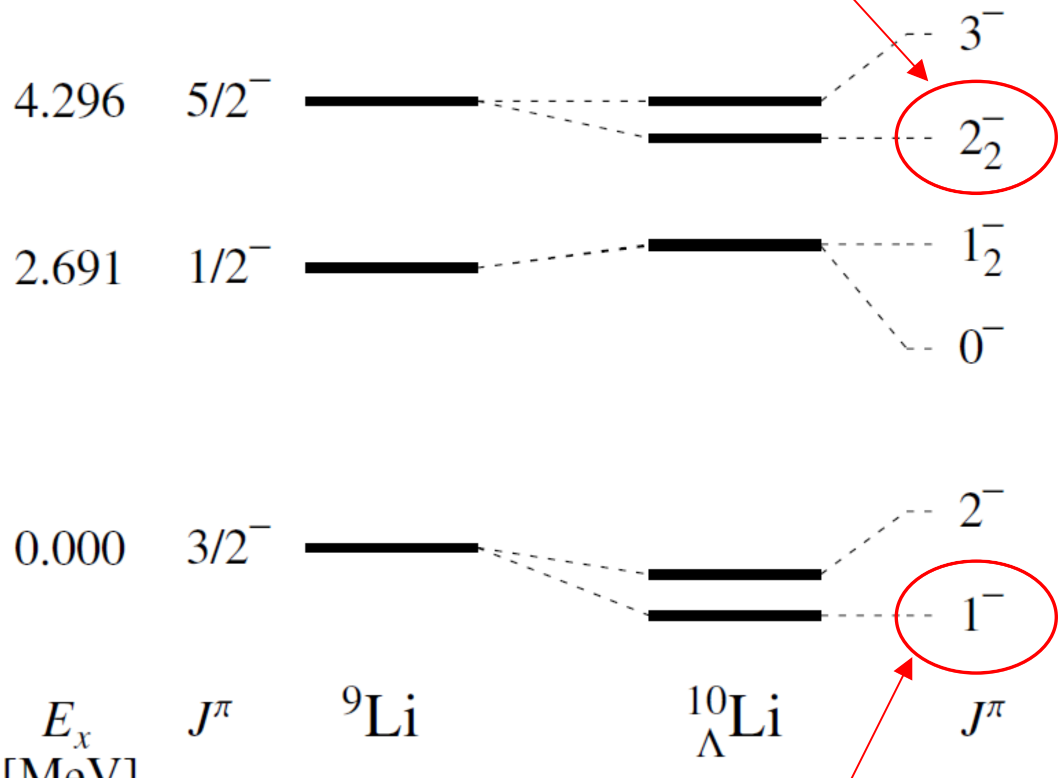
Umeya, Harada, PRC79(200)014603

$^{10}_{\Lambda}\mathrm{Li}$

NSC97e,f

$P_\Sigma = 0.350\%$

$\Delta E \simeq -\Delta M \cdot P_\Sigma$ ~ 数100keV



E_x [MeV]	J^π	$^{9}\mathrm{Li}$
4.296	$5/2^-$	
2.691	$1/2^-$	
0.000	$3/2^-$	

$^{10}_{\Lambda}\mathrm{Li}$ J^π	E_x [MeV]	ΔE [MeV]	Σ^0[%]	Σ^-[%]
3^-	4.944	0.139	0.071	0.104
2^-_2	4.590	0.282	0.162	0.187
1^-_2	3.566	0.181	0.098	0.128
0^-	3.551	0.150	0.086	0.098
2^-	0.395	0.134	0.070	0.096
1^-	0.000	0.280	0.159	0.183

Σ-mixing Prob.

$P_\Sigma = 0.345\%$

Λ-Σ coupling strengths

Umeya, Harada, PRC79(200)014603

Σ- mixing probability

$P(^{10}{}_{\Lambda}\mathrm{Li}) = 0.345\%$,

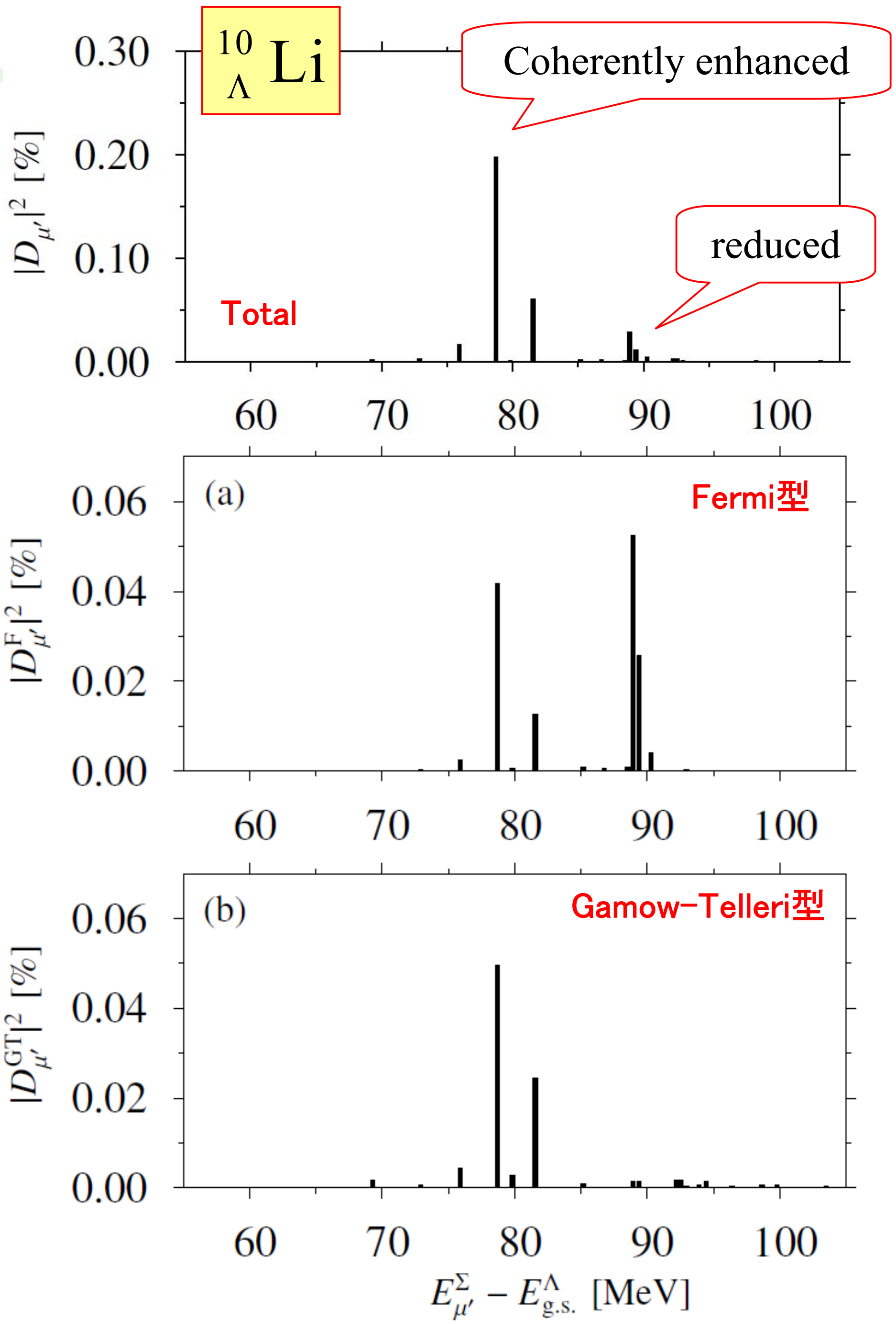
Energy-shift ΔE=280 keV

Fermi-type coupling

$$|D^{\mathrm{F}}_{\mu'}|^2 = \left| \frac{\langle \psi^{\Lambda}_{\mathrm{g.s.}}; T\,J \,|\, V^{\mathrm{F}}_{\Sigma\Lambda} \,|\, \psi^{\Sigma}_{\mu'}; T\,J \rangle}{E^{\Sigma}_{\mu'} - E^{\Lambda}_{\mathrm{g.s.}}} \right|^2$$

Gamow-Teller-type coupling

$$|D^{\mathrm{GT}}_{\mu'}|^2 = \left| \frac{\langle \psi^{\Lambda}_{\mathrm{g.s.}}; T\,J \,|\, V^{\mathrm{GT}}_{\Sigma\Lambda} \,|\, \psi^{\Sigma}_{\mu'}; T\,J \rangle}{E^{\Sigma}_{\mu'} - E^{\Lambda}_{\mathrm{g.s.}}} \right|^2$$



