基研研究会「ハドロン物質の諸相と状態方程式
-- 中性子星の観測に照らして ---」
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京大基研，京都市

ストレンジネス核物理と中性子星

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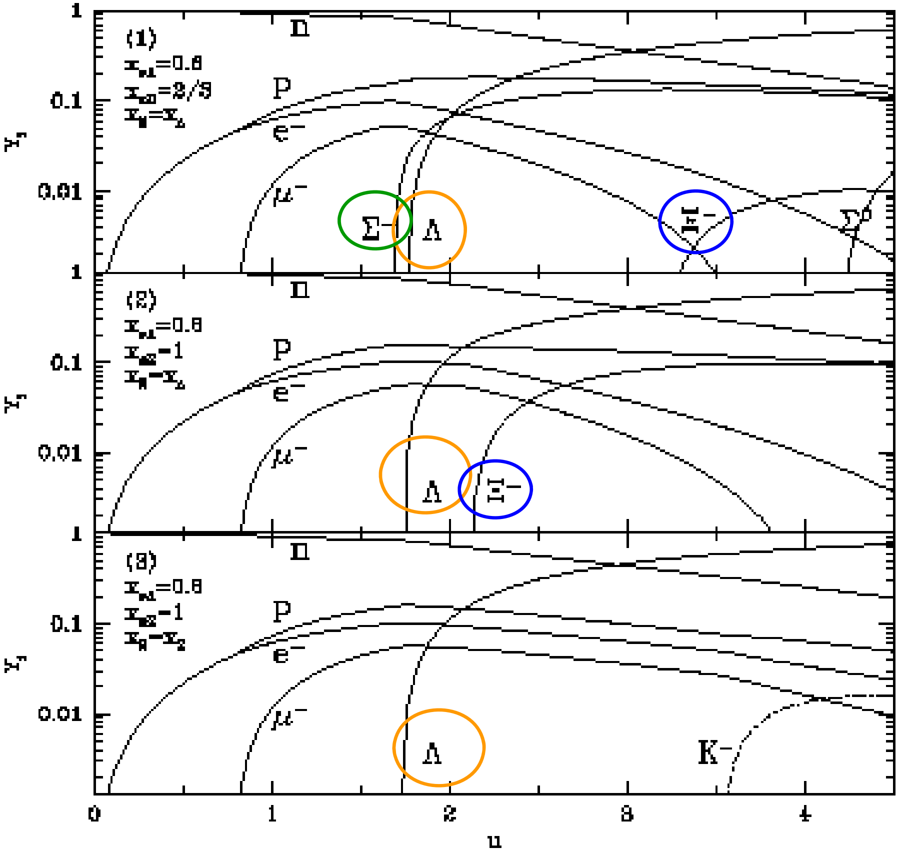
Neutron star core

= "An interesting neutron-rich hypernuclear system"

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

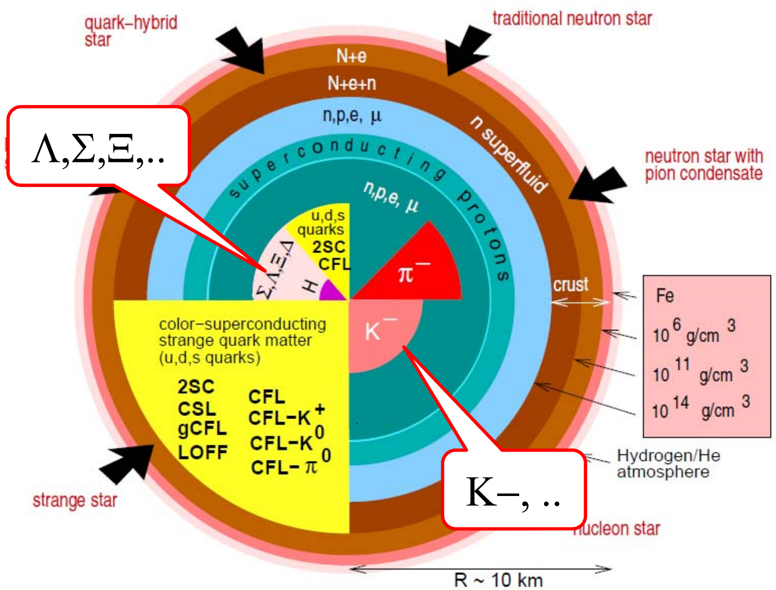


$U_\Sigma < 0$
$U_\Xi < 0$

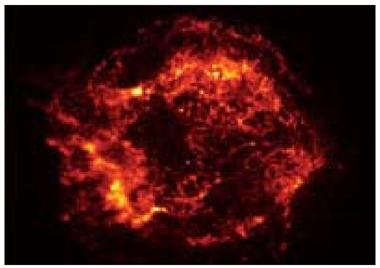
$U_\Sigma > 0$
$U_\Xi < 0$

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

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



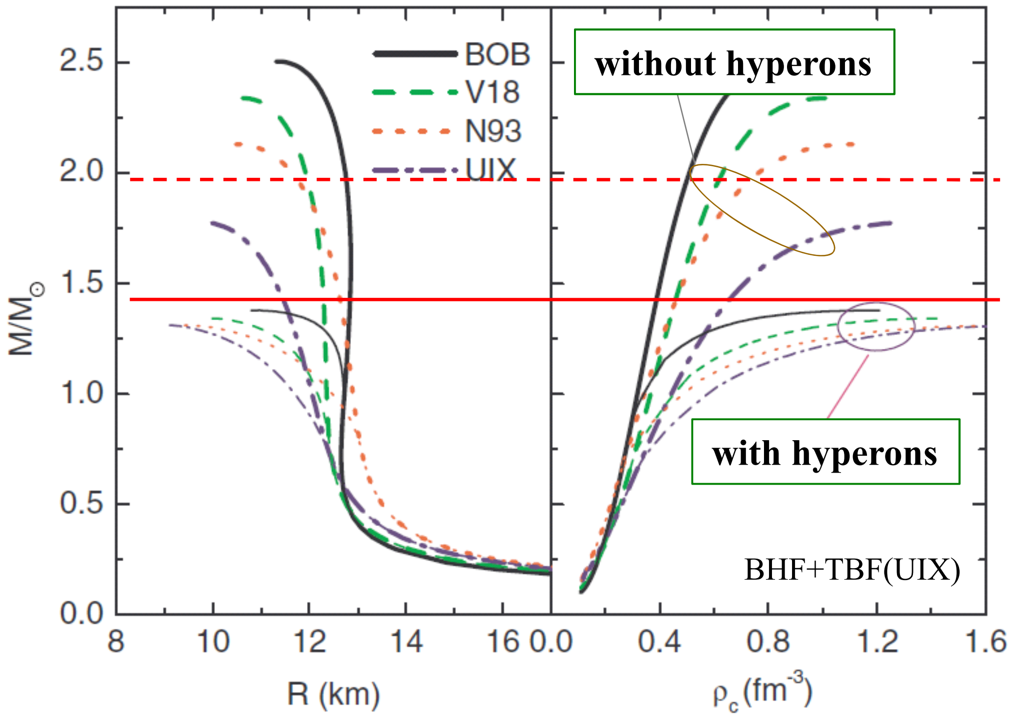
[F. Weber, PPNP 54(2005)193]



Cassiopeia A nebula
NASA/CXC/SAO.

Hyperon-mixing

Neutron Stars and EOS



BHF

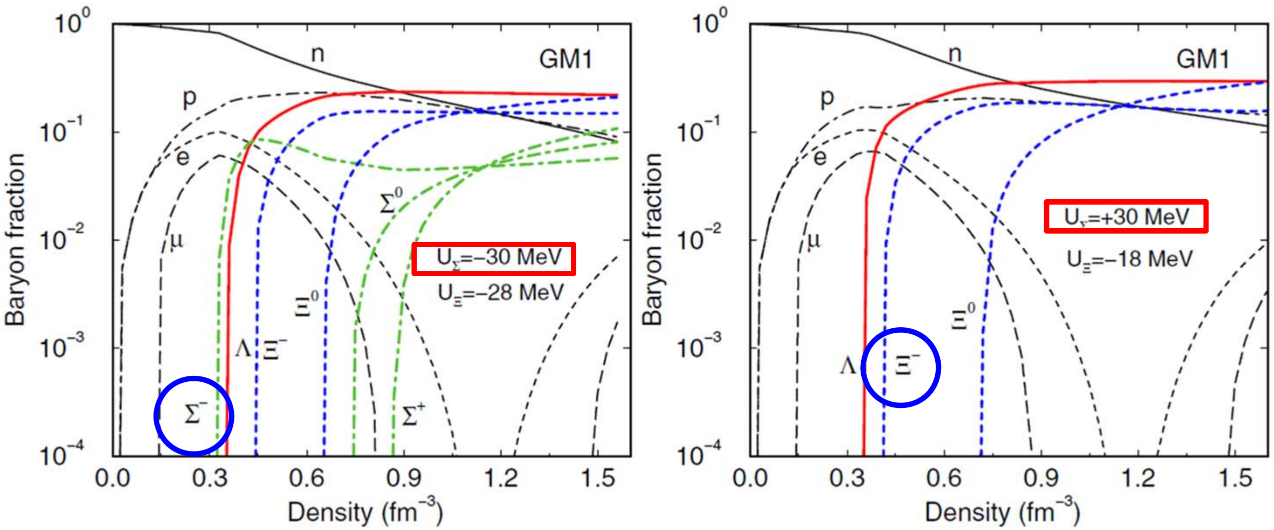
Z.H.Li, H.-J.Schulze,
PRC 78 (2008) 028801

$1.97M_\odot$ ← PSR J1614-2230

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

$1.44M_\odot$

最大質量/半径



RMF

J. Schaffner-Bielich,
NPA 835 (2010) 279

hyperon s.p. pot.

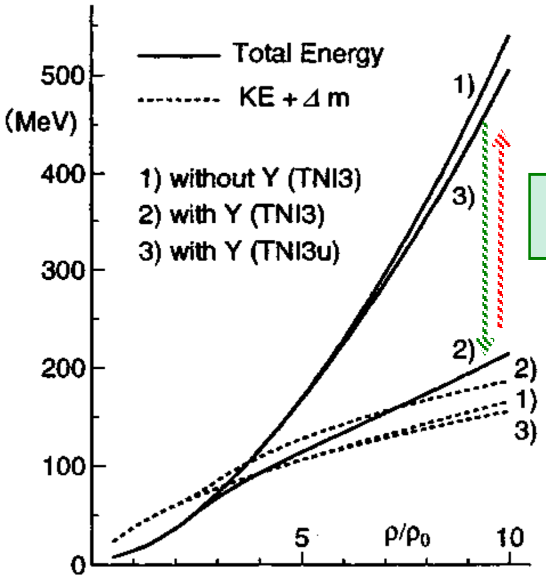
➡ ハイペロン混合に
よって強く影響

Hyperons and massive neutron stars

Softening on the EOS

RMF

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

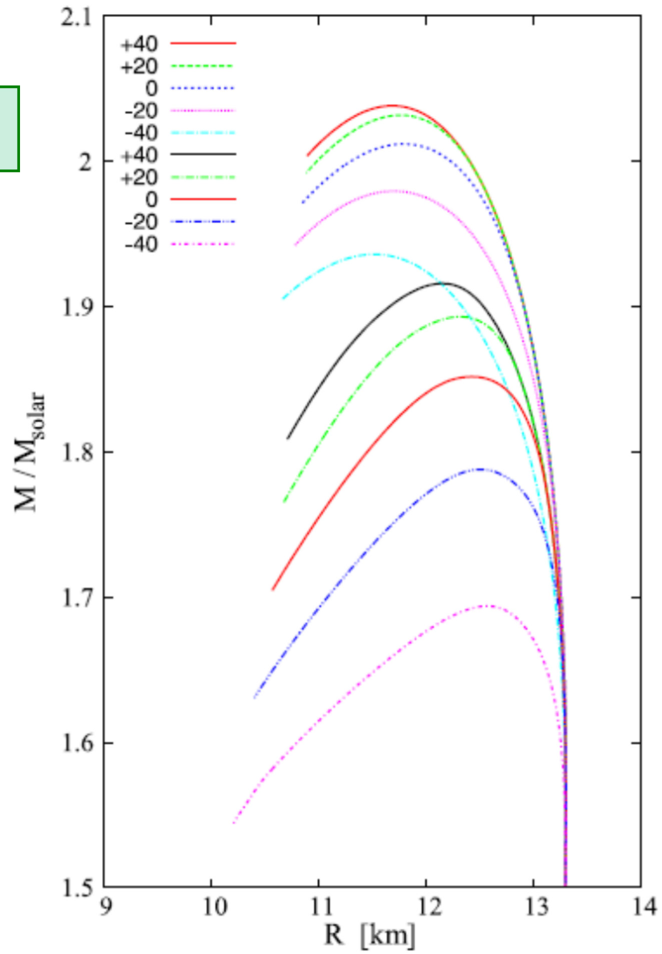
$n_C(Y) \approx (2-3)n_0$

YN,YY: extra repulsion TNIu

$M_{\max} > M_{\rm OBS}$ $n_C(Y) \approx (4-5)n_0$

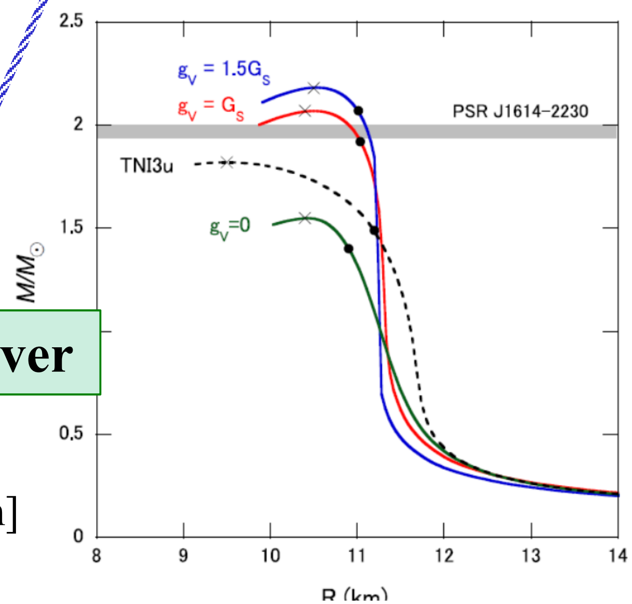
The role of hyperon potentials

S. Weissenborn, et al.,NPA881(2012)62.



Hadron-Quark crossover

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



Thermal evolution of neutron stars

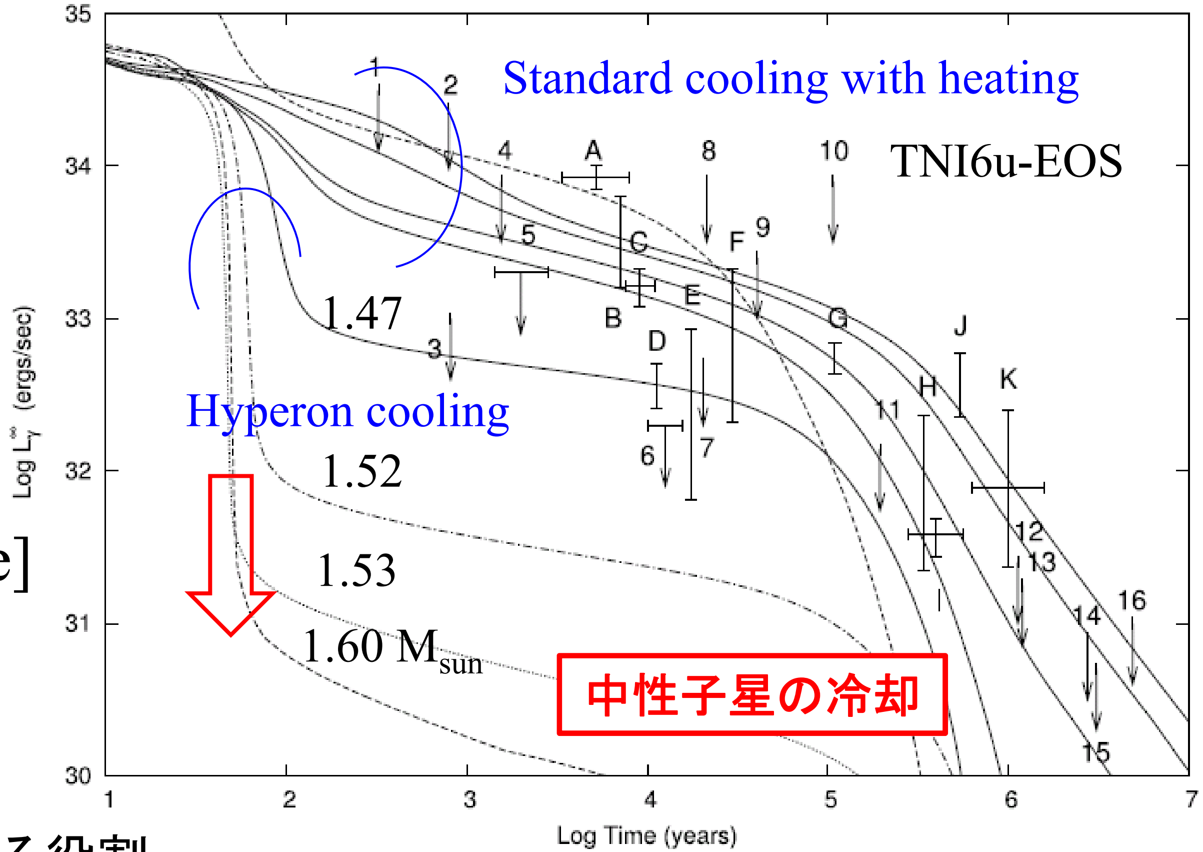
Rapid neutrino emission
via weak processes
(Direct/Modified Uruca)

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

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

- Cooper pair
  - $^1S_0$ [iner crust]
  - $^3P_2$-$^3F_2$(n), $^1S_0$(p) [core]
  - → Standard cooling
- YY pairing
  - → Hyperon cooling
  - Rapid coolingを抑制する役割

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



- Hyperon superfluidity v.s. YY intarctions
  - Nagara event $\Delta B_{\Lambda\Lambda}$~0.7 MeV → no ΛΛ superfluidity ?

