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」
2012年10月26日−10月27日
理化学研究所，和光市

ハイパー核生成と中性子星内部のストレンジネス

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

Contents

1. Introduction — Neutron stars and strangeness
2. S = –1 Nuclei
   - Λ hypernuclei
   - Σ hypernuclei
3. S = –2 Nuclei
   - Ξ hypernuclei
   - ΛΛ hypernuclei
4. Deeply bound K^{bar} Nuclei
5. Summary — D01「中性子星と核物質の理論研究」
   高密度中性子星物質グループ 研究計画

■Keywords

Hyperon mixing

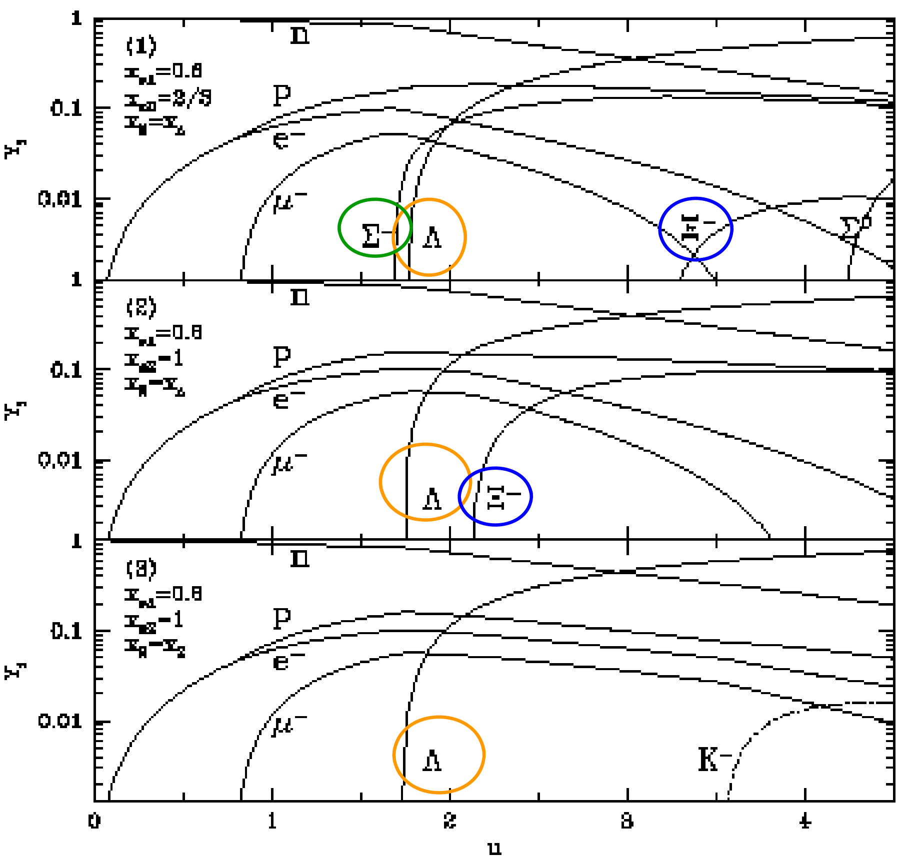
+

DCX

Neutron star core

= “An interesting neutron-rich hypernuclear system”

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

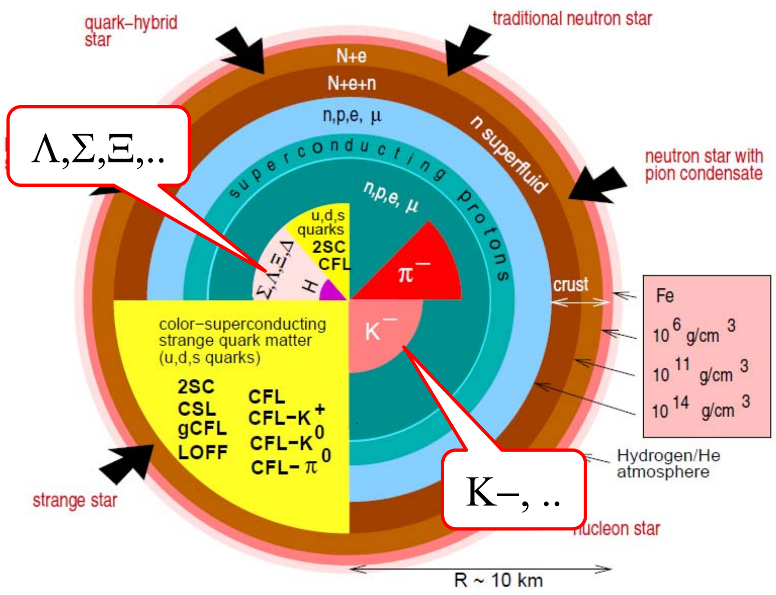


$U_\Sigma < 0$
$U_\Xi < 0$

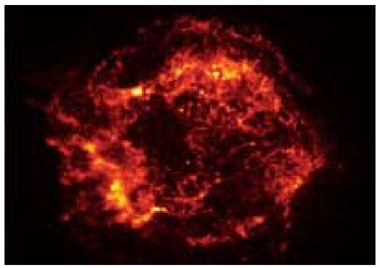
$U_\Sigma > 0$
$U_\Xi < 0$

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

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



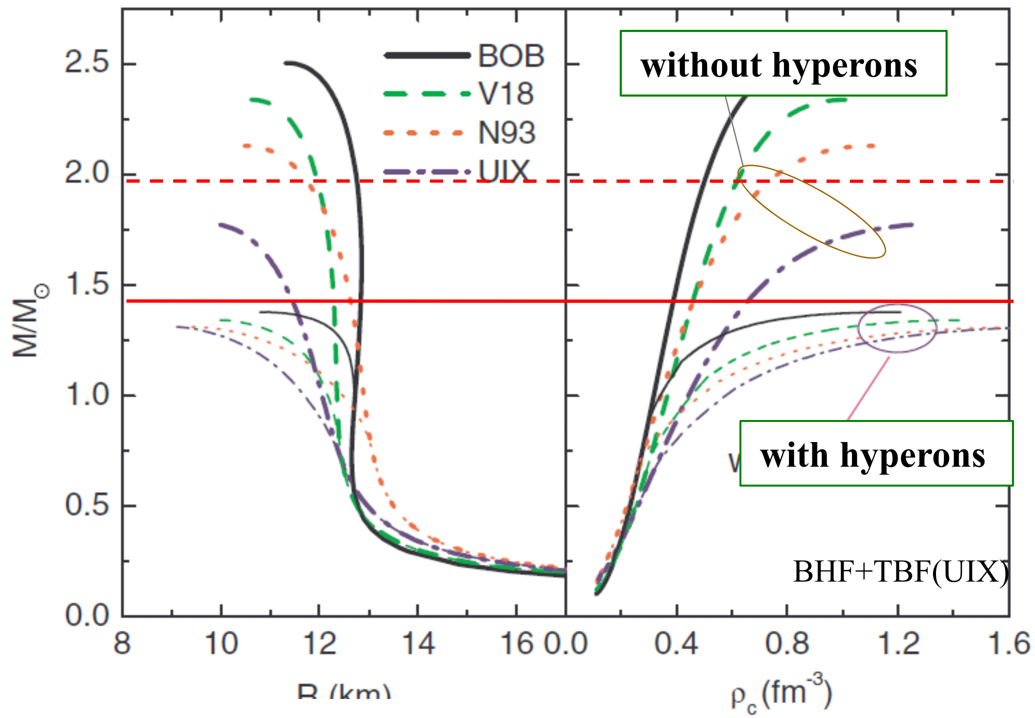
[F. Weber, PPNP 54(2005)193]



Cassiopeia A nebula
NASA/CXC/SAO.

Hyperon-mixing

Hyperons and massive neutron stars



BHF

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

$1.97 M_\odot$ ⟵ PSR J1614-2230

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

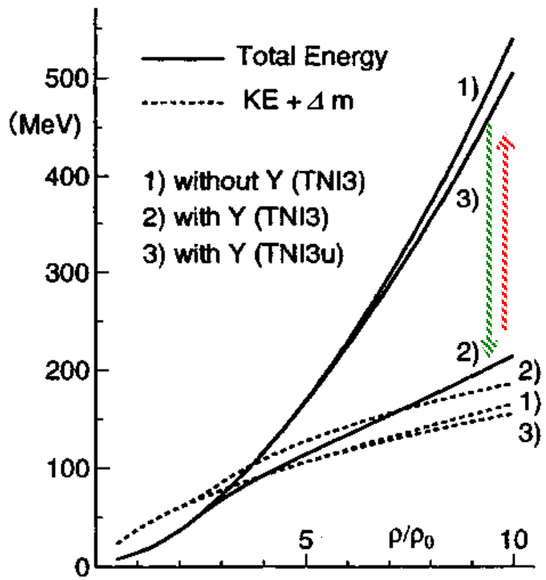
$1.44 M_\odot$

Maximum Mass/Radius

Softening on the EOS

YN,YY: extra repulsion TNIu

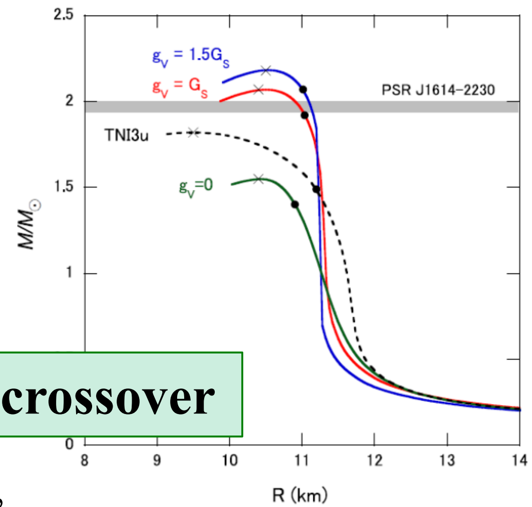
S. Nishizaki, T. Takatsuka, Y. Yamamoto, PTP105(2001)607; NPA691(2001)432



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]

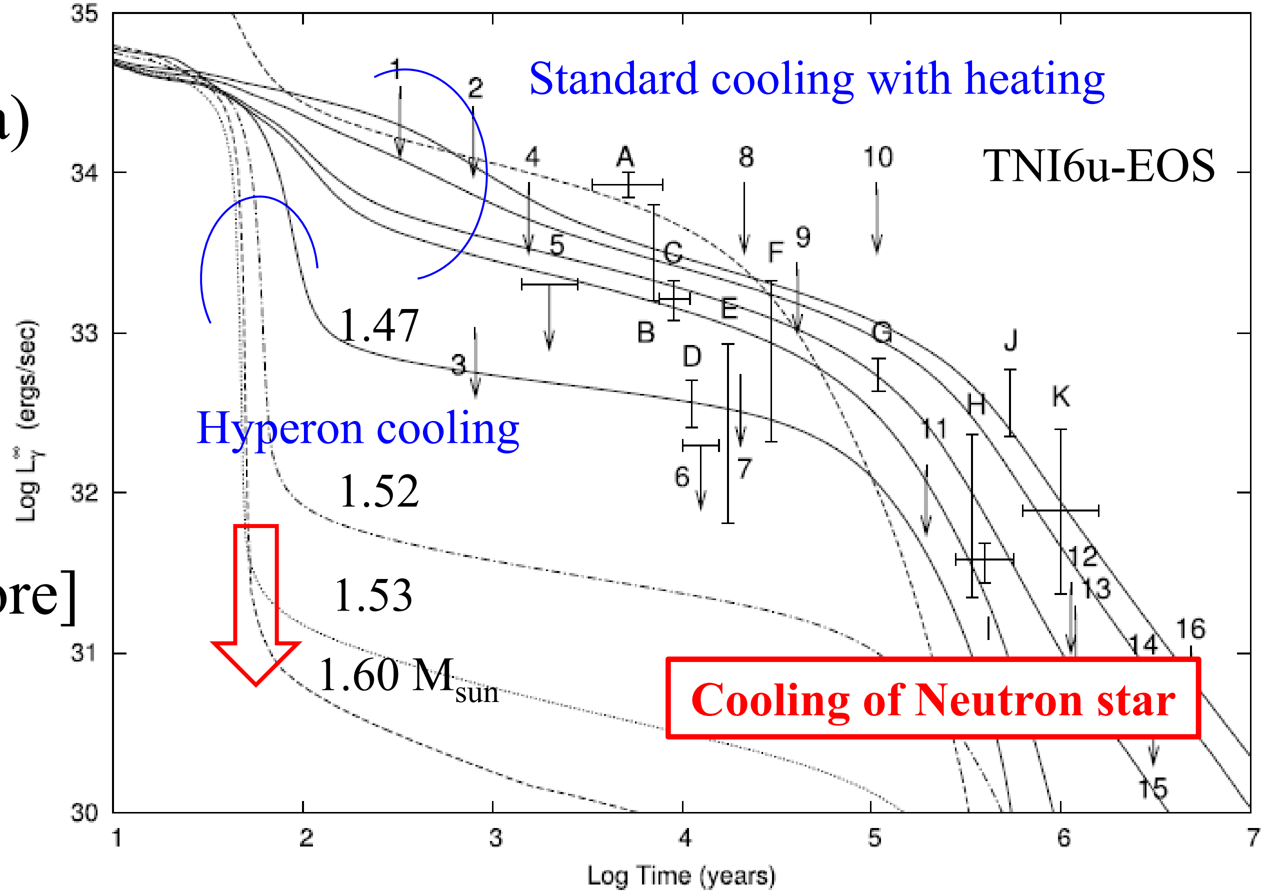
Thermal evolution of neutron stars

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**

NN, YN, YY Interactions

Flavor $SU(3)_f$ symmetry

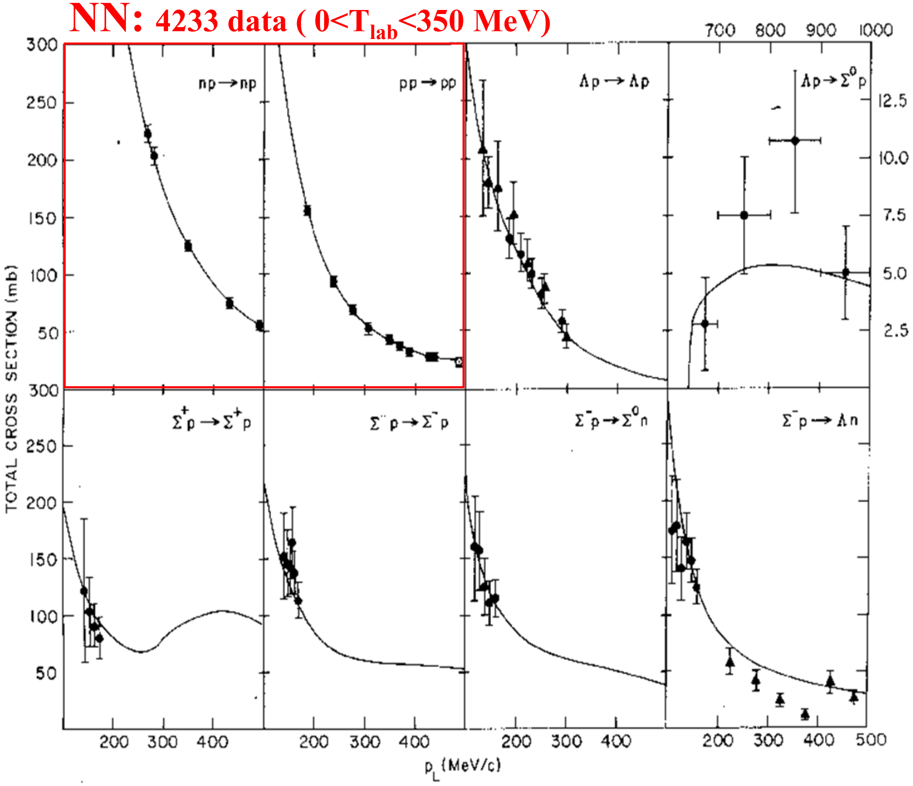
symmetric antisymmetric

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

$^1S_0$ $^3S_1$ ΛΛ

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

NN: 4233 data ($0<T_{lab}<350$ MeV)



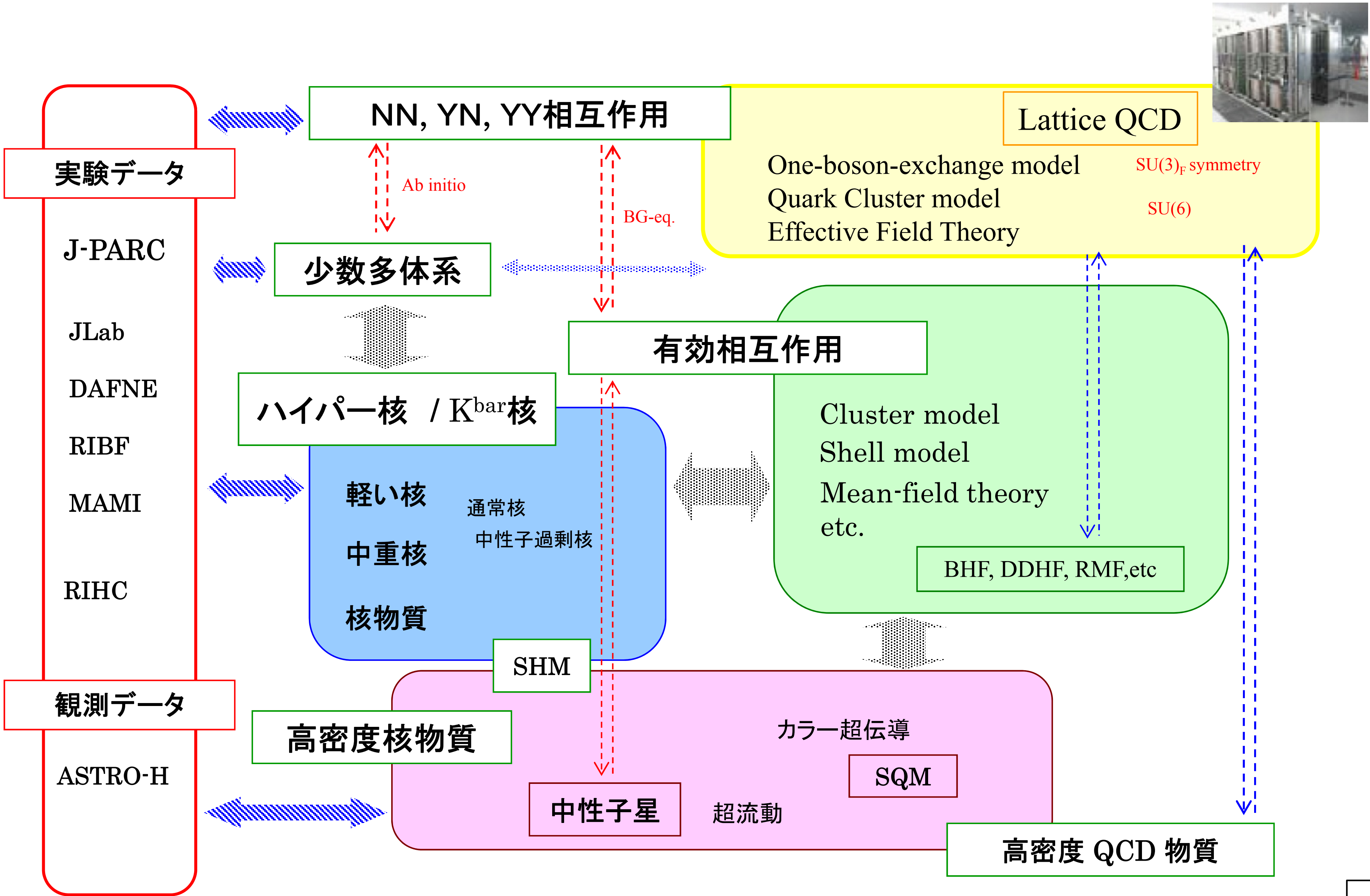
NN	NN		S= 0
ΣN,ΣN-ΛN,ΛN		35 data	S= −1
ΣΣ,ΞN-ΣΛ-ΣΣ,ΞN-ΣΣ-ΛΛ			S= −2
ΞΣ,ΞΣ-ΞΛ			S= −3
ΞΞ	ΞΞ		S= −4

- One-Boson-Exchange model
- Quark Cluster model
- Chiral LO Effective Field Theory
- Latice QCD

