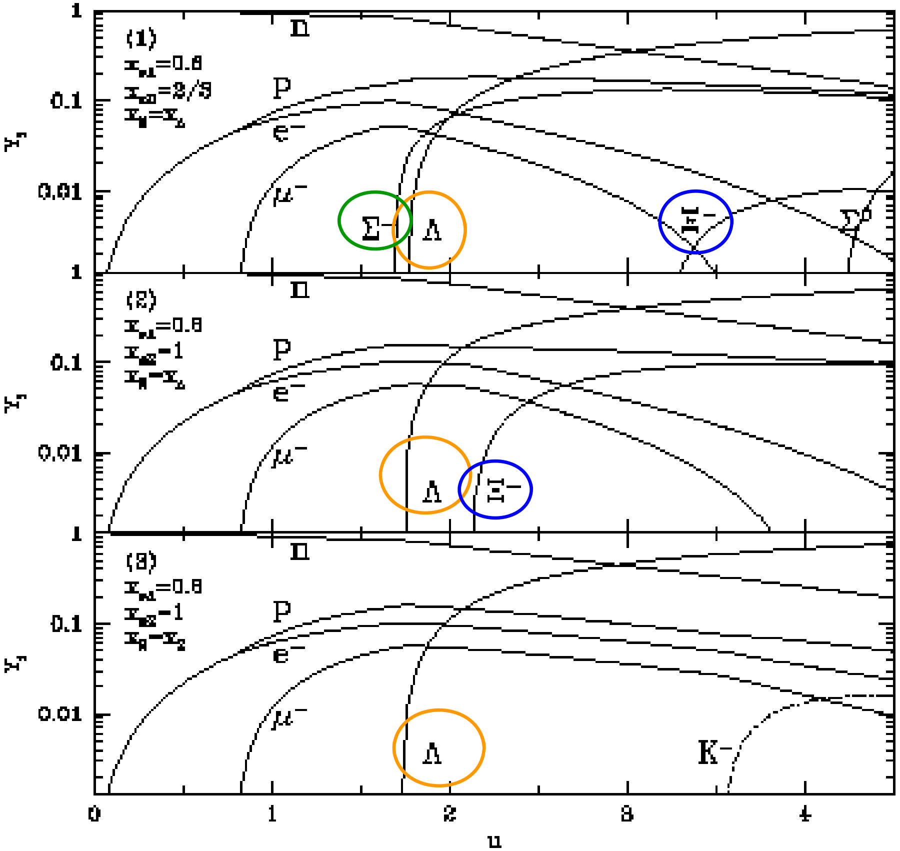
# Neutron star core

## = “An interesting neutron-rich hypernuclear system”

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

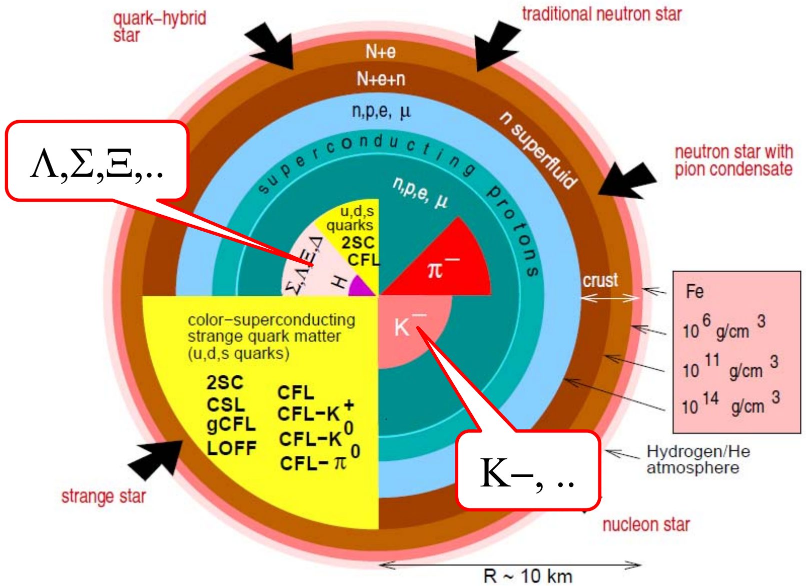



$U_\Sigma < 0$
$U_\Xi < 0$

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

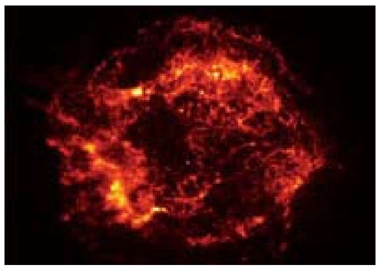
$U_\Sigma > 0$
$U_\Xi > 0$

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




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

***Hyperon-mixing***



Cassiopeia A nebula
NASA/CXC/SAO.

# Thermal evolution of neutron stars

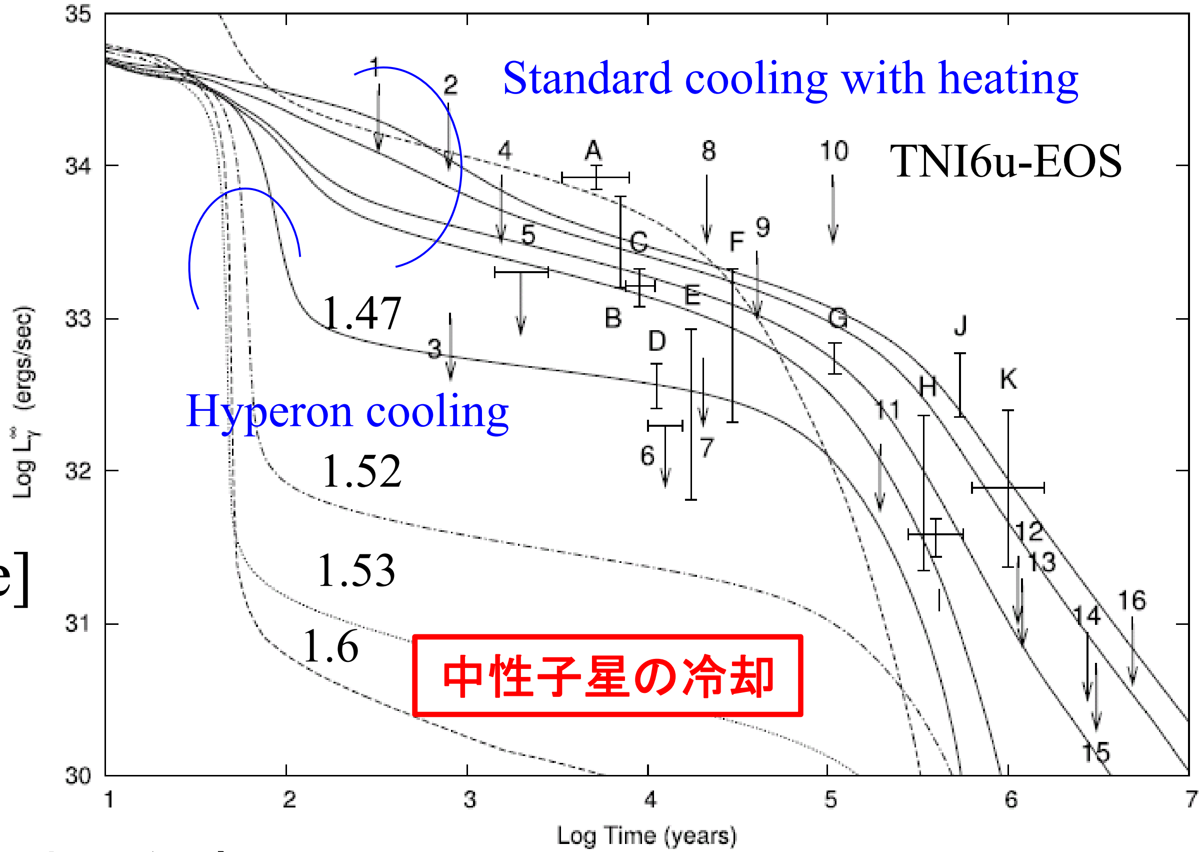
Rapid neutrino emission
via weak processes
(Direct/Modified Uruca)

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

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

- 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]



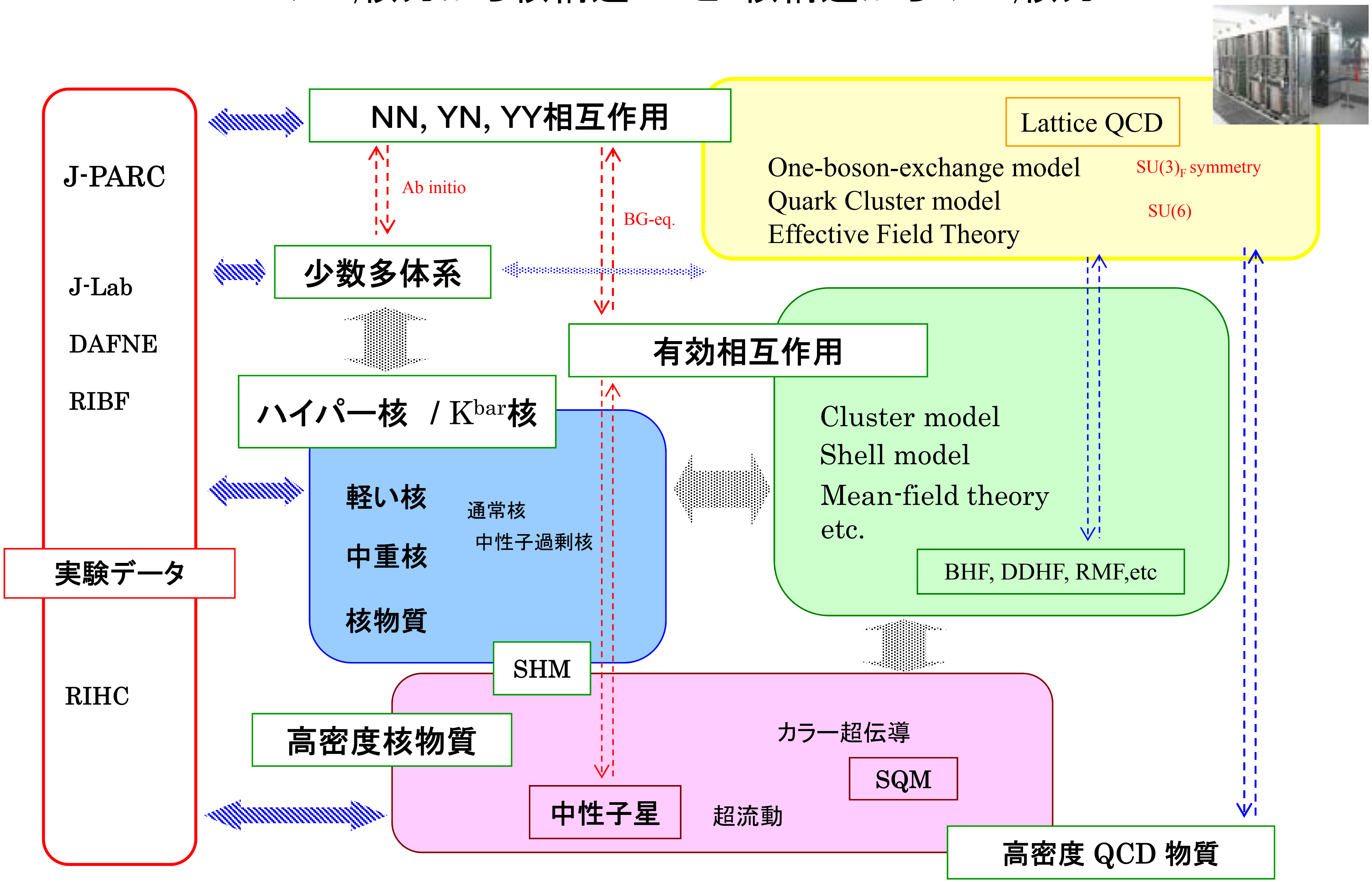

- Hyperon superfluidity v.s. YY intarctions
  - Nagara event $\Delta B_{\Lambda\Lambda}$~0.7 MeV → no ΛΛ superfluidity ?

➡ **YN, YY相互作用の性質によって強く依存する**

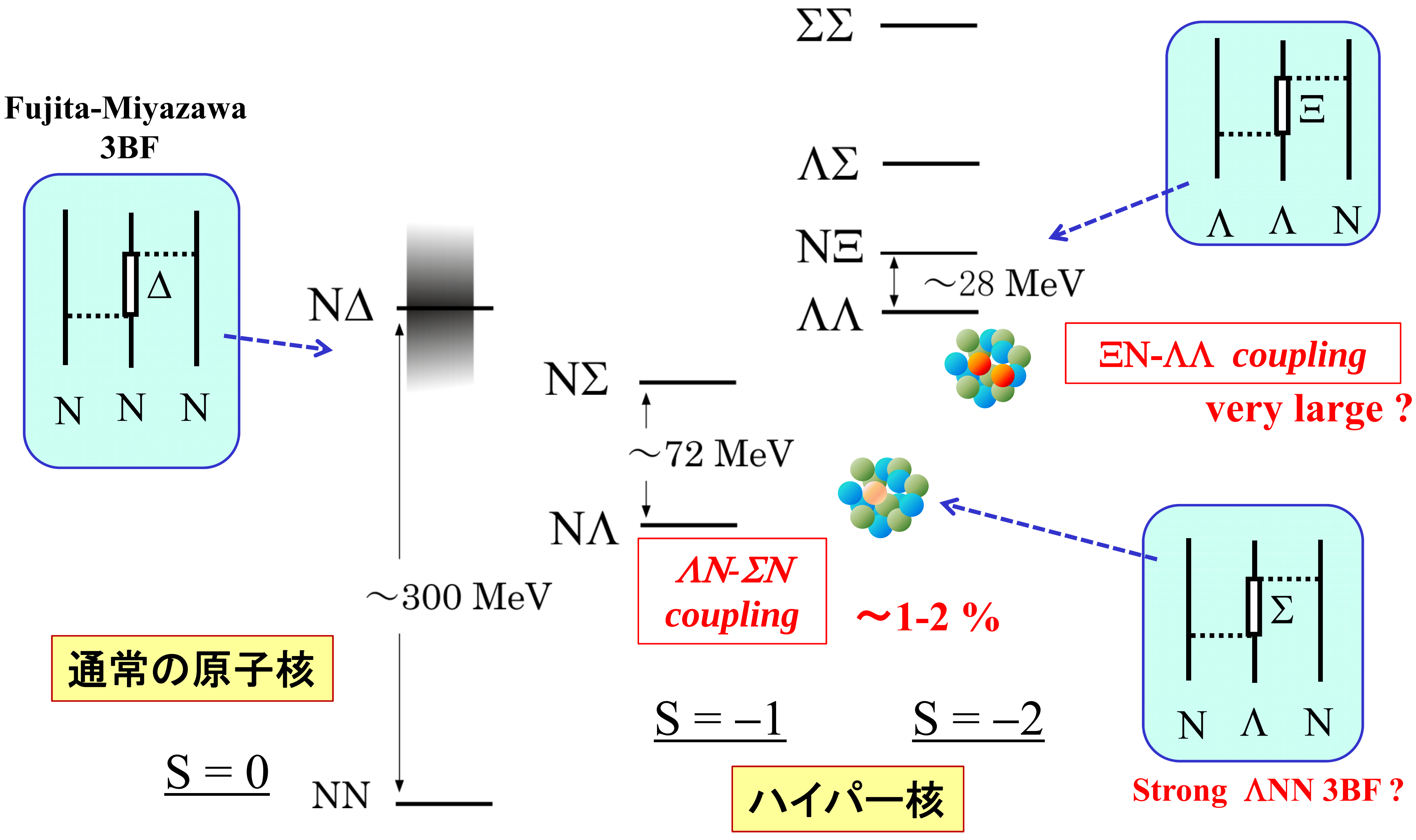
# ストレンジネス核物理の展開

by E.Hiyama

“QCD,核力から核構造へ”と“核構造からQCD,核力へ”