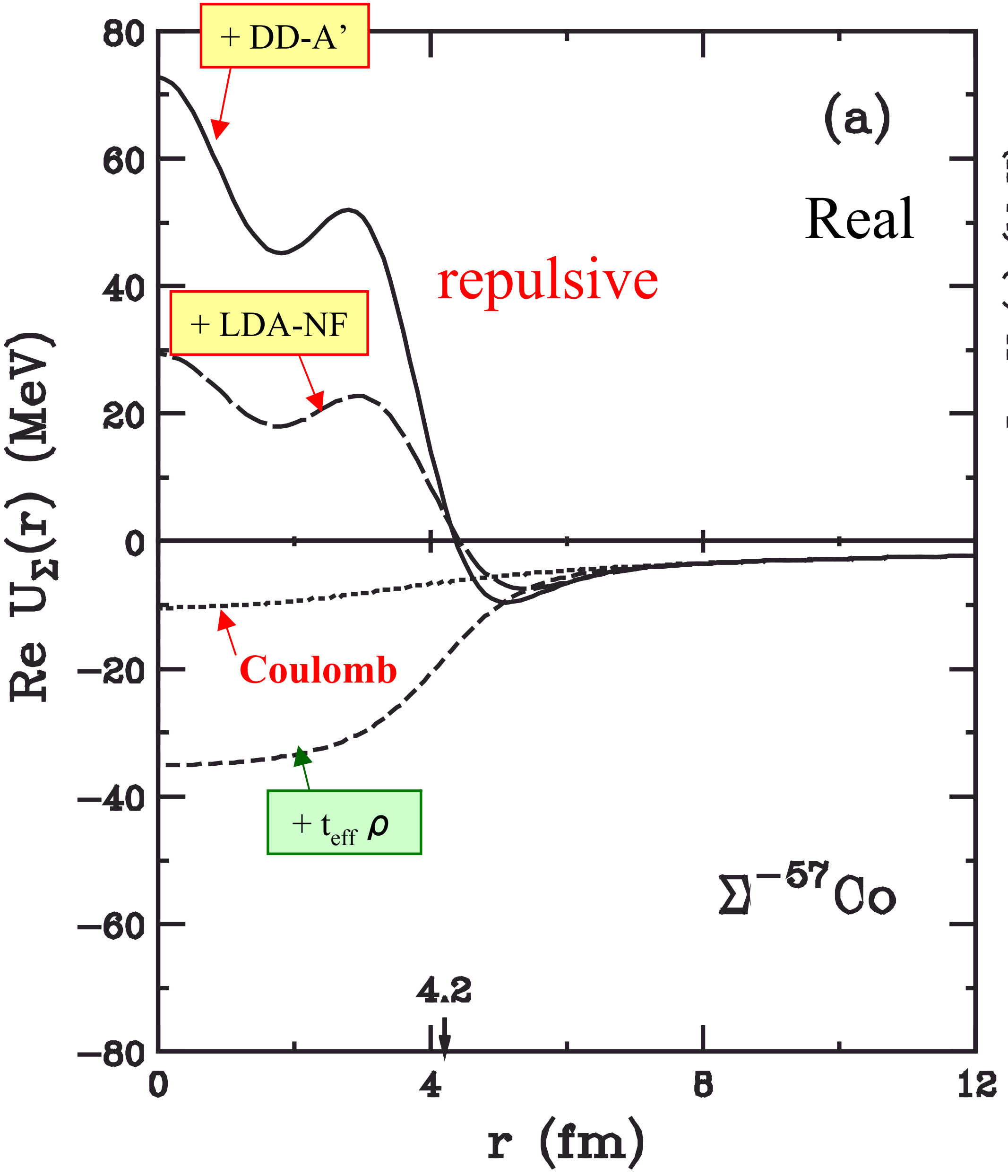
(1) コヒーレントな Fermi型とGT型結合

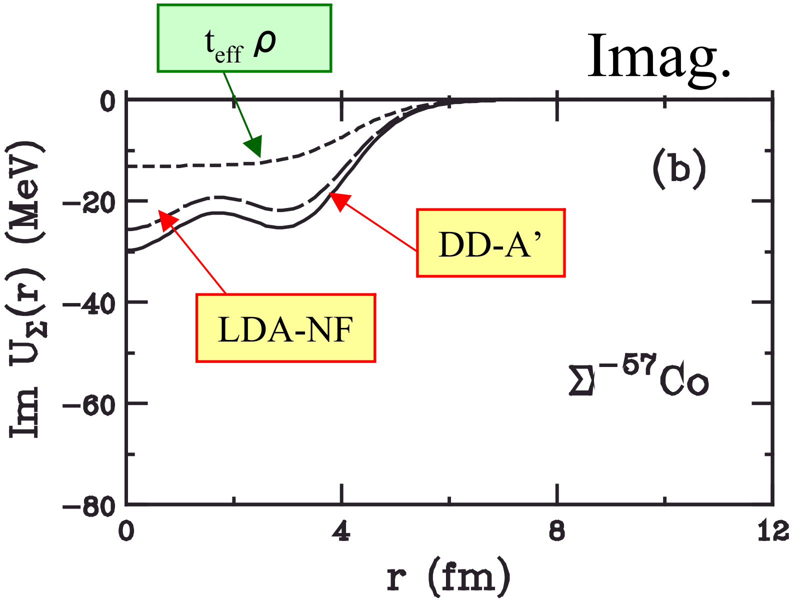
(2) 中性子過剰核ではT(T+1)に比例

Coulomb-assisted Σ^- -nucleus bound state in the (K^-, π^+) production reaction

T.H and Y. Hirabayashi, (2009) in preparation.

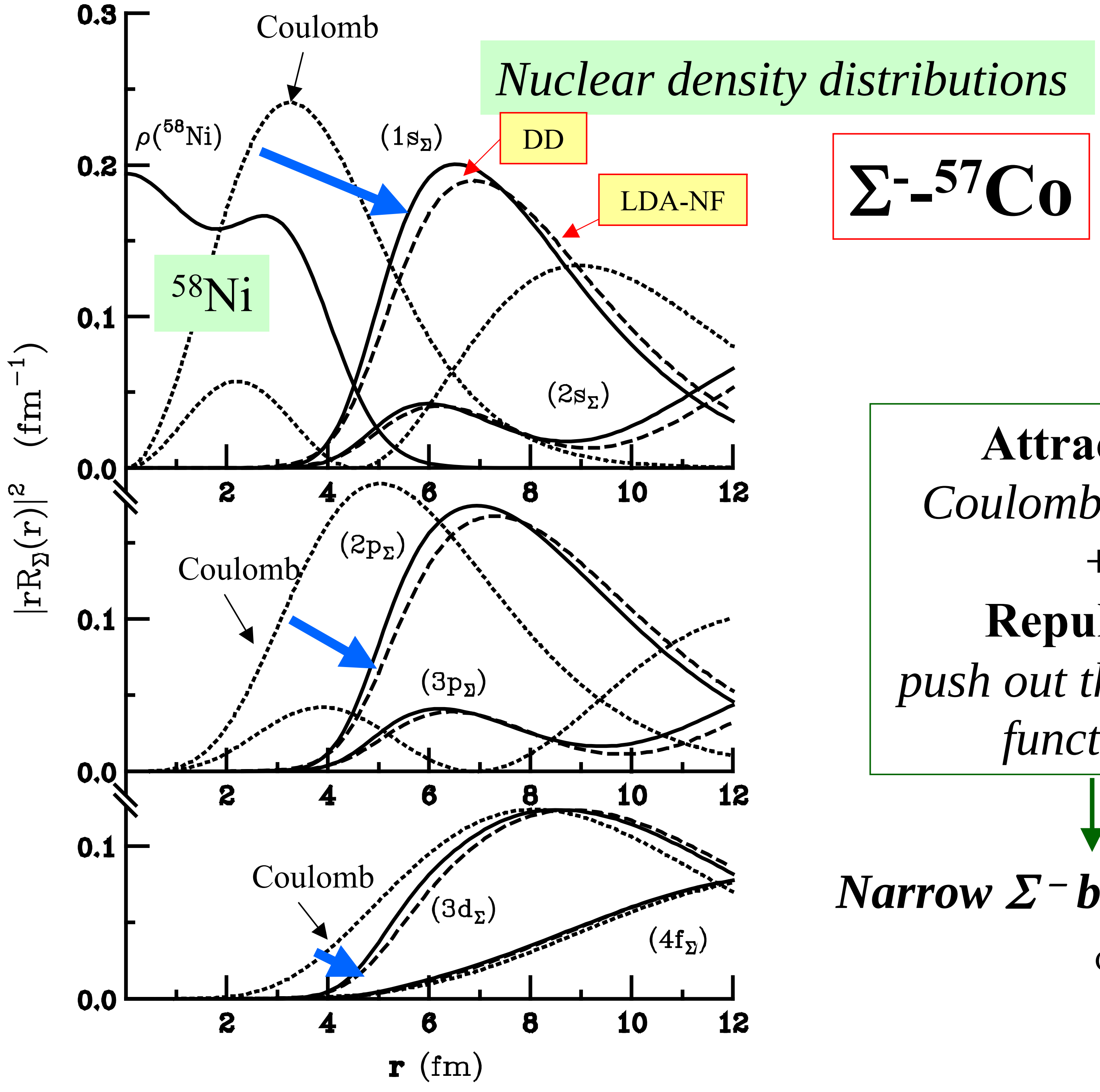
Σ^--nucleus optical potentials in ^{57}Co+Σ^-





$$U_D \approx \left\langle \underset{\text{strongly repulsive}}{\frac{1}{2} g_{1,3/2}} + \underset{\text{attractive}}{\frac{1}{6} g_{0,3/2}} + \underset{\text{attractive}}{\frac{1}{4} g_{1,1/2}} + \underset{\text{repulsive}}{\frac{1}{12} g_{0,1/2}} \right\rangle$$

Quark Pauli-forbidden



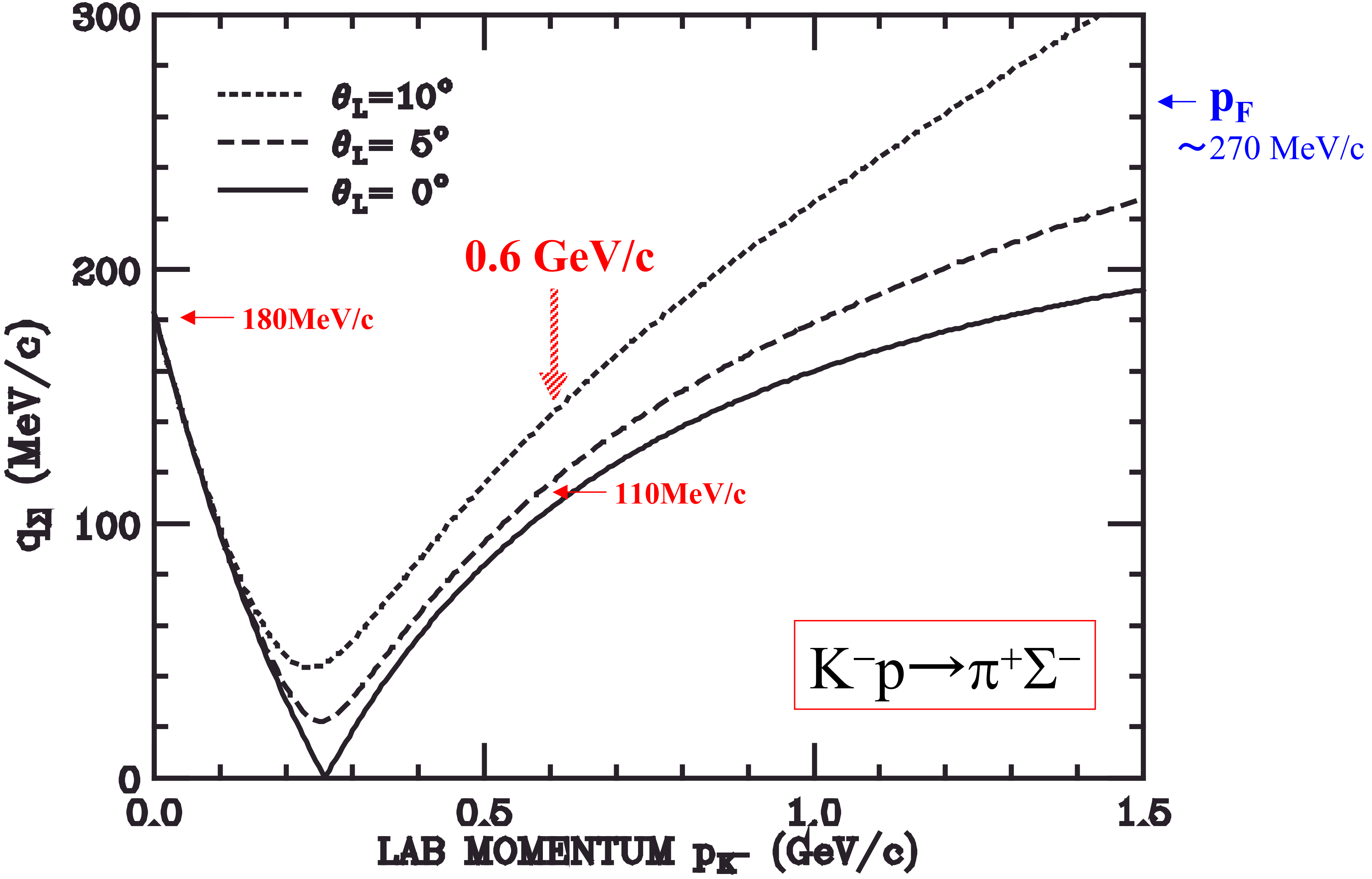
Σ^--^{57}Co

Attraction:
Coulomb-assisted
+
Repulsion:
push out the Σ-wave functions.