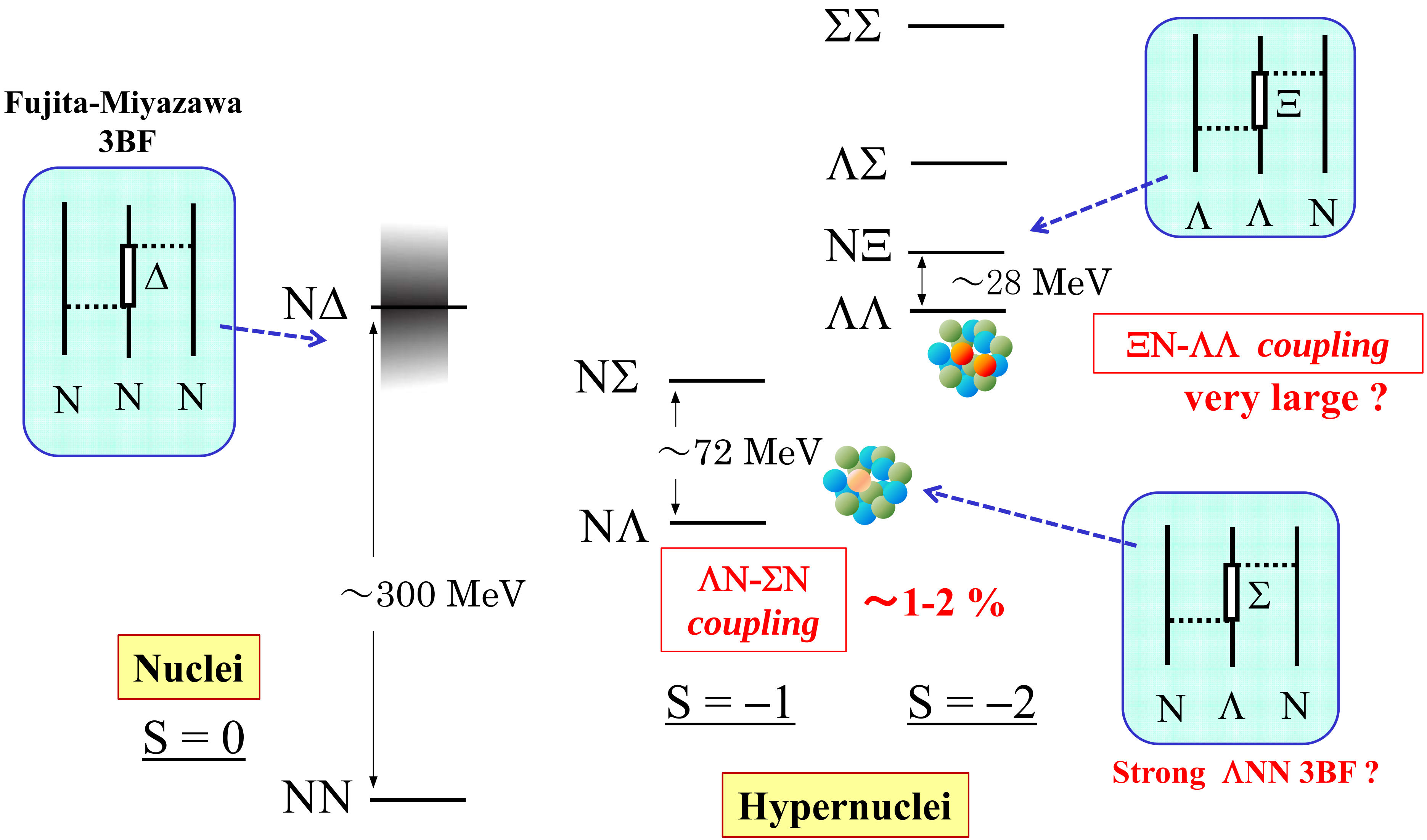
ストレンジネス核物理の展開

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



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

ストレンジネス核物理

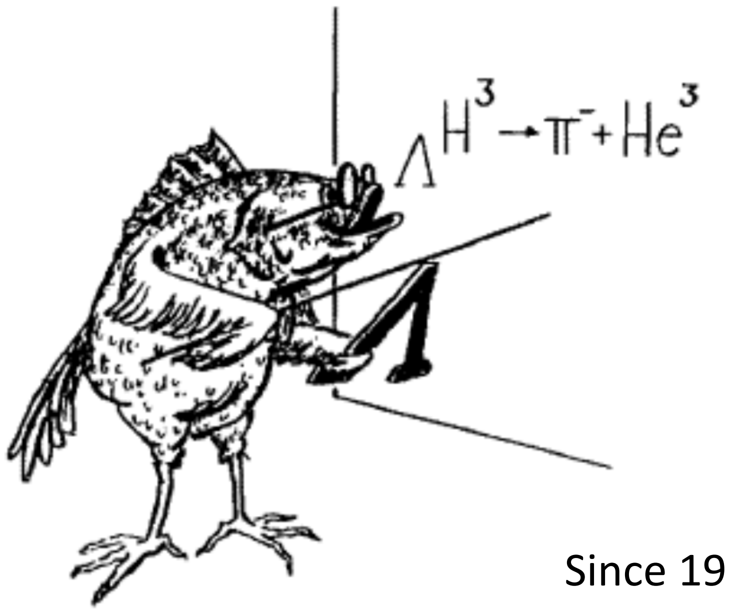
- ストレンジネスは原子核深部を探るプローブ
  - ハイペロンはパウリ排他律を受けない
- Impurity Physics
  - "糊"としての役割
  - 原子核構造の変化
- Baryon-Baryon Interaction
  - YN, YY Interaction based on SU_f (3)
  - 核力の統一的理解・斥力芯の起源
- "Exotic" Nuclear Physics
  - ストレンジネスが拓く新しい原子核の面白さ
- Neutron Starの構造と進化
  - 高密度核物質, EOS, 最大質量, 冷却, …

  ←Serious Problems from hyperon-mixing (Takatsuka)

■Keywords

Hyperon mixing

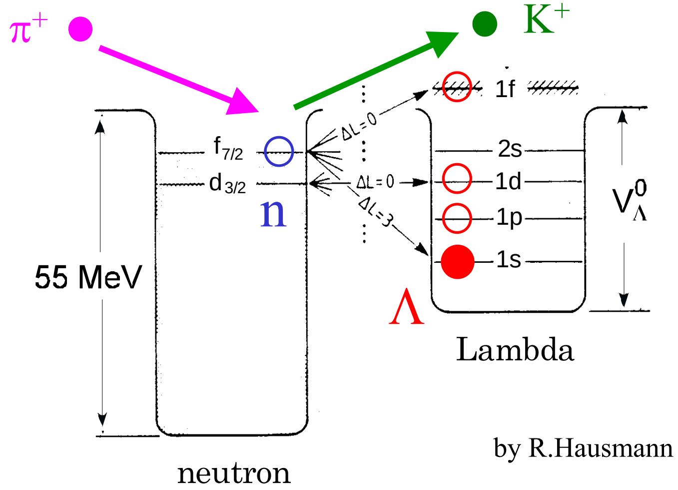
2. $S = -1$ Nuclei



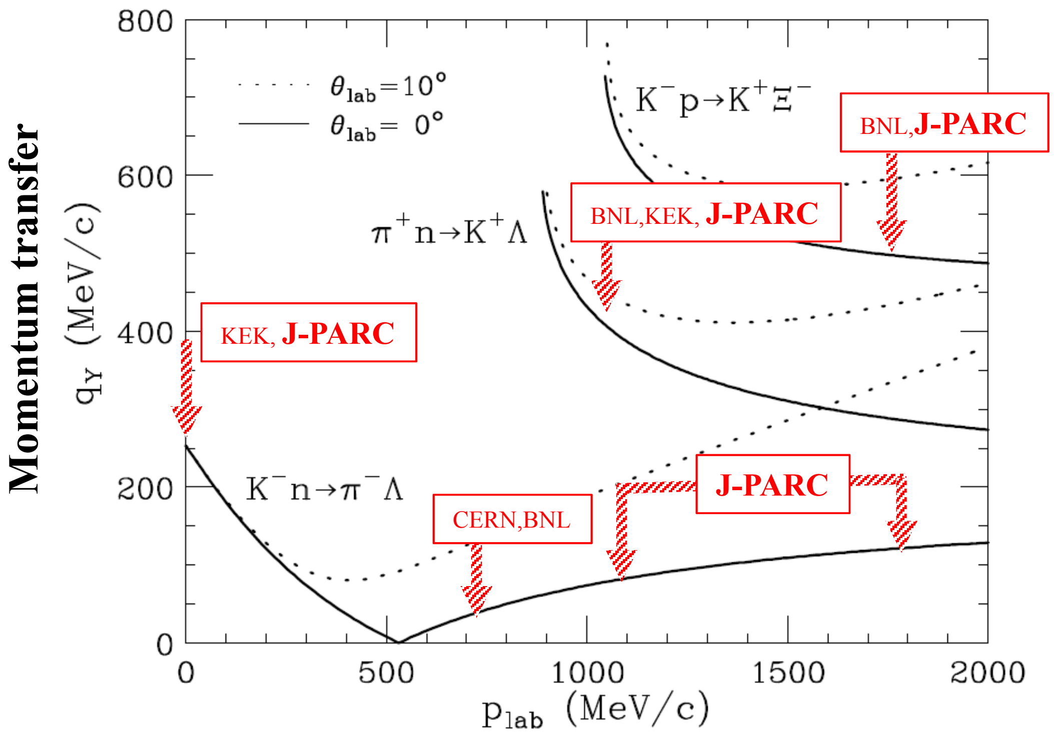
Since 1969, ANL

Hypernuclear Production Reactions

(π^+,K^+) reaction



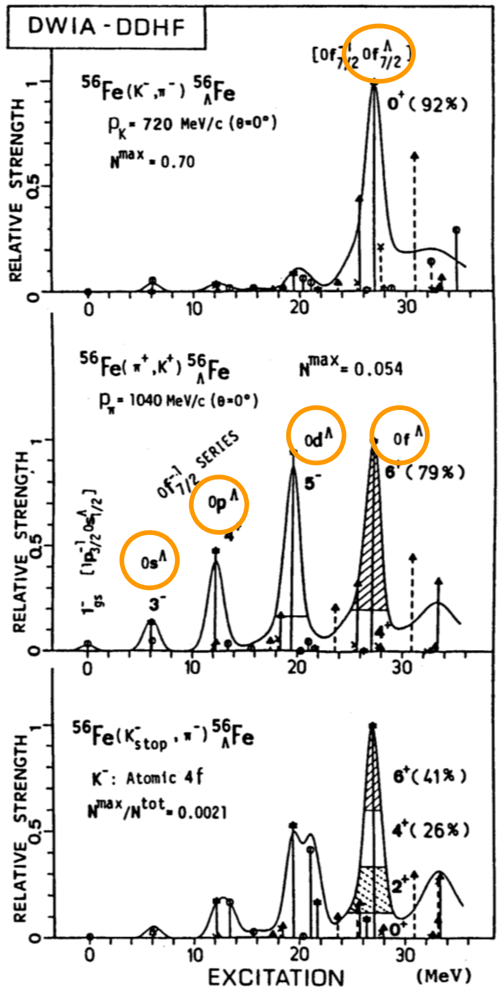
by R.Hausmann and W.Weise



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-

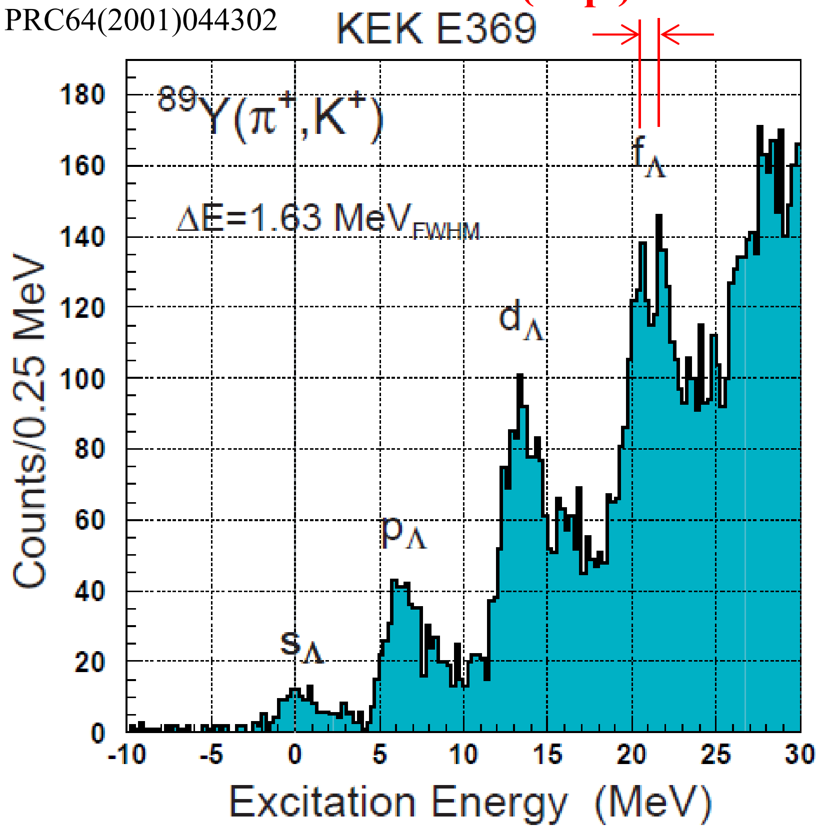
$q_\Lambda \sim$280MeV/c

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

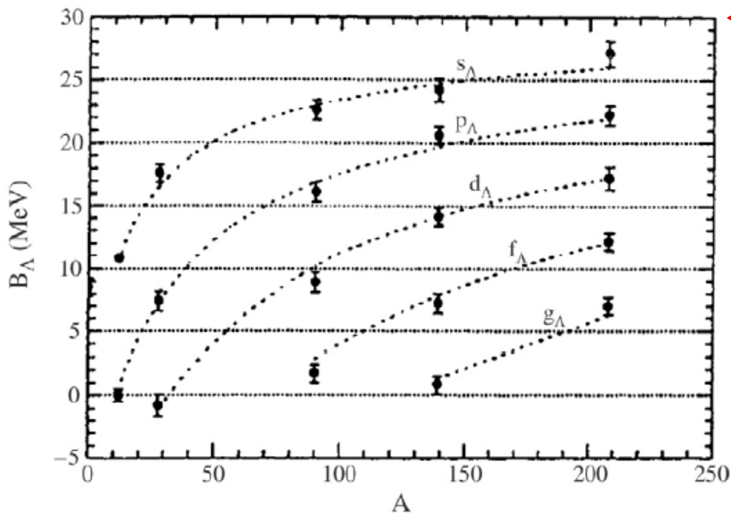
V_Λ ?

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

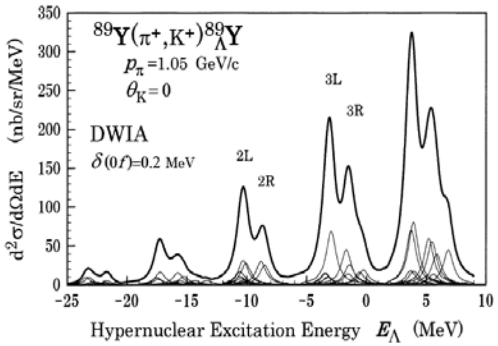
WS analysis

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

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

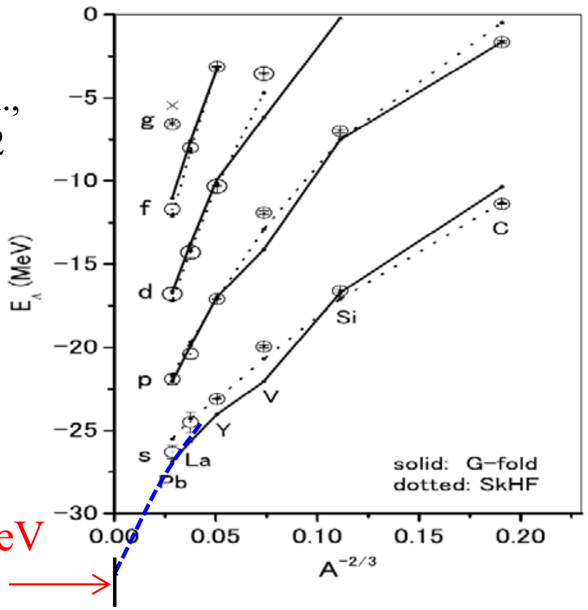
SM analysis
- ΛN^{-1} particle-hole ex.
- inter-shell coupling

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



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

G-matrix folding model

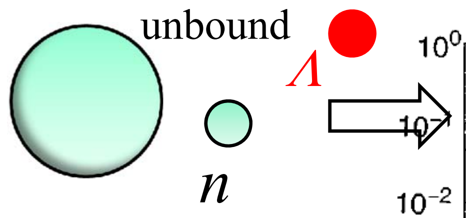


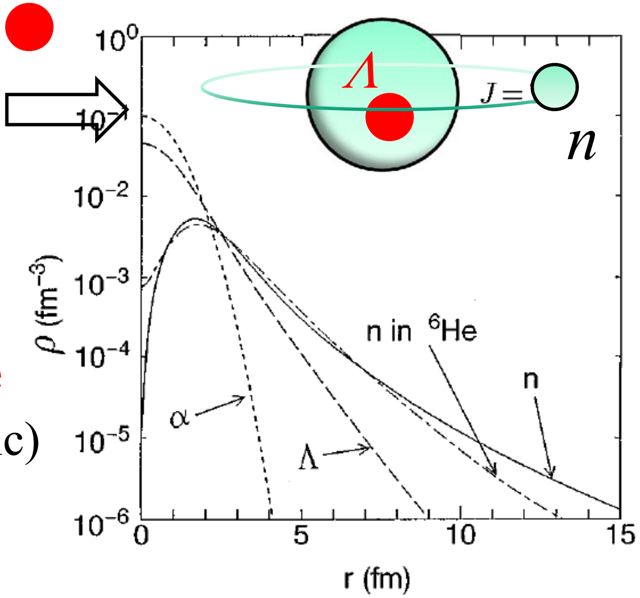
$V_0^\Lambda \simeq -37.2$ MeV
$(A \to \infty)$

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

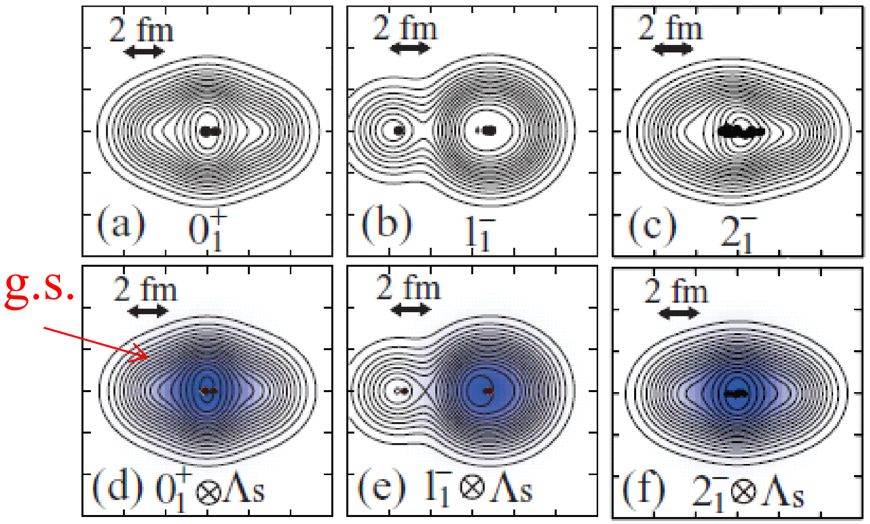
E. Hiyama, et al.,PRC59(1999)2351
Tretyakova, Lanskoy, EPJ.A5(1999) 391.

$^{6}_{\Lambda}$He
(α+N+Λ calc)

"Stabilizing"+"Deformation"

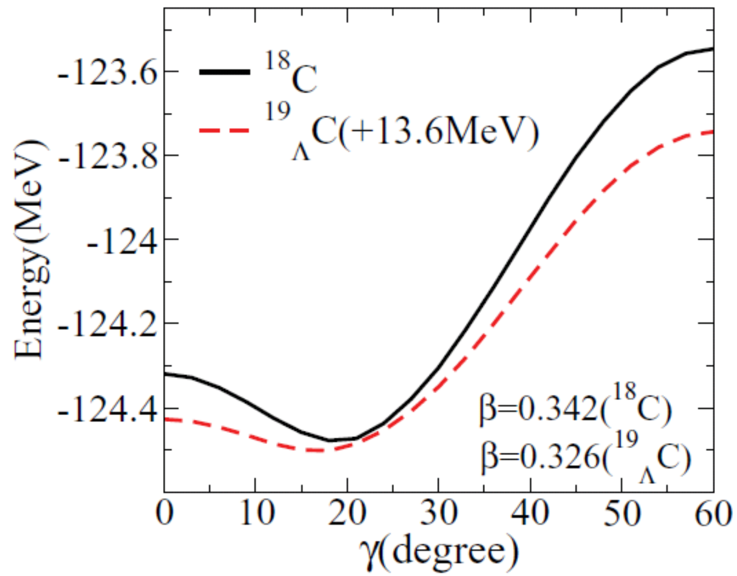
$^{21}_{\Lambda}$Ne, $^{25}_{\Lambda}$Mg (AMD)