# Dynamics in Strangeness Nuclear Systems

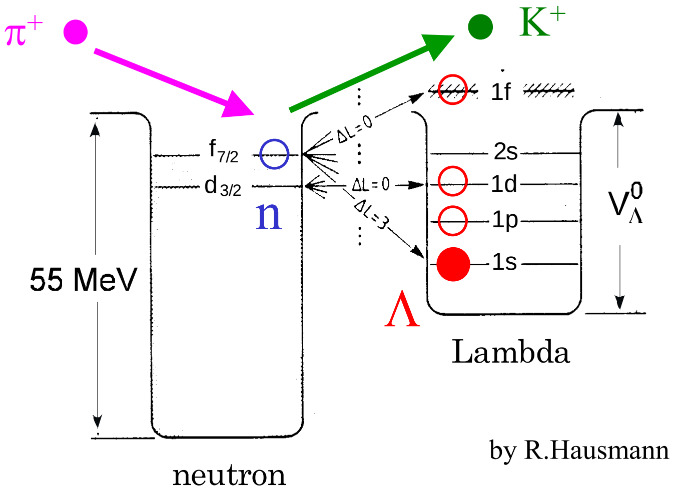



- ハイペロン混合による多彩な振る舞い
- 核内における3体力 (3BF)の役割

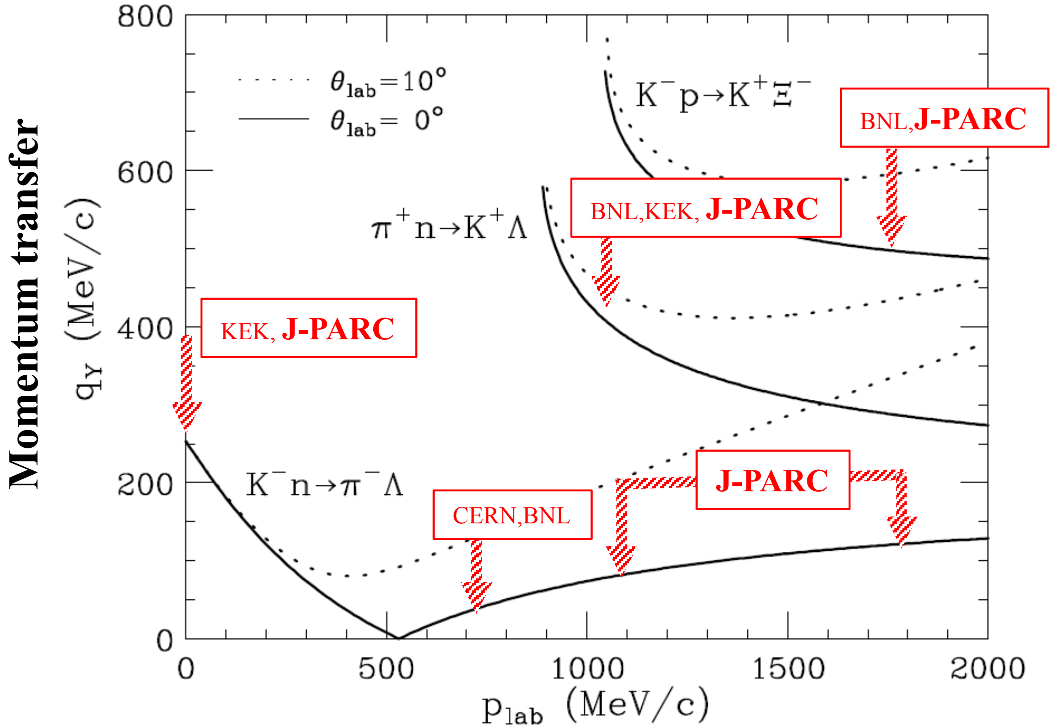
# S＝−1の原子核

# Hypernuclear Production Reactions

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



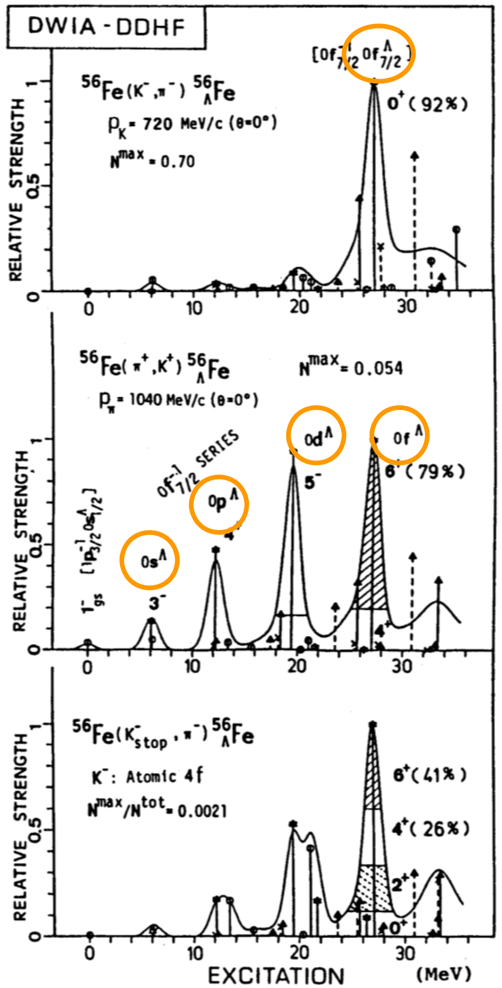

by R.Hausmann and W.Weise




## Theoretical calculations

$^{56}$Fe target

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




**($K^-$,$\pi^-$)** **720 MeV/c**

$q_\Lambda$ ～60-100MeV/c

**"Substitutional"**

$\Delta\ell \simeq 0$

**($\pi^+$,$K^+$)** **1040 MeV/c**

$q_\Lambda$～400MeV/c

**"Spin-Stretched"**

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

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

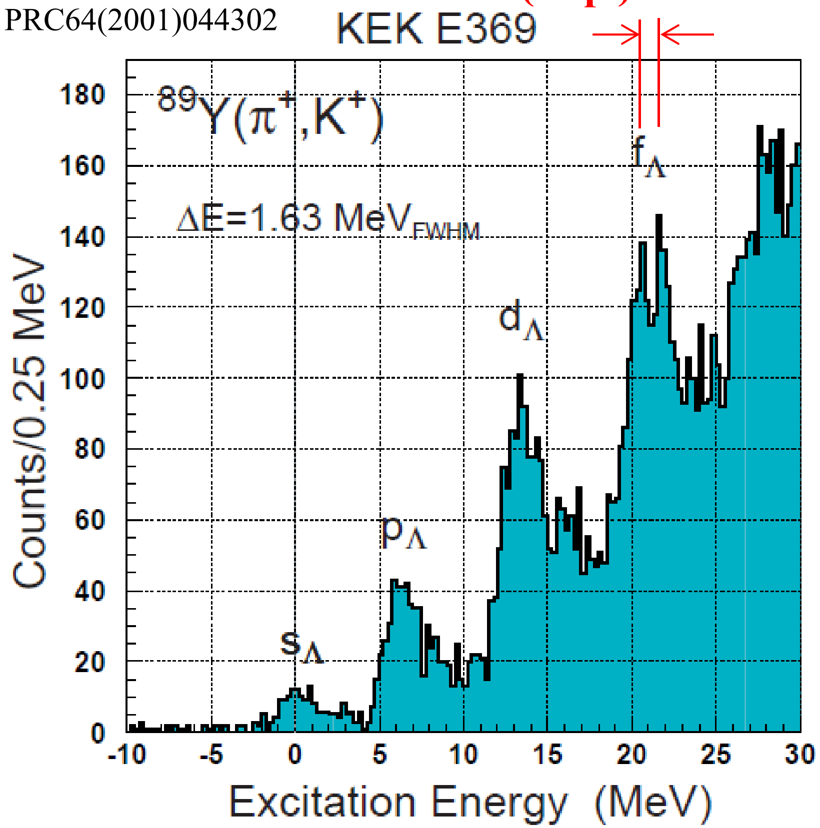
**($K^-$,$\pi^-$)** **Stooped K-**

$q_\Lambda$～280MeV/c

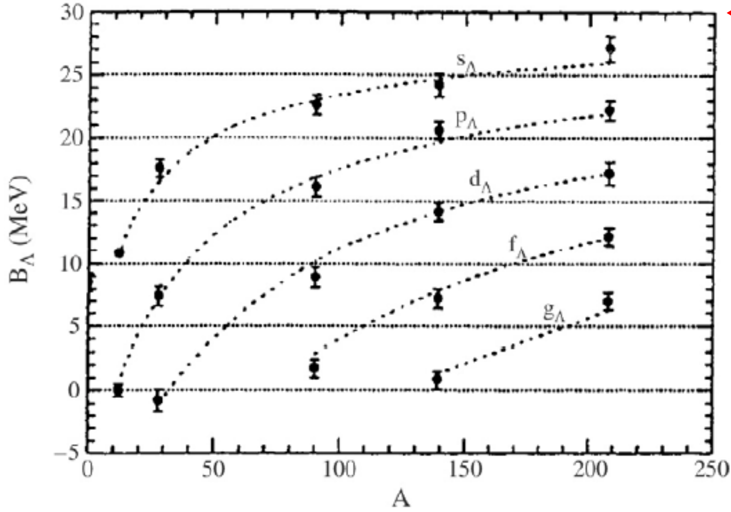
# $\Lambda$ s.p. potential and $\Lambda$ spin-orbit splitting in $^{89}_{\Lambda}$Y

$V_\Lambda$ ?

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




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




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

$a = 0.6$ fm

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

WS analysis

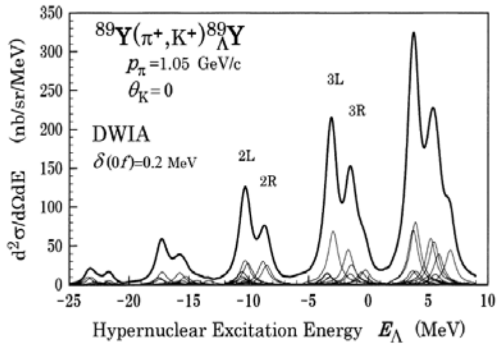
[O. Hashimoto, T. Tamura, PPNP57(2006)564]

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

SM analysis

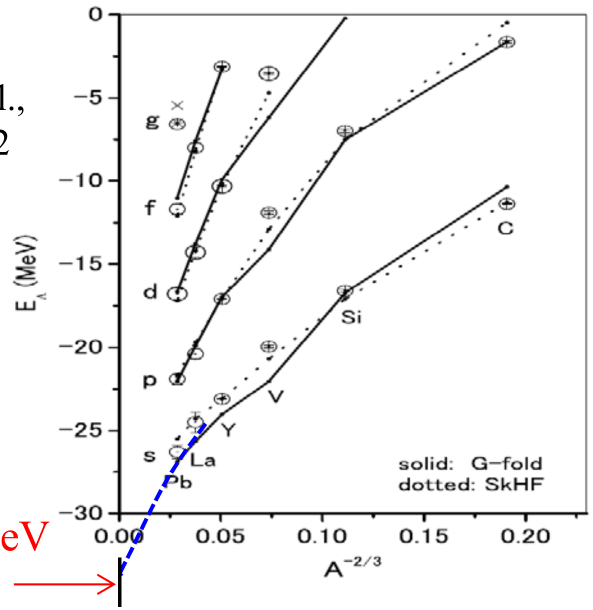
- $\Lambda N^{-1}$ particle-hole ex.
- inter-shell coupling

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




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

G-matrix folding model

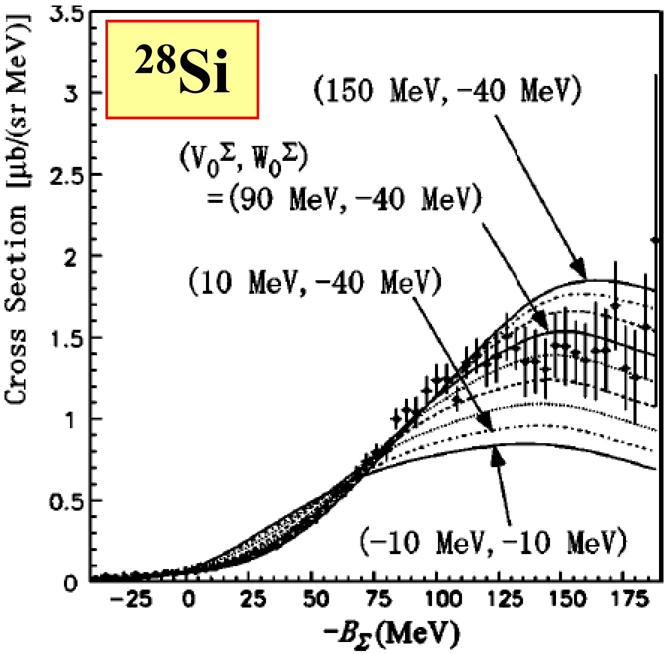


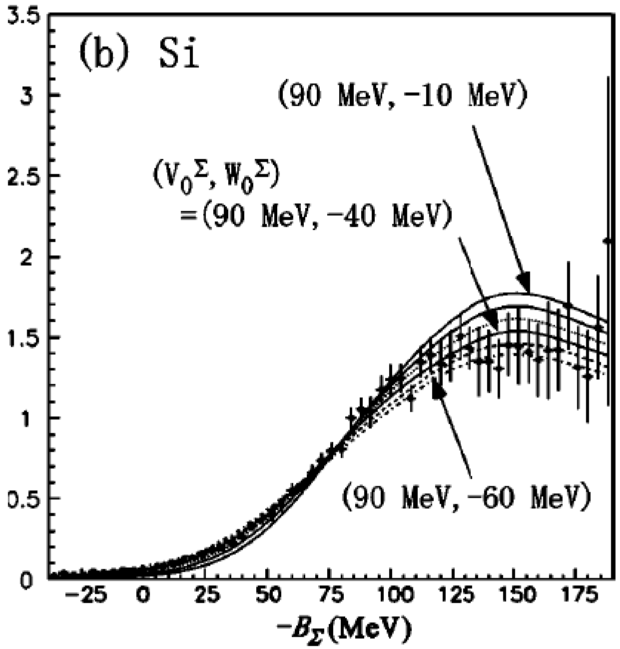

$V_0^\Lambda \simeq -37.2$ MeV ($A \to \infty$)