YN, YY相互作用の性質によって強く依存する

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, …

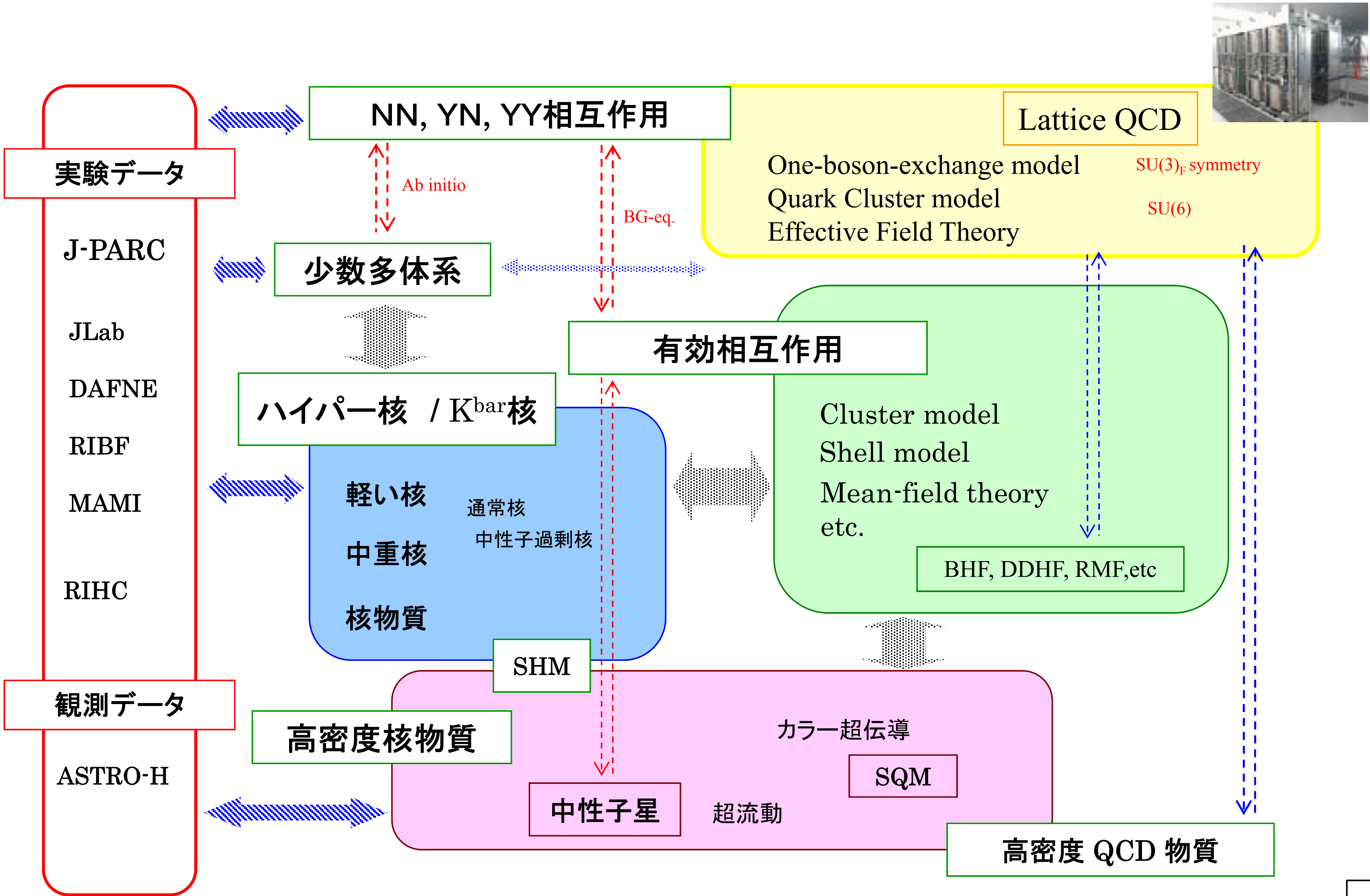
    ←Serious Problems from hyperon-mixing (Takatsuka)

“Hyperon-mixing” で探る

ストレンジネス核物理の展開

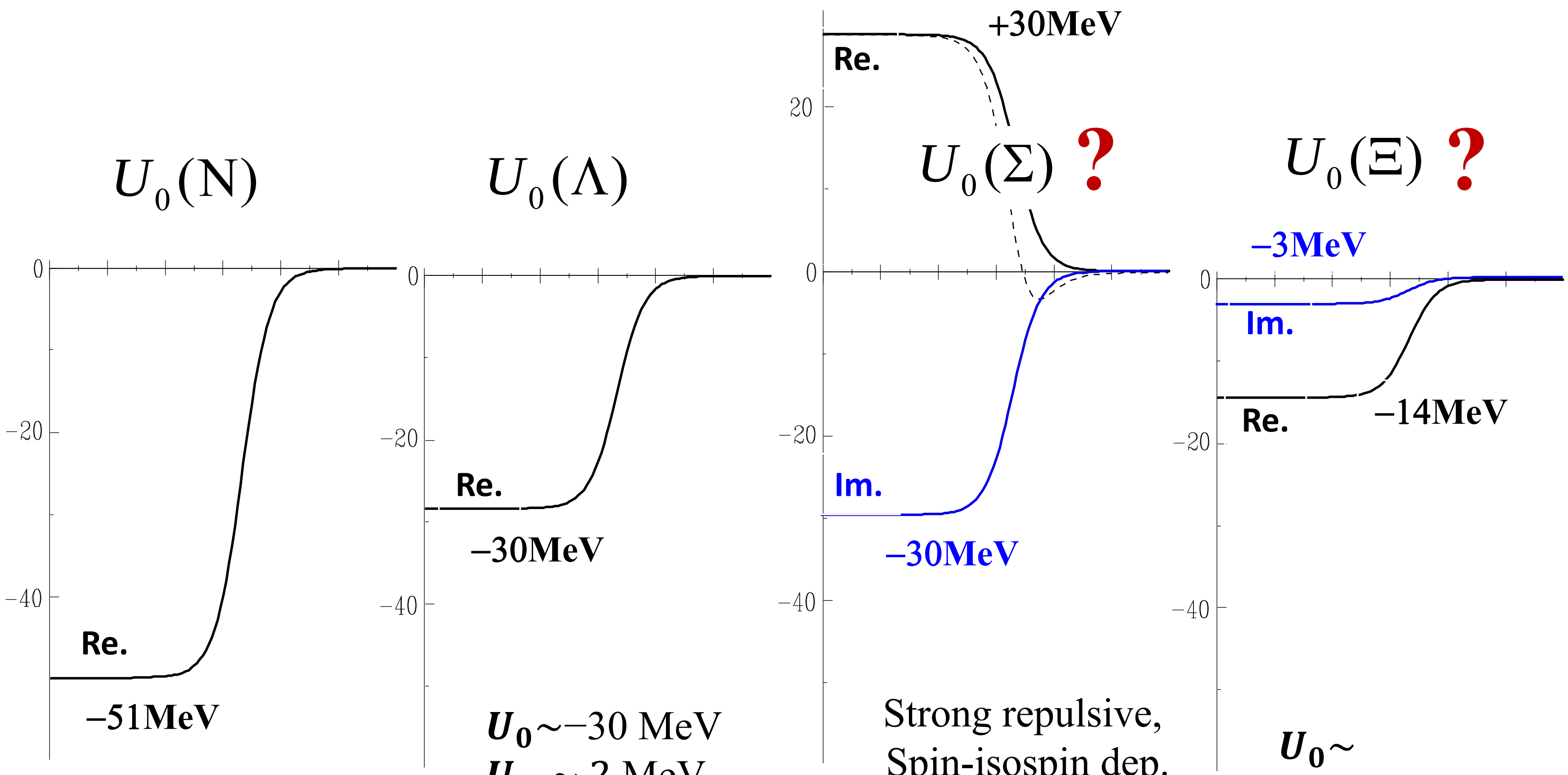
by E.Hiyama

“QCD,核力から核構造へ”と“核構造からQCD,核力へ”



Our understanding of hyperon s.p. potentials

N	Λ	Σ	Ξ



N:
U_0~−51 MeV
U_{LS}~ 22 MeV

Λ:
U_0~−30 MeV
U_{LS}~ 2 MeV

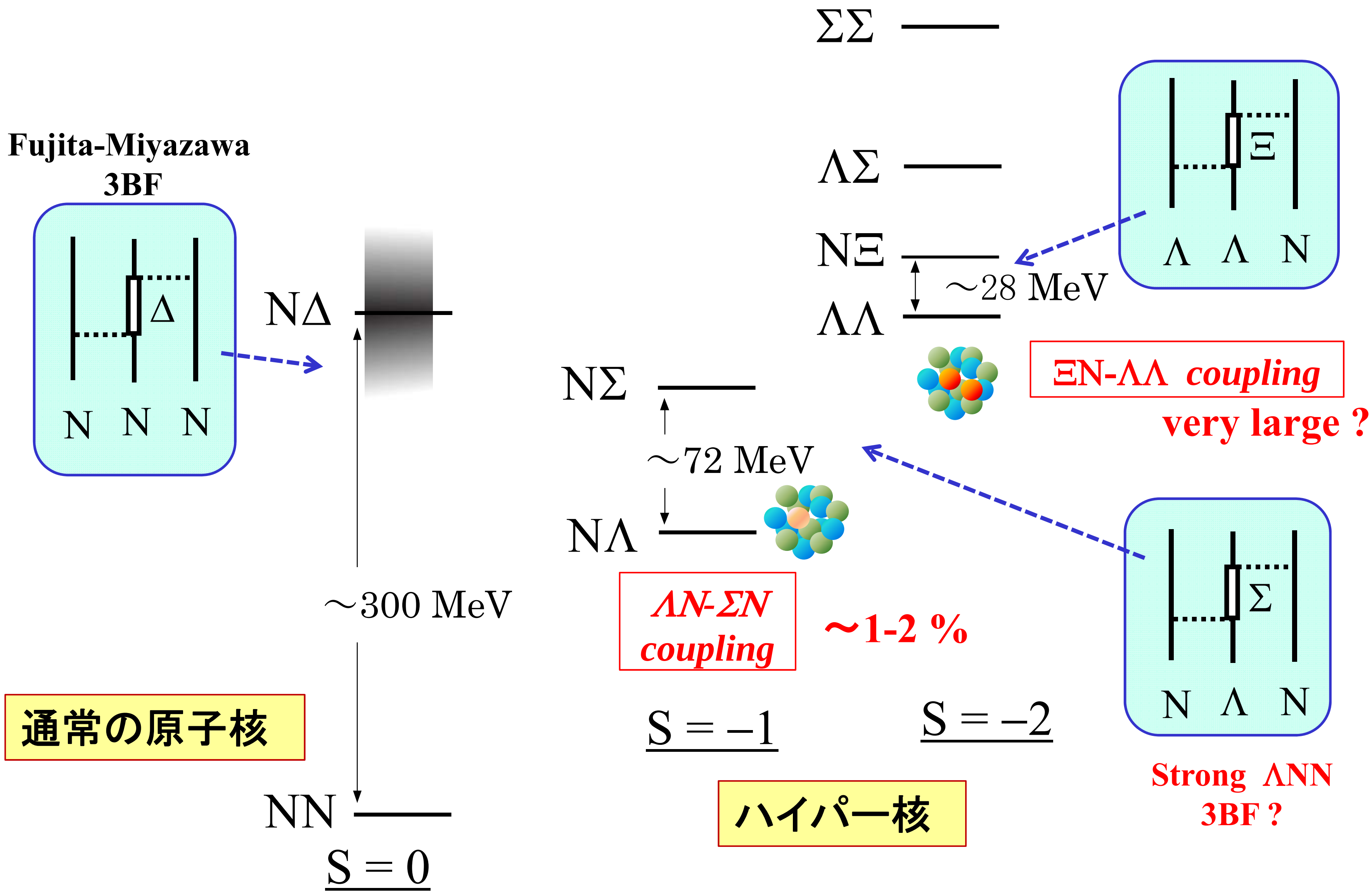
ΛΛN 3BF ?
Σ mixing Prob.?

Σ:
Strong repulsive,
Spin-isospin dep.

U_0~+30 MeV
U_{LS} ?, Σ width ?

Ξ:
U_0~
(−14)□(0)MeV ?
Ξ width ?
ΛΛ-ΞN mixing ?
H-particle ?

Dynamics in Strangeness Nuclear Systems



- ハイペロン混合による多彩な振る舞い
- 核内における3体力 (3BF)の役割

2. S＝−1の原子核

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

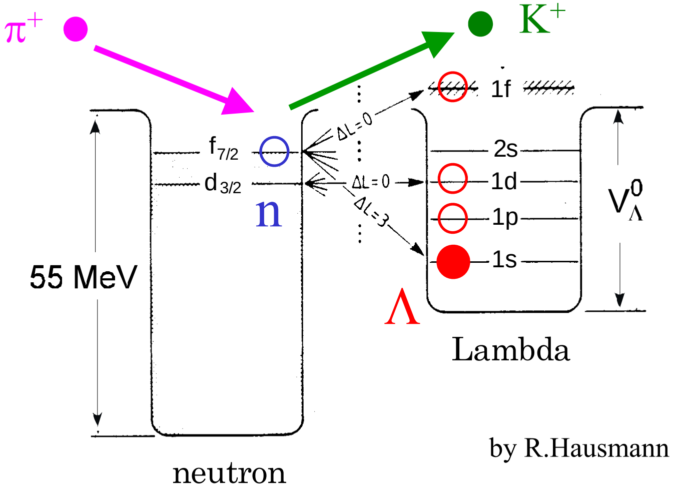
- Overbinding Problem on s-Shell Hypernuclei

- 中性子過剰ハイパー核

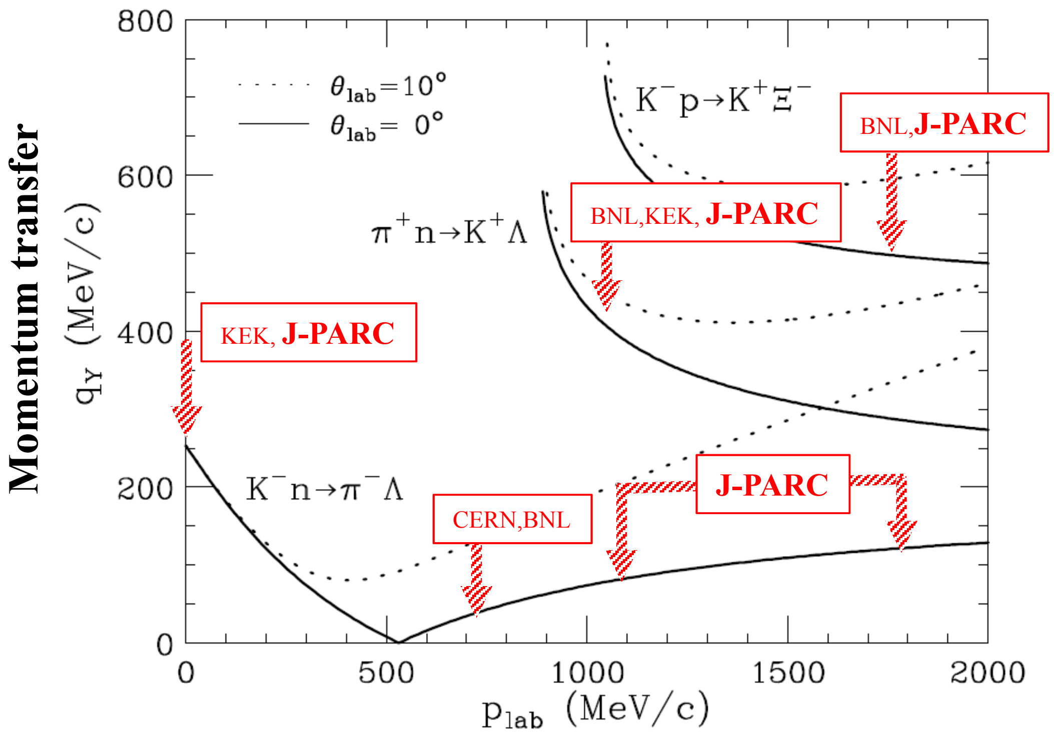
- Λハイパー核の弱崩壊

Hypernuclear Production Reactions

(π^+,K^+) reaction

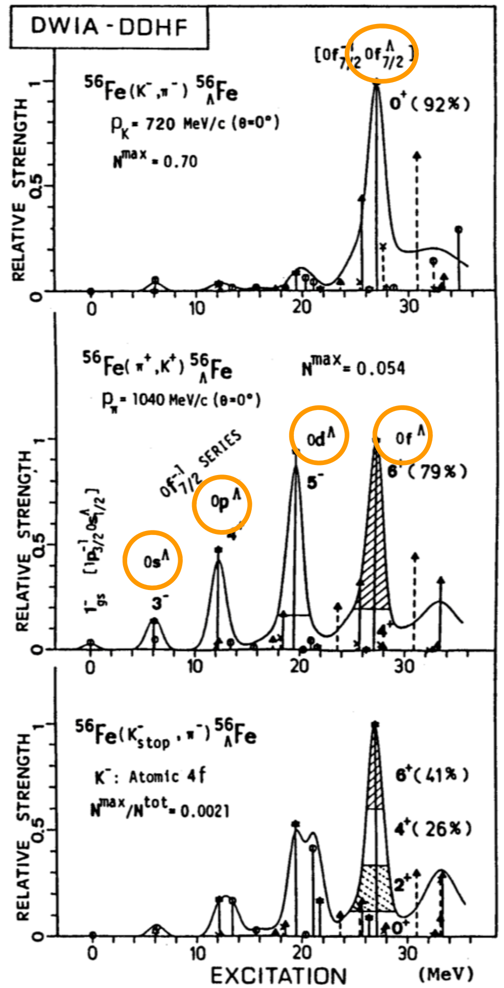


by R.Hausmann and W.Weise



Theoretical calculations ^{56}Fe target

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



(K^-,π^-)
720 MeV/c

$q_\Lambda \sim$60-100MeV/c

"Substitutional"

$\Delta\ell \simeq 0$

(π^+,K^+)
1040 MeV/c

$q_\Lambda \sim$400MeV/c

"Spin-Stretched"

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

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

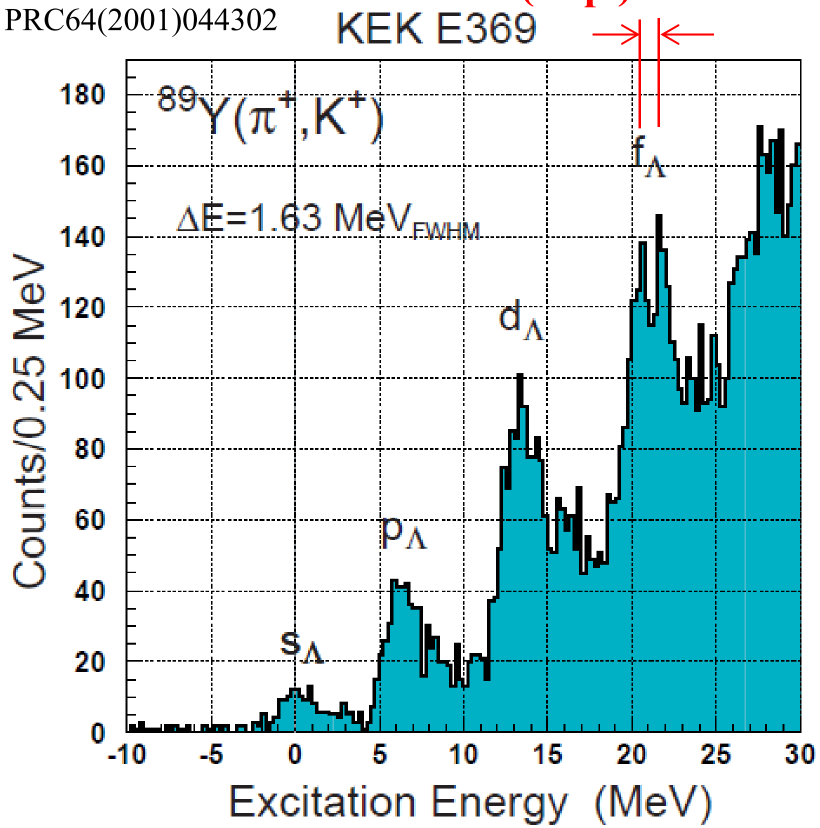
(K^-,π^-)
Stooped K-

$q_\Lambda \sim$280MeV/c

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

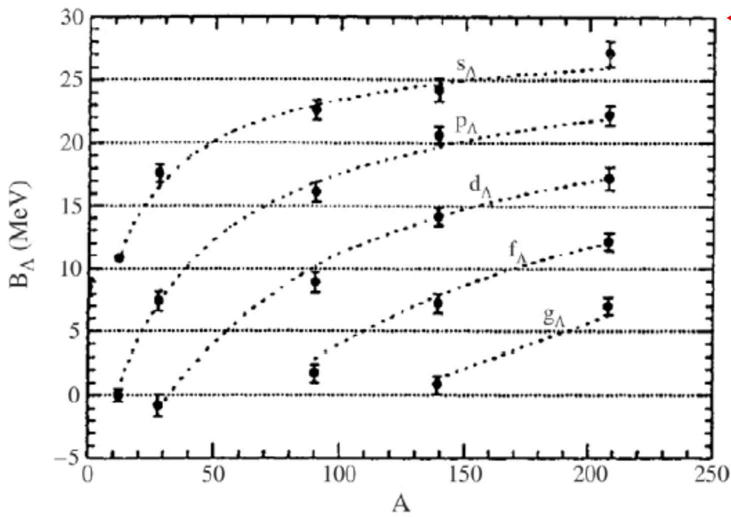
H. Hotchi et al., PRC64(2001)044302

(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_Λ ?



