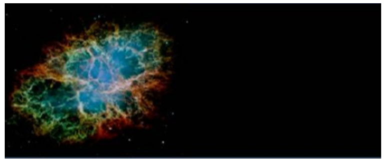


新学術領域研究

「実験と観測で解き明かす中性子星の核物質」

新学術セミナー
2012年11月24日
KEK東海キャンパス，東海

核物質中のΣハイペロン

原田 融

Toru Harada

Osaka Electro-Communication University/
J-PARC Branch, KEK Theory Center

Contents

■Keywords

Hyperon mixing + DCX

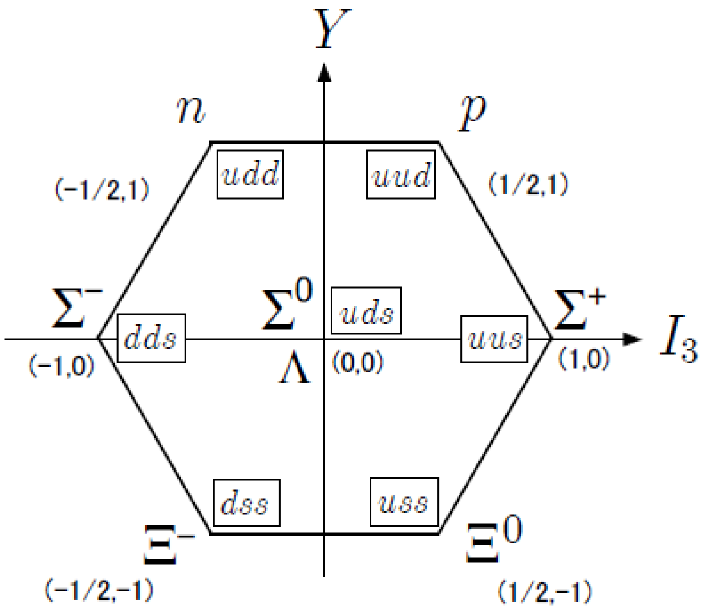
1. はじめに

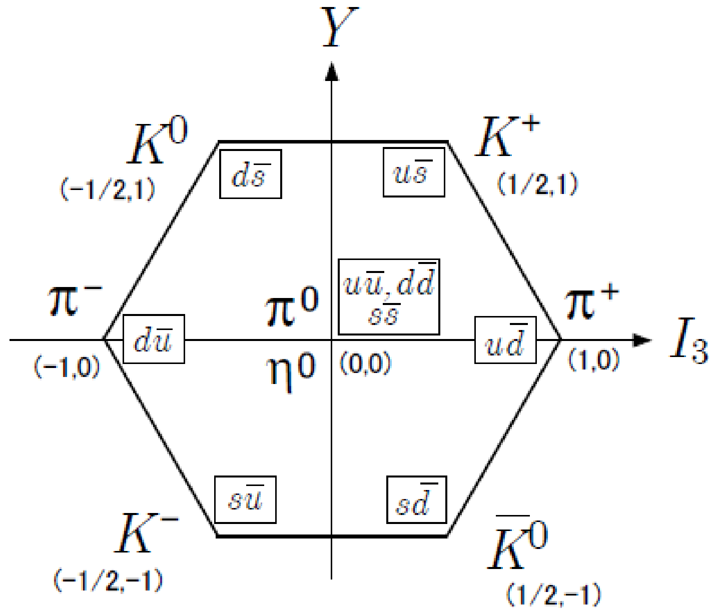
ストレンジネス核物理

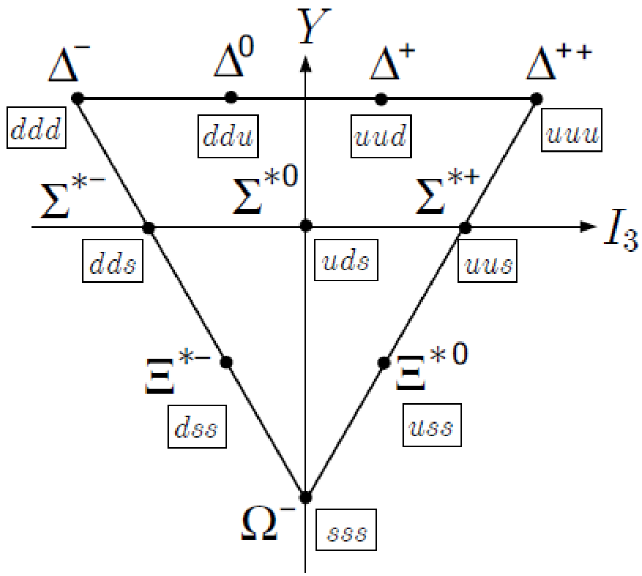
- ストレンジネスは原子核深部を探るプローブ
  - –ハイペロンはパウリ排他律を受けない
- Impurity Physics
  - – "糊"としての役割
  - – 原子核構造の変化
- Baryon-Baryon Interaction
  - – YN, YY Interaction based on $SU_f(3)$
  - – 核力の統一的理解・斥力芯の起源
- "Exotic" Nuclear Physics
  - – ストレンジネスが拓く新しい原子核の面白さ
- Neutron Starの構造と進化
  - – 高密度核物質, EOS, 最大質量, 冷却, …
  - ←Serious Problems from hyperon-mixing (Takatsuka)

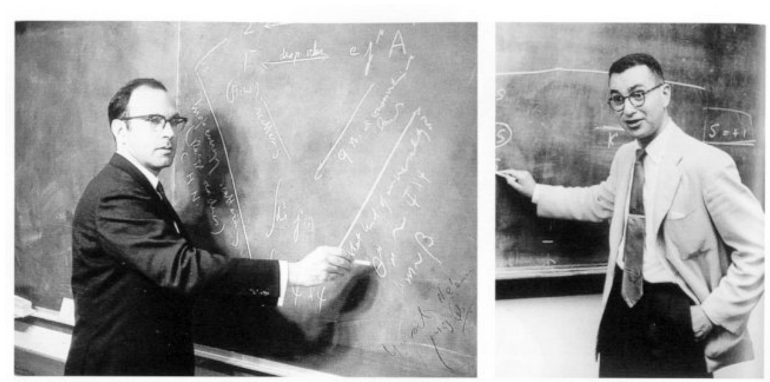
■Keywords

Hyperon mixing









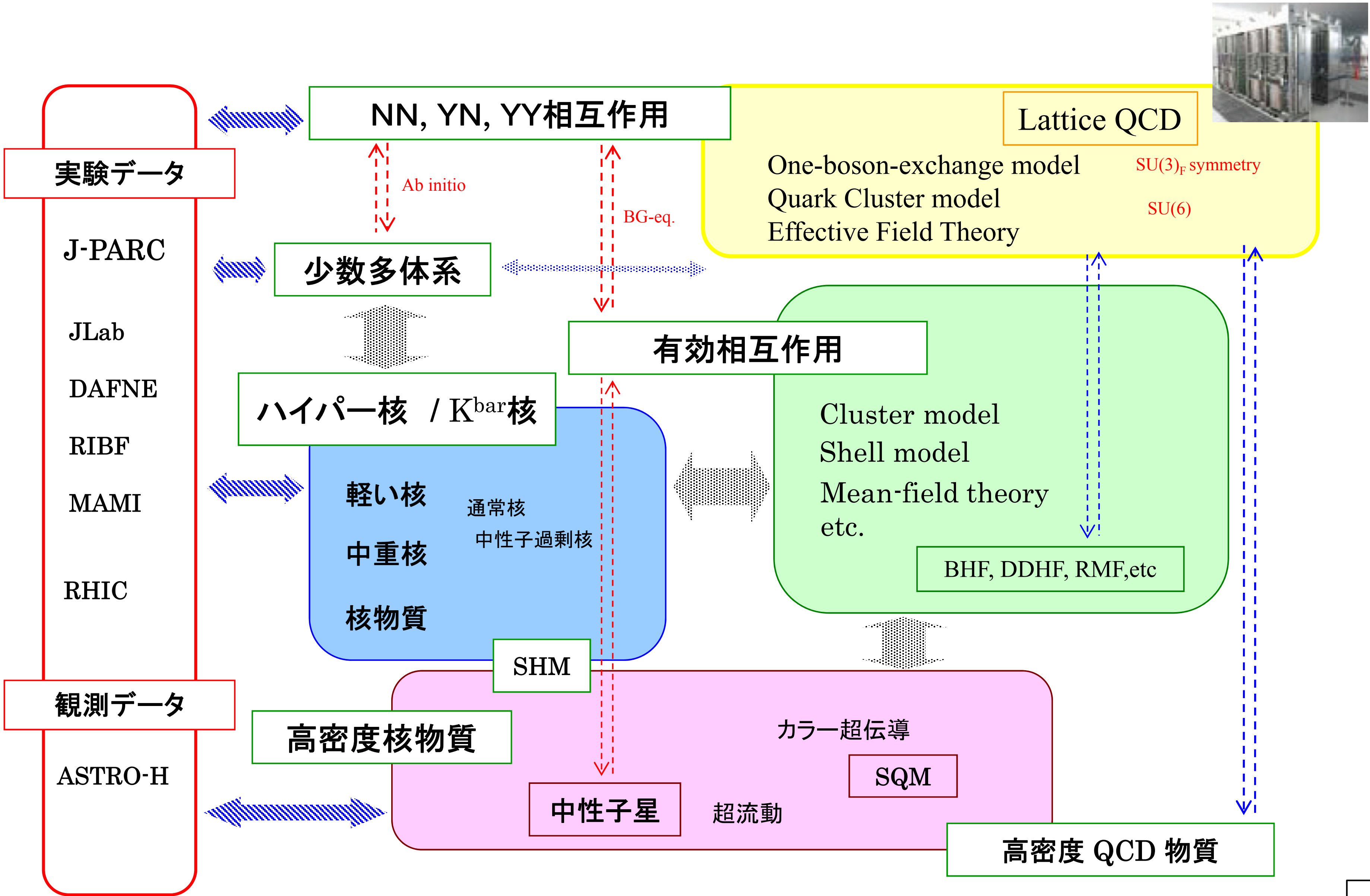
Yuval Ne'eman

Murray Gell-Mann

ストレンジネス核物理の展開

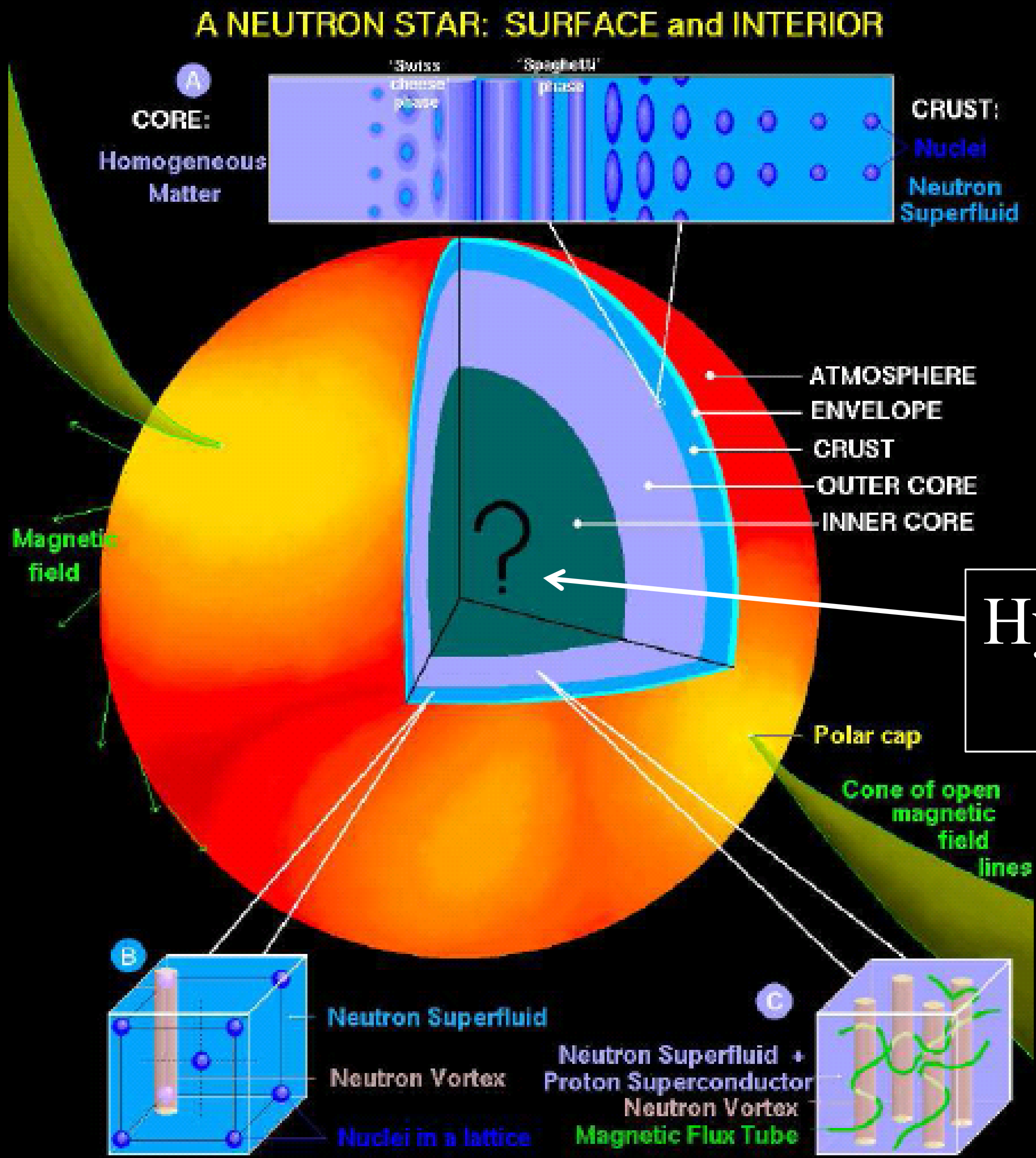
by E.Hiyama

“QCD,核力から核構造へ”と“核構造からQCD,核力へ”



中性子星物質とハイペロン

by J.M. Lattimer, M. Prakash,



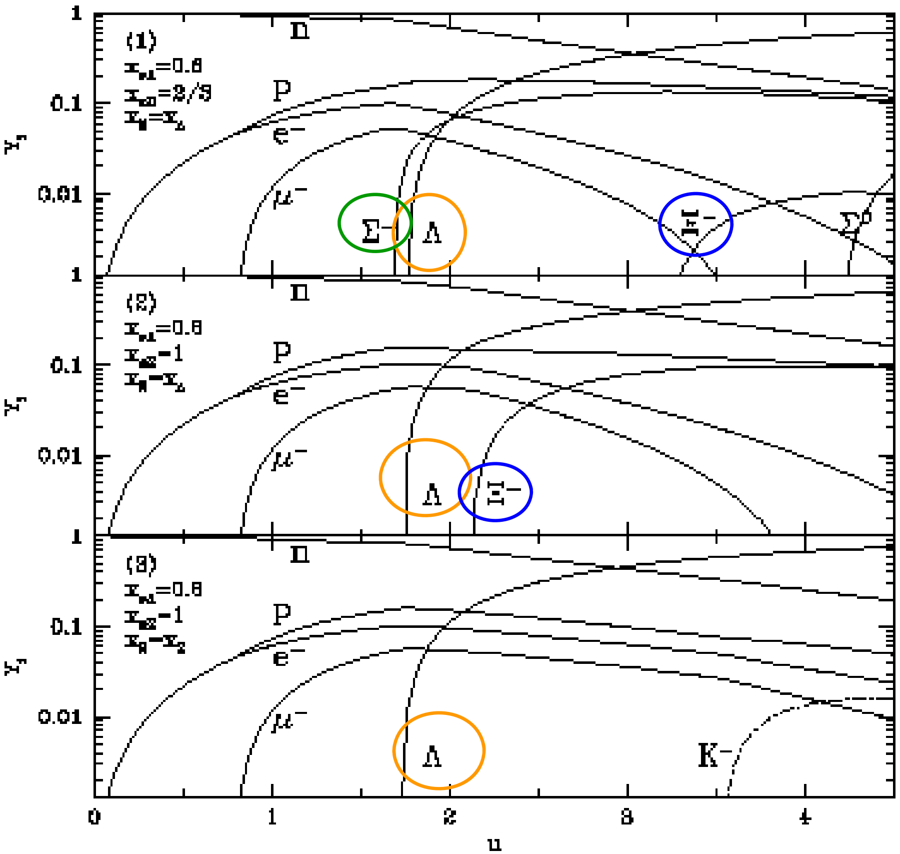
Hyperon mixing

$\rho \sim (2\text{-}3)\ \rho_0$

Neutron star core

= "An interesting neutron-rich hypernuclear system"

Coupling constant ratio; $x_{iY} = g_{iY}/g_{iN}$ $(i = \sigma, \omega, \rho)$

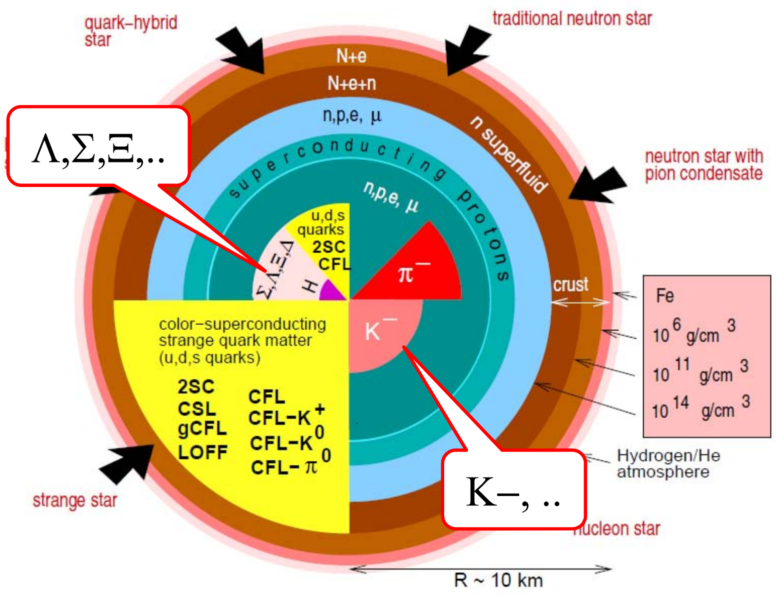


$U_\Sigma < 0$
$U_\Xi < 0$

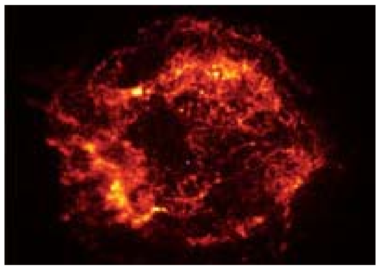
$U_\Sigma > 0$
$U_\Xi < 0$

$U_\Sigma > 0$
$U_\Xi > 0$

[R. Knorren, M. Prakash, P.J.Ellis, PRC52(1995)3470]



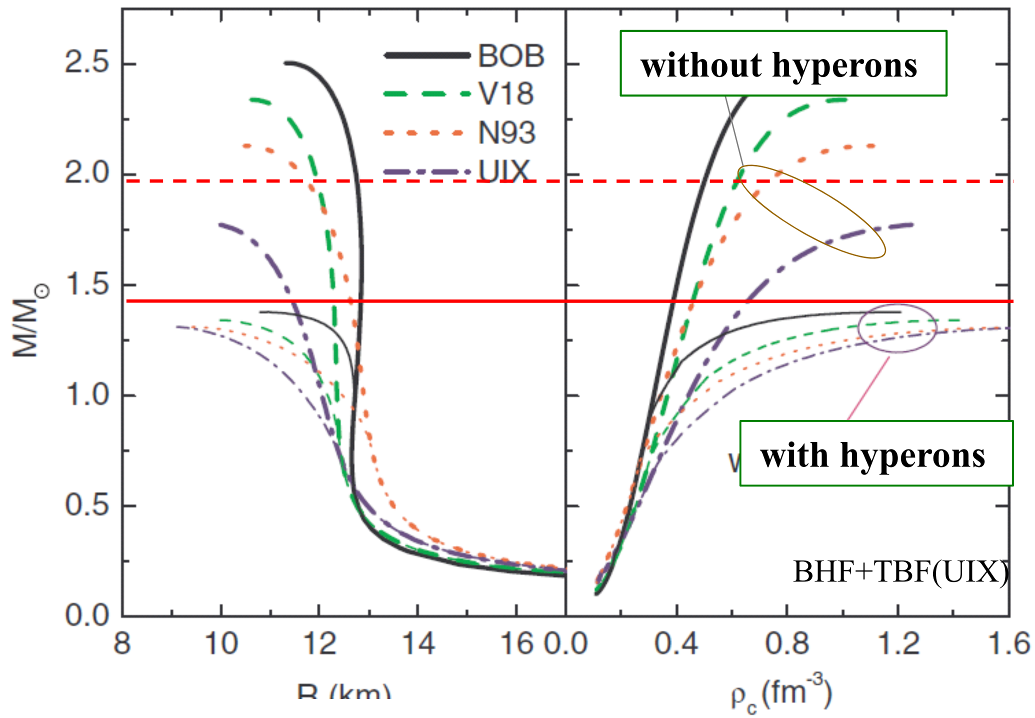
[F. Weber, PPNP 54(2005)193]



Cassiopeia A nebula
NASA/CXC/SAO.

Hyperon-mixing

Hyperons and massive neutron stars



BHF

Z.H.Li, H.-J.Schulze,
PRC 78 (2008) 028801

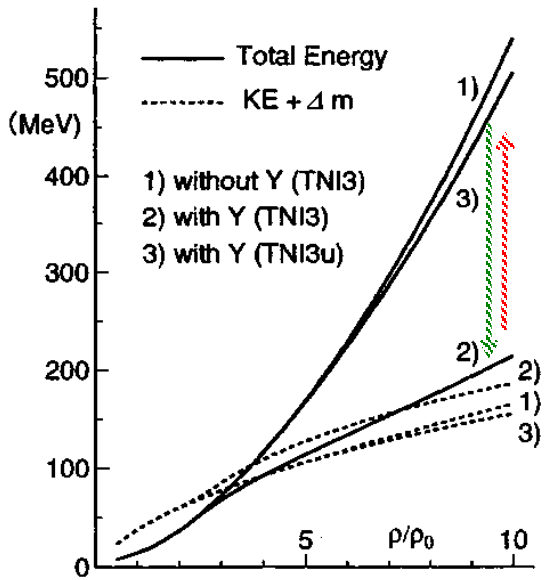
$1.97 M_{\text{sun}}$ ← PSR J1614-2230

P. B. Demorest et al.,
Nature467(2010)1081

$1.44 M_{\text{sun}}$

Maximum Mass/Radius

Softening on the EOS

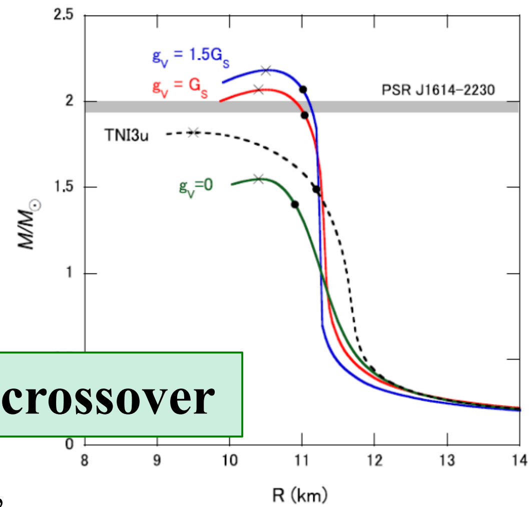


YN,YY: extra repulsion TNIu

S. Nishizaki, T. Takatsuka, Y. Yamamoto,
PTP105(2001)607; NPA691(2001)432

短距離斥力をハイペロン混合により回避

$n_C(Y) \approx (2-3)n_0$



Hadron-Quark crossover

K. Masuda, et al.,
arXiv:1205.3621v2 [nucl-th]

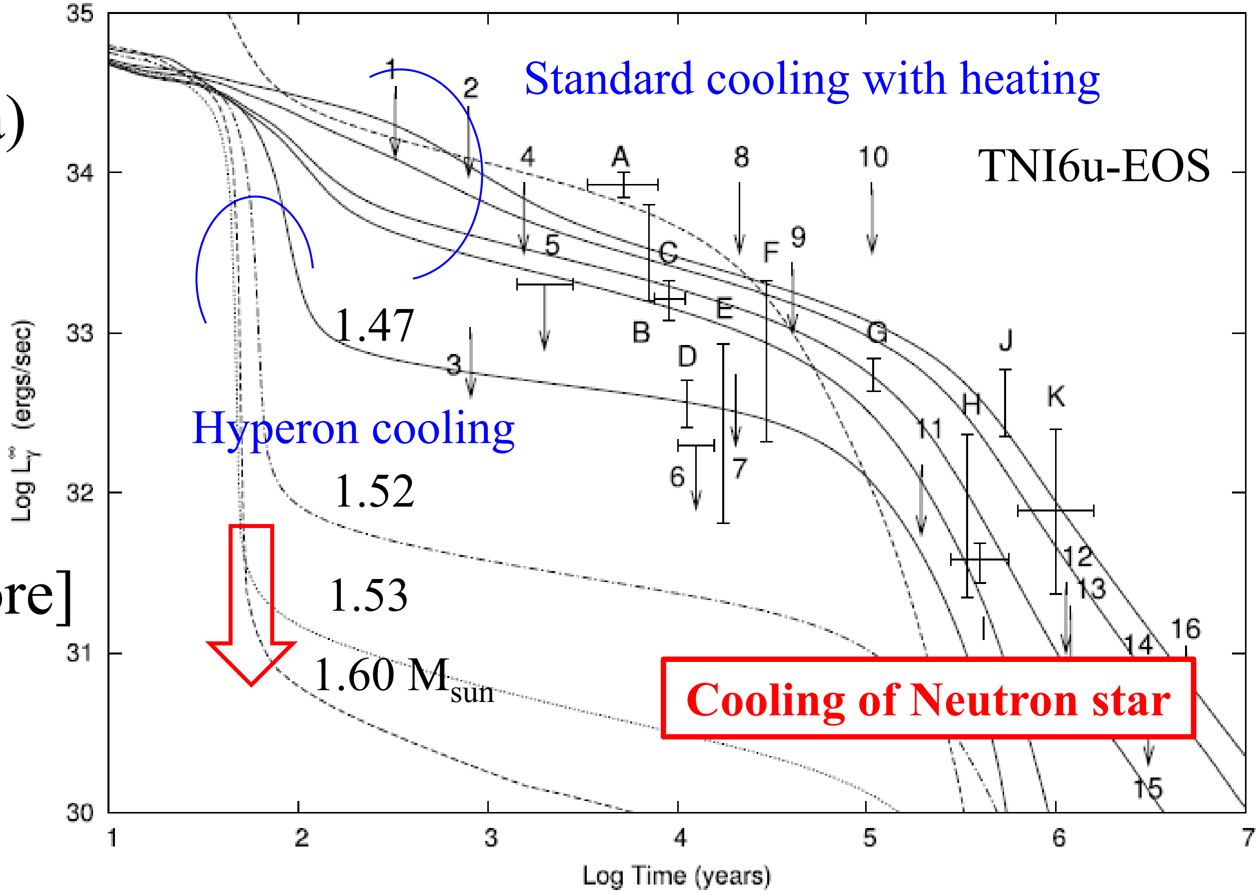
Thermal evolution of neutron stars

Rapid neutrino emission
via weak processes
(Direct/Modified Uruca)

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

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

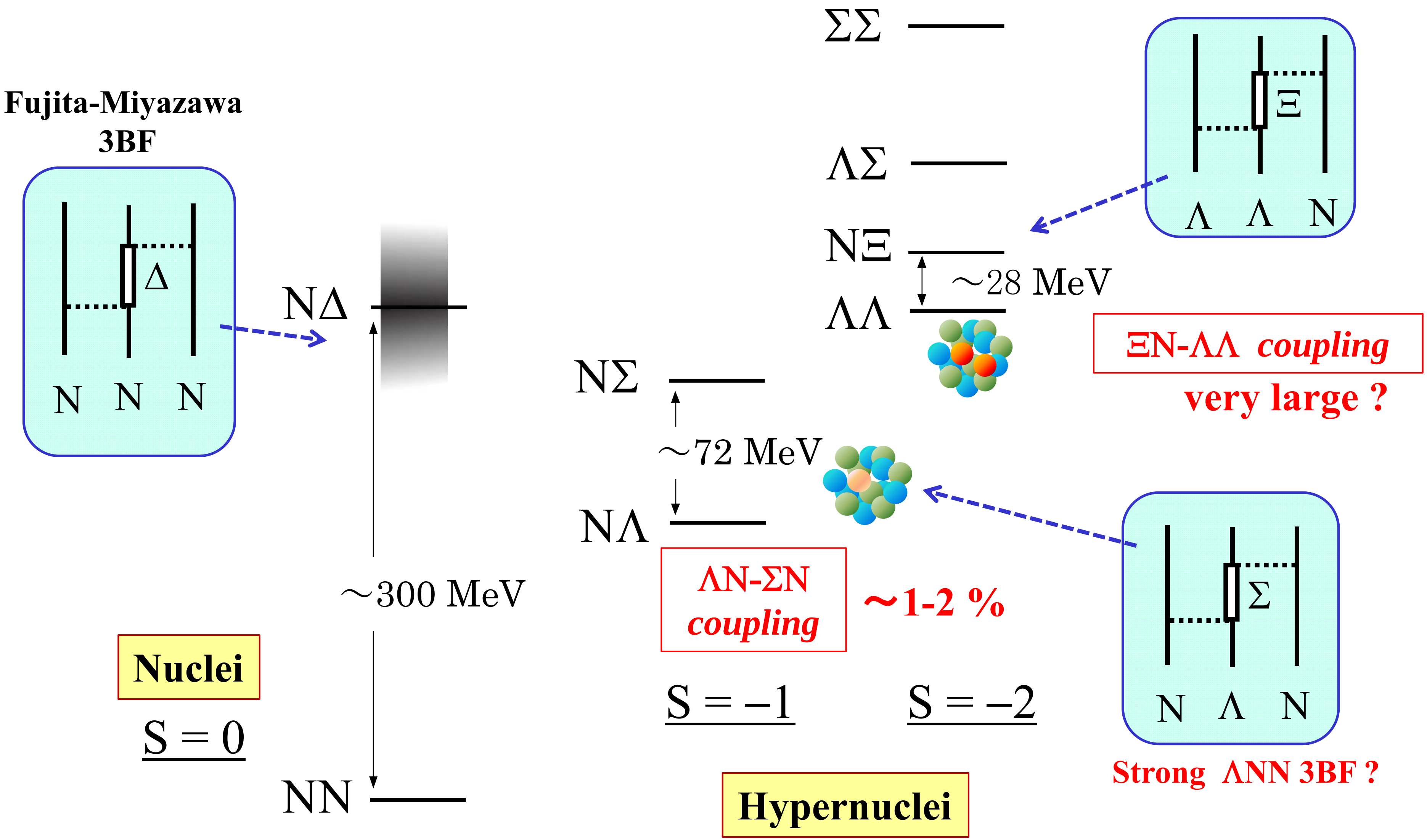
[S. Tsuruta et al., Astrophys. J 691(2009)621]



- Cooper pair
  - $^1S_0$ [iner crust]
  - $^3P_2$-$^3F_2$(n),$^1S_0$(p) [core]
  - → Standard cooling
- YY pairing
  - → Hyperon cooling
  - Cooling relaxation?
- Hyperon superfluidity v.s.YY intarctions
  - Nagara event $\Delta B_{\Lambda\Lambda}$~0.67 MeV → no ΛΛ superfluidity ?

very sensitive to properties of YN, YY interactions

Dynamics in Strangeness Nuclear Systems



- Various effects on the hyperon mixing
- Related to the 3BF in nuclei

ハイペロン-核子間相互作用

■One-Boson-Exchange model

- ➢**Nijmegen potential**

  NHC-D/F→NSC89→NSC97e,f→ESC04a-d→
  ESC06→ESC08a-c [Th.A. Rijken, M. M. Nagels,Y. Yamamoto, PTPS185(2010)14

- ➢**Funabashi-Gifu potential**

  [I. Arisaka et al., PTP104(2000)995]

■Quark Cluster model

- ➢**Kyoto-Niigata potential**

  RGM-F→FSS→fss2 [Y. Fujiwara et al, PRC54(1996) 2180; PPNP58 (2007)439]

■Chiral LO Effective Field Theory

- ➢**Julich potential**

  [H.Polinder, et al., NPA779 (2006) 244;PLB653 (2007) 29]

■Latice QCD

- ➢ **HAL QCD Collaboration**

  [H. Nemura, et al., PLB 673 (2009) 136; T. Inoue, et al., PTP124 (2010) 591;
  PRL106 (2011) 162002]

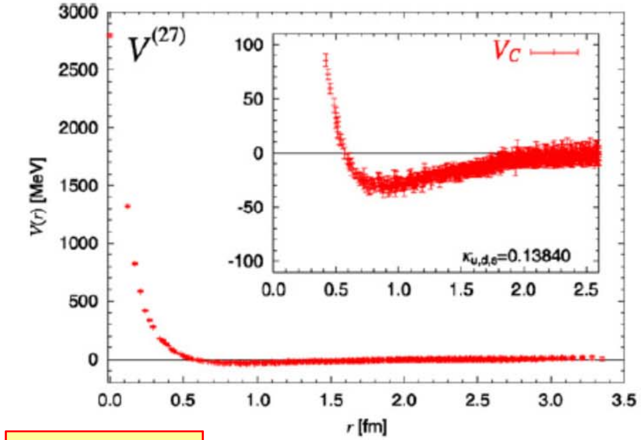
Baryon-Baryon force in SU(3) basis from lattice QCD

T. Inoue et al., HAL QCD Collaboration, NPA881 (2012) 28.

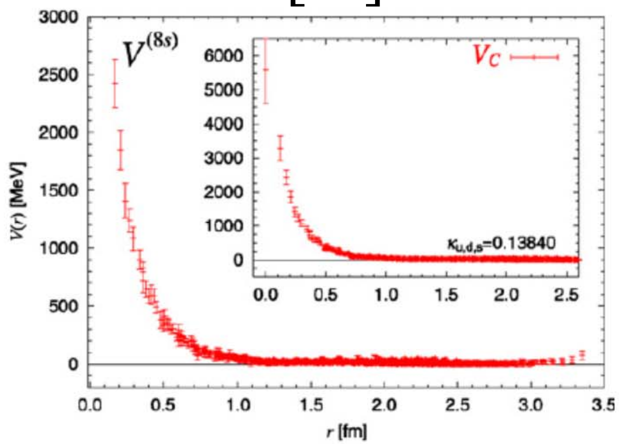
$$[8]\otimes[8]=[27]\oplus[8_s]\oplus[1]\oplus[10^*]\oplus[10]\oplus[8_a]$$

$^1S_0$

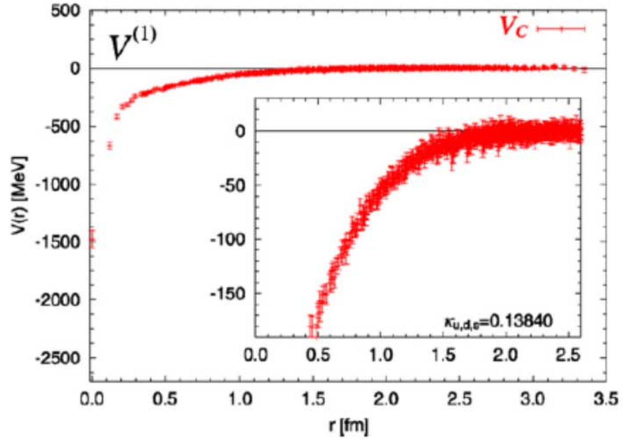
[27]



[8s]

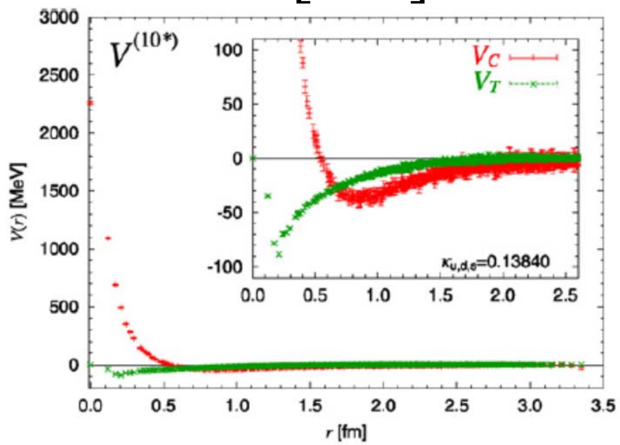


[1]

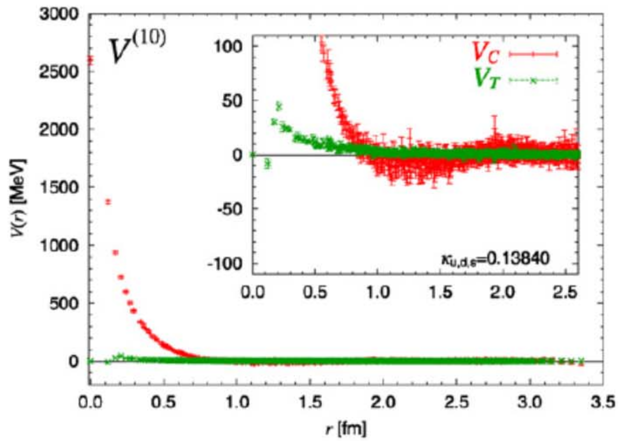


$^3S_1$-$^3D_1$

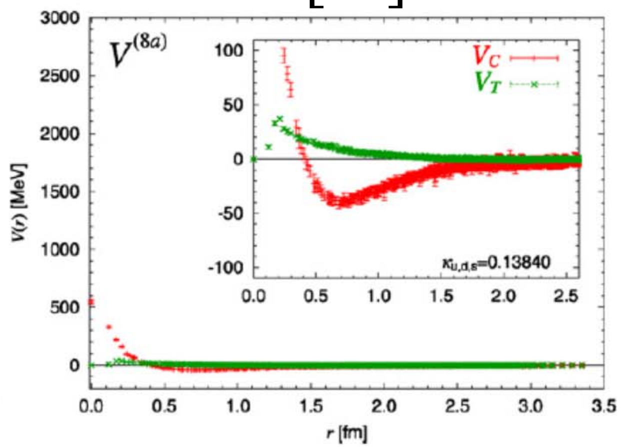
[10*]



[10]



[8a]



- at the $SU(3)_F$ limit corresponding to Mπ = MK = 837 MeV.
- possibility of a bound H-dibaryon in the limit.