Narrow Σ^- bound state !!

Cf. deeply pionic atoms

Momentum transfer in (K^{-},π^{+}) reactions



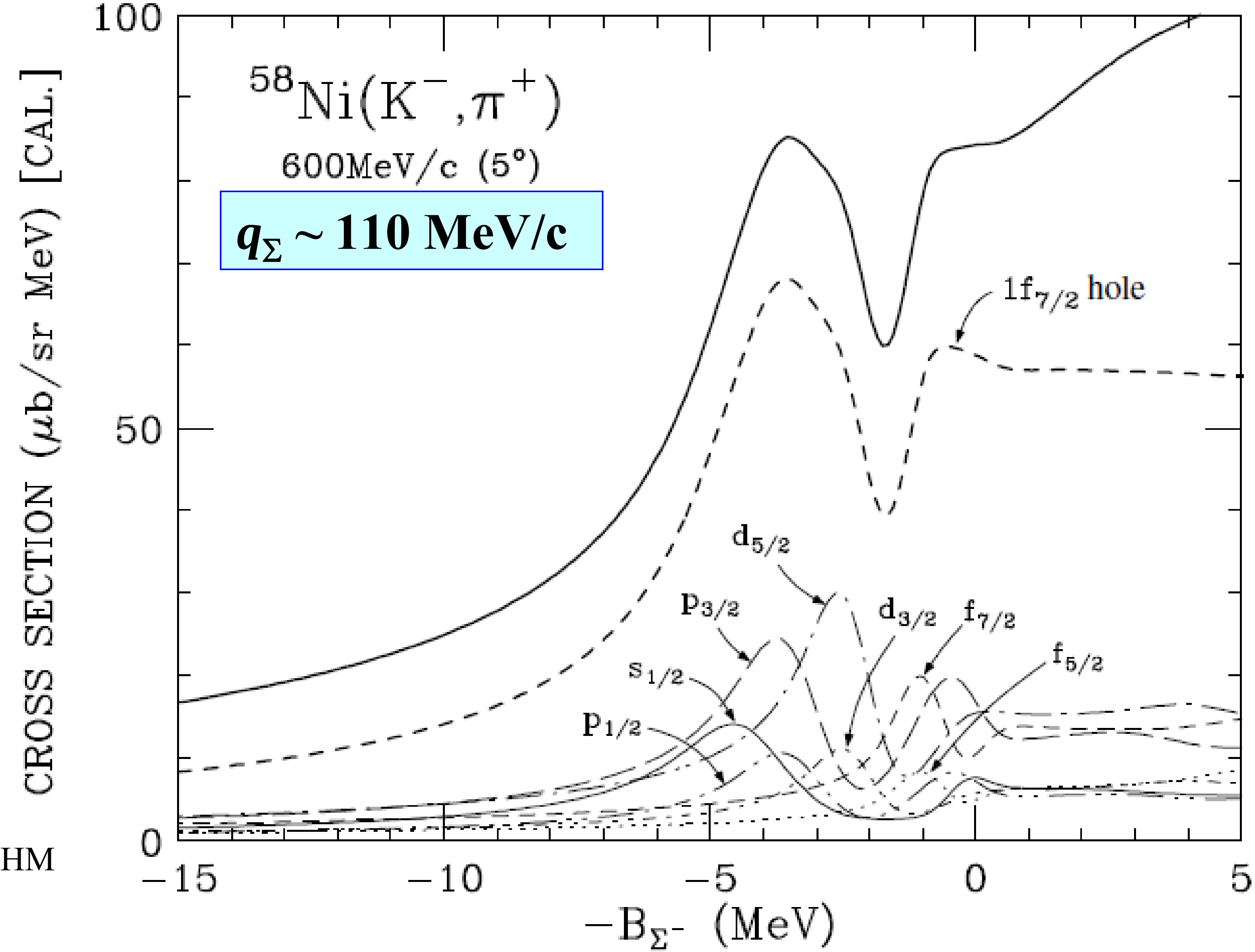
$K^{-}p \rightarrow \pi^{+}\Sigma^{-}$

Σ^--nucleus bound states in the (K^-,π^+) reaction

DD

^{58}Ni

Σ^-



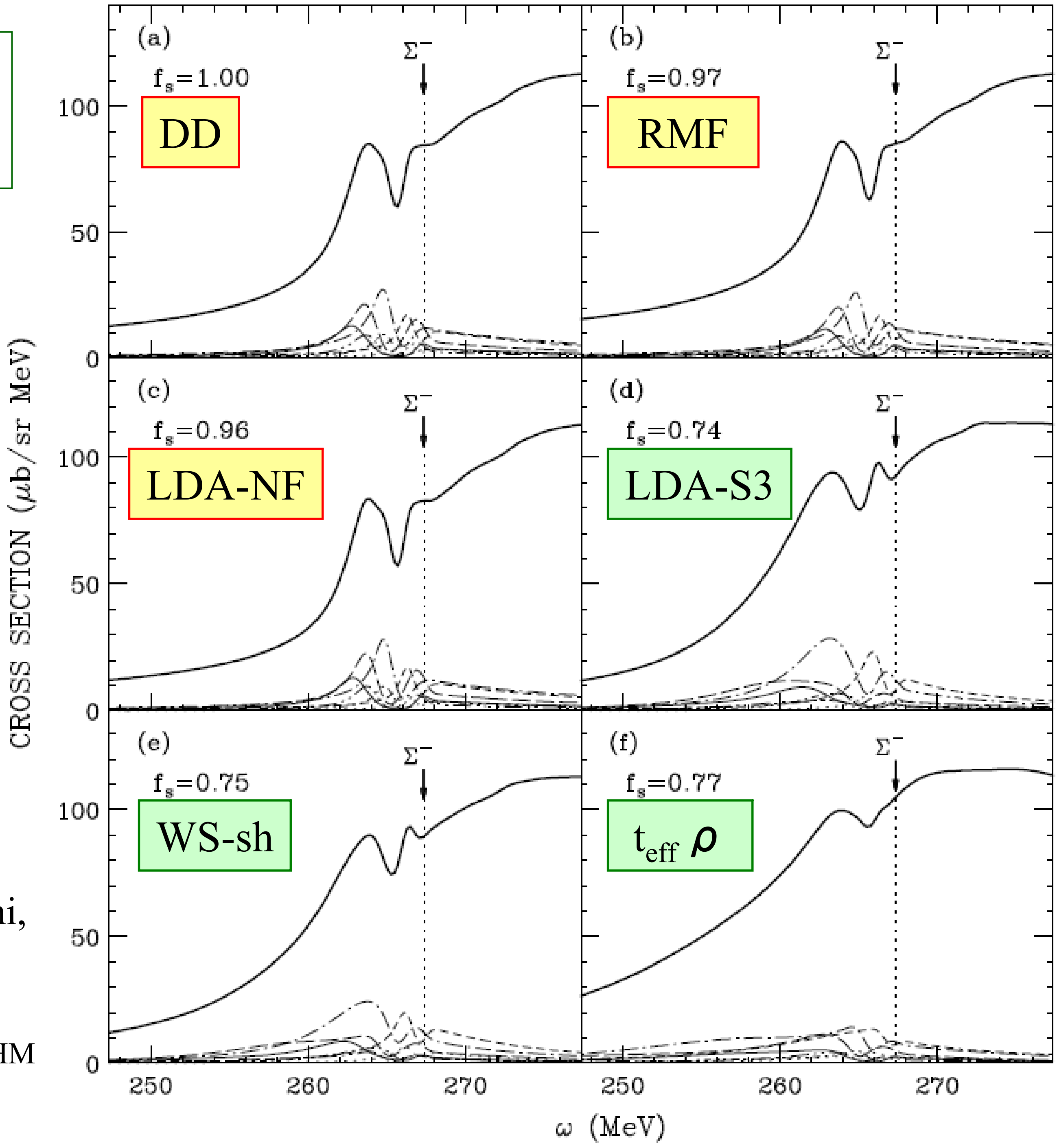
$q_\Sigma \sim 110$ MeV/c

1.5MeV FWHM

(K^-, π^+) reaction at 600 MeV/c

^{58}Ni

Σ^-



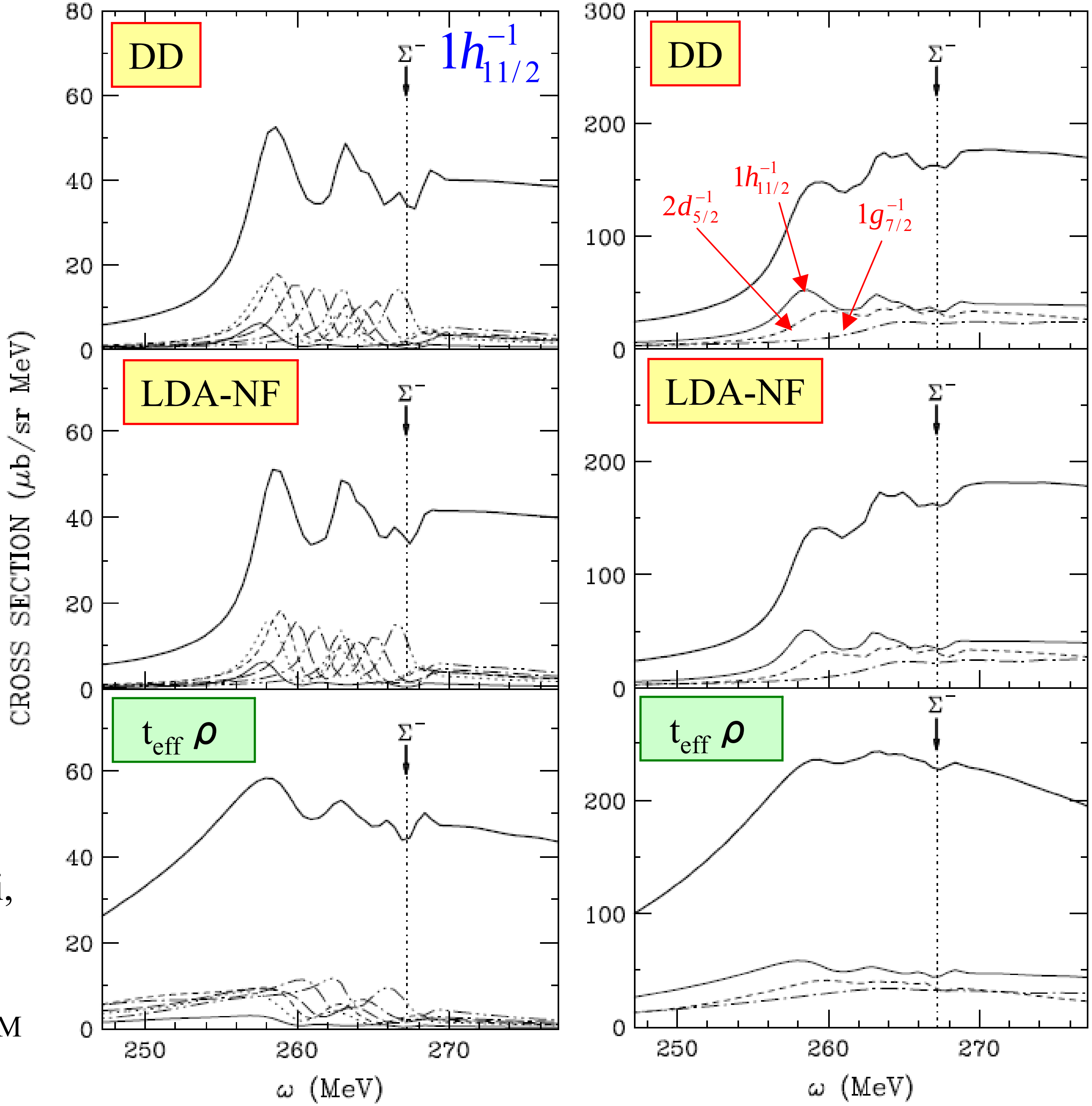
T.Harada, Y.Hirabayashi, (2009), in preparation.

1.5MeV FWHM

(K^-, π^+) reaction at 600 MeV/c

^{208}Pb

Σ^-



T.Harada, Y.Hirabayashi, (2009), in preparation.

1.5MeV FWHM

Ξ^--hypernuclear production from the nuclear (K^-, K^+) reaction

$^{16}O(K^-, K^+)^{16}_{\Xi^-}C$ at p_K=1.65GeV/c