$V_0^\Lambda \simeq -30$ MeV

$(A \to \infty)$

$a = 0.6$ fm

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

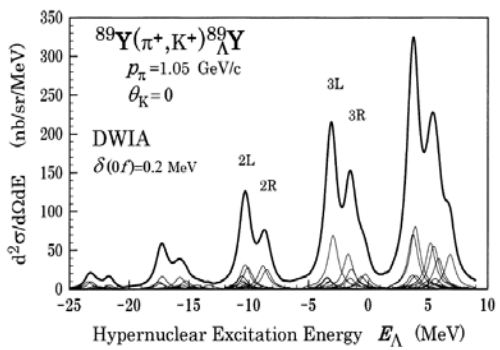
WS analysis

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

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

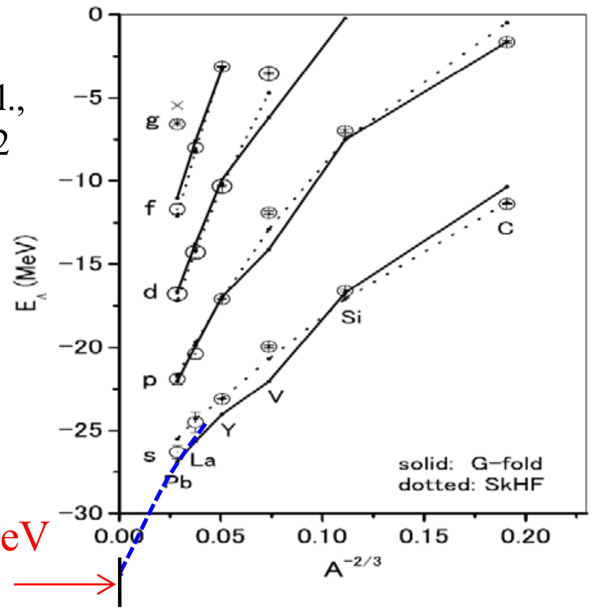
SM analysis
- ΛN^{-1} particle-hole ex.
- inter-shell coupling

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



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

G-matrix folding model



$V_0^\Lambda \simeq -37.2$ MeV

$(A \to \infty)$

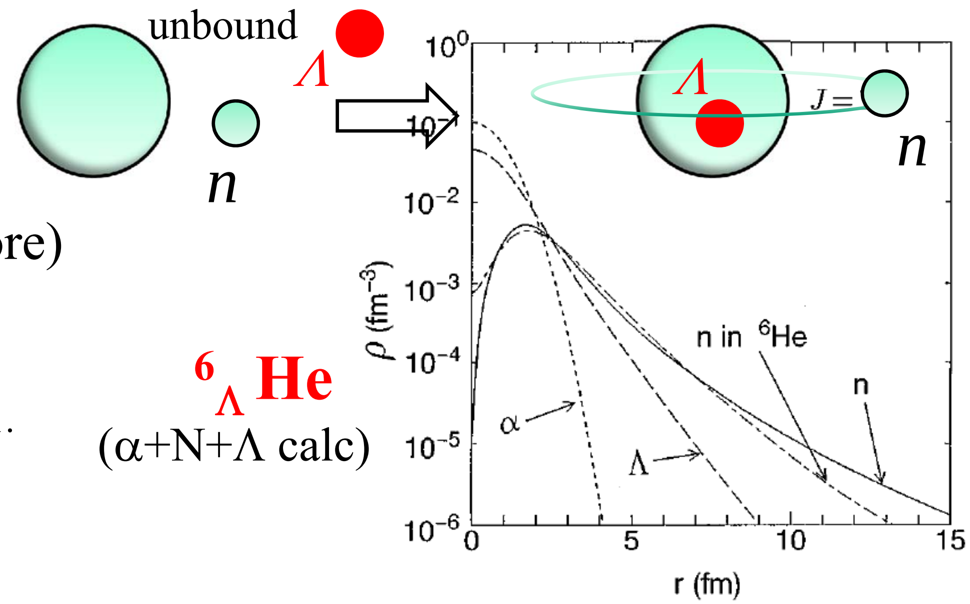
Role of the Λ-hyperon in nuclei

"gule"

T. Motoba, et al.,PTP70(1983)189
E. Hiyama, et al.,PRC59(1999)2351

- Shrinkage effects (19% for the ^{6}Li core)
- neutron-skin or neutron halo

E. Hiyama, et al.,PRC59(1999)2351
Tretyakova, Lanskoy, EPJ.A5(1999) 391.

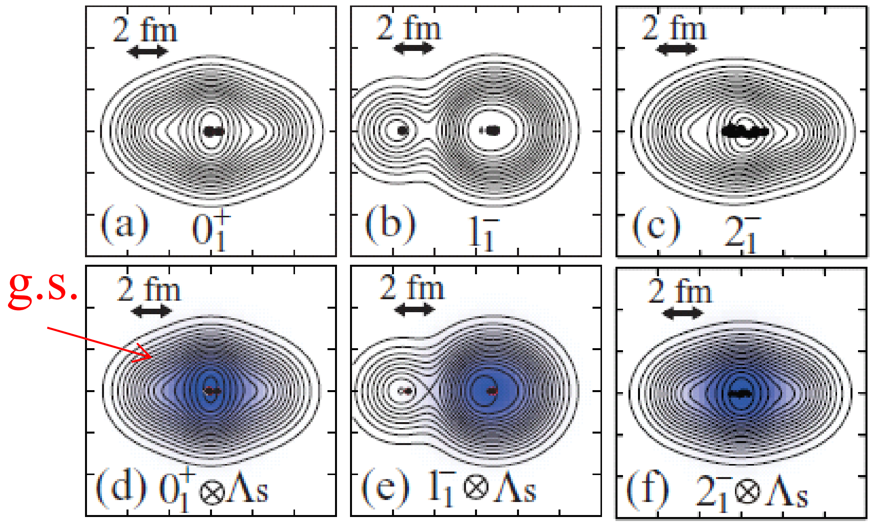


$^{6}_{\Lambda}$**He**
(α+N+Λ calc)

"Stabilizing"+"Deformation"

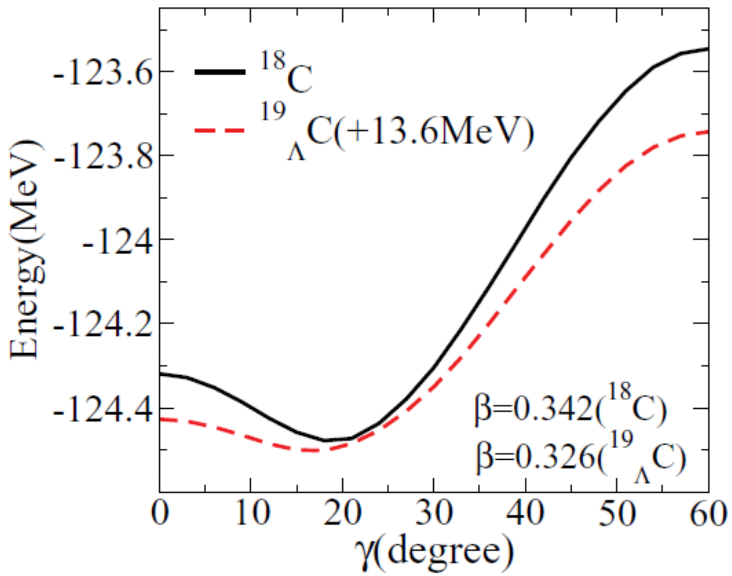
$^{21}_{\Lambda}$Ne, $^{25}_{\Lambda}$Mg (AMD)

M. Isaka et al, PRC83(2011)054304



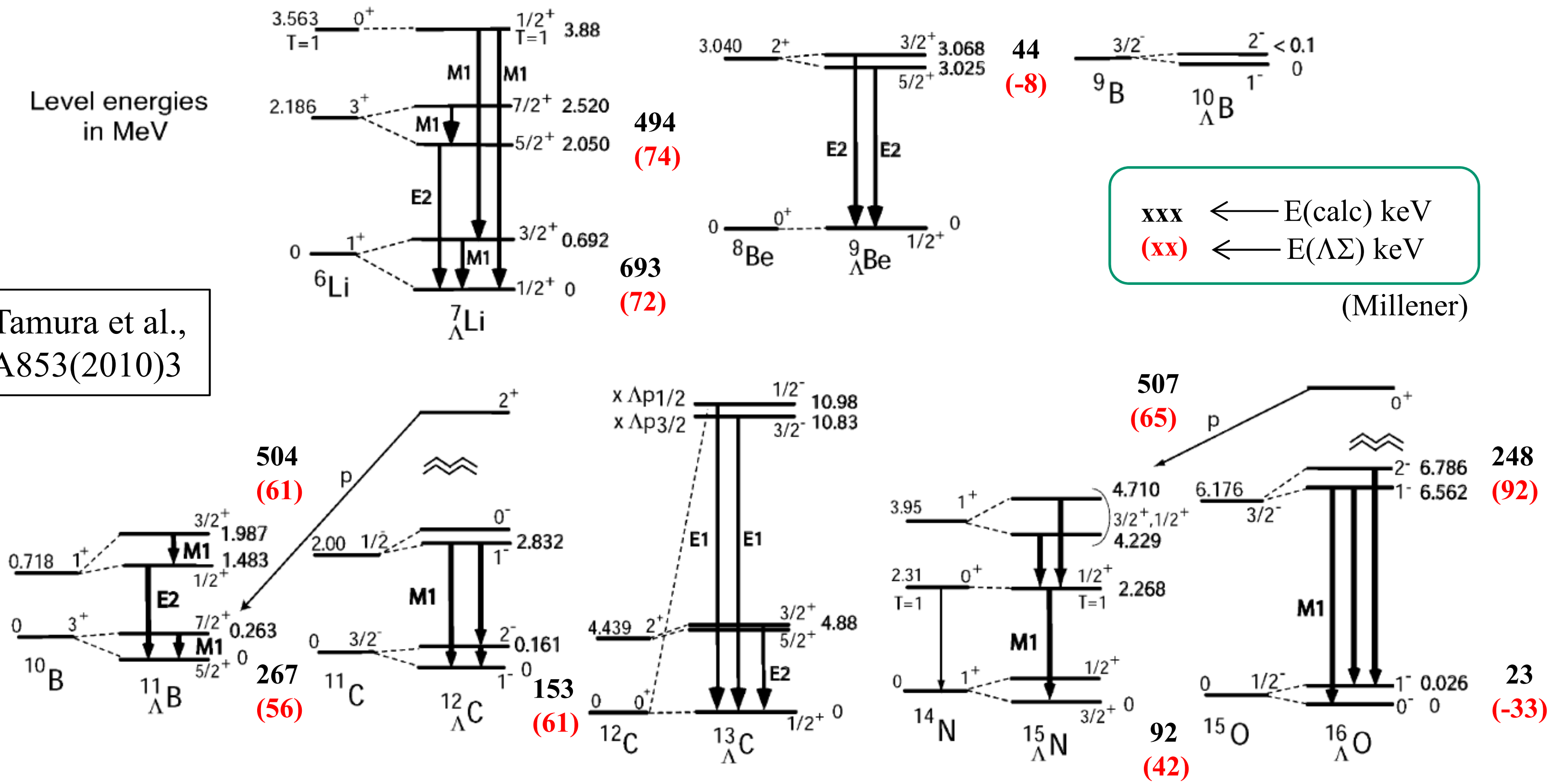
$^{19}_{\Lambda}$C, $^{29}_{\Lambda}$Si, $^{25}_{\Lambda}$Mg, (CSHF+BCS)

M.T. Win, K.Hagino et al, PRC83 (2011) 014301



Gamma-ray spectroscopy of light hypernuclei

H. Tamura et al., NPA853(2010)3



Spin-dependence of the effective ΛN interaction [R.H.Dalitz, A.Gal, AnnPhys.116(1978)167]

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

Microscopic Shell-Model

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

G-matrix calculation in symmetric nuclear matter

Λ single-particle potential depth

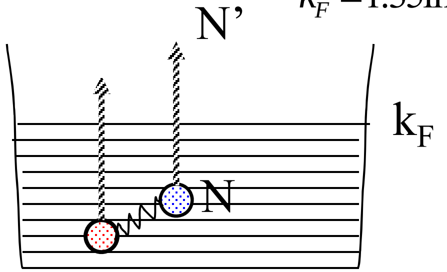
$$U_\Lambda(k_F, \varepsilon_\Lambda) = \sum_{\mathbf{k}_N} \langle \mathbf{k}_\Lambda, \mathbf{k}_N \,|\, g_{\Lambda N}(\omega = \varepsilon_\Lambda + \varepsilon_N) \,|\, \mathbf{k}_\Lambda, \mathbf{k}_N \rangle$$

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

G-matrix

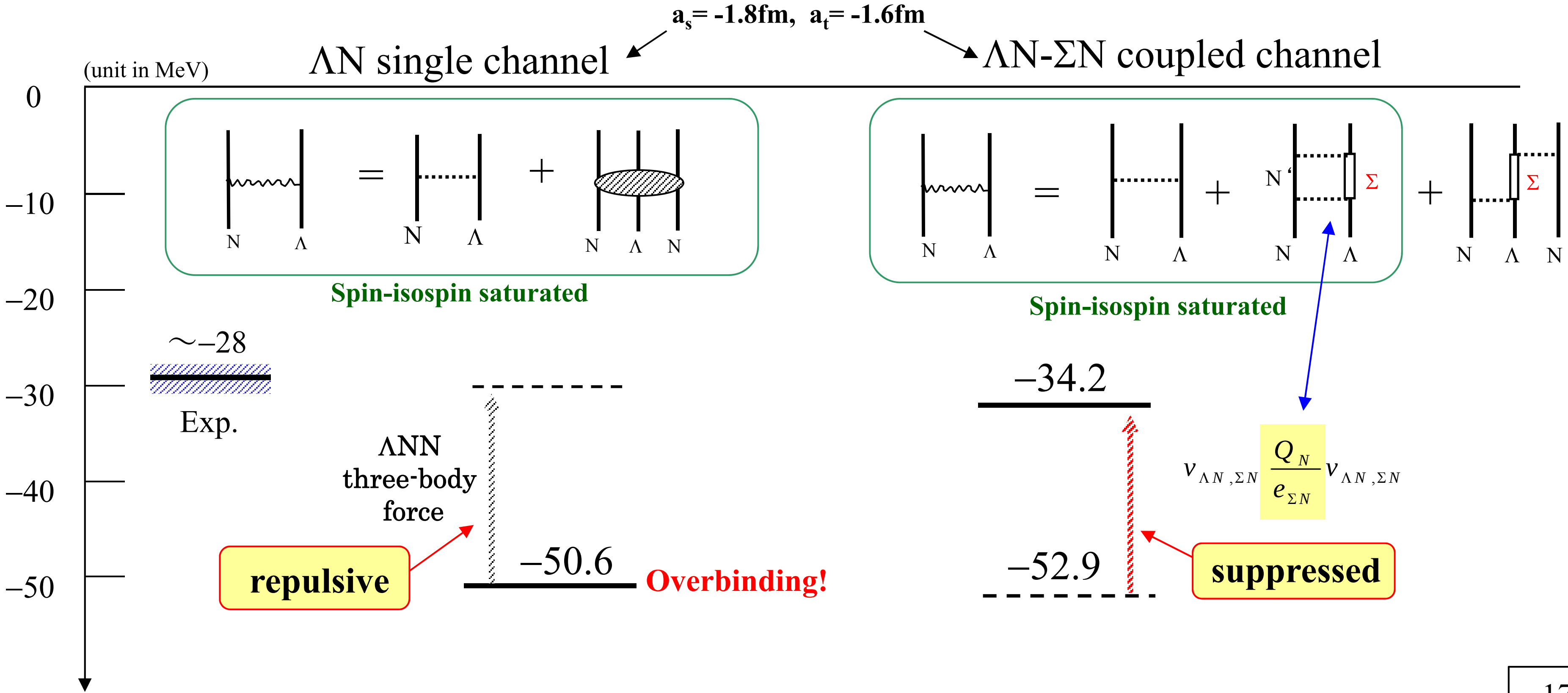
Pauli-operator

$k_F = 1.35 \mathrm{fm}^{-1}$



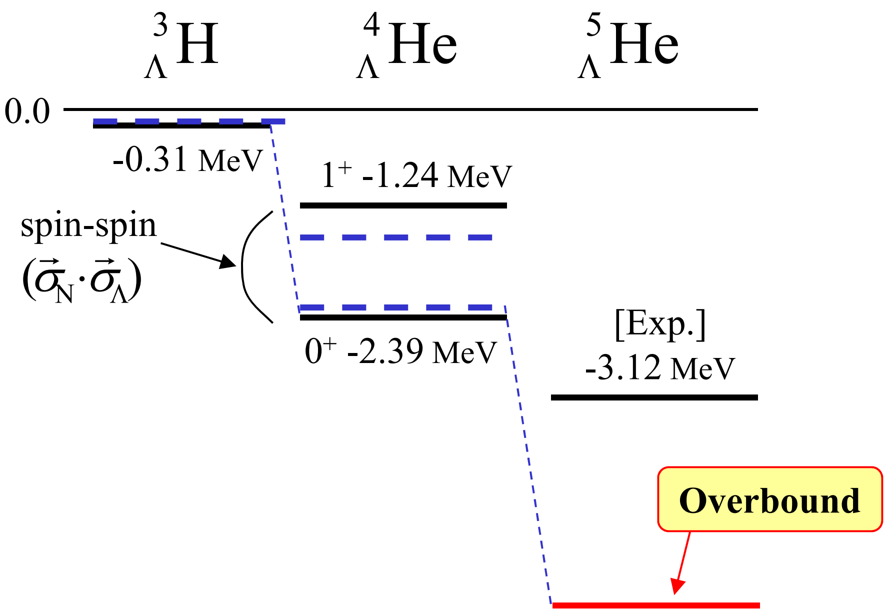
Effects of the ΛN-ΣN coupling in nuclear matter

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



Overbinding Problem on s-Shell Hypernuclei

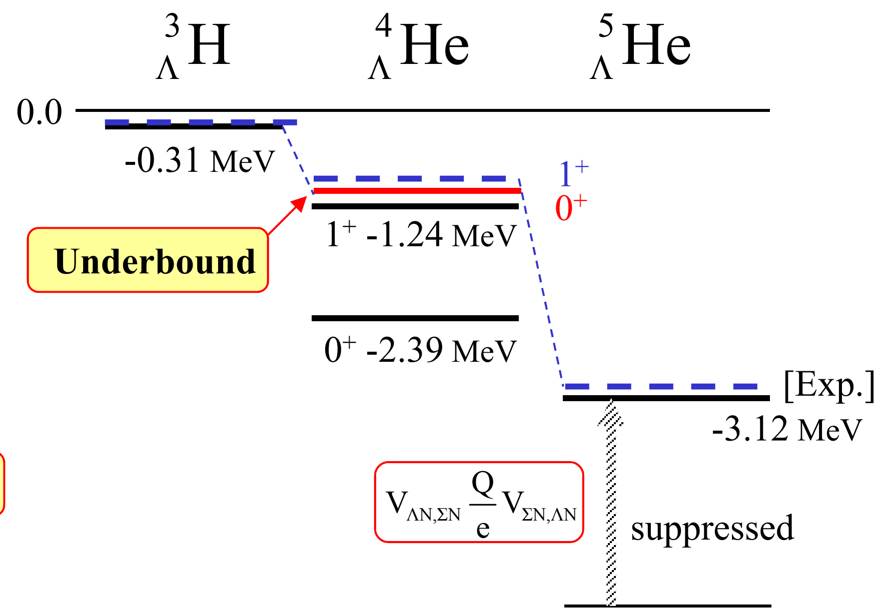
The Overbinding Problem



ΛN single-channel calc.