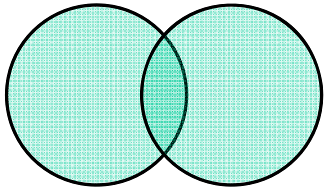
Short-range repulsive core in baryon-baryon interaction

Spin-flavor SU(6) symmetry

Quark Cluster Model

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

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
8_S	**1**		ΣN(I=1/2,$^1S_0$) ***Pauli forbidden***
27	4/9	5/9	NN($^1S_0$)

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

E40@J-PARC: Σ^+p Scattering

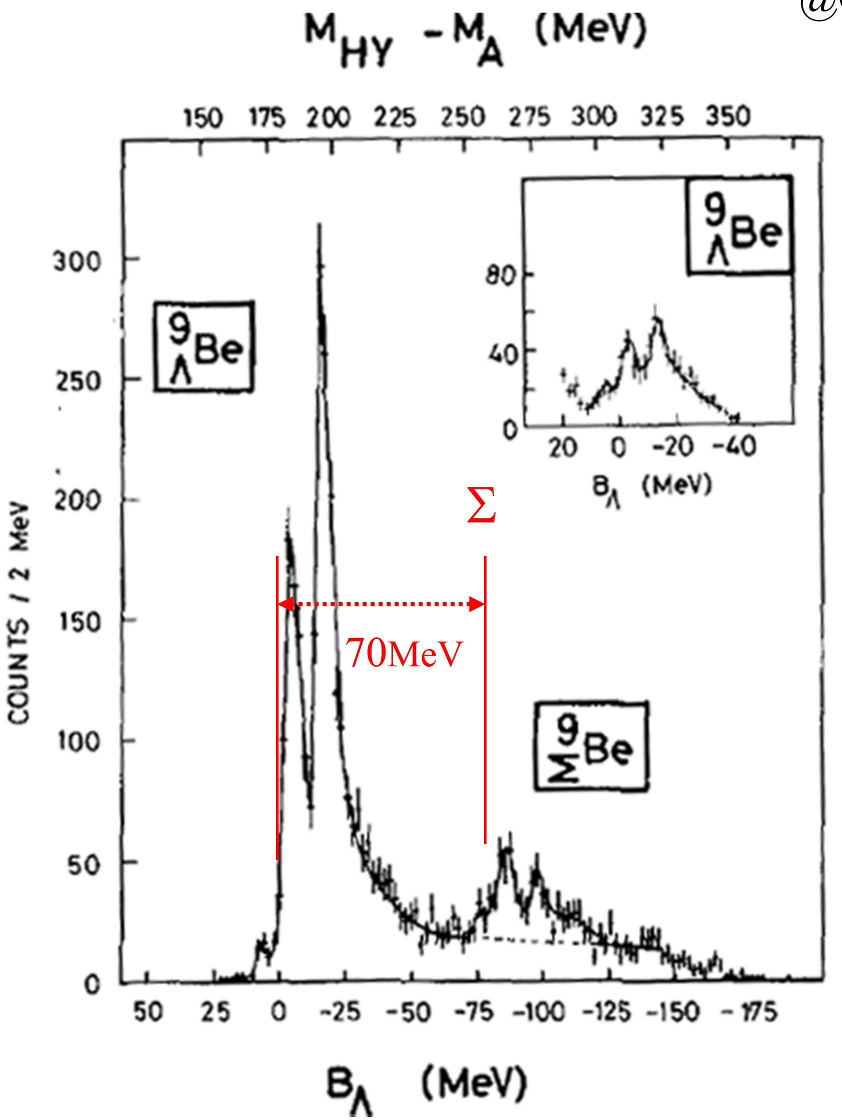
➢SU(6)sp symm. → Strongly spin-isospin dependence

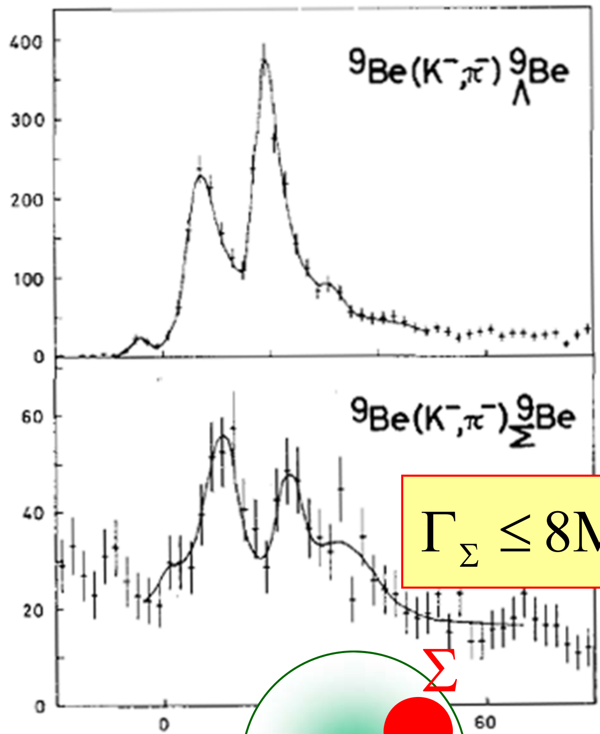
2. Σハイパー核

Searching for Sigma-Hypernuclei (1980-)

@CERN-PS, 720 MeV/c (0deg.)

R.Bertini al.,PB90(1980)375

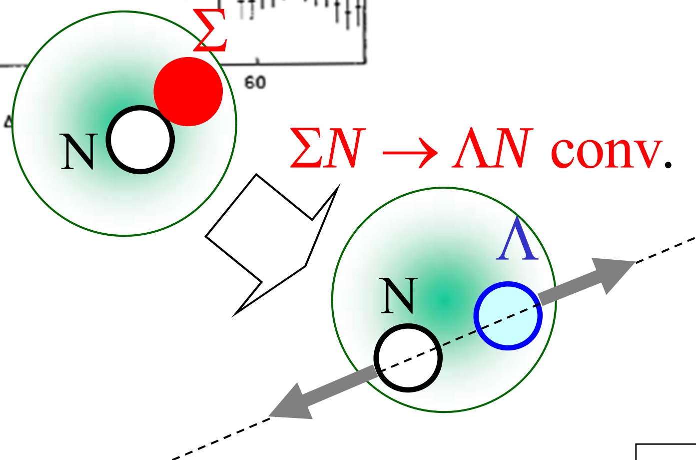




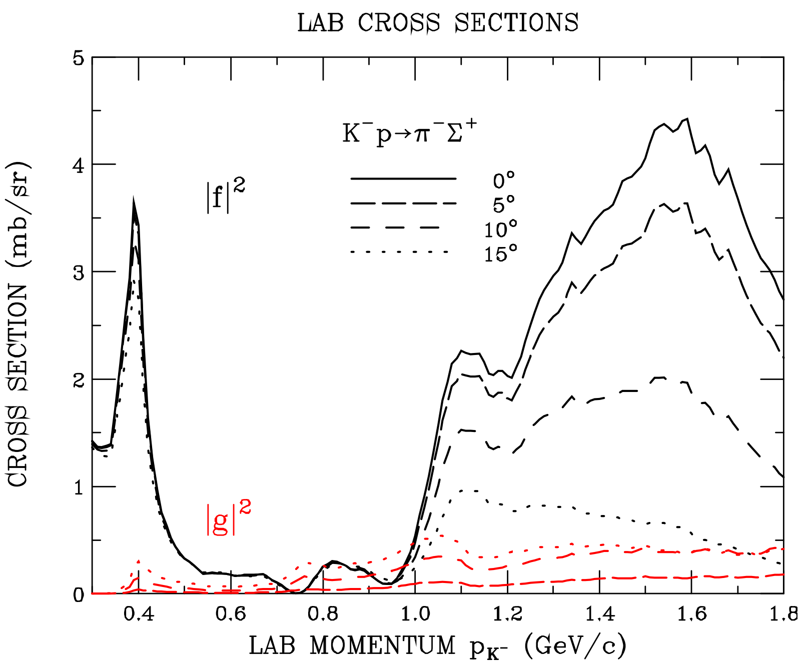
$\Gamma_{\Sigma} \leq 8\text{MeV}$

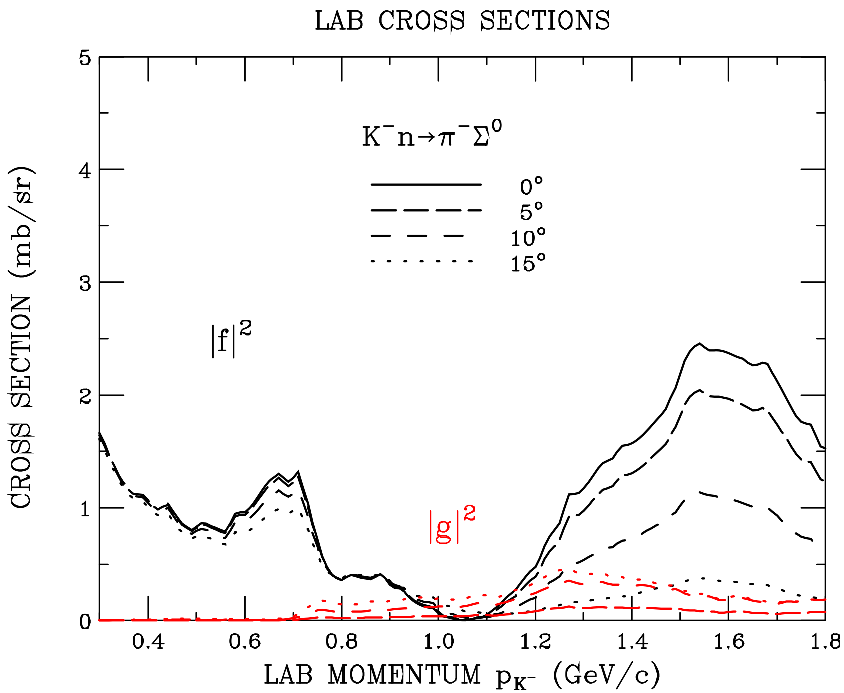
理論予想

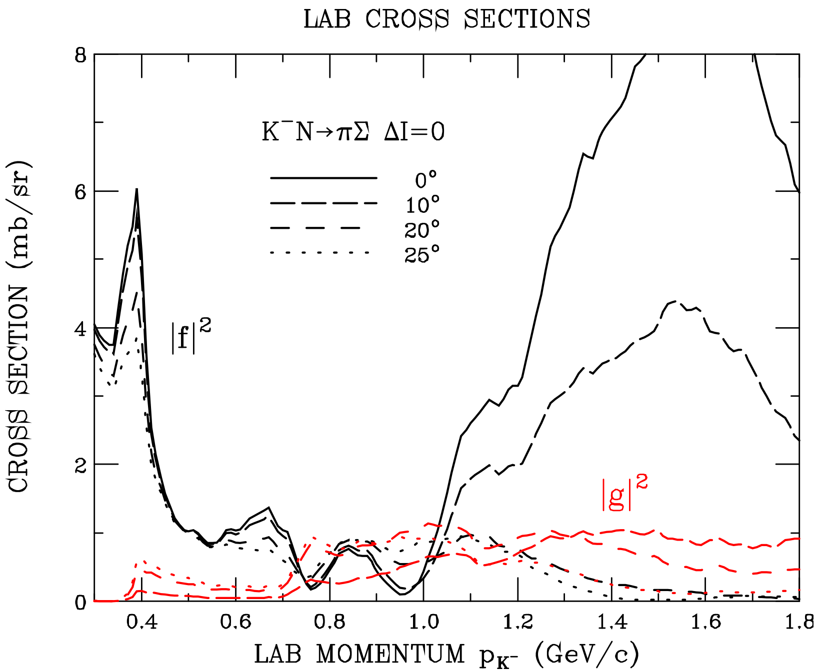
< 20MeV

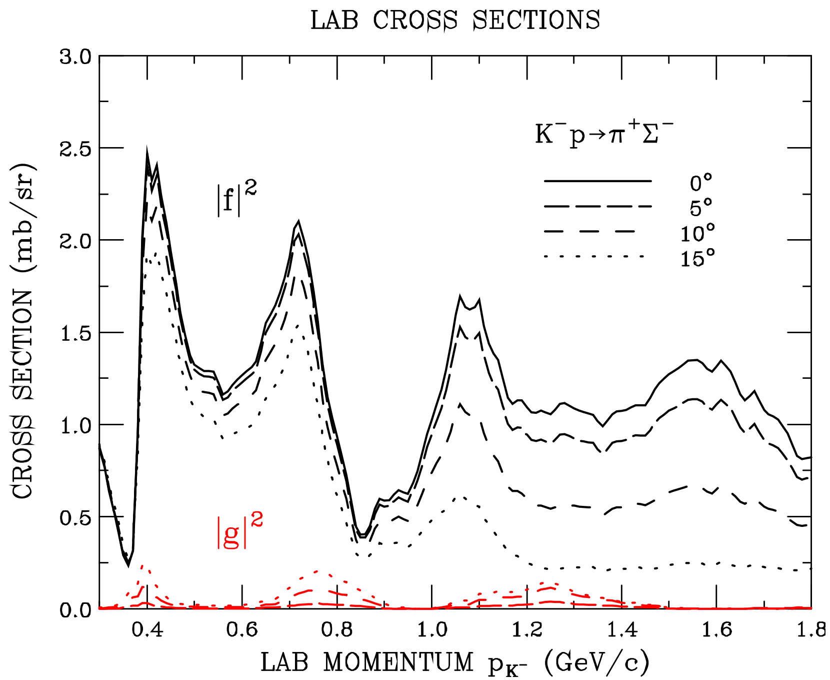


"狭い幅の状態"の問題の始まり


LAB CROSS SECTIONS
K⁻p→π⁻Σ⁺
|f|²
|g|²
0°
5°
10°
15°
CROSS SECTION (mb/sr)
LAB MOMENTUM pK- (GeV/c)
0
1
2
3
4
5
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8

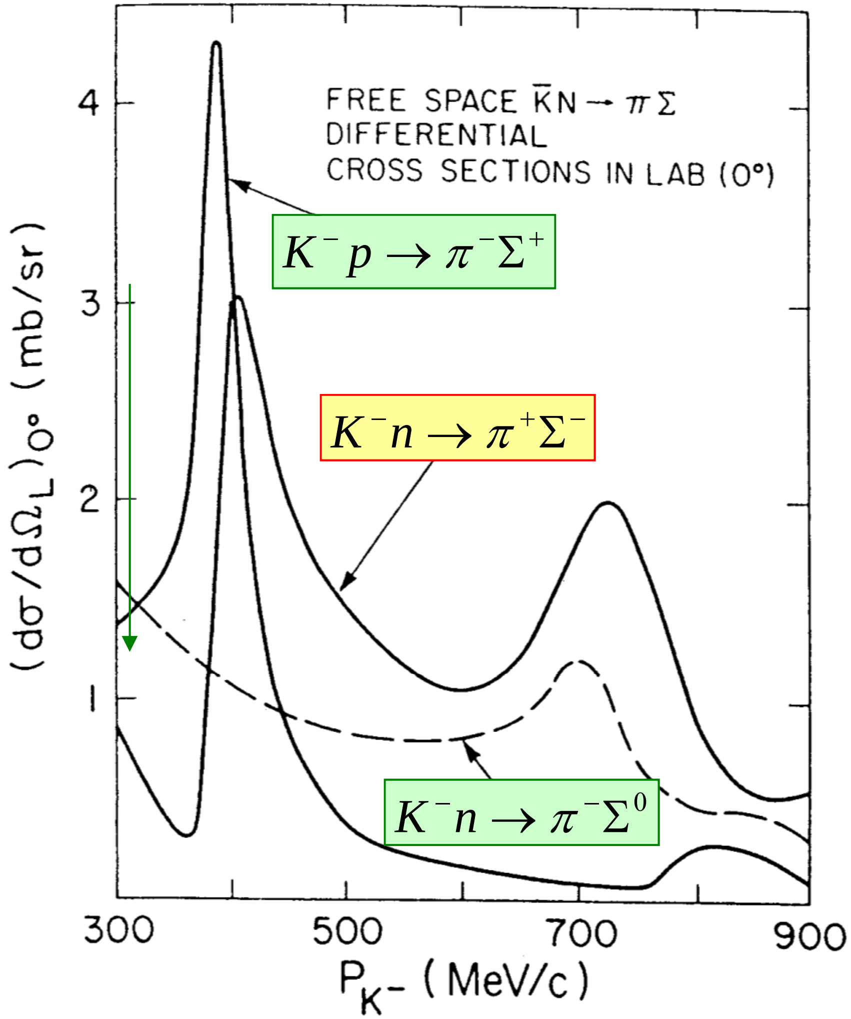

LAB CROSS SECTIONS
K⁻n→π⁻Σ⁰
|f|²
|g|²
0°
5°
10°
15°
CROSS SECTION (mb/sr)
LAB MOMENTUM pK- (GeV/c)
0
1
2
3
4
5
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8


LAB CROSS SECTIONS
K⁻N→πΣ ΔI=0
|f|²
|g|²
0°
10°
20°
25°
CROSS SECTION (mb/sr)
LAB MOMENTUM pK- (GeV/c)
0
2
4
6
8
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8

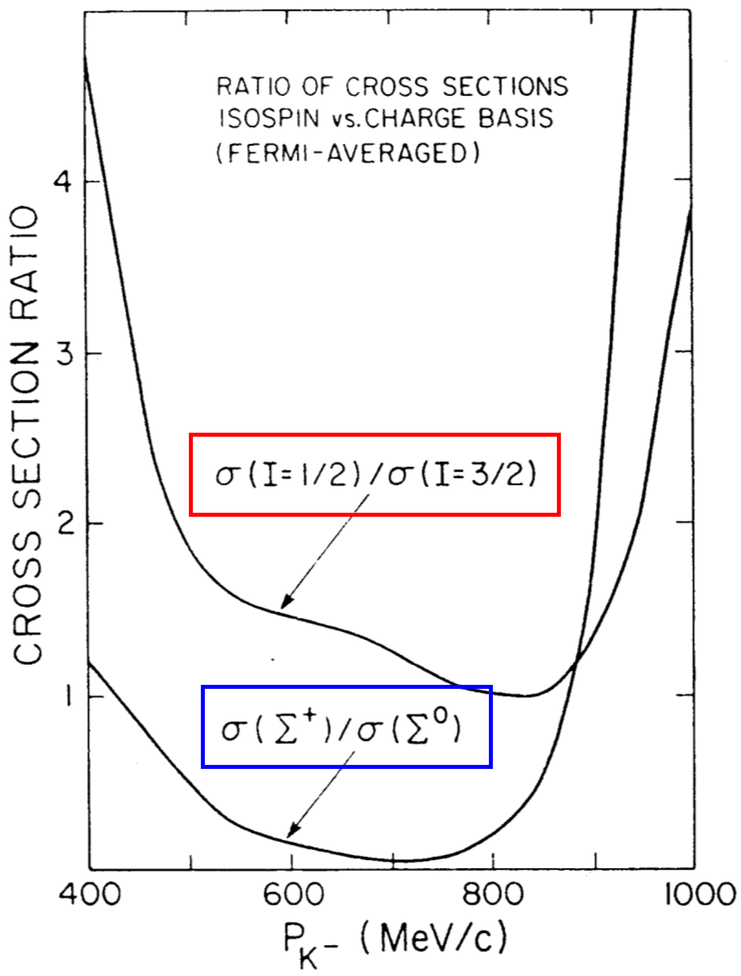

LAB CROSS SECTIONS
K⁻p→π⁺Σ⁻
|f|²
|g|²
0°
5°
10°
15°
CROSS SECTION (mb/sr)
LAB MOMENTUM pK- (GeV/c)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8

Elementary $(K^-,\pi^\pm)$ reactions

$$\left[\frac{d\sigma}{d\Omega_L}\right]^{elem}$$

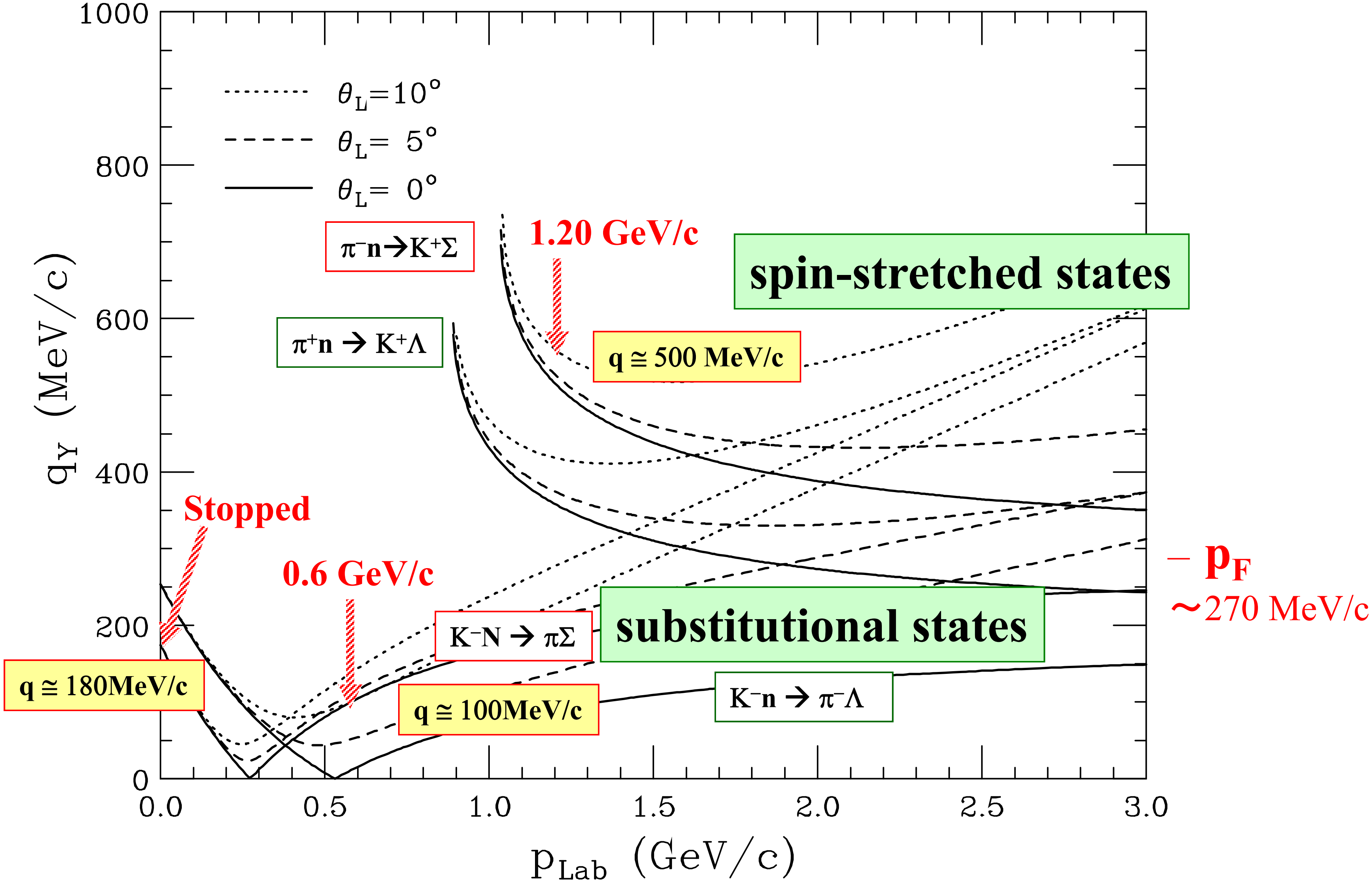


G.P.Gopal et al., NPB119(1977)362.



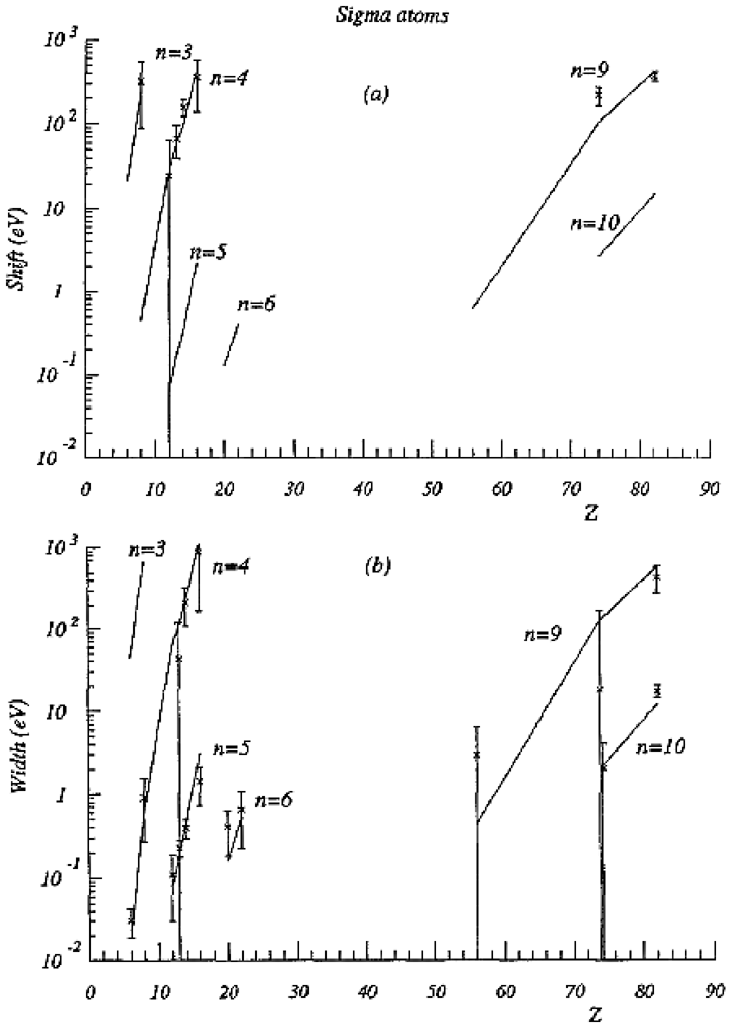
C.B.Dover, D.J.Millener and A.Gal, Phys. Rep.184(1989)1.

Momentum transfer to Λ, Σ-hyperons



Σ⁻原子のx線データとΣ⁻-原子核間ポテンシャル

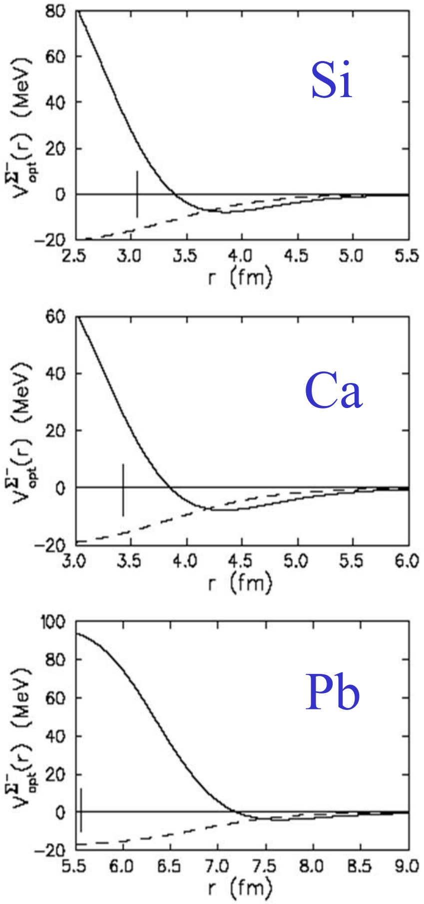
C.J.Batty et al., Phys.Rep.287(1997)385



Only 23 measurements !!

RMF

J. Mares et al., NPA594(1995)311



LDA+YNG-F

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

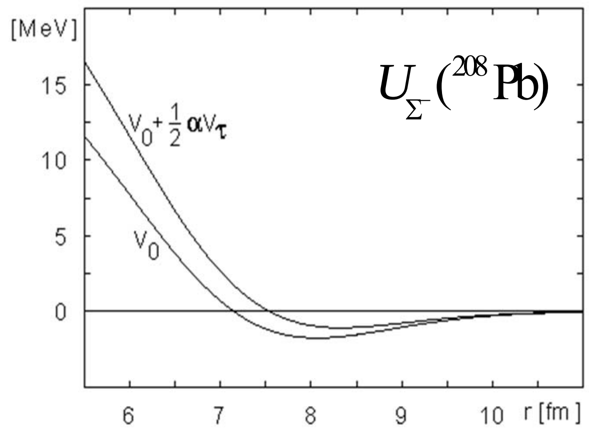


Fig. 2. Potential V_{Σ^-} in ^{208}Pb.

- Repulsive core + attractive tail
- Laneポテンシャルは斥力的
- NHC-Fが良い？

NSC97a-f のLane項は引力で不適！

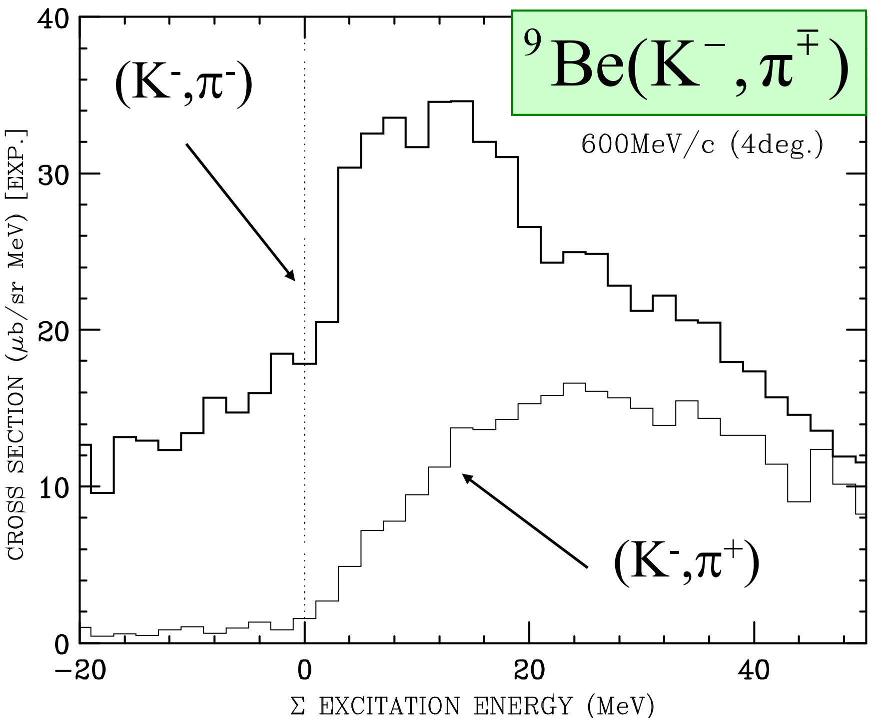
J. Dabrowski, PRC61(1999)025802

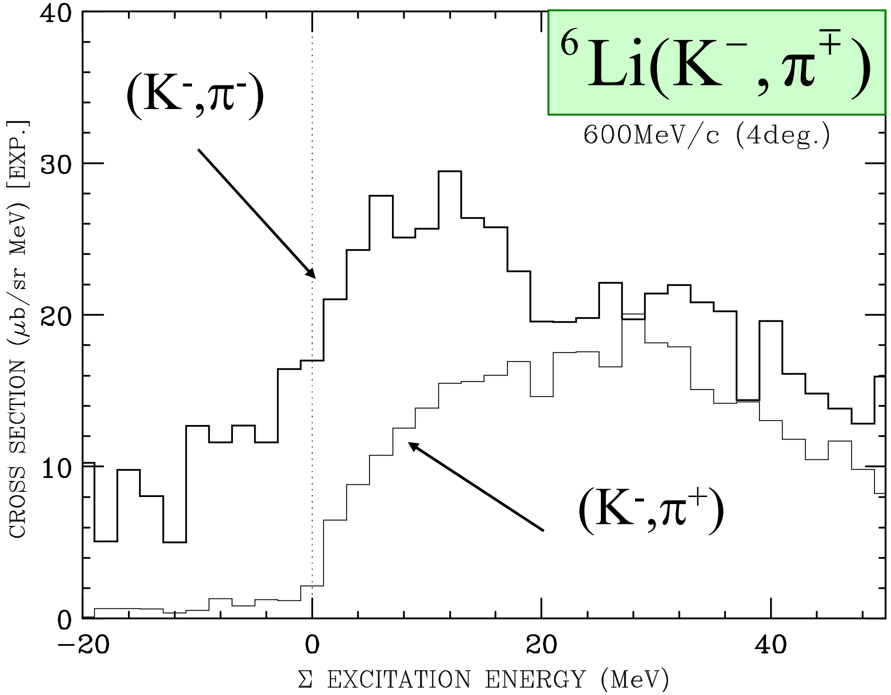
$(K^-,\pi^\pm)$ Experiments at BNL-AGS 600MeV/c (4deg.)

“狭い幅の状態の問題”の終焉 (-1999)

高統計のデータ

S.Bart et al.,PRL83(1999)5238





- There is no Σ bound state on both ^6Li and ^9Be.
- The π^- and π^+ spectra are very different each other.

➡ Strong isospin dependence of the Σ-nucleus potentials

シグマハイパー核の諸問題(1980s-)

- シグマハイパー核は存在するのか？
  - 狭い幅の状態の問題は? CERN,BNL,KEK
  - ΣN(T=1/2, $^3S_1$)の束縛状態は？ ANL,BNL
  - A=4の束縛状態の存否は? KEK,BNL
- Σポテンシャルは引力か斥力か？
  - シグマ原子のX線データ v.s.
  - (π^-, K^+)反応によるシグマ生成スペクトル KEK
- ラムダ核におけるΣ混合の割合は？
- アイソスピンは良い量子数か？
- スピン-軌道力の大きさは？

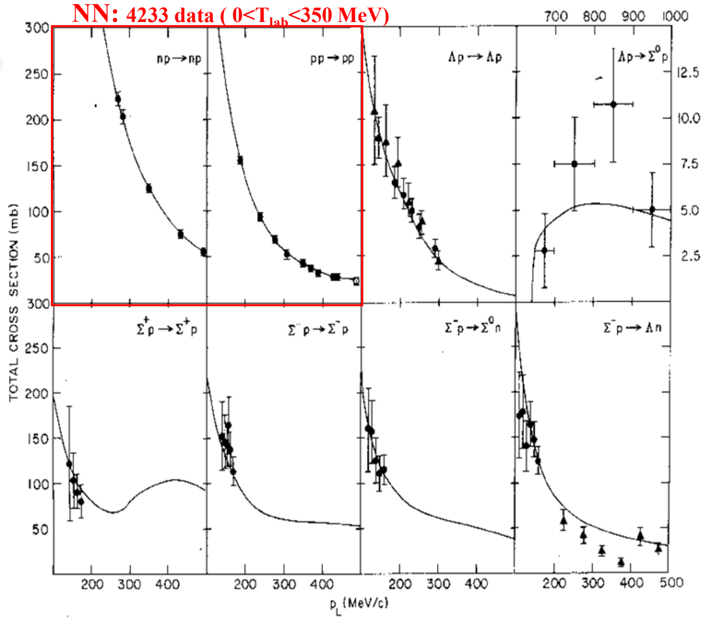
NN, YN interactions

$$\{8\}\otimes\{8\}=\{27\}\oplus\{10^*\}\oplus\{10\}\oplus\{8\}_s\oplus\{8\}_a\oplus\{1\}$$

SU(3)$_f$

$^1S_0$ $^3S_1$ ΛΛ

NN	NN		S= 0
ΣN,ΣN-ΛN,ΛN		**35 data**	S= –1
ΣΣ,ΞN-ΣΛ-ΣΣ,ΞN-ΣΣ-ΛΛ			S= –2
ΞΣ,ΞΣ-ΞΛ			S= –3
ΞΞ	ΞΞ		S= –4



C.B. Dover and H. Feshbach, Ann. Phys. 198(1990)321

Nijmegen soft-core potential NHC-D, NHC-F → NSC89 → NSC97 a-f → ESC04a-d, ESC08

Th.A. Rijken, V.G.J.Stoks, Y. Yamamoto, PRC59(1999)21
V.G.J. Stoks, Th.A. Rijken, PRC59(1999)3009
Th.A. Rijken, Y. Yamamoto, PRC73(2006)044008

One-Boson-Exchange model

Funabashi-Gifu potential

I. Arisaka, K. Nakagawa, S. Shinmura, M. Wada, PTP104(2000)995; FBS.Suppl.12(2000)395

Kyoto-Niigata potential RGM-F → FSS → fss2

Quark Cluster model

T. Fujita, Y. Fujiwara, C. Nakamoto, Y. Suzuki, et al., FBS.Suppl.12(2000)399; PRC64(2001)054001

$K^-d \rightarrow \pi^-\Lambda p$ Reactions (1960s-1970s)

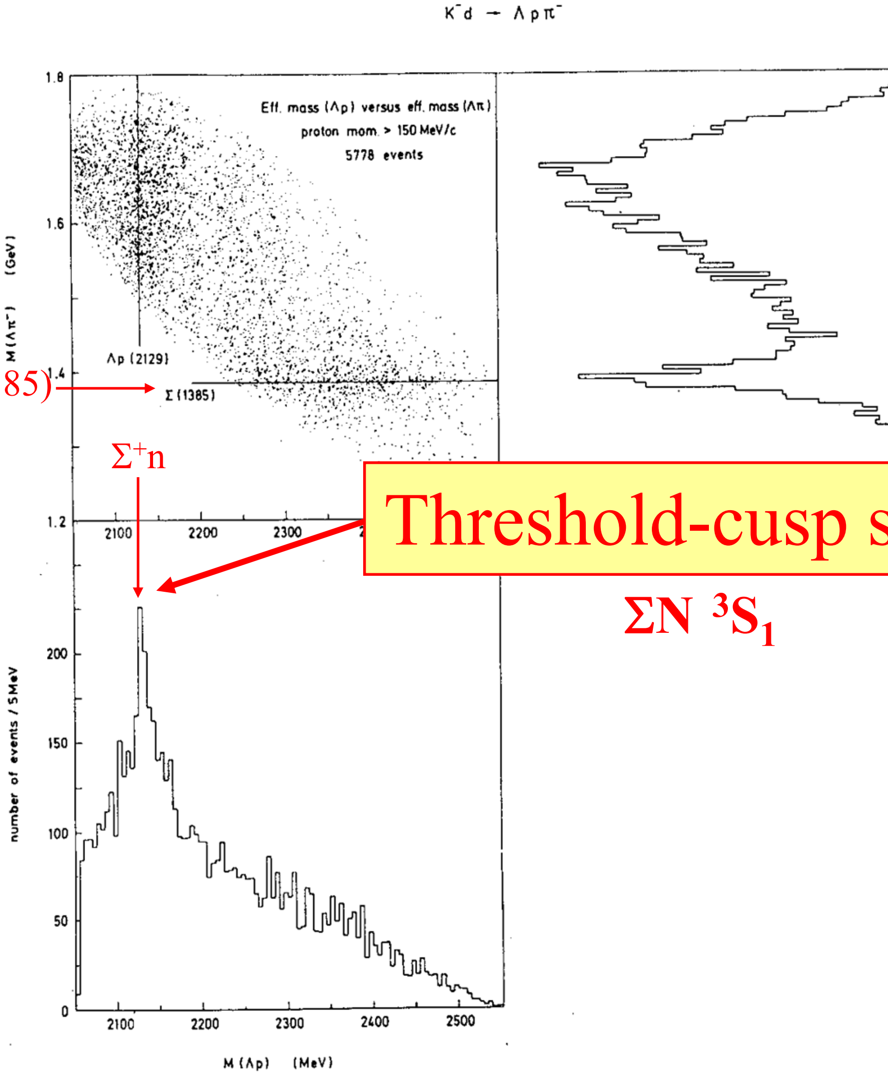


Fig. 1. Scatter diagram of the effective (Λp) mass *versus* the effective (Λπ⁻) mass in the $K^-d \rightarrow \Lambda p \pi^-$.

Σ(1385)

$\Sigma^+ n$

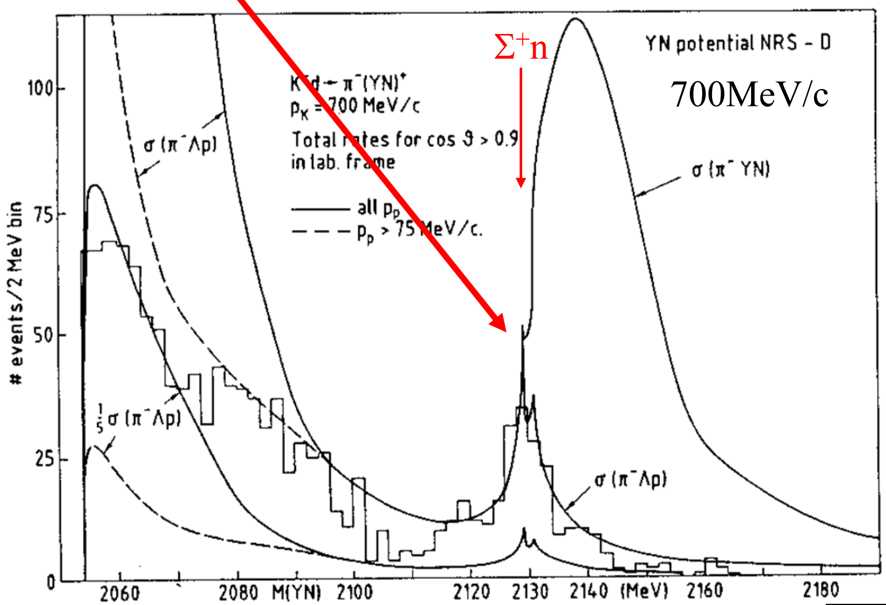
Threshold-cusp state !!

$\Sigma N\ ^3S_1$

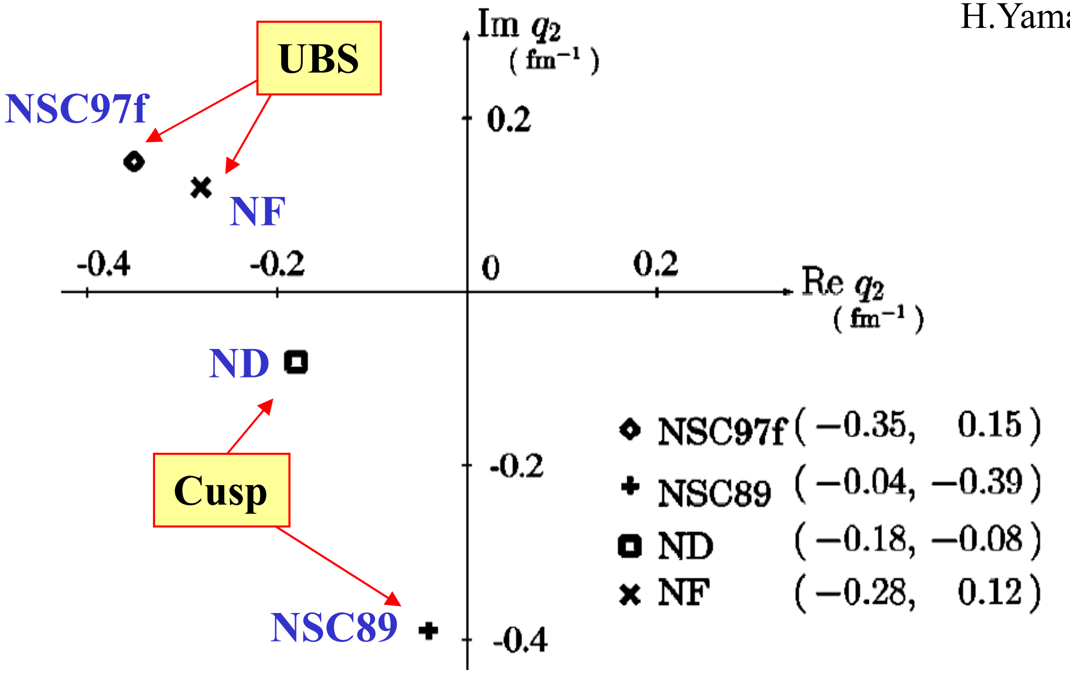
T.H.Tan, PRL23(1969)395.
O.Braun et al., NPB124(1977)45.
D.Eastwood et al.,PRD3(1971)2603.