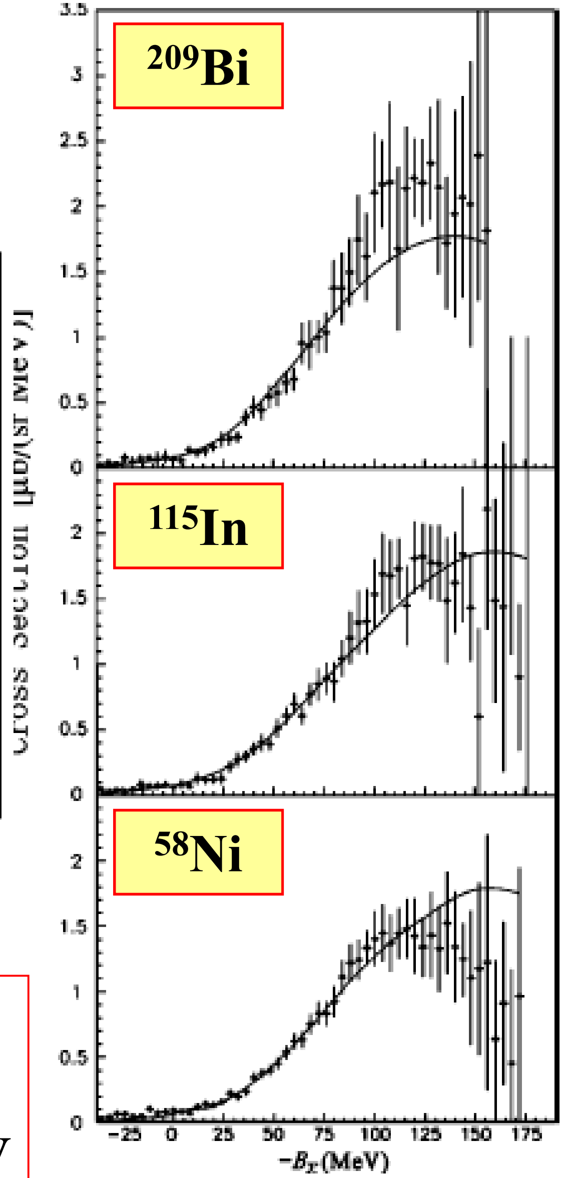
# $\Sigma^-$ spectrum by $(\pi^-,K^+)$ reaction at 1.2GeV/c

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

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

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

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

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

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

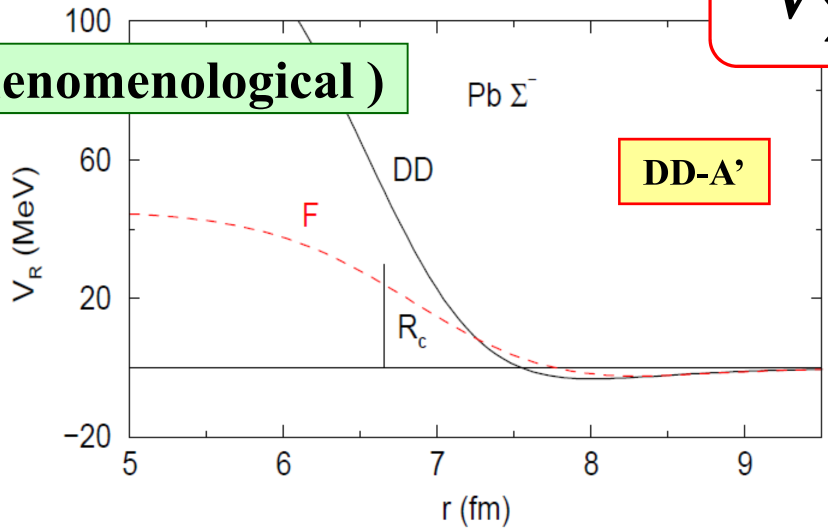
**Strong repulsion with large imaginary**

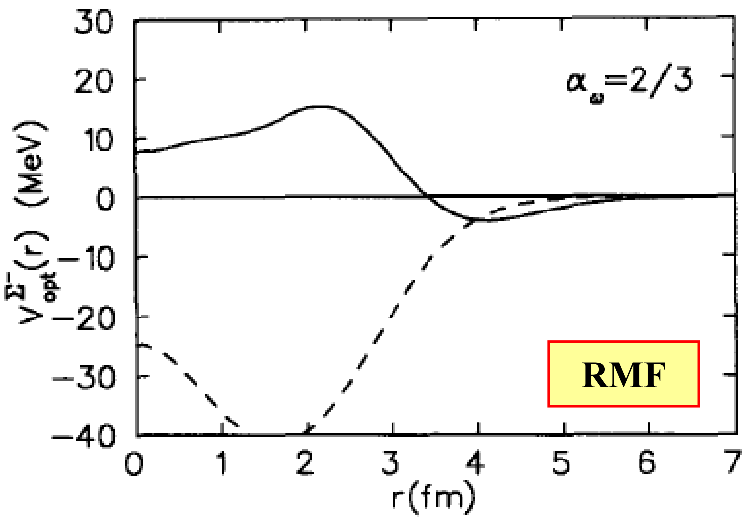
# $\Sigma^-$ s.p. potentials (fitted to the $\Sigma^-$ atomic data)

$V_\Sigma$ ?

## 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.



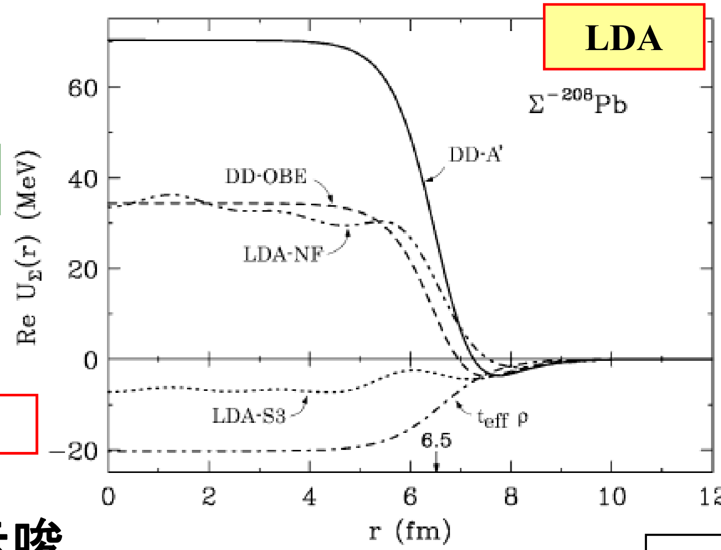

## Relativistic mean-field (RMF) potential

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

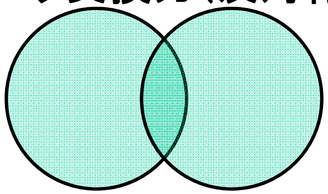
# バリオン-バリオン間相互作用の短距離斥力

Quark Cluster Model

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

Spin-flavor SU(6) symmetry

クォーク交換力（反対称化）



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, $^3S_1$) |

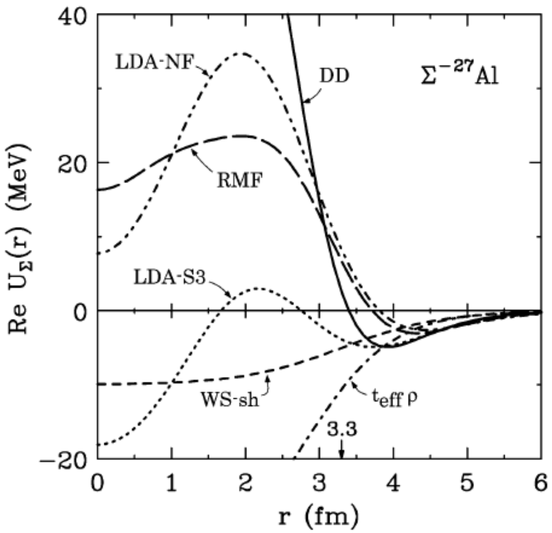
➢SU(6)sp symm. → Strongly spin-isospin dependence, $V_{ALS}(\Lambda N) \sim V_{LS}(\Lambda N)$

# $^{28}Si(\pi^-,K^+)$ reaction at 1.2GeV/c

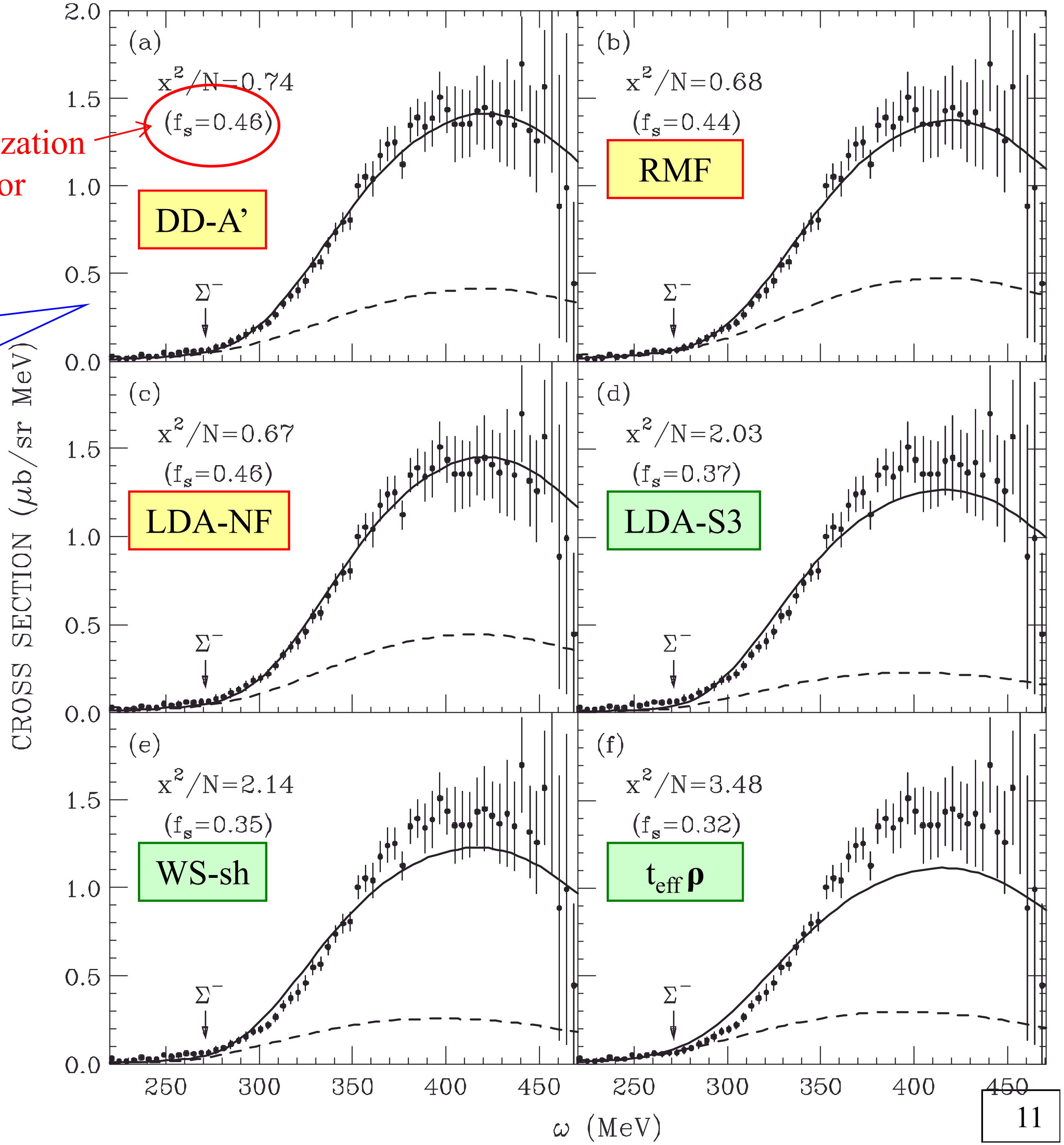
$^{28}Si$

Normalization factor

***Consistent with the potentials fitted to $\Sigma^-$ atomic data !!***

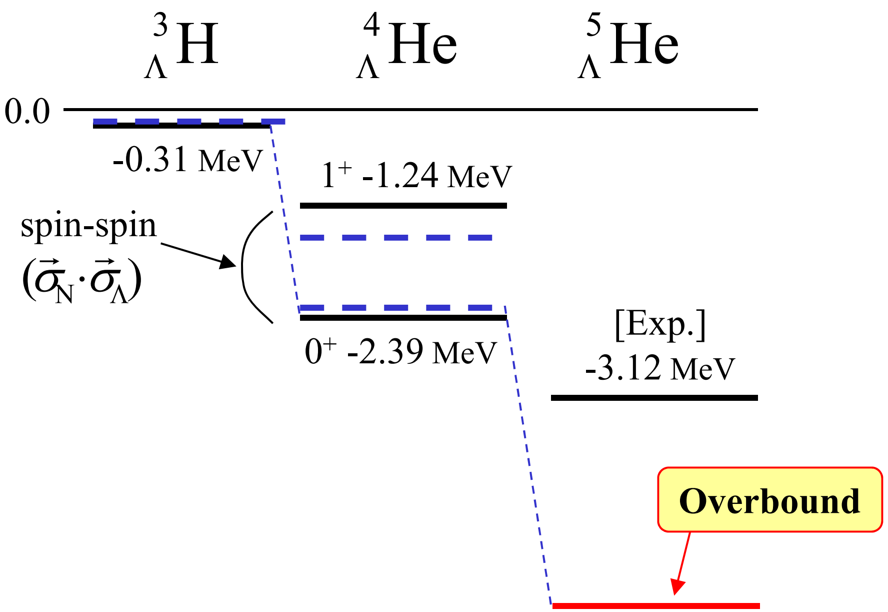



T.Harada, Y.Hirabayashi, NPA759 (2005) 143



# Overbinding Problem on s-shell Hypernuclei

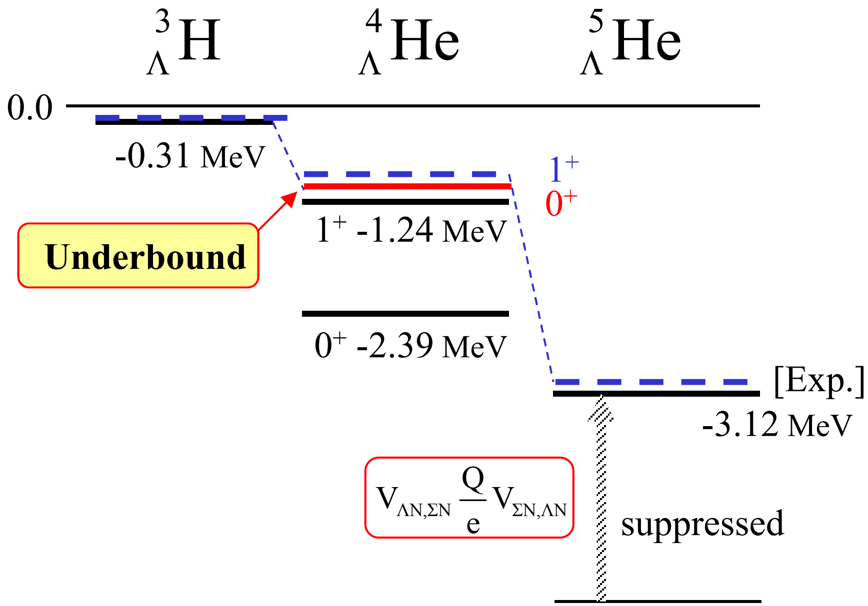
**The Overbinding Problem**




ΛN single-channel calc.