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

The Underbinding Problem

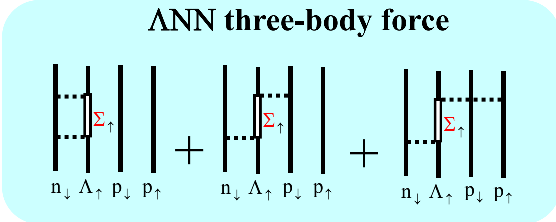


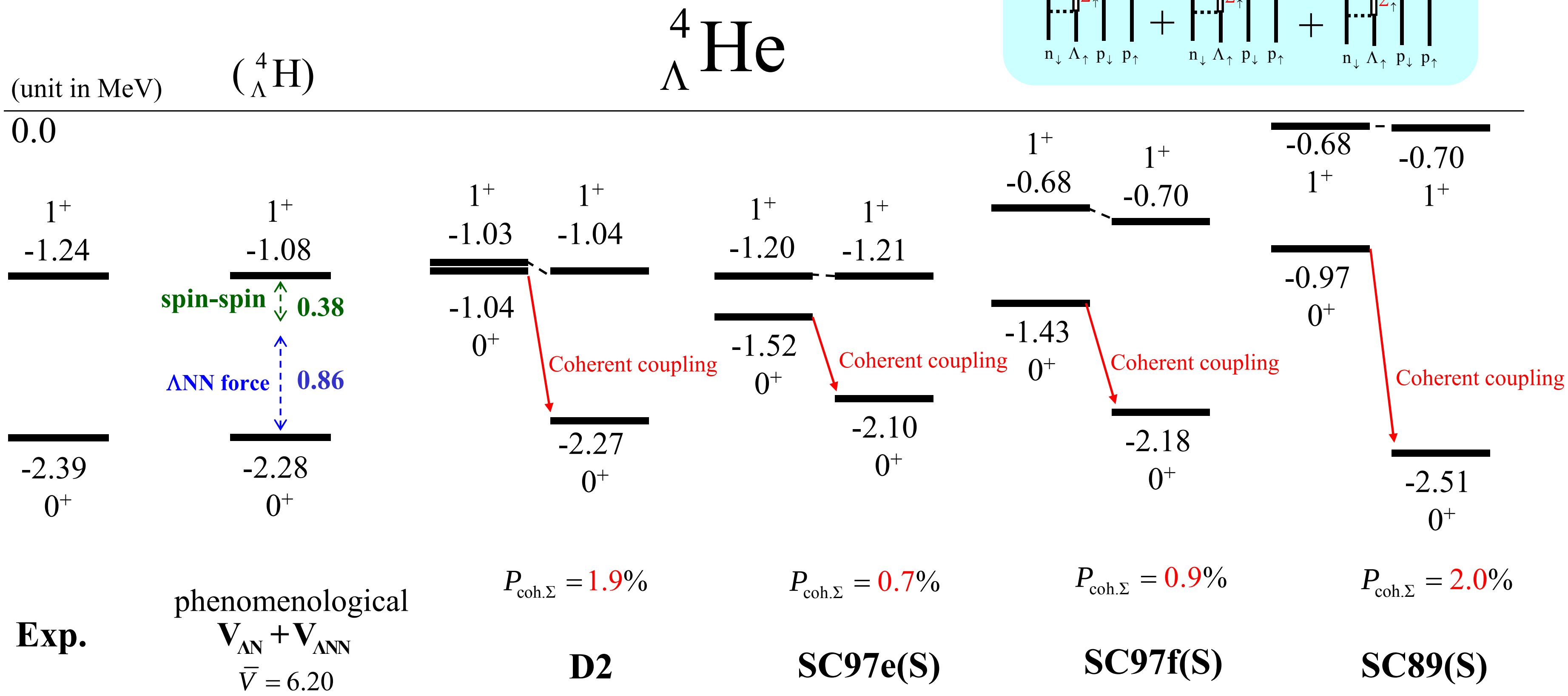
g-matrix calc. with ΛN-ΣN(D2)

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

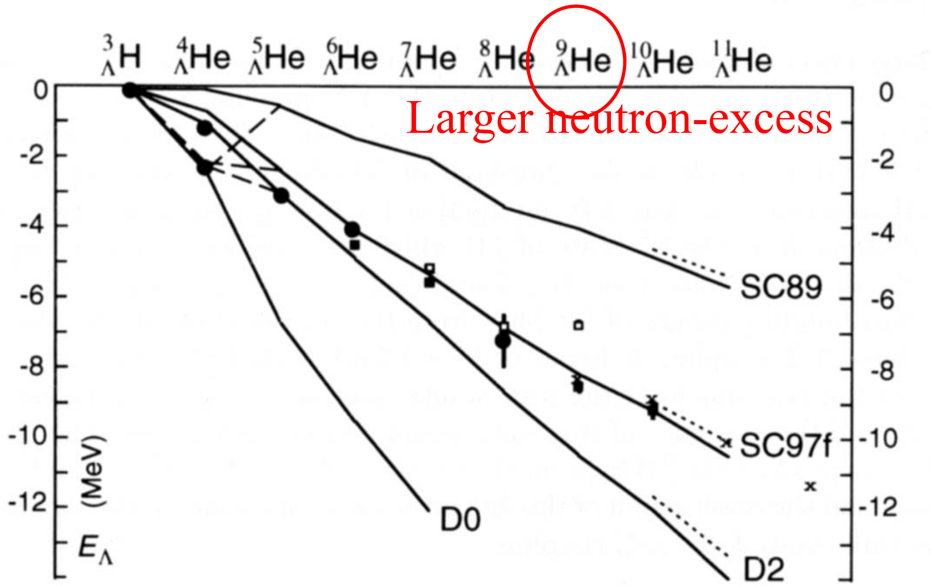
Production of neutron-rich Λ-hypernuclei with the DCX reaction

E10@J-PARC

$$^{6}\mathrm{Li}(\pi^-,K^+)\,^{6}_{\Lambda}\mathrm{H}$$
$$^{9}\mathrm{Be}(\pi^-,K^+)\,^{9}_{\Lambda}\mathrm{He}$$

$^{9}_{\Lambda}$**He**

Khin Swe Myint et al., FBS. Suppl. 12(2000)383

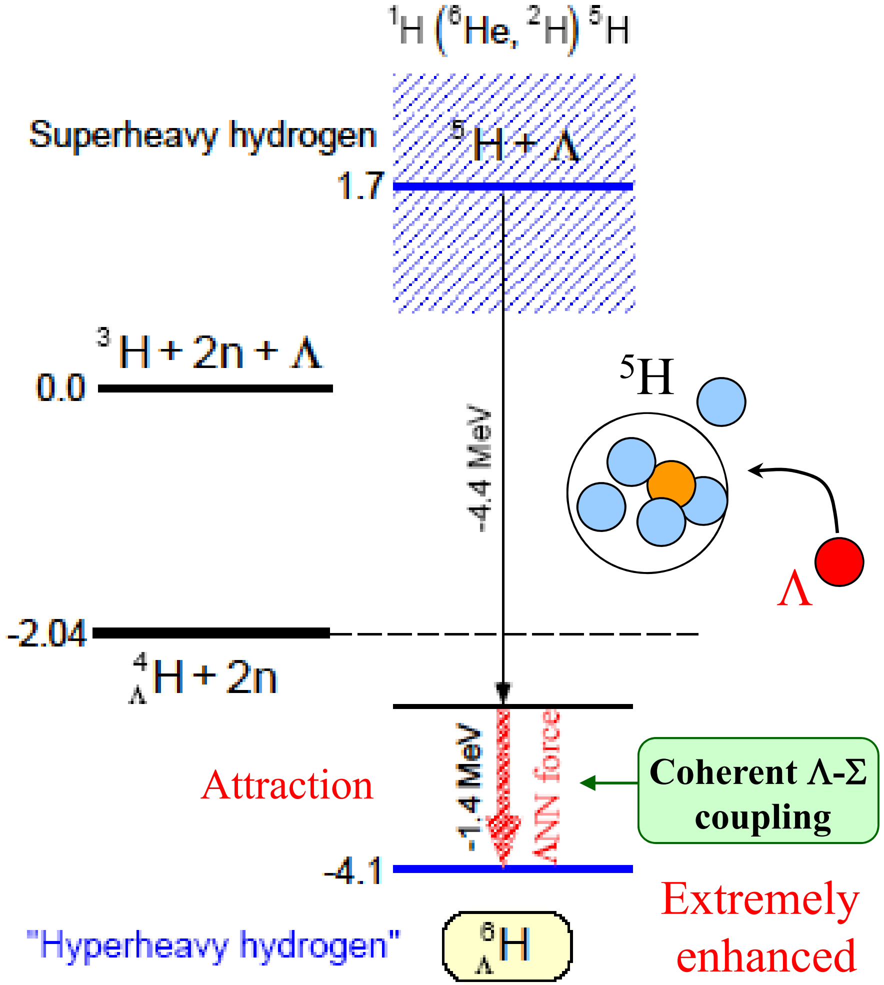


Λ binding energies

$^{6}_{\Lambda}$**H**

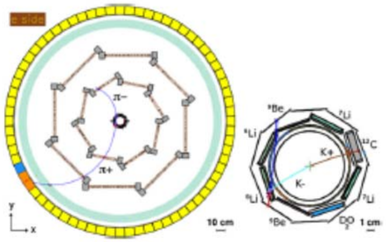
"Hyperheavy hydrogen"

Y.Akaishi, NPA738(2004)80c



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

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



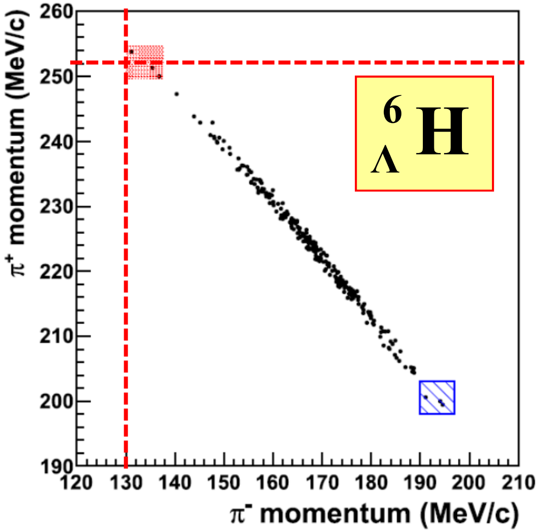
M. Agnello et al., NPA881(2012)269.
M. Agnello, et al., PRL108 (2012) 042501.

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

  B_{Λ} = 4.0 ± 1.1 MeV

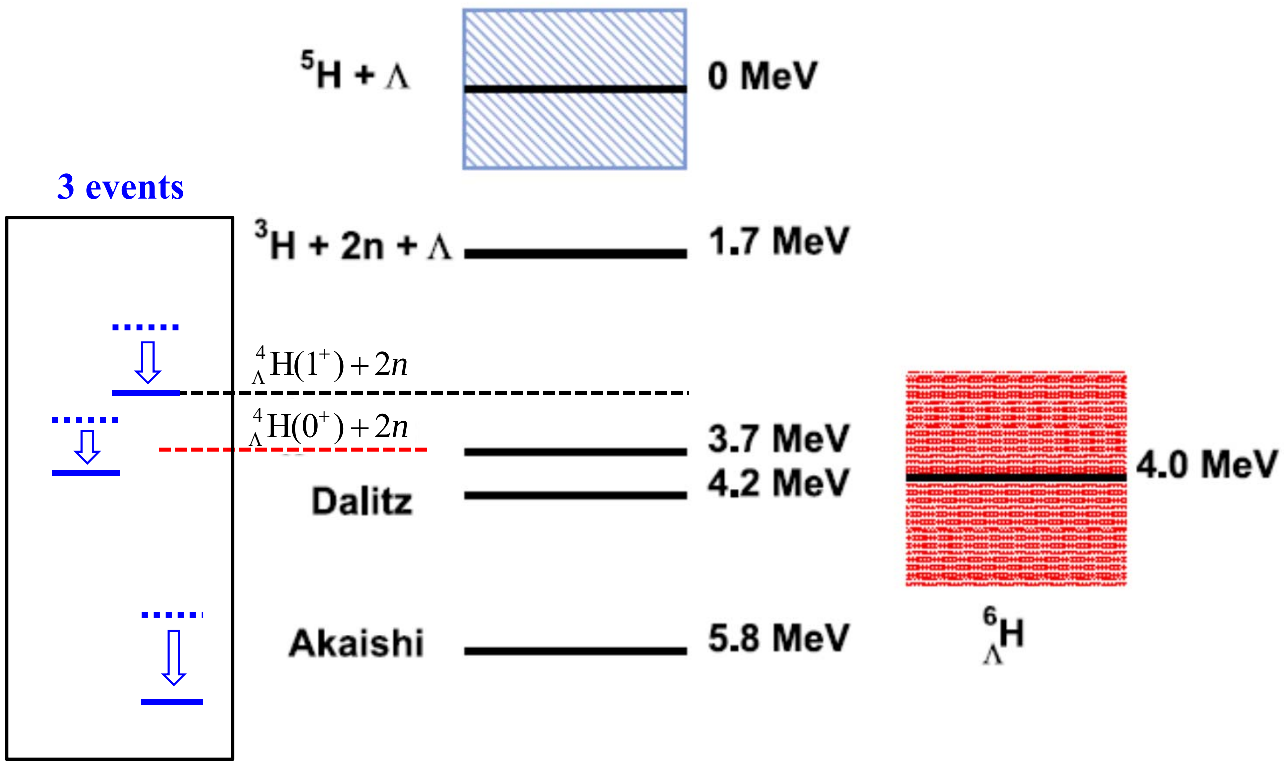
- BR(DCX) / BR(NCX,12LC) ~ 3×10^{-3}

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



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

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



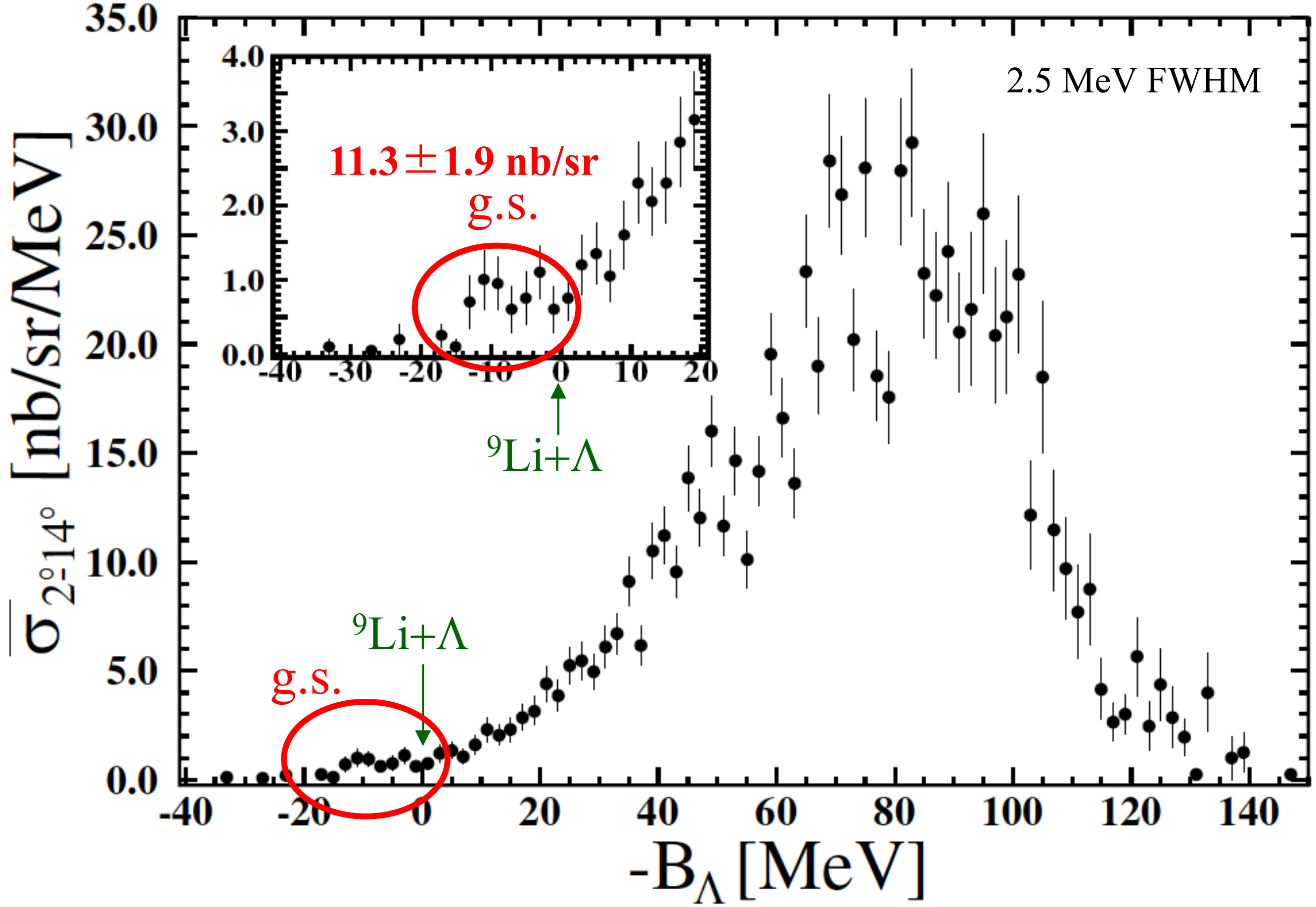
→E10@J-PARC

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

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

$\frac{d\sigma}{d\Omega_L} \approx$ **11.3±1.9** nb/sr

- p_π=1.05 GeV/c

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

~1/1000

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

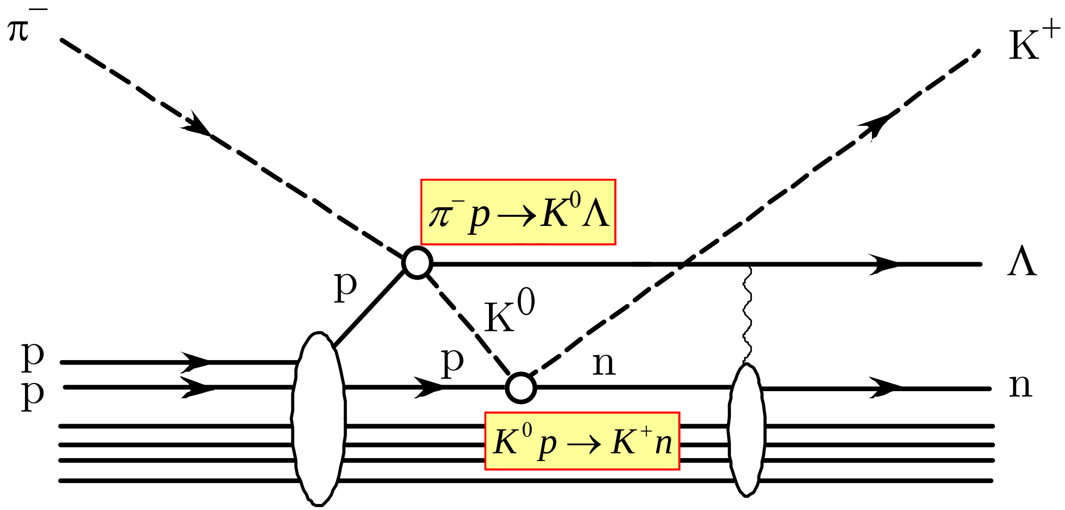
17.5±0.6 μb/sr

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

***Two-step process*:**

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

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

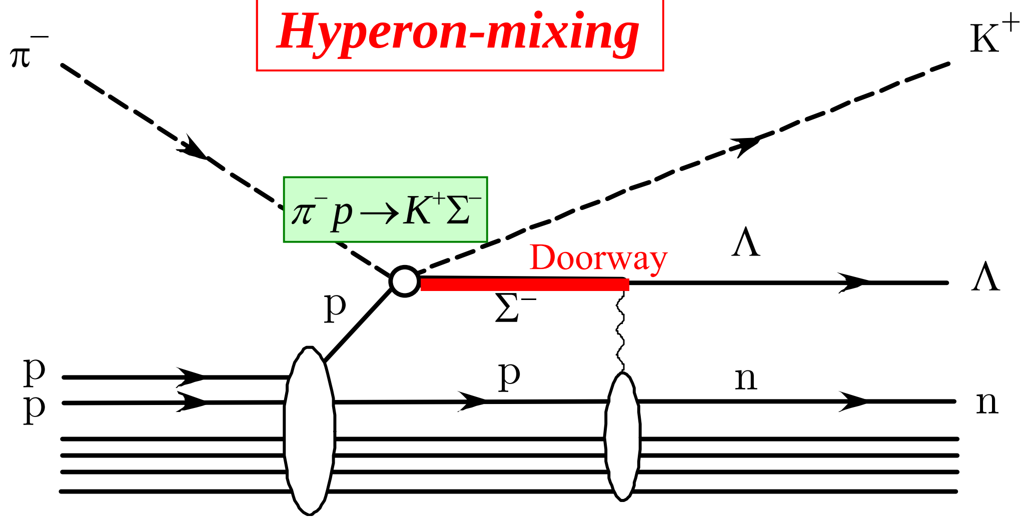


***One-step process*:**

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

via Σ^- doorways caused by ΛN-ΣN coupling

Hyperon-mixing



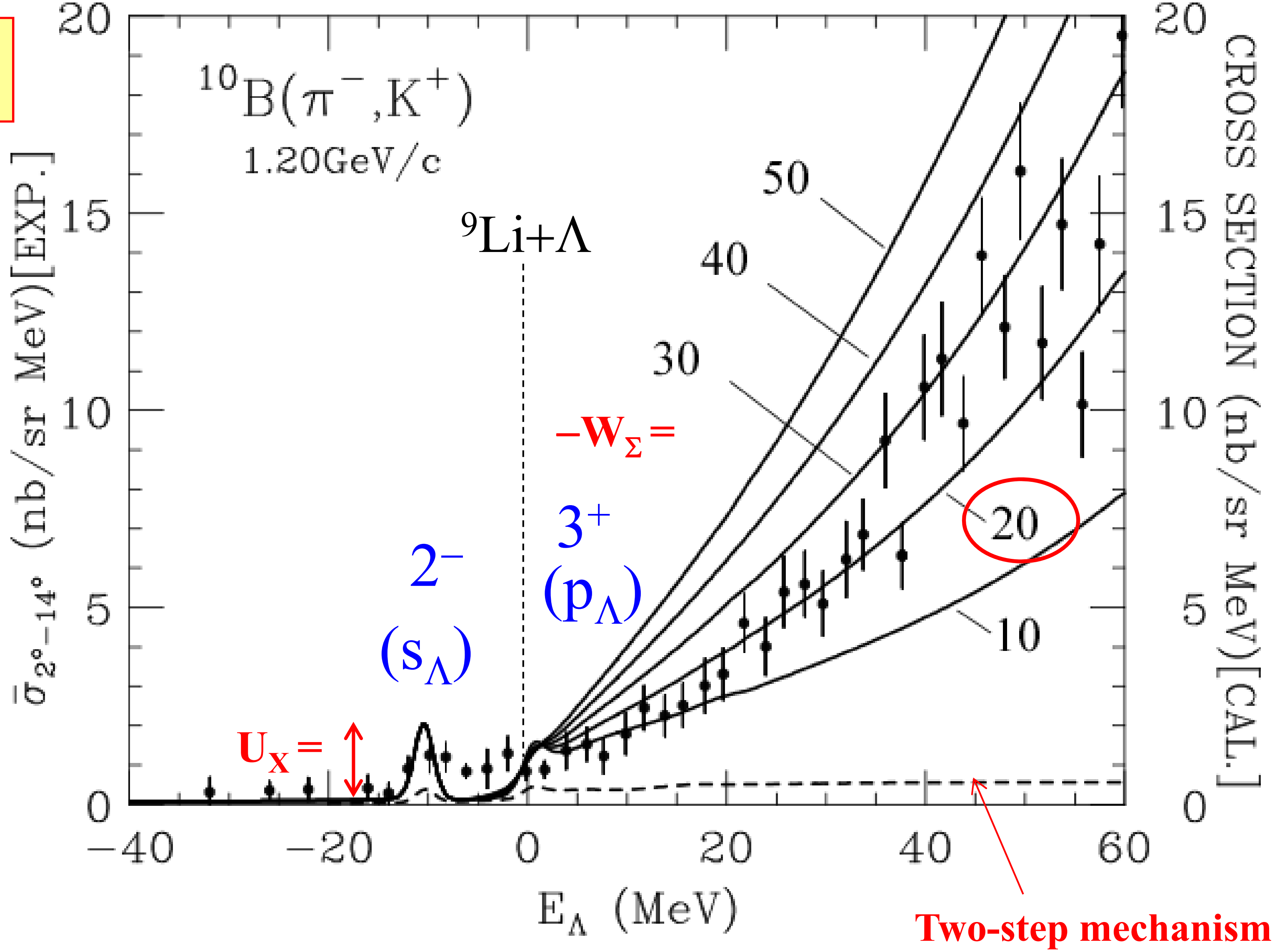
Λ spectrum by DCX (π^-,K^+) reactions at 1.2GeV/c