M. Isaka et al, PRC83(2011)054304

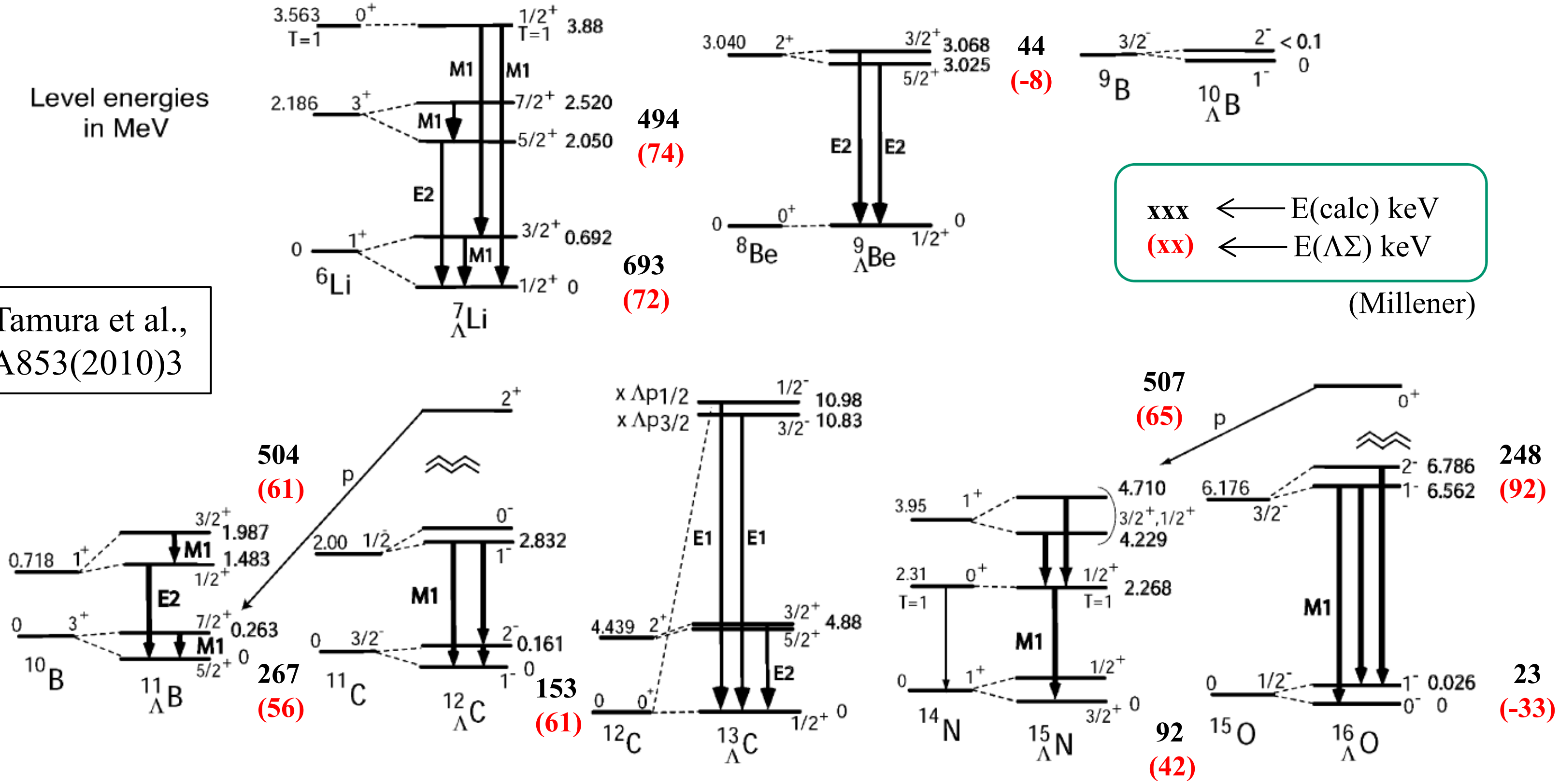


$^{19}_{\Lambda}$C, $^{29}_{\Lambda}$Si, $^{25}_{\Lambda}$Mg, (CSHF+BCS)

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]

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

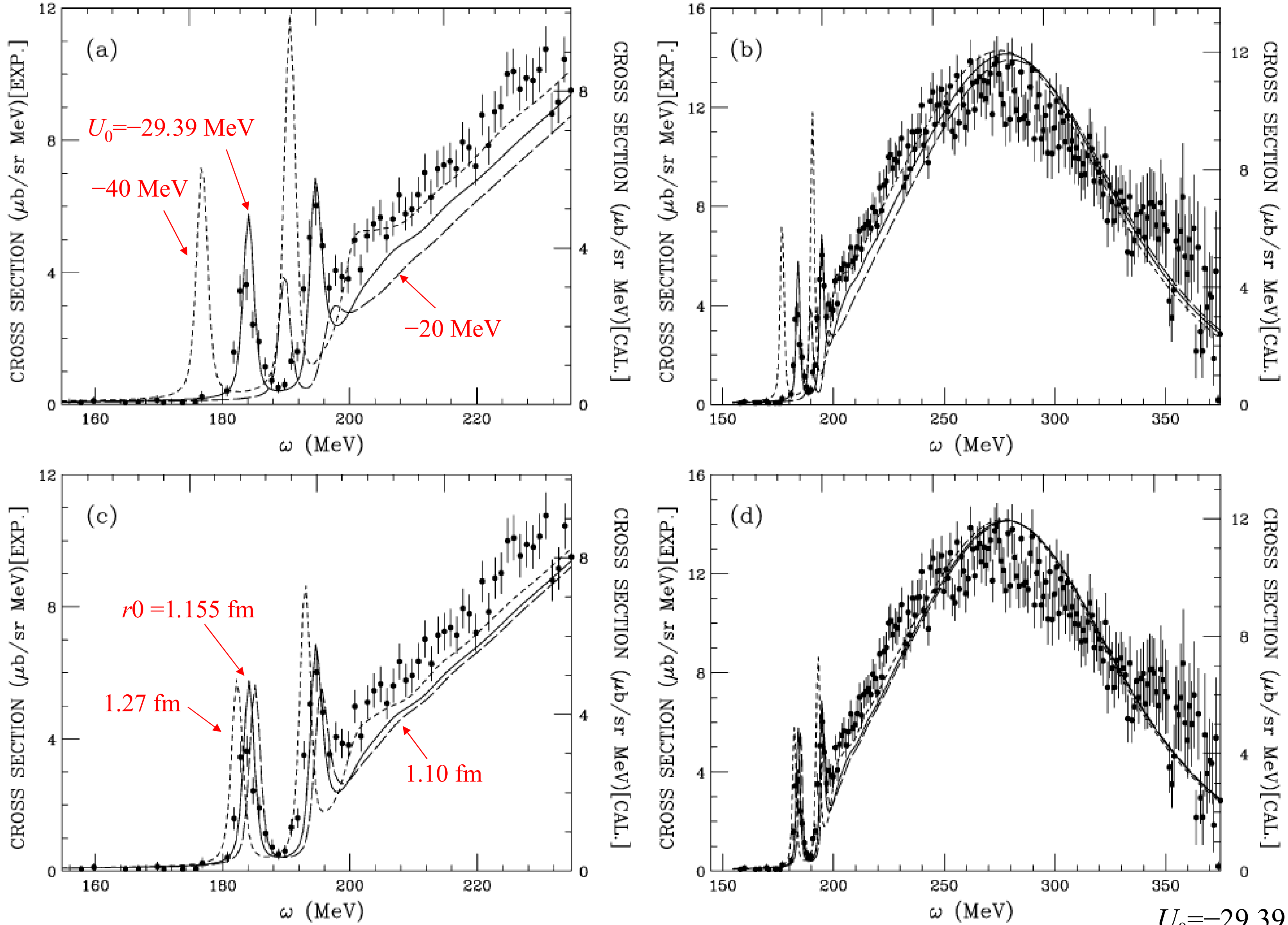
^{12}C

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



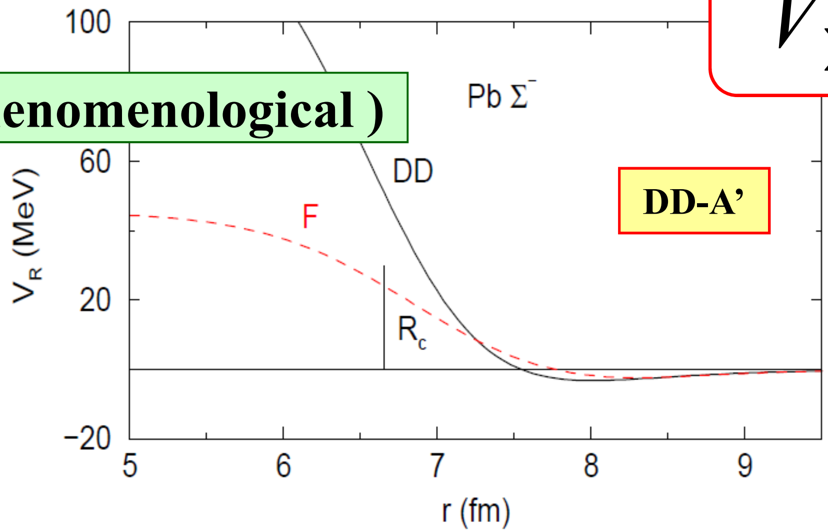
U_0=−29.39 MeV

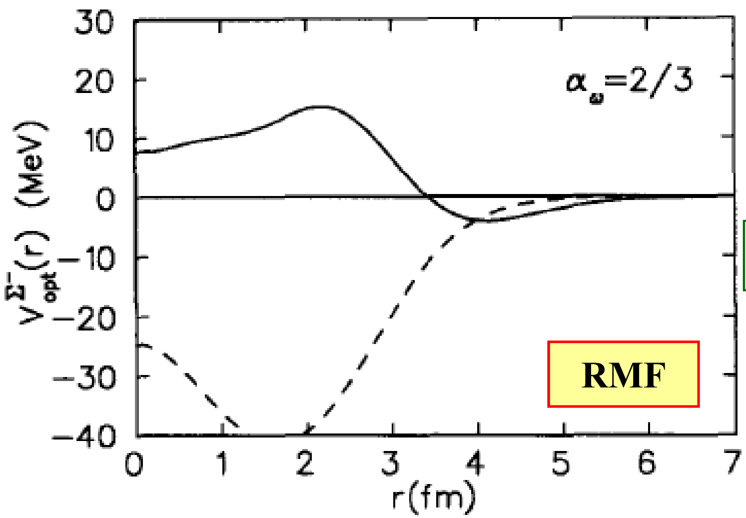
Σ^- s.p. potentials (fitted to the Σ^- atomic data)

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.





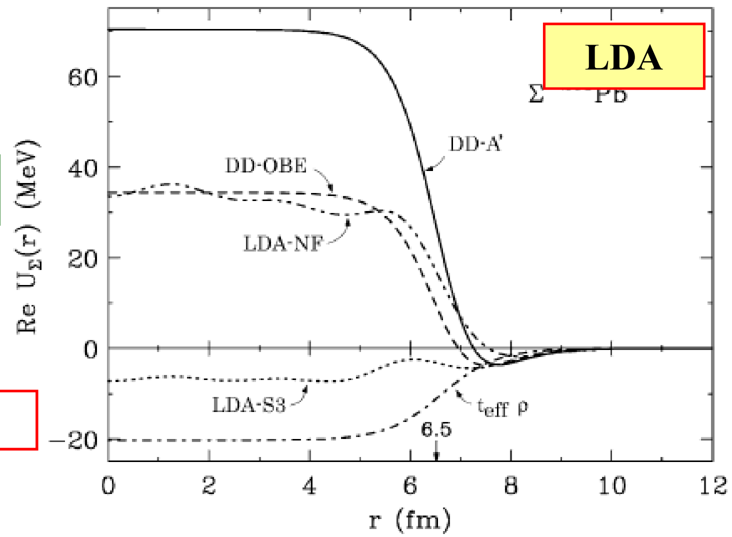
Relativistic mean-field (RMF) potential

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

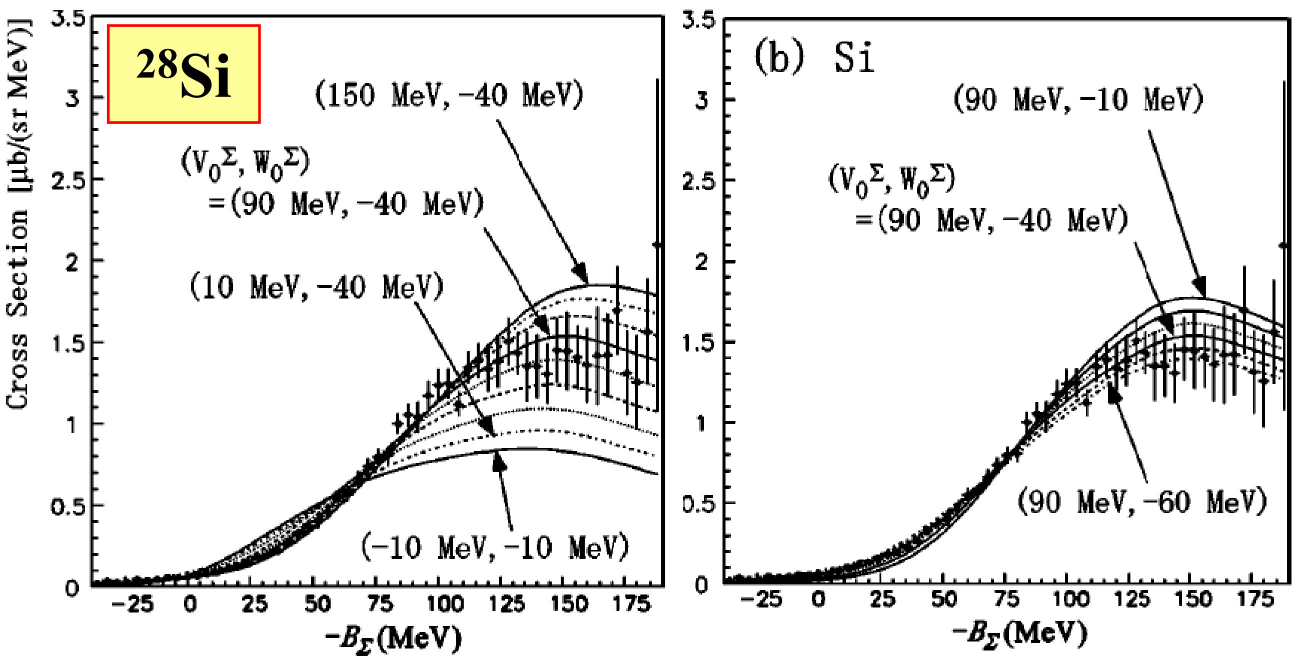


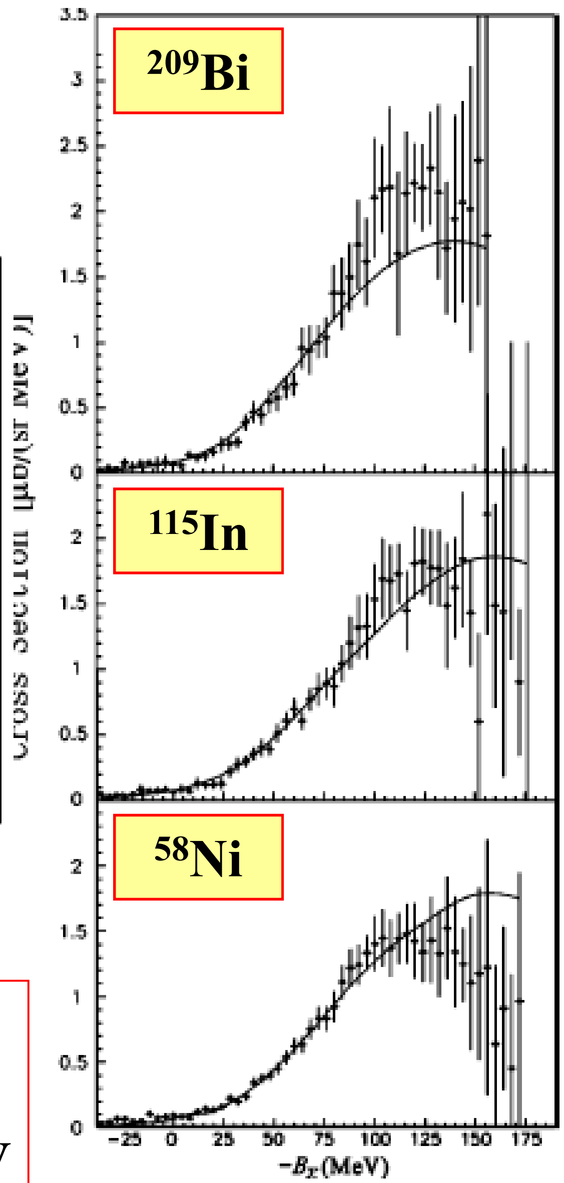
- **It suggests that Σ-nucleus potentials have a strong repulsion in the real part.**

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

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

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

$a = 0.67$ fm $\quad r_0 = 1.1$fm

$$V_\Sigma = +90 \text{ MeV}$$
$$W_\Sigma = -40 \text{ MeV}$$

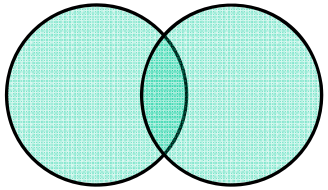
Strong repulsion with large imaginary

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

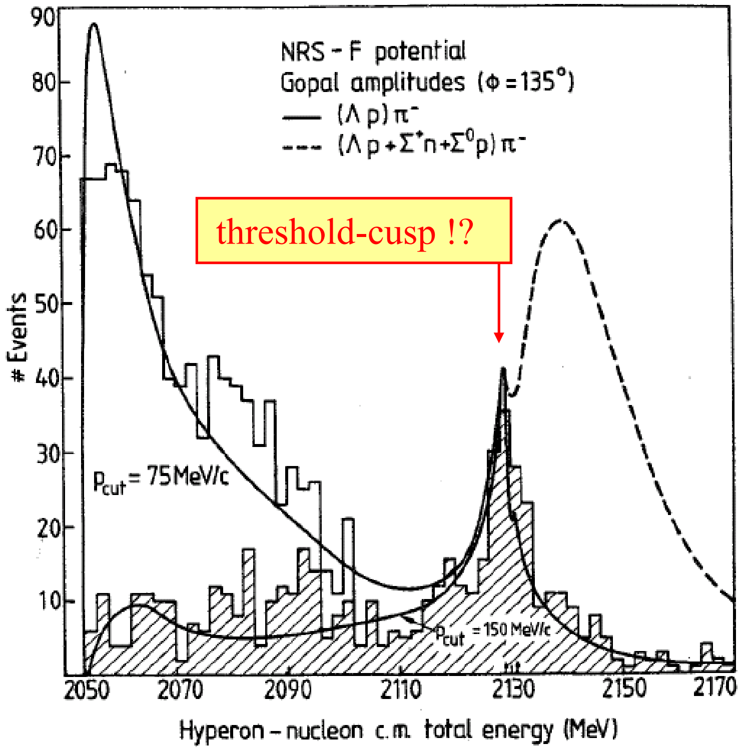
S = 0 state	[51]	[33]	
1			ΛΛ-ΞN-ΣΣ(I=0), H-dibaryon
8_S	1		$\Sigma N(I=1/2,{}^1S_0)$ ***Pauli forbidden***
27	4/9	5/9	$NN({}^1S_0)$

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

E40@J-PARC: Σ^+p Scattering

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

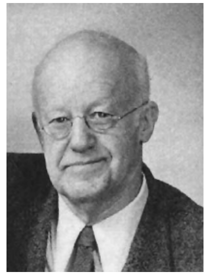
$K^-d \rightarrow \pi^- \Lambda p$ Reaction in Flight



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

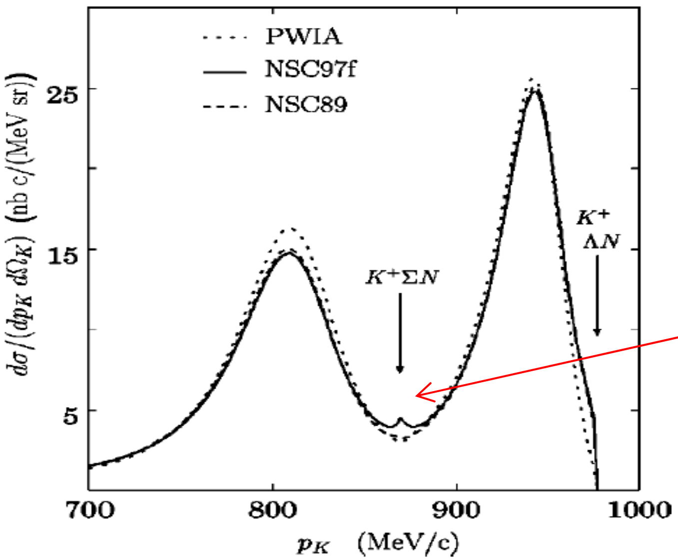
R.H.Dalitz, A. Deloff,
Aust. J. Phys., 36 (1983) 617