- S= – 1 dibaryon search
- YN interaction study
- (K^-,π) reaction study

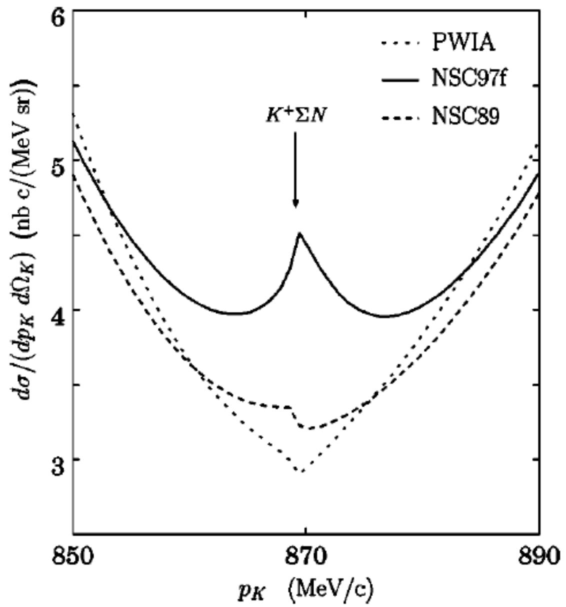
R.H.Dalitz, Deloff, Czech.J.Phys.B32(1982)1021

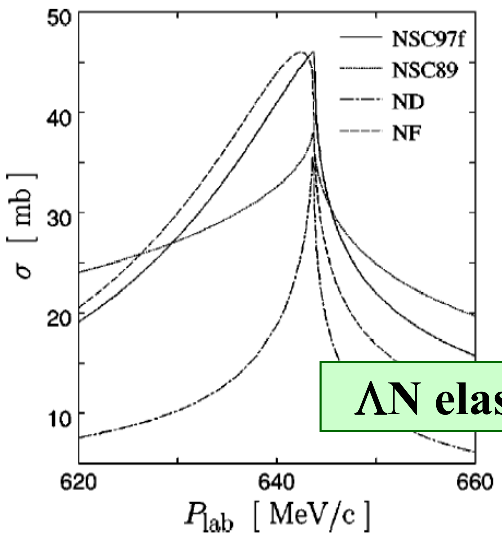


d(γ,K$^+$) spectrum near the ΣN threshold



H.Yamamura, K. Miyagawa, et al., PRC61(1999)014001

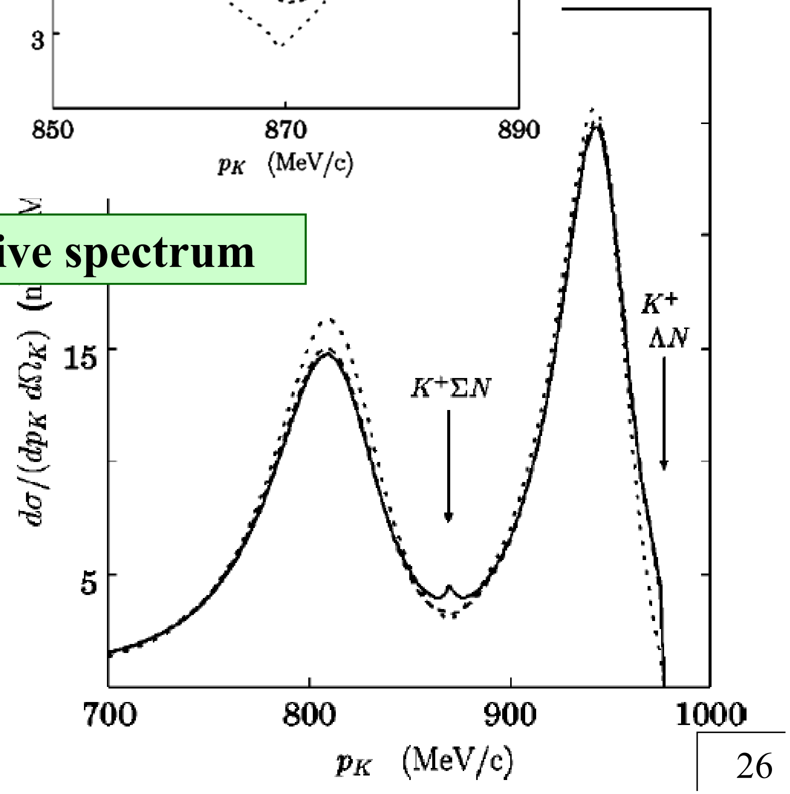




ΛN elastic cross section

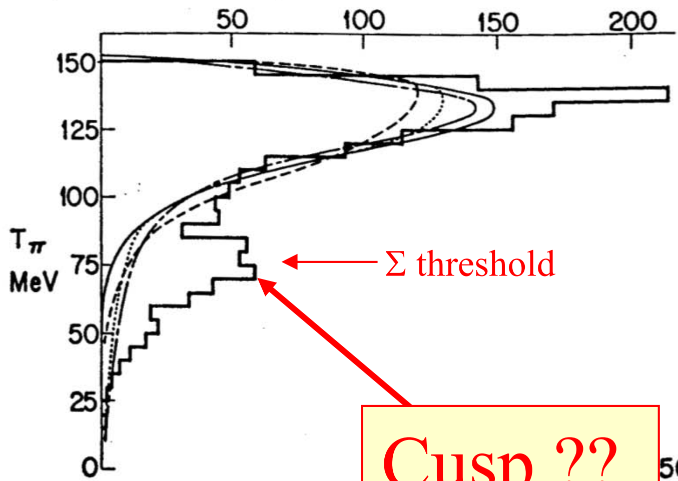
K. Miyagawa, H.Yamamura, PRC60(1999)024003

d(γ,K$^+$) inclusive spectrum

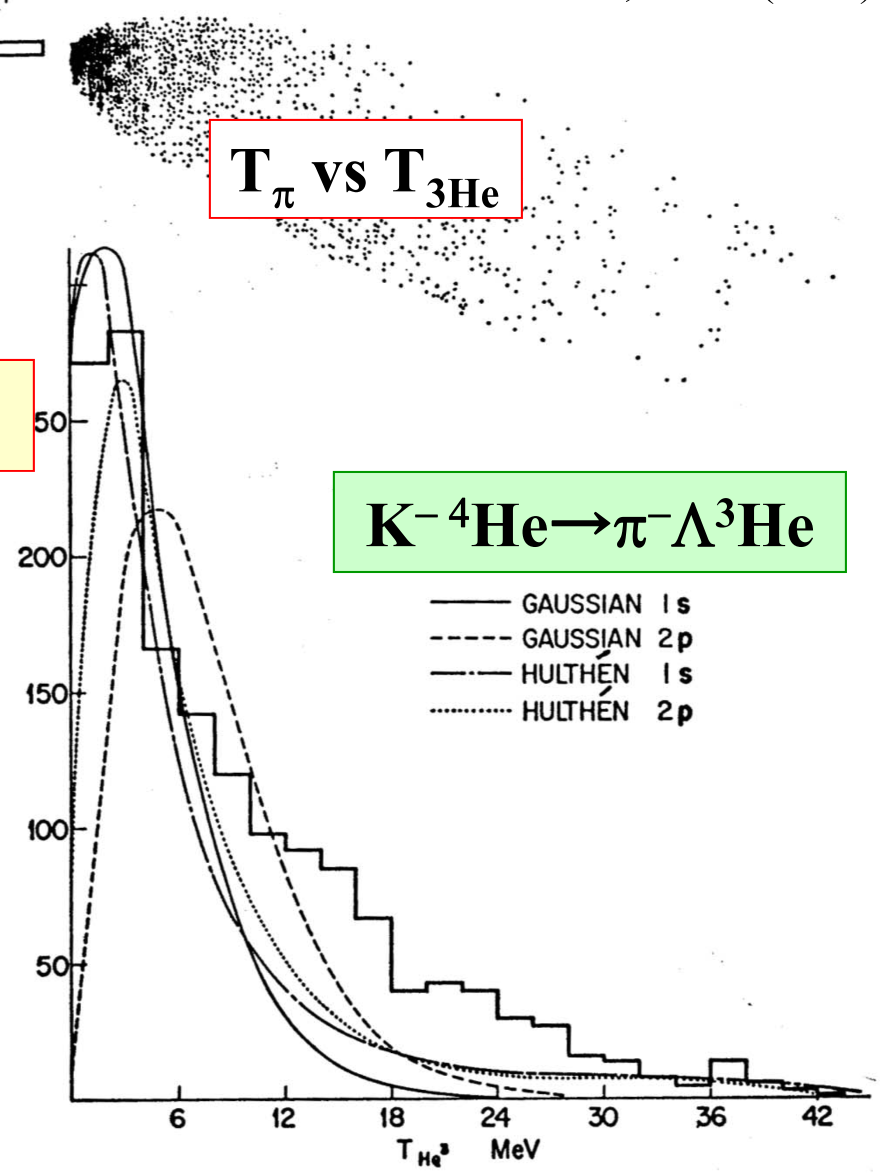


HeBC Study of $K^{-4}He$ Interactions (1960s-1970s)

K. Bunnell et al, PRD1 (1970) 98.



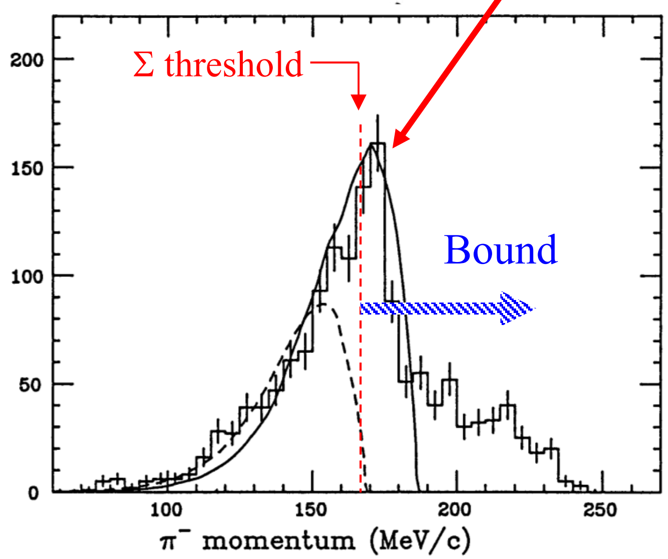
Cusp ??



$K^{-4}He \rightarrow \pi^- \Lambda pd$

$K^{-4}He \rightarrow \pi^- \Lambda ^3He$

R. Roosen et al., Nuovo Cimento A94 (1979) 217.



Σハイパー核の束縛状態の探索

- **理論的予測 (1987-)**
  T.Harada, S.Shinmura, Y.Akaishi, H.Tanaka, NPA507(1990)715
- **HeBC exp. at ANL (1970s)**
- **^{4}He(stopped K^{-},p) exp. at KEK (1989)**
- **^{4}He(K^{-},p) exp. at BNL (1992,1995)**
- **理論的解析 (-2000)**
  T.Harada, PRL80 (1998) 1605; NPA672 (2000) 181

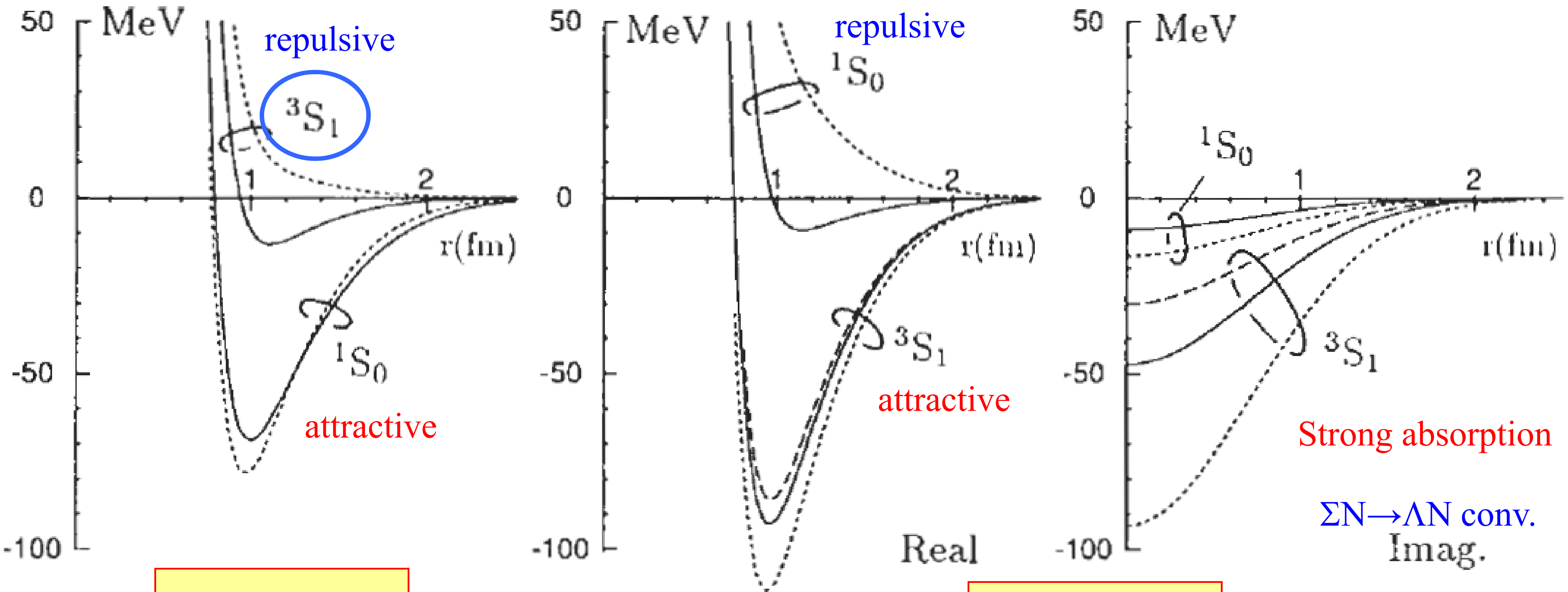
Two-body ΣN potentials in free space

Sigma-nucleon absorptive potential (SAP)

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

簡単であるが特長を捉えやすい

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



T=3/2

T=1/2

Strong spin-isospin dependence

ハイペロン-原子核間ポテンシャルの導出

$$U(\mathbf{R}) = \left(\Phi_0\,\mathbf{R}\,|\,\mathrm{V}^{\mathrm{ex}}\hat{\mathrm{F}}^{\mathrm{ex}}\,|\,\Phi_0\right)$$

□ $$\left\langle \Phi_0\mathbf{R} \middle| \mathrm{V}^{\mathrm{ex}}\,|\,\Psi^{\mathrm{ATMS}} \right\rangle \Big/ \left\langle \Phi_0\mathbf{R} \middle| \Psi^{\mathrm{ATMS}} \right\rangle$$

KAT Theory

Kurihara, Akaishi, Tanaka, PTP71(1984)561

$$\mathrm{V}^{\mathrm{ex}} = \sum_{\mathrm{ij}} \mathrm{V}^{\mathrm{ex}}_{\mathrm{ij}}$$

多重散乱理論

$$\hat{\mathrm{F}}^{\mathrm{ex}} = 1 + \sum_{(\mathrm{ij})} \frac{Q}{e}\mathrm{v}^{\mathrm{ex}}\hat{\mathrm{F}}^{\mathrm{ex}}$$

$$\hat{\mathrm{F}}^{\mathrm{ex}} = 1 + \sum_{(\mathrm{ij})} \frac{Q}{e} g_{\mathrm{ij}} \hat{\mathrm{F}}^{\mathrm{ex}}_{\mathrm{ij}}$$

$$Q = 1 - |\Phi_0)(\Phi_0|$$

$$\hat{\mathrm{F}}^{\mathrm{ex}}_{\mathrm{ij}} = 1 + \sum_{(\mathrm{kl})}{}' \frac{Q}{e} g_{\mathrm{kl}} \hat{\mathrm{F}}^{\mathrm{ex}}_{\mathrm{kl}}$$

$$e = E - H^{\mathrm{in}} - T_{\mathbf{R}}$$

$$g_{\mathrm{ij}} = \mathrm{v}^{\mathrm{ex}}_{\mathrm{ij}} + \mathrm{v}^{\mathrm{ex}}_{\mathrm{ij}} \frac{Q}{e} g_{\mathrm{ij}}$$

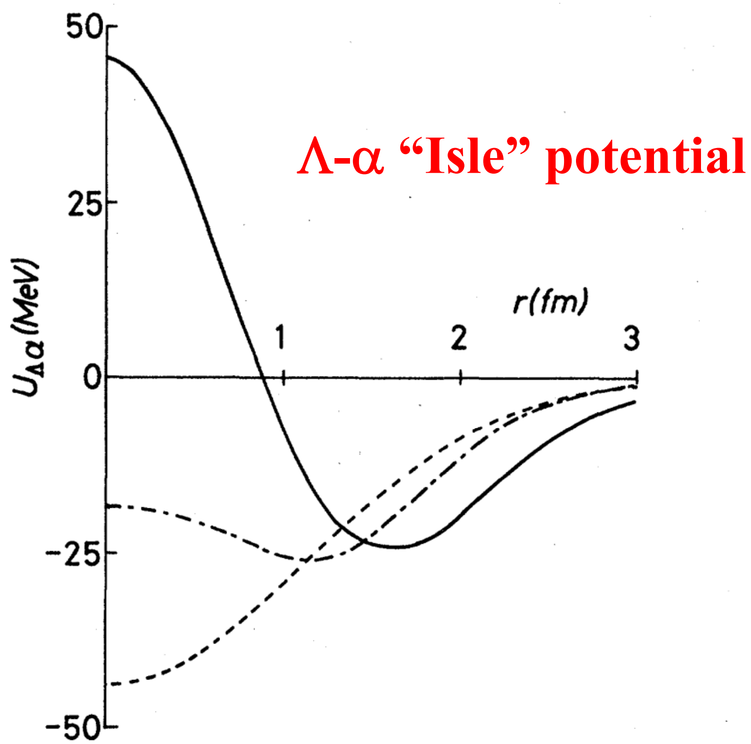


FIG. 1. Λ-α potentials. The solid, dashed, and dashed-dotted lines denote the isle, SG, and Maeda-Schmid (MS) (Ref. 7) potentials, respectively.

STRUCTURE OF THE $^{4}_{\Sigma}$He HYPERNUCLEAR BOUND STATE

Toru HARADA, Shoji SHINMURA[1], Yoshinori AKAISHI and Hajime TANAKA[2]
Department of Physics, Hokkaido University, Sapporo 060, Japan
[1] *Department of Applied Mathematics, Gifu University, Gifu 501-11, Japan*
[2] *Sapporo Gakuin University, Ebestu 067, Japan*

Received 20 April 1989
(Revised 18 September 1989)

Abstract: The structure of $^{4}_{\Sigma}$He is theoretically investigated on the basis of realistic ΣN interaction. The bound state has spin-parity $J^{\pi}=0^{+}$ and isospin $T\sim\frac{1}{2}$ (99%), binding energy $B_{\Sigma^+}=3.7$–4.6 MeV and a narrow $\Sigma N\rightarrow\Lambda N$ conversion width of $\Gamma=4.5$–7.9 MeV, which are in agreement with experimental data obtained at KEK. The existence of the Σ bound state with such a narrow width is explained from characteristic properties of the nucleus-Σ potential derived from the microscopic four-body calculation.

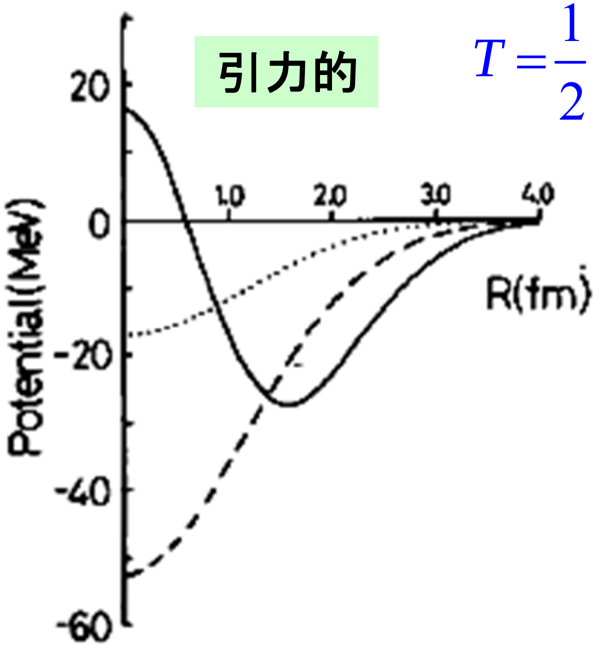
NN pot.: C3G
Tamagaki

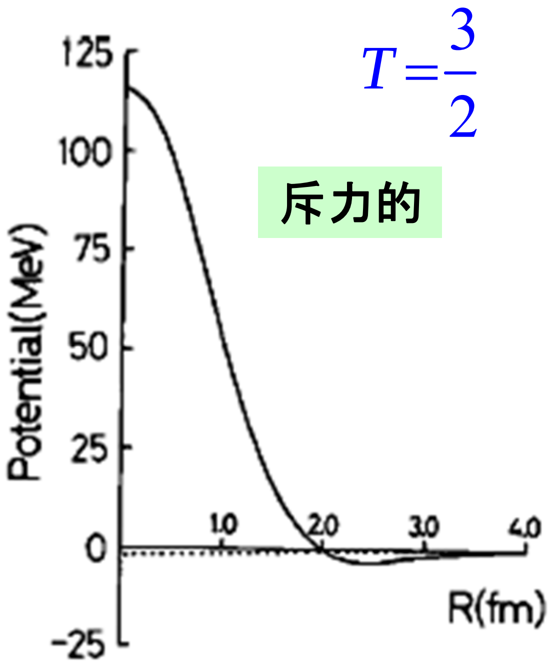
ΣN pot: ASP
Shinmura

ATMS

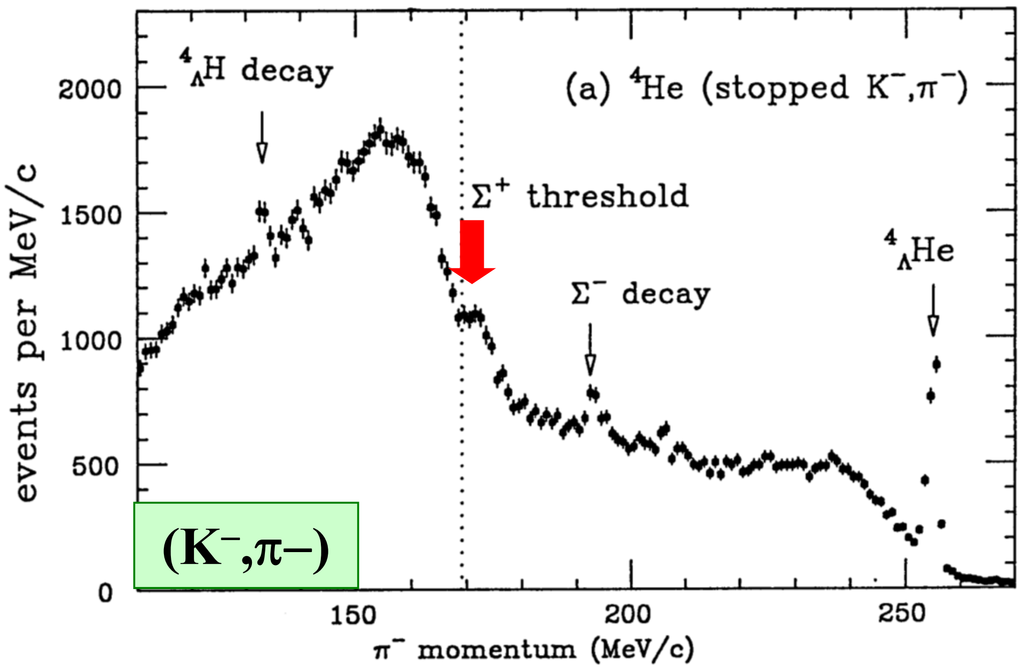
KAT Theory
Kurihara

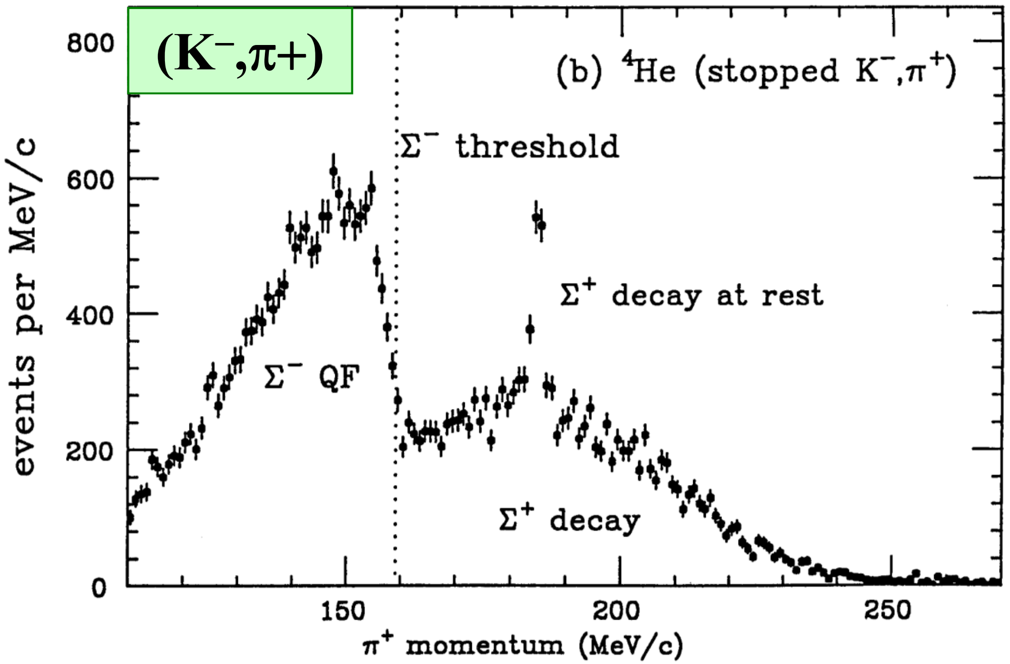
$^{4}_{\Sigma}$He
1989
理論的予測





"研究室の伝統と先輩方に感謝！"





First Observation of a Bound Σ Hypernuclear State

KEK-E167 (1989)

R.S.Hayano, T.Ishikawa, M.Iwasaki, H.Outa, E.Takeda, H.Tamura, A.Sakaguchi, M.Aoki T.Yamazaki, Phys.Lett. B231(1989)355.

$^{4}_{\Sigma}\mathrm{He}$

$B_{\Sigma^+} = 3.2 \pm 0.3^{+0.1}_{-1.1}$ MeV

$\Gamma = 4.6 \pm 0.5^{+1.6}_{-1.3}$ MeV

Strong Lane term

$$U_\Sigma = U_0 + U_\tau(\vec{\mathbf{T}} \cdot \vec{\mathbf{t}})$$

$U_0 - U_\tau$ attractive

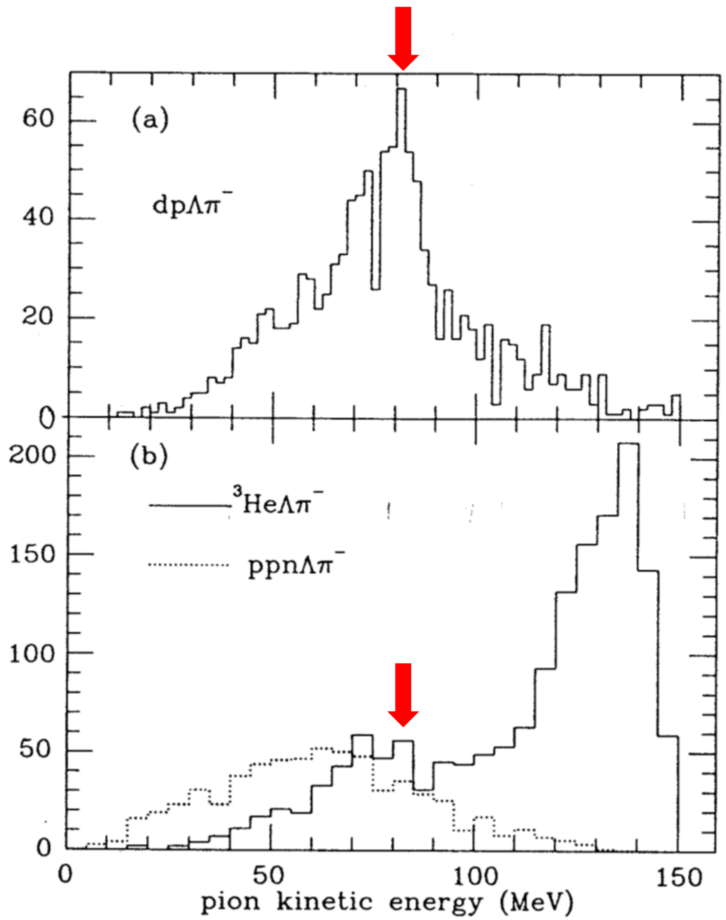
$U_0 + U_\tau / 2$ repulsive

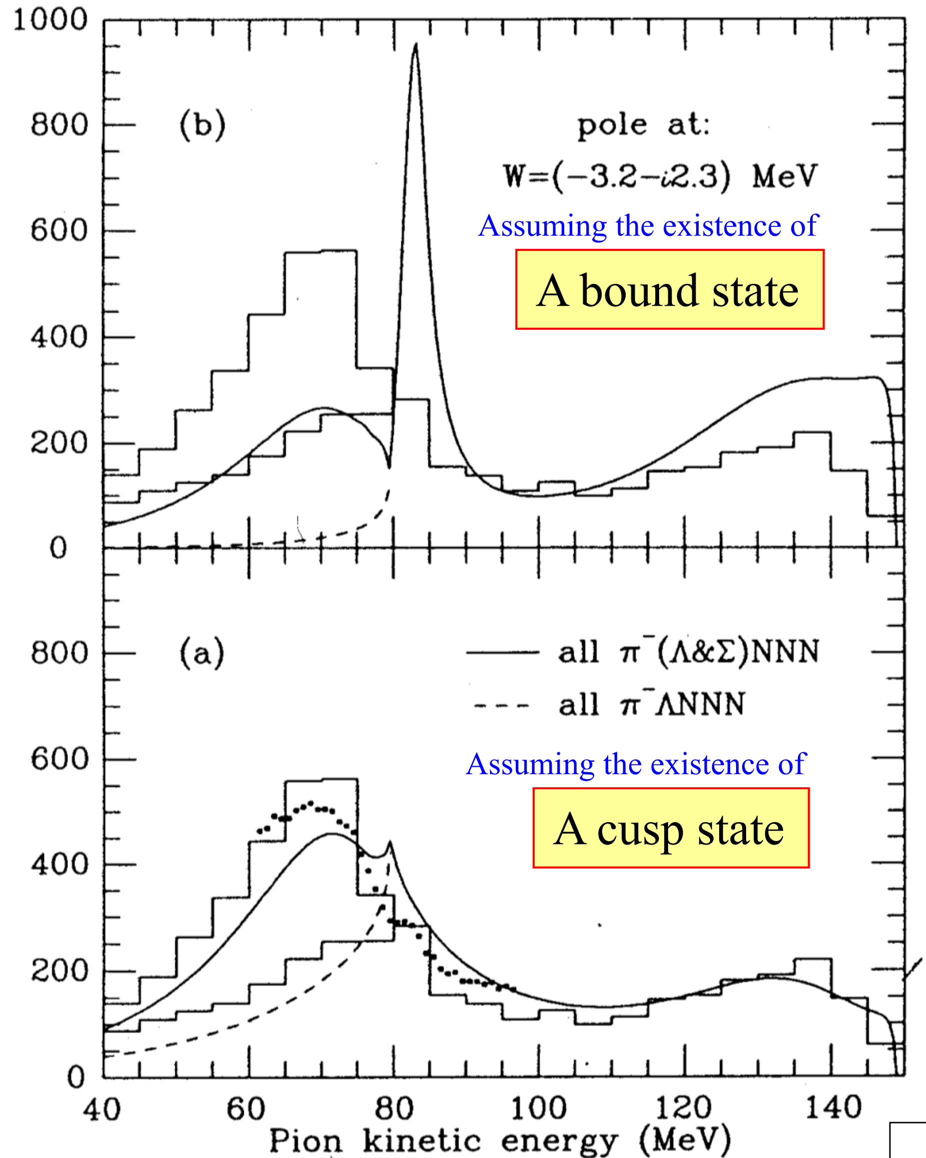
T.Harada, S.Shinmura, Y.Akaishi, H.Tanaka, NPA507(1990)715.

“IS THERE A BOUND $^{4}_{\Sigma}$He ?” (1990)

R.H.Dalitz, D.H. Davis and A.Deloff, PLB236(1990)76

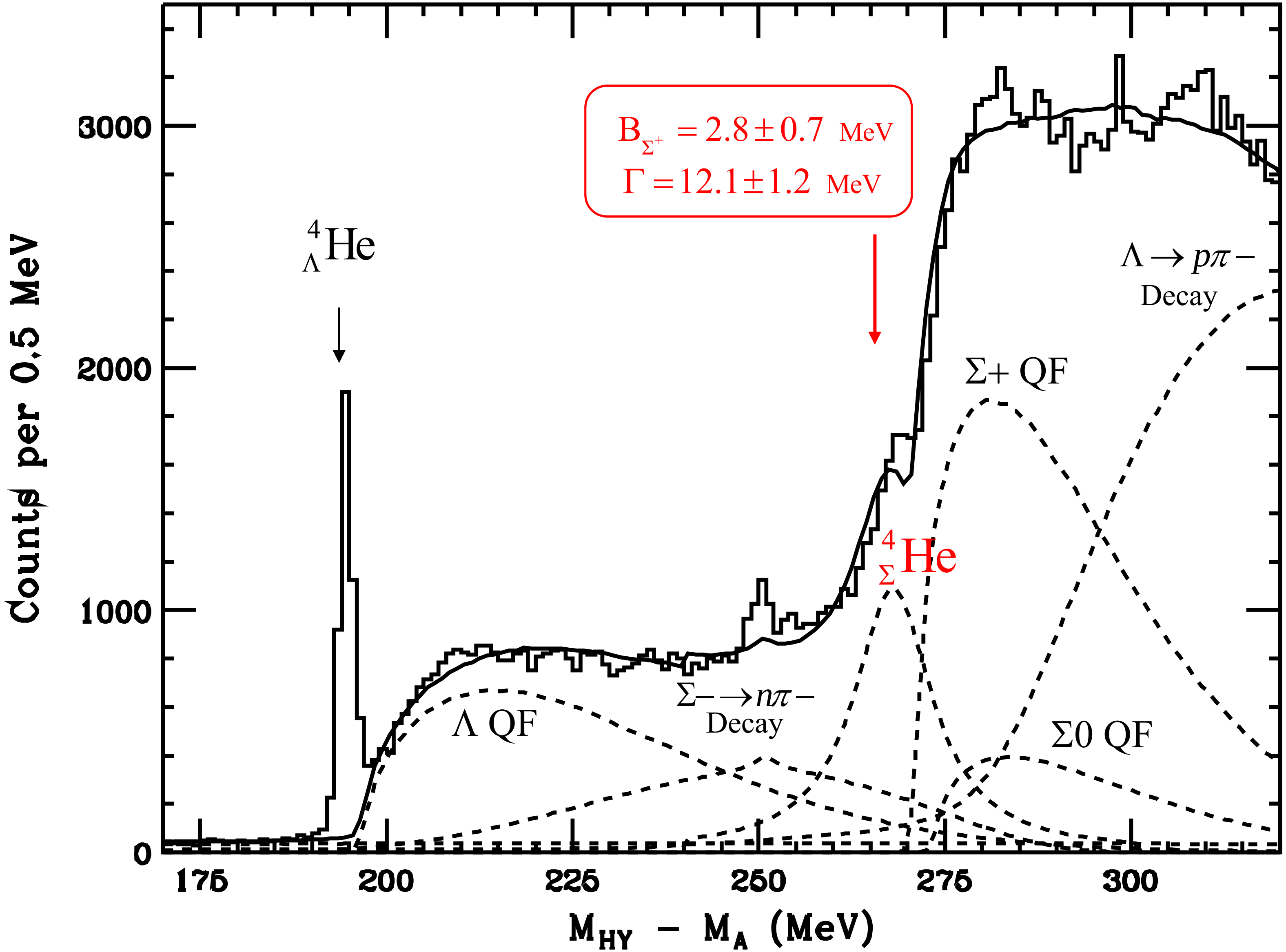
R. Roosen, Ph.D. thesis
(Carnegie-Mellon University,1970)





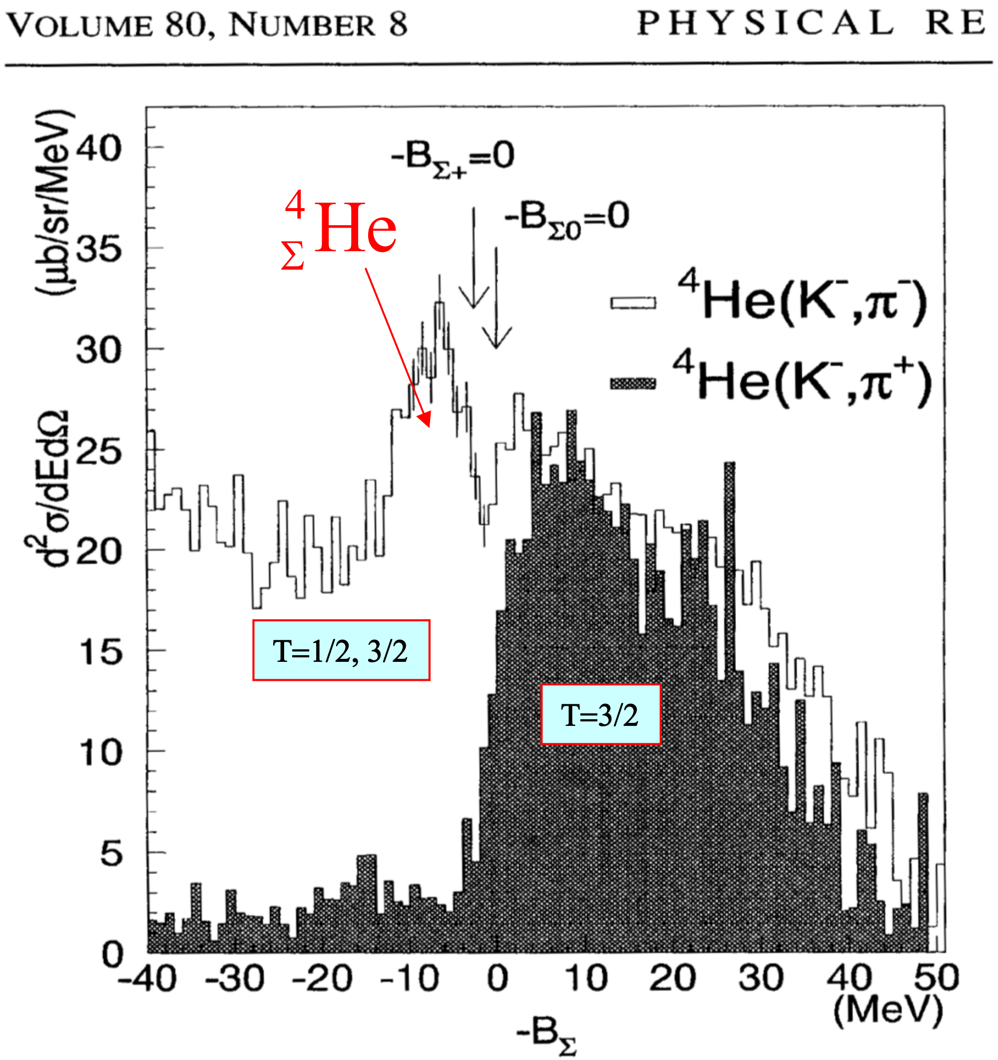
Subtraction of hyperon decay background and Λ component from the π⁻ spectrum

H. Outa et al., PTP.Suppl. 117(1994)177.



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.