Harada, Umeya,Hirabayashi, PRC79(2009)014603

Spreading potential dep. W_Σ

U_X =11 MeV is fixed. P_{Σ^-}=0.57%

^{10}B



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

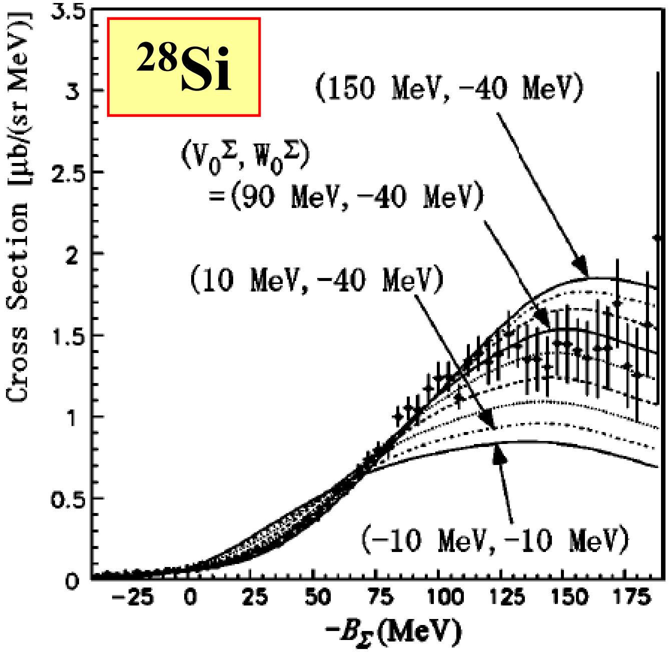
➢ HAL QCD Collaboration

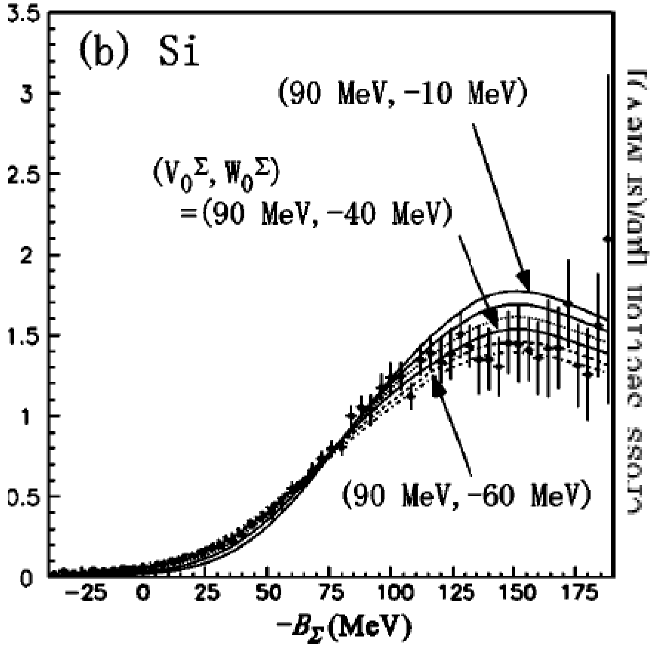
[H. Nemura, et al., PLB 673 (2009) 136; T. Inoue, et al., PTP124 (2010) 591;
PRL106 (2011) 162002]

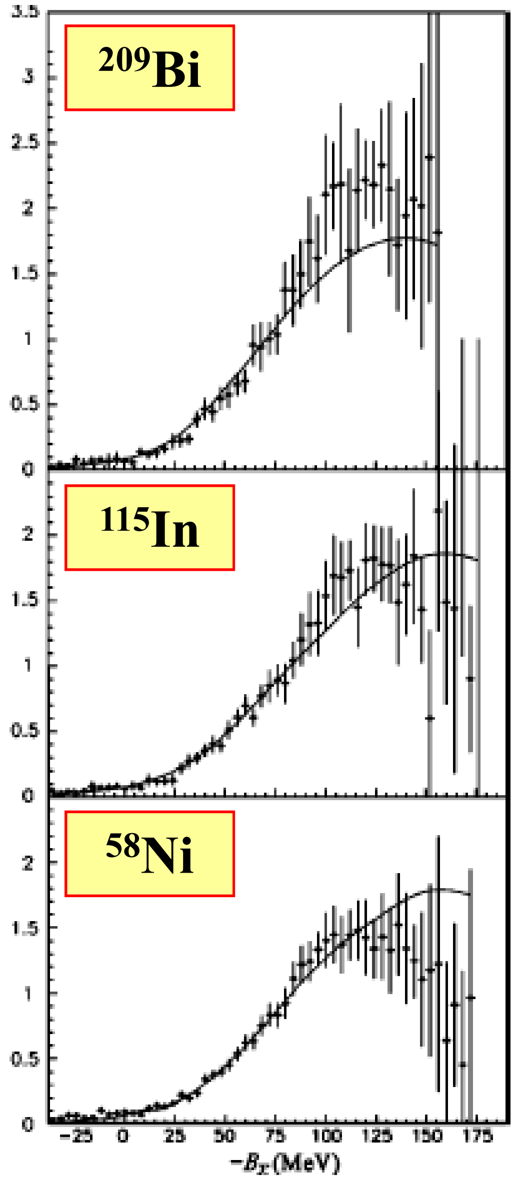
Σ^- spectrum by (π^-, K^+) reaction at 1.2GeV/c

Study of Σ s.p. potentials for havier targets

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







Woods-Saxon form

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

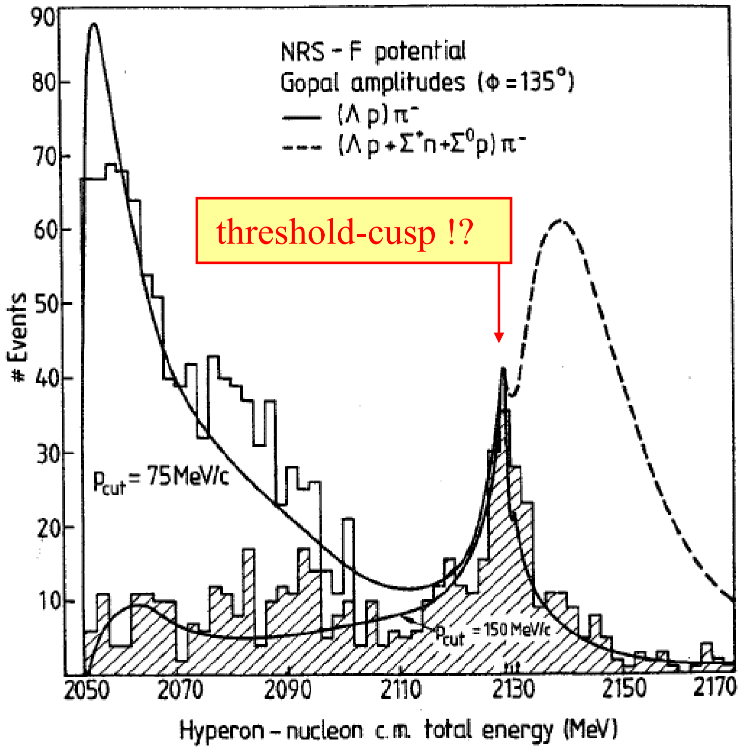
$$R = r_0 (A-1)^{1/3}\,\mathrm{fm}$$

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

$$V_\Sigma = +90\ \mathrm{MeV}$$

$$W_\Sigma = -40\ \mathrm{MeV}$$

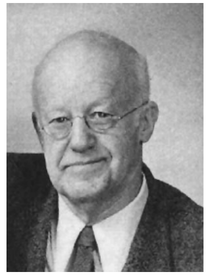
Strong repulsion with large imaginary



$K^-d \rightarrow \pi^- \Lambda p$ Reaction in Flight

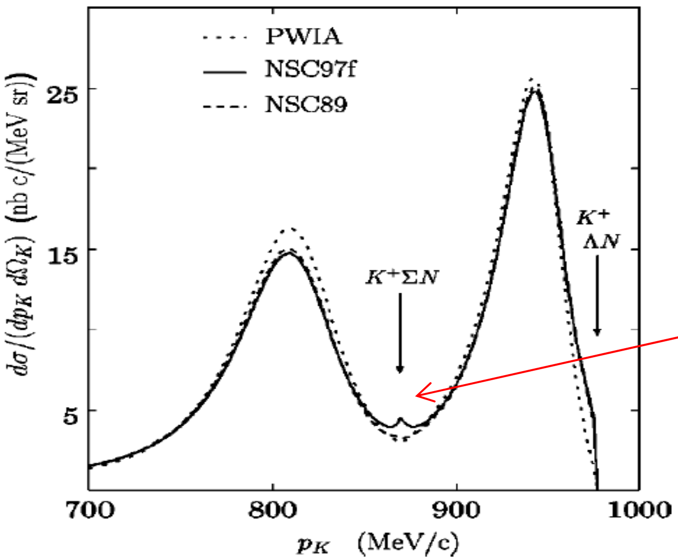
ΣN $^3S_1$ [10*]:
"Strangeness partner of deuteron"

R.H.Dalitz, A. Deloff,
Aust. J. Phys., 36 (1983) 617

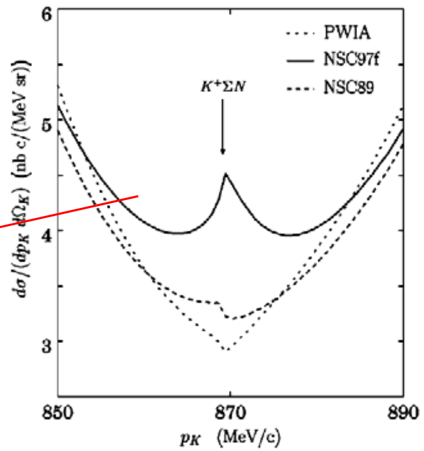


R.H.Dalitz

NHC-F



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



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

$d(\gamma,K^+)$ inclusive spectrum

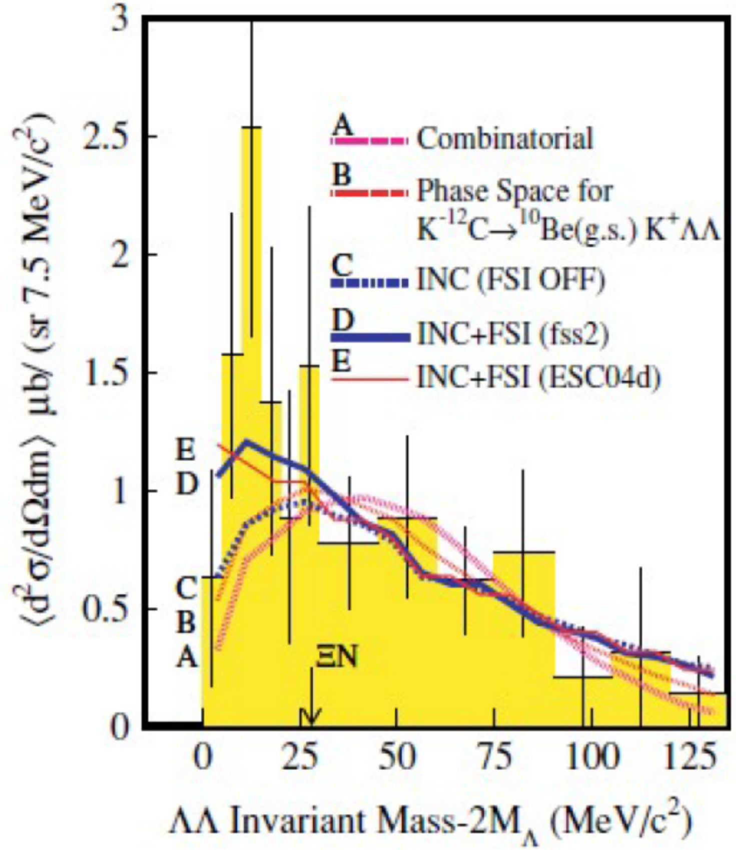
ΛΛ correlation from production nuclei

- **From (K-,K+ΛΛ) reaction**

C.J.Yoon et al., (KEK-E522),PRC75(2007)022201(R)

S=-2 dibaryon (uuddss) "H"

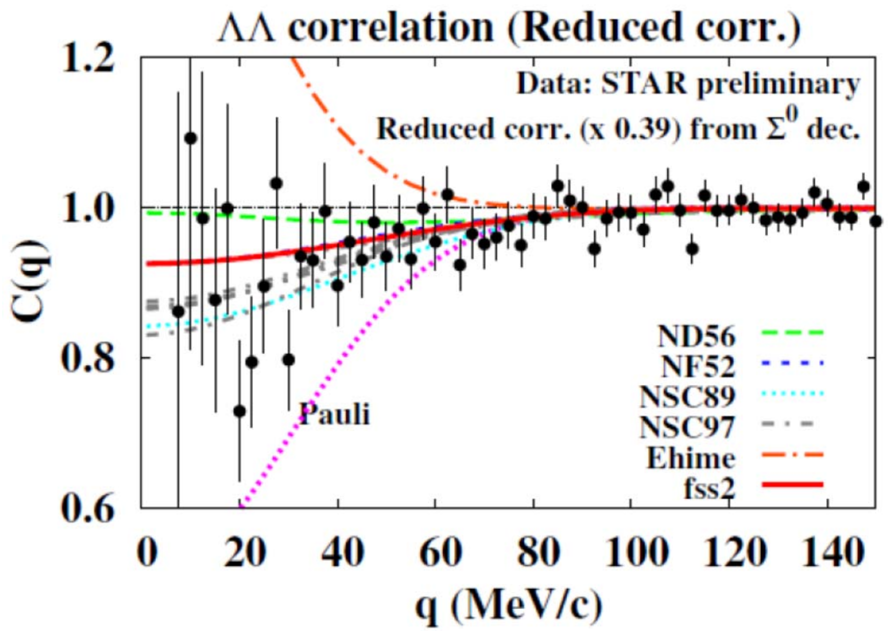
2 σ bump at $E_{\Lambda\Lambda}$ ~ 15 MeV



- **From Heavy-ion Collisions**

A. Ohnishi, T. Furumoto, K. Morita (2012)

Data: N.Shah, et al. (STAR Collab.)



- STAR data clearly show enhanced ΛΛ correlation
- Preferred ΛΛ interactions $1/a_0 < -0.8$ fm-1, $r_{eff} > 3$ fm.

→P42@J-PARC

Search for H-Dibaryon with a Large Acceptance Hyperon Spectrometer (J.K. Ahn, K. Imai)

Σハイパー核

- Σ single-particle potentialの性質
  - (π^-, K^+)反応スペクトルの解析
  - Σ-原子のX線データの解析

- 強いアイソスピン依存性
  - (K^-, π^+)反応スペクトルの解析

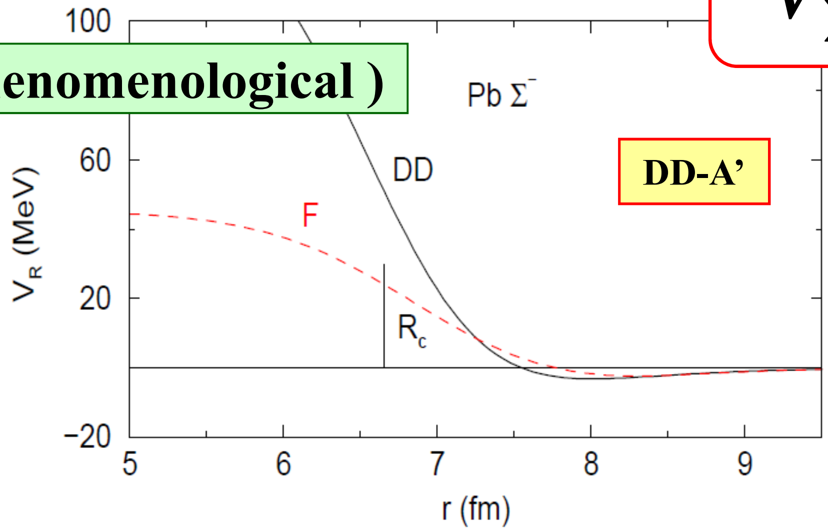
- Σハイパー核の束縛状態, $^4_\Sigma He$
  - Coherent Lane-term / Coherent Λ-Σ coupling term
  - α粒子のstrangeness partner

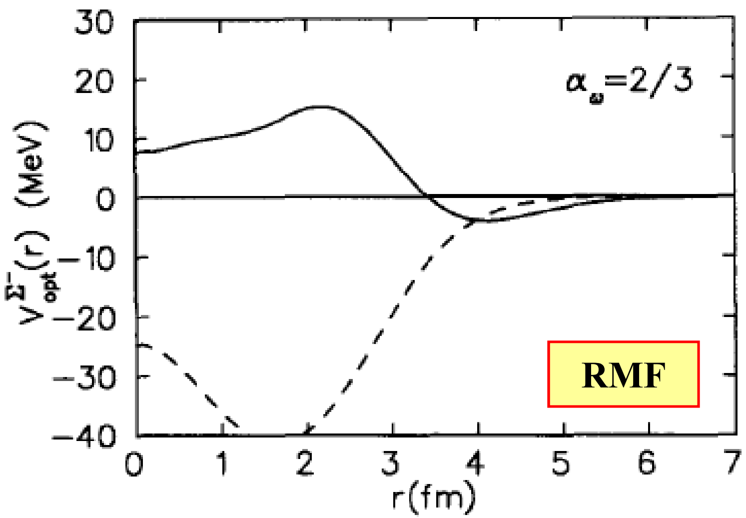
Σ^- s.p. potentials (fitted to the Σ^- atomic data)

V_Σ ?

Density-dependent (DD) potential (Phenomenological)

C.J.Batty et al., Phys.Rep.287(1997)385,
E. Friedman and A. Gal, Phys. Rep. 452 (2007)89.