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

**The Underbinding Problem**

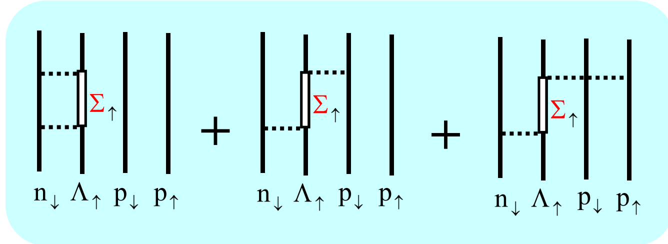



g-matrix calc. with ΛN-ΣN(D2)

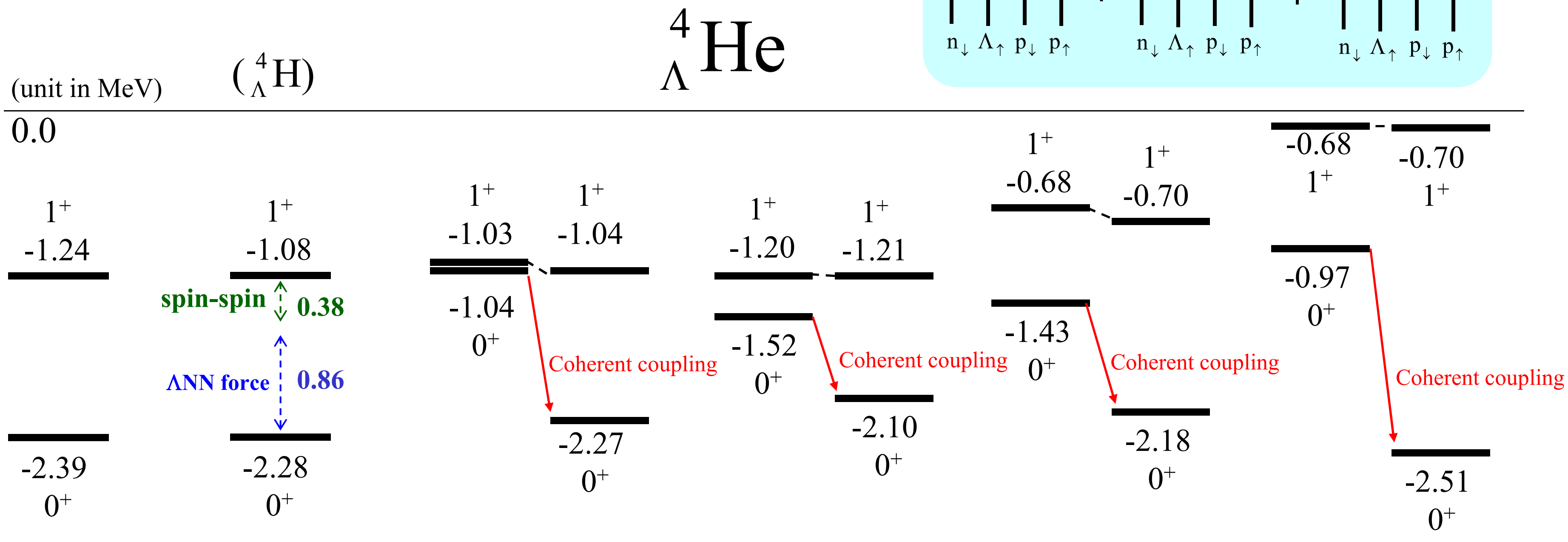
Akaishi et al., PRL **84** (2000) 3539.

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

ΛNN three-body force




*Hyperon-mixing*




| Exp. | phenomenological $V_{\Lambda N}+V_{\Lambda NN}$ $\bar{V}=6.20$ | D2 | SC97e(S) | SC97f(S) | SC89(S) |
|---|---|---|---|---|---|
| | | $P_{coh.\Sigma}=1.9\%$ | $P_{coh.\Sigma}=0.7\%$ | $P_{coh.\Sigma}=0.9\%$ | $P_{coh.\Sigma}=2.0\%$ |

**VMC**

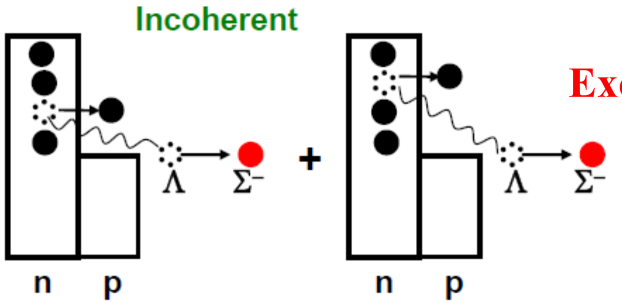
R. Sinha, Q.N.Usmani, NPA684(2001)586c

**Breuckner-Hartree-Fock**

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

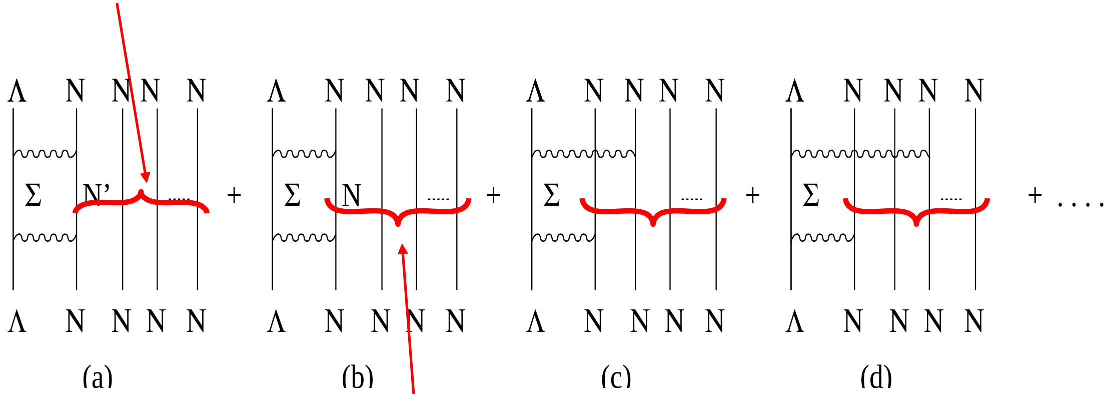
# The Λ-Σ coupling effects in neutron matter