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

$\Gamma = 7 \pm 0.7$ MeV

Theoretical Prediction
4.6 MeV
7.9 MeV

$T \,\square\, 1/2$

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

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

DWIA calculation for production cross sections

Green's function method

O. Morimatsu, K. Yazaki, NPA483(1988)493

スペクトル計算の理論的基盤
多方面でも適用され威力を発揮！

Inclusive differential cross section

$$\frac{d^2\sigma}{dE_\pi d\Omega} = \frac{k_\pi E_\pi}{(2\pi)^2 v_K} \frac{1}{[J_i]} \sum_{M_i} \sum_f |< f|\hat{O}|i>|^2 \delta(E_\pi - E_K + \omega)$$

Strength function

Green's function

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

Coupled-channel Green's function

T.Harada, NPA672(2000)181

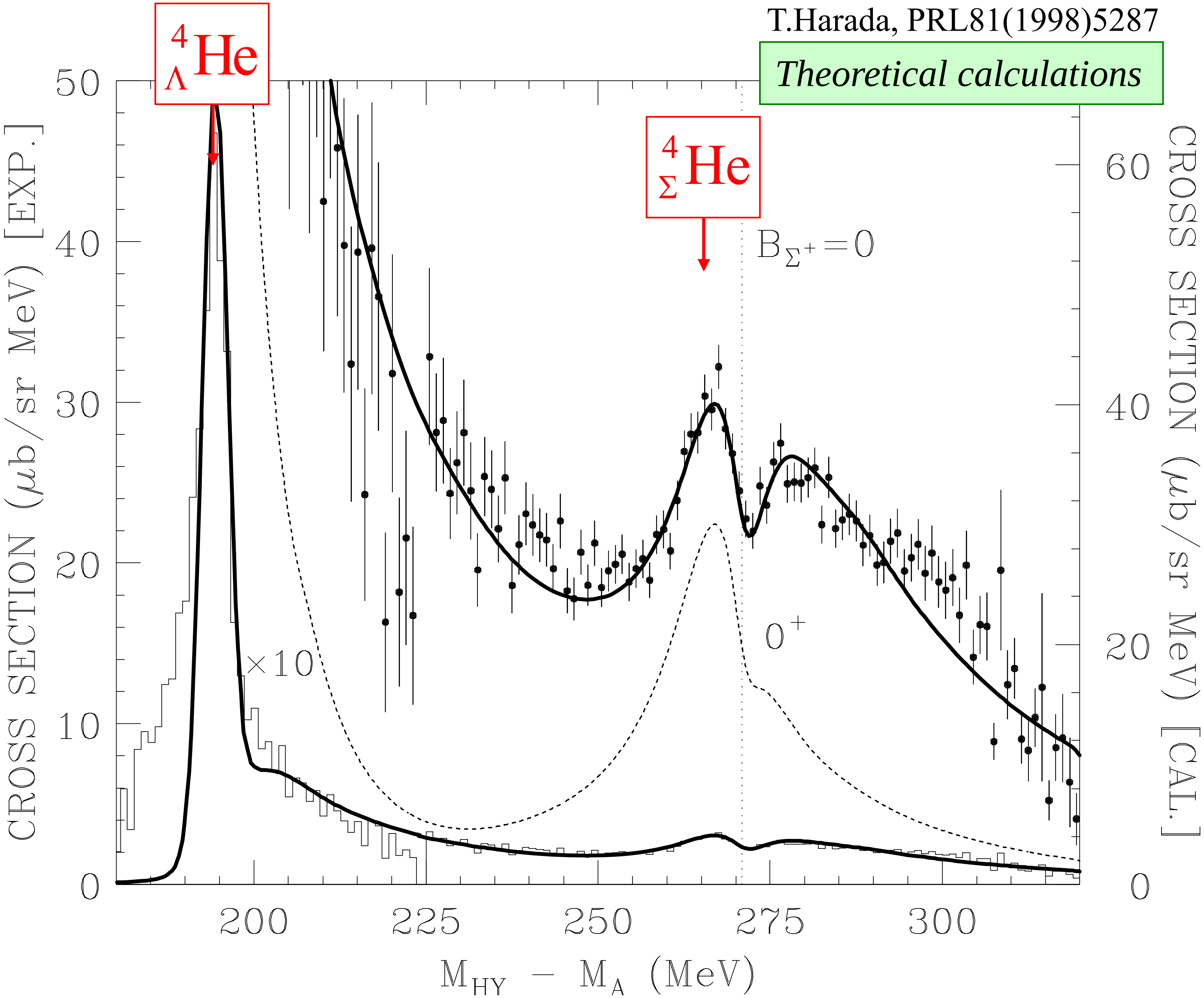
$$\hat{\mathbf{G}}(E_f) = \hat{\mathbf{G}}^{(0)}(E_f) + \hat{\mathbf{G}}^{(0)}(E_f)\hat{\mathbf{U}}\hat{\mathbf{G}}(E_f)$$

$$\hat{\mathbf{G}}^{(0)}(E_f) = \begin{bmatrix} G_\Lambda^{(0)} & & \\ & G_{\Sigma^+}^{(0)} & \\ & & G_{\Sigma^0}^{(0)} \end{bmatrix} \quad \hat{\mathbf{U}} = \begin{bmatrix} U_{\Lambda,1/2} & U_{X,1/2} & 0 \\ U_{X,1/2} & U_{\Sigma,1/2} & 0 \\ 0 & 0 & U_{\Sigma,3/2} \end{bmatrix}$$

$$\mathrm{Im}\hat{G} = \underbrace{\hat{\Omega}^{(-)\dagger}\{\mathrm{Im}\hat{G}_\Lambda^{(0)}\}\hat{\Omega}^{(-)}}_{\Lambda \text{ escape}} + \underbrace{\hat{\Omega}^{(-)\dagger}\{\mathrm{Im}\hat{G}_{\Sigma^+}^{(0)}\}\hat{\Omega}^{(-)}}_{\Sigma^+ \text{ escape}} + \underbrace{\hat{\Omega}^{(-)\dagger}\{\mathrm{Im}\hat{G}_{\Sigma^0}^{(0)}\}\hat{\Omega}^{(-)}}_{\Sigma^0 \text{ escape}} + \underbrace{\hat{G}^\dagger\{W_{Y,T}\}\hat{G}}_{\text{Spreading (3N breakup)}}$$

^{4}He(K$^-$,π^-) spectrum at 600 MeV/c (BNL)

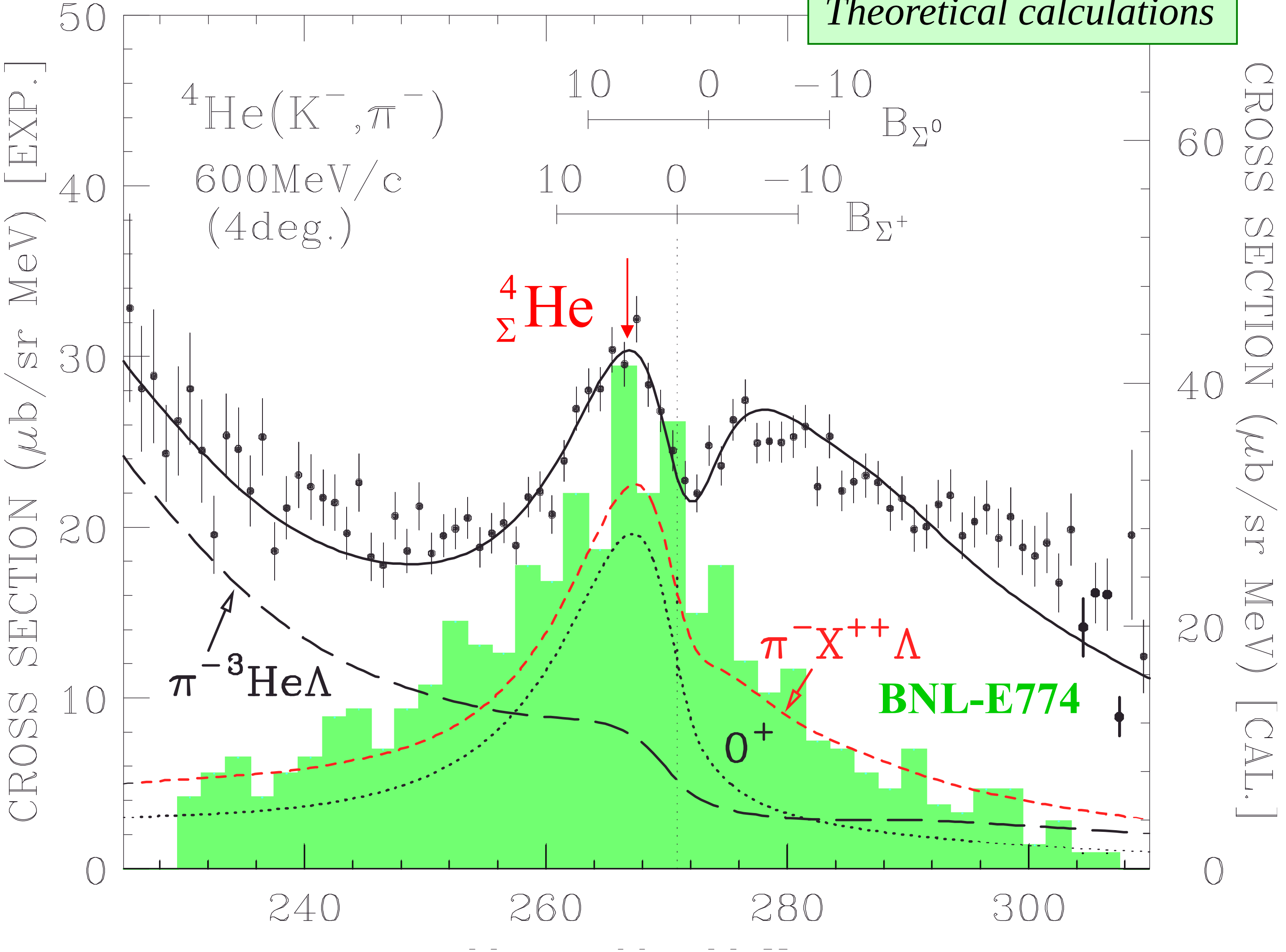
T.Harada, PRL81(1998)5287



$^4He(K^-,\pi^-)$ spectrum at 600 MeV/c (BNL)

T.Harada, PRL81(1998)5287

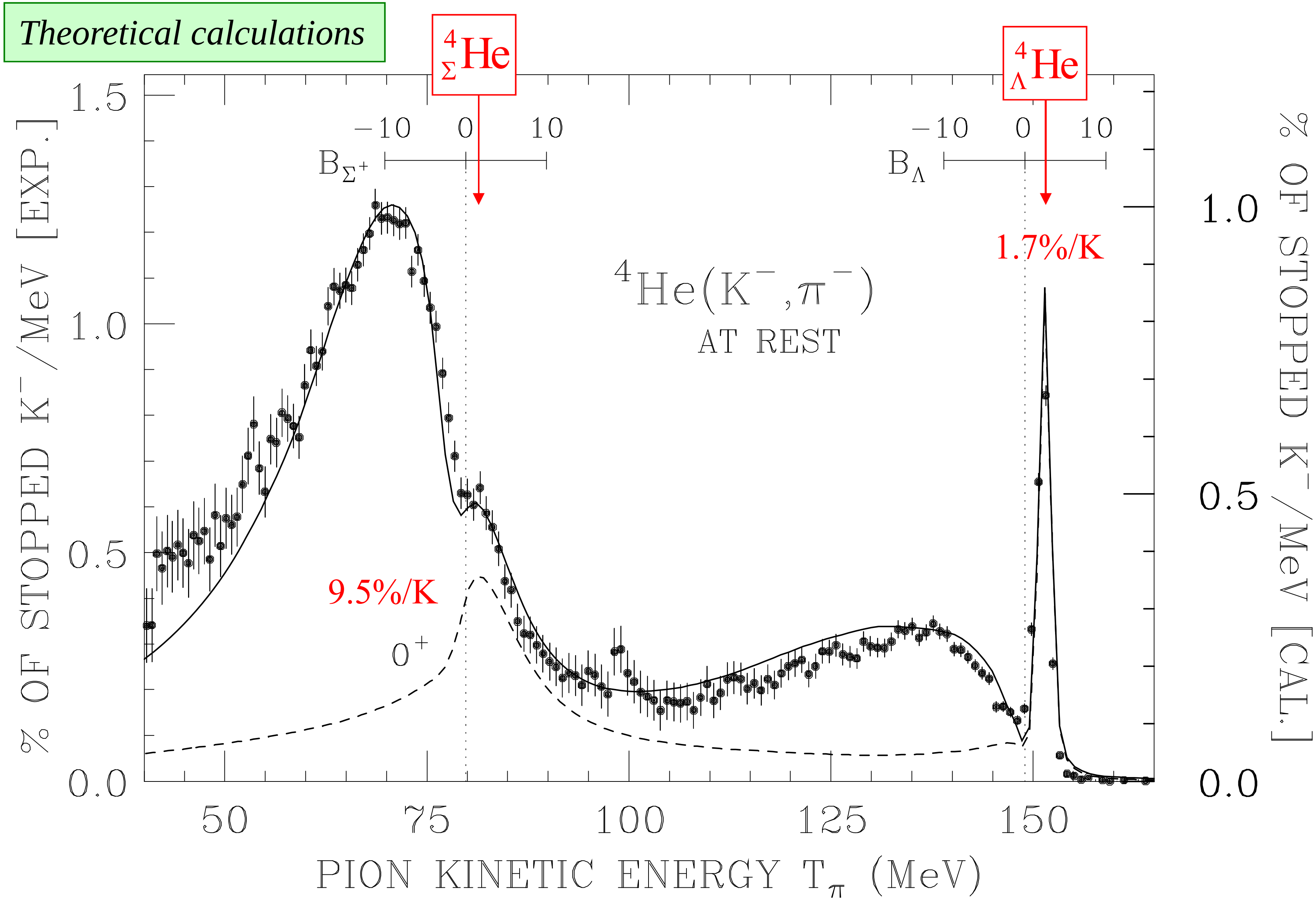
Theoretical calculations

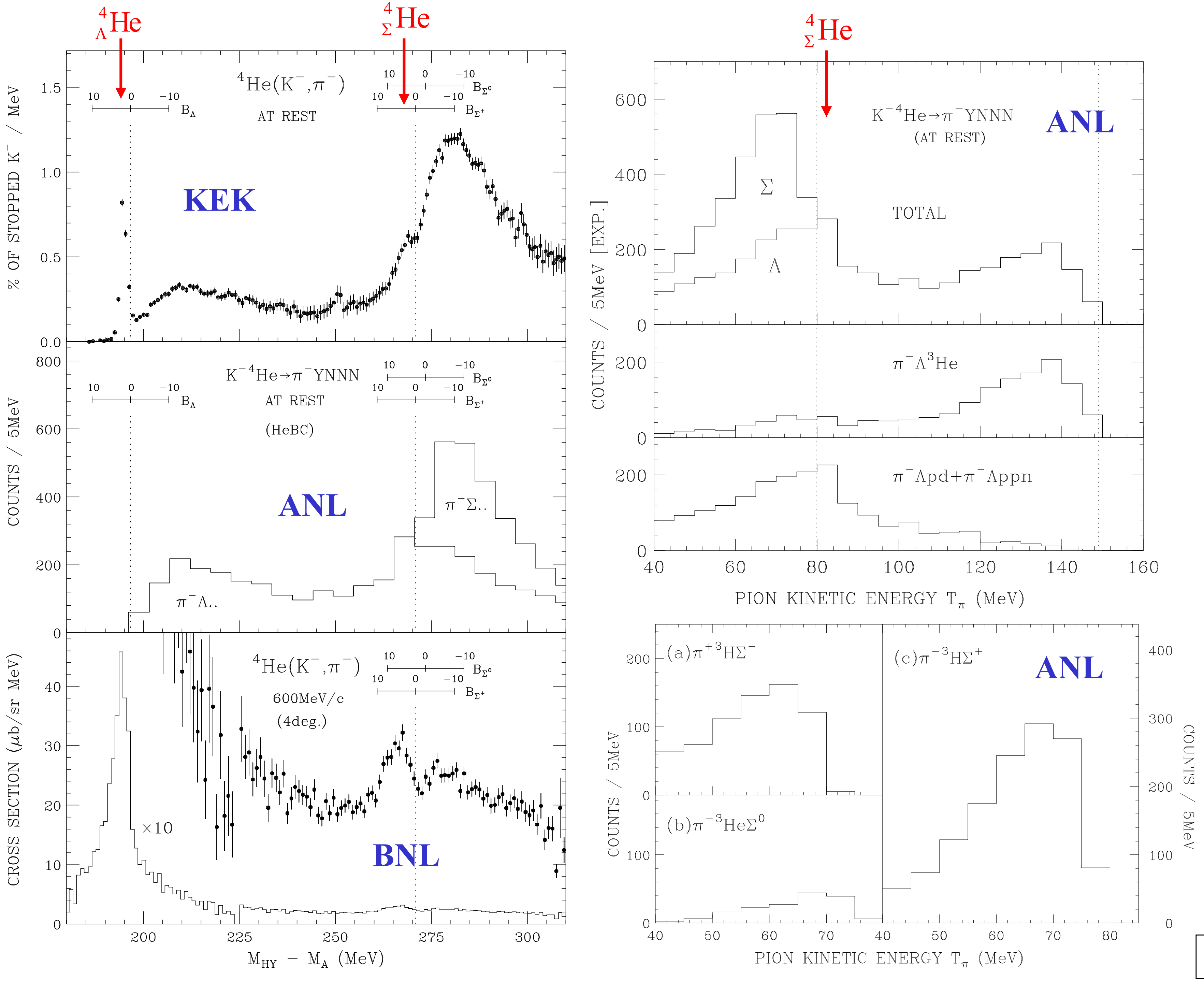


$^4He(K^-,\pi^-)$ spectrum at Rest (KEK)

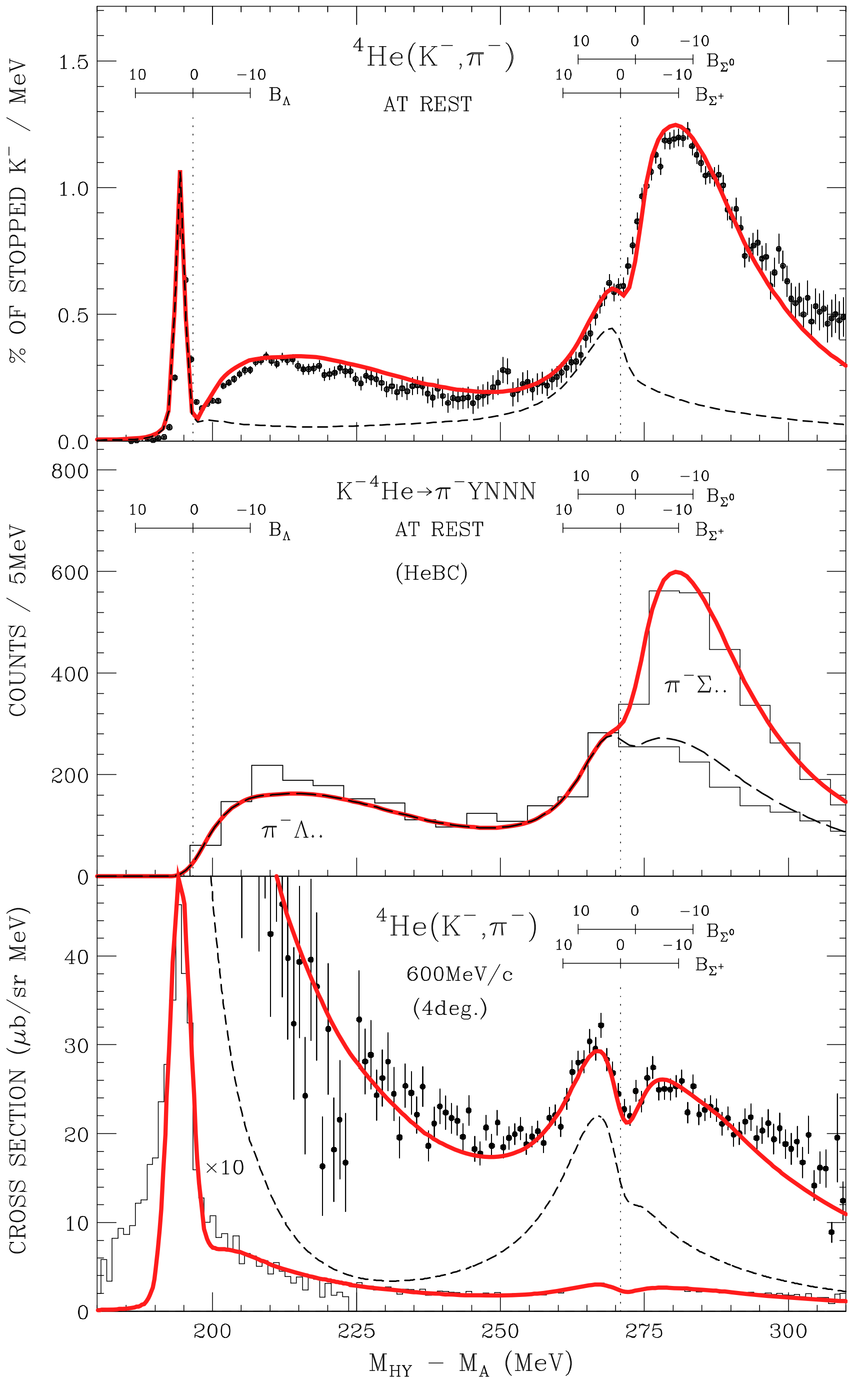
T.Harada, NPA672(2000)181

Theoretical calculations

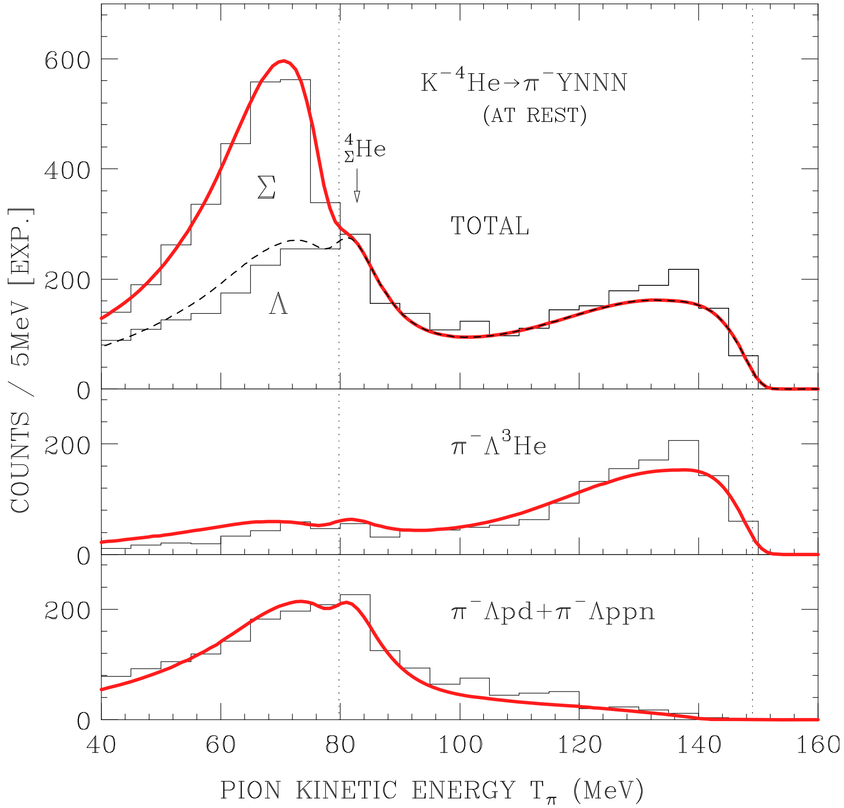




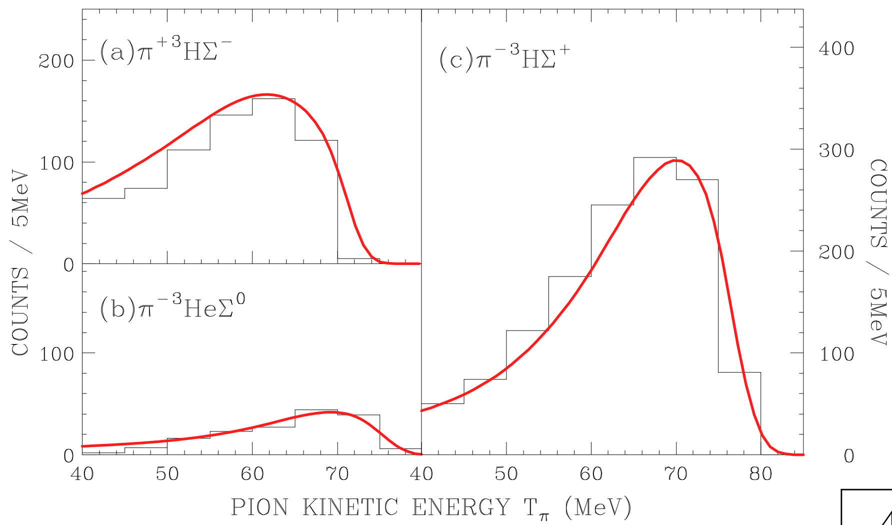
${}^4_\Lambda$He
${}^4_\Sigma$He
^{4}He(K$^-$,π^-)
AT REST
KEK
% OF STOPPED K$^-$ / MeV
K$^-$ ^{4}He→π^-YNNN
AT REST
(HeBC)
ANL
$\pi^-\Sigma$..
$\pi^-\Lambda$..
COUNTS / 5MeV
^{4}He(K$^-$,π^-)
600MeV/c
(4deg.)
×10
BNL
CROSS SECTION (μb/sr MeV)
B_Λ
B_{Σ^0}
B_{Σ^+}
M$_{HY}$ − M$_A$ (MeV)
K$^-$ ^{4}He→π^-YNNN
(AT REST)
ANL
Σ
Λ
TOTAL
$\pi^-\Lambda^3$He
$\pi^-\Lambda$pd+$\pi^-\Lambda$ppn
COUNTS / 5MeV [EXP.]
PION KINETIC ENERGY T$_\pi$ (MeV)
(a)π^{+3}HΣ^-
(b)π^{-3}HeΣ^0
(c)π^{-3}HΣ^+
ANL
COUNTS / 5MeV
PION KINETIC ENERGY T$_\pi$ (MeV)



^{4}He(K^-,π^-)
AT REST
B_Λ
B_{Σ^0}
B_{Σ^+}
% OF STOPPED K^- / MeV
K^{-4}He→π^-YNNN
AT REST
(HeBC)
COUNTS / 5MeV
$\pi^-\Sigma$..
$\pi^-\Lambda$..
^{4}He(K^-,π^-)
600MeV/c
(4deg.)
×10
CROSS SECTION (μb/sr MeV)
M_{HY} − M_A (MeV)

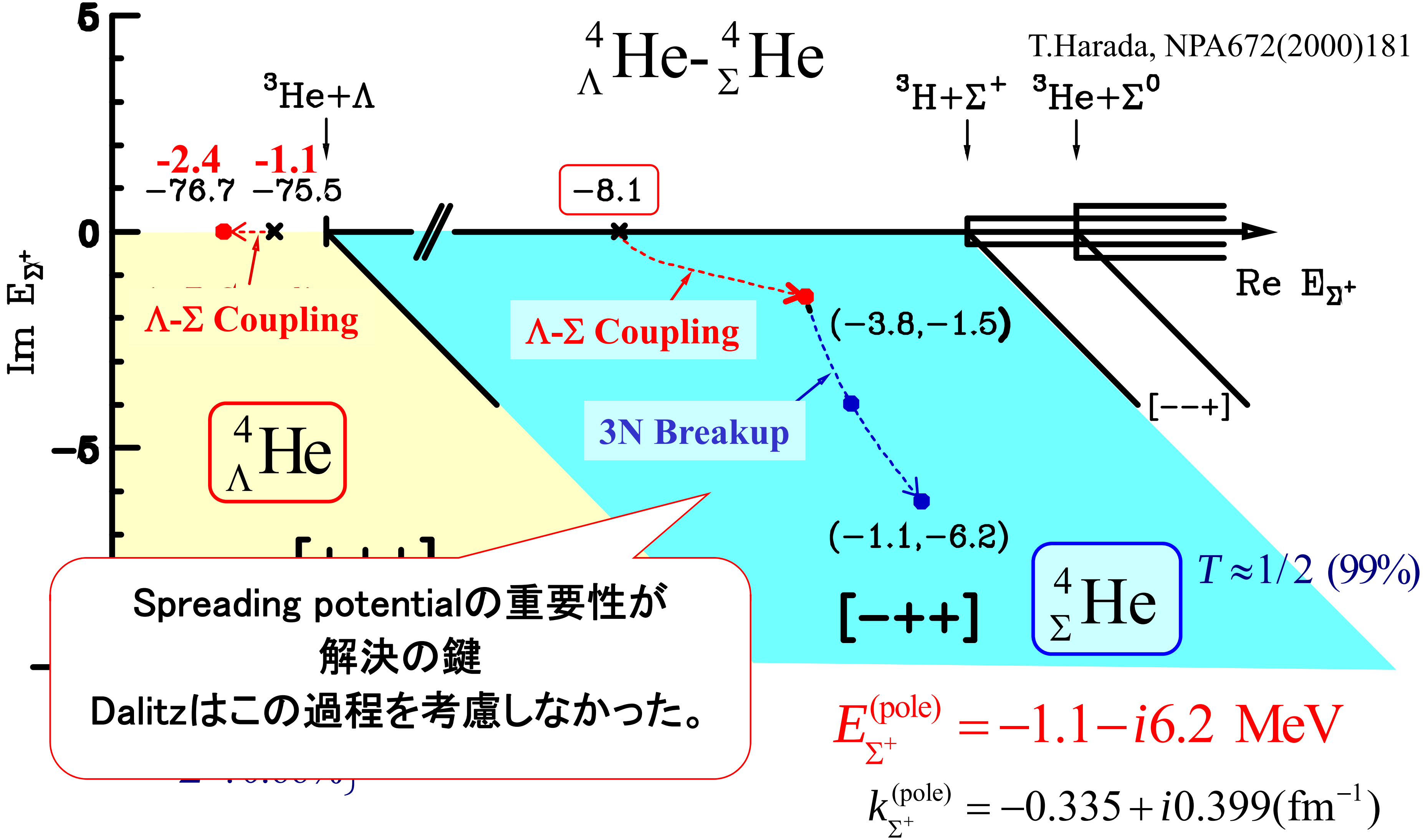


K^{-4}He→π^-YNNN
(AT REST)
$^4_\Sigma$He
Σ
Λ
TOTAL
$\pi^-\Lambda^3$He
$\pi^-\Lambda pd+\pi^-\Lambda ppn$
COUNTS / 5MeV [EXP.]
PION KINETIC ENERGY T_π (MeV)



(a)π^{+3}HΣ^-
(b)π^{-3}HeΣ^0
(c)π^{-3}HΣ^+
COUNTS / 5MeV
PION KINETIC ENERGY T_π (MeV)

Pole positions of the *Y-3N* hypernucleus



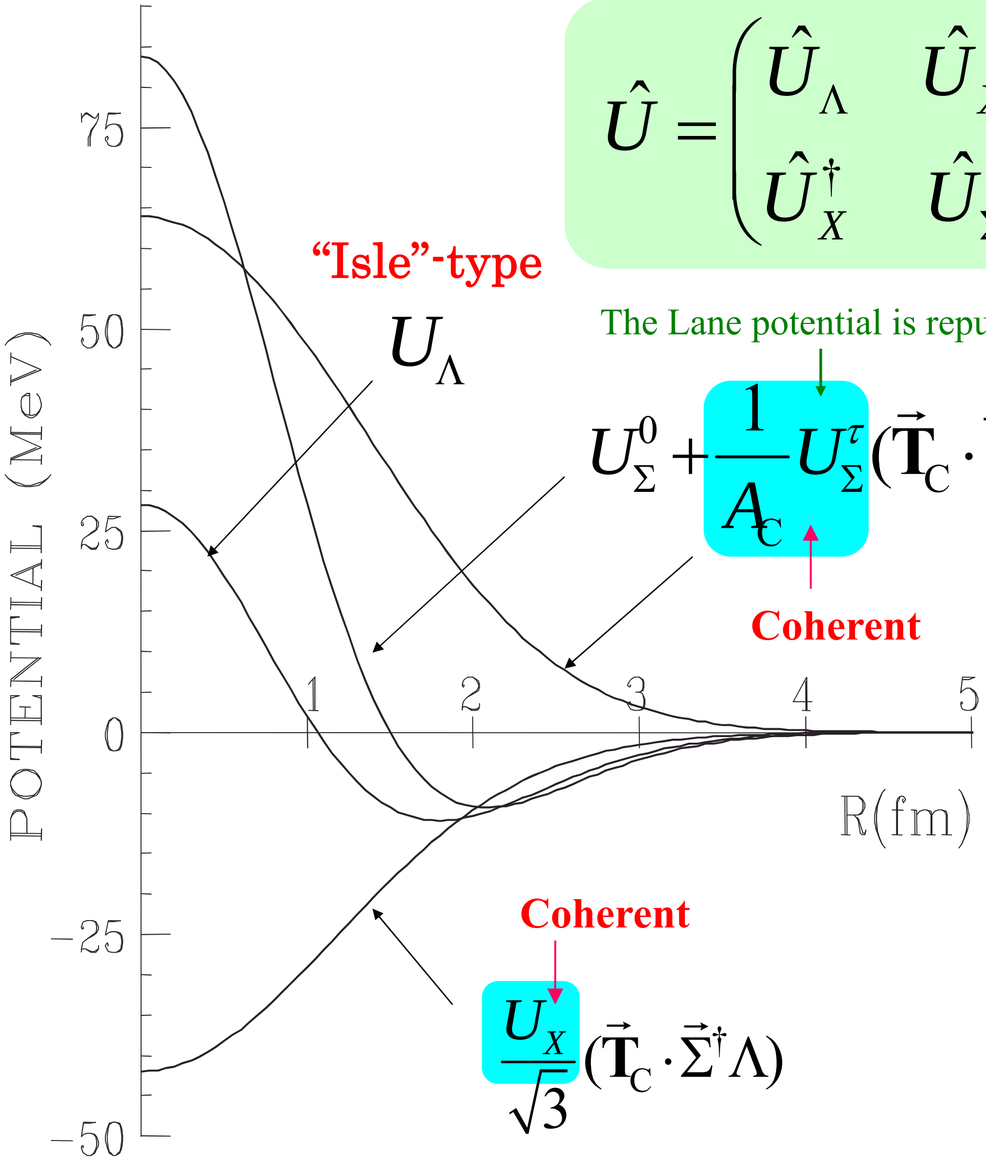
Spreading potentialの重要性が
解決の鍵
Dalitzはこの過程を考慮しなかった。

$$E^{(pole)}_{\Sigma^+} = -1.1 - i6.2 \ \text{MeV}$$

$$k^{(pole)}_{\Sigma^+} = -0.335 + i0.399(\text{fm}^{-1})$$

Properties of the 3N-Y potential

$$\hat{U} = \begin{pmatrix} \hat{U}_\Lambda & \hat{U}_X \\ \hat{U}_X^\dagger & \hat{U}_\Sigma \end{pmatrix}$$



"Isle"-type

U_Λ

The Lane potential is repulsive.

$$U_\Sigma^0 + \frac{1}{A_C} U_\Sigma^\tau (\vec{\mathbf{T}}_C \cdot \vec{\mathbf{t}}_\Sigma)$$

Coherent

Coherent

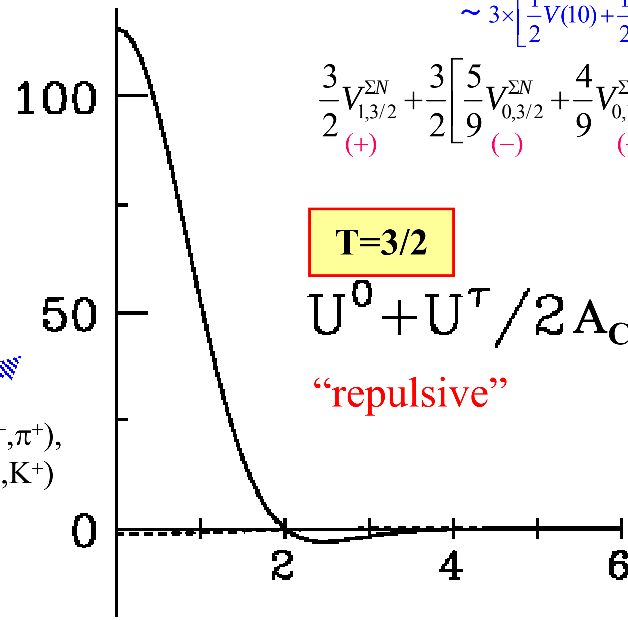
$$\frac{U_X}{\sqrt{3}} (\vec{\mathbf{T}}_C \cdot \vec{\Sigma}^\dagger \Lambda)$$

(K^-,π^+), (π^-,K^+)

(K^-,π^-), (π^+,K^+)

$\sim 3\times\left[\frac{1}{2}V(10)+\frac{1}{2}V(27)\right]$

$\frac{3}{2}\underset{(+)}{V^{\Sigma N}_{1,3/2}} + \frac{3}{2}\left[\frac{5}{9}\underset{(-)}{V^{\Sigma N}_{0,3/2}} + \frac{4}{9}\underset{(+)}{V^{\Sigma N}_{0,1/2}}\right]$



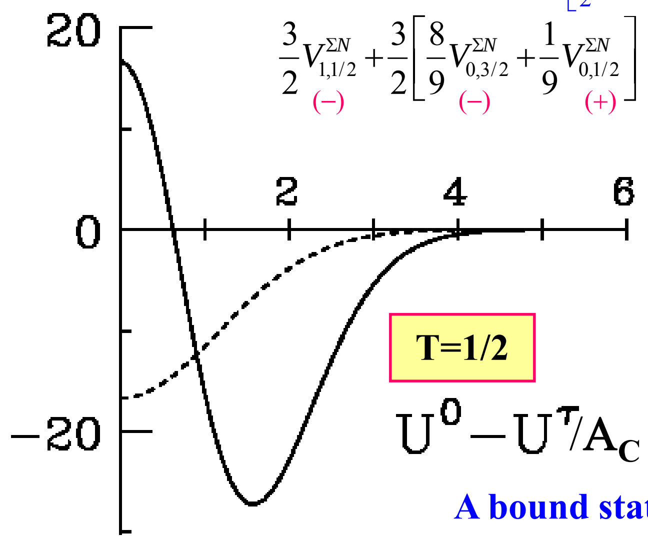
T=3/2

$U^0 + U^\tau / 2A_C$

"repulsive"

$\sim 3\times\left[\frac{1}{2}V(\overline{10})+\frac{1}{2}V(27)\right]$

$\frac{3}{2}\underset{(-)}{V^{\Sigma N}_{1,1/2}} + \frac{3}{2}\left[\frac{8}{9}\underset{(-)}{V^{\Sigma N}_{0,3/2}} + \frac{1}{9}\underset{(+)}{V^{\Sigma N}_{0,1/2}}\right]$



T=1/2

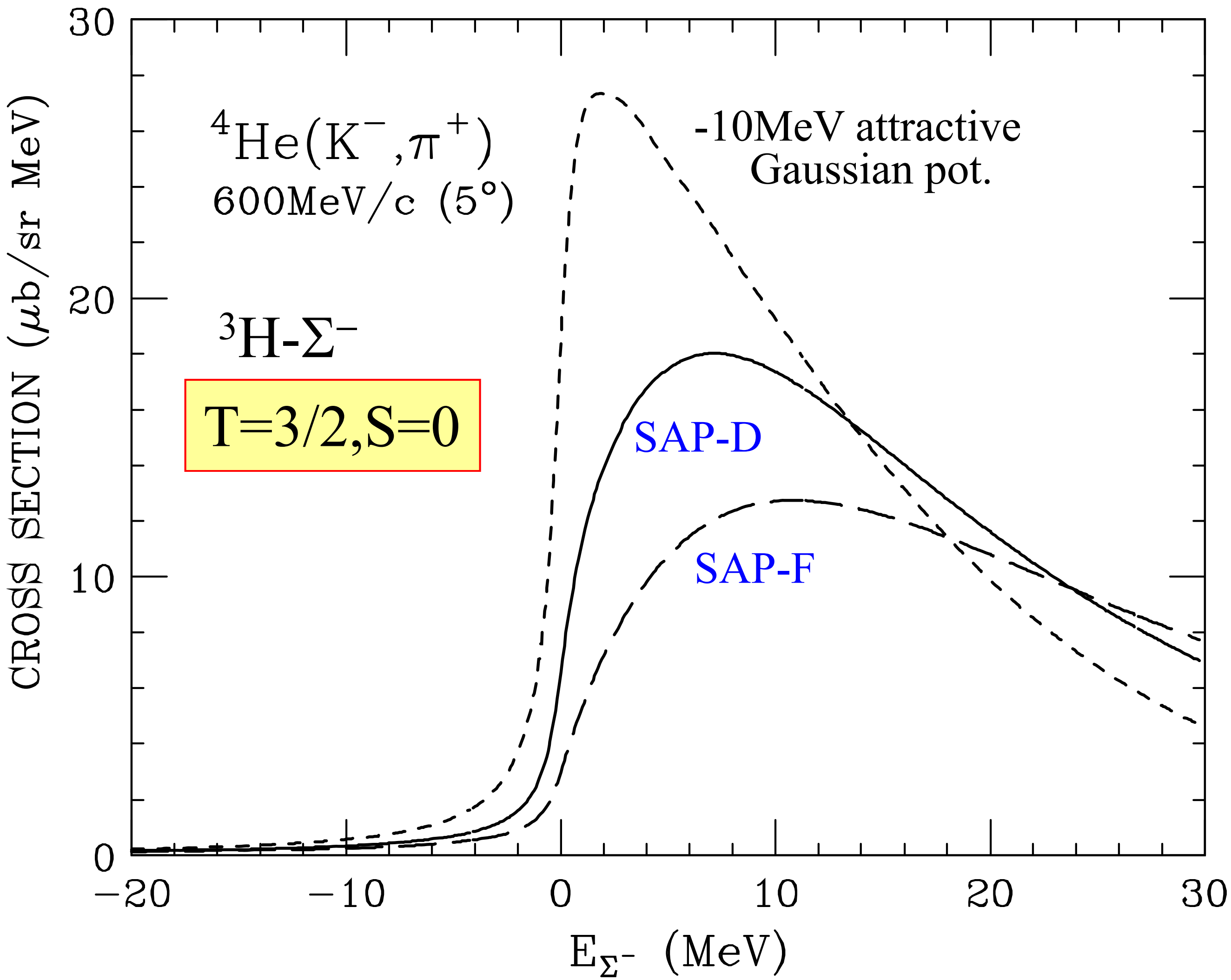
$U^0 - U^\tau / A_C$

A bound state !!