Ξ^- hypernuclear spectrum in the (K$^-$,K$^+$) reactions

Coulomb-assisted hybrid bound state

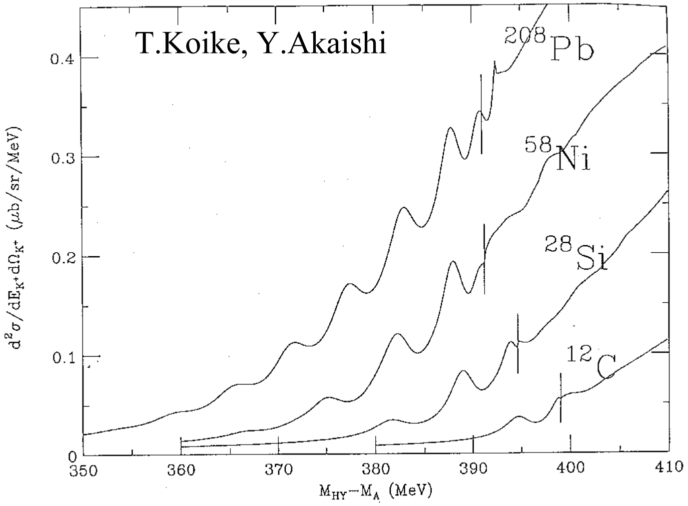
DWIA

- Green's関数法によるスペクトル
- Wood-Saxon型Ξ^-ポテンシャル
- U_Ξ= –24MeV

  W_Ξ= – 1MeV
- ^{12}C(K$^-$,K$^+$)スペクトルから検討

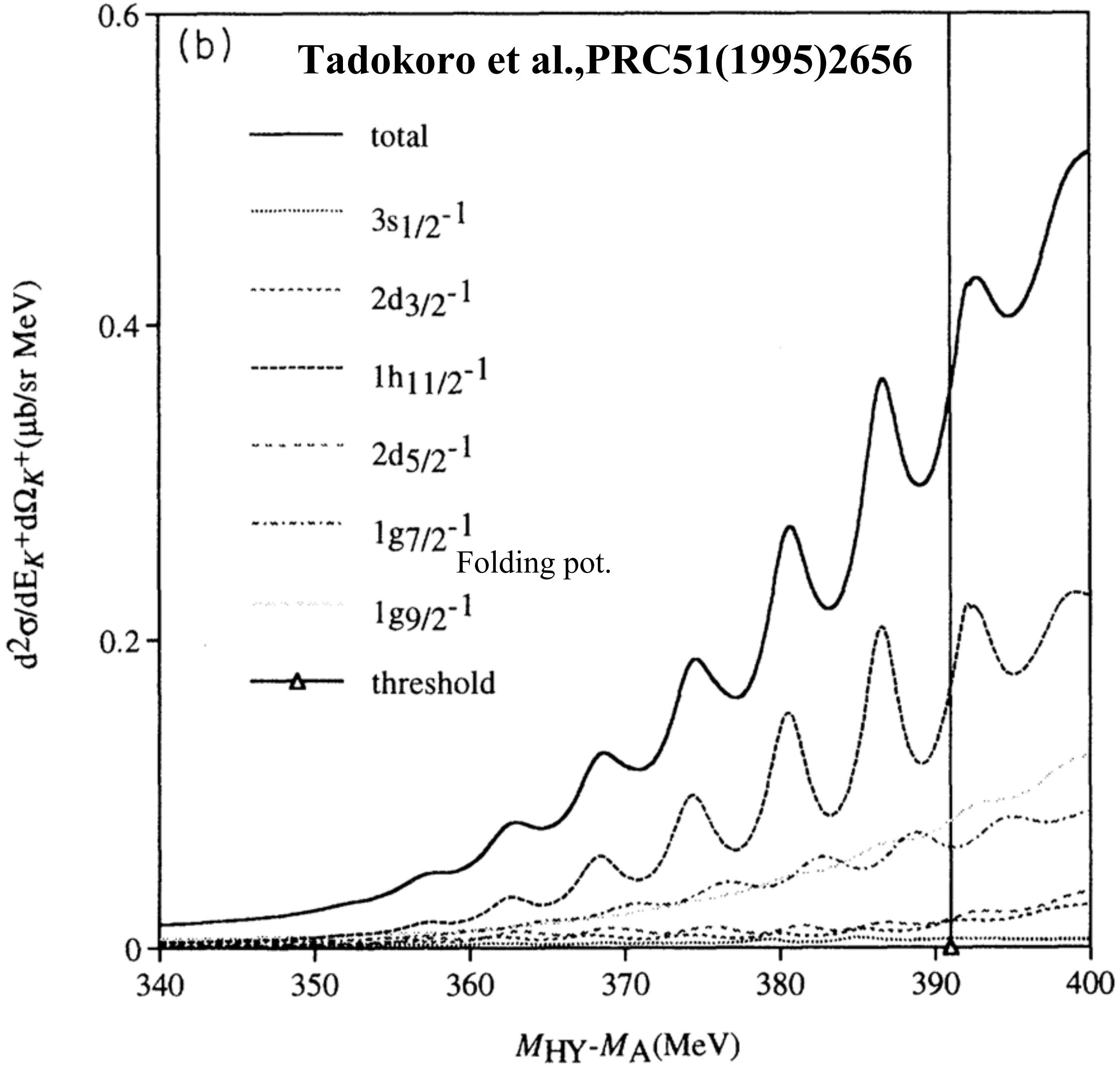
  U_Ξ= – 16MeV
- Shinmura's model-D folding pot.

  rc= 0.454


T.Koike, Y.Akaishi

^{208}Pb(K-,K+) at 1.65GeV/c

2MeV FWHM U_Ξ=24MeV


Tadokoro et al.,PRC51(1995)2656

Folding pot.

Ξ^-ポテンシャルを探る

BNL-E885

$^{12}C(K^-,K^+)^{12}_{\Xi}Be$ at 1.8GeV/c

P.Khaustov et al.,PRC61(2000)054603-1

DWIA

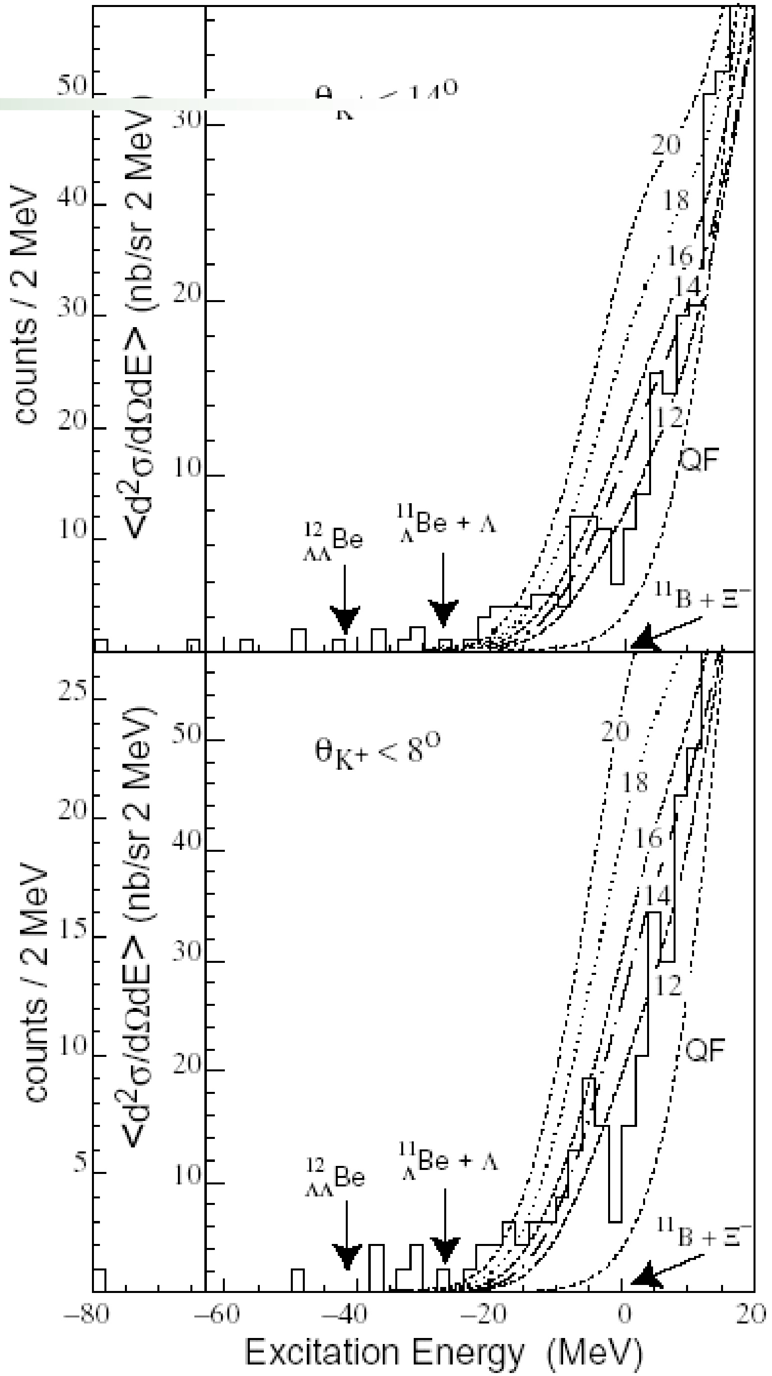
素過程 σ〜35μb/sr

- 束縛ΛΛ領域のスペクトルを再現する
  4MeV FWHM
- Wood-Saxon型Ξ^-ポテンシャルの深さパラメータを決める

YNG Folding potentialによる解析(rc=0.47)