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



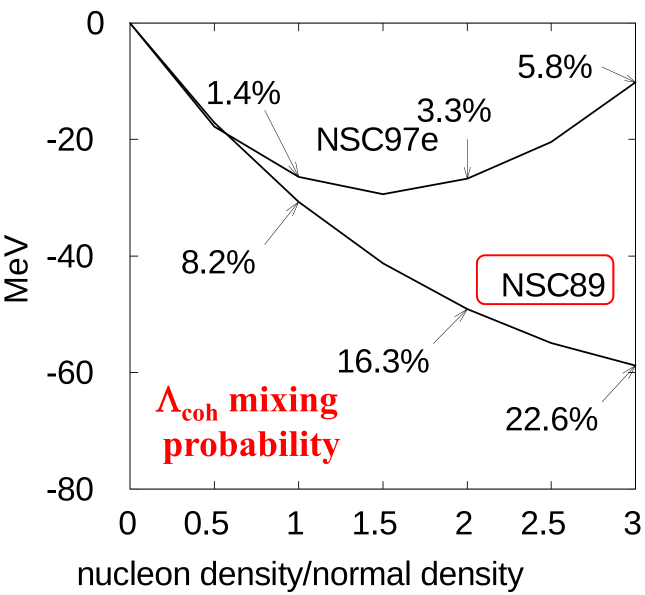

usually included in g-matrix

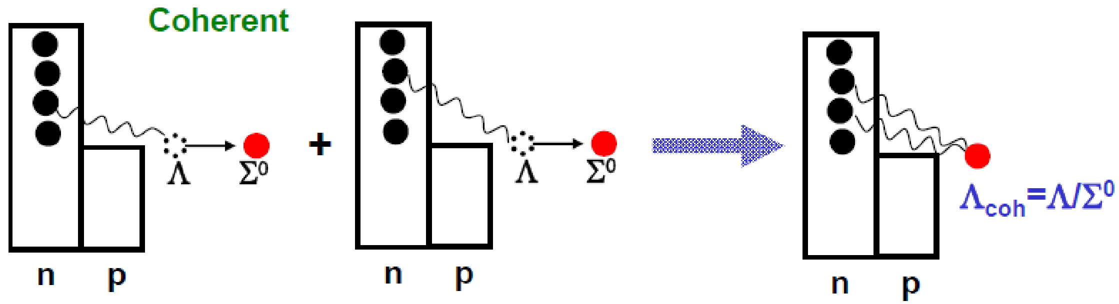
**Excited (1p1h) states**




**Ground states**

**Single particle potential for $\Lambda_{coh}$.**



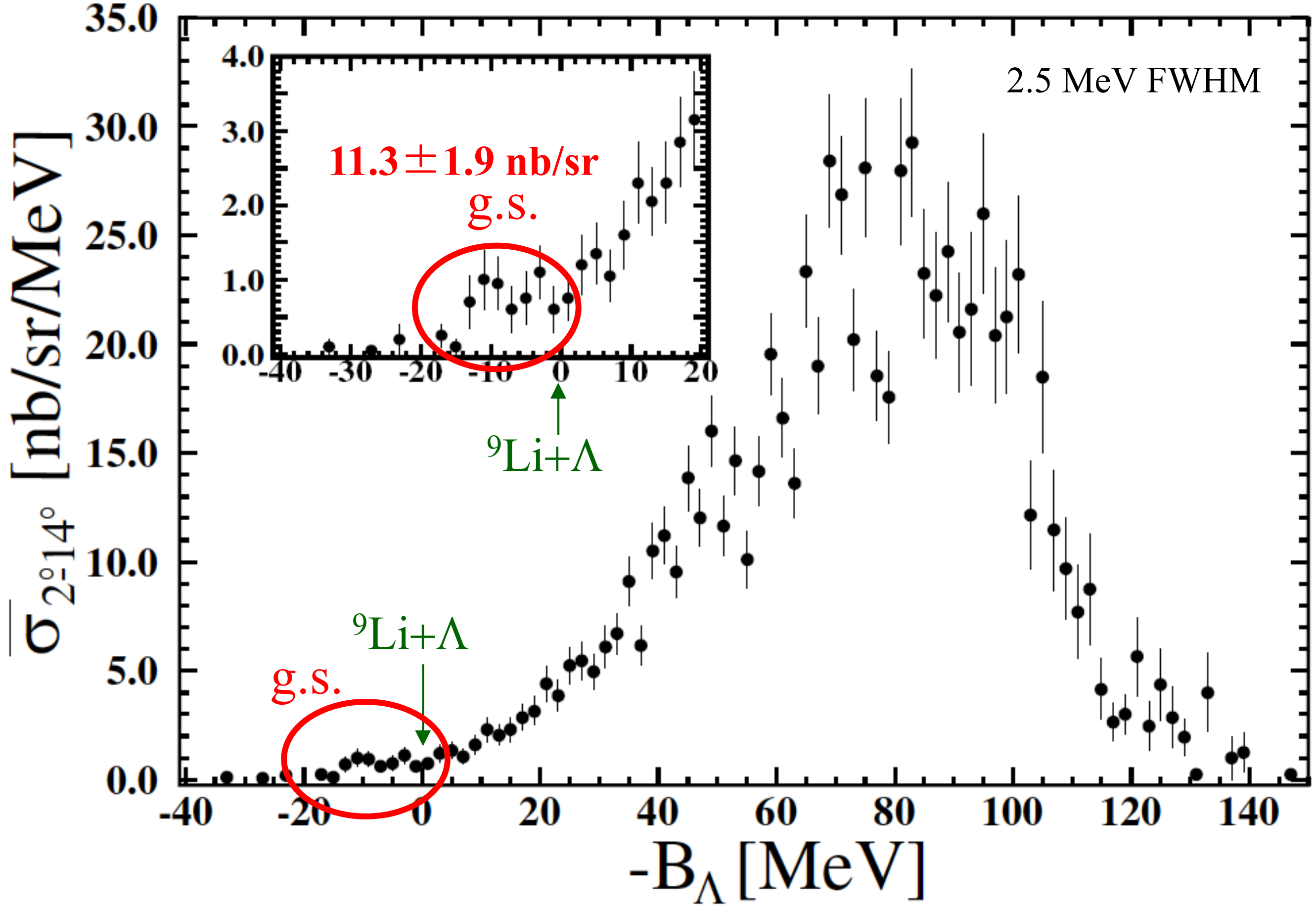

**coherent Λ-Σ coupling**

***The $\Lambda_{coh}$ mixing is enhanced in the neutron-excess environment.***

# First production of neutron-rich Λ hypernuclei

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

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




**Cross sections**

- $p_\pi$=1.20 GeV/c
$\frac{d\sigma}{d\Omega_L} \approx$ **11.3±1.9** nb/sr

- $p_\pi$=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

# $(\pi^-, K^+)$ — Double Charge Exchange (DCX) Reaction

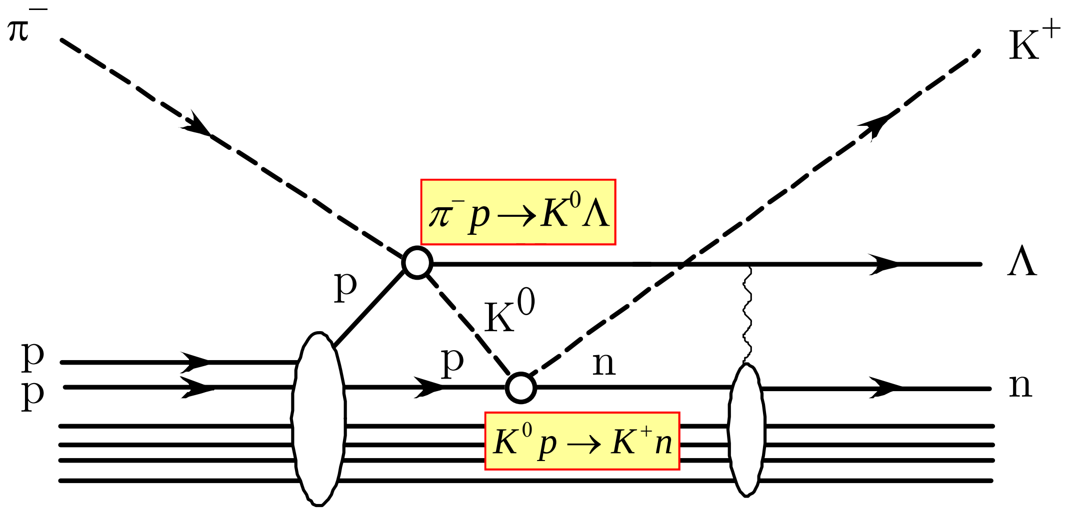
***Two-step process:***

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

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

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

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

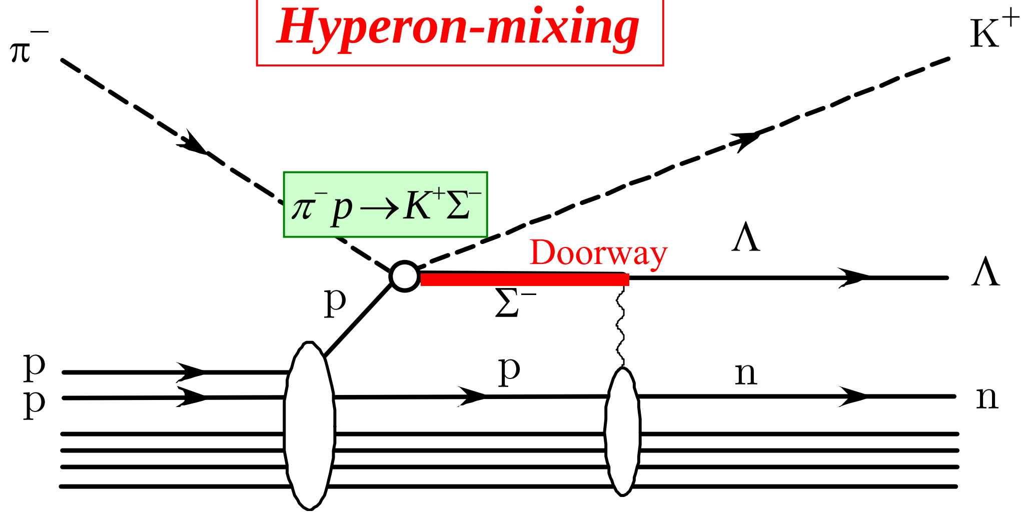



***One-step process:***

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

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

via $\Sigma^-$ doorways caused by ΛN-ΣN coupling



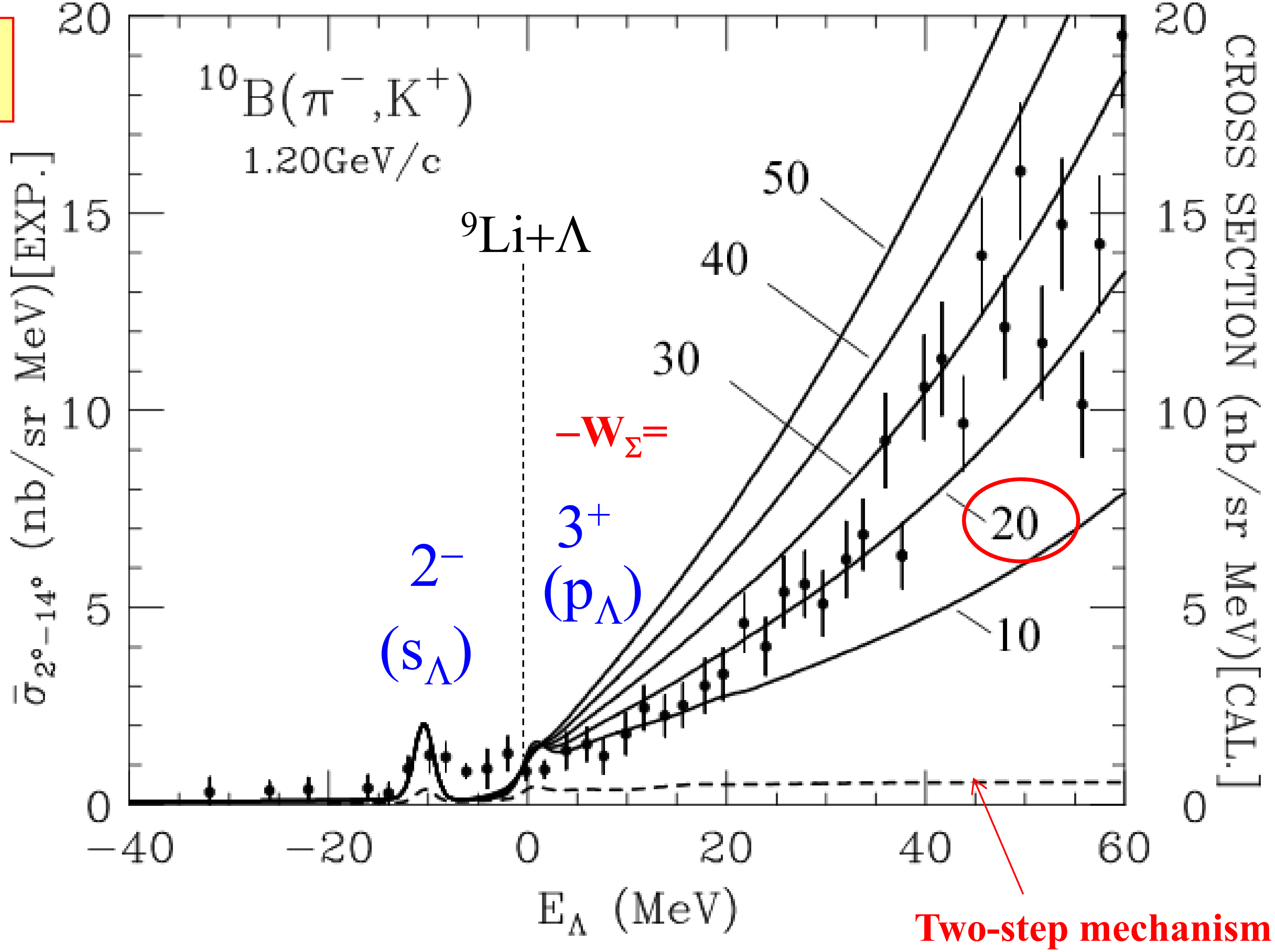
# Λ spectrum by DCX (π⁻,K⁺) reactions at 1.2GeV/c

Harada, Umeya, Hirabayashi, PRC79(2009)014603

Spreading potential dep. $W_\Sigma$

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

$^{10}$B



# $\Lambda$ spectrum by DCX (stopped $K^-$, $\pi^+$) reactions

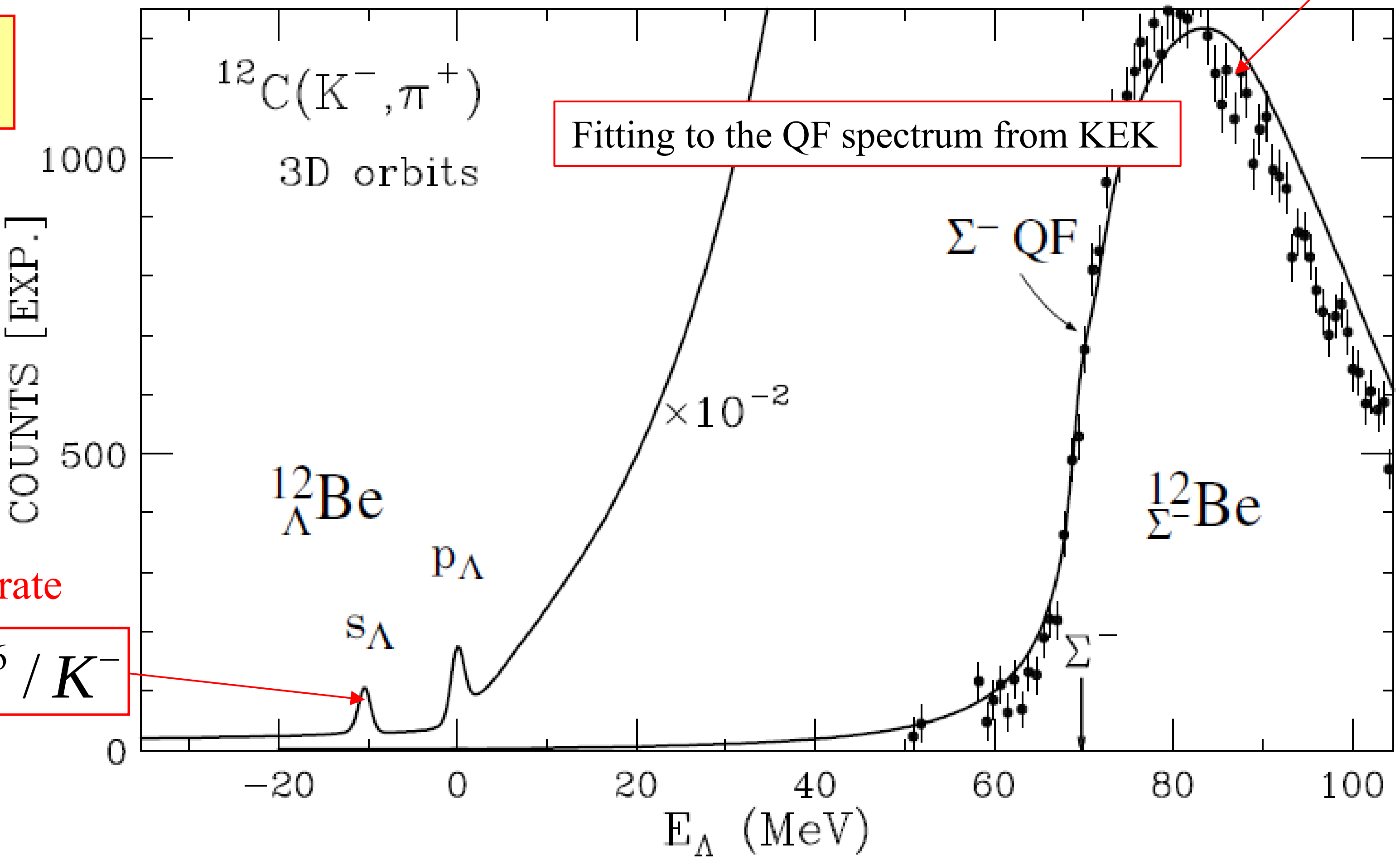
If the $\Sigma^-$ admixture probability of ~0.6 % is assumed in $^{12}_{\Lambda}$Be, we demonstrate the (stopped $K^-$,$\pi^+$) spectrum on a $^{12}$C target.

$^{12}$C

Early KEK data

Integrated production rate

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




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

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

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

**E10@J-PARC**

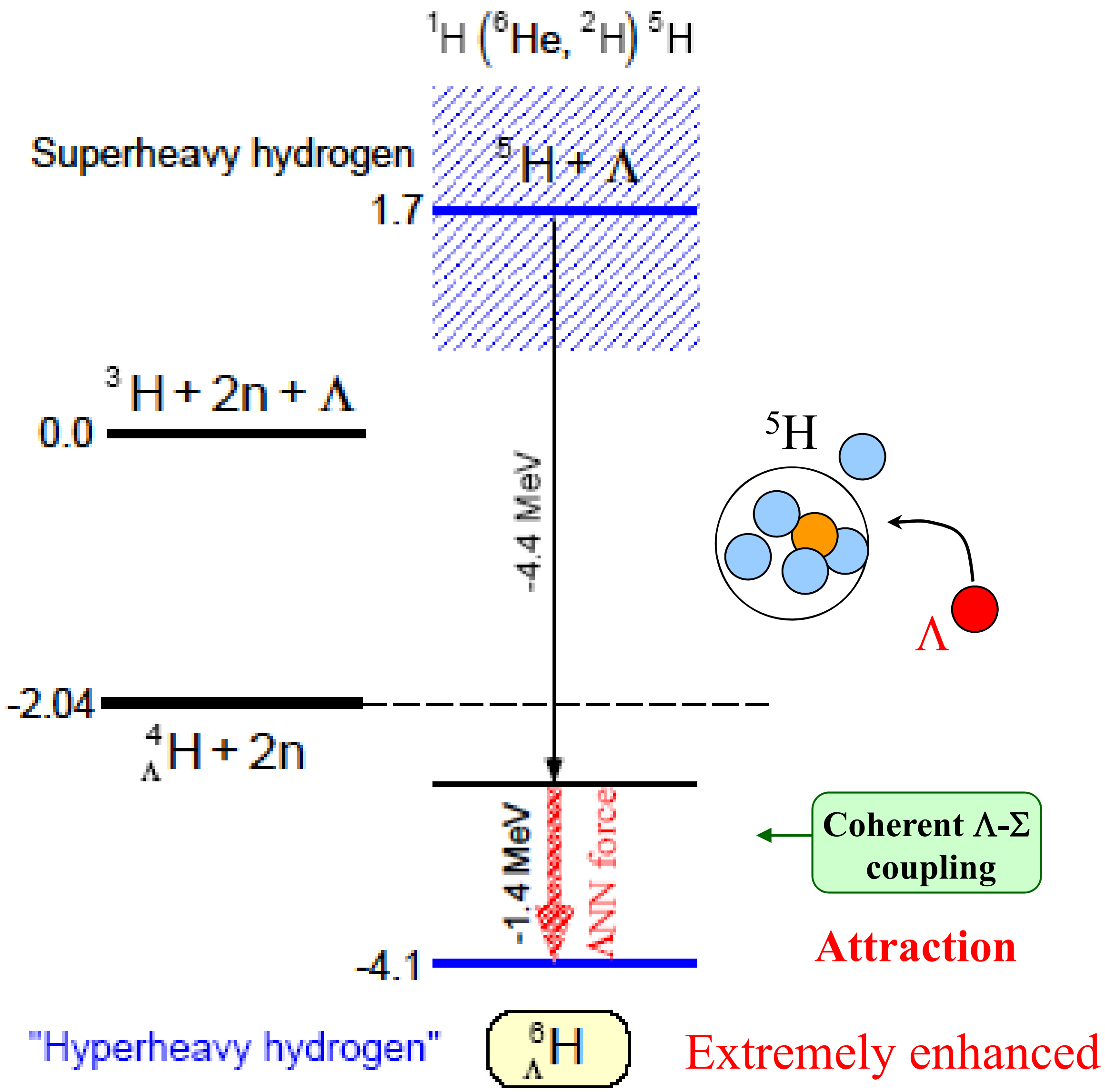
$^{6}_{\Lambda}$H  $^{6}\mathrm{Li}(\pi^-, K^+)^{6}_{\Lambda}\mathrm{H}$

**"Hyperheavy hydrogen"**

[Y.Akaishi, NPA738(2004)80c]

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

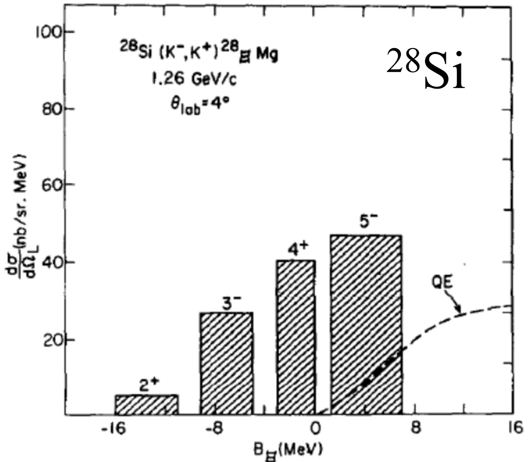
Khin Swe Myint et al.,
FBS. Suppl. 12(2000)383



# S = −2 の原子核

# Studies of Ξ⁻ s.p. potentials

$V_{\Xi}$ ?