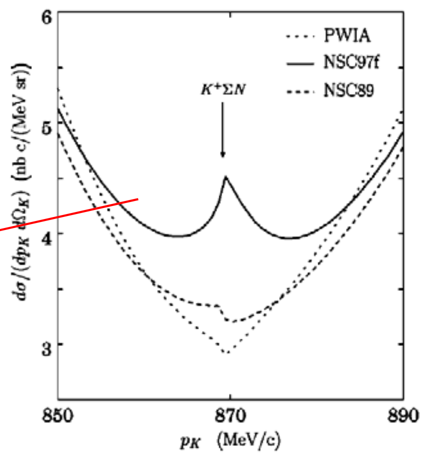
NHC-F



R.H.Dalitz

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



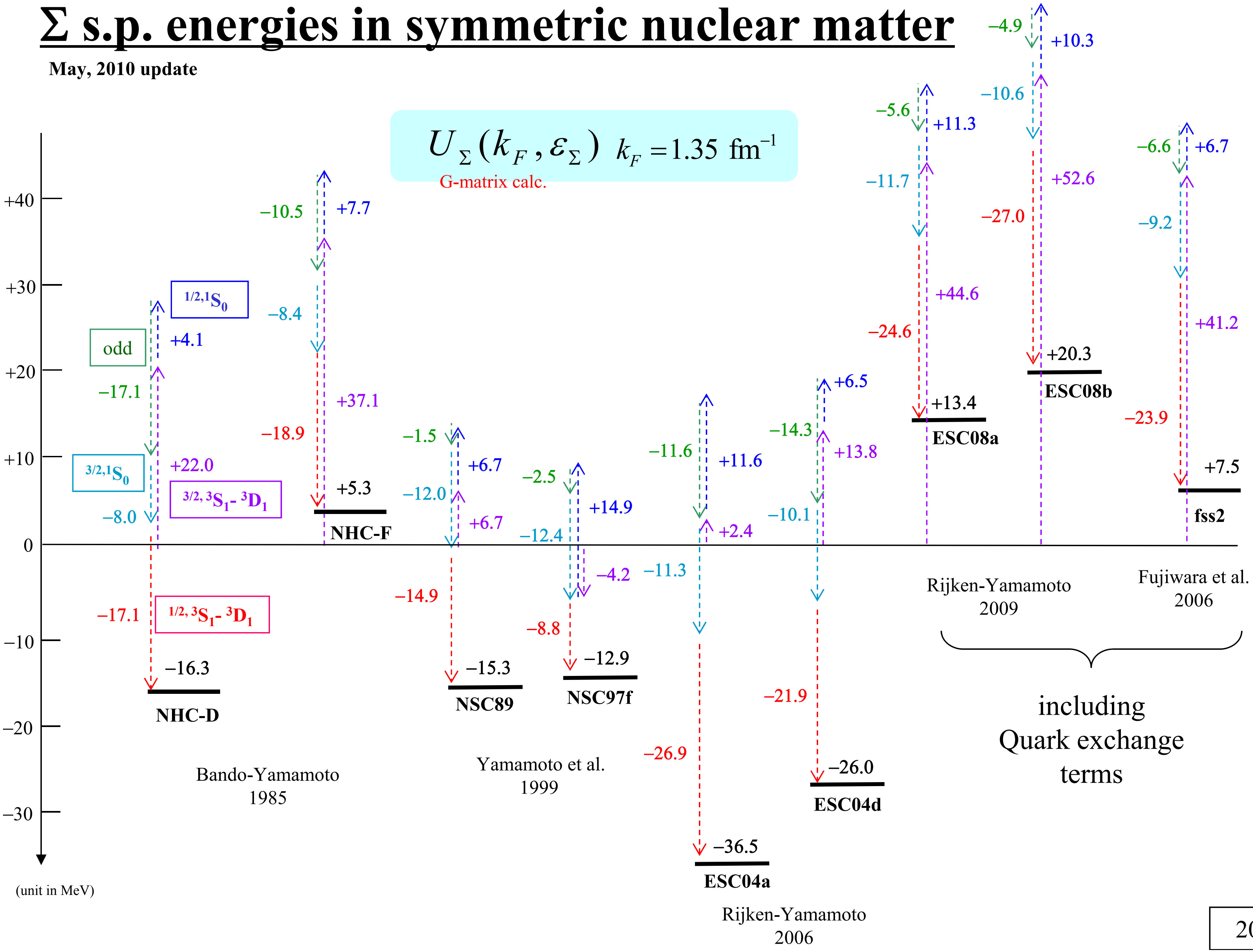


H.Yamamura, K. Miyagawa, et al.,
PRC61 (1999) 014001

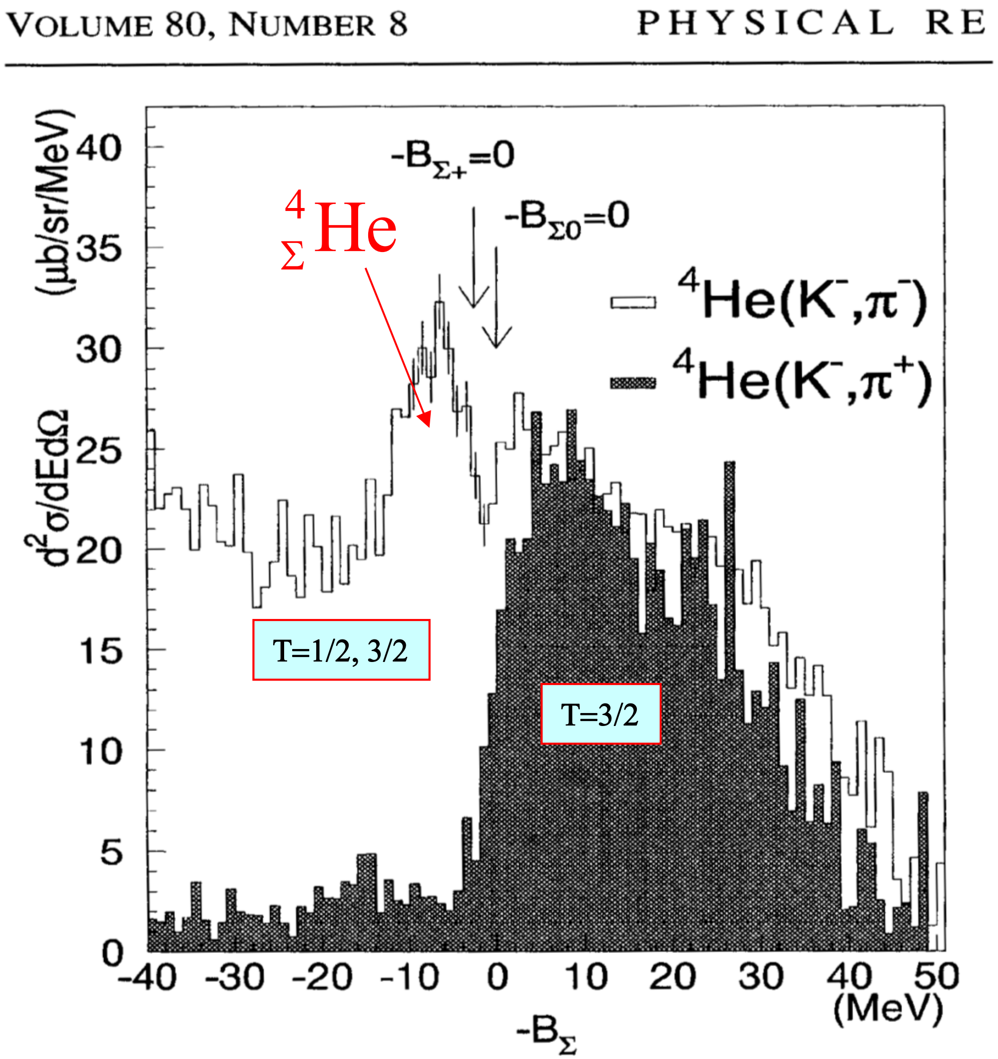
d(γ,K$^+$) inclusive spectrum

Σ s.p. energies in symmetric nuclear matter

May, 2010 update



Observation of a $_{\Sigma}^{4}$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

4.6 MeV

7.9 MeV

Theoretical Prediction

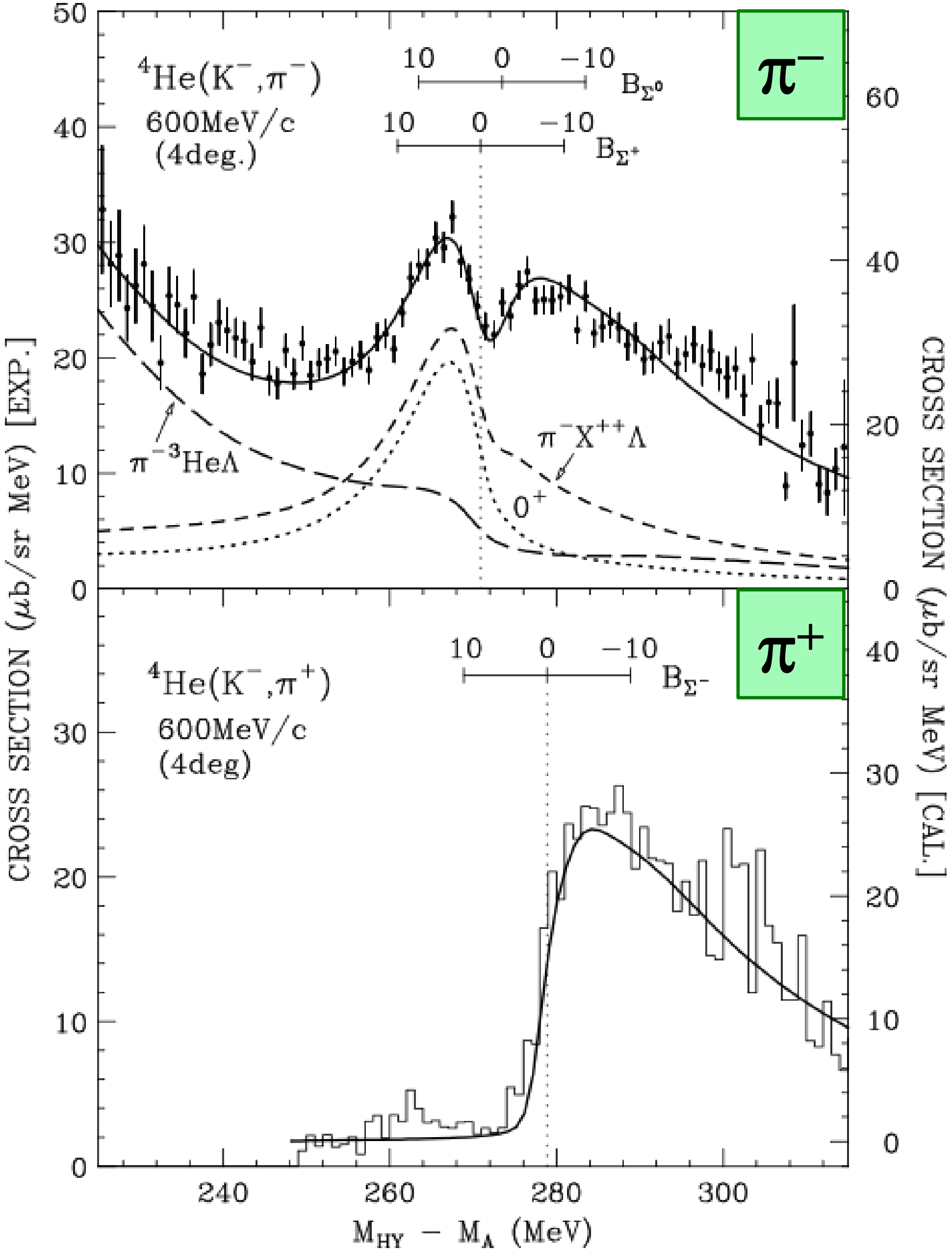
$T \simeq 1/2$

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

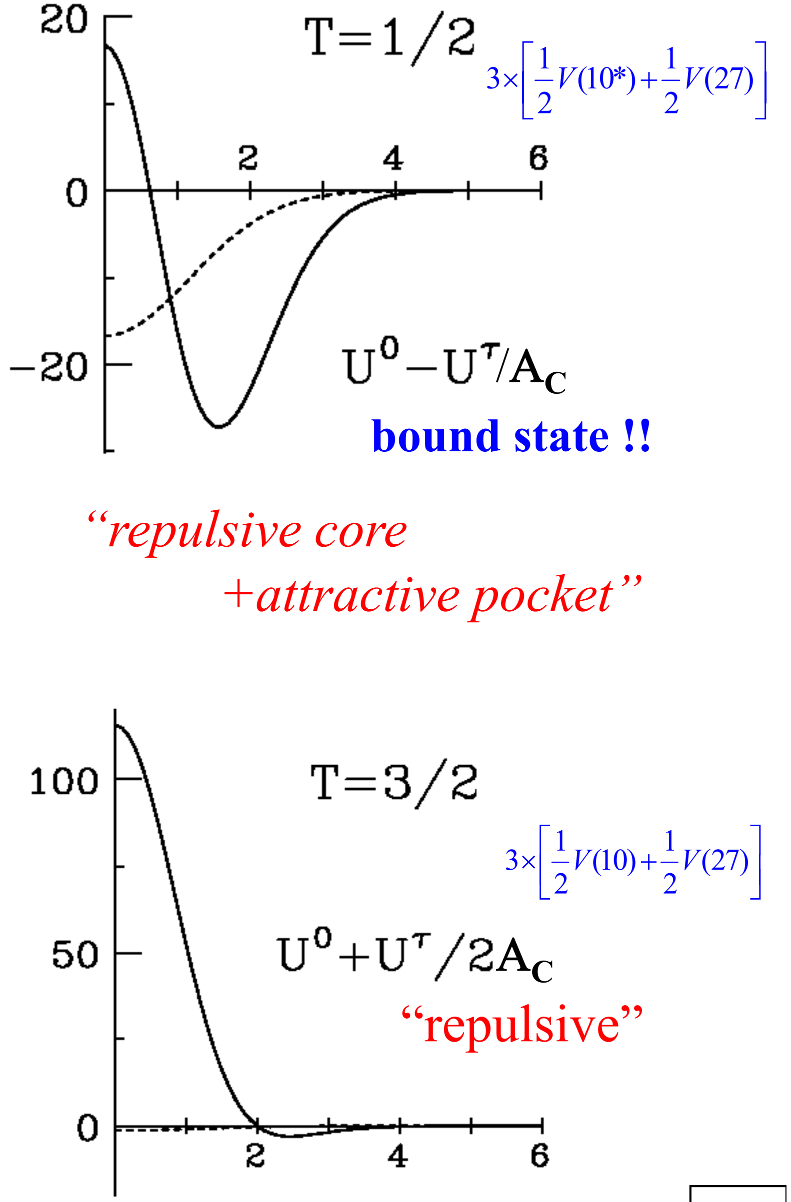
T.Harada, S.Shinmura, Y.Akaishi, H.Tanaka, NPA507(1990)715.

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"

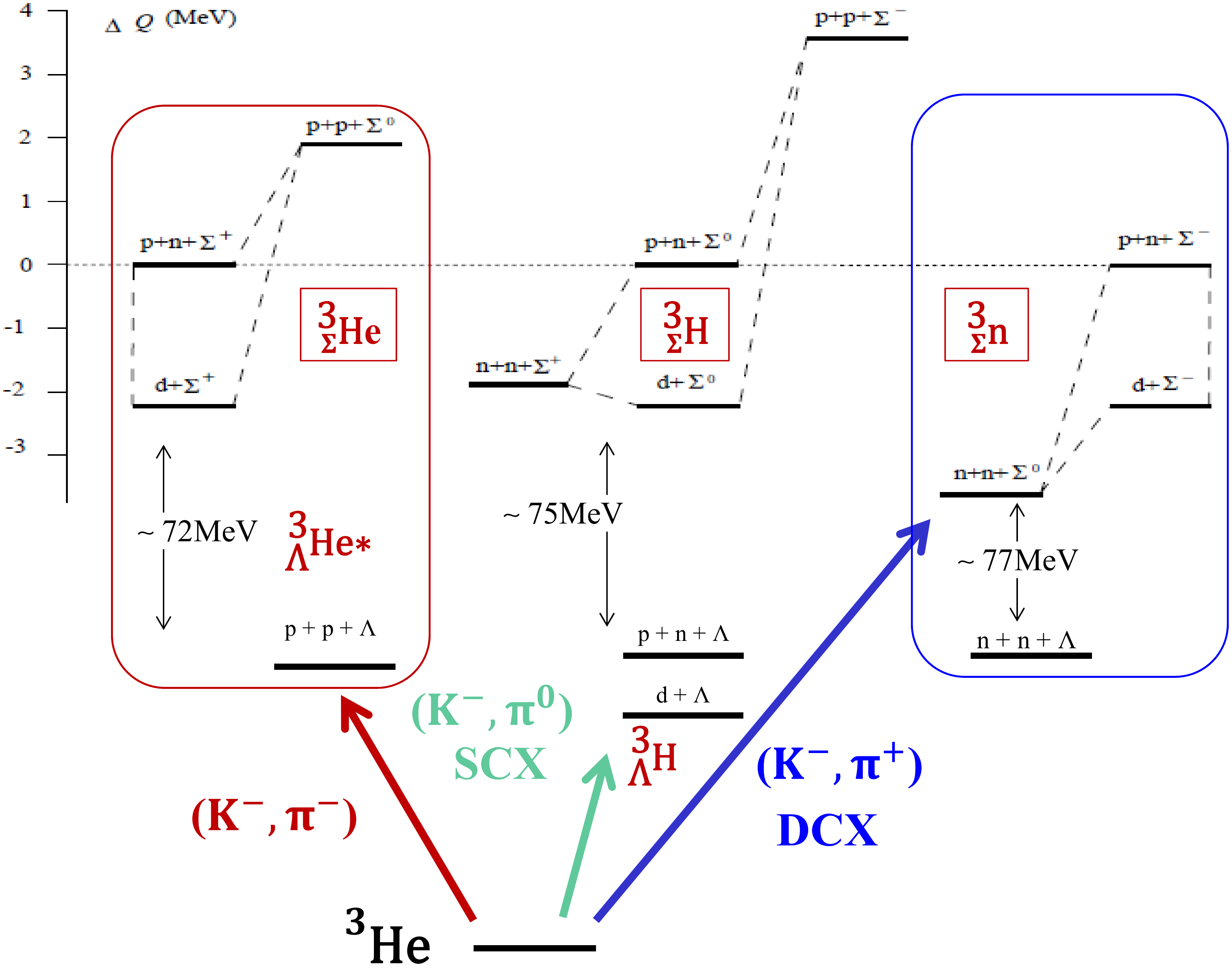
"strong isospin-dependence"

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

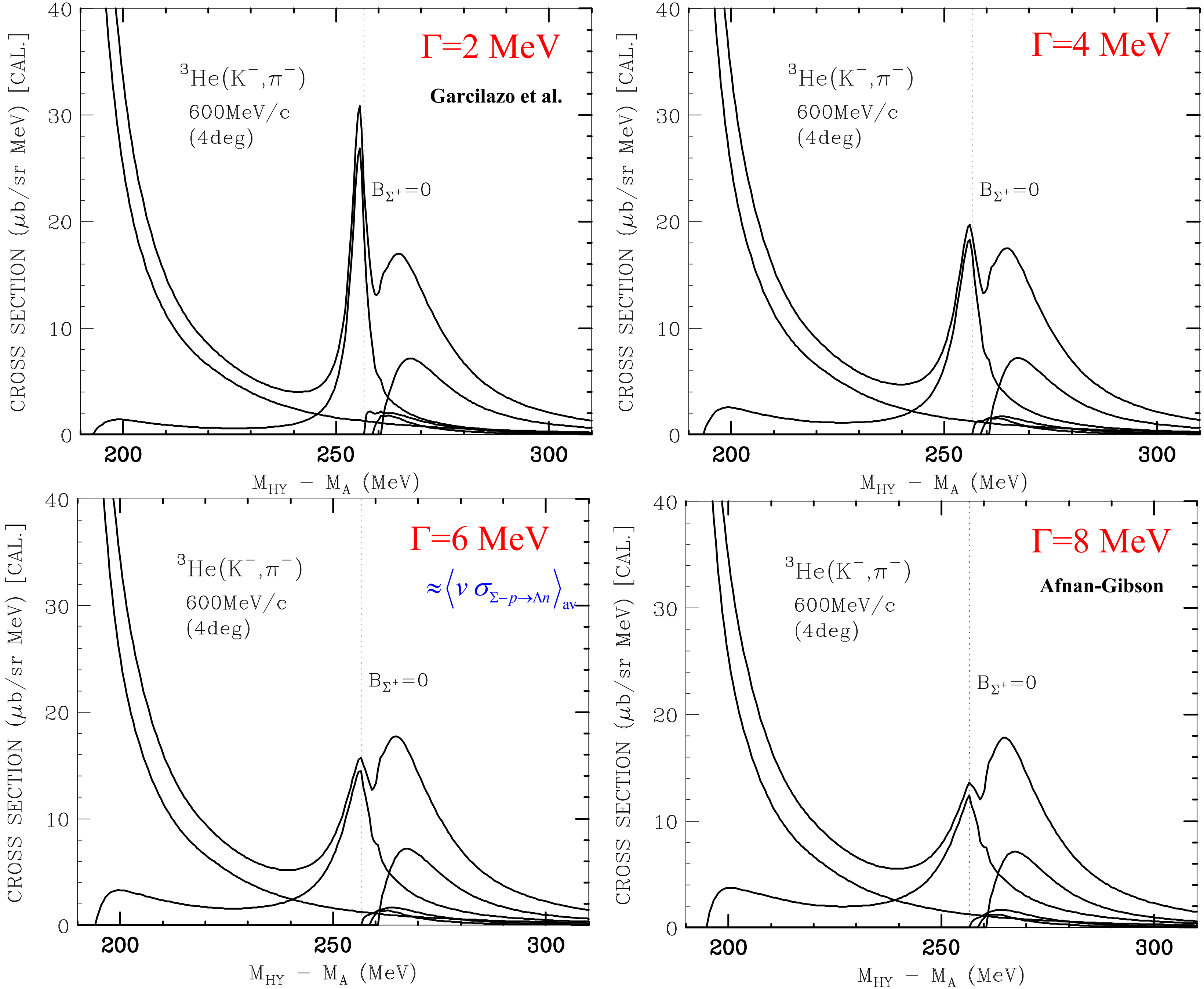
Σ-3N potential: the $_\Sigma{}^4$He bound state with T=1/2, J^π=0^+

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

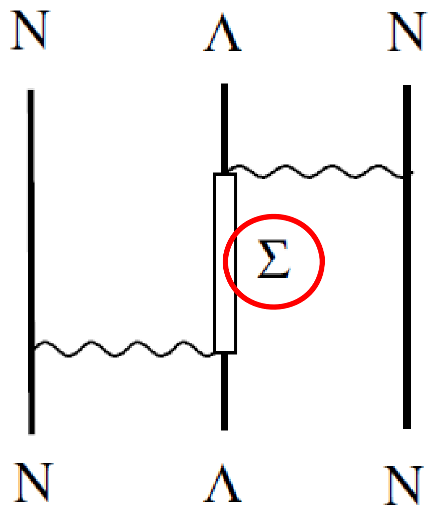
Production by K^- beam from ^{3}He targets



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



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

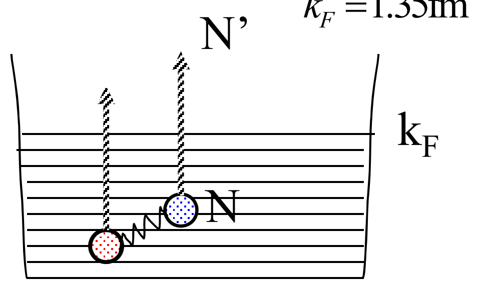
$$U_\Lambda(k_F,\varepsilon_\Lambda)=\sum_{\mathbf{k}_N}\langle \mathbf{k}_\Lambda,\mathbf{k}_N\,|\,g_{\Lambda N}(\omega=\varepsilon_\Lambda+\varepsilon_N)\,|\,\mathbf{k}_\Lambda,\mathbf{k}_N\rangle$$