$^7_\Sigma\mathrm{Li}$ Cf. T.Yamada, K. Ikeda, PRC46(1992)1315.

"repulsive core+attractive pocket"

^{4}He(K$^-$,π^+) spectrum at 600 MeV/c (5deg)



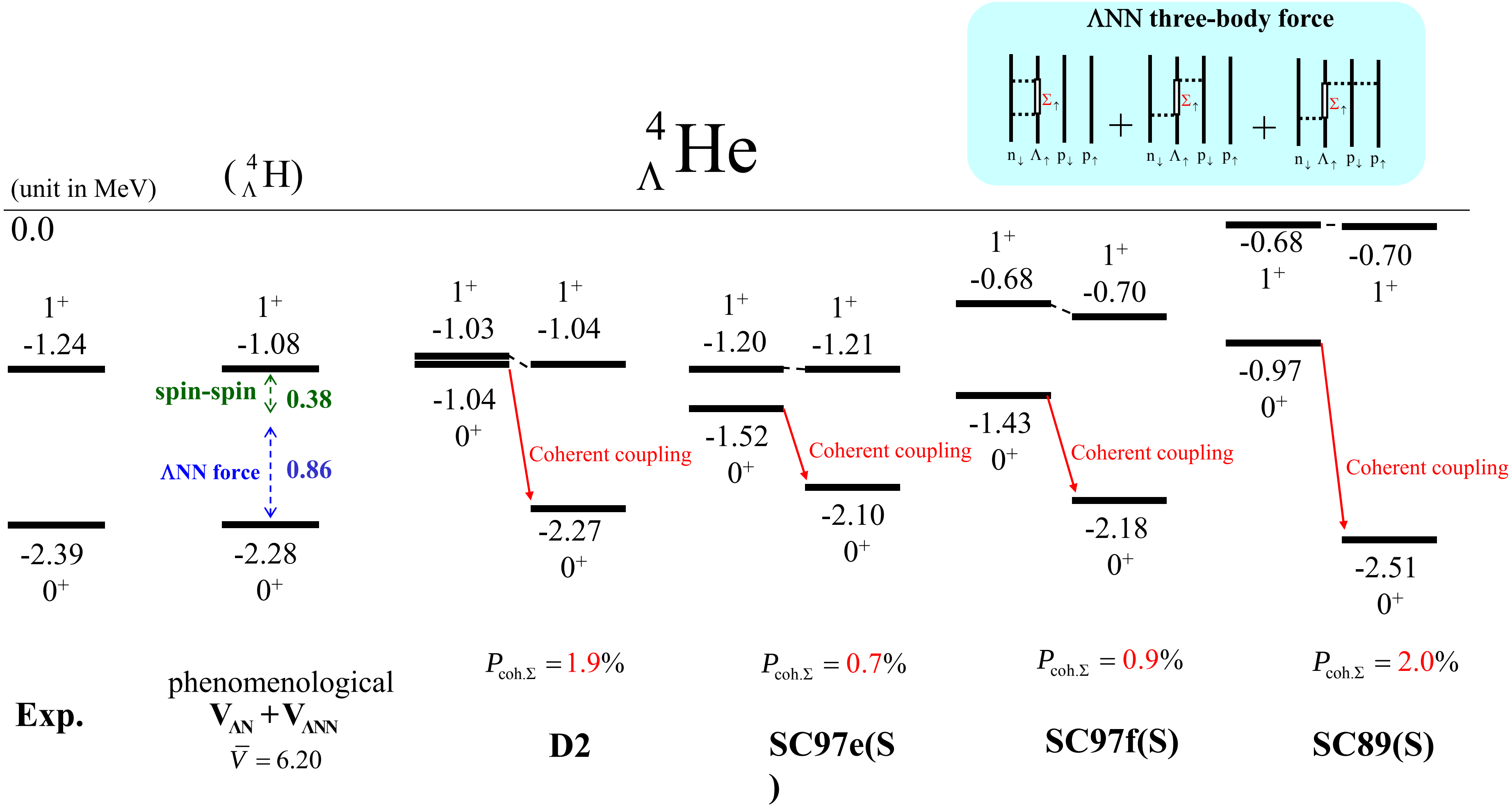
Coherent isospin and Λ-Σ Coupling in ${}^{4}_{\Lambda}\mathrm{He}$-${}^{4}_{\Sigma}\mathrm{He}$

B.F. Gibson *et al.*, PRC6 (1972) 741
T. Harada *et al.*, NPA507(1990) 715
Y.Akaishi *et al.*, PRL84 (2000) 3539.

$$\left|{}^{4}_{\Lambda,\Sigma}\mathrm{He}\right\rangle = \phi_\Lambda(\mathbf{r})\left|{}^{3}\mathrm{He}\right\rangle + \phi_{\Sigma^+}(\mathbf{r})\left|{}^{3}\mathrm{H}\right\rangle + \phi_{\Sigma^0}(\mathbf{r})\left|{}^{3}\mathrm{He}\right\rangle$$

	0⁺		**1⁺**
$T=\frac{3}{2}$	(+) + [(−) + (+)] $\frac{3}{2}g^{\Sigma N}_{1,3/2}+\frac{3}{2}\left[\frac{5}{9}g^{\Sigma N}_{0,3/2}+\frac{4}{9}g^{\Sigma N}_{0,1/2}\right]$	${}^{4}_{\Sigma}\mathrm{He}$	$\frac{5}{2}\left[\frac{11}{15}g^{\Sigma N}_{1,3/2}+\frac{4}{15}g^{\Sigma N}_{1,1/2}\right]+\frac{1}{2}g^{\Sigma N}_{0,3/2}$
	(+)−(−) − [(−)−(+)] $\frac{3}{3}[g^{\Sigma N}_{1,3/2}-g^{\Sigma N}_{1,1/2}]-\frac{1}{3}[g^{\Sigma N}_{0,3/2}-g^{\Sigma N}_{0,1/2}]$	Lane term $\hat{U}^{\tau}_{\Sigma}$	(+)−(−) + [(−)−(+)] $\frac{1}{3}[g^{\Sigma N}_{1,3/2}-g^{\Sigma N}_{1,1/2}]+\frac{1}{3}[g^{\Sigma N}_{0,3/2}-g^{\Sigma N}_{0,1/2}]$
	(−) + [(−) + (+)] $\frac{3}{2}g^{\Sigma N}_{1,1/2}+\frac{3}{2}\left[\frac{8}{9}g^{\Sigma N}_{0,3/2}+\frac{1}{9}g^{\Sigma N}_{0,1/2}\right]$	${}^{4}_{\Sigma}\mathrm{He}$	$\frac{5}{2}\left[\frac{8}{15}g^{\Sigma N}_{1,3/2}+\frac{7}{15}g^{\Sigma N}_{1,1/2}\right]+\frac{1}{2}g^{\Sigma N}_{0,1/2}$
$T=\frac{1}{2}$	$\frac{3}{2}g^{\Lambda N,\Sigma N}_{1,1/2}-\frac{1}{2}g^{\Lambda N,\Sigma N}_{0,1/2}$	Λ-Σ coupling $\hat{U}_X$	$\frac{1}{2}g^{\Lambda N,\Sigma N}_{1,1/2}+\frac{1}{2}g^{\Lambda N,\Sigma N}_{0,1/2}$
	$\frac{3}{2}g^{\Lambda N}_{1,1/2}+\frac{3}{2}g^{\Lambda N}_{0,1/2}$	${}^{4}_{\Lambda}\mathrm{He}$	$\frac{5}{2}g^{\Lambda N}_{1,1/2}+\frac{1}{2}g^{\Lambda N}_{0,1/2}$

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



VMC

Breuckner-Hartree-Fock

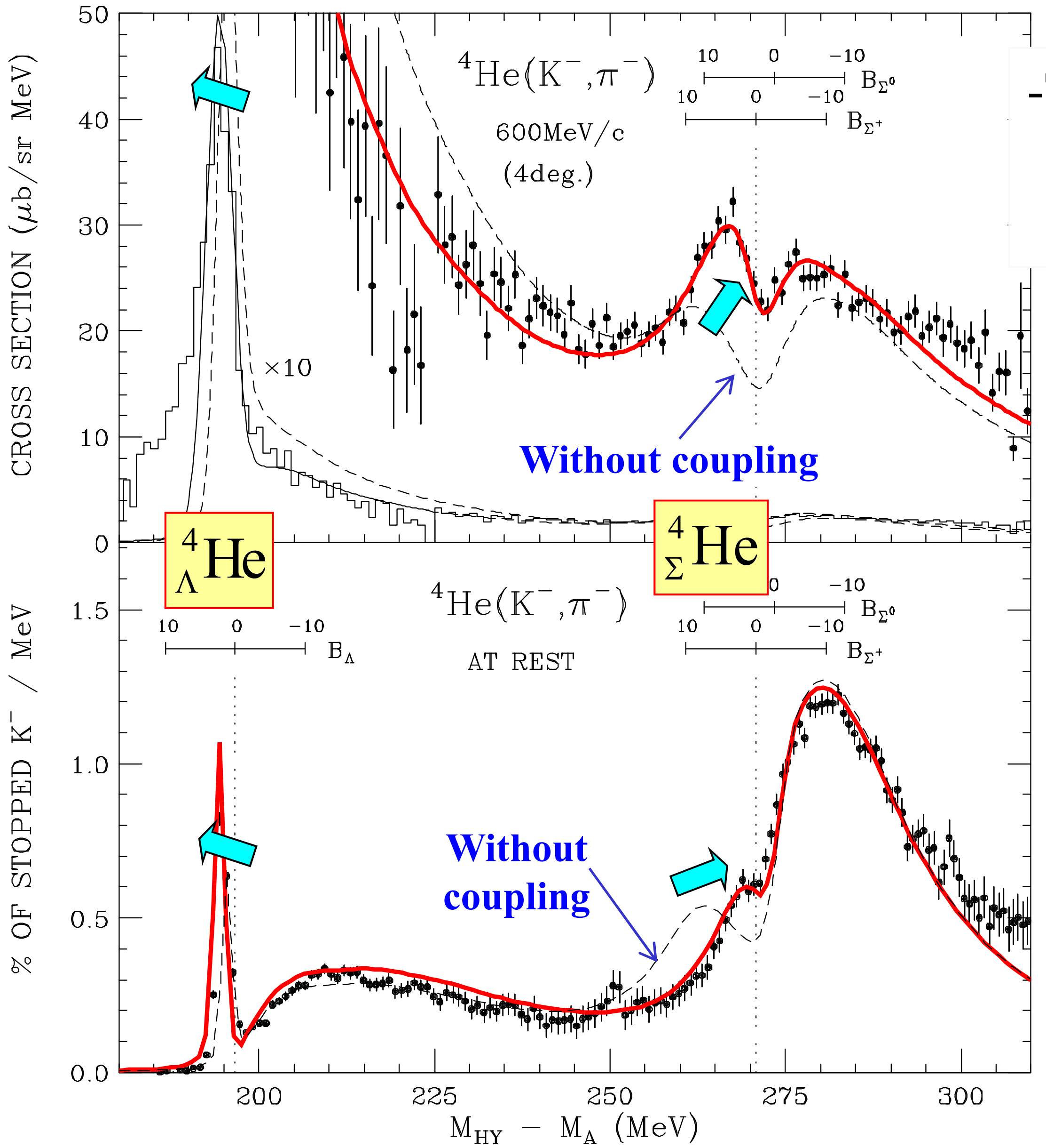
R. Sinha, Q.N.Usmani, NPA684(2001)586c

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

Λ-Σ coupling effects on the (K⁻, π⁻) spectrum

Hyperon-mixing

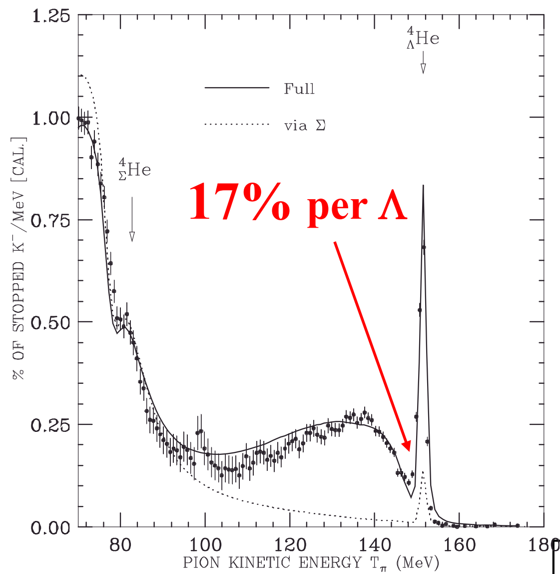
T.Harada, NPA507(1990)715.



- The Λ-Σ coupling effects play a important role in reproducing the spectrum.

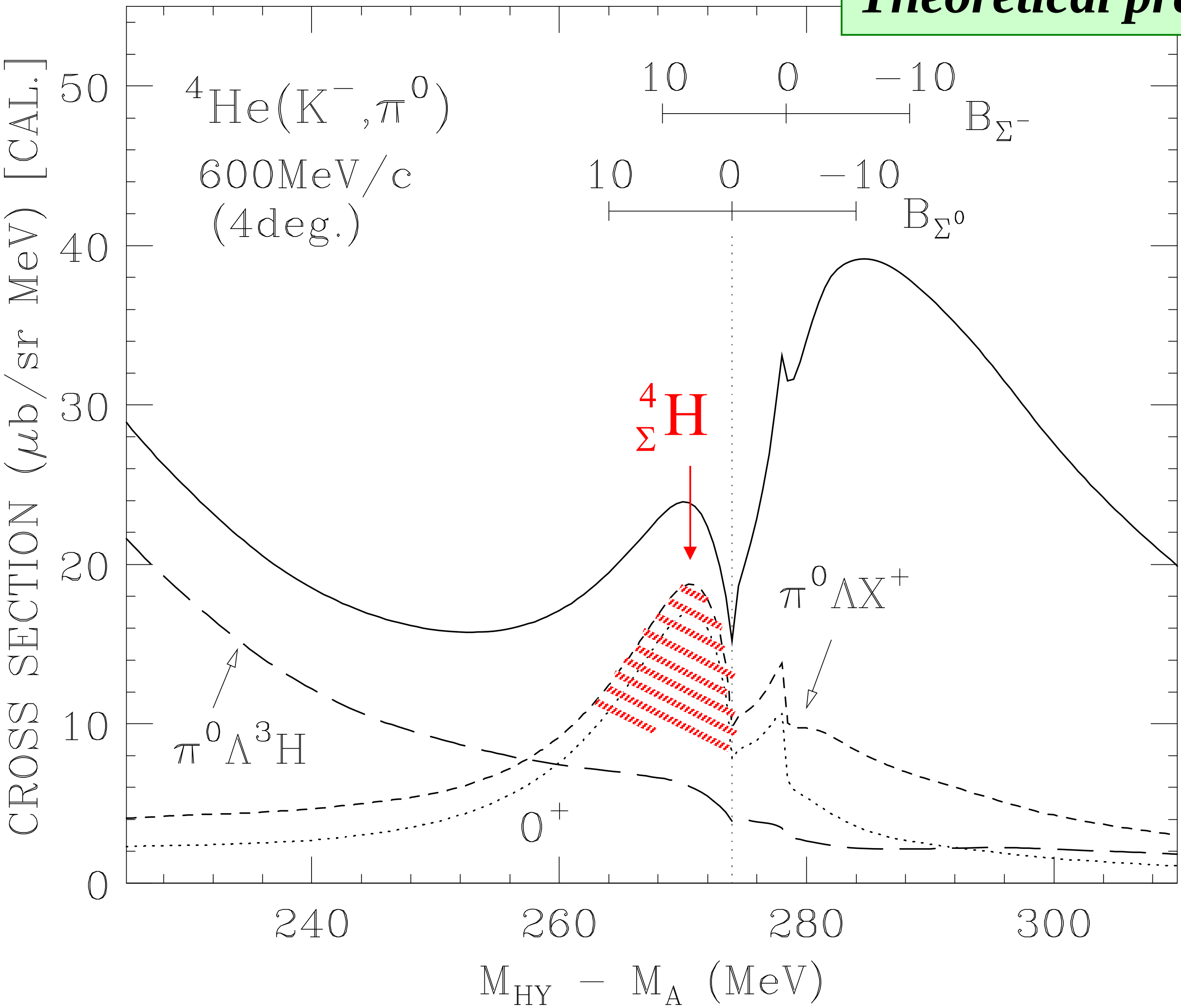
- The Λ state is produced via Σ components in the ground state.

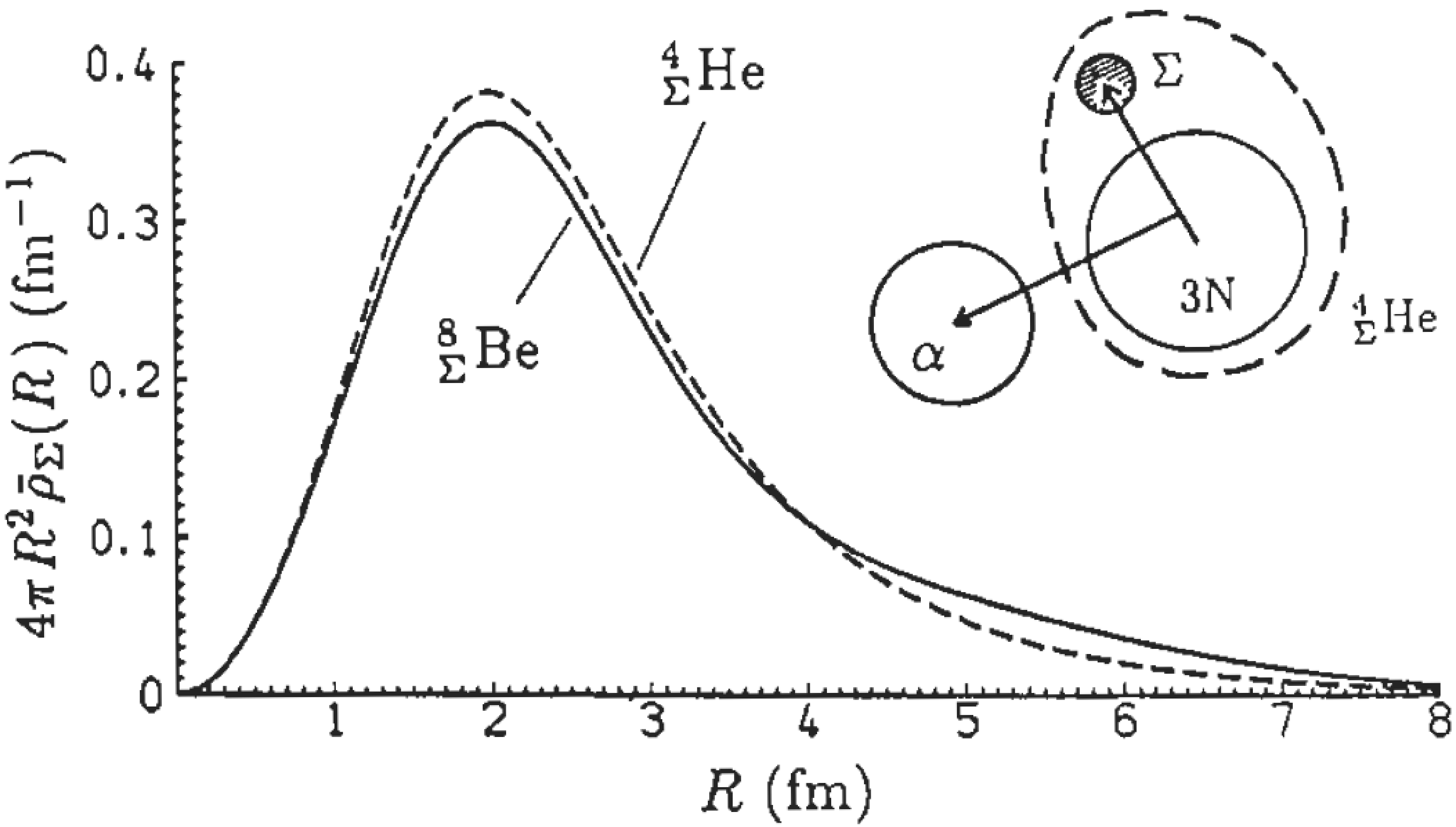
^{4}He(stopped K$^-$,π^-)$^4_\Lambda$He



$^4He(K^-,\pi^0)$ spectrum at 600 MeV/c

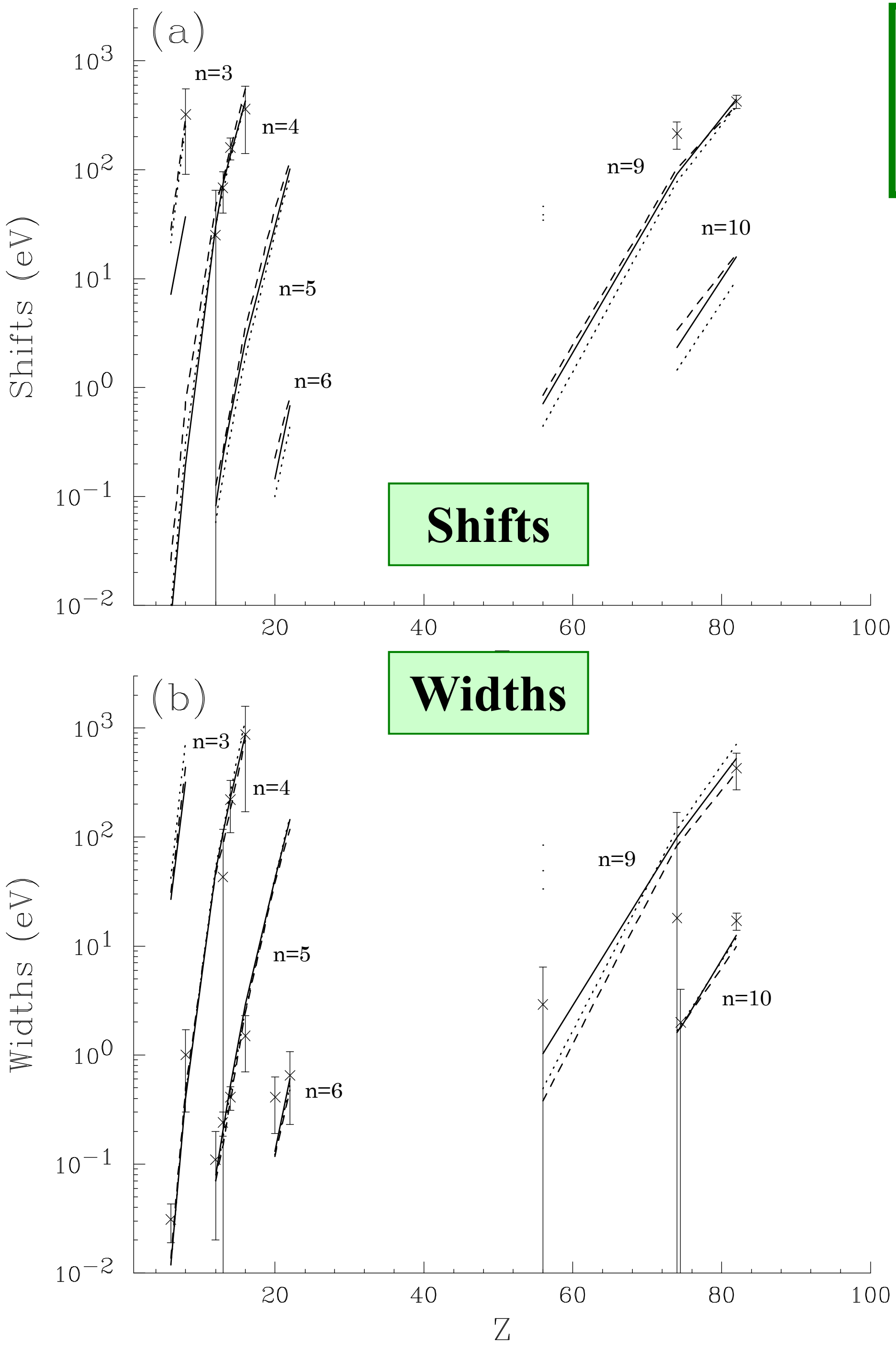
Theoretical prediction





0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
8
$4\pi R^2 \bar{\rho}_\Sigma(R)$ (fm^{-1})
R (fm)
$^4_\Sigma$He
$^8_\Sigma$Be
Σ
3N
α
$^4_\Sigma$He

Σ核ポテンシャルは斥力か？



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 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

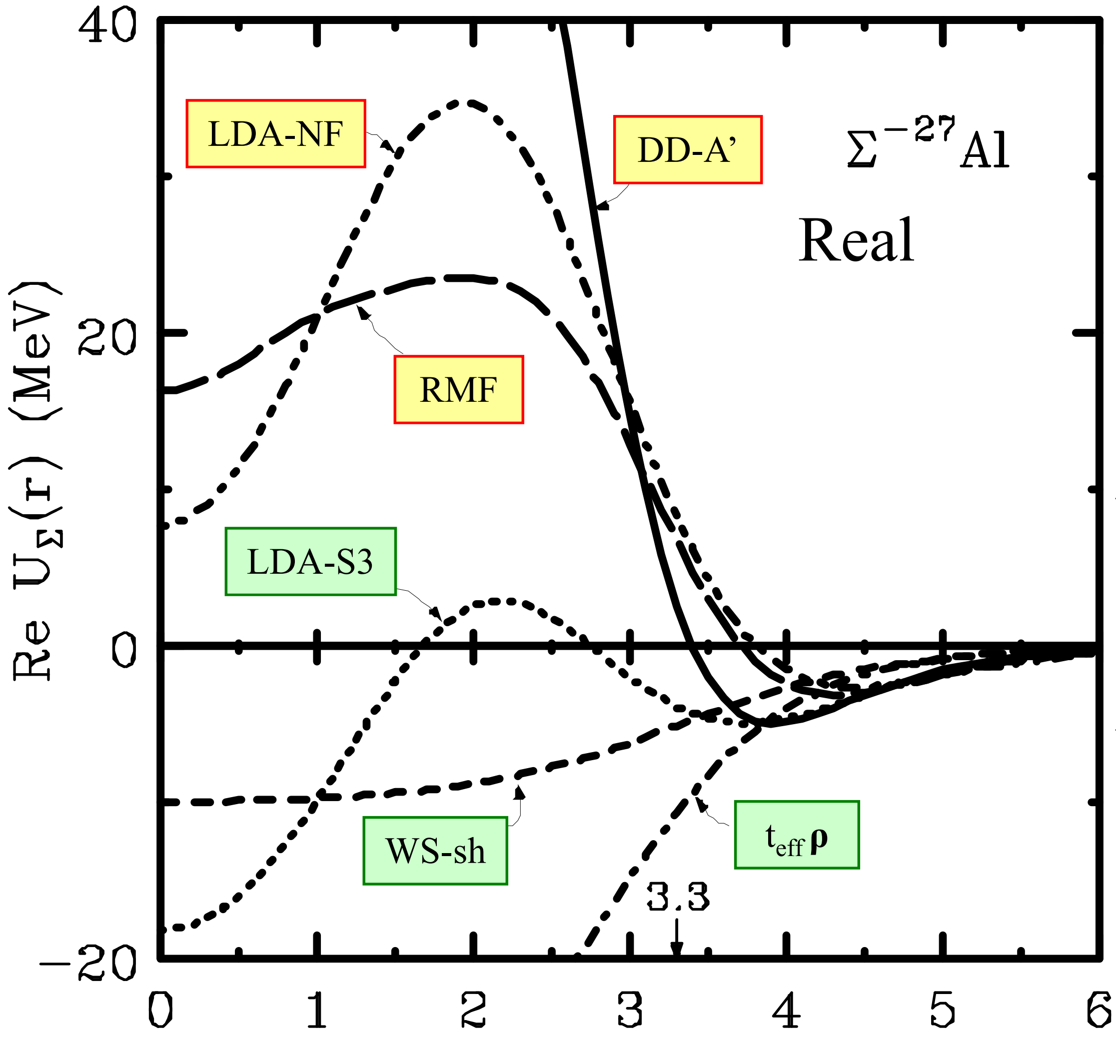
R.S.Hayano, NPA478(1988)113c

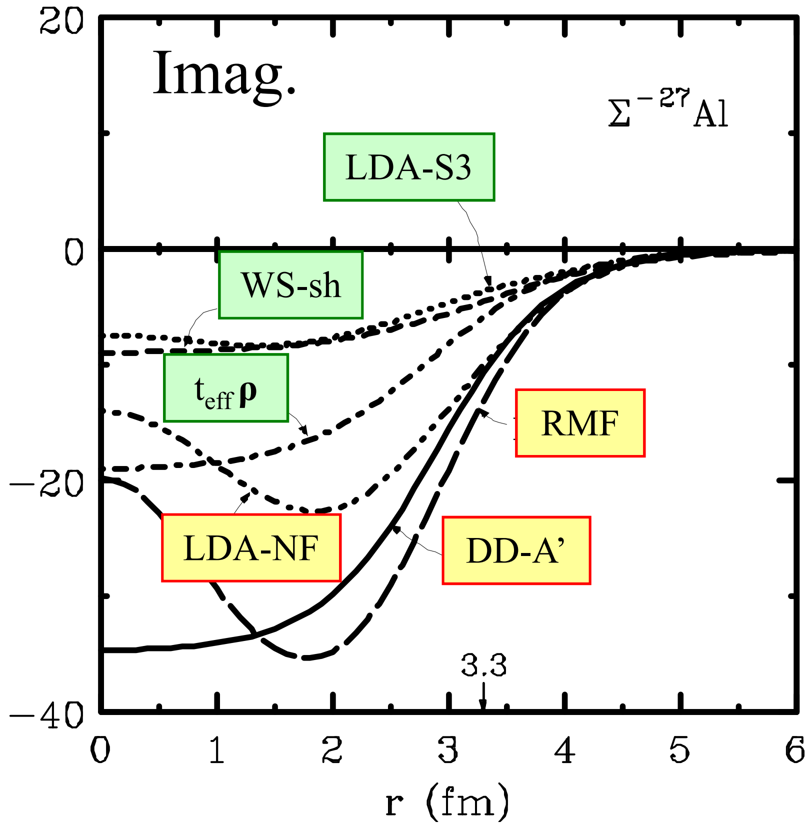
$t_{eff}\,\rho$ **$t_{eff}\,\rho$–type potential ($B_0=B_1=0$):** $a_0=0.36+i0.20$ fm

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

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

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

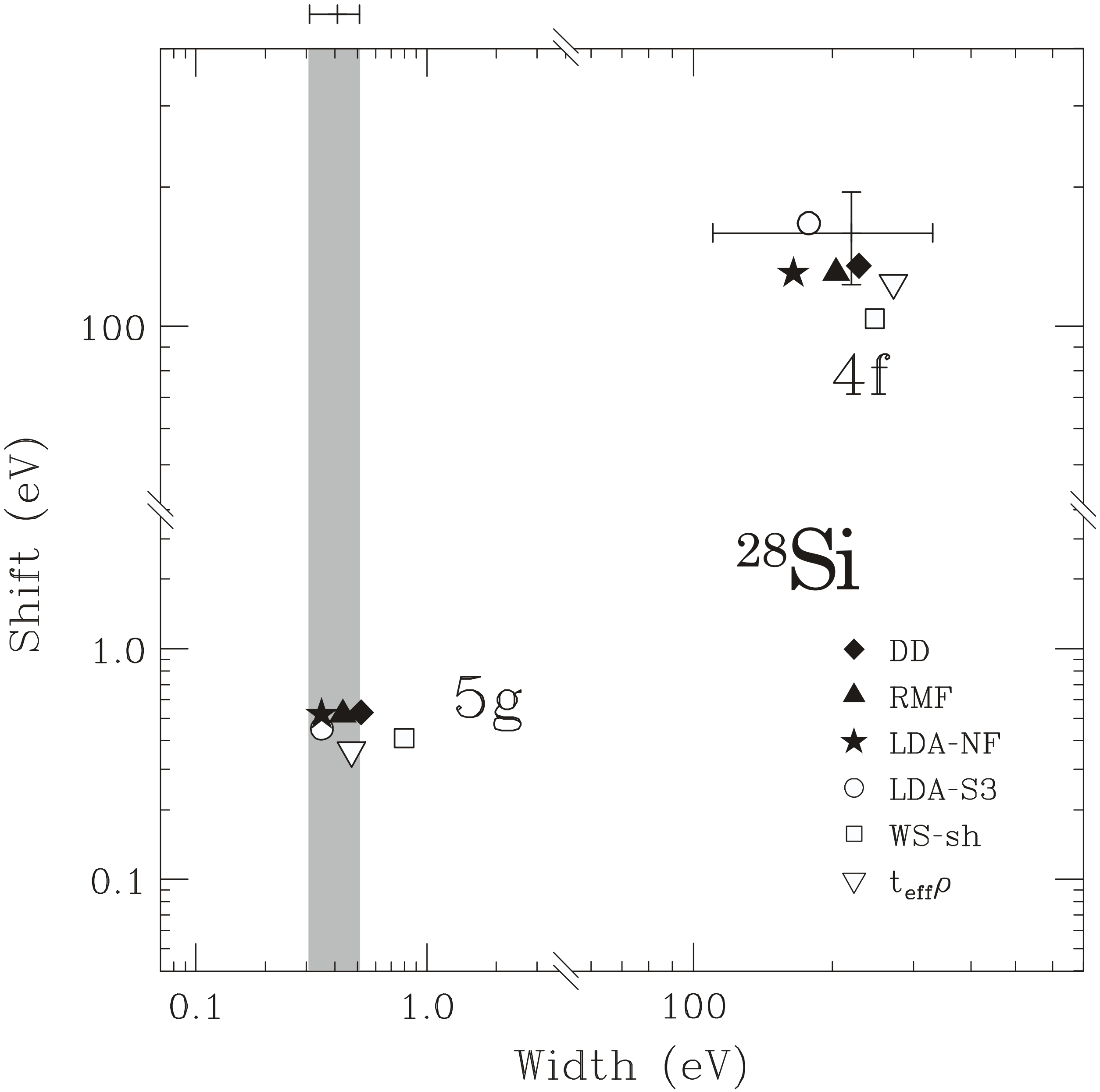




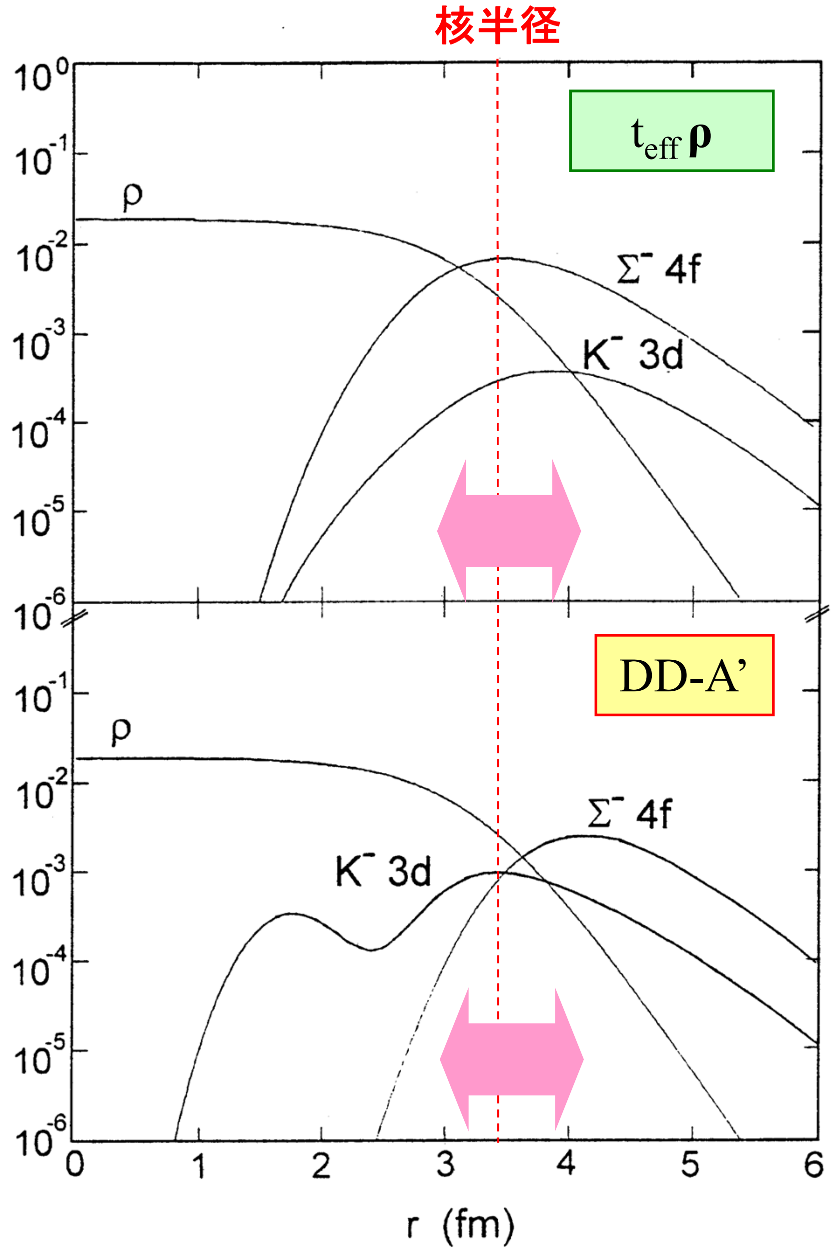
	Real part	Imag. part		Real part	Imag. part
Type I	repulsive	strong (30-40MeV)	**Type II**	(weak) attractive	weak (< 10MeV)

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

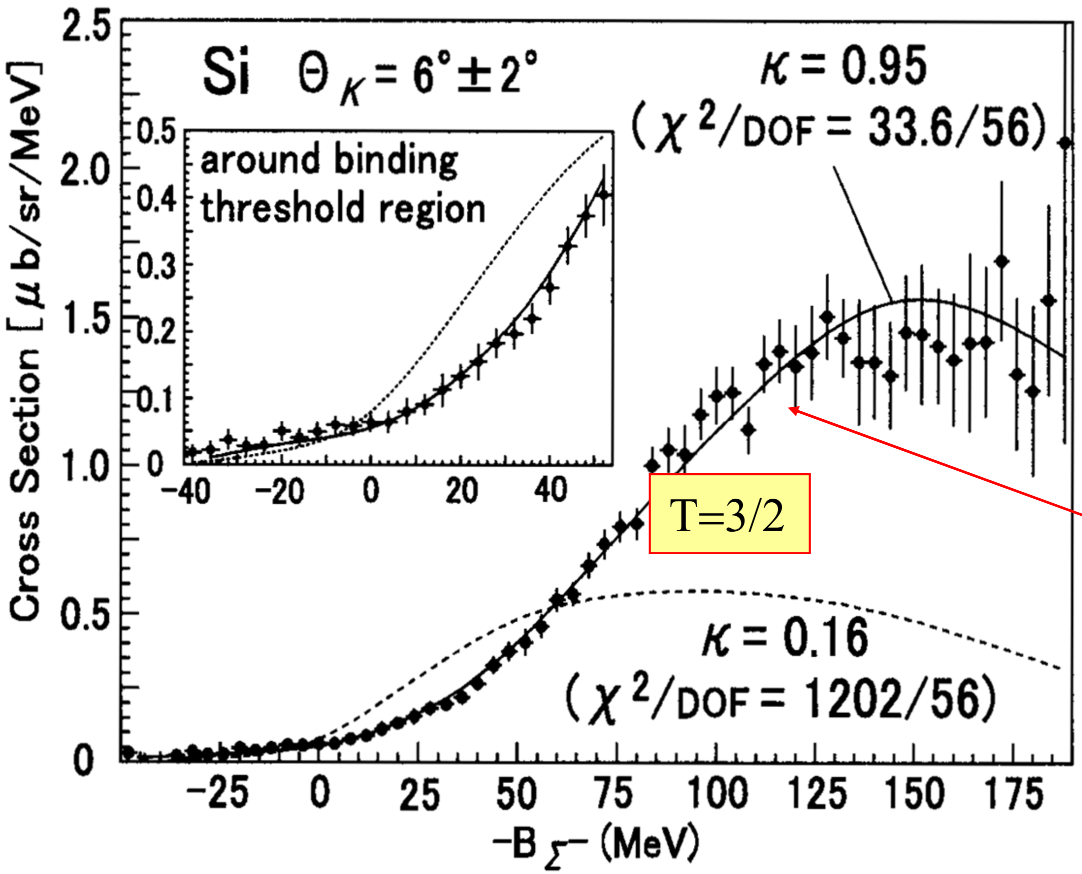
Study of Σ s.p. potential by (π^-,K^+) reactions