**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**

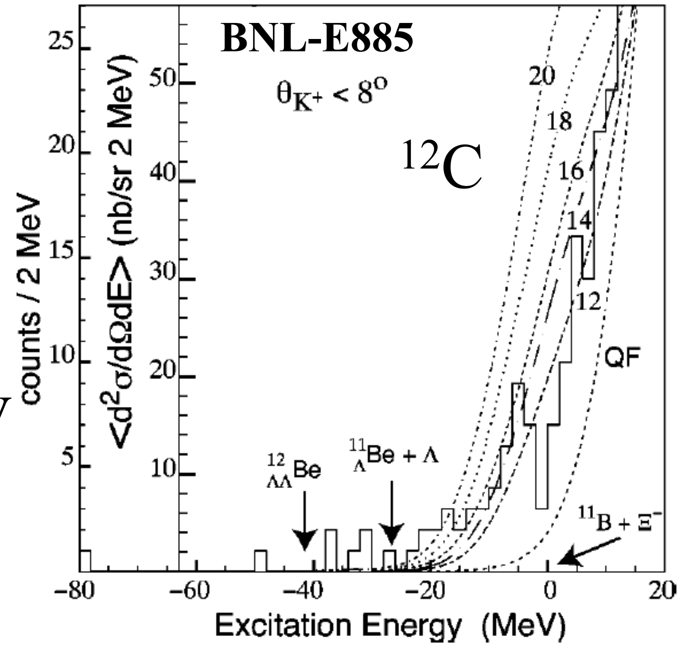
**T.Iijima et al.,NPA546(1992)588.**

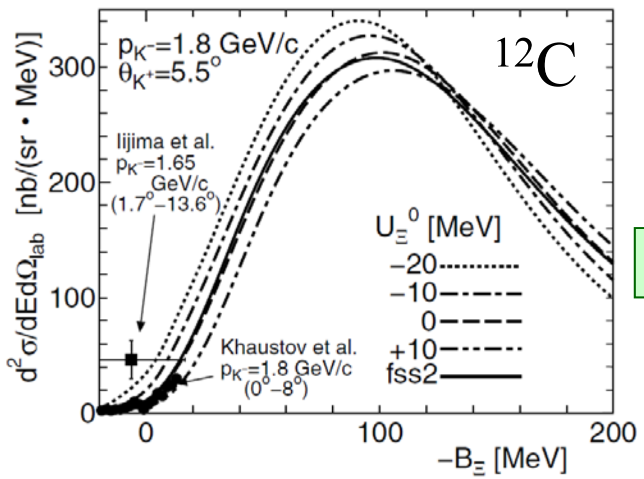
**Tadokoro et al.,PRC51(1995)2656**

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

**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.**

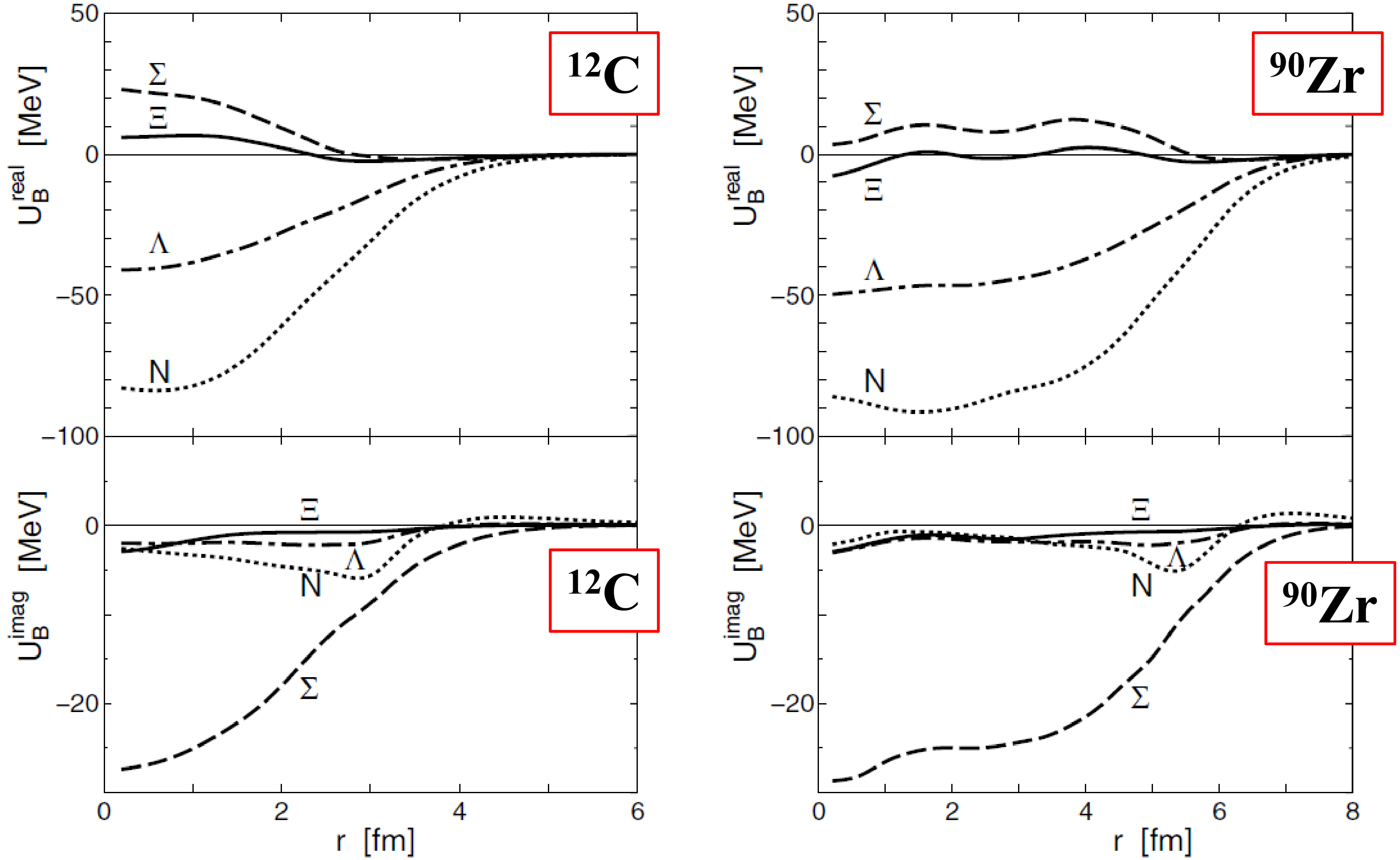
$$V_{\Xi}^{0} = -20, -10, 0, +10, +20\text{MeV} \longleftrightarrow \textbf{fss2}$$

# Hyperon s.p. potentials in finite nuclei

**G-matrix+local density approximation**

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

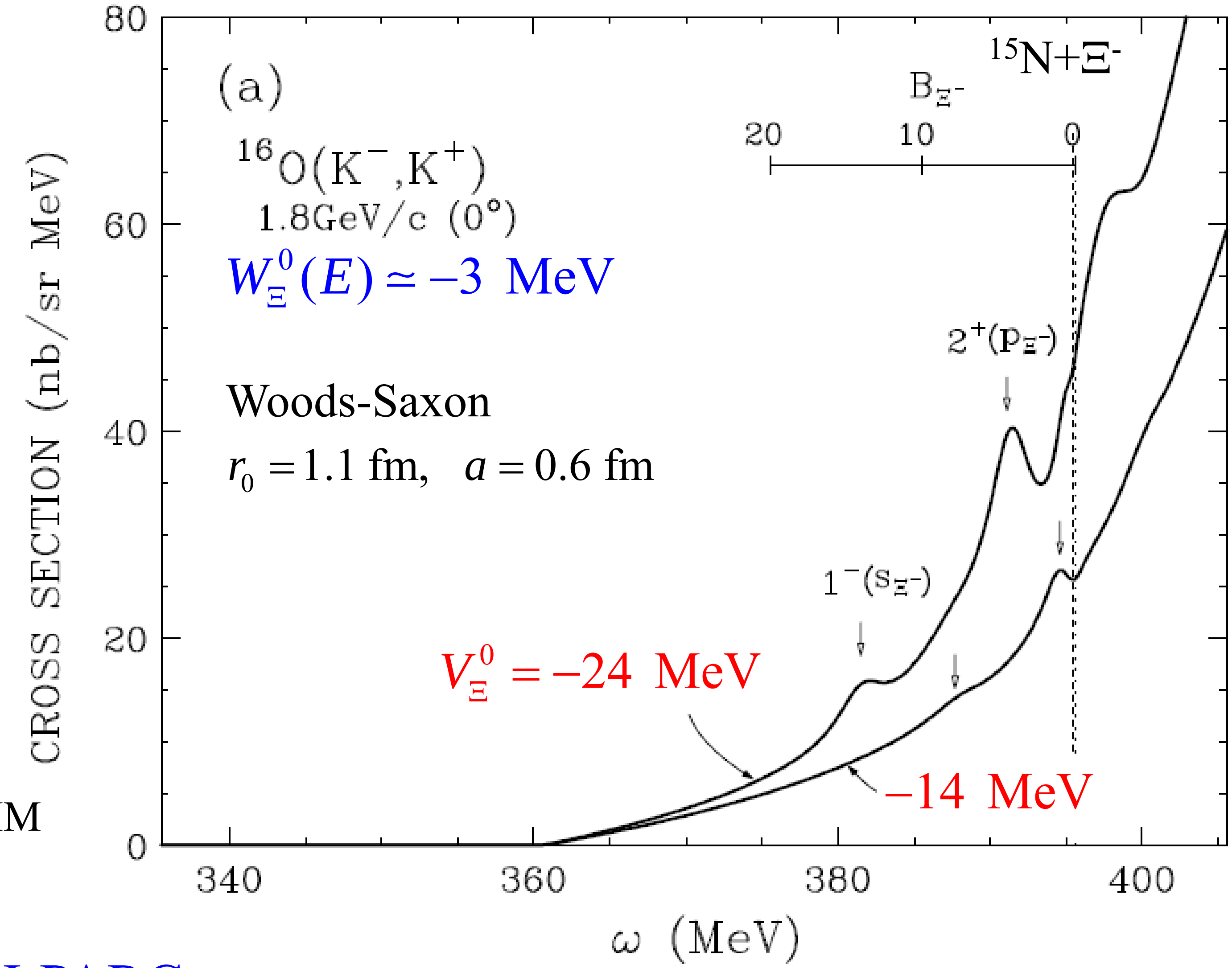
**fss2 : $SU_6$ quark-model BB interaction by Kyoto-Niigata group**



# $\Xi^-$ spectrum in DCX $(K^-,K^+)$ reactions at 1.8GeV/c

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

$^{16}O$




1.5MeV FWHM

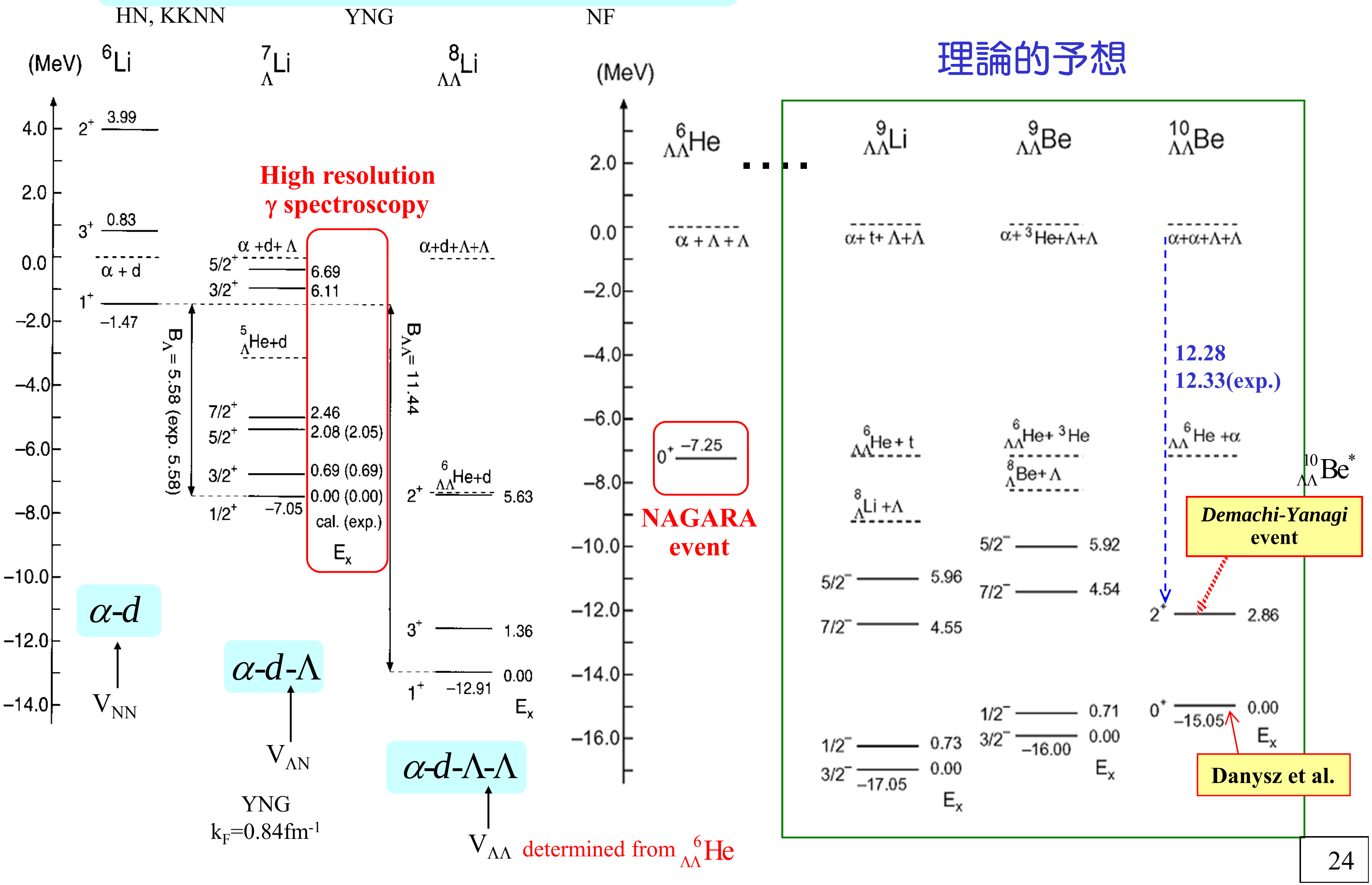
E05@J-PARC

Spectroscopic study of Ξ-hypernucleus, $^{12}{}_{\Xi}Be$ via the $^{12}C(K^-,K^+)$ reaction