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

G-matrix

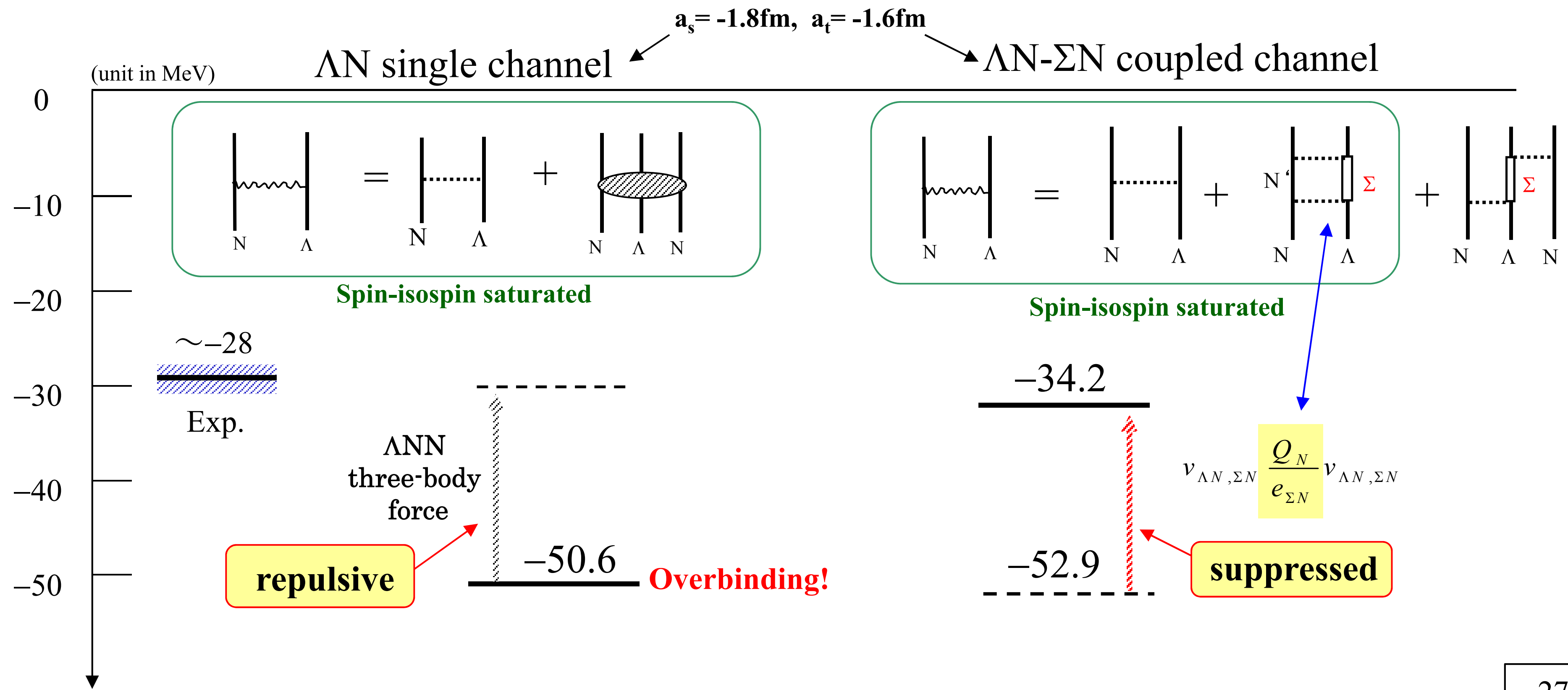
Pauli-operator

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



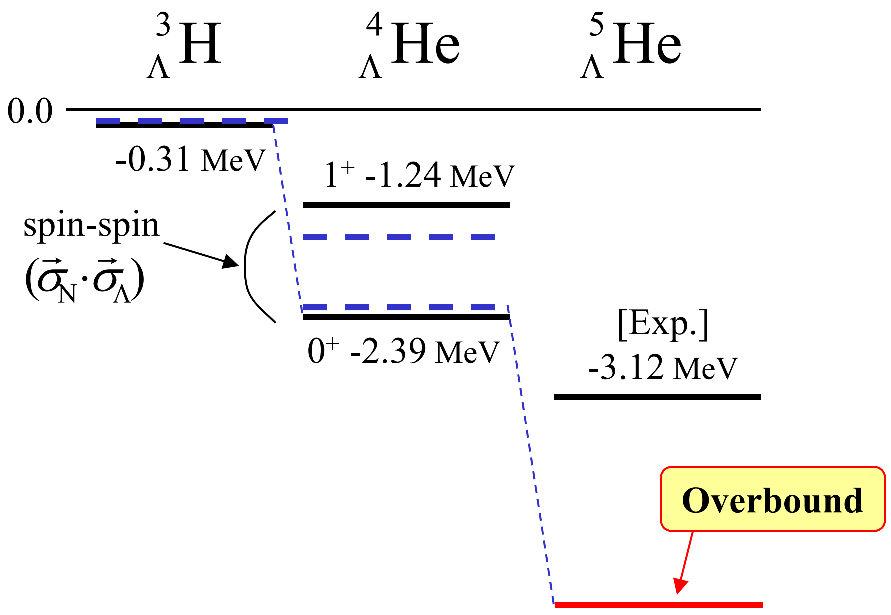
Effects of the ΛN-ΣN coupling in nuclear matter

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



Overbinding Problem on s-Shell Hypernuclei

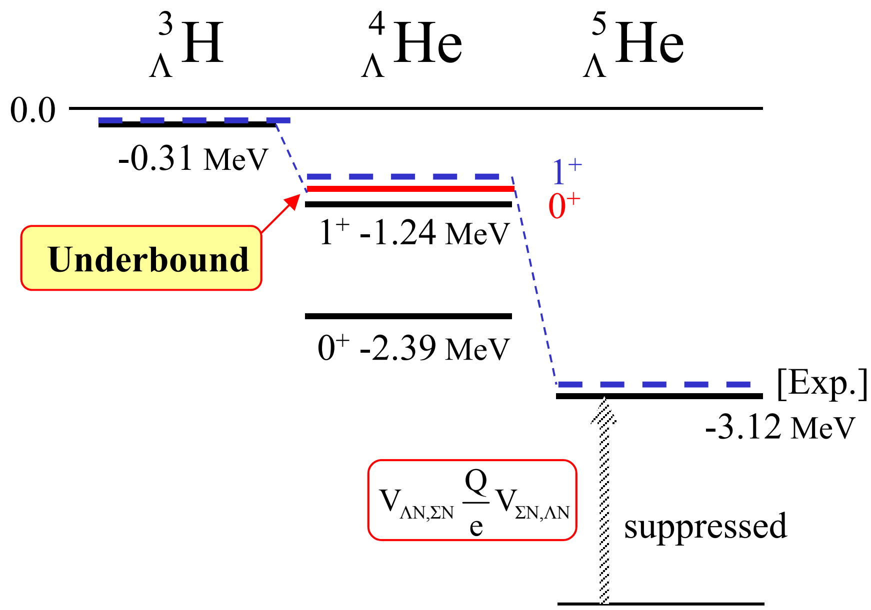
The Overbinding Problem



ΛN single-channel calc.

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

The Underbinding Problem

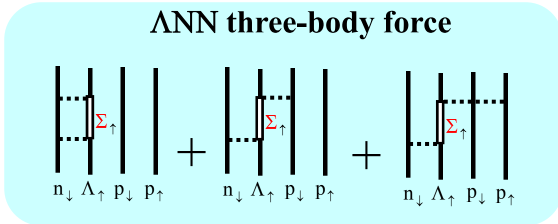


g-matrix calc. with ΛN-ΣN(D2)

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

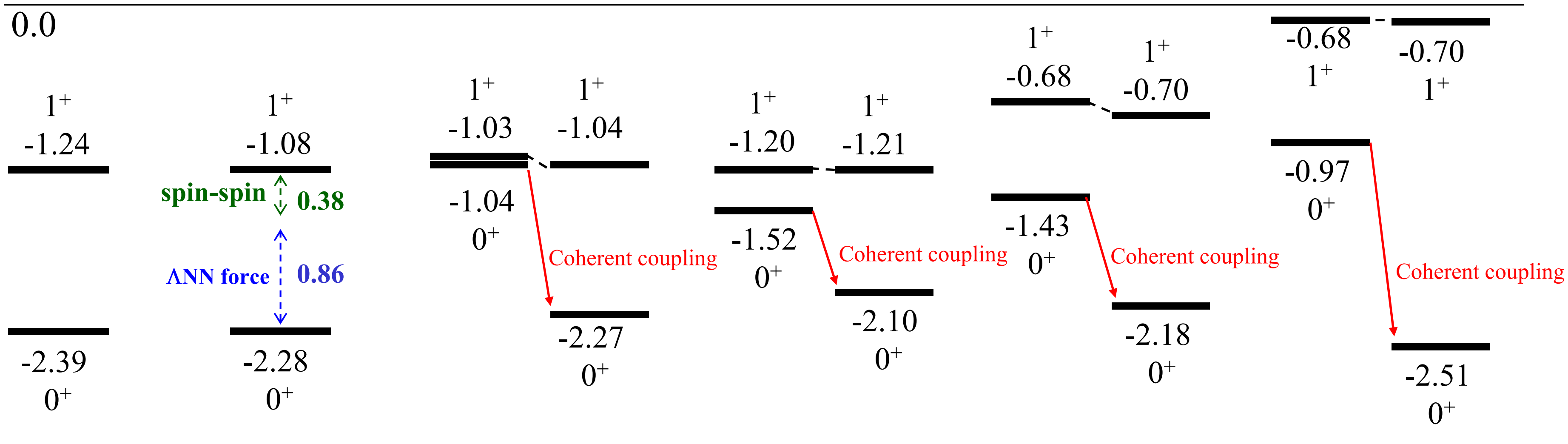
“The 0^+-1^+ difference is not a measure of ΛN spin-spin interaction.”
by B.F. Gibson

Hyperon-mixing



$^4_\Lambda$He

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



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

VMC

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

Breuckner-Hartree-Fock

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

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

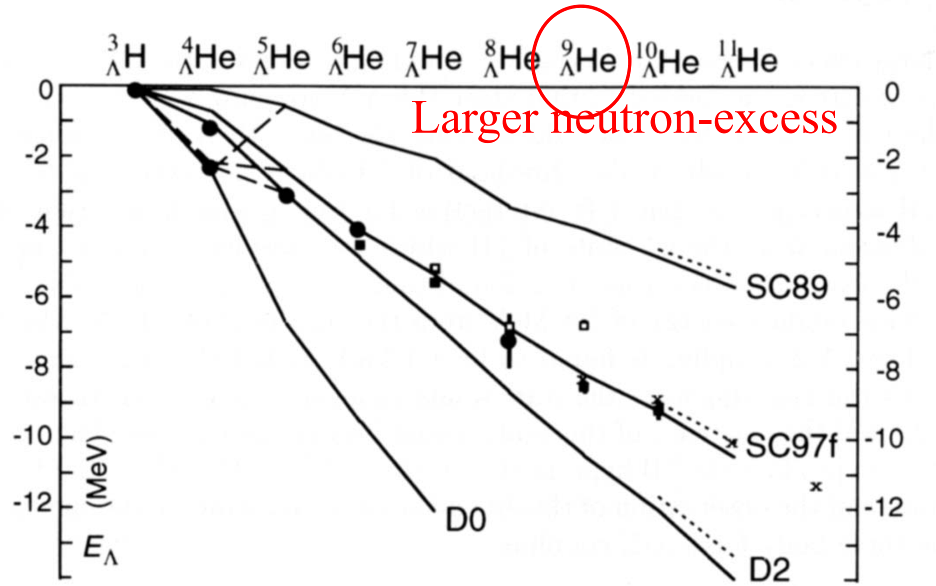
E10@J-PARC

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

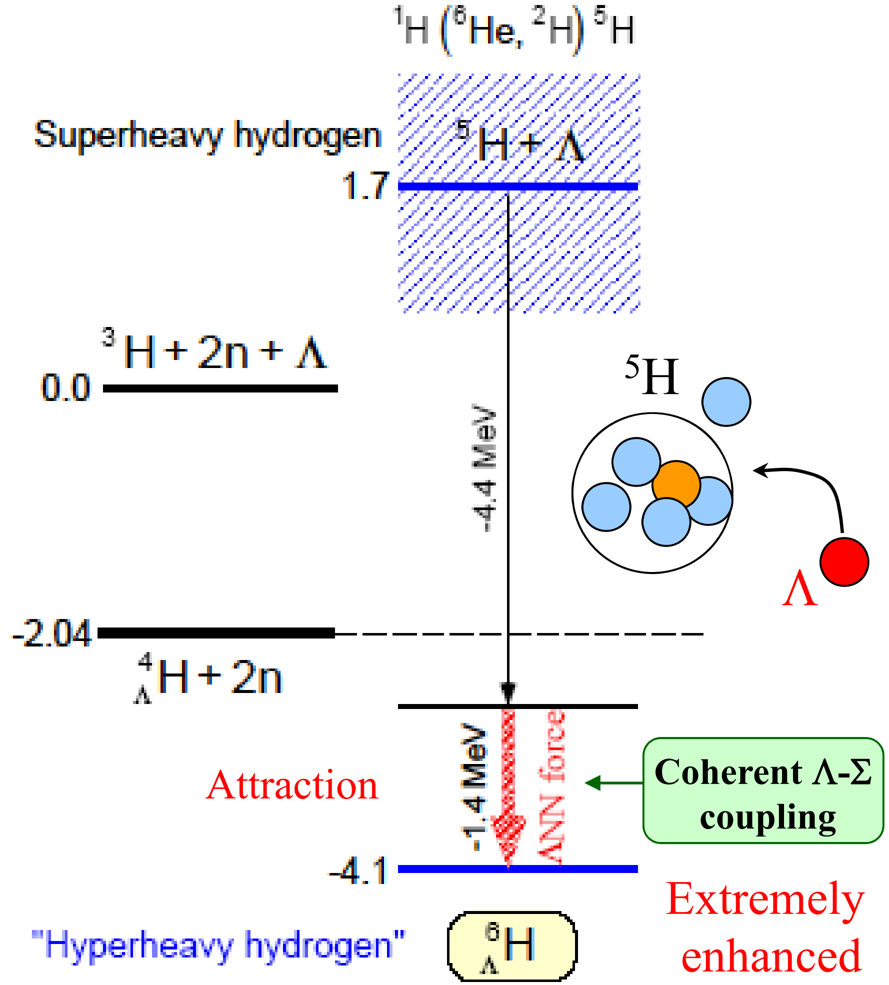
$^{6}_{\Lambda}\mathrm{H}$ **"Hyperheavy hydrogen"**

Y.Akaishi, NPA738(2004)80c

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



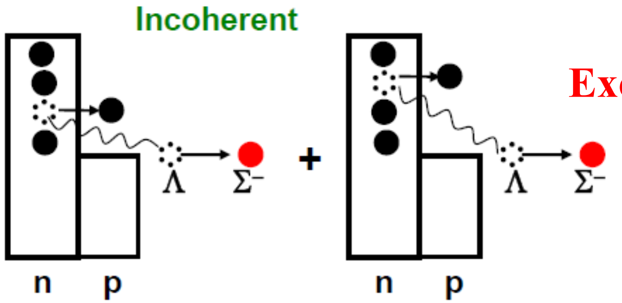
Λ binding energies



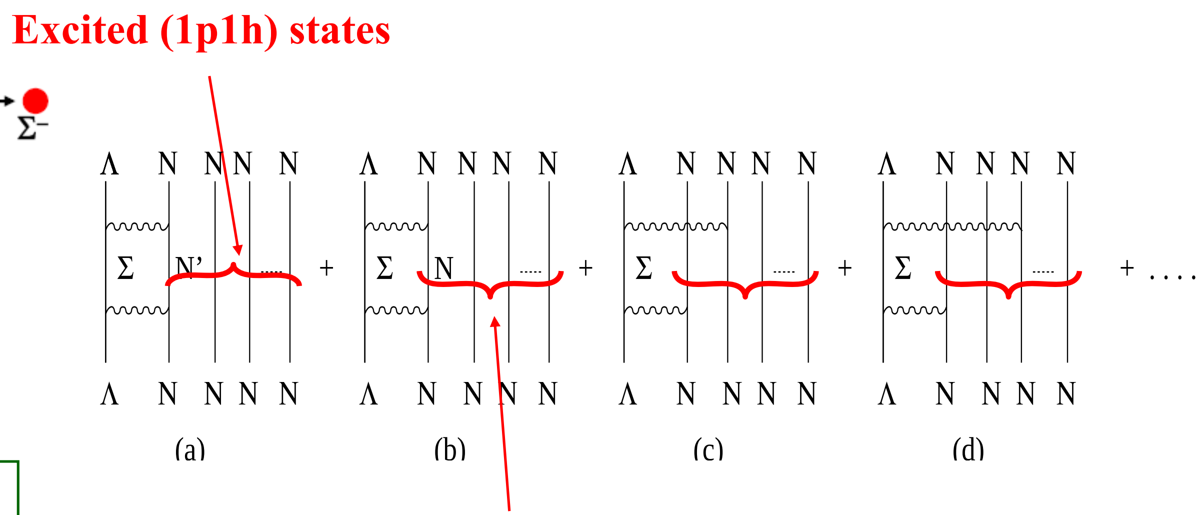
➢ **Coherent Λ-Σ coupling in neutron-excess environment**

The Λ-Σ coupling effects in neutron matter

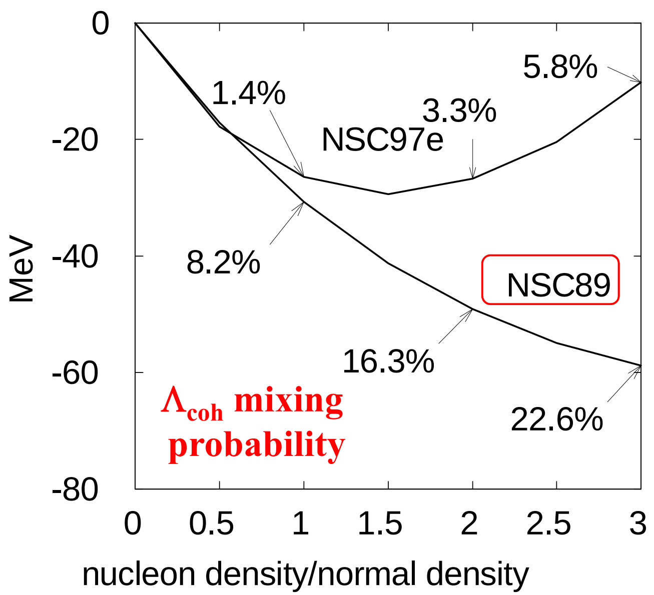
S.Shinmura, Khin Swe Myint, T.H., Y.Akaishi, J.Phys.G28(2002)L1

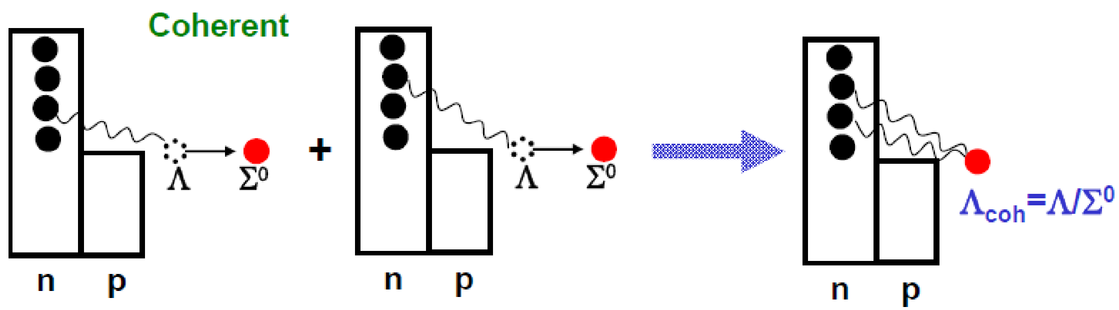


usually included in g-matrix



Single particle potential for Λ_{coh}.

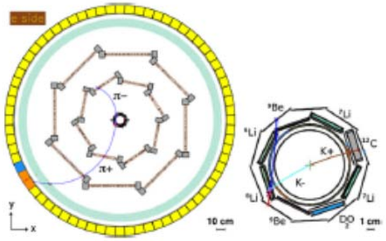




coherent Λ-Σ coupling

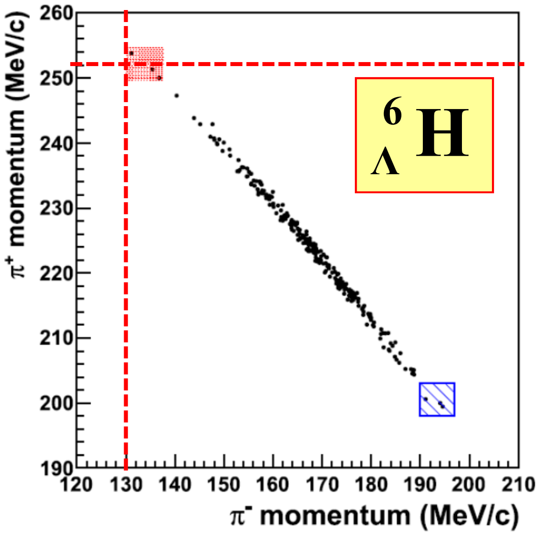
The Λ_{coh} mixing is enhanced in the neutron-excess environment.