Targets: ^{28}Si, ^{58}Ni, ^{115}In, ^{209}Bi

Direct Σ production at the nuclear inside

^{28}Si

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



Woods-Saxon form

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

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

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

$V_\Sigma = +150$ MeV

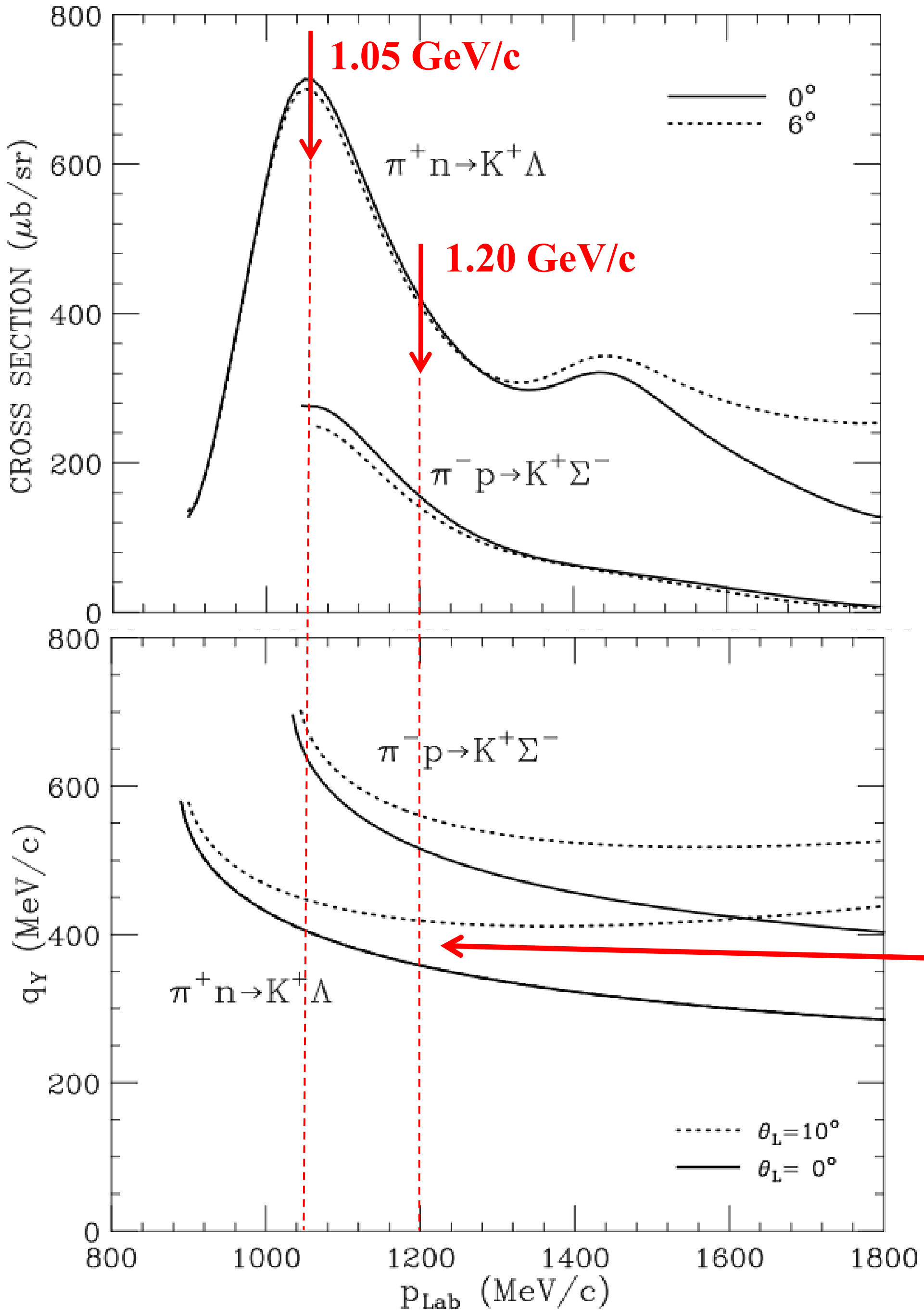
$W_\Sigma = -15$ MeV

+90 MeV

−40 MeV

(Revised)

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



Elementary processes of the $\pi^+p \to K^+\Lambda$ and $\pi^-p \to K^+\Sigma^-$ reactions

Production cross sections

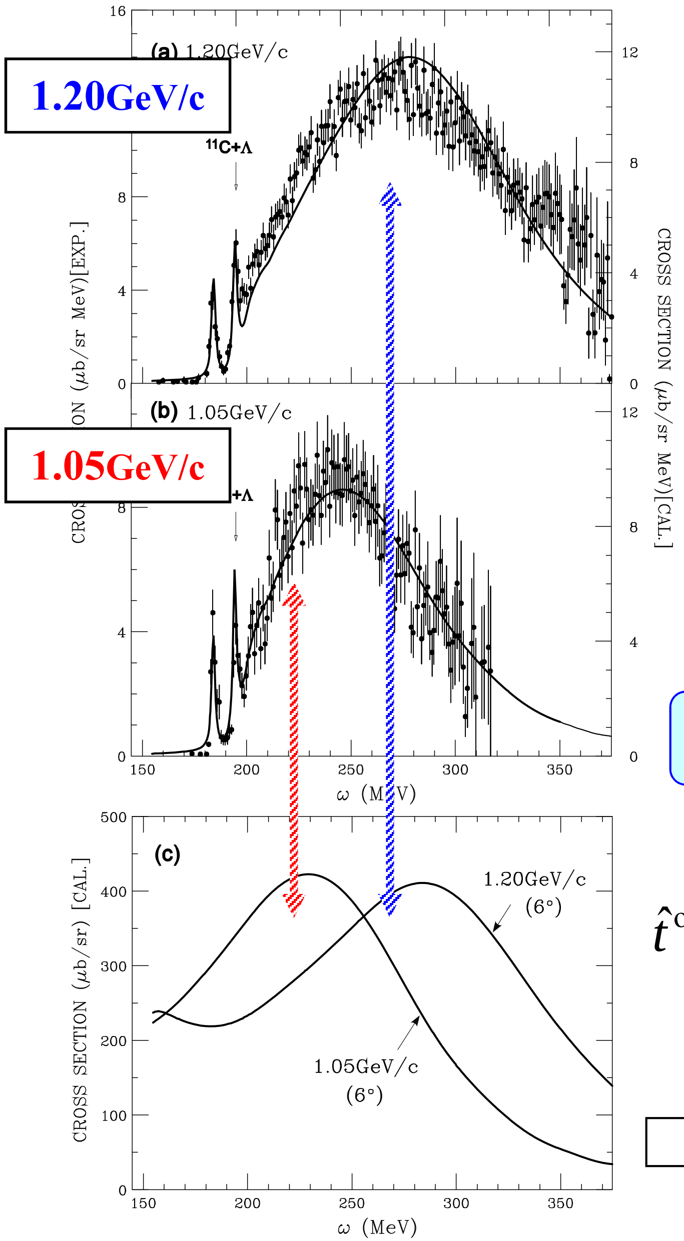
The reason comes from the fact that the cross section at 1.05GeV/c is larger than that at 1.20GeV/c.

Large momentum transfer

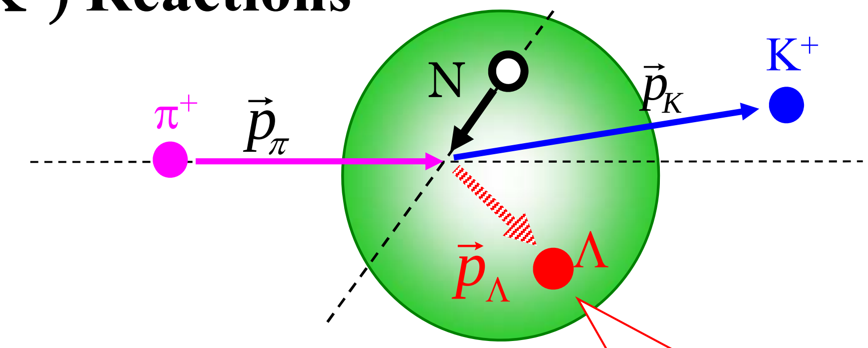
$$q_\Lambda \approx 400 \text{ MeV/c}$$

Optimal Fermi-averaging for an elementary t-matrix

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



$^{12}C(\pi^+,K^+)$ Reactions



「面白い！」
平林

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

Strength function

"Optimal Fermi-averaging" t-matrix

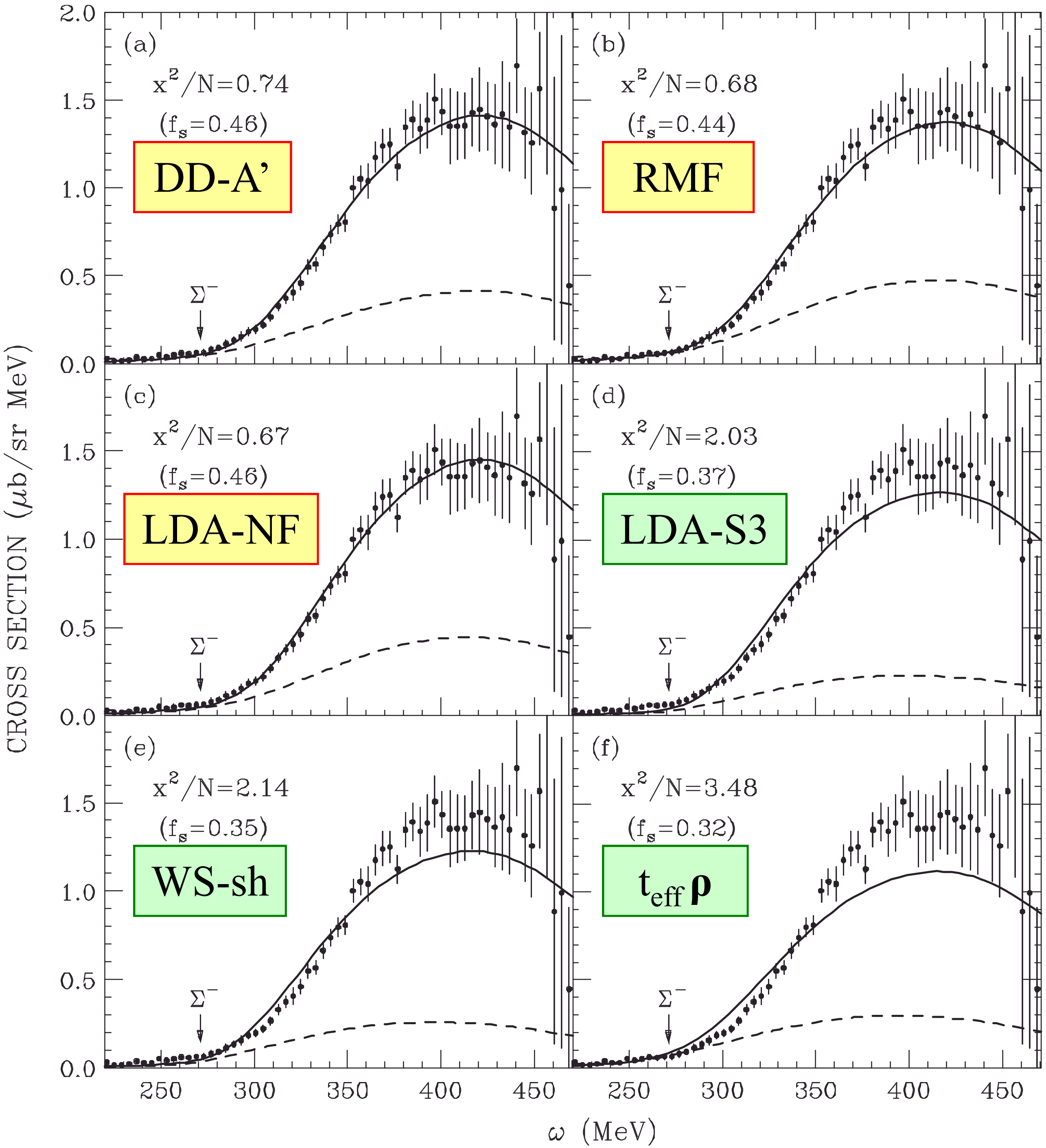
$$\hat{t}^{\rm opt}(p_\pi;\omega,\mathbf{q}) = \left.\frac{\int_0^\pi \sin\theta d\theta \int_0^\infty p_N^2 dp_N \hat{t}_{Lab}(E_{\pi N}; p_\pi, p_N)\rho(p_N)}{\int_0^\pi \sin\theta d\theta \int_0^\infty p_N^2 dp_N \rho(p_N)}\right|_{\mathbf{p}_N=\mathbf{p}_N^*}$$

⇒ 実験データのエネルギー依存性をよく説明する

(π^-,K^+) reaction at 1.2GeV/c

^{28}Si

Σ^-

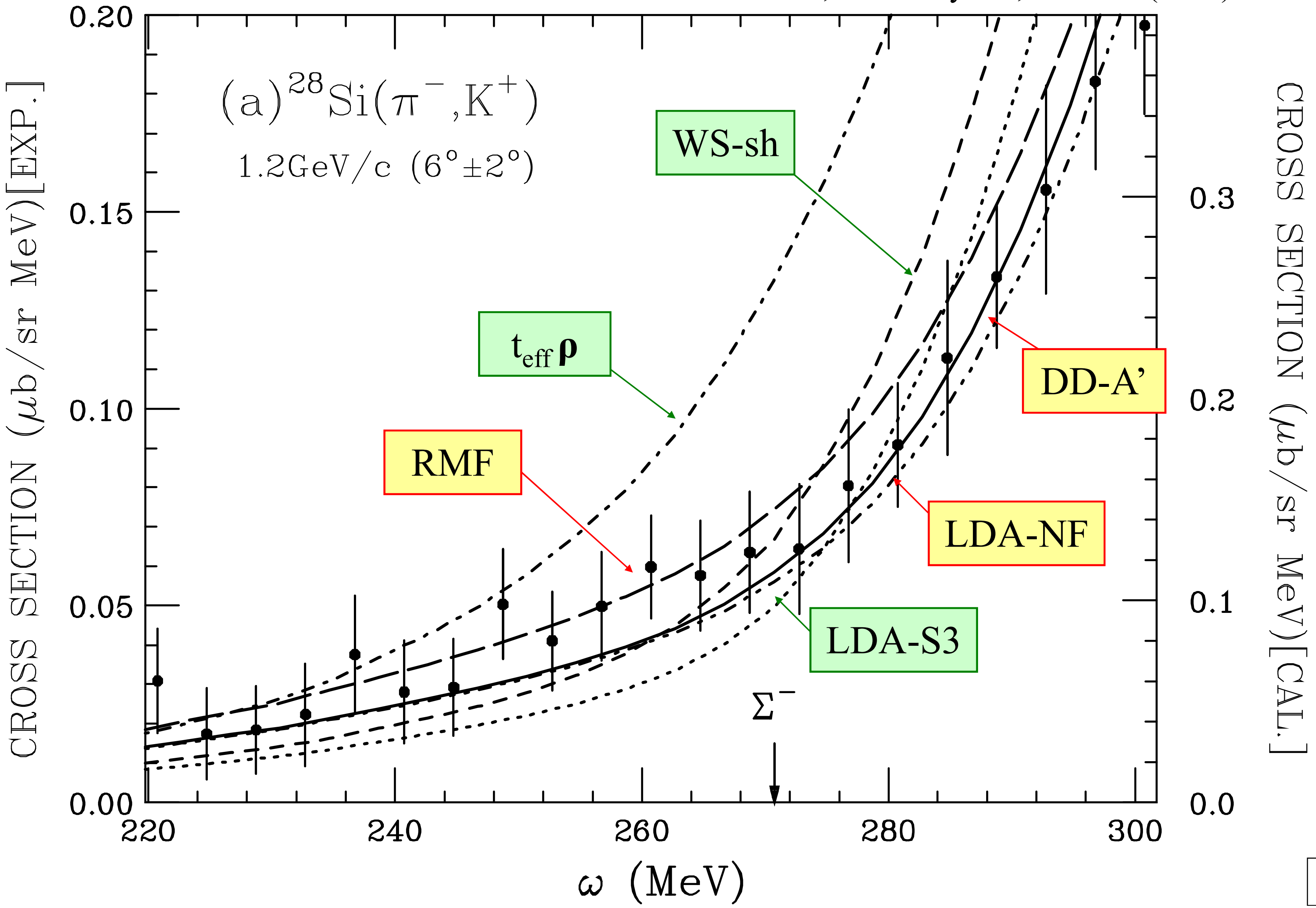


DWIA analysis with the optimal Fermi-averaging

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

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

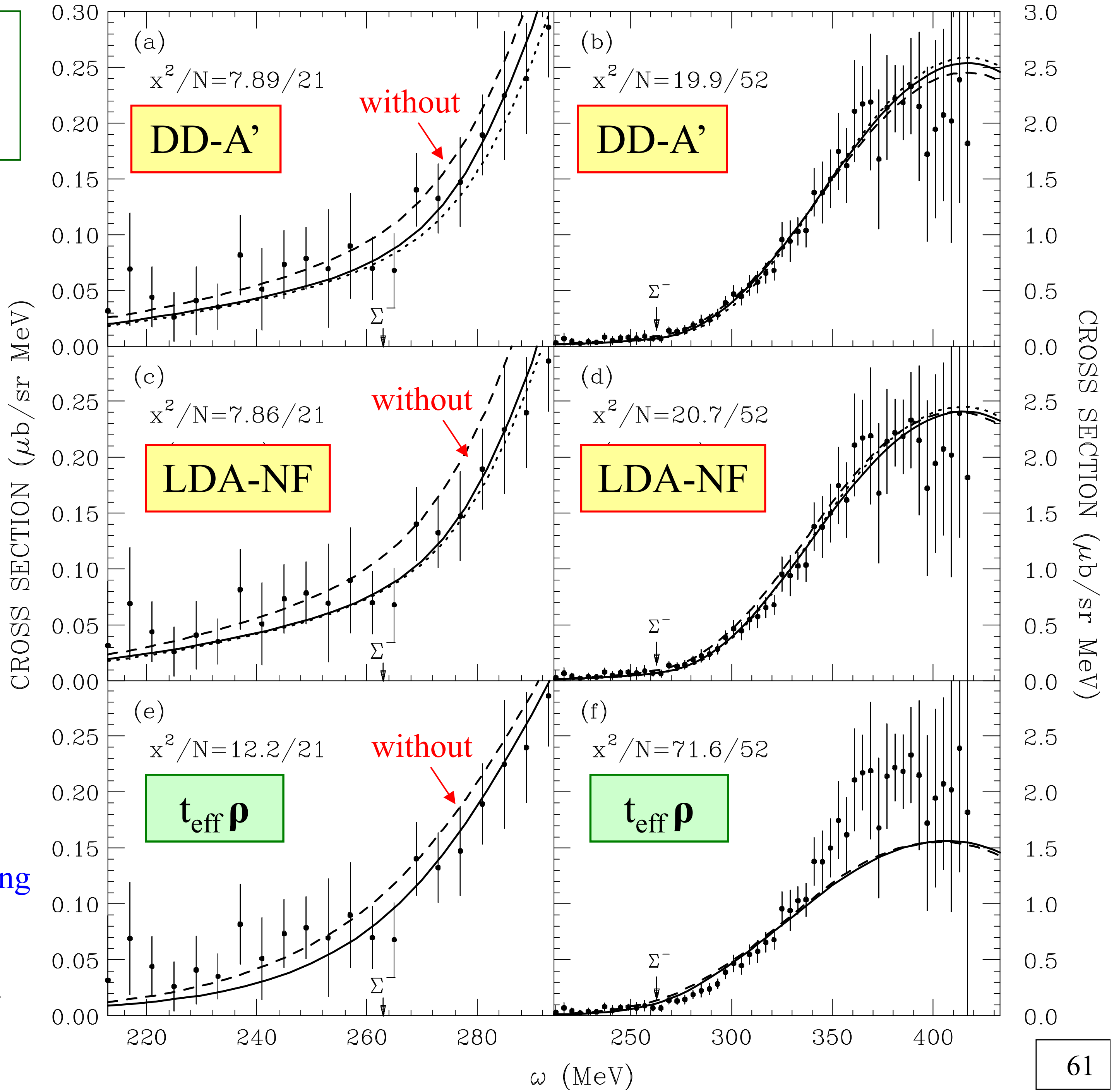
T.Harada, Y.Hirabayashi, NPA759 (2005) 143



(π^-, K^+) reaction at 1.2GeV/c

^{209}Bi

Σ^-

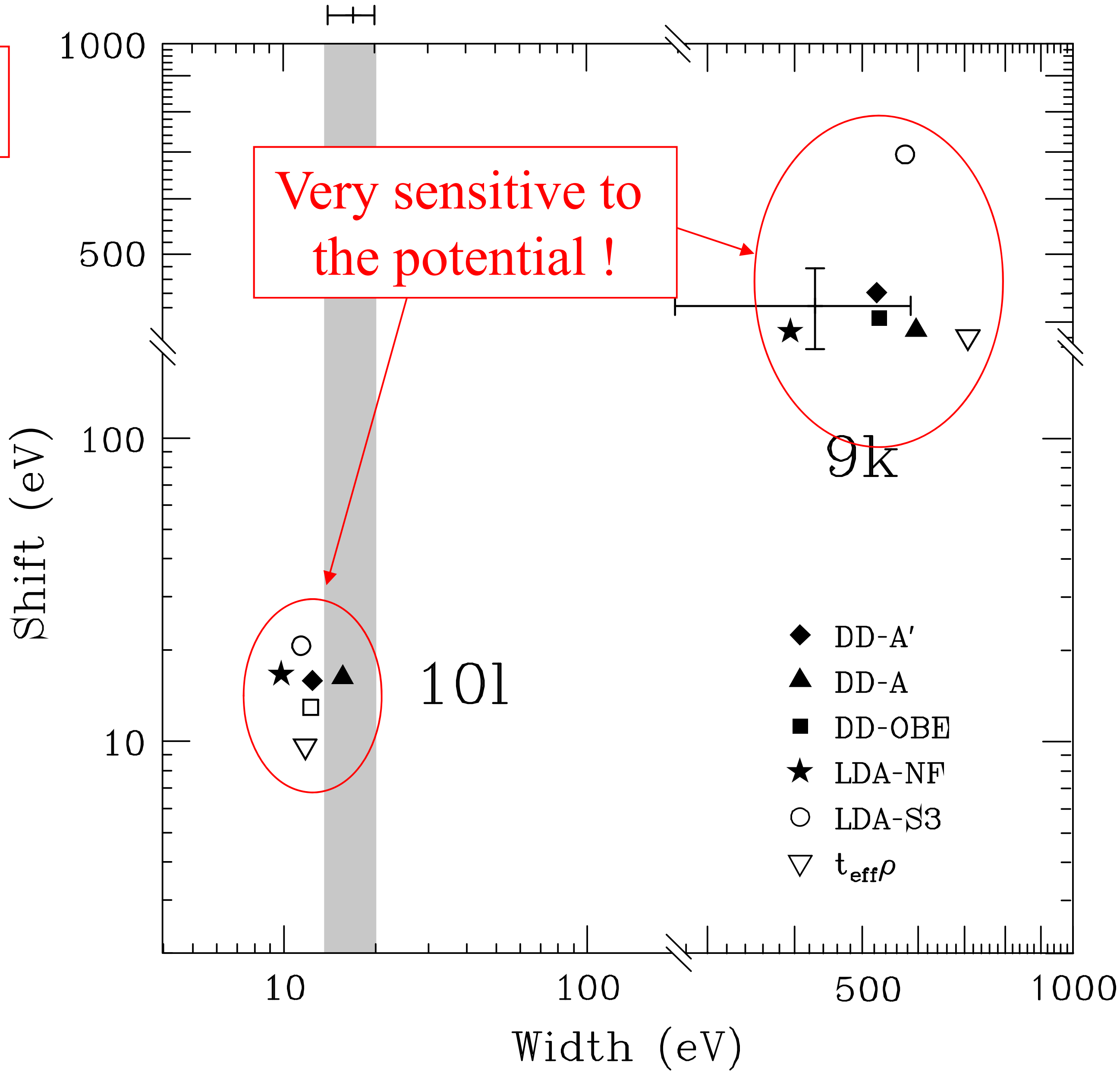


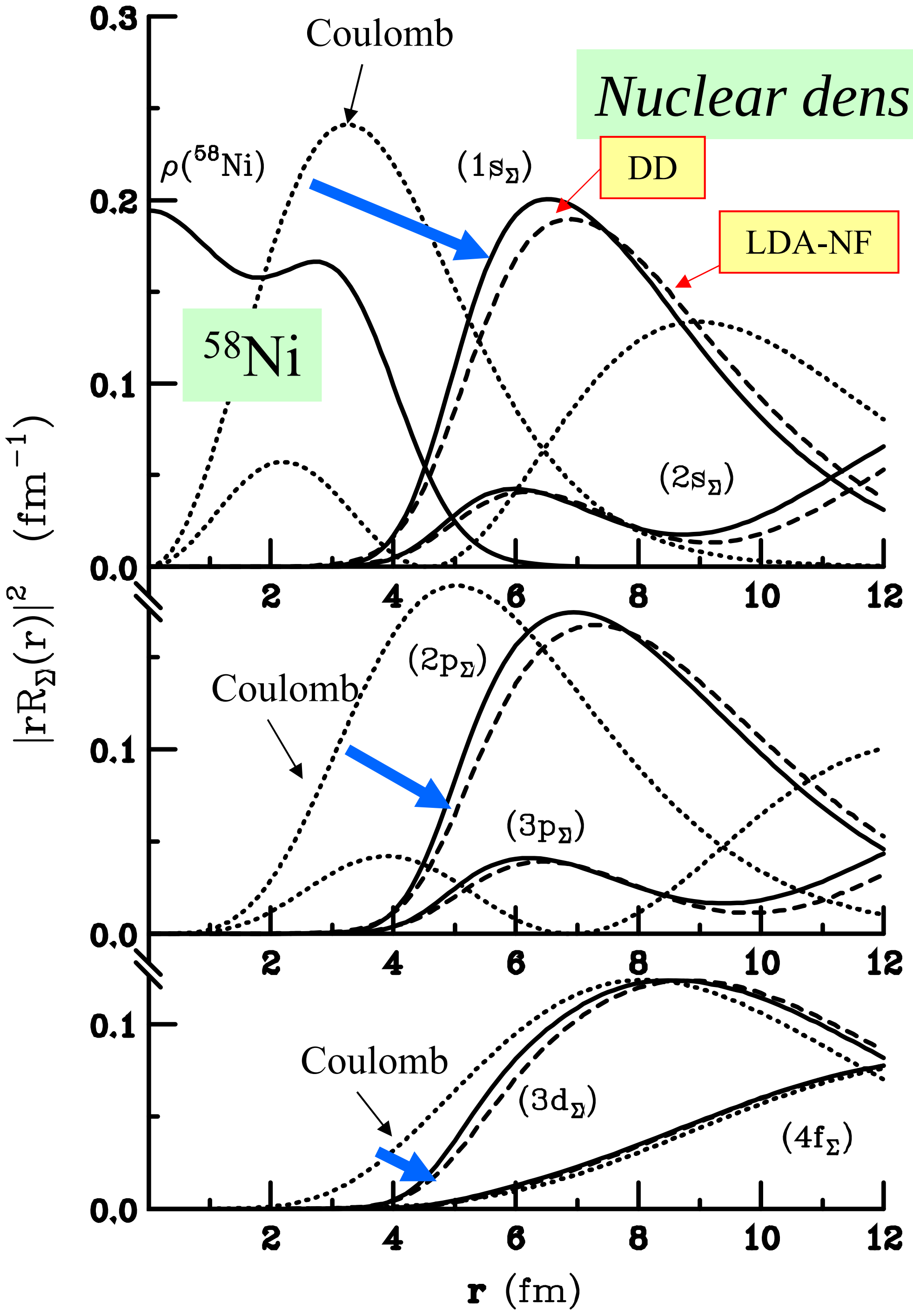
DWIA analysis with the optimal Fermi-averaging

T.Harada, Y.Hirabayashi, Nncl. Phys. A767 (2006)206.

Strong-shifts and widths on Σ^- atoms

$\Sigma^{-}\ {}^{208}Pb$





Σ^--^{57}Co

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

Narrow Σ^- bound state !!

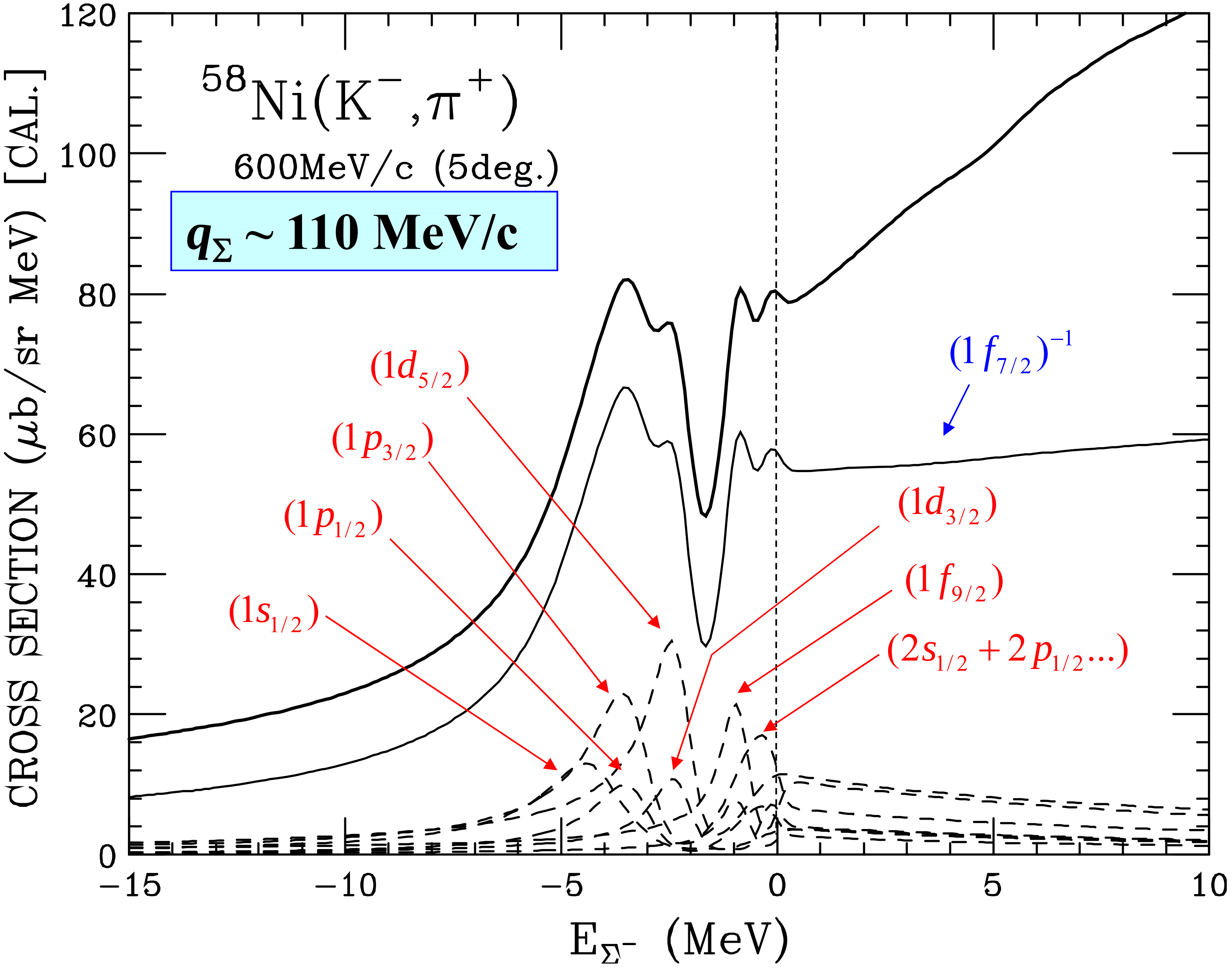
Cf. deeply pionic atoms

Σ^- substitutional states by (K^-,π^+) reaction (I)

DD-A'

^{58}Ni

Σ^-



1.0MeV FWHM

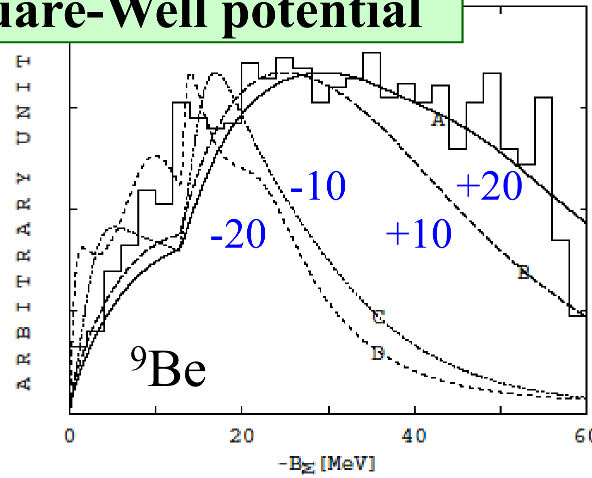
The recoilless reaction provides to produce a promising Σ^- bound state.

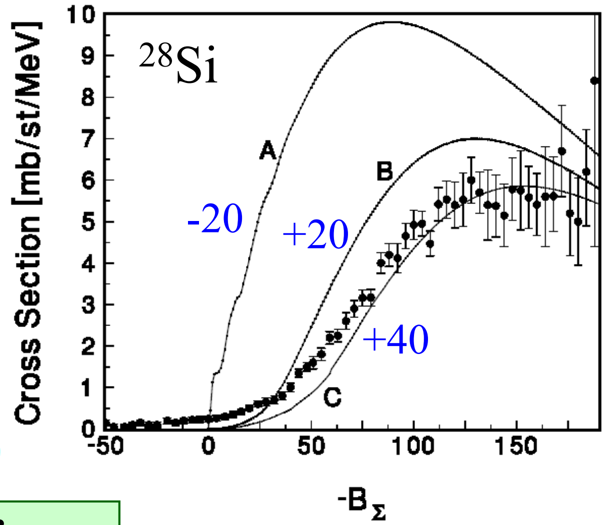
Comparison with resent studies

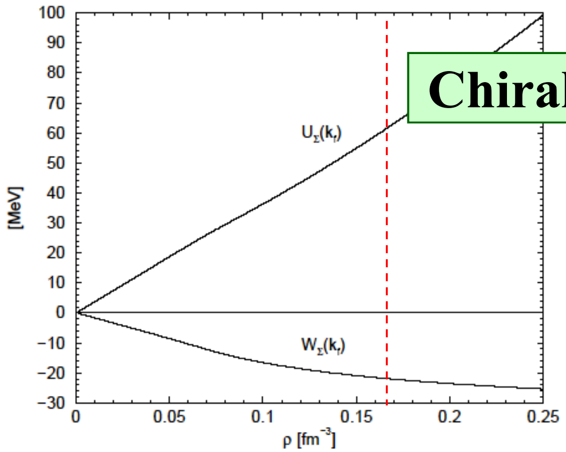
PWIA Analysis with the Square-Well potential

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

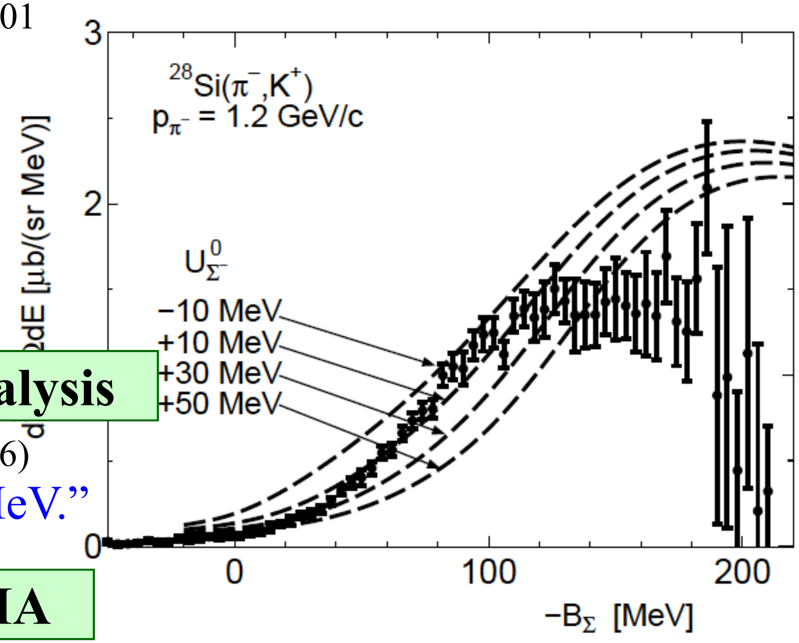
$U_\Sigma(\rho_0) \sim 59$MeV repulsive

$W_\Sigma(\rho_0) \sim -21$MeV

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."