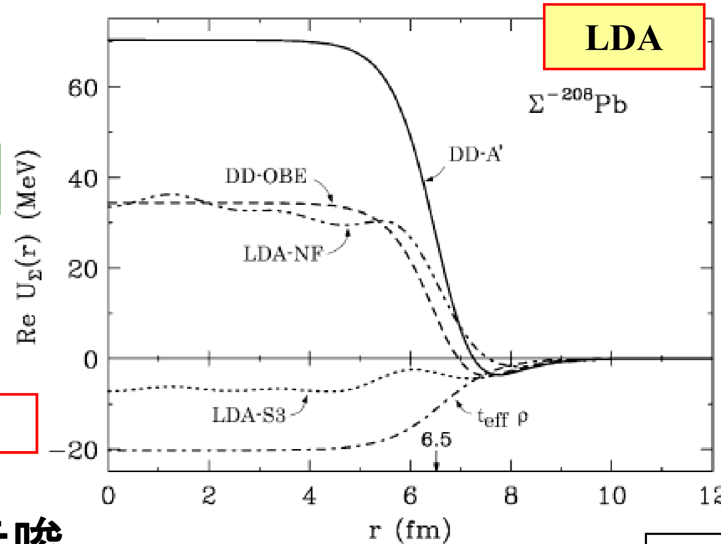
Relativistic mean-field (RMF) potential

J. Mares et al., NPA594(1995)311.
K.Tsubakihara et al., EPJA33(2007)295

Folding-model potential for LDA with G-matrix

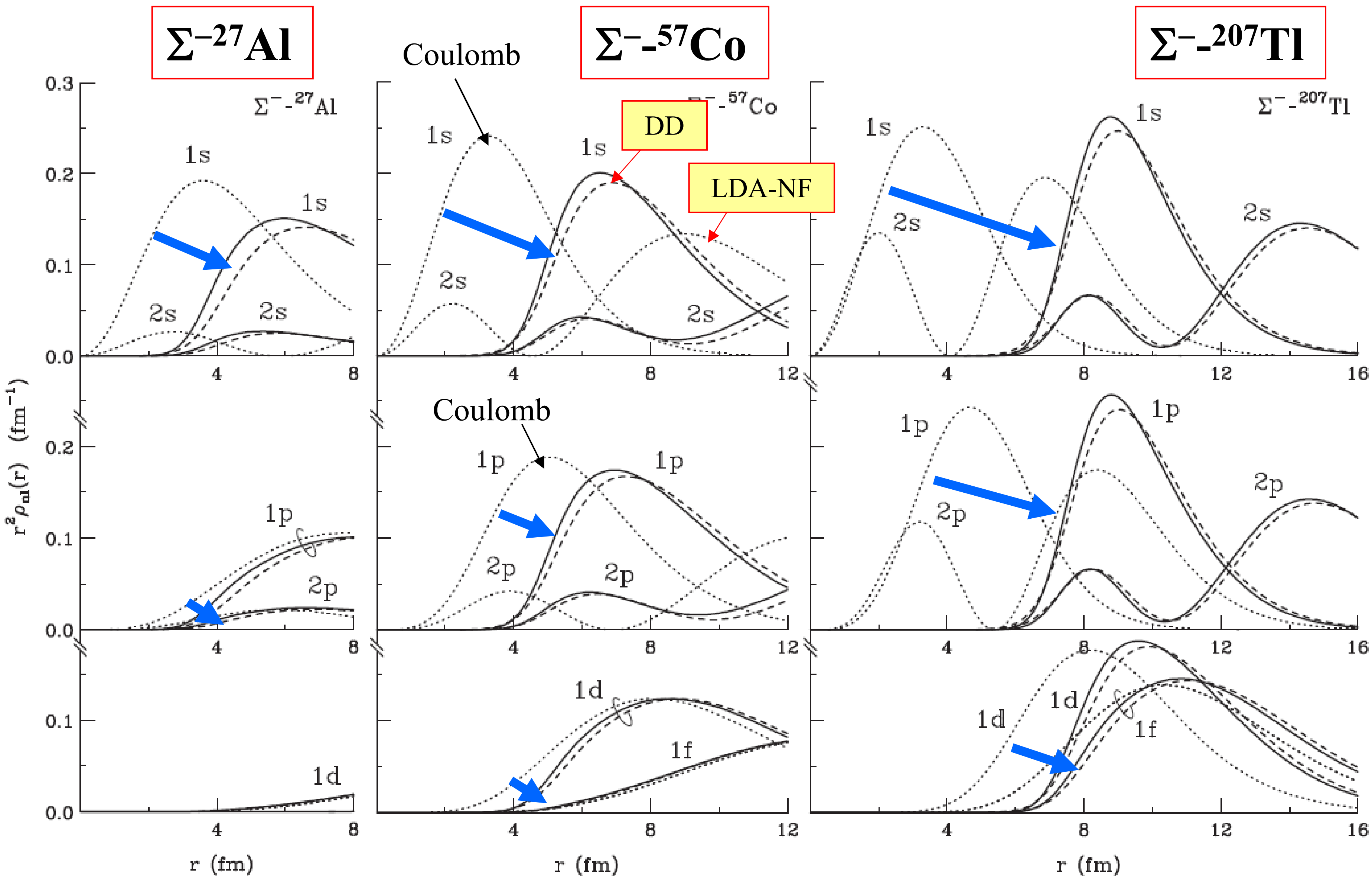
D. Halderson, Phys. Rev. C40(1989)2173.
T.Yamada and Y.Yamamoto, PTP. Suppl. 117(1994)241
J. Dabrowski, Acta Phys. Pol. B31(2001)2179
T.Harada, Y.Hirabayashi, NPA759 (2005) 143; 767(2006)206

YNG-F



➢ Σ-1粒子ポテンシャルは強い斥力であることを示唆

Nuclear density distributions of Σ⁻ hyperon



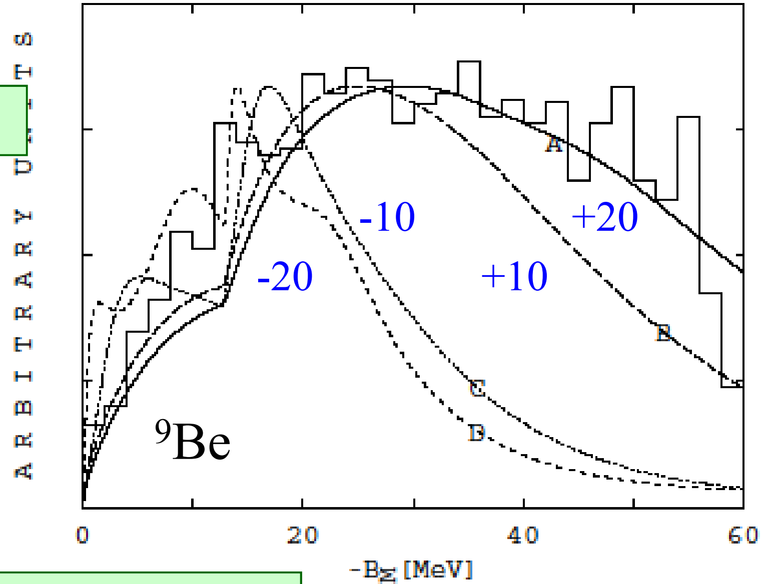
➢ Push out the Σ-wave functions due to the repulsive core !!

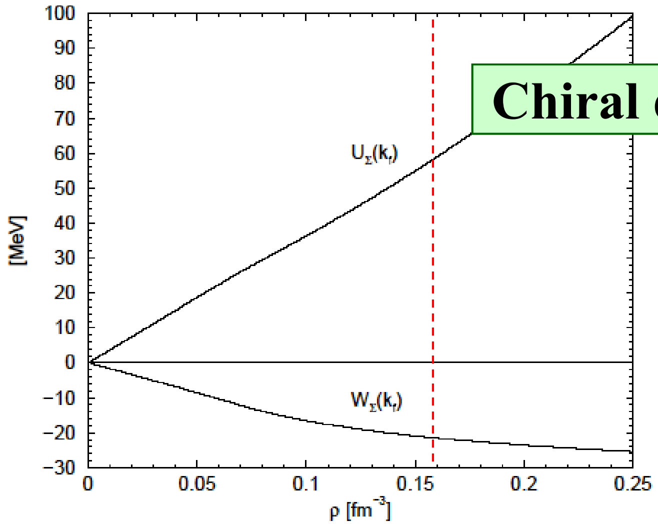
Comparison with resent studies

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."



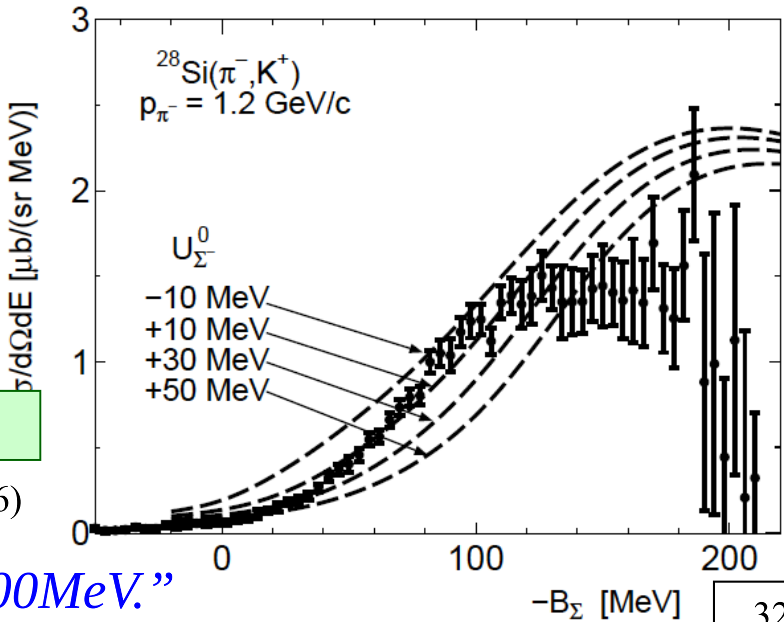


Chiral dynamics in the nuclear medium

N. Kaiser, PRC71 (2005) 068201

$U_{\Sigma}(\rho_0) \sim 59$MeV : repulsive

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



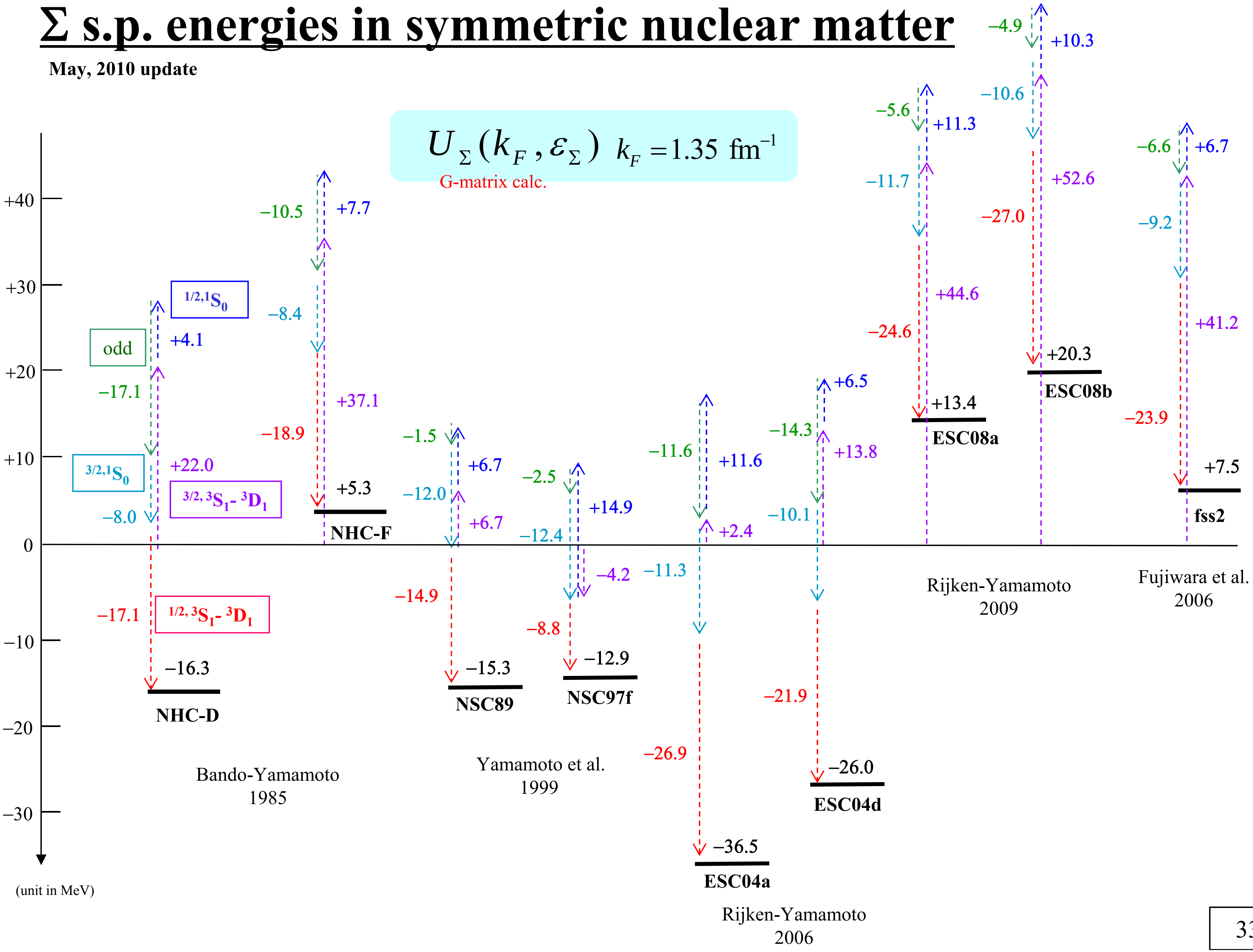
Semi-Classical Distorted Wave Model Analysis

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

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

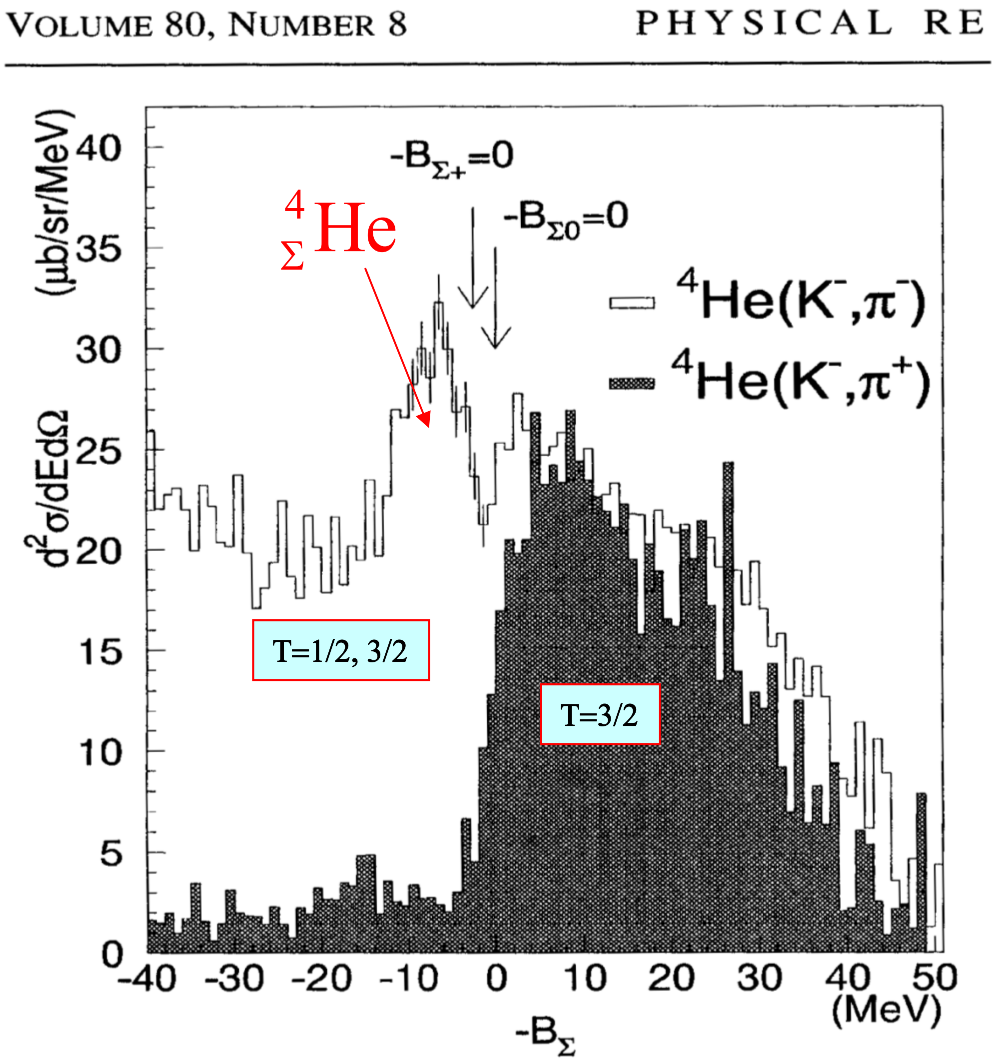
Σ s.p. energies in symmetric nuclear matter