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



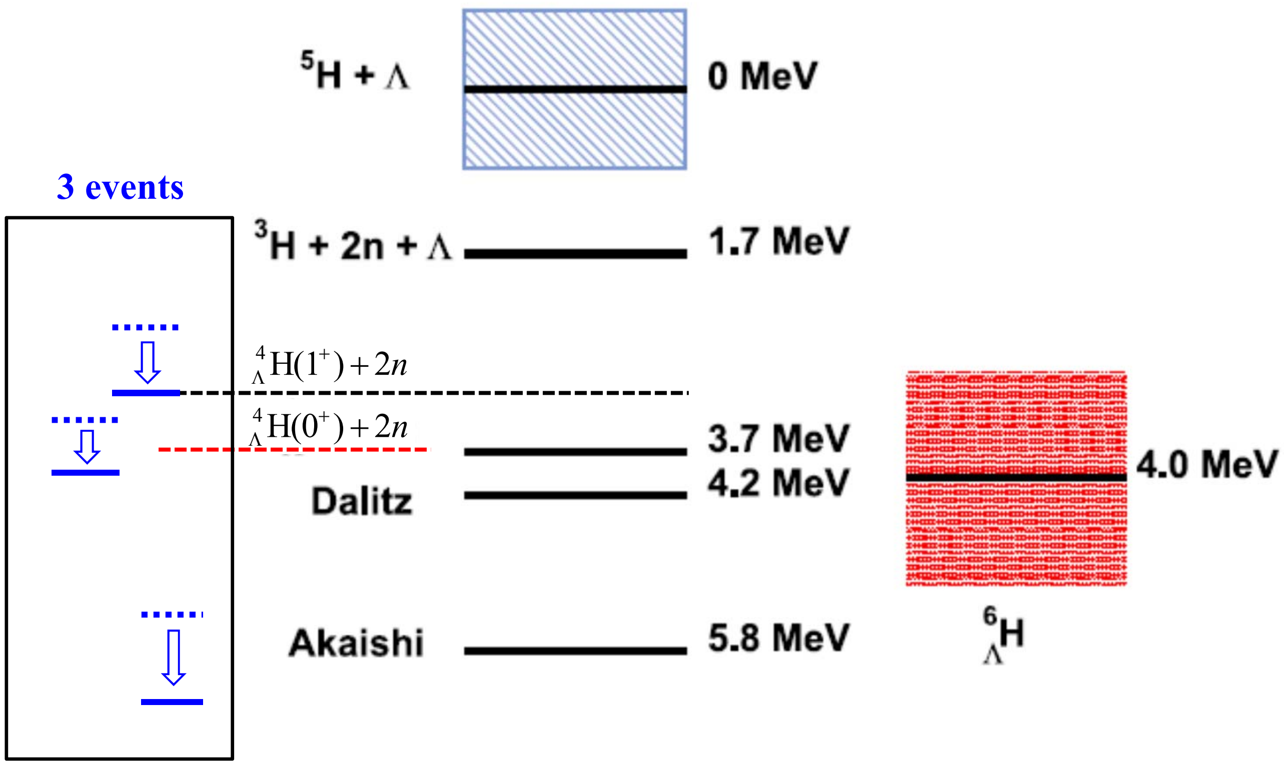
M. Agnello et al., NPA881(2012)269.
M. Agnello, et al., PRL108 (2012) 042501.

- observation of 3 candidate events of $^{6}_{\Lambda}H$ bound state
  B_{Λ} = 4.0 ± 1.1 MeV
- BR(DCX) / BR(NCX,12LC) ~ $3x10^{-3}$
  R = (5.9 ± 4.0) · $10^{-6}/K^{-}_{stop}$



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

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



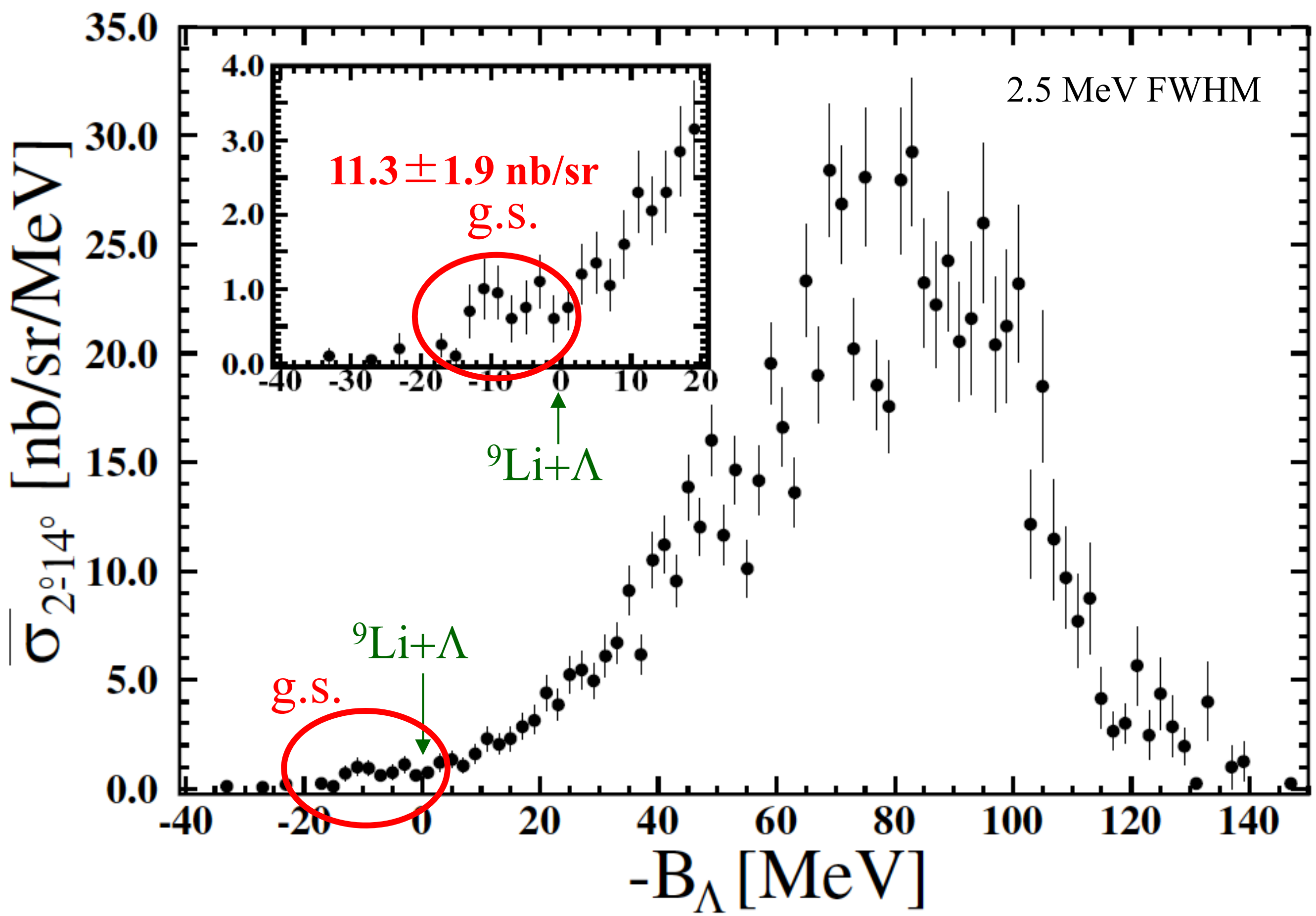
→E10@J-PARC

- 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

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

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

~1/1000

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

17.5±0.6 μb/sr

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

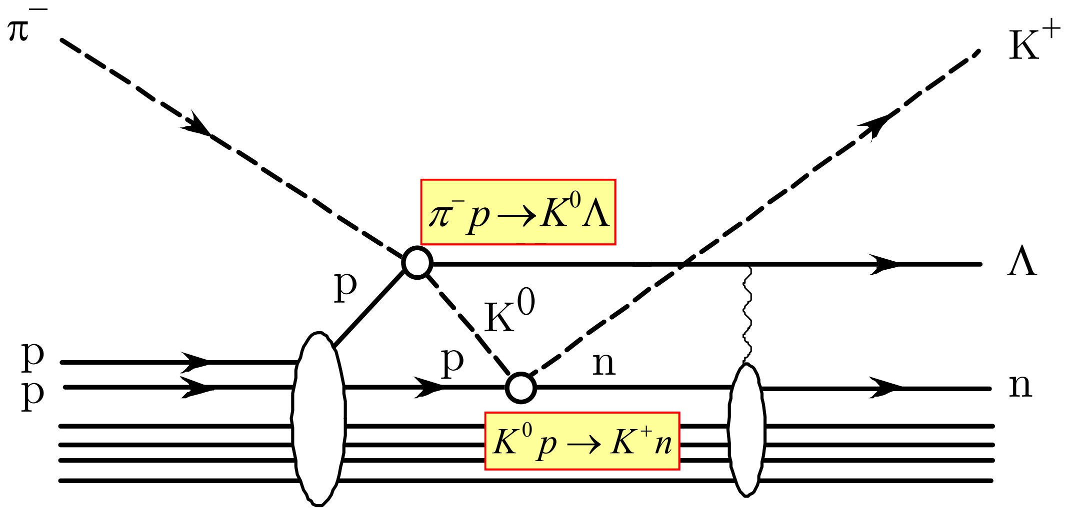
***Two-step process*:**

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

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

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

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

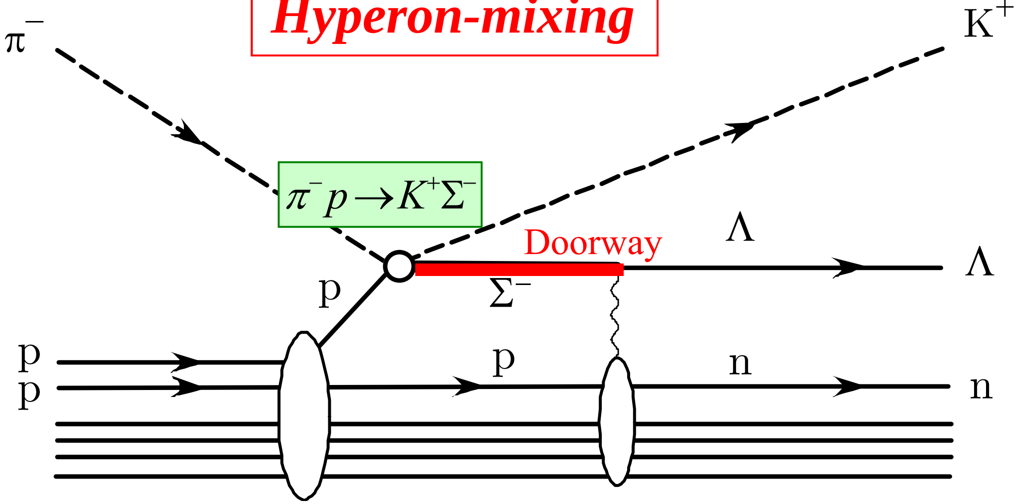


***One-step process*:**

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

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

via Σ^- doorways caused by ΛN-ΣN coupling



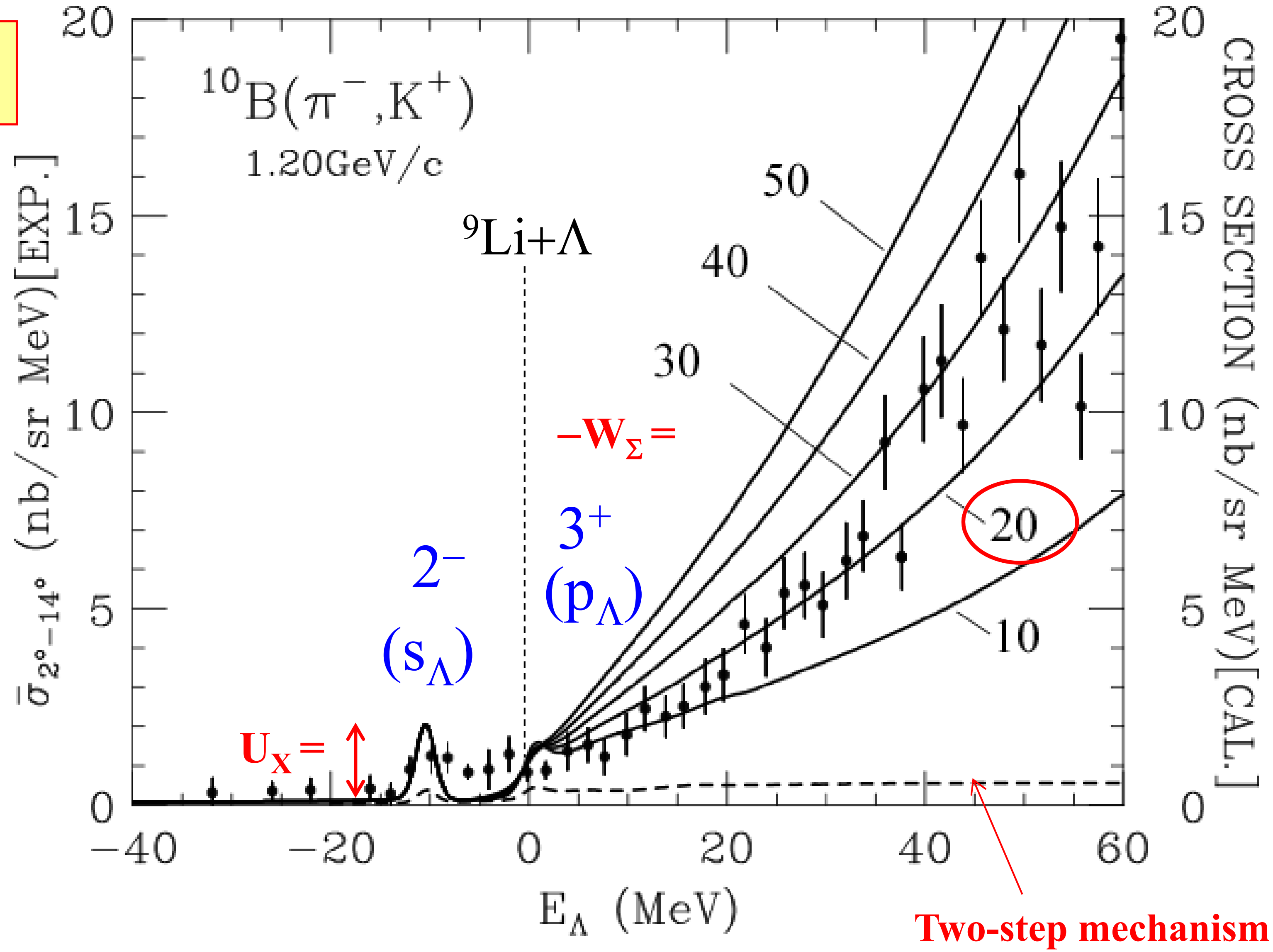
Λ spectrum by DCX (π⁻,K⁺) reactions at 1.2GeV/c

Harada, Umeya,Hirabayashi, PRC79(2009)014603

Spreading potential dep. W_Σ

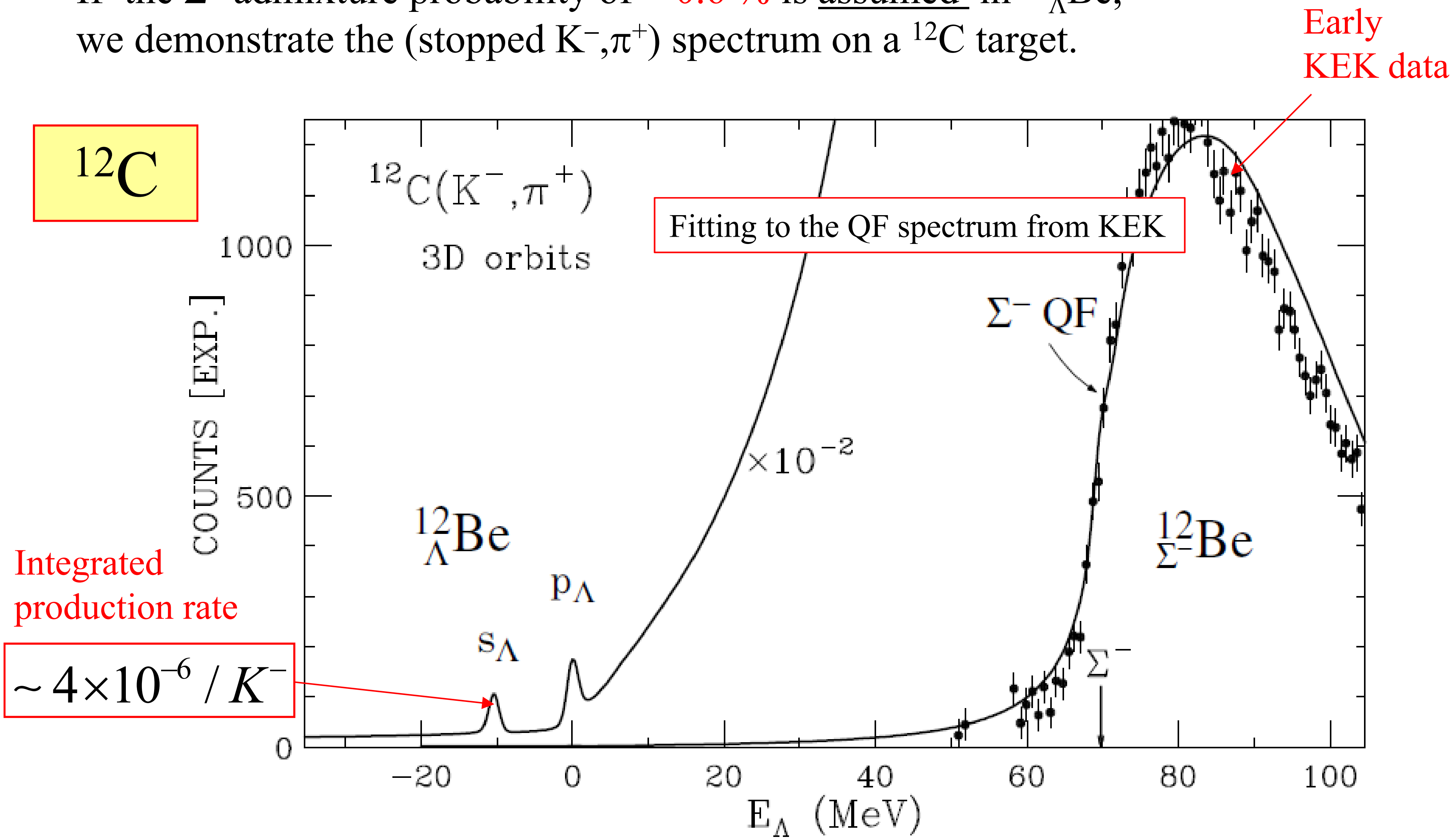
U_X =11 MeV is fixed. $P_{\Sigma-}$=0.57%

^{10}B



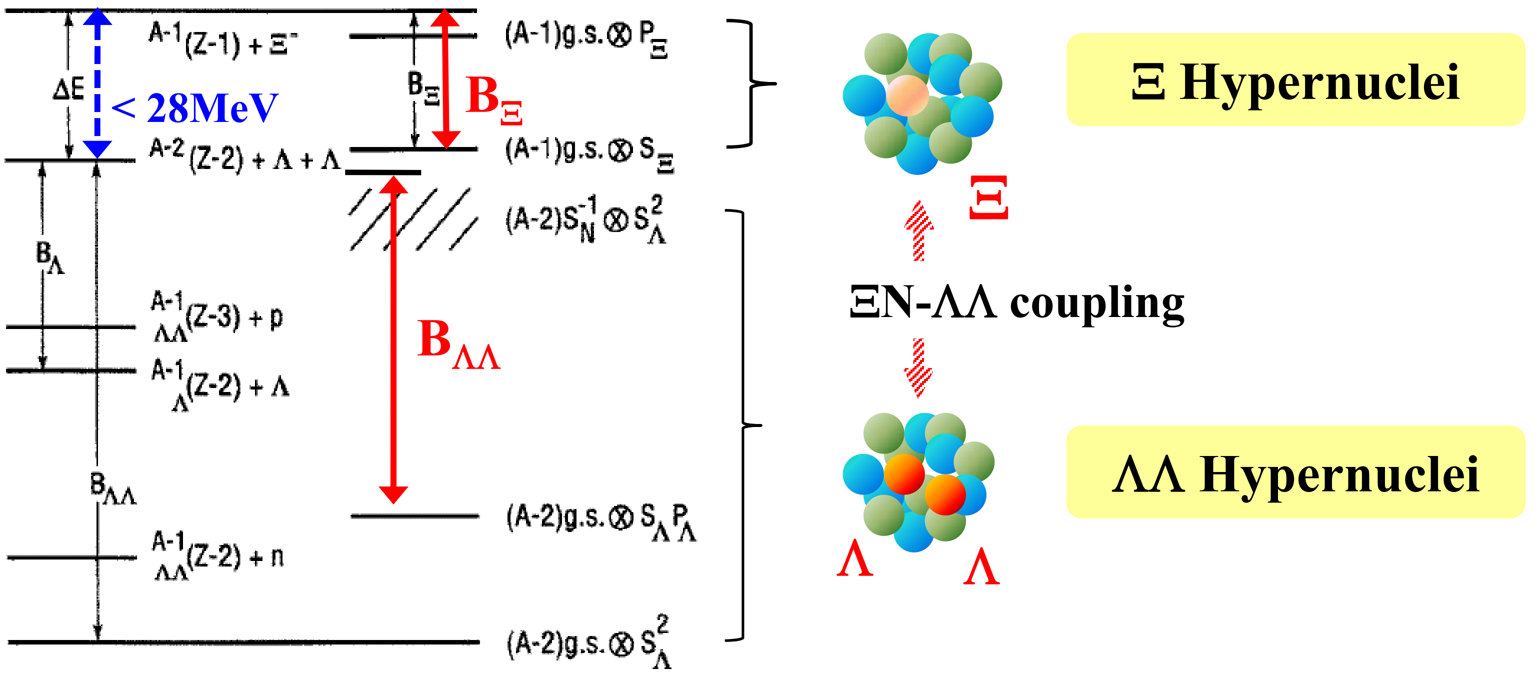
Λ spectrum by DCX (stopped K^-, π^+) reactions

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.