⇩

Ξ^-核ポテンシャル　Well depth〜12-14MeV



Double Λ-hypernuclear production via a $\Xi^{-}p \rightarrow \Lambda\Lambda$ coupling in the (K^{-}, K^{+}) reaction

$^{16}_{\Lambda\Lambda}\mathrm{C}$ T.H, A.Umeya, Y. Hirabayashi, (2009), in preparation

Observation of a ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ Double Hypernucleus

静止Ξ-によるハイブリッド・エマルジョン法 KEK-E373

H.Takahashi et al.,PRL87(2001)212502

NAGARA event

$${}^{12}\mathrm{C}+\Xi^{-}\rightarrow {}^{6}_{\Lambda\Lambda}\mathrm{He}+{}^{4}\mathrm{He}+t$$

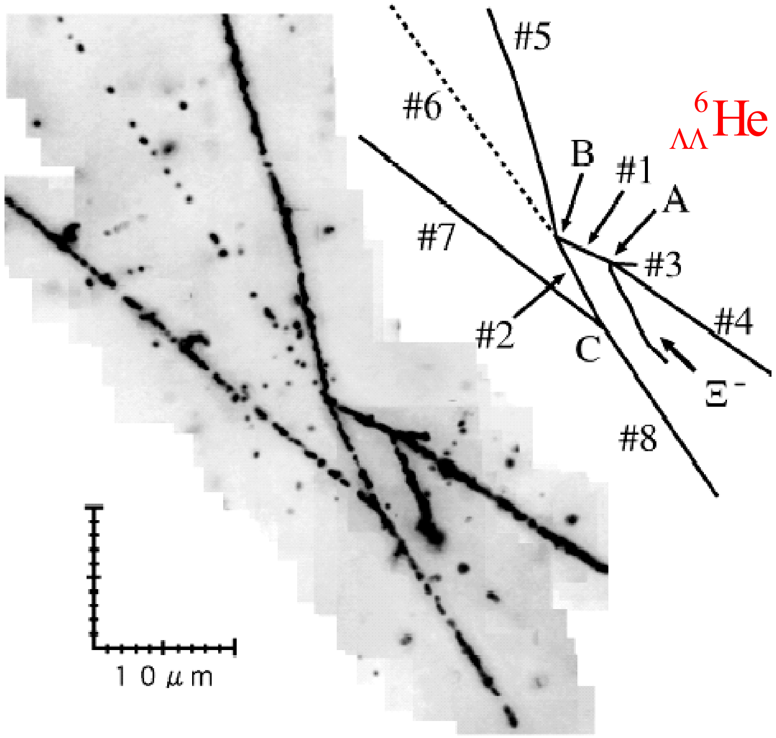
$$\hookrightarrow {}^{5}_{\Lambda}\mathrm{He}+p+\pi^{-}$$

${}^{6}_{\Lambda\Lambda}\mathrm{He}$

$$B_{\Lambda\Lambda}=7.25\pm0.19^{+0.18}_{-0.11}\,\mathrm{MeV}$$

$$\Delta B_{\Lambda\Lambda}=1.01\pm0.20^{+0.18}_{-0.11}\,\mathrm{MeV}$$

$$\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He})=B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He})-2\underbrace{B_{\Lambda}({}^{5}_{\Lambda}\mathrm{He})}_{-3.12\pm0.02}$$



$\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He})\sim4.7$ MeV D.J. Prowse, PRL17(1966)783

$\Delta B_{\Lambda\Lambda}({}^{10}_{\Lambda\Lambda}\mathrm{Be})\sim4.5$ MeV M. Danysz et al., NP49(1963)121

~1.3 MeV $({}^{10}_{\Lambda\Lambda}\mathrm{Be}\rightarrow{}^{9}_{\Lambda}\mathrm{Be}^{*}(3.1\mathrm{MeV})+p+\pi^{-})$

$\Delta B_{\Lambda\Lambda}({}^{13}_{\Lambda\Lambda}\mathrm{Be})\sim4.8$ MeV S. Aoki et al., PTP85(1991)1287

$$2M_{\Lambda}-B_{\Lambda\Lambda}<M_{\mathrm{H}}$$

H-dibaryon

R.L. Jaffe, PRL38(1977)195

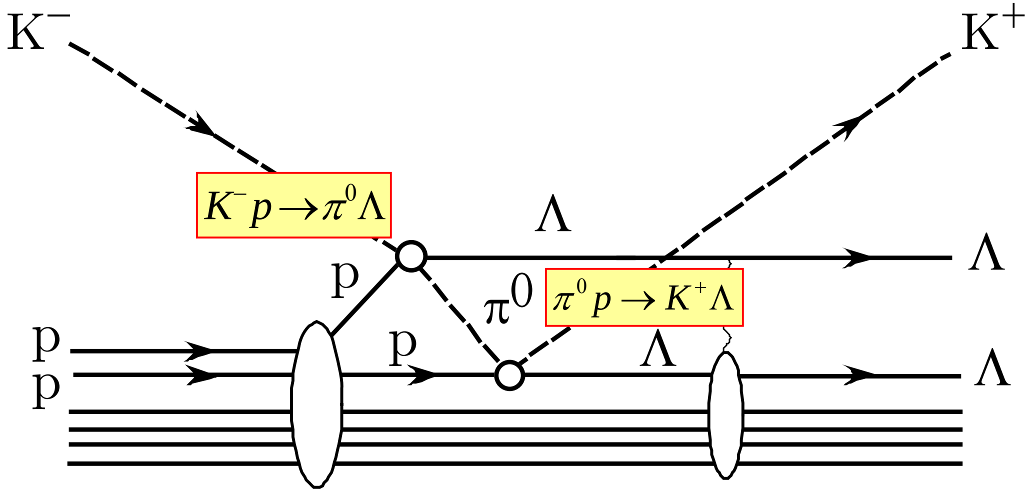
$$|H:\{1\}\rangle=\sqrt{1/8}\,|\Lambda\Lambda\rangle+\sqrt{4/8}\,|\Xi N\rangle-\sqrt{3/8}\,|\Sigma\Sigma\rangle$$

(K$^-$, K$^+$) －Double Charge Exchange (DCX) Reaction

- ***Two-step process:***

$$K^- p \rightarrow \pi^0 \Lambda$$

$$\pi^0 p \rightarrow K^+ \Lambda$$



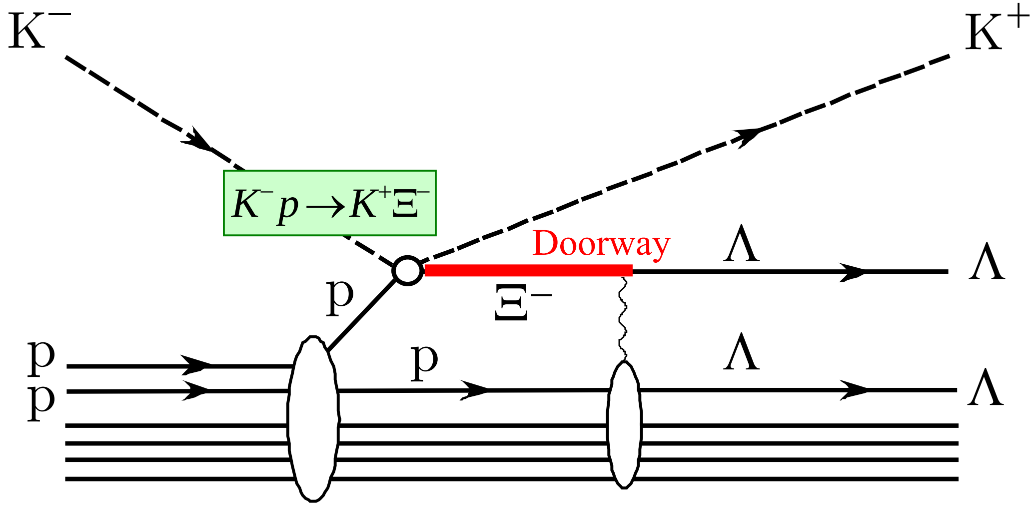
(a)

- ***One-step process:***

$$K^- p \rightarrow K^+ \Xi^-$$

$$\Xi^- p \leftrightarrow \Lambda\Lambda$$

ΞN-ΛΛ coupling



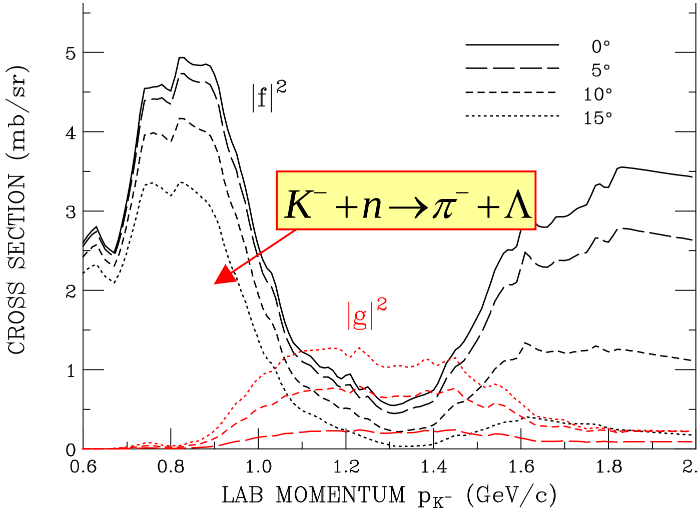
(b)