May, 2010 update



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

$T \simeq 1/2$

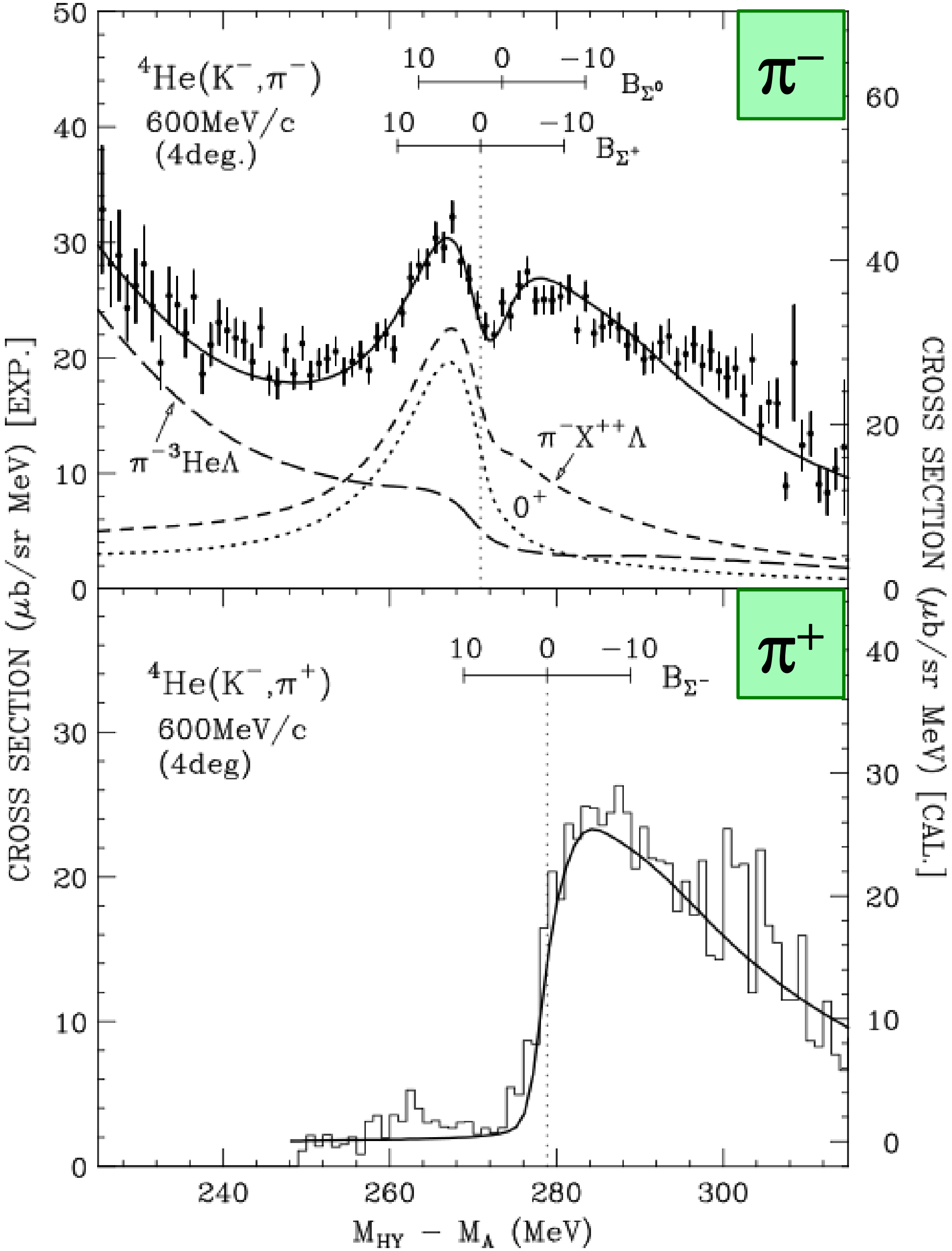
$J^{\pi} = 0^{+}$

Theoretical Prediction
4.6 MeV
7.9 MeV

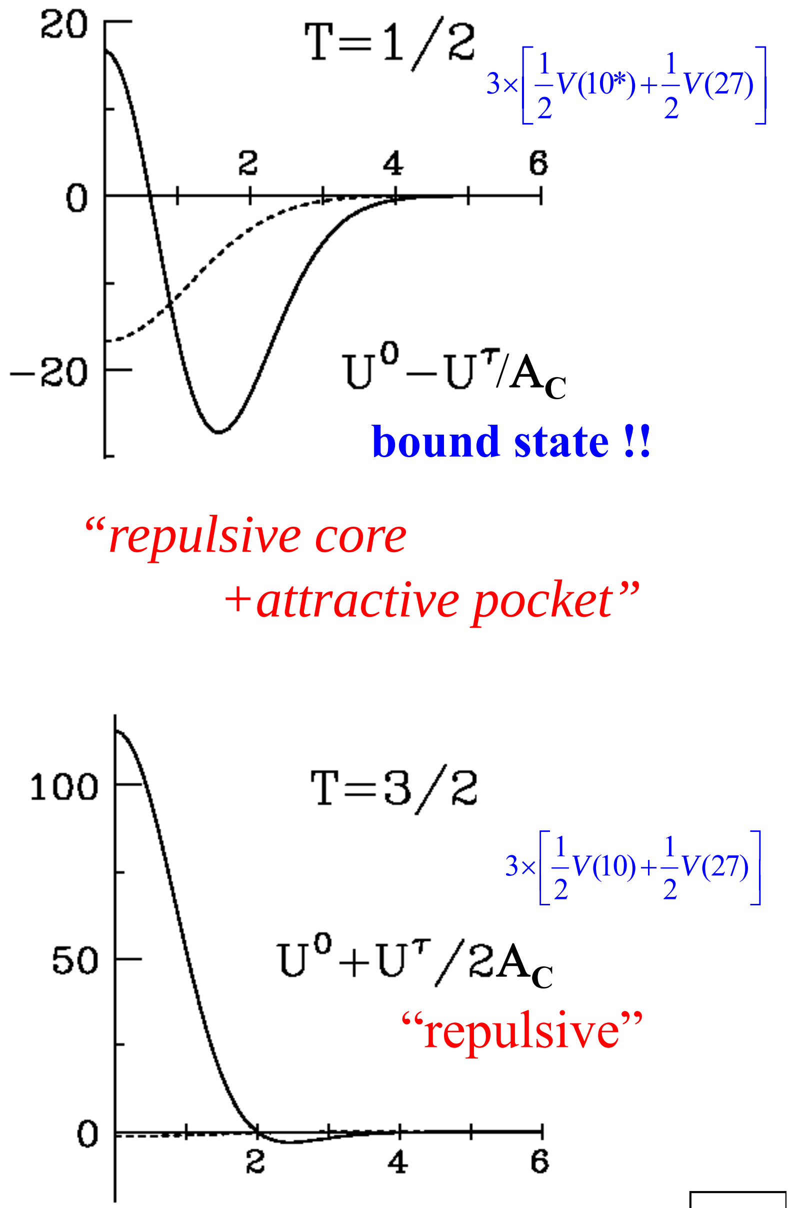
T.Harada, S.Shinmura, Y.Akaishi, H.Tanaka, NPA507(1990)715.

Isospin dependence of the (3N)-Σ potentials

T.Harada, PRL81(1998)5287.



T.Harada, NPA507 (1990) 715.



Remarks

Properties of the Σ-nucleus potentials by comparing theoretical calculations with the available data:

$$U_\Sigma(\boldsymbol{r}) = U_\Sigma^0(\boldsymbol{r}) + \frac{1}{A_{\rm core}} U_\Sigma^\tau(\boldsymbol{r}) (\vec{\boldsymbol{T}}_{\rm core} \cdot \vec{\boldsymbol{t}}_\Sigma)$$

"repulsion inside the nuclear surface"
"shallow attraction outside the nucleus"

"strong isospin-dependence"

The calculated spectra for ^{4}He(K^-,$\pi^\pm$) reaction can explain consistently the available data from BNL, KEK, and ANL.

Σ-3N potential: the $_\Sigma{}^4$He bound state with $T=1/2$, $J^\pi=0^+$

Strong Lane (isospin-dependent) potential and Coherent Λ-Σ coupling

3. S＝−2 の原子核

Ξハイパー核

■Ξ single-particle potentialの性質

(K^-,K^+)反応スペクトルの解析

Ξ -原子のX線の測定へ

■(K^-,K^+)反応によるΞハイパー核の生成

ΛΛハイパー核

■エマルジョンによるΛΛハイパー核の発見

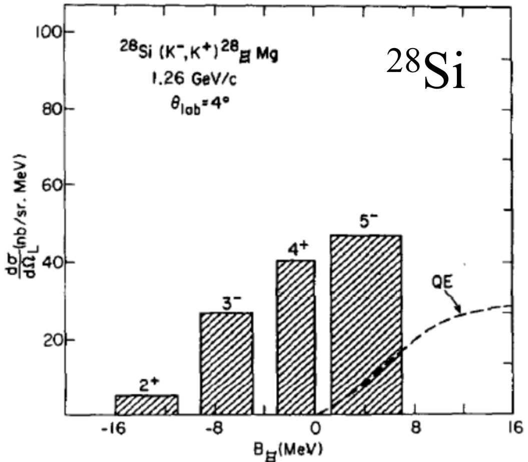
ΛΛ bond energy

■ΛΛ-Ξ coupled channel approach

■(K^-,K^+)反応によるΛΛハイパー核の励起状態の生成

Studies of Ξ⁻ s.p. potentials

V_{Ξ} ?



Ξ-hypernuclei via (K-,K+) reactions

[C.B. Dover, A.Gal, Ann. Phys. 146 (1989) 309.]

$$V_{\Xi}^{0} = -24 \pm 4 \text{ MeV} \quad \text{for} \quad r_0 = 1.1 \text{ fm} \quad (W_{\Xi}^{0} \simeq -1 \text{ MeV})$$

DWIA analysis of ^{12}C(K-,K+) data at 1.8GeV/c

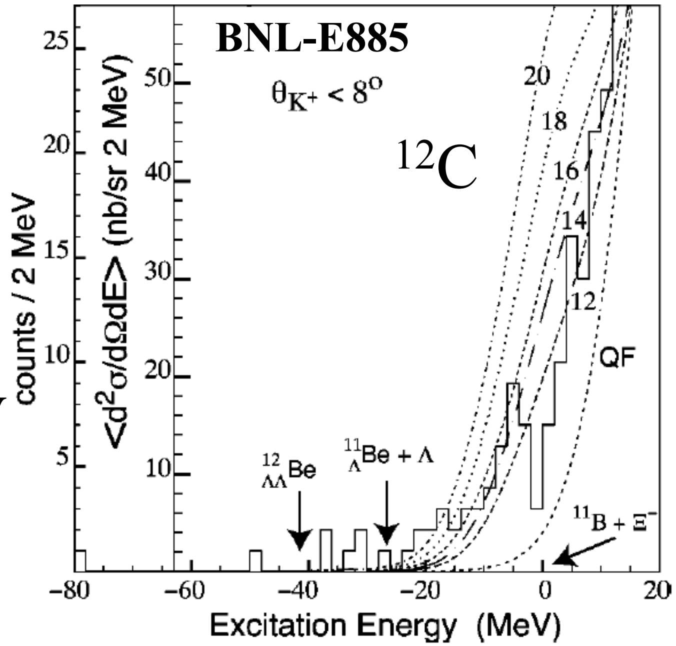
T.Iijima et al.,NPA546(1992)588.

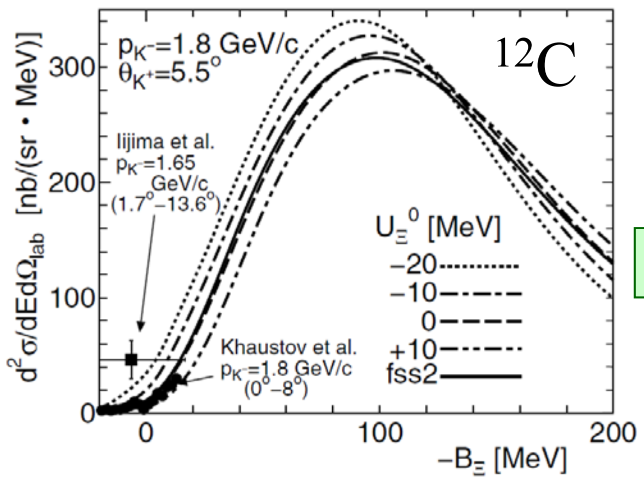
Tadokoro et al.,PRC51(1995)2656

$$V_{\Xi}^{0} \simeq -16 \text{ MeV}$$

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

$$V_{\Xi}^{0} \simeq -14 \text{ MeV}$$





Semi-Classical Distorted Wave Model Analysis

M. Kohno et al.,PTP123(2010)157;NPA835(2010)358.

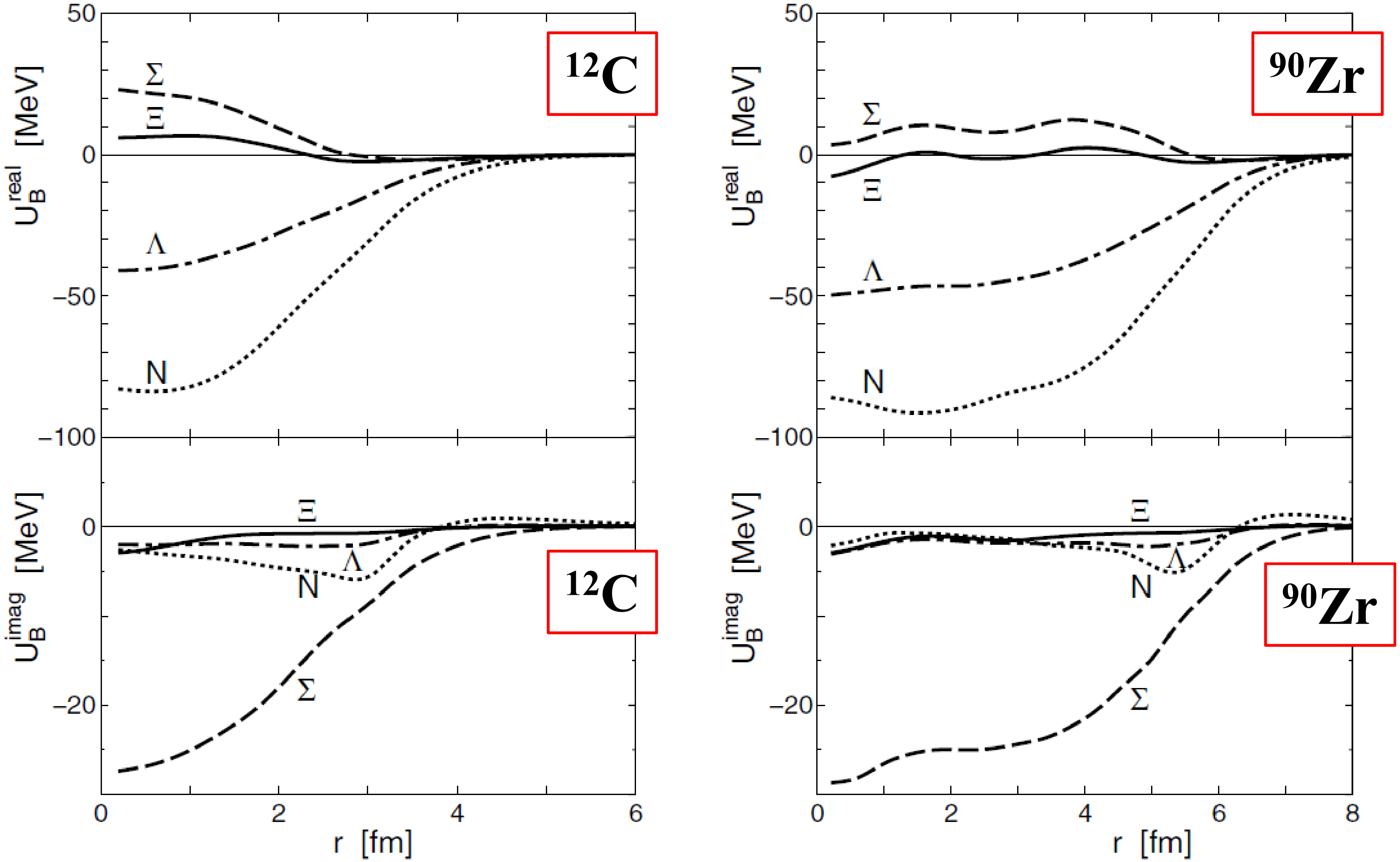
$$V_{\Xi}^{0} = -20, -10, 0, +10, +20 \text{MeV} \quad \longleftrightarrow \quad \textbf{fss2}$$

Hyperon s.p. potentials in finite nuclei

G-matrix+local density approximation

M. Kohno, Y. Fujiwara, PRC79(2009)054318.

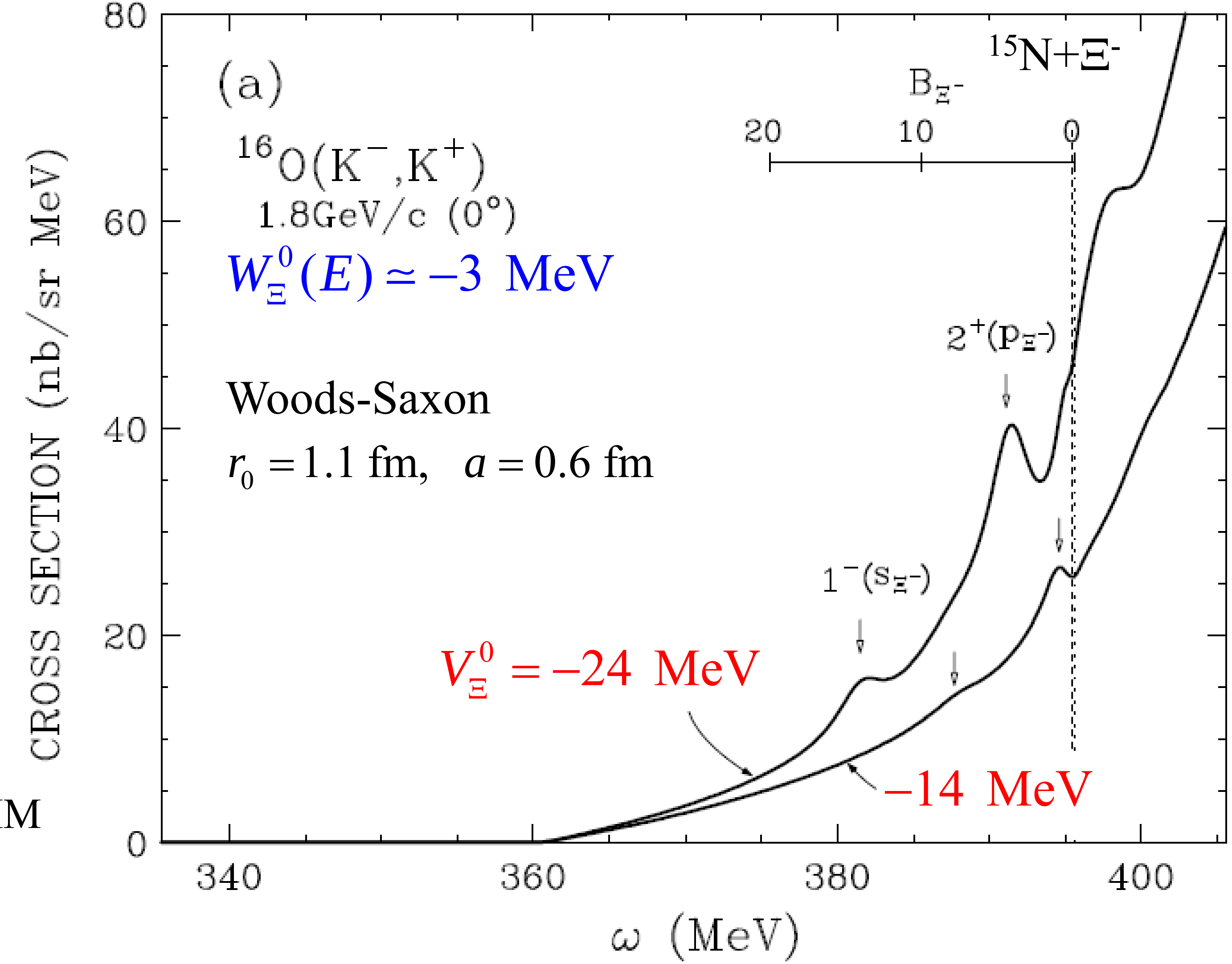
fss2 : SU_6 quark-model BB interaction by Kyoto-Niigata group



Ξ^- spectrum in DCX (K^-,K^+) reactions at 1.8GeV/c

T. Harada, Y. Hirabayashi, A. Umeya, PLB690(2010)363.

^{16}O



1.5MeV FWHM

- **Spin-stretched Ξ^- states can be populated due to the high momentum transfer.**

$d\sigma/d\Omega[^{15}N(1/2^-)\otimes s_\Xi](1-)$ = 6 nb/sr, $d\sigma/d\Omega\ [^{15}N(1/2^-)\otimes p_\Xi](2+)$ = 9 nb/sr for V_Ξ=-14 MeV.