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

3. S = –2 Nuclei

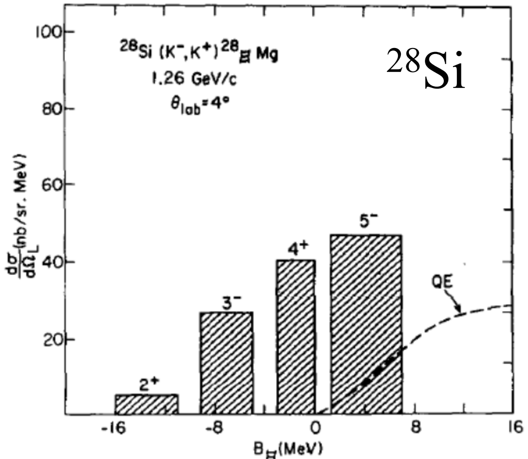


$^{A-1}(Z-1) + \Xi^-$
ΔE
< 28MeV
$^{A-2}(Z-2) + \Lambda + \Lambda$
B_Ξ
$(A-1)g.s. \otimes P_\Xi$
$(A-1)g.s. \otimes S_\Xi$
$(A-2)S_N^{-1} \otimes S_\Lambda^2$
B_Λ
$^{A-1}_{\Lambda\Lambda}(Z-3) + p$
$^{A-1}_{\Lambda}(Z-2) + \Lambda$
$B_{\Lambda\Lambda}$
$(A-2)g.s. \otimes S_\Lambda P_\Lambda$
$^{A-1}_{\Lambda\Lambda}(Z-2) + n$
$(A-2)g.s. \otimes S_\Lambda^2$
Ξ Hypernuclei
Ξ
ΞN-ΛΛ coupling
ΛΛ Hypernuclei
Λ
Λ

Studies of Ξ⁻ s.p. potentials

V_Ξ ?

knowledge is limited



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

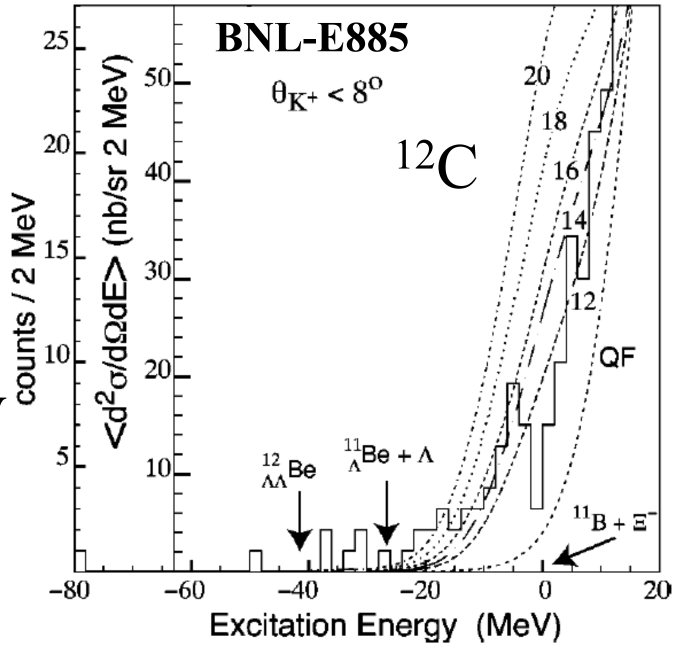
T.Iijima et al.,NPA546(1992)588.

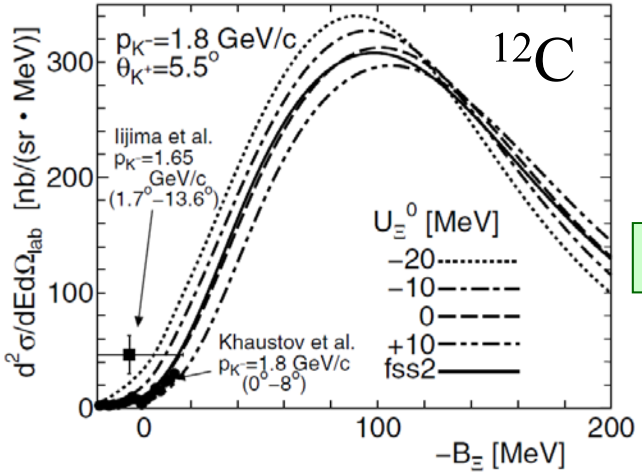
Tadokoro et al.,PRC51(1995)2656

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

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

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





Semi-Classical Distorted Wave Model Analysis

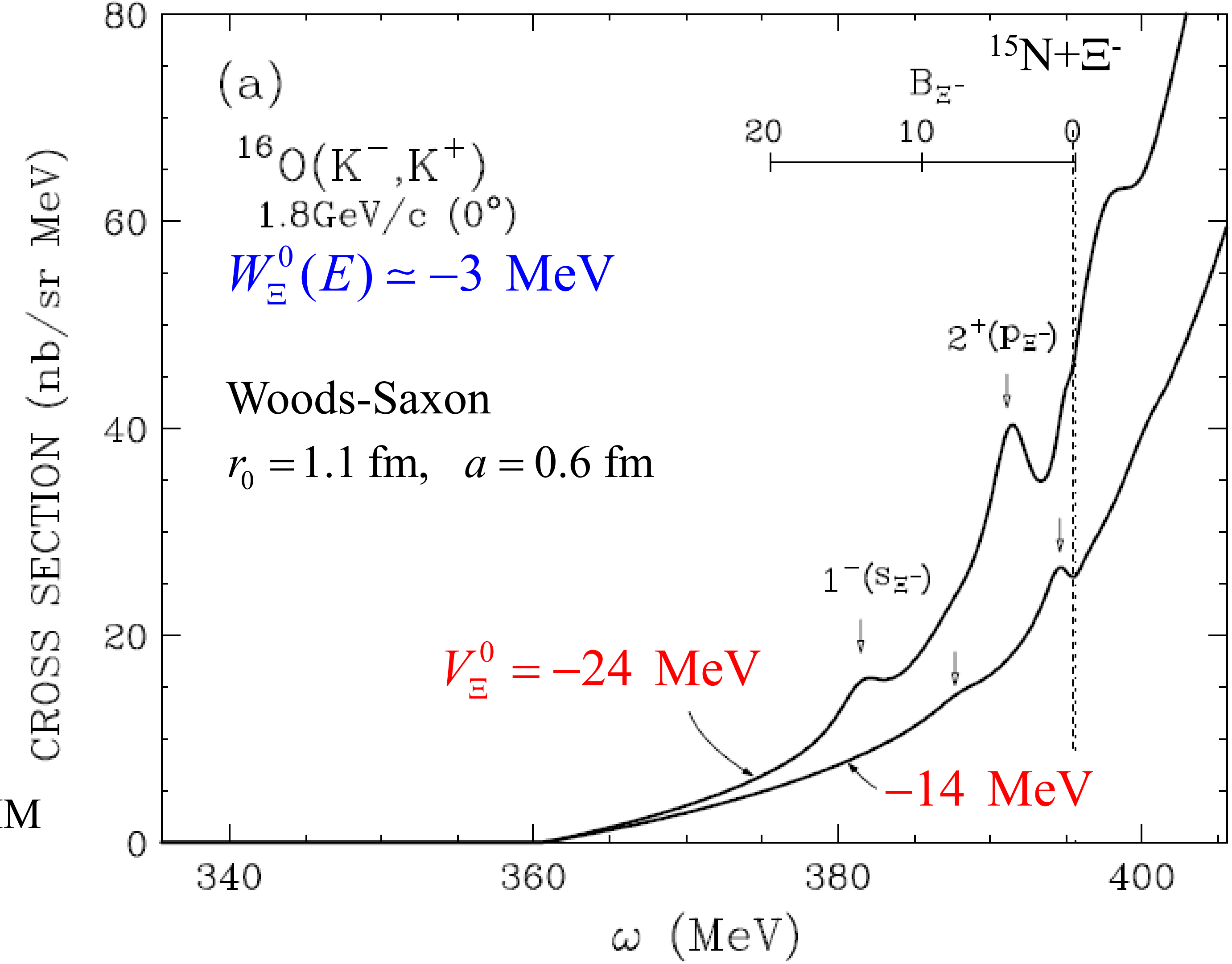
M. Kohno et al.,PTP123(2010)157;NPA835(2010)358.

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

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

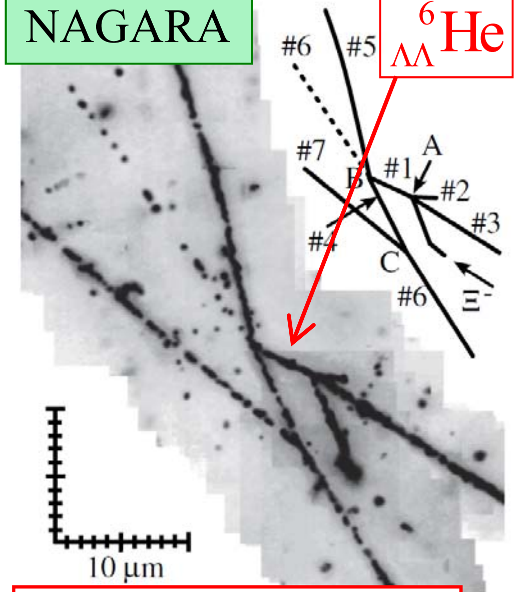
➢ **Spin-stretched Ξ^- states can be populated due to the high momentum transfer.**

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

Observation of ΛΛ Hypernuclei in E176/E373 Hybrid Emulsion

NAGARA

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

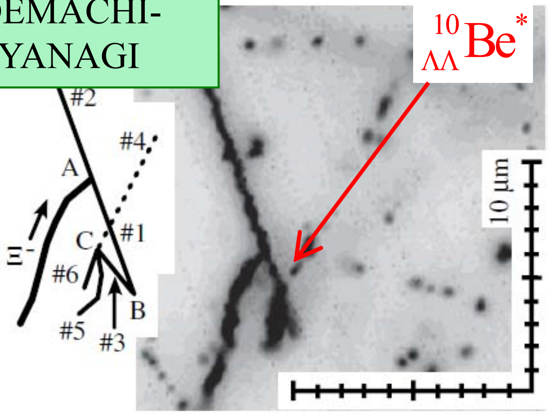


$^{12}\mathrm{C}+\Xi^- \to {}^{6}_{\Lambda\Lambda}\mathrm{He}+{}^{4}\mathrm{He}+t$

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

DEMACHI-YANAGI

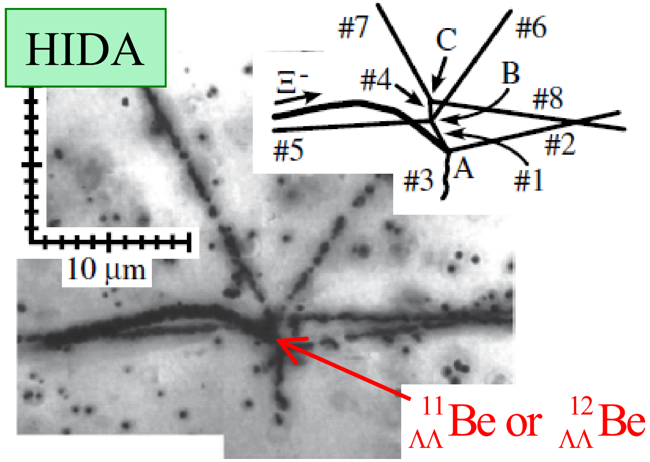
$^{10}_{\Lambda\Lambda}\mathrm{Be}^*$



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

Jaffe, PRL38(1977)195

HIDA



$^{11}_{\Lambda\Lambda}\mathrm{Be}$ or $^{12}_{\Lambda\Lambda}\mathrm{Be}$

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

Gal-Millener, PLB701(2011)342

event	${}^{A}_{\Lambda\Lambda}Z$	Target	$B_{\Lambda\Lambda}$ [MeV]	$\Delta B_{\Lambda\Lambda}$ [MeV]	$B^{CM}_{\Lambda\Lambda}$[MeV]	$B^{SM}_{\Lambda\Lambda}$[MeV]
NAGARA	$^{6}_{\Lambda\Lambda}\mathrm{He}$	$^{12}\mathrm{C}$	6.91 ± 0.16	0.67 ± 0.17	(6.91)	(6.91)
MIKAGE	$^{6}_{\Lambda\Lambda}\mathrm{He}$	$^{12}\mathrm{C}$	10.06 ± 1.72	3.82 ± 1.72		
DEMACHIYANAGI	$^{10}_{\Lambda\Lambda}\mathrm{Be}$	$^{12}\mathrm{C}$	11.90 ± 0.13	−1.52 ± 0.15	11.88	
HIDA	$^{11}_{\Lambda\Lambda}\mathrm{Be}$	$^{16}\mathrm{O}$	20.49 ± 1.15	2.27 ± 1.23	18.23	18.40
	$^{12}_{\Lambda\Lambda}\mathrm{Be}$	$^{14}\mathrm{N}$	22.23 ± 1.15	–		20.27
E176	$^{13}_{\Lambda\Lambda}\mathrm{B}$	$^{14}\mathrm{N}$	23.3 ± 0.7	0.6 ± 0.8		23.21
Danysz *et al*[17]	$^{10}_{\Lambda\Lambda}\mathrm{Be}({}^{9}_{\Lambda}\mathrm{Be}^*)$	$^{14}\mathrm{N}$	14.7 ± 0.4	1.3 ± 0.4	14.74 (g.s.)	14.97 (g.s.)

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

$\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}) \simeq$ 4.7 ⟶ 1.01 ⟶ 0.67

Prowse, 1966 — Nagara,2001 — Ξ mass update

"weak attractive"

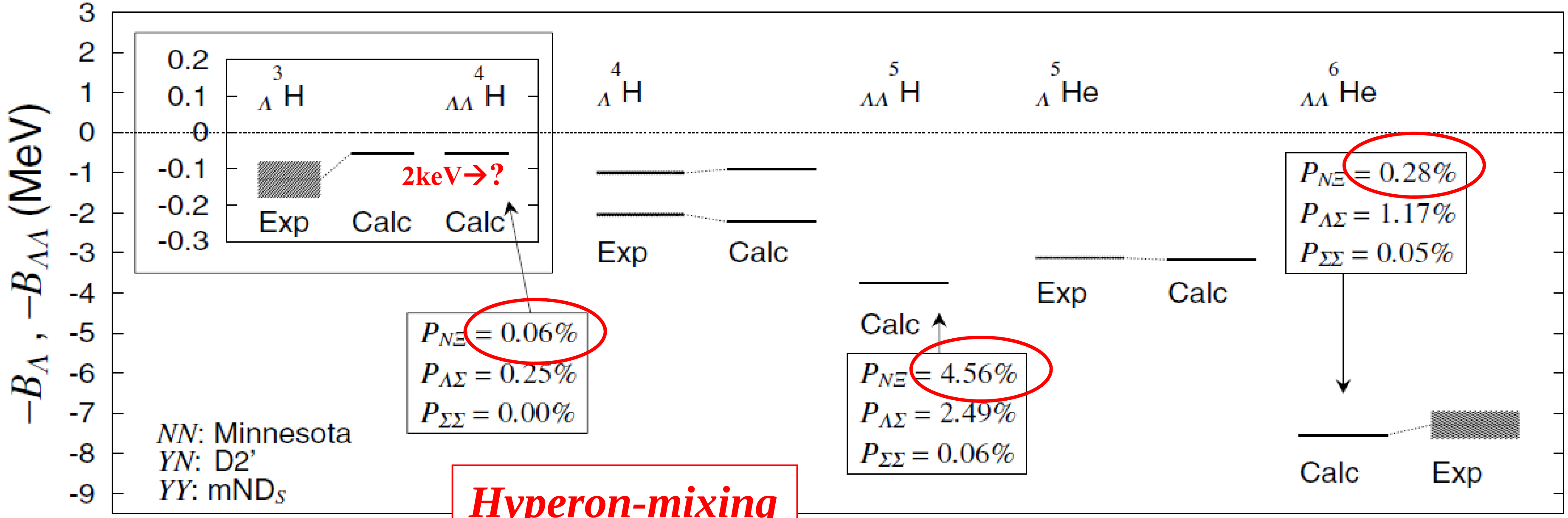
Coupled Channel Approach to Doubly Strange Hypernuclei

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



Hyperon-mixing

αΞN-αΛΛ coupled-channel calculations

T. Yamada, PRC69(2004)044301.

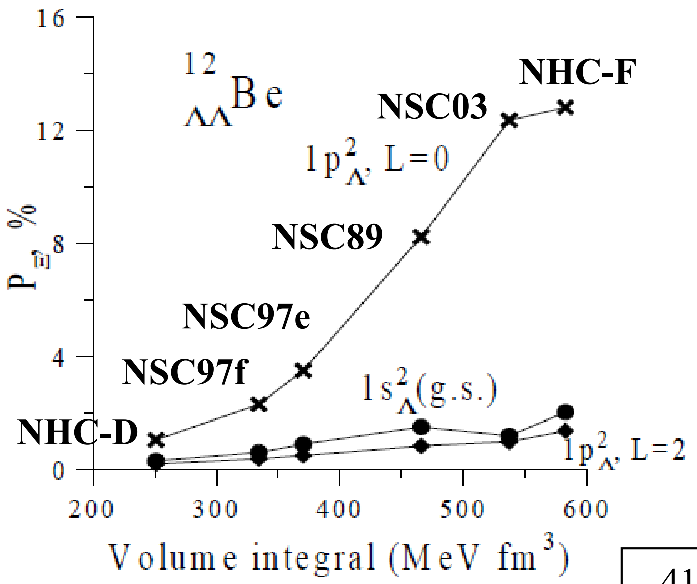
Y. Yamamoto and Th.A. Rijken, PRC69(2004)014303.

ΛΛ-ΞN s-wave: P(Ξ) < 1 %

Ξ-ΛΛ coupled-channel calculations

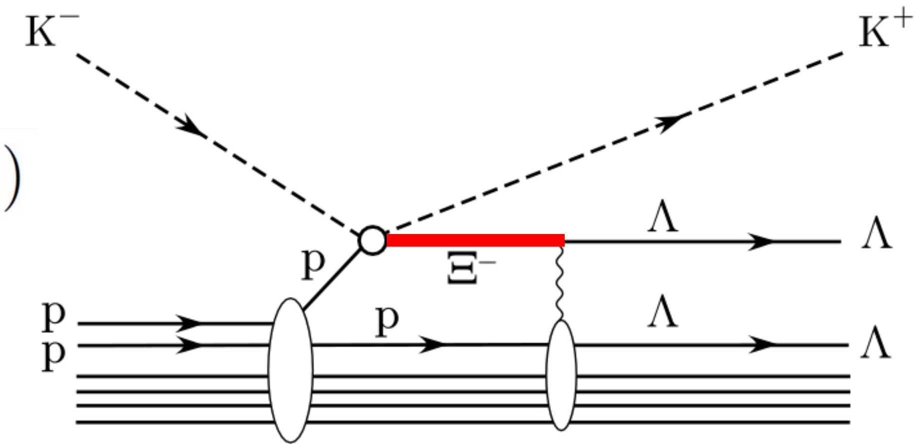
D. E. Lanskoy and Y. Yamamoto, PRC69(2004)014303.