Elementary Cross sections for (K^-,K^+) reactions

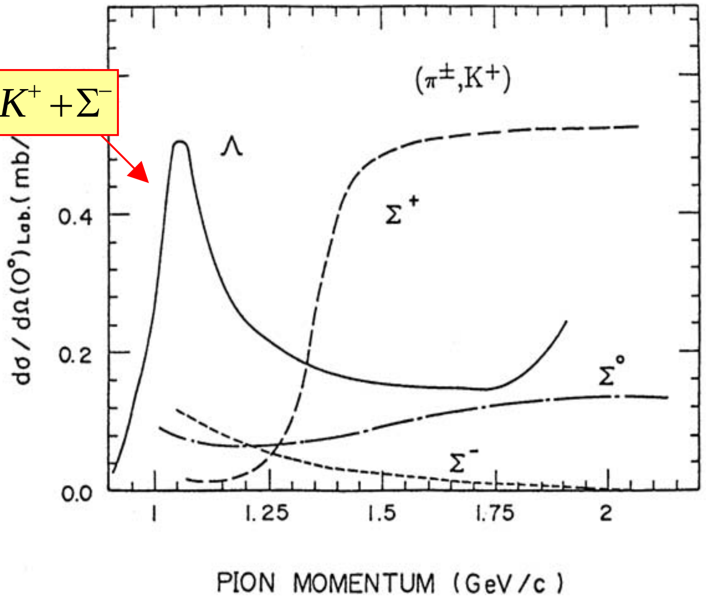
$$K^- + p \to \pi^0 + \Lambda,\ \ \pi^0 + p \to K^+ + \Lambda$$

$$K^- + p \to K^+ + \Xi^-$$

Bando et al., Int.J.Mod.Phys. A5(1990)4021

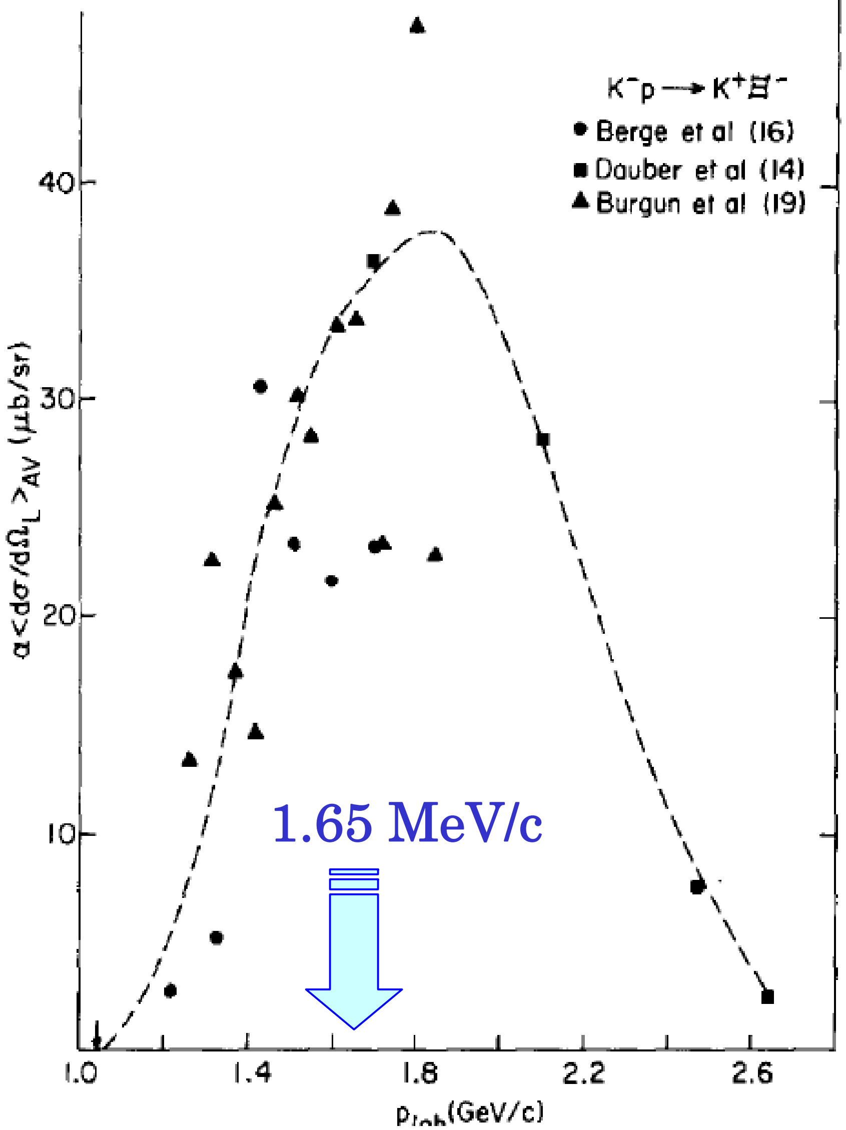


$K^- + n \to \pi^- + \Lambda$



$\pi^- + p \to K^+ + \Sigma^-$

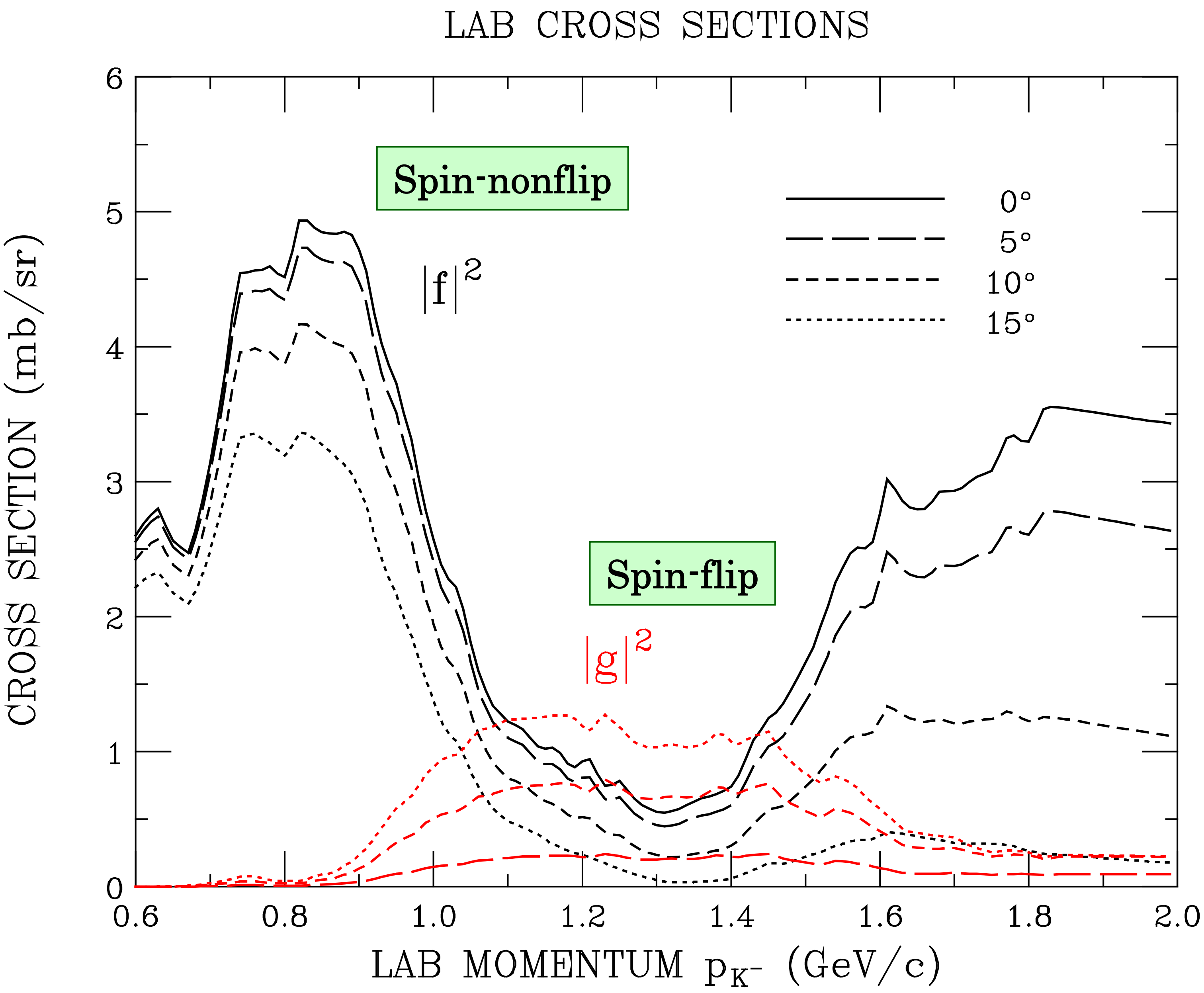
Dover and Gal, Ann. Phys, 146 (1983) 309.



1.65 MeV/c

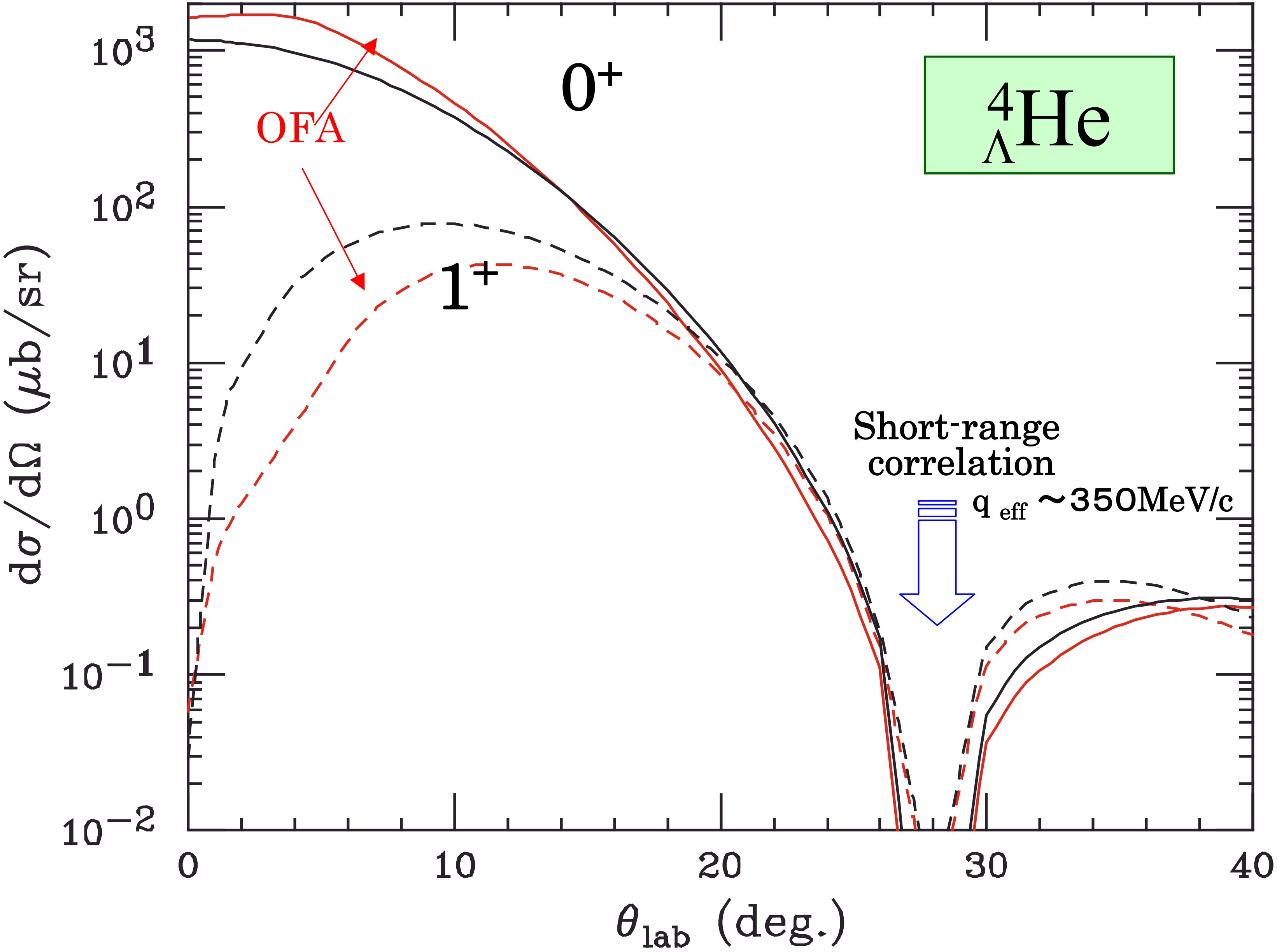
Spinflip and non-spinflip productions of the Λ-hypernucleus ${}^{4}_{\Lambda}\mathrm{He}$ in (K^-, π^-) reactions