# Cluser-Model Calculations for ΛΛ Hypernuclei with A=6-10

OCM+ΛN potential+ΛΛ potential

E. Hiyama et al, PRC 66(2002)024007



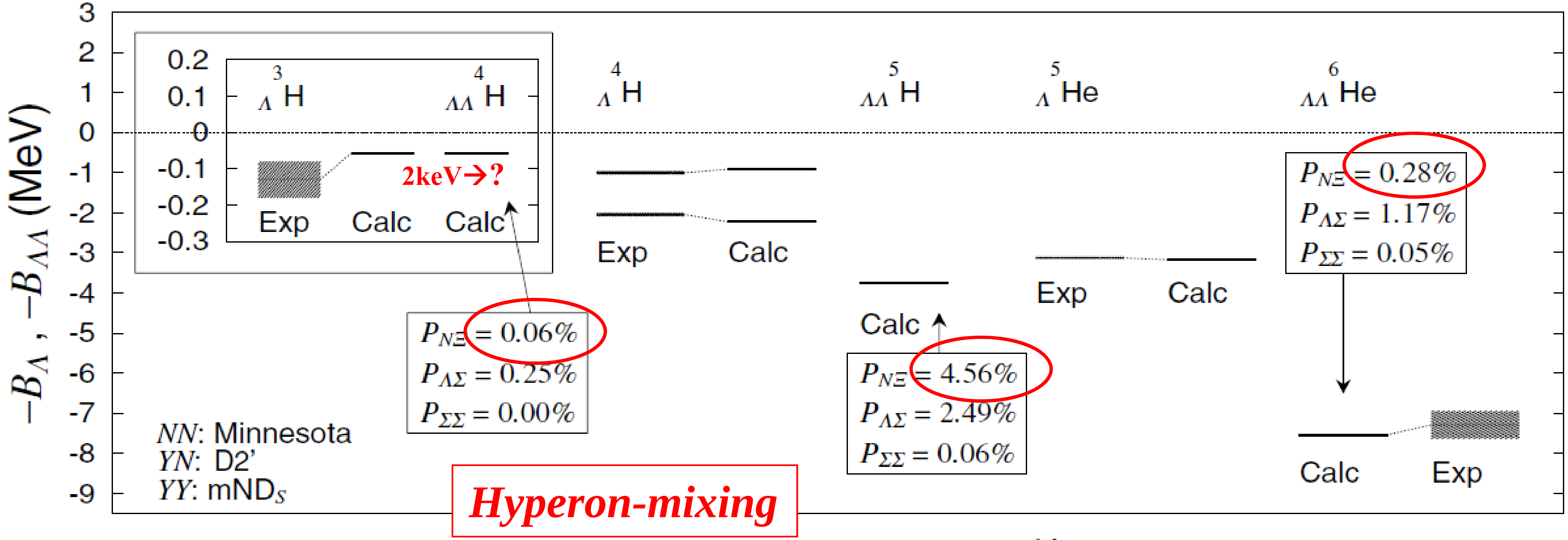
# Coupled Channel Approach to Doubly Strange Hypernuclei

## *Ab initio* calculations by SVM

H. Nemura et al., PRL94(2005)202502

$\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}) \simeq 1.01 \longrightarrow 0.67$

Nagara,2001 — Ξ mass update




## *αΞN-αΛΛ* coupled-channel calculations

T. Yamada, PRC69(2004)044301.

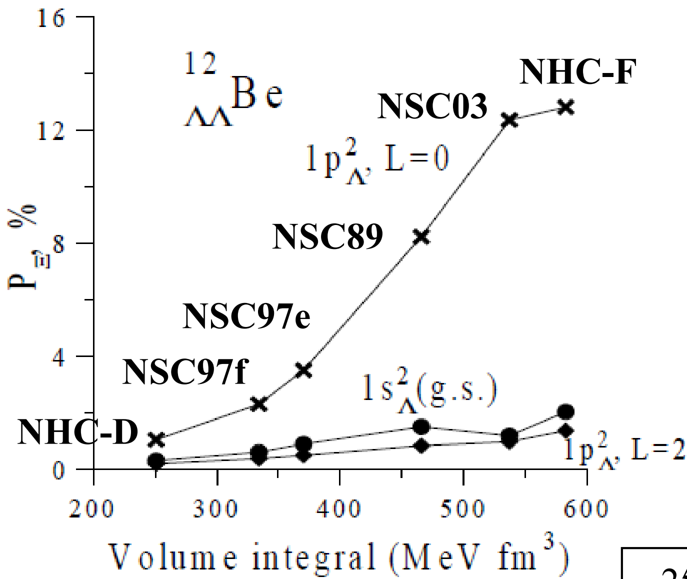
Y. Yamamoto and Th.A. Rijken, PRC69(2004)014303.

ΛΛ-ΞN s-wave: P(Ξ) < 1 %

## *Ξ-ΛΛ* coupled-channel calculations

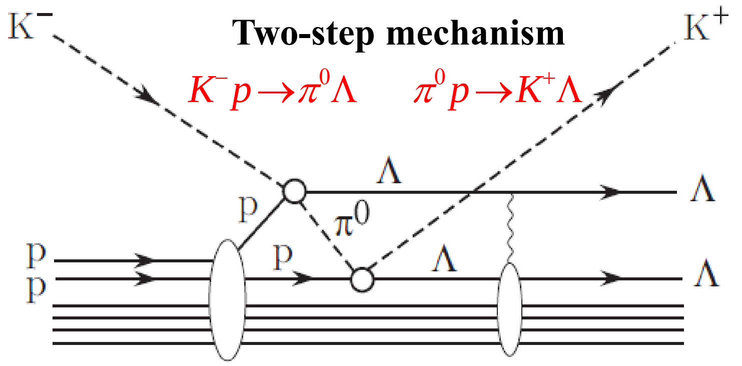
D. E. Lanskoy and Y. Yamamoto, PRC69(2004)014303.

$1s_\Lambda^2$: P(Ξ) < 1 %, $1s_\Lambda 1p_\Lambda$: P(Ξ) ∼10 %

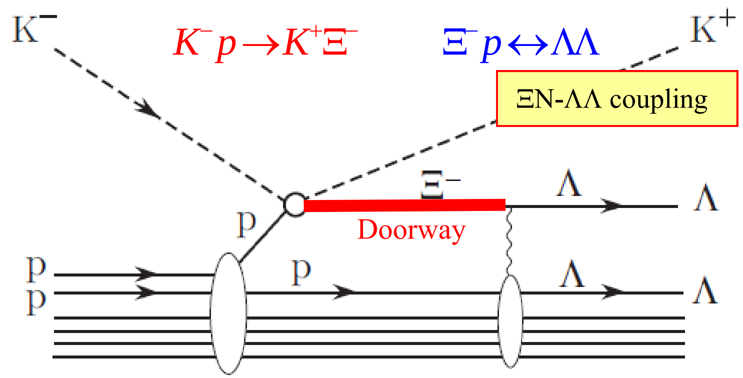


# Ξ-ΛΛ spectrum in DCX ($K^-$,$K^+$) reactions at 1.8GeV/c

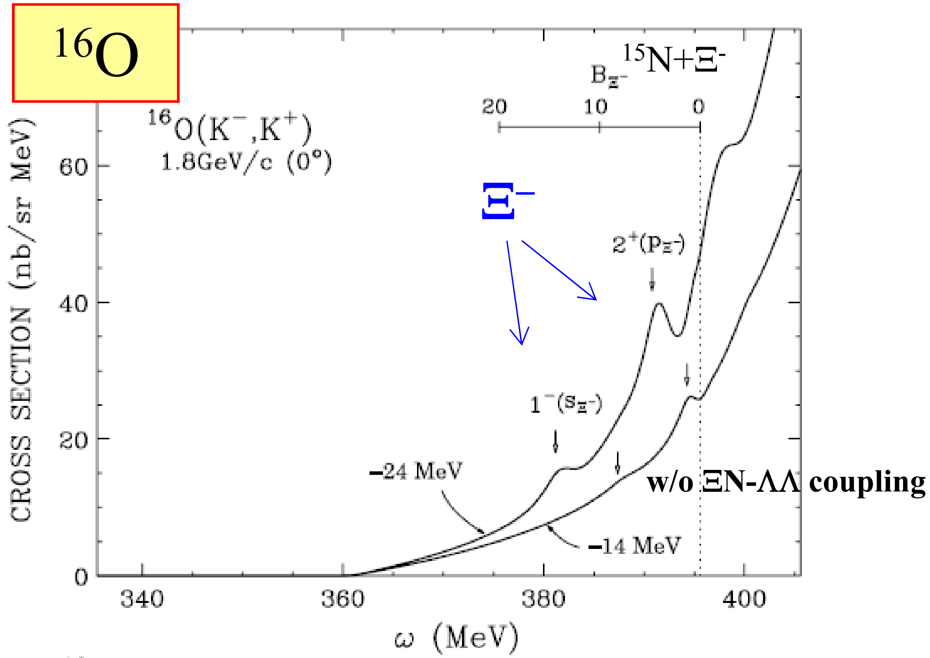
Two-step mechanism

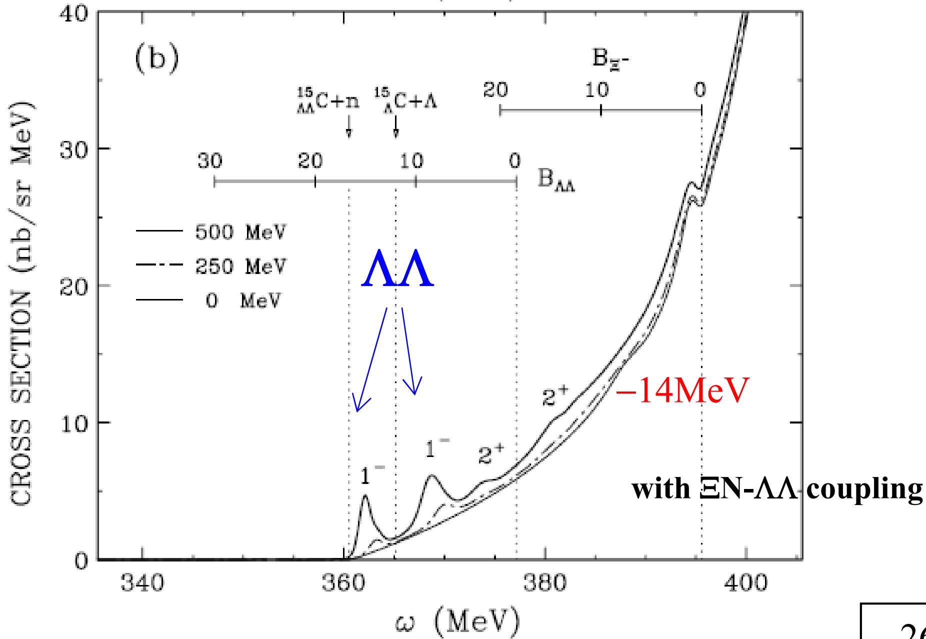



One-step mechanism




***Hyperon-mixing***




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

E07@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) ?

- 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 ?　　E07@J-PARC

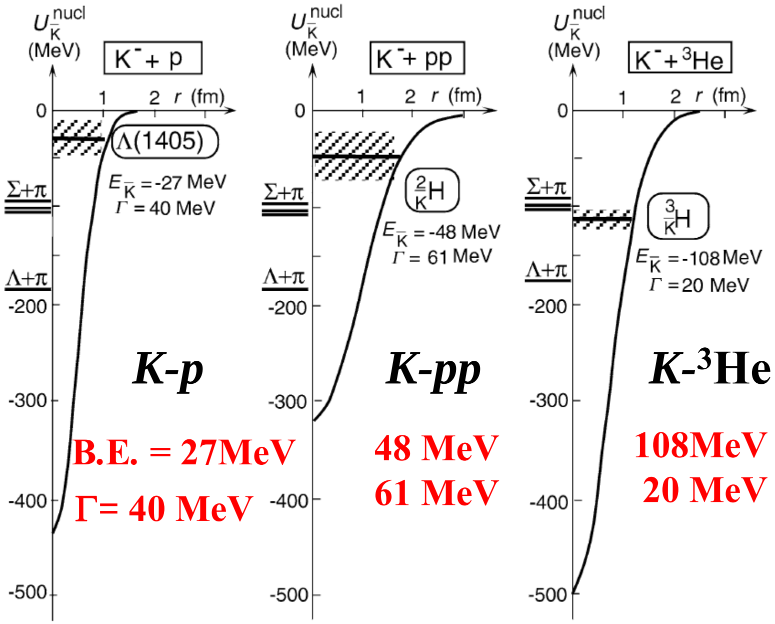
- $K^-$N-Λ(1405)-πΣ

  $U_0$ ($K^-$) ～ deep(–200 MeV) or shallow (–50 MeV)

  → ($K^-$,N)反応　　E15,E23@J-PARC

# $K^{bar}$中間子原子核

# Theoretical prediction for deeply-bound antiKaonic nuclei




## Few-body calculations predicted

T.Yamazaki,Y.Akaishi,PLB535(2002)70; PRC65(2002) 044005

- *K-p* free scattering data
- (1s) level shifts in kaonic hydrogen atoms
- B.E. and Γ of Λ(1405)="*K-+p* quasibound state"

$V_{\bar{K}N}^{I=0}$ $\Lambda(1405) = "K^- p"$

***Strongly attractive***

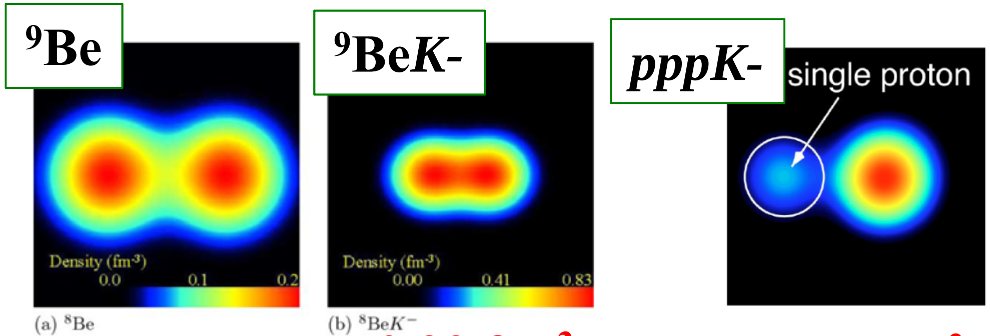
"Super strong nuclear force"

Yamazaki,Akaishi,PJAS. B82(2007)144

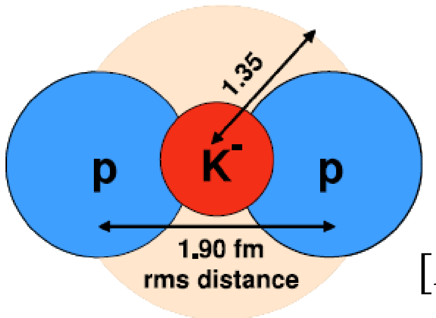
## Exotic states of antiKaonic nuclei by AMD

A. Doté et al., PLB590(2004)51; PRC70(2004)044313.

AMD+G-matrix NN,KN(AY)




$\rho_{AV}$ = 0.33 fm⁻³ 0.66 fm⁻³




***K-pp***

$[\bar{K}^{0^-}_{1/2} \otimes \{N,N\}^{0^+}_1]^{J=0^-}_{I=1/2}$

***Essential* antiKaonic nuclei**

高密度ハドロン物質

# Experimental Candidates for Deeply-Bound State $K^{-}pp$

2011.6

$V_{K^-}$ ?