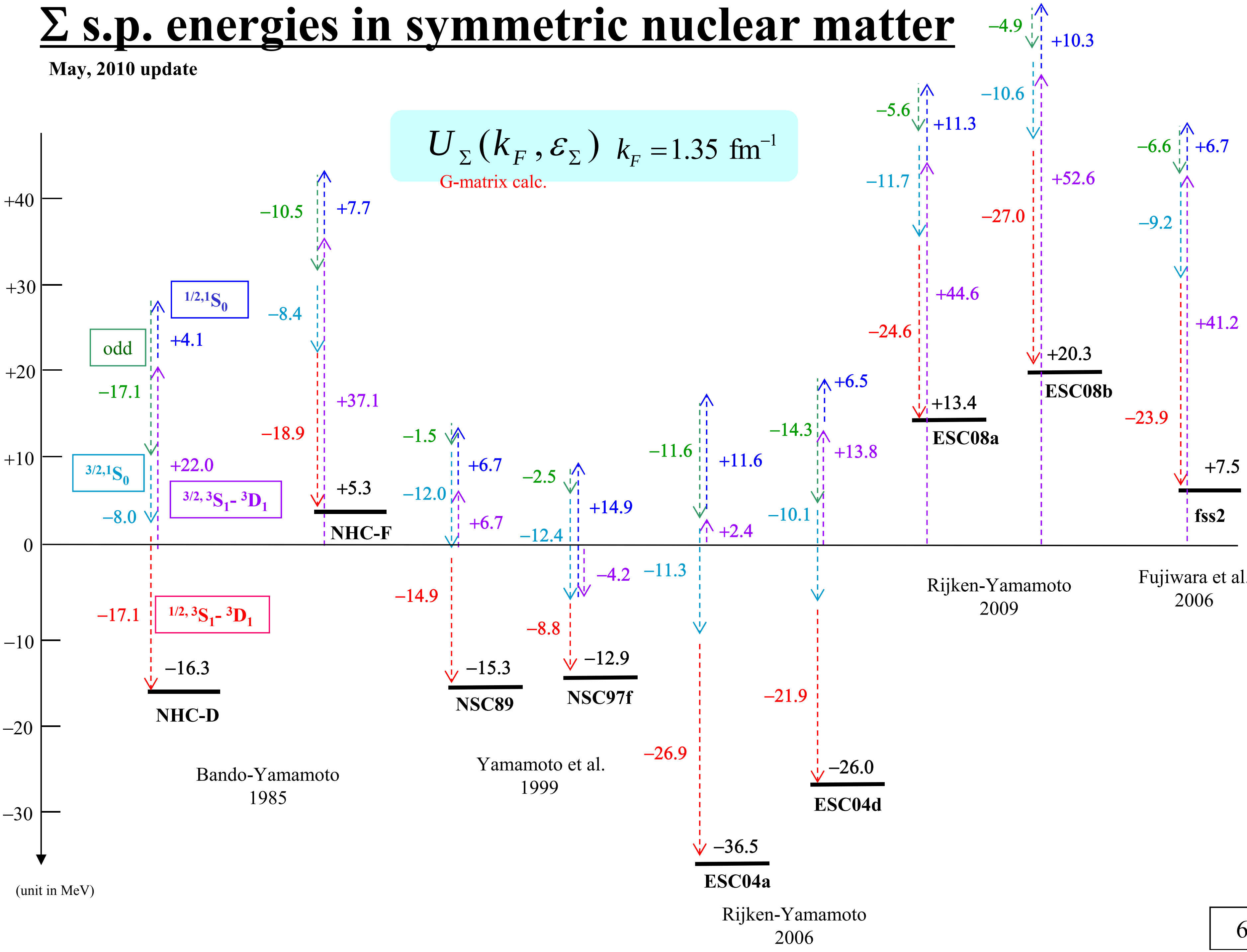


Local Optimal Fermi-averaged t-matrix DWIA

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

Σ s.p. energies in symmetric nuclear matter

May, 2010 update



シグマハイパー核の諸問題(1980s-)

- シグマハイパー核は存在するのか？
  - 狭い幅の状態の問題は? ➡ 存在しない！
  - ΣN(T=1/2, $^3S_1$)の束縛状態は？ ➡ カスプ状態か
  - A=4の束縛状態の存否は? ➡ 存在した(確立)
- Σポテンシャルは引力か斥力か？
  - シグマ原子のX線データ v.s. ➡ 斥力らしい
  - (π^-, K^+)反応によるシグマ生成スペクトル
- ラムダ核におけるΣ混合の割合は？ ➡ ＜1%？
- アイソスピンは良い量子数か？ ➡ OK？
- スピン-軌道力の大きさは？ ➡ ？？

3. Λハイパー核

Λハイパー核

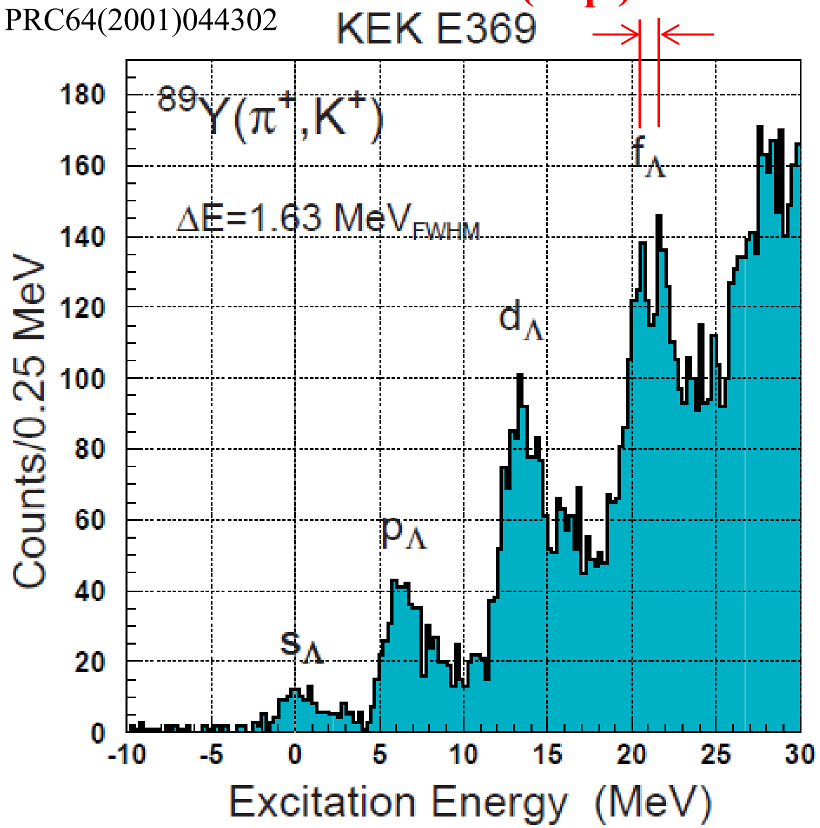
- (π$^+$,K$^+$)反応によるハイパー核の生成
  芯核の励起状態,ハイパー核らしい状態, etc.
- Λ粒子の１粒子ポテンシャルとスピン軌道力
- 核内Λ粒子の働き
- Gamma-ray spectroscopy of light hypernuclei
- Overbinding Problem on s-Shell Hypernuclei
- 中性子過剰ハイパー核
- Λハイパー核の弱崩壊

Λ s.p. potential and Λ spin-orbit splitting in $^{89}_{\Lambda}Y$

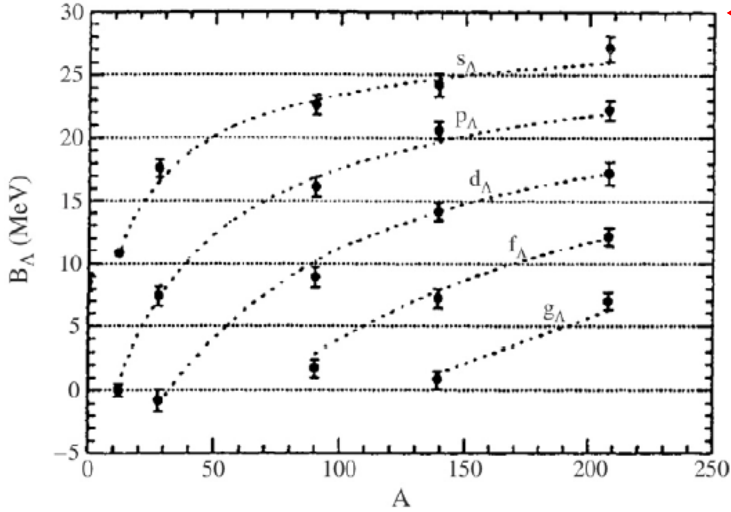
V_{Λ} ?

H. Hotchi et al.,
PRC64(2001)044302

(Exp.) 1.7 MeV



$$U_\Lambda = V_0^\Lambda f(r) + V_{LS}^\Lambda \left(\frac{\hbar}{m_\pi c}\right)^2 \frac{1}{r}\frac{\mathrm{d}f(r)}{\mathrm{d}r}\boldsymbol{ls}$$



$V_0^\Lambda \simeq -30$ MeV
$(A \to \infty)$

$a = 0.6$ fm

$V_{LS}^\Lambda \simeq 2$ MeV

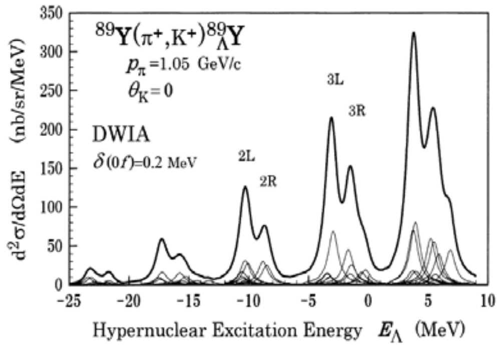
WS analysis

[O. Hashimoto, T. Tamura, PPNP57(2006)564]

T. Motoba et al.,
PTPS185(2010)197

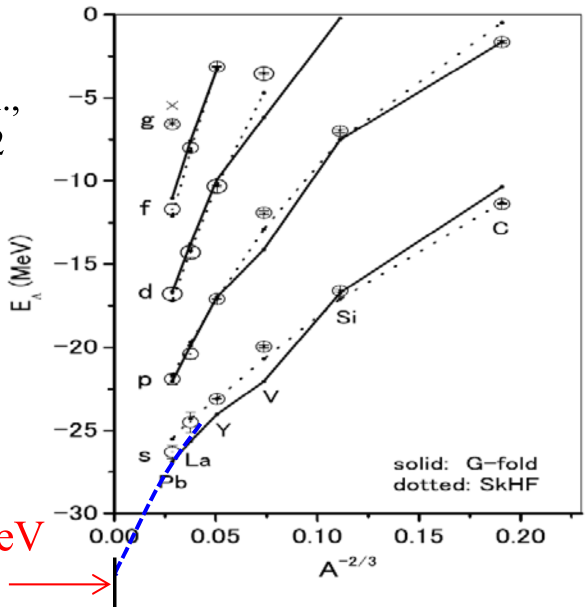
SM analysis
- ΛN^{-1} particle-hole ex.
- inter-shell coupling

$V_{LS}^\Lambda \simeq 0.2$ MeV



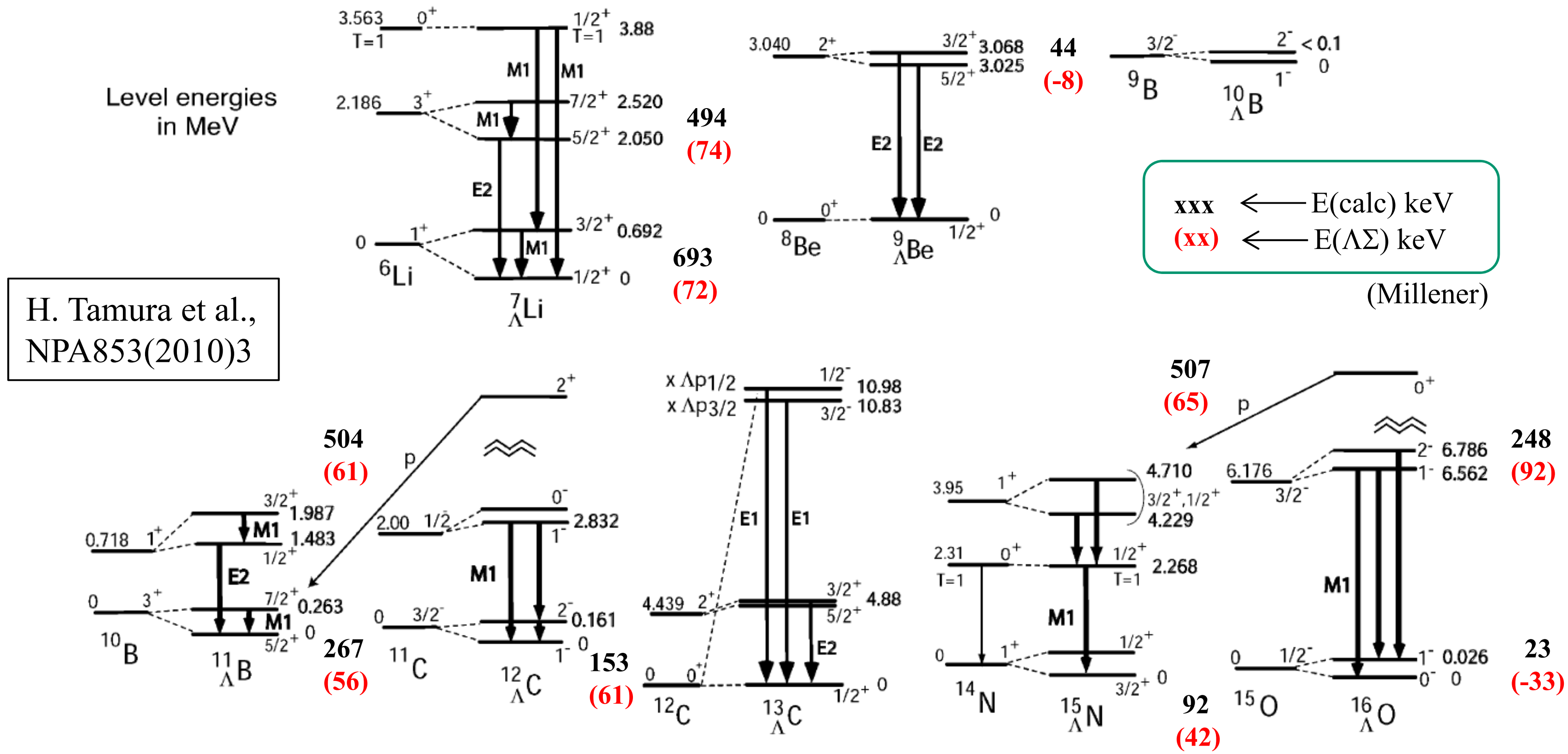
Y. Yamamoto et al.,
PTPS185(2010)72

G-matrix
folding model



$V_0^\Lambda \simeq -37.2$ MeV
$(A \to \infty)$

Gamma-ray spectroscopy of light hypernuclei



Spin-dependence of the effective ΛN interaction

[R.H.Dalitz, A.Gal, AnnPhys.116(1978)167]

Microscopic Shell-Model

$$V_{\Lambda N} = \bar{V} + \Delta\, \vec{s}_N \cdot \vec{s}_\Lambda + S_\Lambda\, \vec{l}_N \cdot \vec{s}_\Lambda + S_N\, \vec{l}_N \cdot \vec{s}_N + T\, S_{12}$$

$A = 7,9 \quad \Delta = 430,\ S_\Lambda = -15,\ S_N = -390,\ T = 30$ (keV)

$A > 9 \quad \Delta = 330,\ S_\Lambda = -15,\ S_N = -350,\ T = 23.9$ (keV)

including **ΛN-ΣN coupling effects**

[D.J.Millener,NPA835(2010)11]

E13@J-PARC

- ΛN spin-dependent force/ΛN-ΣN coupling force/Charge symmetry breaking (Λp≠Λn)
- Magnetic moments μ_Λ in a nucleus from B(M1)

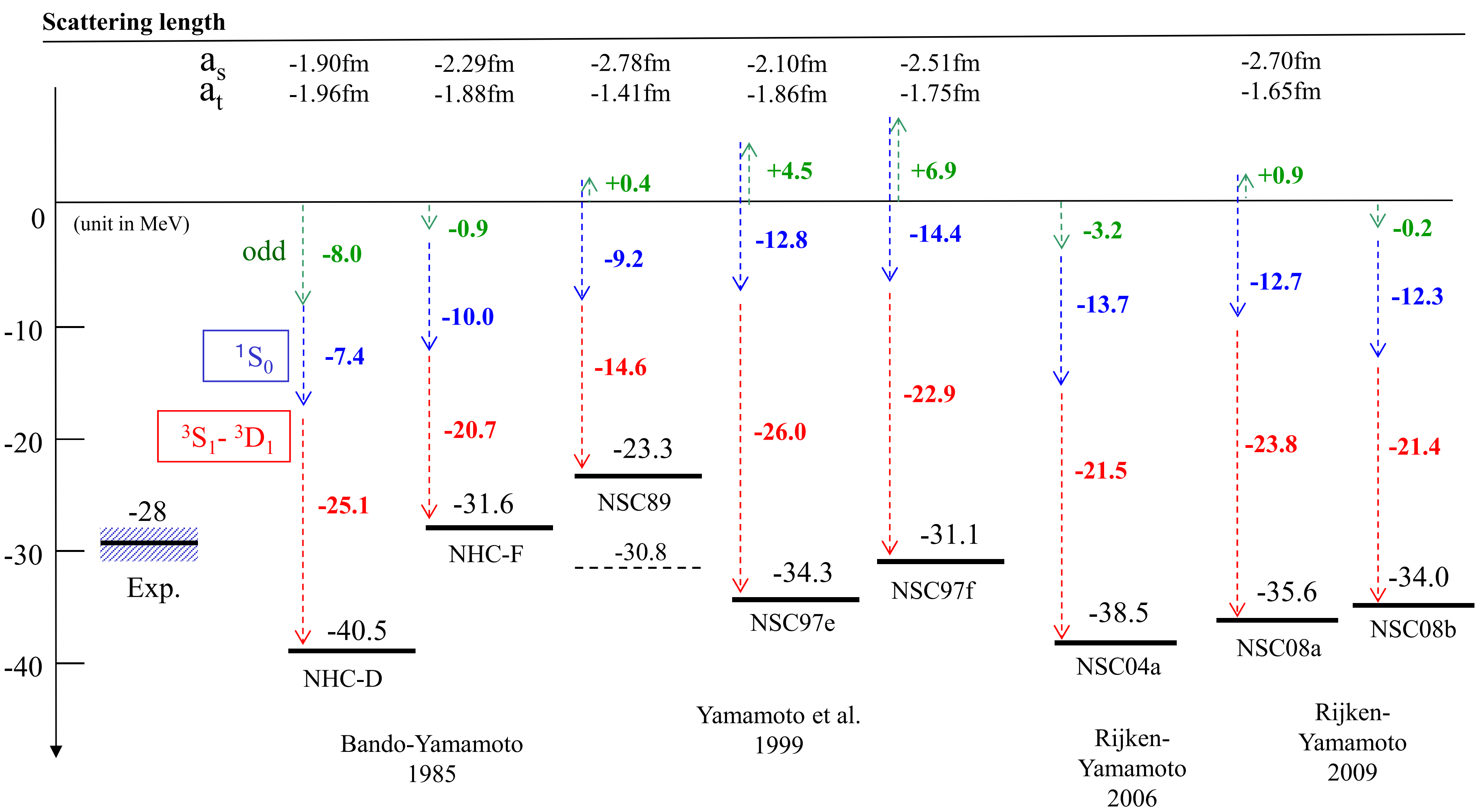
$^4_\Lambda$He, $^{10}_\Lambda$B, $^{11}_\Lambda$B, $^{19}_\Lambda$F

Λ single-particle energies in symmetric nuclear matter

OBEP: Nijmegen YN potential Models

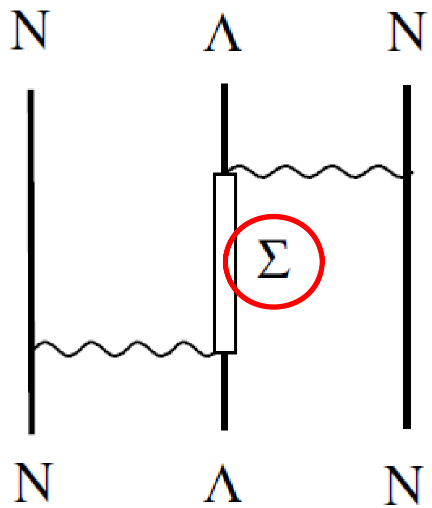
$U_\Lambda(k_F, \varepsilon_\Lambda) \quad k_F = 1.35\mathrm{fm}^{-1}$

G-matrix calc. QTQ



Y. Yamamoto, H. Bando, PTP.Suppl.81(1985)9; Y. Yamamoto, et al.,PTP.Suppl.117(1994)361;
Th.A.Rijken, V.G.J.Stoks, Y.Yamamoto, PRC59(1999)21; Th.A.Rijken, Y.Yamamoto, PRC73(2006) 044008;
Y.Yamamoto, T.Motoba, T.A.Rijken, PTP.Suppl.185(2010)72.

核物質中のΣハイペロンの役割



G-matrix calculation in symmetric nuclear matter

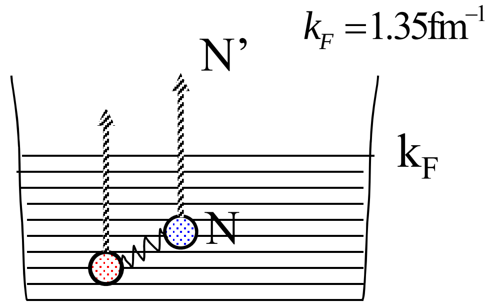
Λ single-particle potential depth

$$U_\Lambda(k_F,\varepsilon_\Lambda)=\sum_{\mathbf{k}_N}\langle \mathbf{k}_\Lambda,\mathbf{k}_N\,|\,g_{\Lambda N}(\omega=\varepsilon_\Lambda+\varepsilon_N)\,|\,\mathbf{k}_\Lambda,\mathbf{k}_N\rangle$$

$$g_{YN}(\omega)=v_{YN}+v_{YN}\frac{Q_N}{\omega-QTQ}g_{YN}(\omega)$$

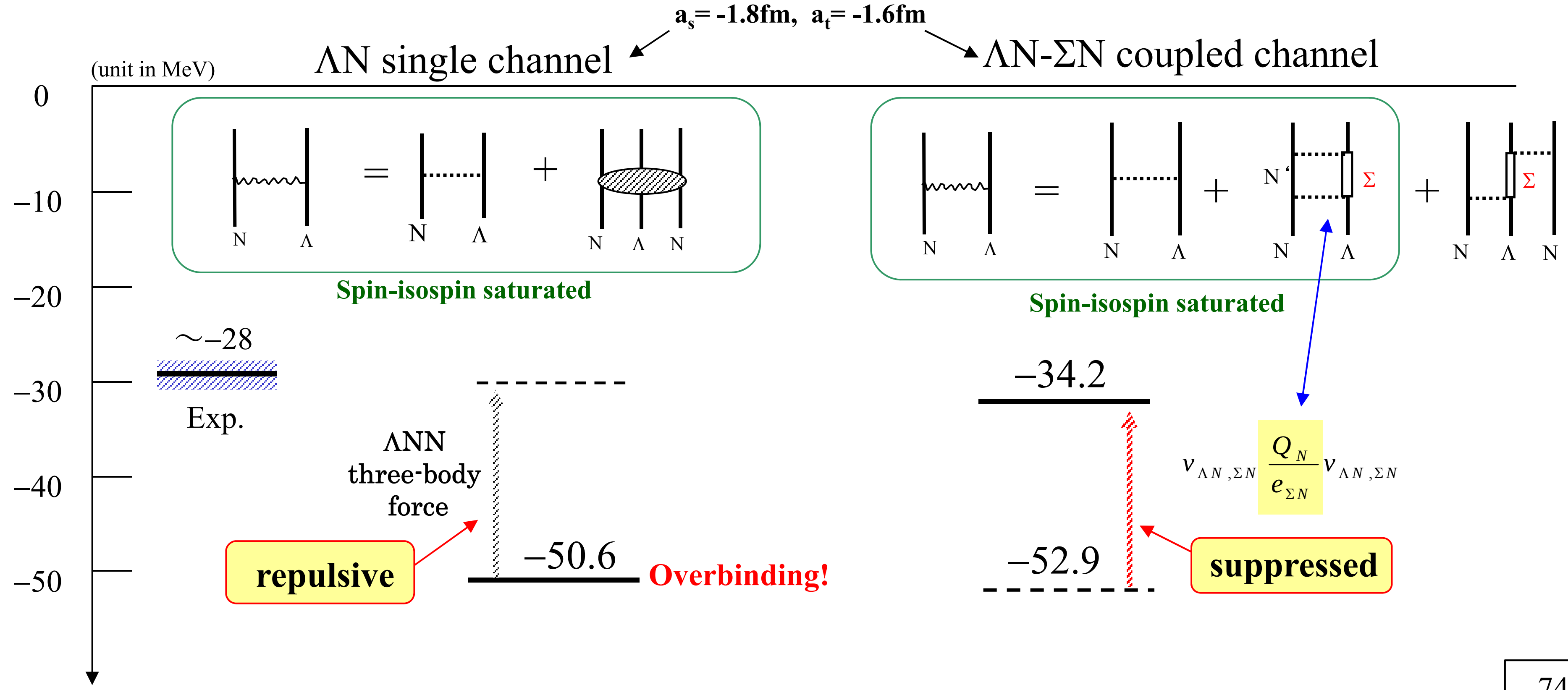
G-matrix

Pauli-operator



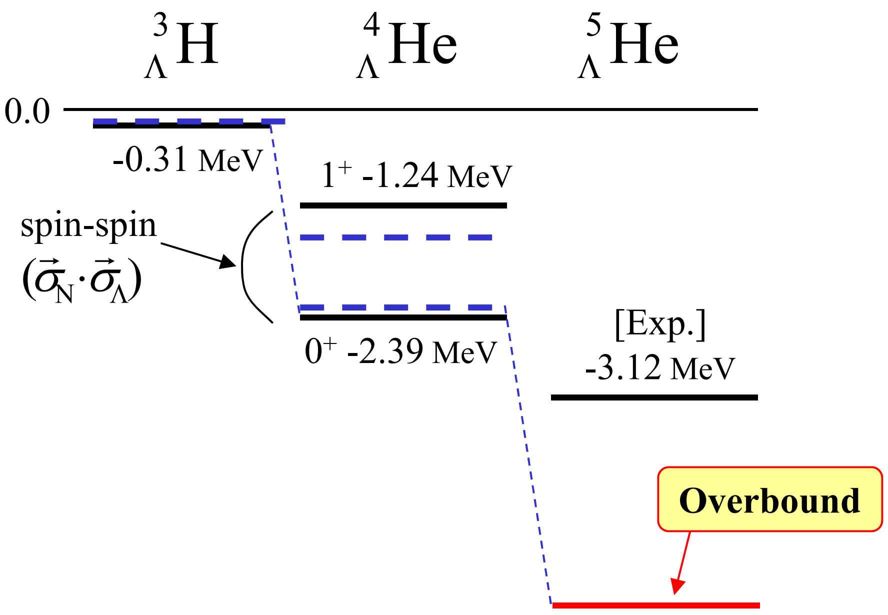
Effects of the ΛN-ΣN coupling in nuclear matter

Y.Nogami, E.Satoh, NPB19(1970)93



Overbinding Problem on s-Shell Hypernuclei

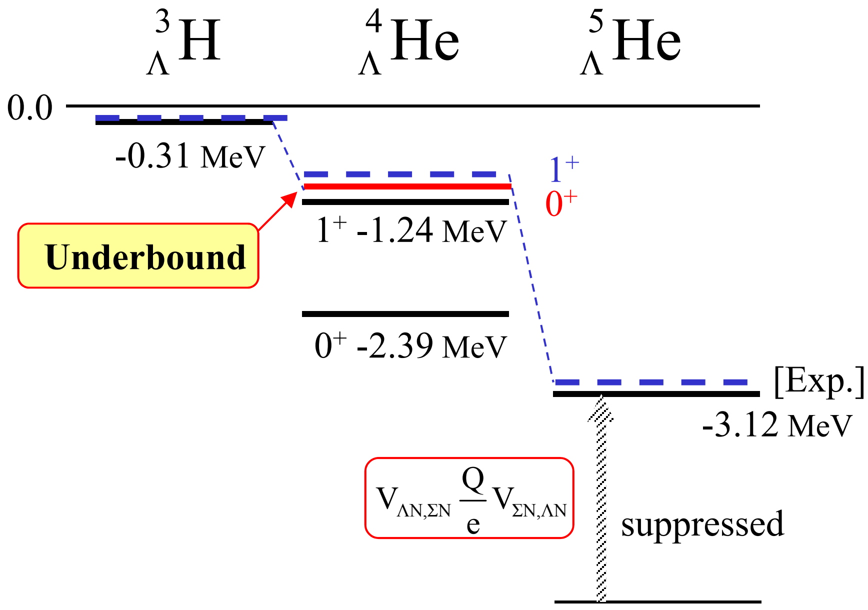
The Overbinding Problem



ΛN single-channel calc.

Dalitz et al., NP **B47** (1972) 109.

The Underbinding Problem

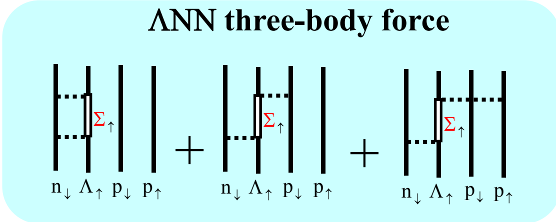


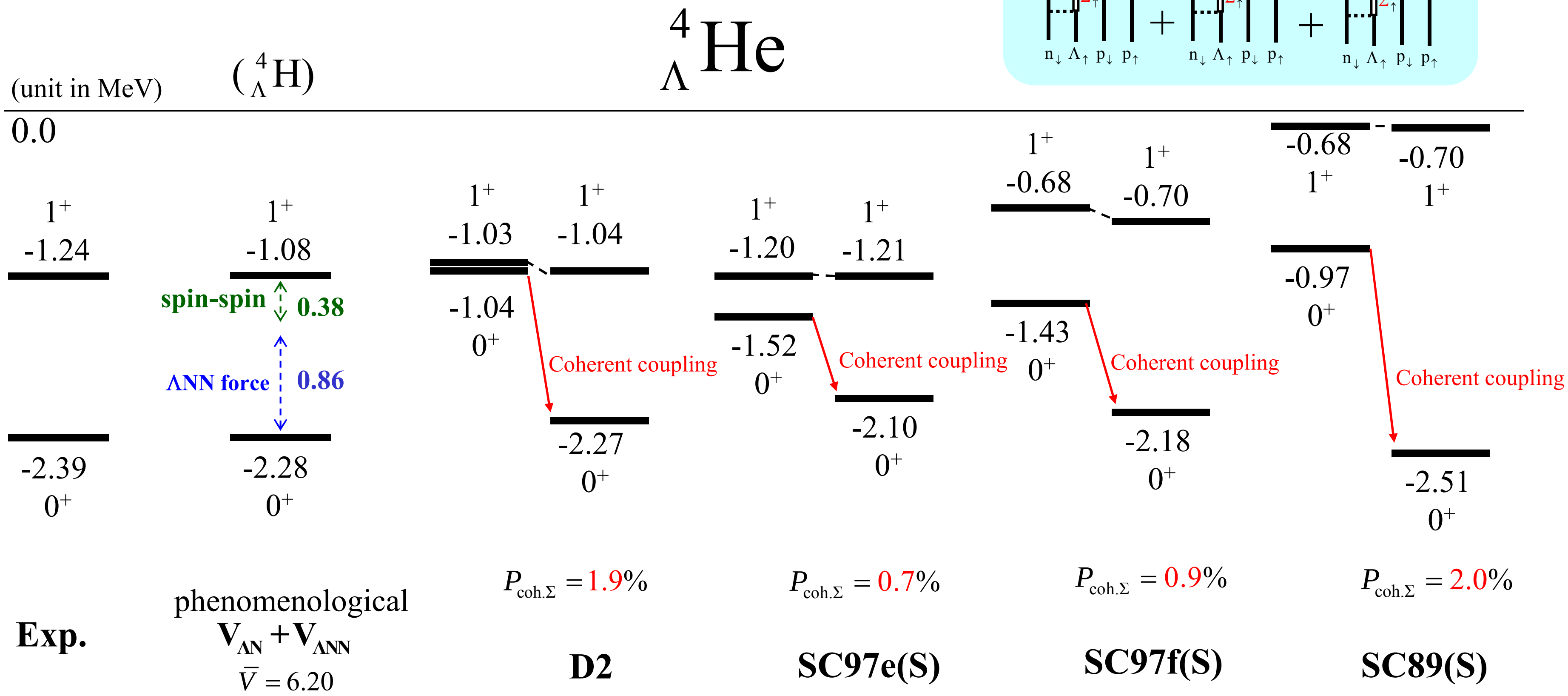
g-matrix calc. with ΛN-ΣN(D2)

Akaishi et al., PRL **84** (2000) 3539.

"The 0^+-1^+ difference is not a measure of ΛN spin-spin interaction."
by B.F. Gibson

Hyperon-mixing





VMC

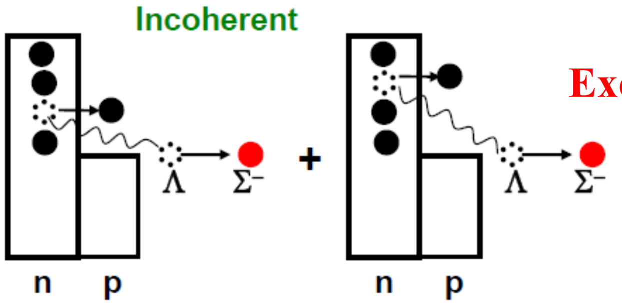
Breuckner-Hartree-Fock

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

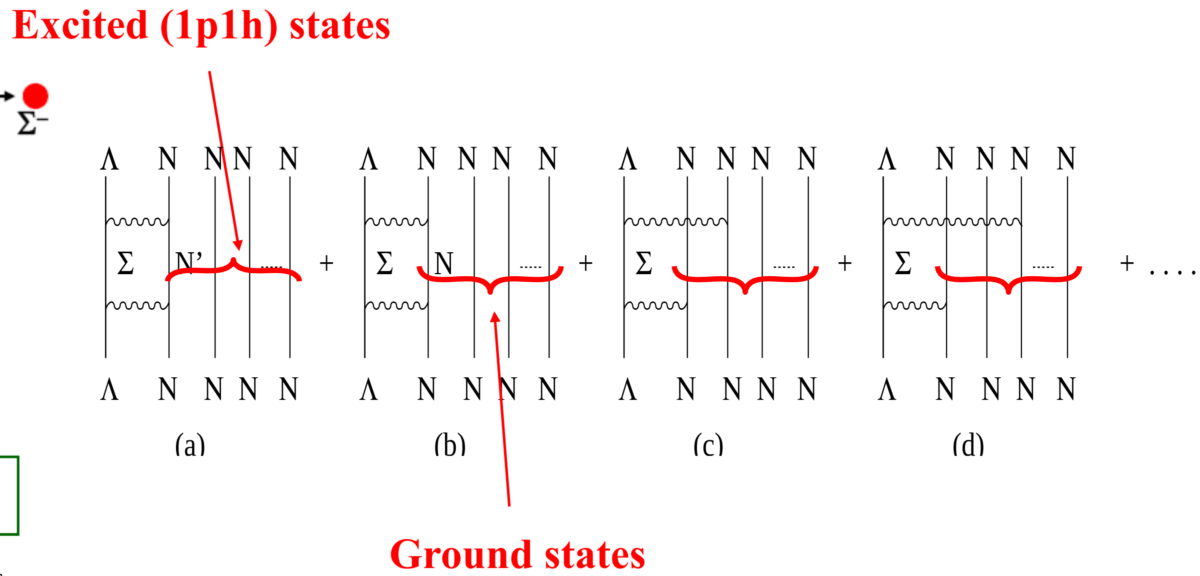
Y. Akaishi, T.Harada, S.Shinmura, Khun Swe Myint, PRL84(2000)3539

The Λ-Σ coupling effects in neutron matter

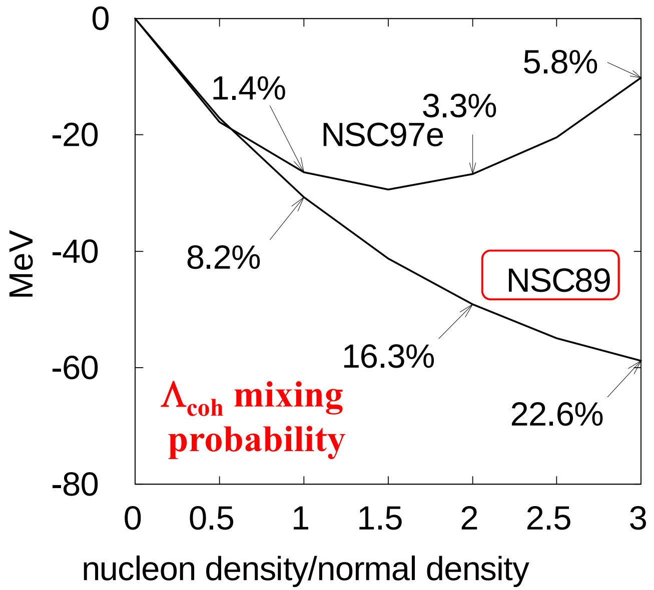
S.Shinmura, Khin Swe Myint, T.H., Y.Akaishi, J.Phys.G28(2002)L1

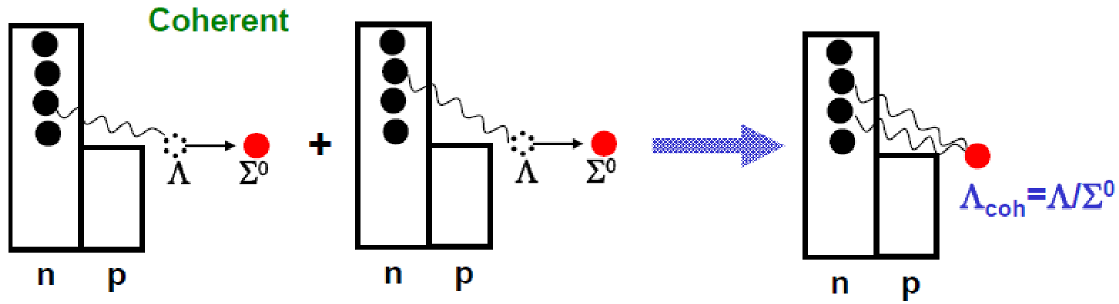


usually included in g-matrix



Single particle potential for Λ_{coh}.





coherent Λ-Σ coupling

The Λ_{coh} mixing is enhanced in the neutron-excess environment.

Production of neutron-rich Λ-hypernuclei with the DCX reaction

E10@J-PARC

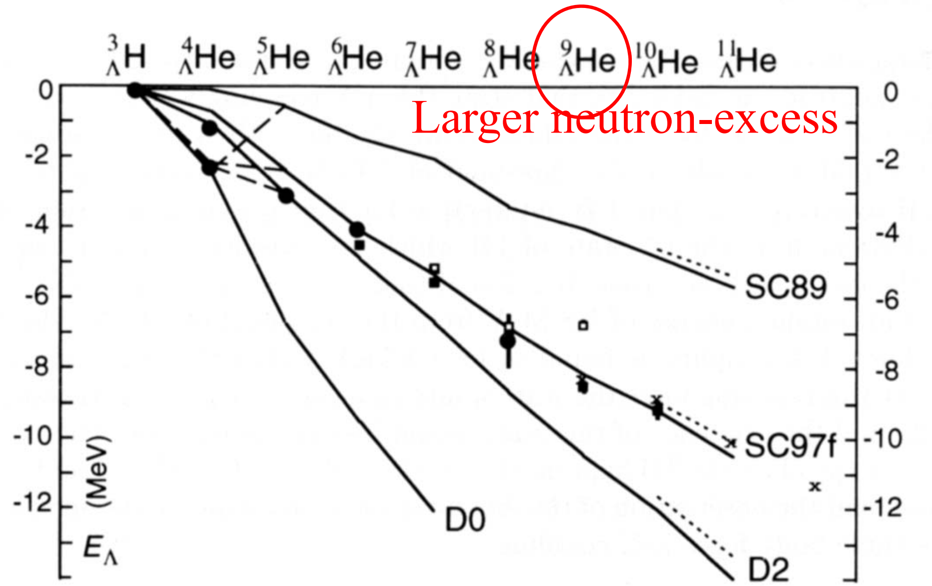
$$^{6}\mathrm{Li}(\pi^-, K^+)\,^{6}_{\Lambda}\mathrm{H}$$

$$^{9}\mathrm{Be}(\pi^-, K^+)\,^{9}_{\Lambda}\mathrm{He}$$

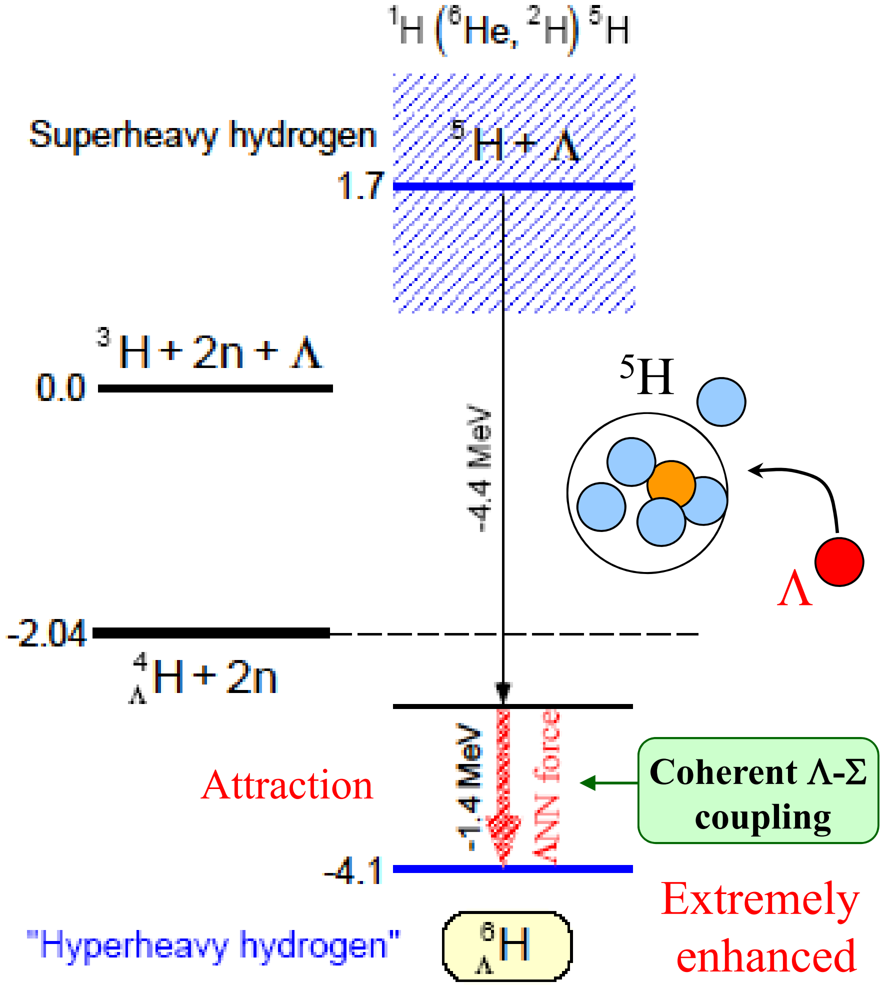
$^{6}_{\Lambda}\mathrm{H}$ "Hyperheavy hydrogen"

Y.Akaishi, NPA738(2004)80c

$^{9}_{\Lambda}\mathrm{He}$ Khin Swe Myint et al., FBS. Suppl. 12(2000)383

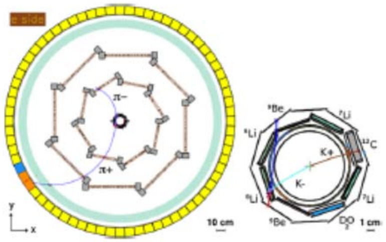


Λ binding energies



- **Coherent Λ-Σ coupling in neutron-excess environment**

First observation of the superheavy hydrogen $_{\Lambda}^{6}H$



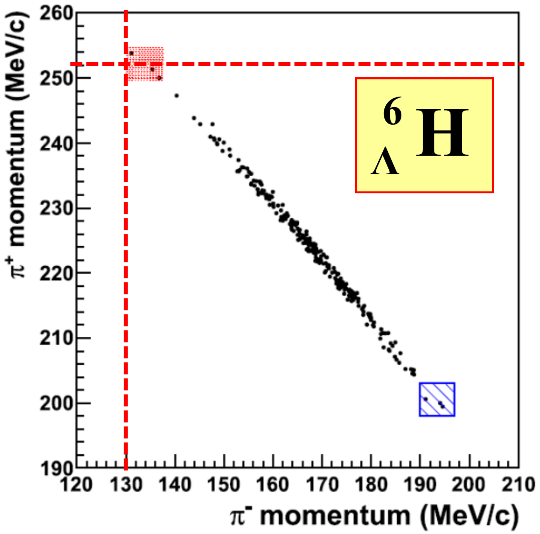
M. Agnello et al., NPA881(2012)269.
M. Agnello, et al., PRL108 (2012) 042501.