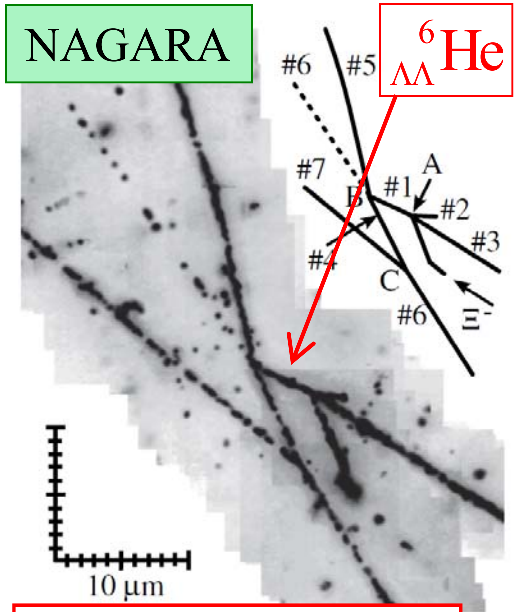
Observation of ΛΛ Hypernuclei in E176/E373 Hybrid Emulsion

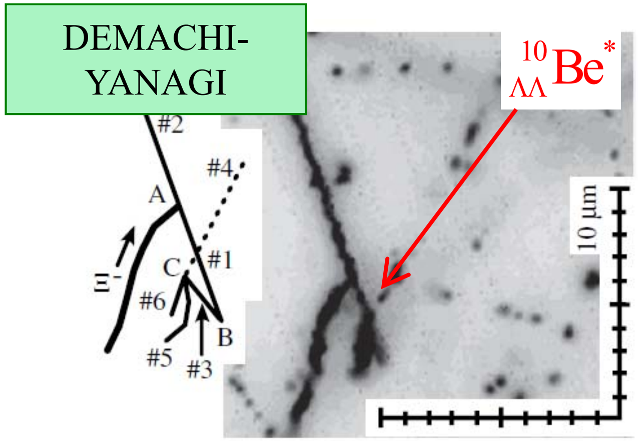
$^{12}C + \Xi^- \rightarrow {}^{6}_{\Lambda\Lambda}He + {}^{4}He + t$

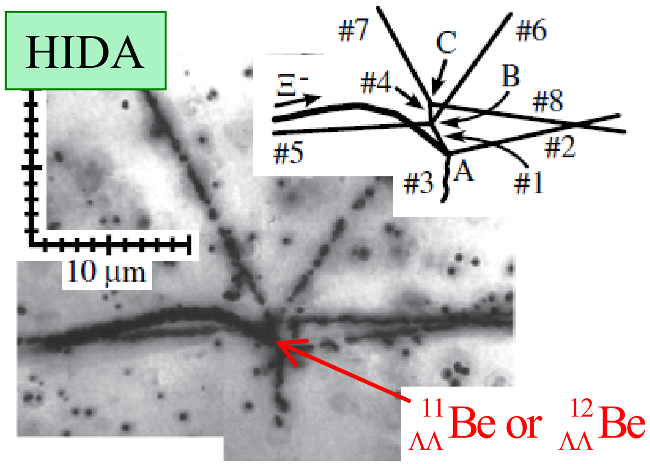
$\hookrightarrow {}^{5}_{\Lambda}He + p + \pi^-$

$2M_\Lambda - B_{\Lambda\Lambda} < M_H$ H-dibaryon

Jaffe, PRL38(1977)195







ΛΛ bound energy

$$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) - 2B_\Lambda({}^{A-1}_{\Lambda}Z)$$

Hiyama et al.
PRL104(2010)212502

event	${}^{A}_{\Lambda\Lambda}Z$	Target	$B_{\Lambda\Lambda}$ [MeV]	$\Delta B_{\Lambda\Lambda}$ [MeV]	$B^{Cal}_{\Lambda\Lambda}$[MeV]
NAGARA	${}^{6}_{\Lambda\Lambda}He$	^{12}C	6.91 ± 0.16	0.67 ± 0.17	(6.91)
MIKAGE	${}^{6}_{\Lambda\Lambda}He$	^{12}C	10.06 ± 1.72	3.82 ± 1.72	
DEMACHIYANAGI	${}^{10}_{\Lambda\Lambda}Be$	^{12}C	11.90 ± 0.13	−1.52 ± 0.15	11.88
HIDA	${}^{11}_{\Lambda\Lambda}Be$	^{16}O	20.49 ± 1.15	2.27 ± 1.23	18.23
	${}^{12}_{\Lambda\Lambda}Be$	^{14}N	22.23 ± 1.15	–	
E176	${}^{13}_{\Lambda\Lambda}B$	^{14}N	23.3 ± 0.7	0.6 ± 0.8	
Danysz *et al*[17]	${}^{10}_{\Lambda\Lambda}Be({}^{9}_{\Lambda}Be^*)$	^{14}N	14.7 ± 0.4	1.3 ± 0.4	14.74

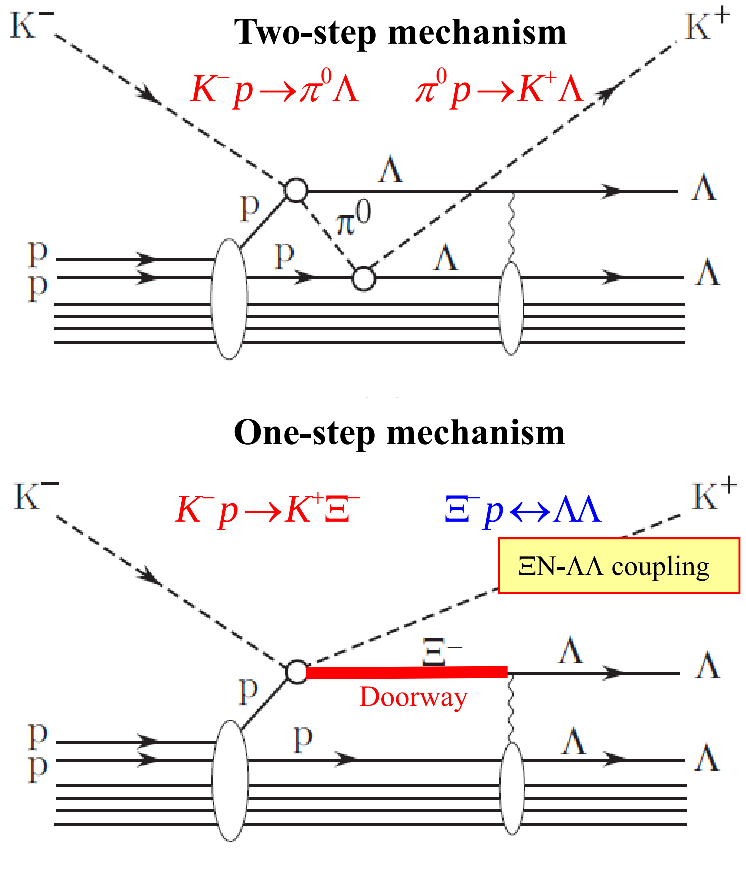
H.Takahashi et al.,PRL87(2001)212502
K.Nakazawa , NPA 835 (2010)207
K.Nakazawa , H.Takahashi,NPA 835 (2010)207

$\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}He) \simeq$ 4.7 ⟶ 1.01 ⟶ 0.67 **"weak attractive"**

Prowse, 1966 — Nagara,2001 — Ξ mass update

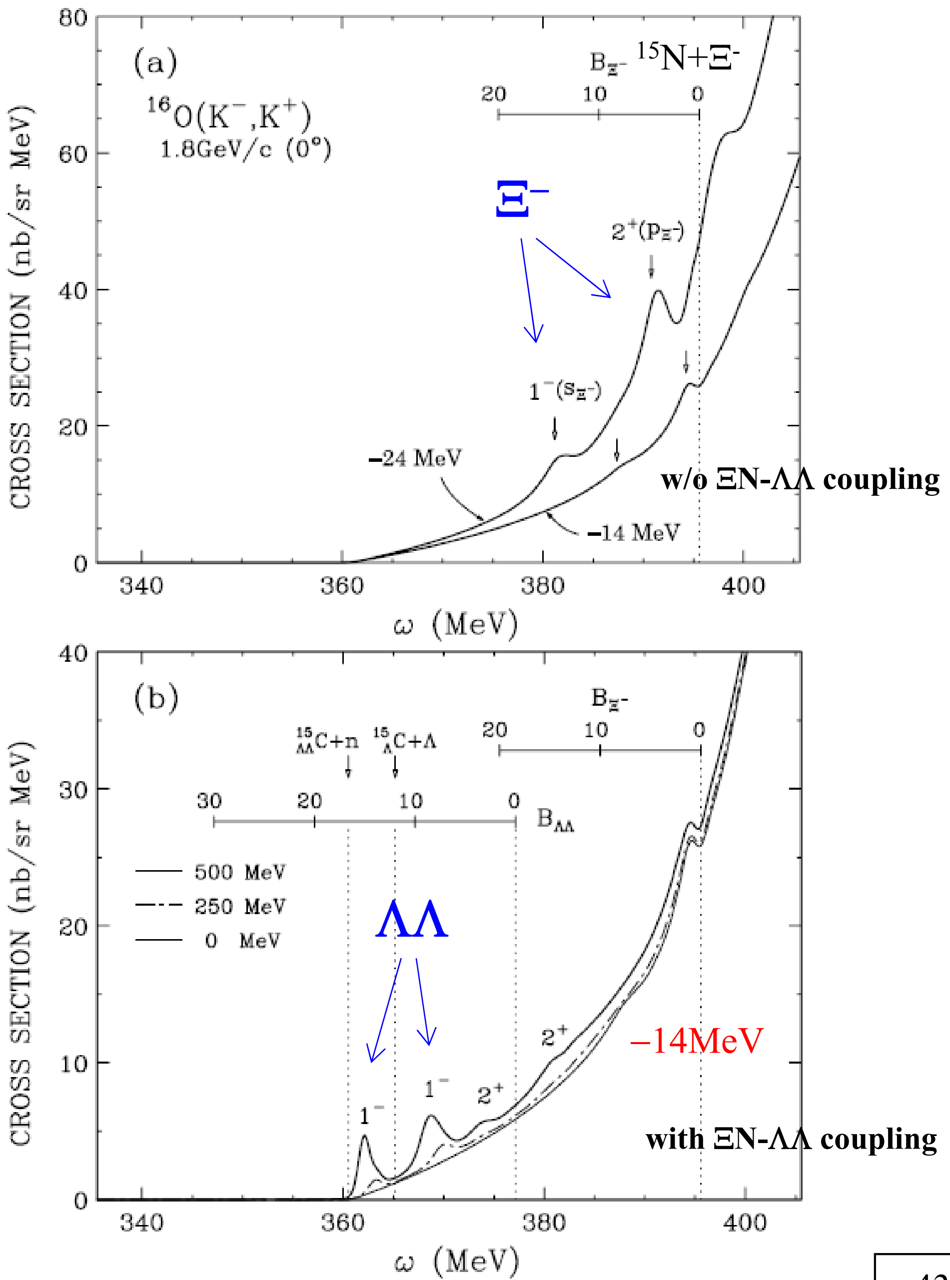
Ξ-ΛΛ spectrum in DCX (K^-,K^+) reactions at 1.8GeV/c

^{16}O



Hyperon-mixing

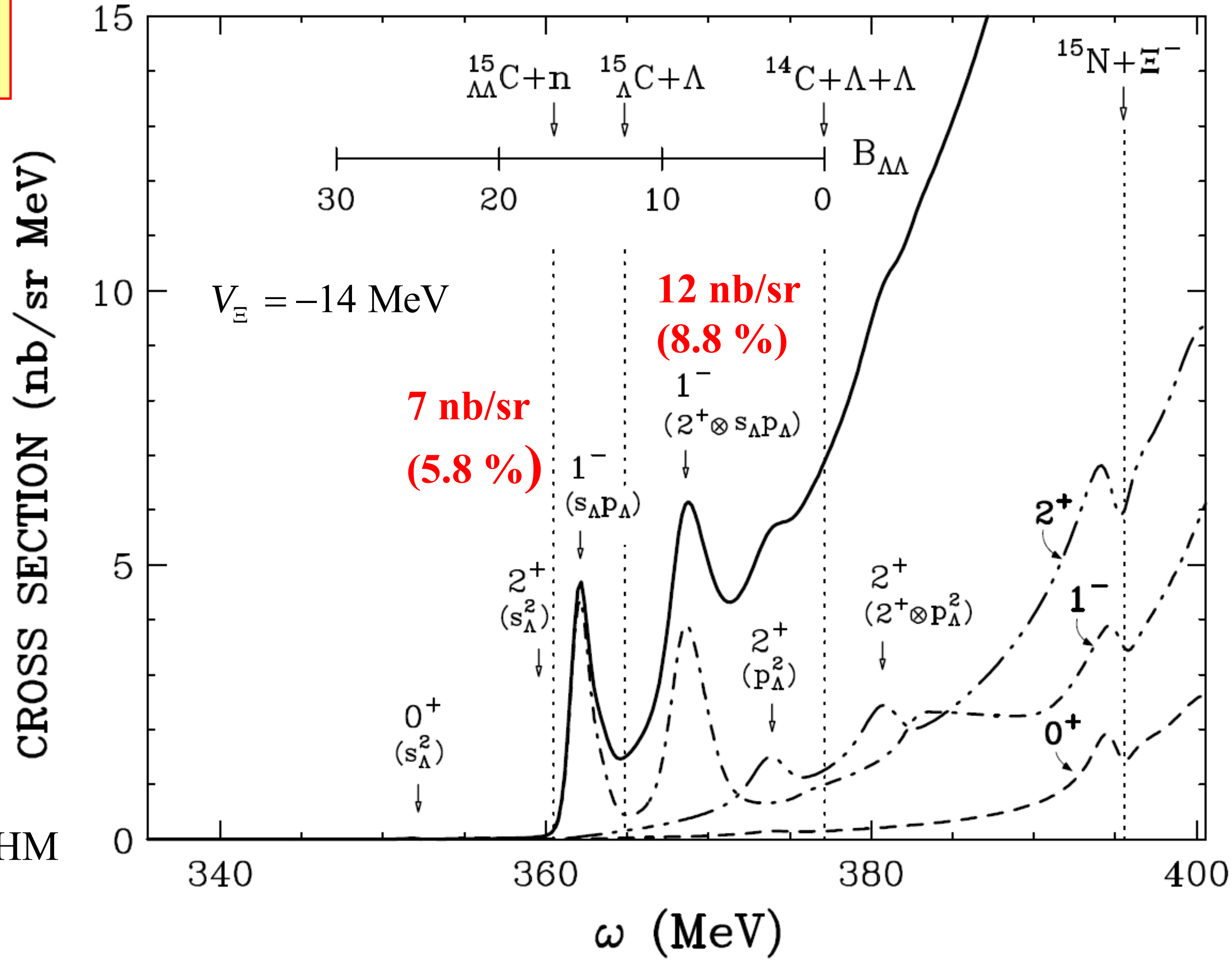
[T. Harada, Y. Hirabayashi, A. Umeya, PLB690(2010)363]



Ξ^--ΛΛ spectrum in DCX (K^-,K^+) reactions at 1.8GeV/c

T. Harada, Y. Hirabayashi, A. Umeya, PLB690(2010)363.

^{16}O

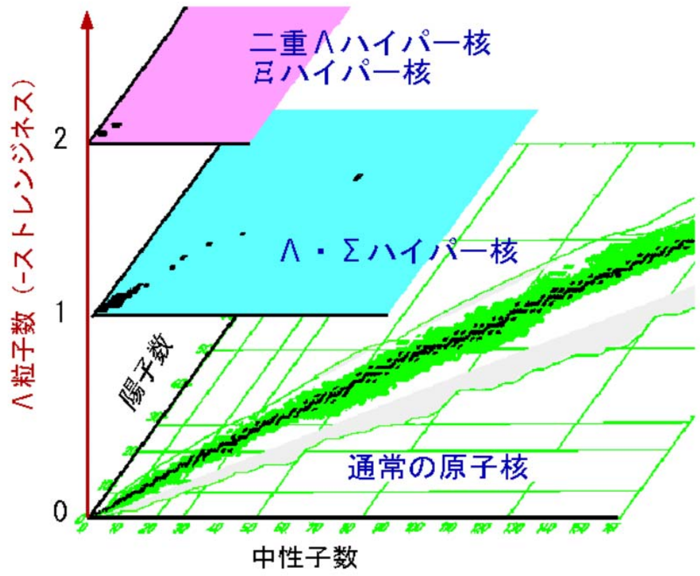


1.5MeV FWHM

The large momentum transfer $q_{\Xi^-} \simeq 400$ MeV/c leads to *the spin-stretched* Ξ^- *doorways states* followed by $[^{15}N(1/2^-, 3/2^-) \otimes s_{\Xi^-}]1^- \rightarrow [^{14}C(0^+, 2^+) \otimes s_\Lambda p_\Lambda]1^-$

Remark

Studies of the DCX reactions $(\pi^{+},K^{-}),(K^{-},K^{+})$
for hypernuclear productions
are
very important and promising .



■ Future subjects:

More microscopic calculations based on YN, YY potentials are needed to compare them with the forthcoming experimental data at J-PARC.

ハイペロン相互作用–中性子星の解明を目指して

■ΛN

U_0 (Λ) ~ (–30) MeV, U_{LS} (Λ) ~ 2 MeV → 精密測定

–38 MeV ?

E13@J-PARC

■ΣN

U_0 (Σ) ~ 斥力的, U_{LS} (Σ) ? →$\Sigma^+ p(=\Sigma^- n)$散乱 P40@J-PARC

■ΛN-ΣN

a few % mixing, ΛNN3体力 →中性子過剰ハイパー核

E10@J-PARC

■ΞN

U_0 (Ξ) ~ (–14)-(–0) MeV ? → (K–,K+)反応, Ξ-原子X線

E03,05@J-PARC

■ΛΛ-ΞN-ΣΣ

mixing prob. ?, H-particle ? →Hybrid-emulsion, ΛΛ相関

E07, P42@J-PARC

■K^-N-Λ(1405)-πΣ

U_0 (K^-) ~ –200 MeV/–50 MeV ? , "K-pp" ?

→ (K^-,N), (π^+,K^+)反応

E15,E23@J-PARC

$^3He(K^-,n)K$-pp spectrum at 1.0GeV/c (0deg)

E15@J-PARC A search for deeply-bound kaonic nuclear states by in-flight $^3He(K^-,n)$ reaction, T.Koike and T.Harada, PRC80(09)055208.

missing mass spectroscopy
+invariant mass spectroscopy

Integrated cross section in the bound region
~ 3.5 mb/sr (for YA)

^{3}He標的の優位性

- Distortion effects

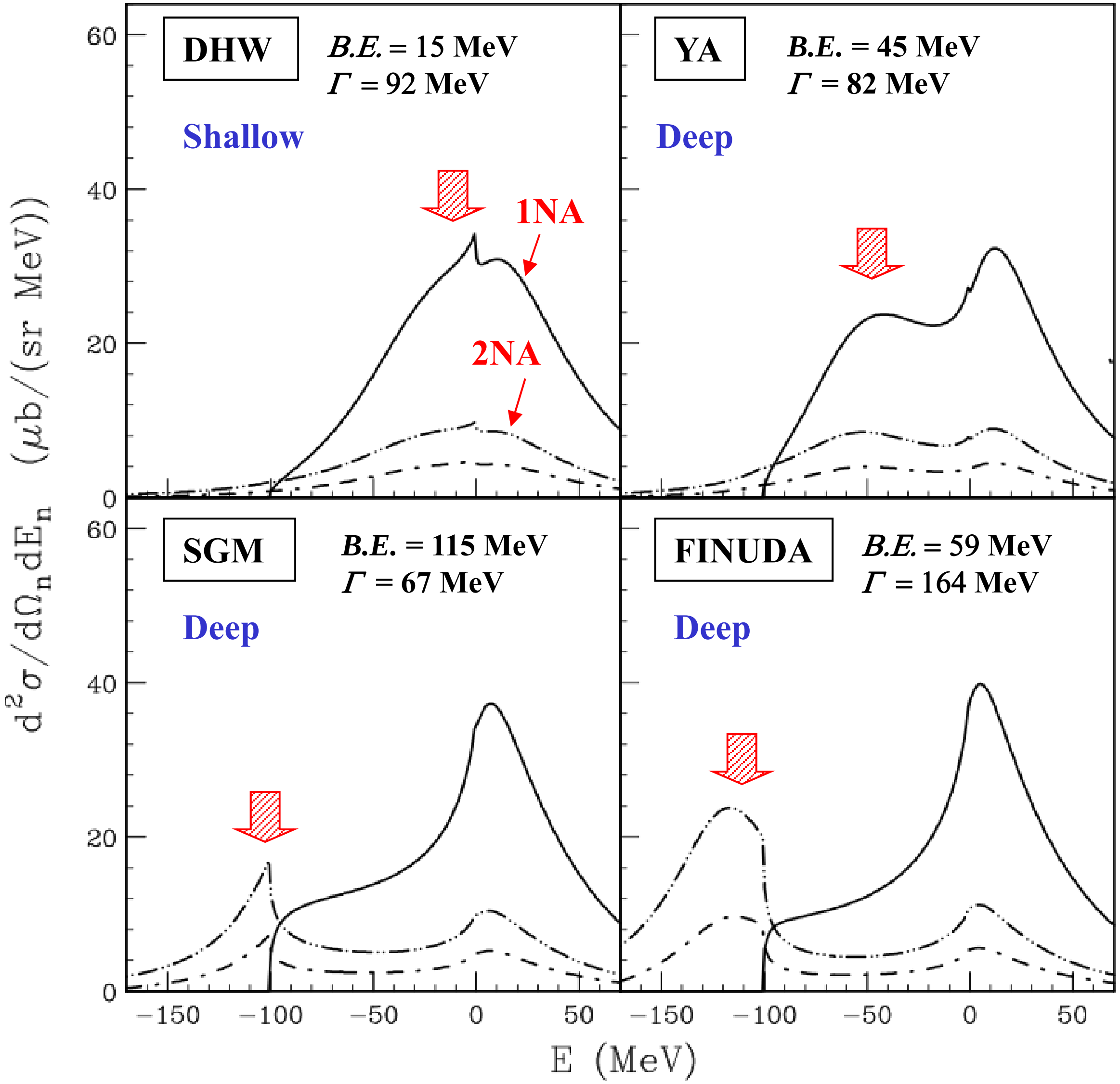
$$\frac{D_{\rm dist}[^3{\rm He}(1s_N \rightarrow 1s_K)]}{D_{\rm dist}[^{12}{\rm C}(1p_N \rightarrow 1s_K)]} = 0.47/0.095$$ → 5倍

- Recoil effects

M_C/M_A ~2/3 → 1.8倍

- Small-size effects

L=0状態だけが束縛



Conclusion

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

- 中性子星の構造・進化の解明を目指して→高密度QCD物質
- バリオン-バリオン間相互作用の理解、短距離斥力の起源
- 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

キーワード

ハイペロン混合，荷電交換反応

Thank you very much.