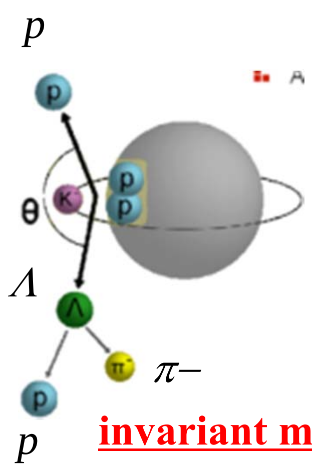
FINUDA Collaboration@DAΦNE

M. Agnello et al.,PRL94(2005)212303

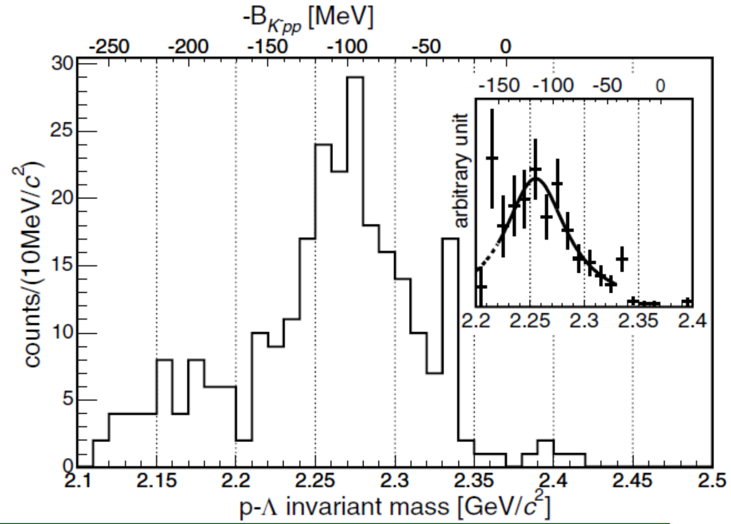
**B.E. = 115 ± 9MeV**

**$\Gamma = 67^{+16}_{-14}$ MeV**

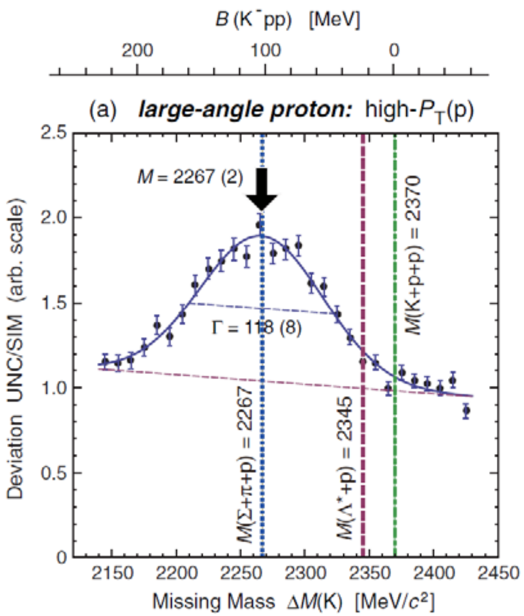
-- *K*- absorption on
6Li, 7Li,12C,27Al at Rest
-- *Λp* invariant mass distrib.




**invariant mass spectroscopy**




DISTO Collaboration@SATURNE-Saclay



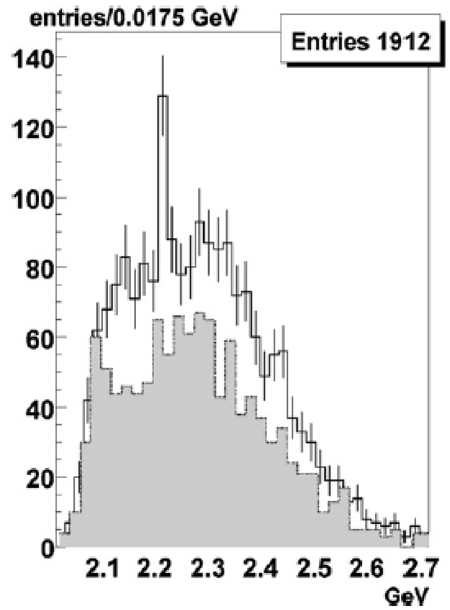

T.Yamazaki et al.,
PRL104(2010)132502

**B.E. = 103±3±5 MeV**

**Γ=118±8±10MeV**

-- *p*+*p*→*K*$^+$+*Λ*+*p* at 2.85GeV
-- *Λp* invariant mass distrib.

OBELIX Collaboration@LEAR-CERN




G. Bendiscioli etal.,
NPA789(2007)222.

**B.E. = 160.9±4.9 MeV**

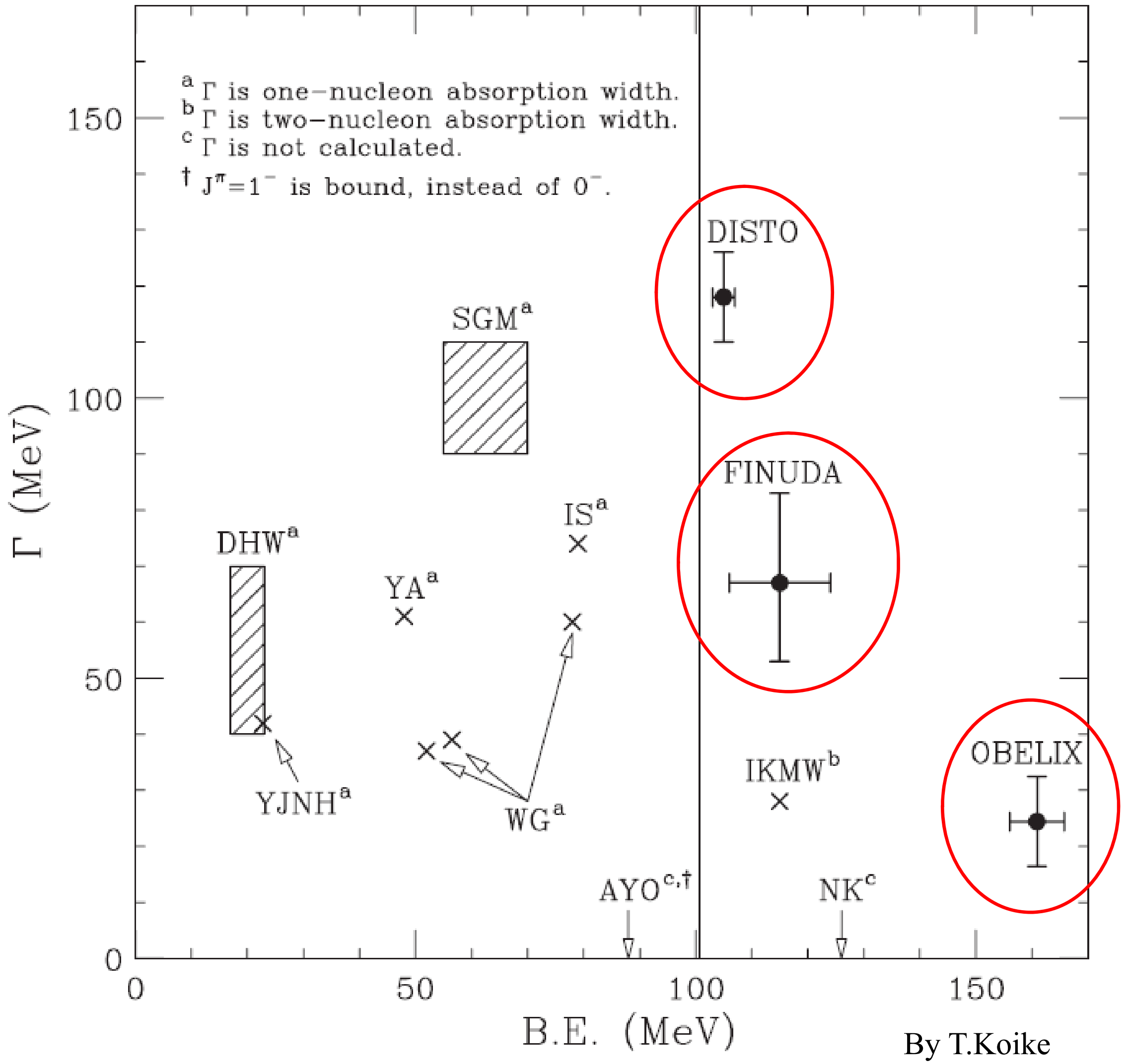
**Γ < 24.4±8.0MeV**

-- anti p+4He at rest
-- *pπ−p* invariant mass
distrib.

# Theoretical predictions of deeply-bound $K^{-}pp$

$[I=\frac{1}{2},\ J^{\pi}=0^{-}]$

| | B.E. (MeV) | $\Gamma_{mesonic}$ (MeV) |
|---|---|---|
| AY | 48 | 61 |
| DHW | 20±3 | 40-70 |
| IS | 60-95 | 45-80 |
| SGM | 50-70 | 90-110 |
| WG | 40-80 | 40-85 |




By T.Koike

Status

- すべての理論計算が準束縛状態の存在を示唆。幅は広い。
- B.E.とΓの違いは$K^{bar}N$ int.や3体系計算方法の違いによるもの？
- **“πΣN decay”** チャンネル効果が必要

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

E15@J-PARC

A search for deeply-bound kaonic nuclear states by in-flight $^3$He(K$^-$,n) reaction

**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

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

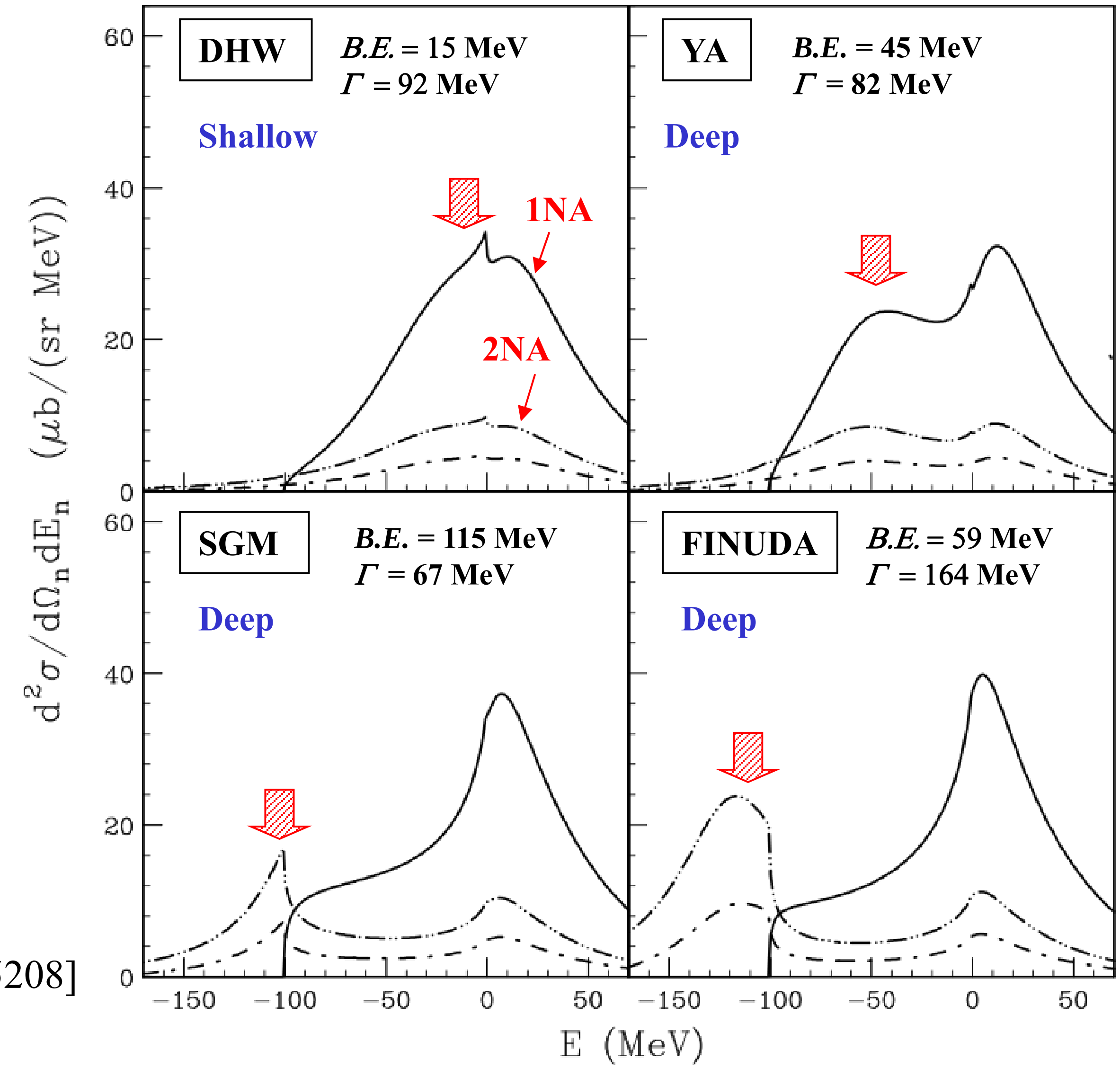
- Recoil effects

$M_C/M_A$ ~2/3 → 1.8倍

- Small-size effects

$L$=0状態だけが束縛

[T.Koike, T.Harada, PRC80(2009)055208]



# J-PARC (Japan Proton Accelerator Research Complex)


J-PARC 施設配置図( http://j-parc.jp/より)

**大強度陽子加速器施設**
茨城県那珂郡東海村
(2008- )


ハドロン実験ホール
K1.8ビームライン
2009/5/12現在

# Proposed experiments for SNP @J-PARC

S＝−2

- E03 : Measurement of X rays from $\Xi^-$ atom /K. Tanida (Kyoto)
- E05: Spectroscopic study of Ξ-hypernucleus, $^{12}_{\Xi}Be$, via the $^{12}C(K^-,K^+)$ reaction /T. Nagae (Kyoto) [Day 1]
- E07: Systematic study of double strangeness system with an emulsion-counter hybrid method/K. Imai (Kyoto), K. Nakazawa (Gifu), H. Tamura (Tohoku)

S＝−1

- E10: Production of neutron-rich Lambda-hypernuclei with the double charge exchange reaction /A. Sakaguchi (Osaka), T. Fukuda (Osaka E. -C.)
- E13 : Gamma-ray spectroscopy of light hypernuclei/H. Tamura (Tohoku) [Day 1]
- E15 : A search for deeply-bound kaonic nuclear states by in-flight $^3He(K^-,n)$ reaction/M. Iwasaki (RIKEN), T. Nagae (Kyoto) [Day 1]
- E17: Precision spectroscopy of kaonic $^3He$ 3d→2p X-rays /R. S. Hayano (Tokyo), H. Outa (RIKEN) [Day 1]
- E18: Coincidence measurement of the weak decay of $^{12}_{\Lambda}C$ and the three-body weak interaction process/H. C. Bhang (Seoul), H. Outa (RIKEN), H. Park (KRISS)
- E22: Exclusive study on the ΛN weak interaction in A=4 Λ-Hypernuclei/S. Ajimura (Osaka), A. Sakaguchi (Osaka)
- E23: Search for a nuclear Kbar bound state $K^-pp$ in the $d(\pi^+,K^+)$ reaction/T. Nagae (Kyoto)

# 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**