Elementary cross section of $K^{-}n \rightarrow \pi^{-}\Lambda$ reactions



Cross section of the ^{4}He(K^{-},π^{-})$^{4}_{\Lambda}$He reaction at 1.0 GeV/c

with the recoil effects

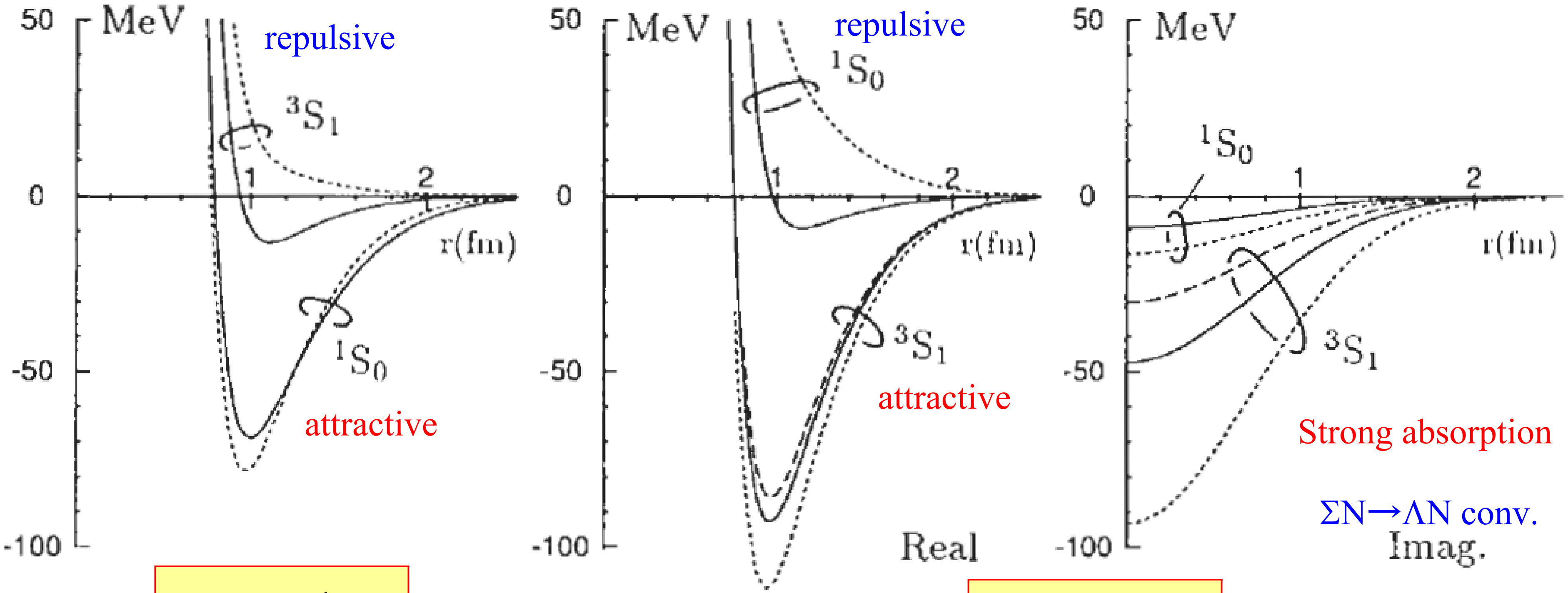


Production of the Σ-hypernuclear bound ΣNN states in the (K^{-}, π^{-}) reactions

Two-body ΣN potentials in free space

Sigma-nucleon absorptive potential (SAP)

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



repulsive

attractive

repulsive

attractive

Strong absorption

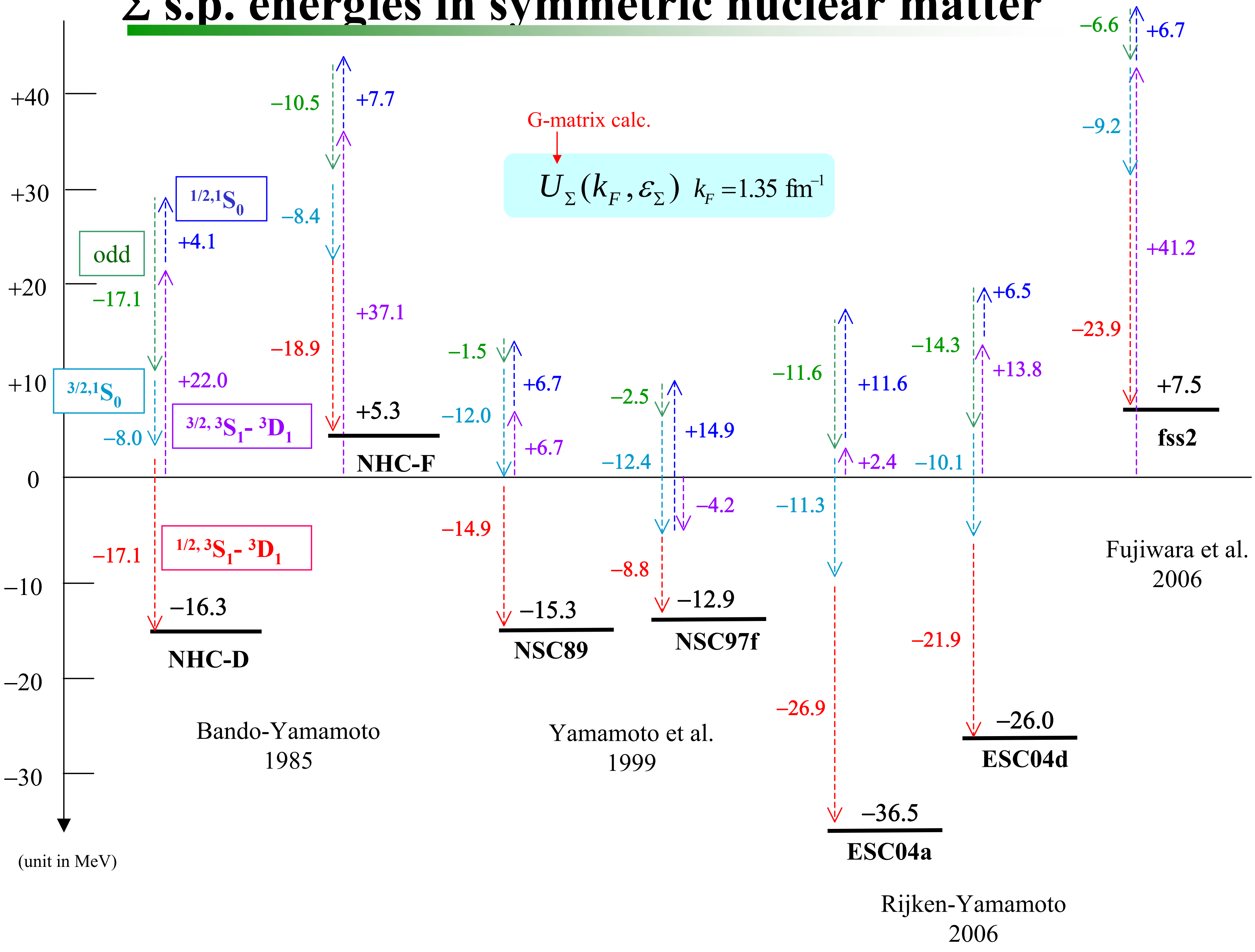
ΣN→ΛN conv.