- observation of 3 candidate events of $^{6}_{\Lambda}H$ bound state

  B_{Λ} = 4.0 ± 1.1 MeV

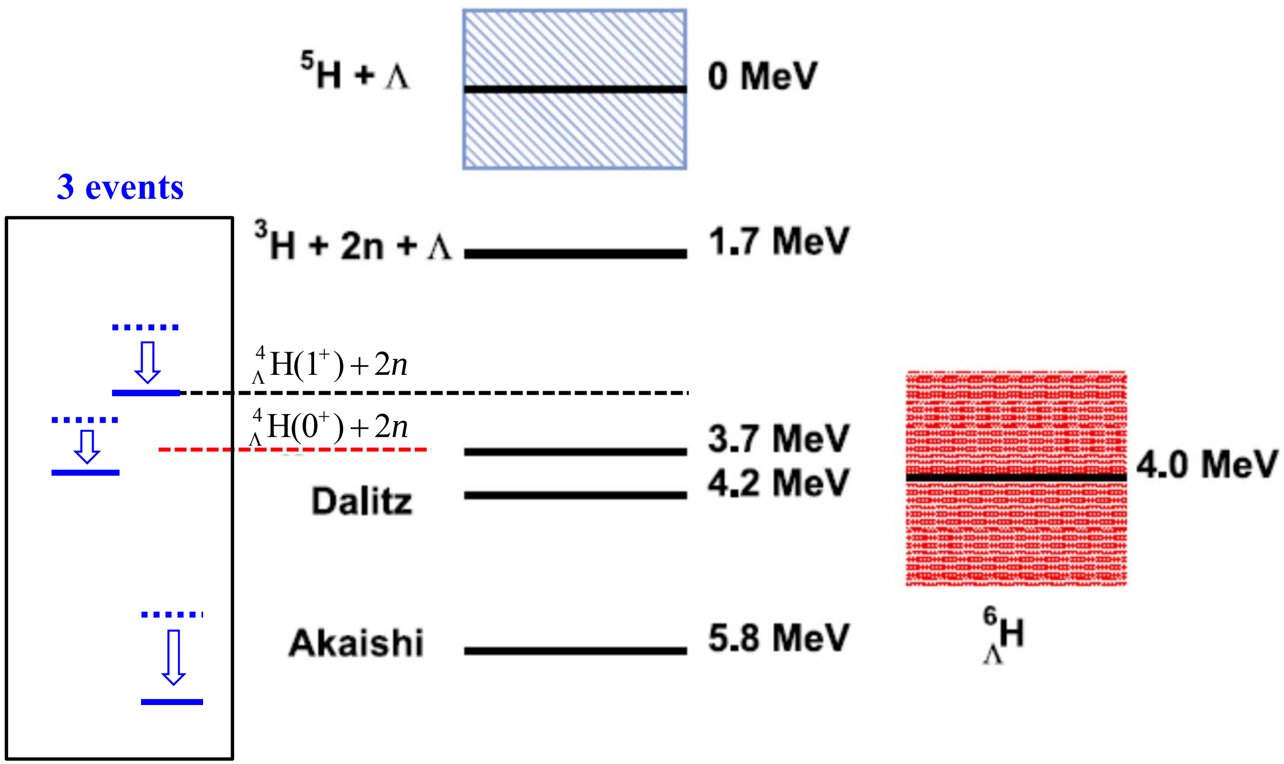
- BR(DCX) / BR(NCX,12LC) ~ 3×10^{-3}

  R = (5.9 ± 4.0) · $10^{-6}/K^{-}_{stop}$



$K^{-}_{Stop} + {}^{6}Li \rightarrow {}^{6}_{\Lambda}H + \pi^{+}$ (252MeV/c)

${}^{6}_{\Lambda}H \rightarrow {}^{6}He + \pi^{-}$ (130MeV/c)

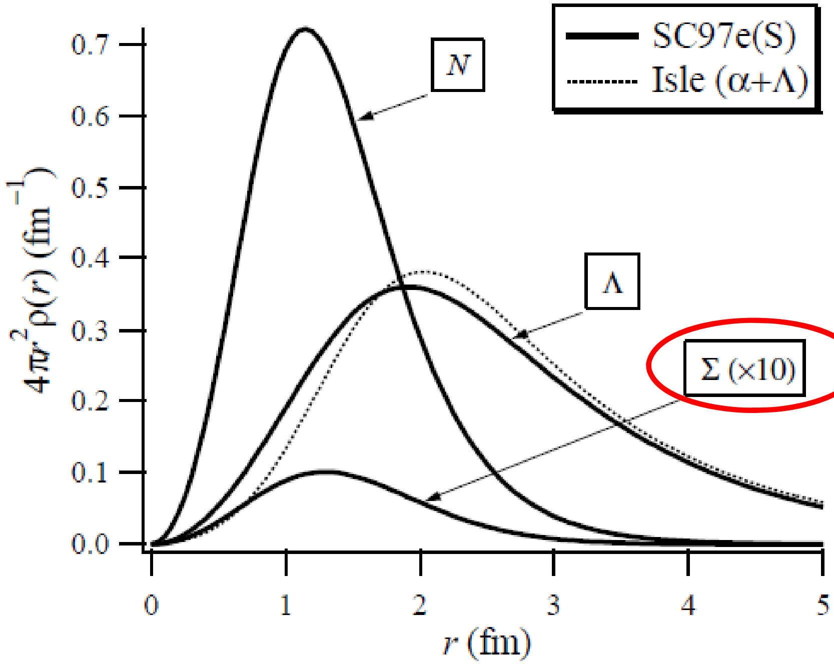


→E10@J-PARC

- Produce neutron-rich hypernuclei: $^{6}_{\Lambda}H$ and $^{9}_{\Lambda}He$
- precise measurement of B.E. of $^{6}_{\Lambda}H$ is possible

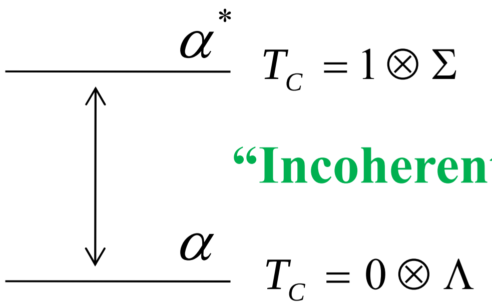
Ab initio calculation of $_{\Lambda}^{5}$He with full realistic interactions

H.Nemura et al., PRL89(2002)142504



Better understanding of the Λ-Σ coupling and Tensor force

Hyperon-mixing



~ 1.5 % admixture

"Incoherent Λ-Σ coupling"

	$L=0$, $S=\frac{1}{2}$, $S_c=0$	$L=0$, $S=\frac{1}{2}$, $S_c=1$	$L=2$, $S=\frac{3}{2}$, $S_c=1$	$L=2$, $S=\frac{3}{2}$, $S_c=2$	$L=2$, $S=\frac{5}{2}$, $S_c=2$
$^{5}_{\Lambda}$He					
$(T_c=0)\otimes\Lambda$	89.14	0.03	0.19	3.74	5.36
$(T_c=1)\otimes\Sigma$	0.10	0.09	1.34	~ 0	0.01
^{4}He	89.56			10.44	

-The Σ admixture of ~1.5 % appears in $^{5}_{\Lambda}$He.

-The α-particle is not a rigid core.

The incoherent Σ admixture is also important.

The Λ-Σ coupling effect in $^{10}_{\Lambda}$Li hypernucleus

microscopic shell model

Σ- mixing probability

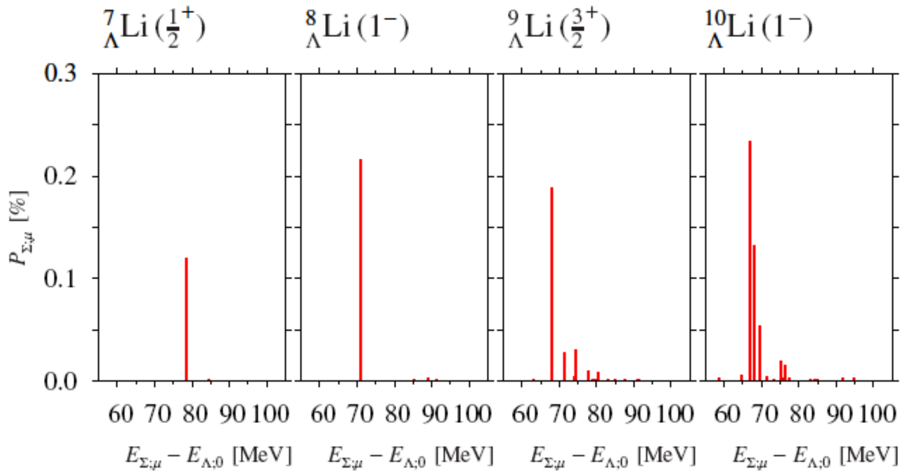
P($^{10}{}_{\Lambda}$Li) = 0.48 %, ΔE=0.33 MeV

(1) コヒーレントな Fermi型 and GT型結合

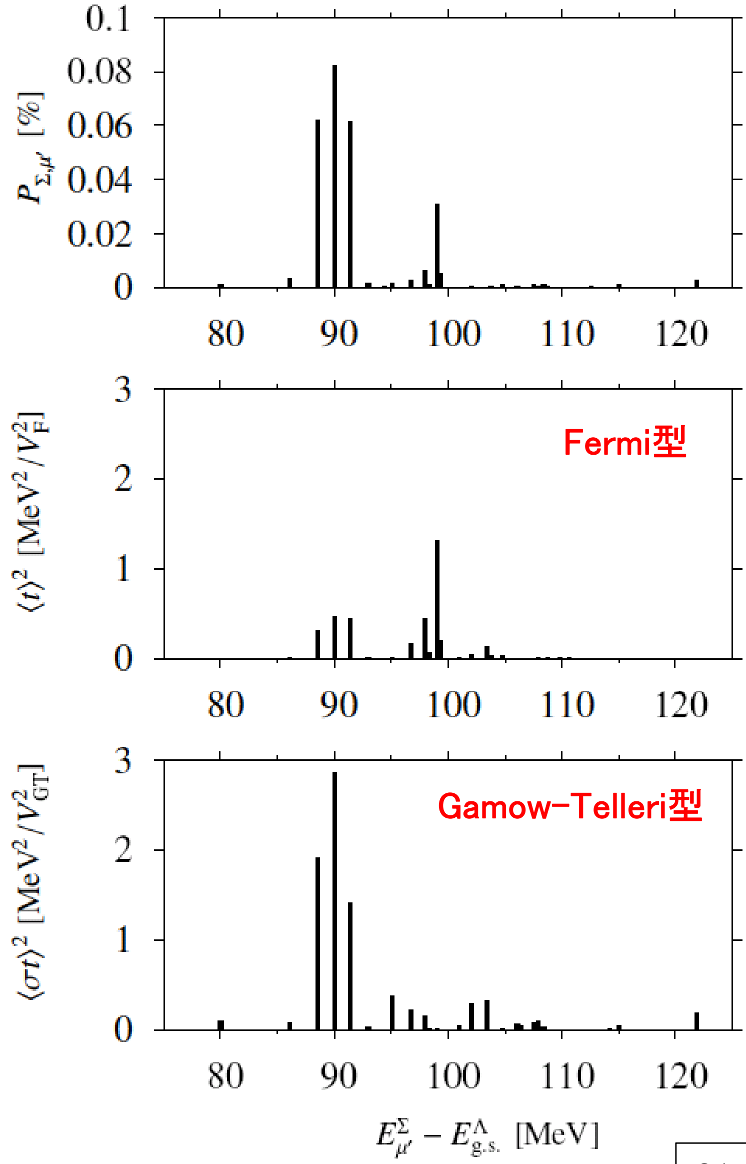
(2) 中性子過剰核ではT(T+1)に比例

(3) $^{7}{}_{\Lambda}$Liに比較して5倍大きい

$^{7}_{\Lambda}$Li, $^{8}_{\Lambda}$Li, $^{9}_{\Lambda}$Li, $^{10}_{\Lambda}$Li の基底状態におけるΛ-Σ 結合強度

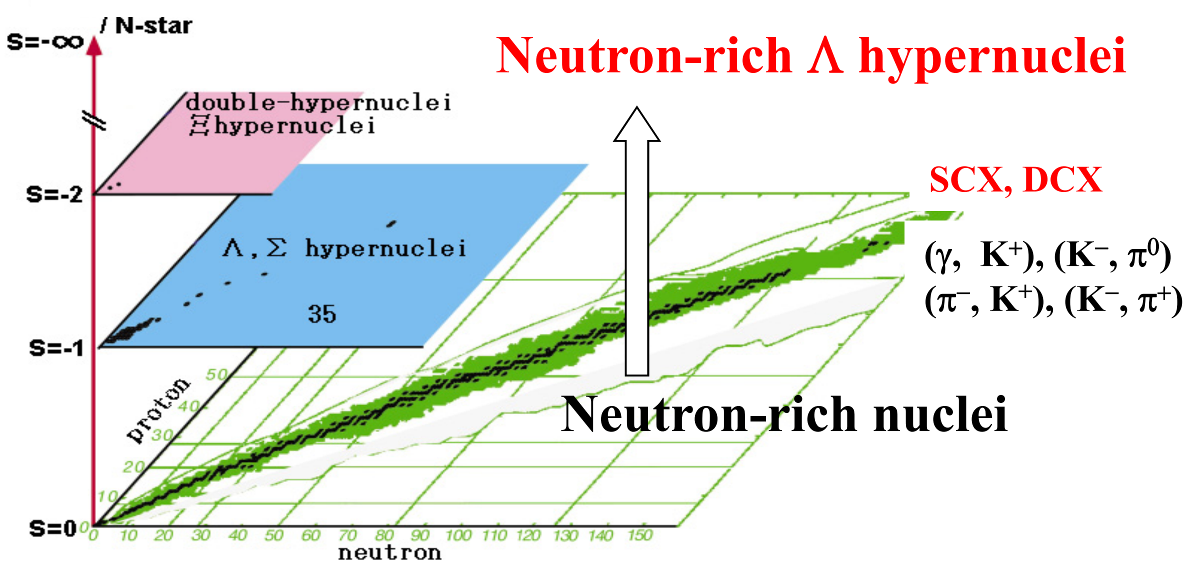


Umeya, Harada, PRC79(2009)024315



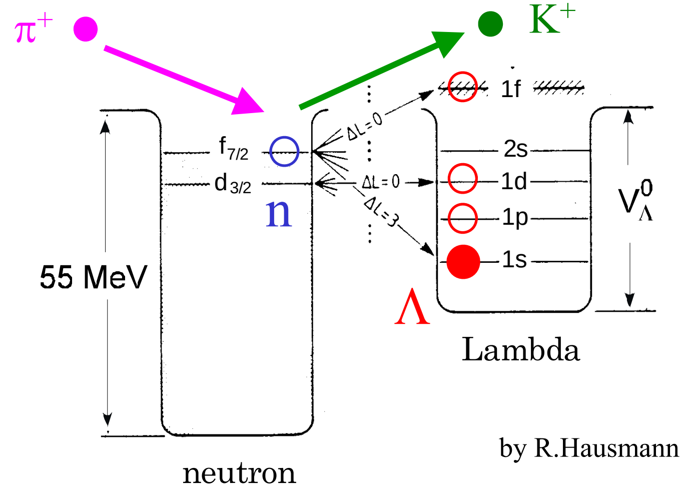
中性子過剰Λハイパー核の生成

E10@J-PARC

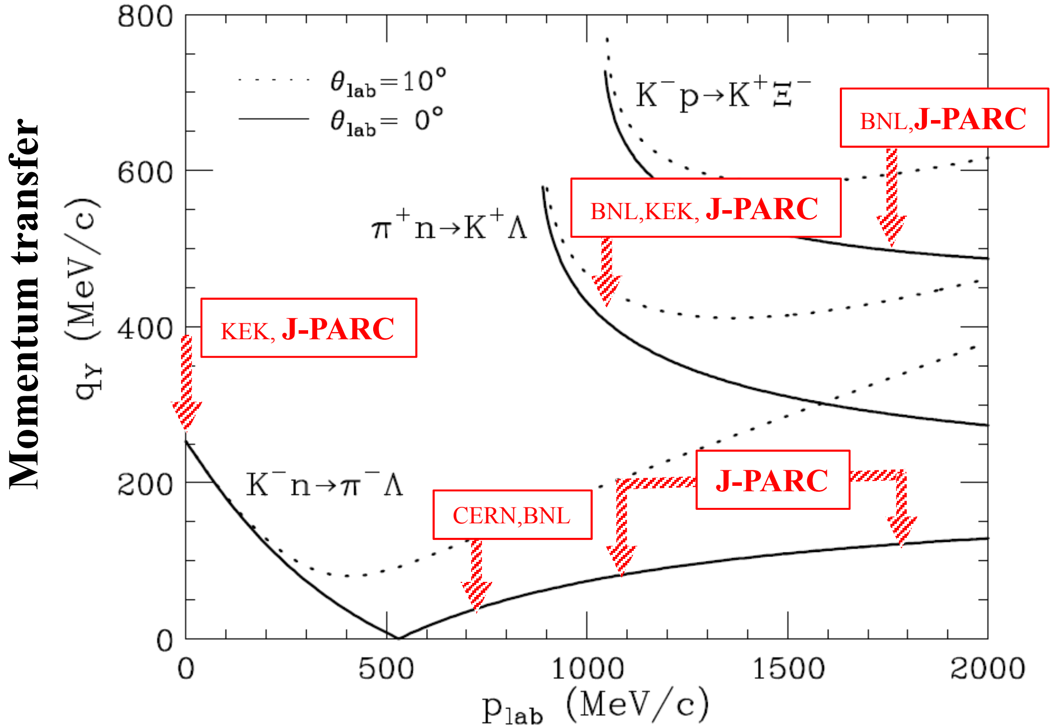


Hypernuclear Production Reactions

(π^+,K^+) reaction

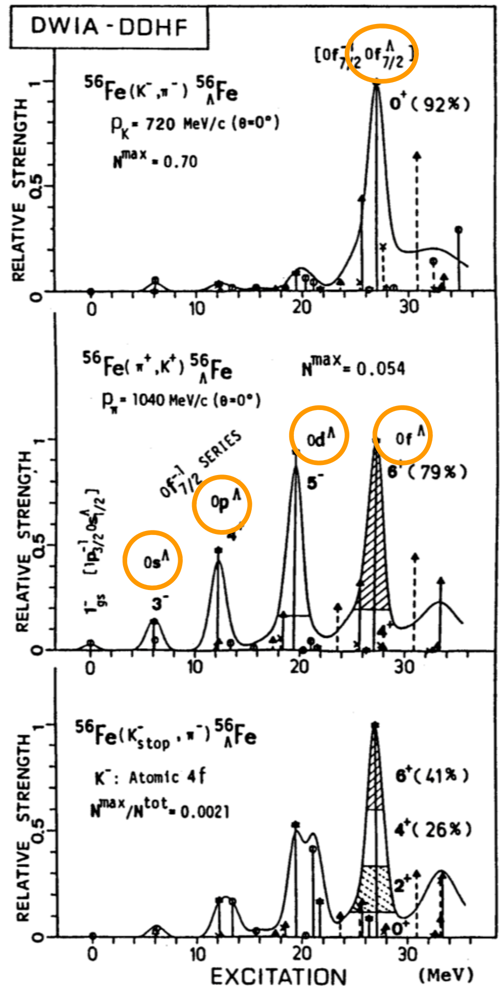


by R.Hausmann and W.Weise



Theoretical calculations ^{56}Fe target

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



(K^-,π^-)
720 MeV/c

q_Λ ~60-100MeV/c

"Substitutional"

$\Delta\ell$ □ 0

(π^+,K^+)
1040 MeV/c

q_Λ~400MeV/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_Λ~280MeV/c

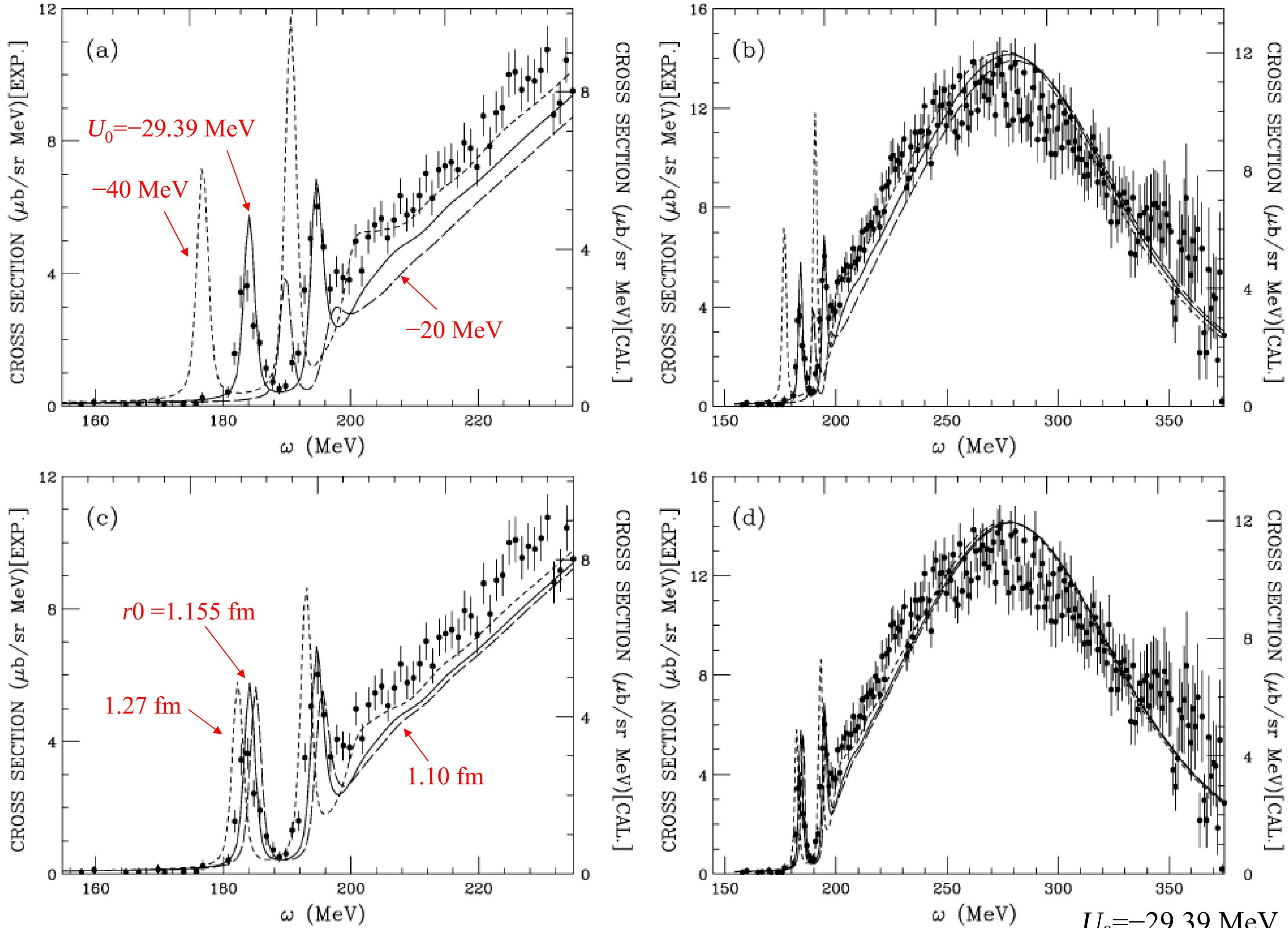
^{12}C

Λ spectrum by (π^+,K^+) reaction at 1.2 GeV/c (6°)

Harada, Hirabayashi, NPA744 (2004) 323.

Sensitivity of the spectrum to the Λ–nucleus potential parameters

r_0 = 1.155 fm

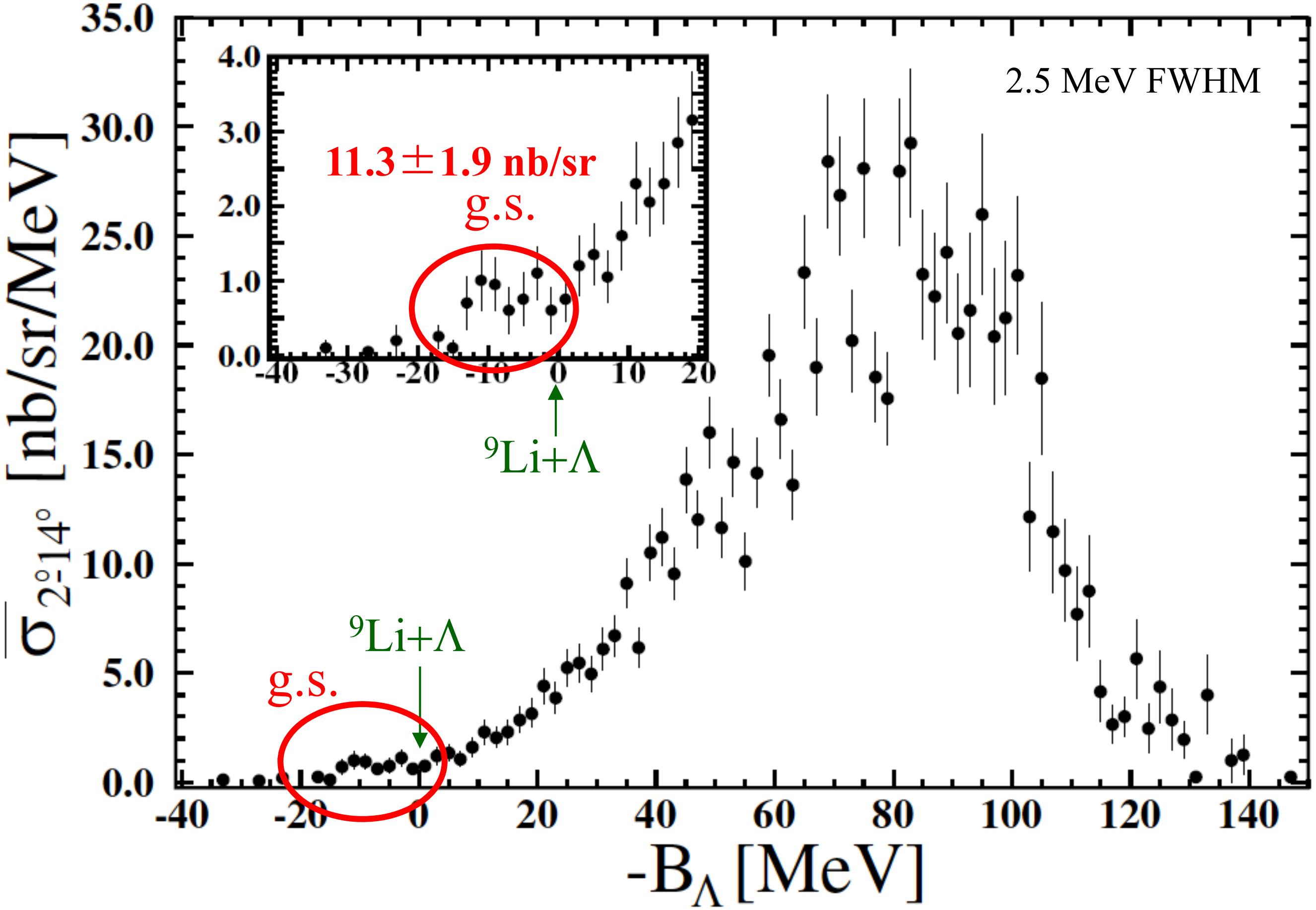


U_0=−29.39 MeV

First production of neutron-rich Λ hypernuclei

$^{10}\mathrm{B}(\pi^-,K^+)^{10}_{\Lambda}\mathrm{Li}$ Λ spectrum by DCX (π^-,K^+) reaction at 1.2GeV/c

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



Cross sections

- p_π=1.20 GeV/c

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

- p_π=1.05 GeV/c

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

~1/1000

$^{12}\mathrm{C}(\pi^+,K^+)^{12}_{\Lambda}\mathrm{C}$ (1.2 GeV/c)

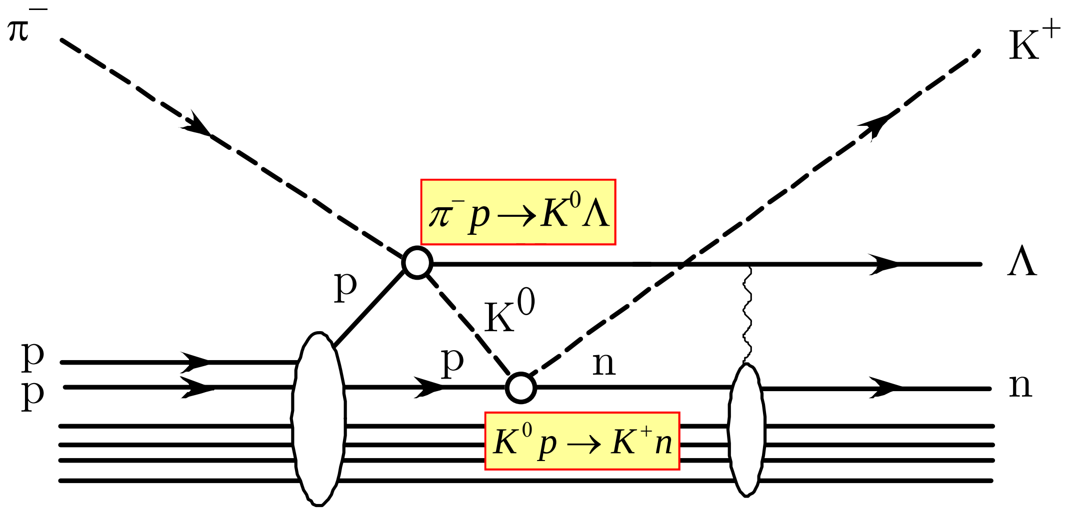
17.5±0.6 μb/sr

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

***Two-step process*:**

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

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

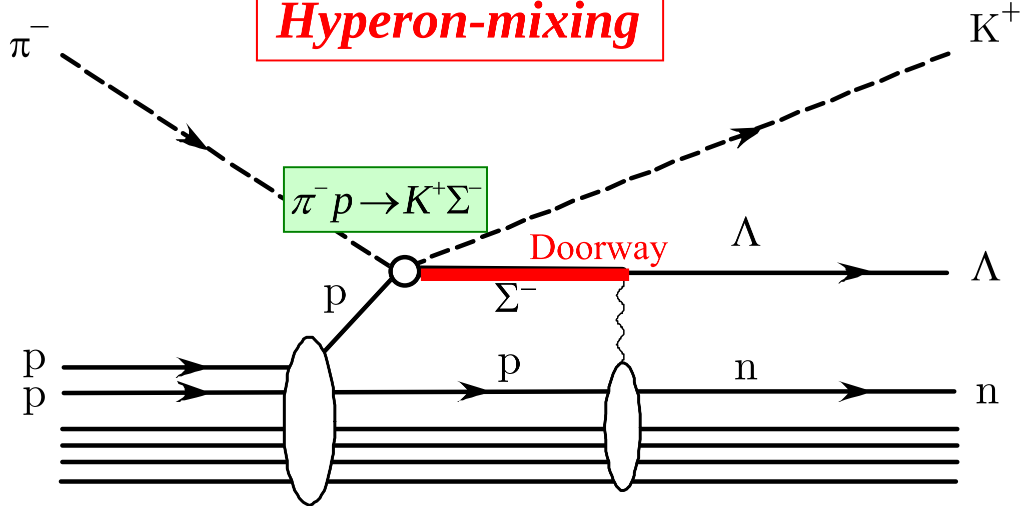


***One-step process*:**

$$\pi^- p \rightarrow K^+ \Sigma^-$$
$$\Sigma^- p \leftrightarrow \Lambda n$$

via Σ^- doorways caused by ΛN-ΣN coupling

Hyperon-mixing



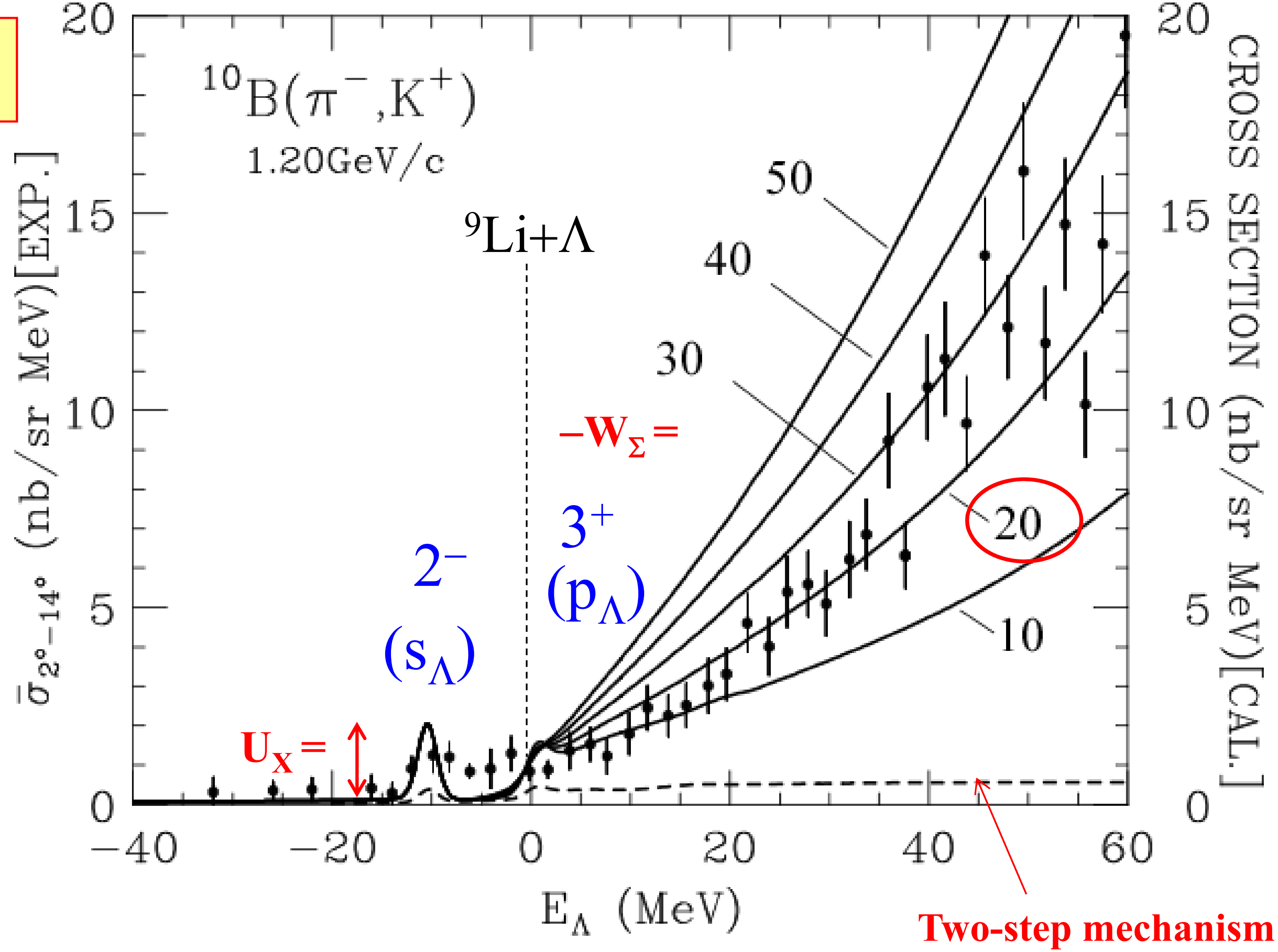
Λ spectrum by DCX (π^-,K^+) reactions at 1.2GeV/c

Harada, Umeya,Hirabayashi, PRC79(2009)014603

Spreading potential dep. W_Σ

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

^{10}B



Λ spectrum by DCX (stopped K^-, π^+) reactions

If the Σ^- admixture probability of ~0.6 % is assumed in $^{12}{}_{\Lambda}Be$, we demonstrate the (stopped K^-,π^+) spectrum on a ^{12}C target.

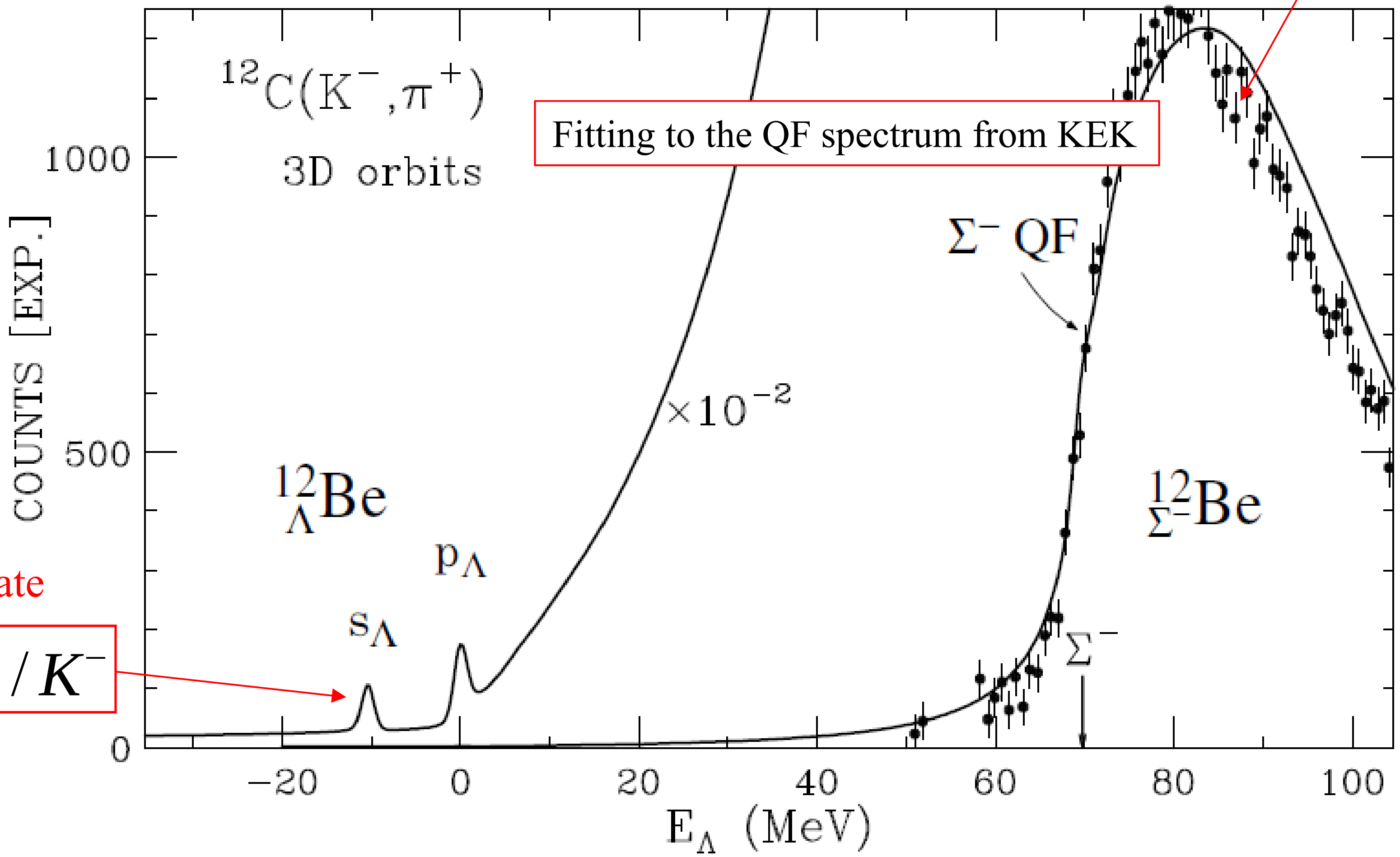
^{12}C

Early KEK data

Fitting to the QF spectrum from KEK

Integrated production rate

$\sim 4\times10^{-6} / K^-$



DAΦNE data: U.L. $(2.0\pm0.4)\times10^{-5} / K^-$ M.Agnello, et al.,PLB640(2006)145.

4. まとめ

核物質中のΣハイペロン

- ΣN $^3S_1$ [10*]: Strangeness partner of deuteron
- Repulsive core: Quark Pauli forbidden states [51]
- ΛNN three-body force: ΛN-ΣN coherent coupling
- Production of neutron-rich Λ hypernuclei: Σ doorways
- Magnetic moments
- ....

■Keywords

Hyperon mixing + DCX

Conclusion

Studies of
the production and spectroscopy of
strangeness nuclei are
very interesting and exciting
at J-PARC.

- ストレンジネスが拓く新しい状態の発見、”エキゾチック”な原子核
- バリオン-バリオン間相互作用の理解、短距離斥力の起源
- ハイペロン混合と中性子星の2大問題

⇩

中性子星物質の状態方程式の解明

Thank you very much.