T=3/2

T=1/2

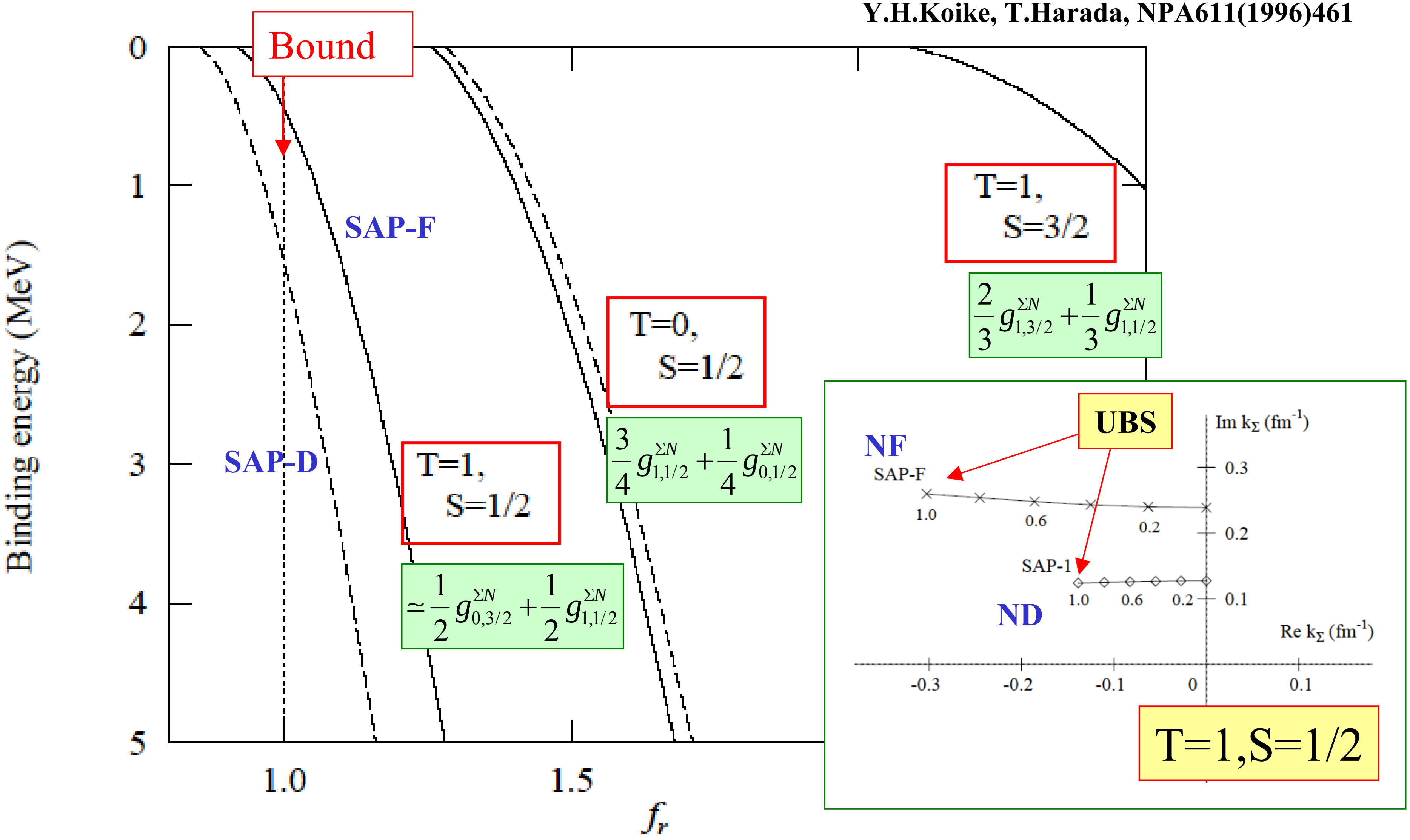
Strong spin-isospin dependence

Σ s.p. energies in symmetric nuclear matter



Possible existence of three-body NNΣ states

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

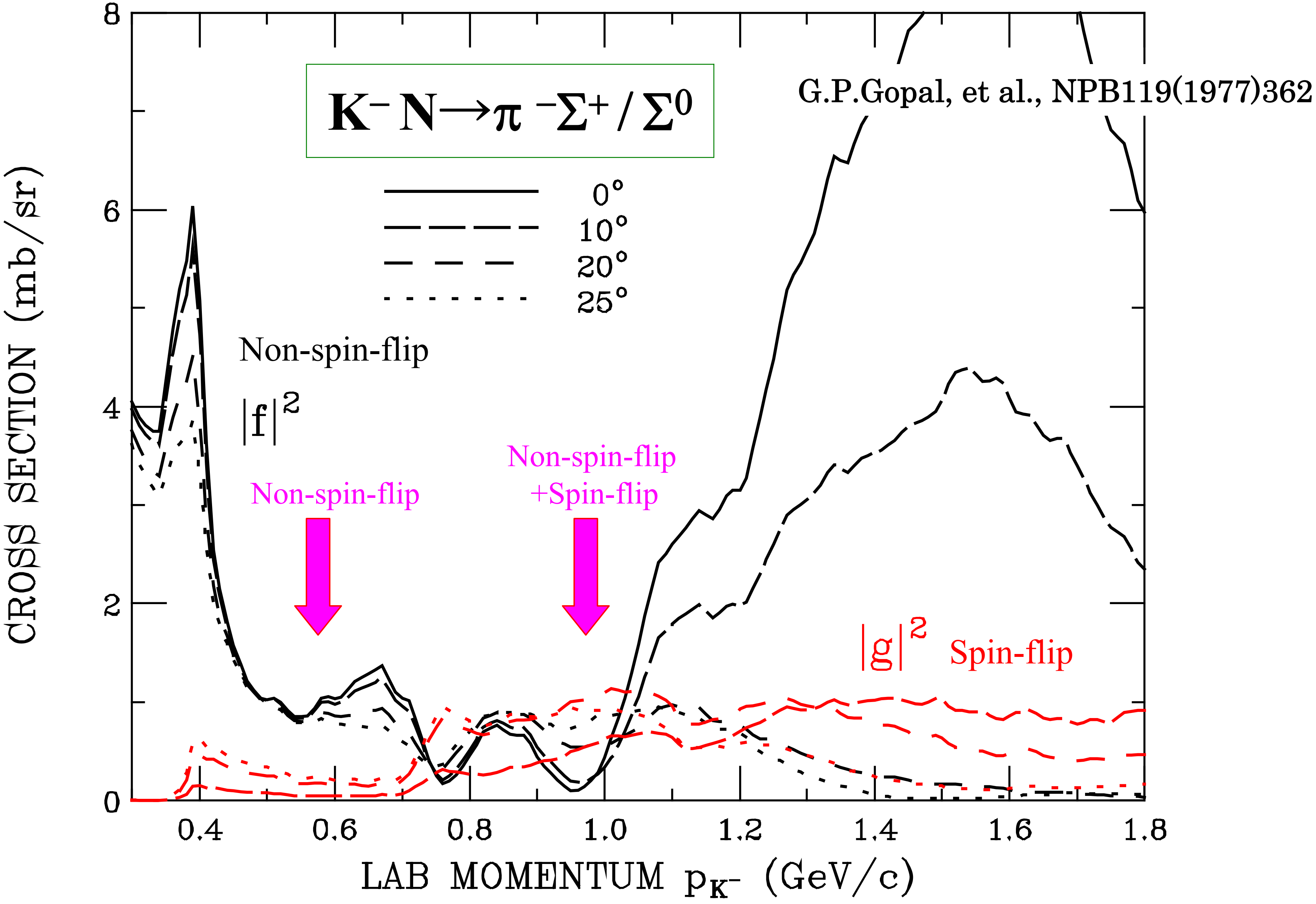


I. R. Afnan and B. F. Gibson, PRC 47 (1993) 1000. **Separable-pot + Faddeev calc. → Γ=8MeV**

H. Garcilazo, et al., PRC75(2007) 034002; PRC76(2007) 034001.

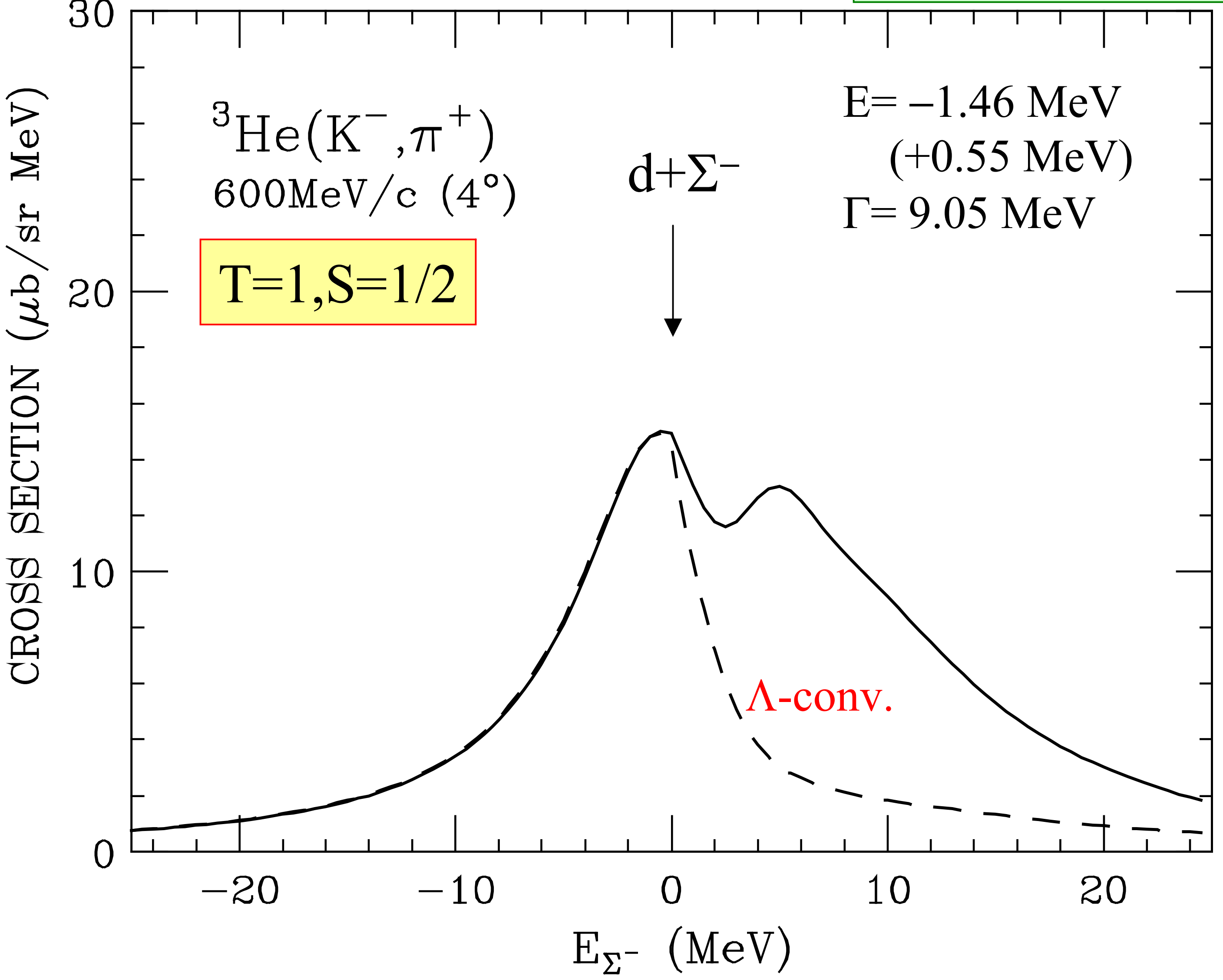
Chiral constituent quark model pot.+ Faddeev calc. → Γ=2.1MeV

Lab cross sections for the elementary process



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

Theoretical calculations



-これまでにどういう新しい物理を明らかにしてきたか？

- 生成のメカニズムとDWIA計算の改良
- Σ–nucleus potentialの性質　Σ原子 v.s.(π$^-$, K$^+$)反応
- 中性子過剰ハイパー核生成　シグマ混合率

- 今後、どういう新しい展開が期待できるのか？

- ２重荷電交換反応によるハイパー核生成！

- J-PARCに対して、どういう実験を提案していくのか？