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



Coupled-channels DWIA calculation for ΛΛ-Ξ production

Coupled-channel Green's function



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

$$\boldsymbol{G}(\omega) = \begin{pmatrix} G_\Lambda(\omega) & G_X(\omega) \\ G_X(\omega) & G_\Xi(\omega) \end{pmatrix} \qquad \boldsymbol{U} = \begin{pmatrix} U_\Lambda & U_X \\ U_X & U_\Xi \end{pmatrix}$$

Inclusive cross sections

DWIA+CCGFM

T. Harada, NPA672(2000)181

$$\left(\frac{d^2\sigma}{d\Omega_K dE_K}\right)_{\text{lab}} = \beta \frac{1}{[J_A]} \sum_{M_z} \sum_{\alpha'\alpha} \left(-\frac{1}{\pi}\right) \text{Im}\left[\int d\boldsymbol{r}' d\boldsymbol{r}\, F_\Xi^{\alpha'\dagger}(\boldsymbol{r}')\, G_\Xi^{\alpha'\alpha}(\omega, \boldsymbol{r}', \boldsymbol{r}) F_\Xi^{\alpha}(\boldsymbol{r})\right]$$

The decomposition of the inclusive spectrum into components

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

ΛΛ escape

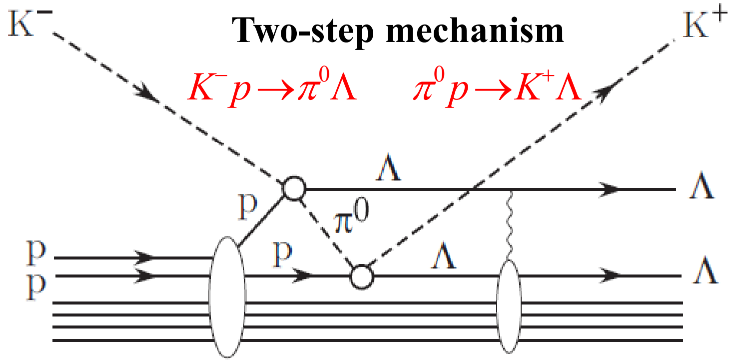
Ξ^- escape

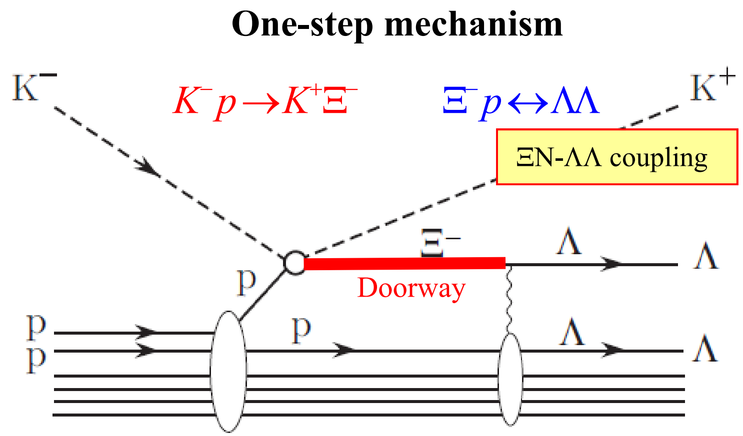
Spreading (nuclear-core breakup)
= Complicated excited states

Distorted waves for mesons

Eikonal distortion: $\sigma_{K-} = 19.4$ mb, $\sigma_{K+} = 28.9$ mb, $\alpha_\pi = \alpha_K = 0$

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

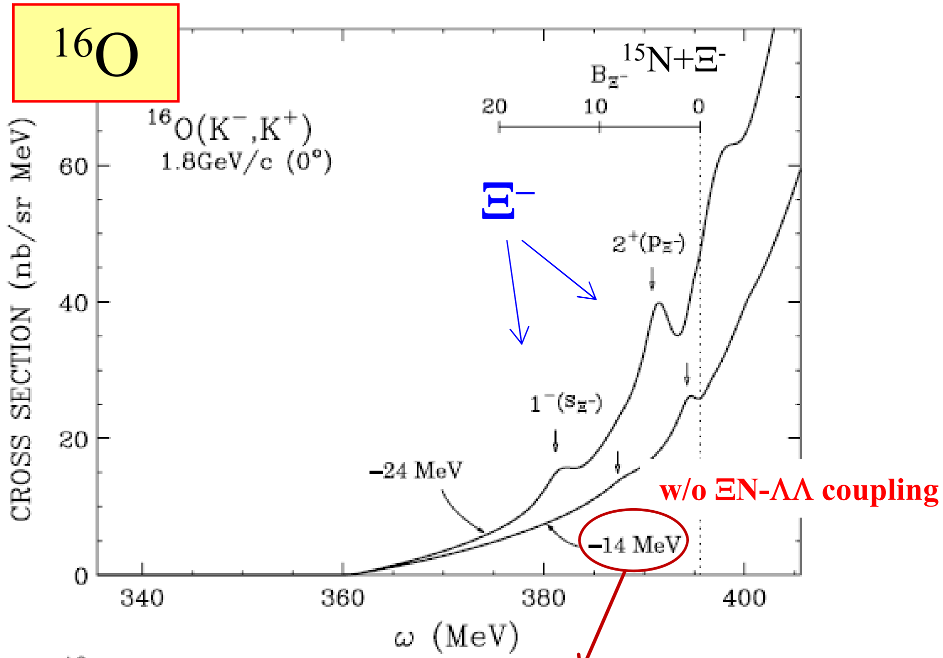


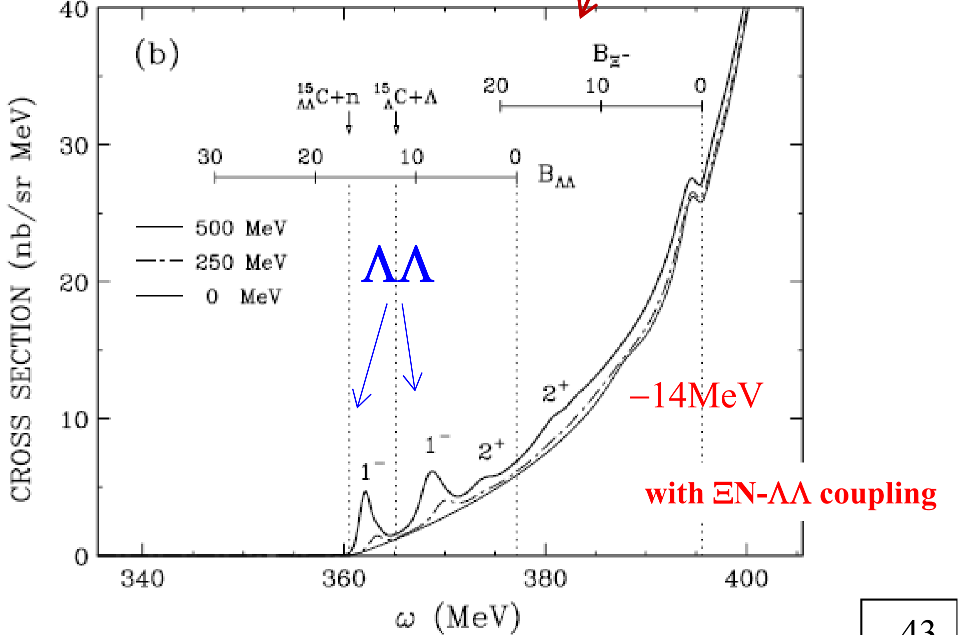


Hyperon-mixing

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

E07@J-PARC

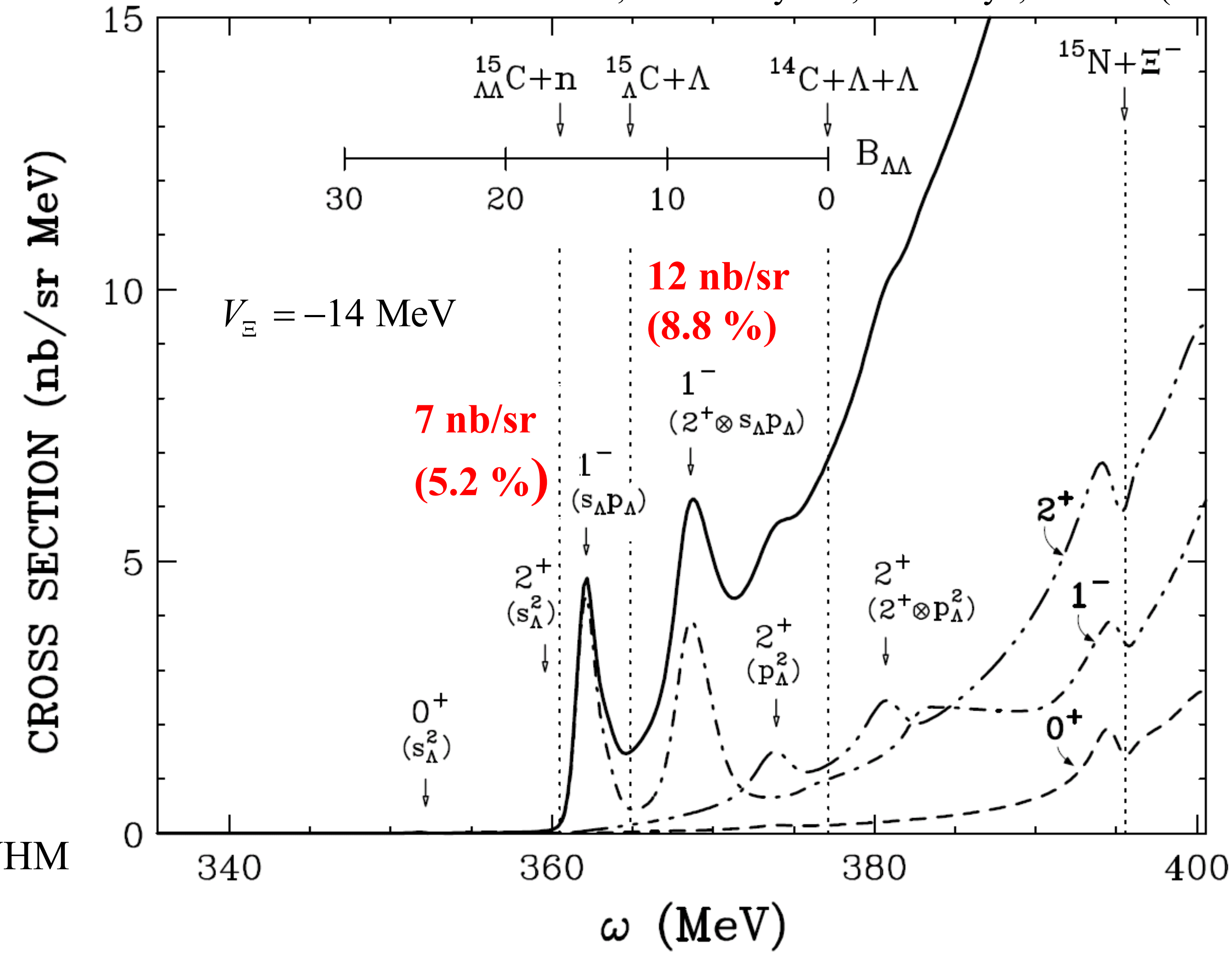




Ξ^- spectrum in DCX (K^-,K^+) reactions at 1.8GeV/c

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

^{16}O

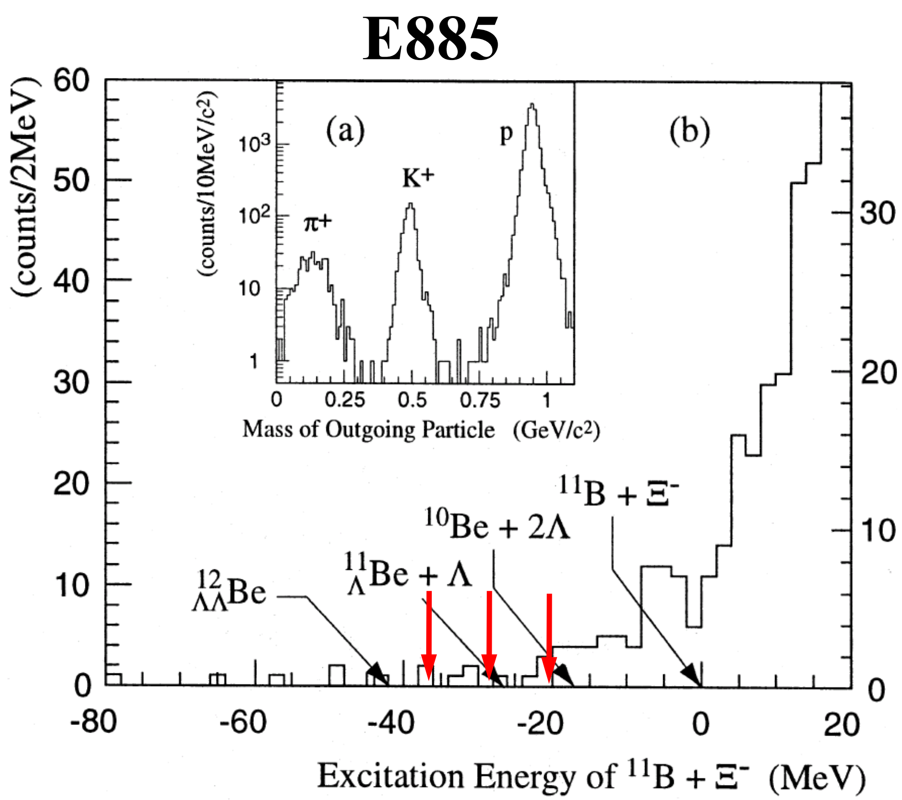


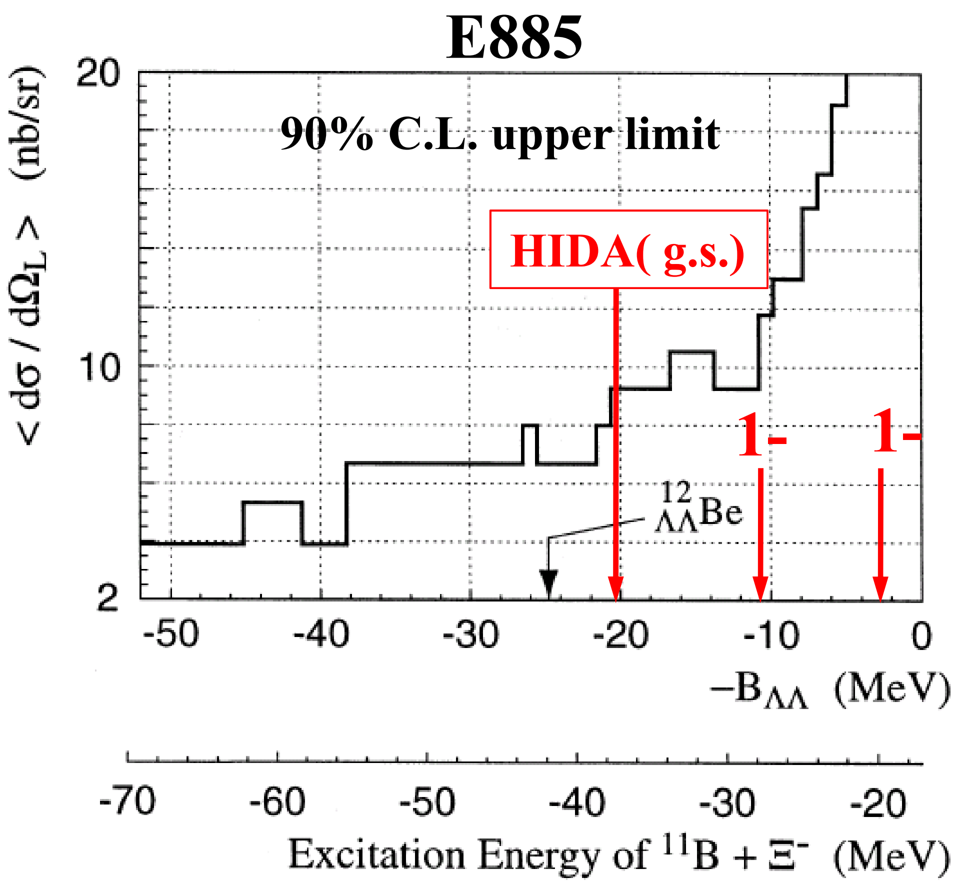
1.5MeV FWHM

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

Search for ΛΛ hypernuclei in the (K^-,K^+) reaction on ^{12}C

K. Yamamoto et al. (E885 Collaboration), PLB478(2000)401.

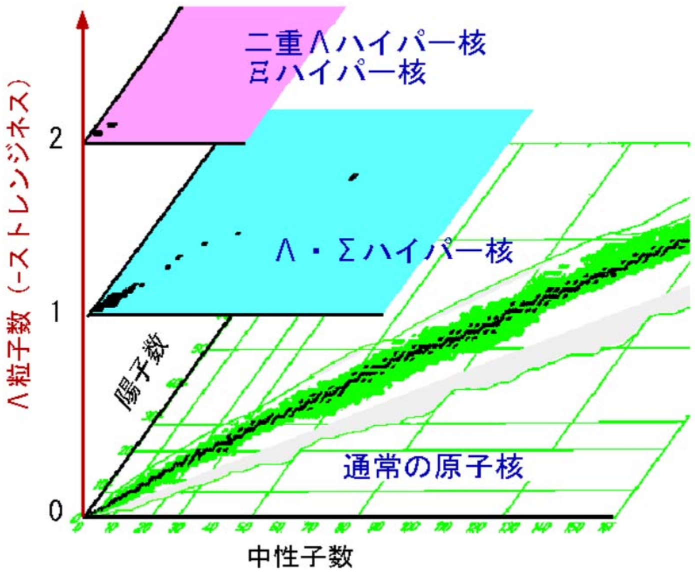




- Our results seem to be consistent with the E885 data, which taken from ^{12}C , not ^{16}O.

Remark

Studies of the DCX reactions (π^-,K^+),(K^-,K^+)
for hypernuclear productions
are
very important and promising .

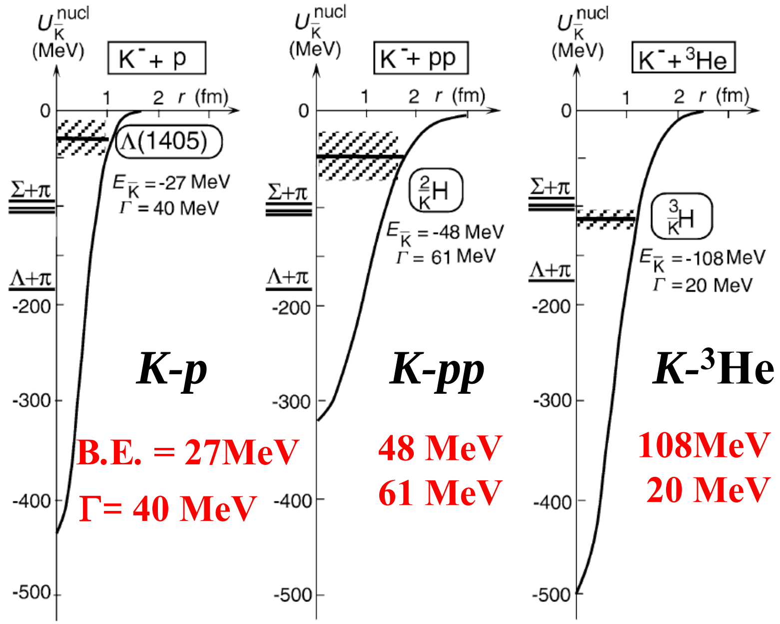


■Keywords

Hyperon mixing
+
DCX

5. Deeply Bound K^{bar} Nuclei

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

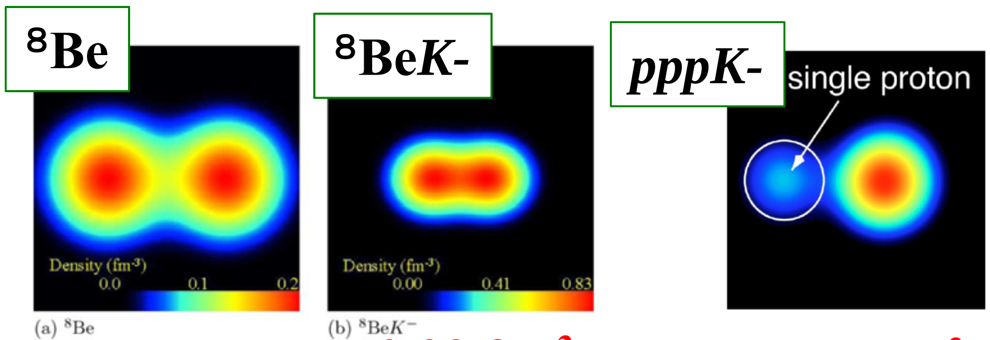
"Super strong nuclear force"

Yamazaki,Akaishi,PJAS. B82(2007)144

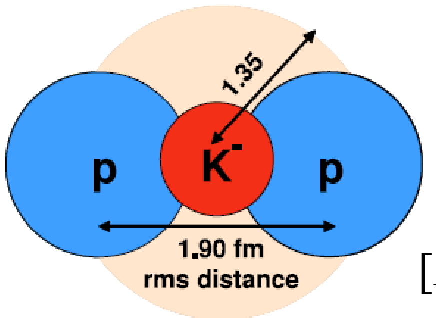
Exotic states of antiKaonic nuclei by AMD

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**

High dense hadronic matter

Experimental Candidates for Deeply-Bound State K^-pp

2011.6

FINUDA Collaboration@DAΦNE

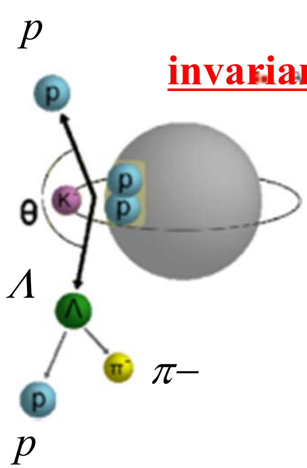
M. Agnello et al.,PRL94(2005)212303

B.E. = 115 ± 9MeV

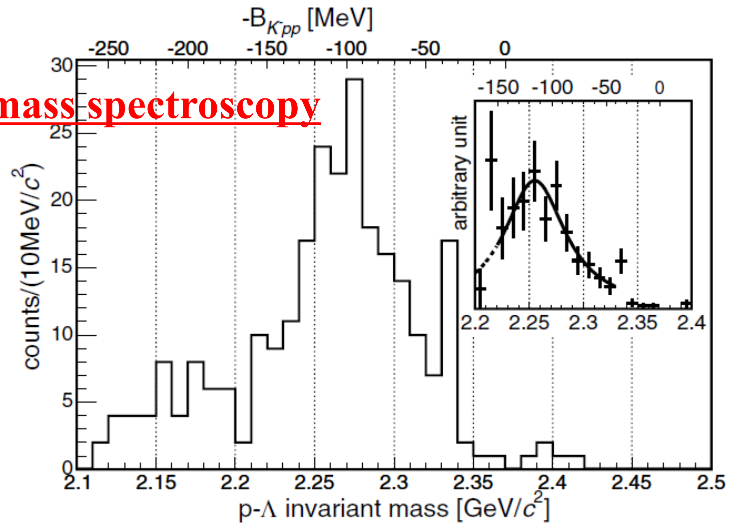
$\Gamma = 67^{+16}_{-14}$ MeV

-- K- absorption on
6Li, 7Li,12C,27Al at Rest

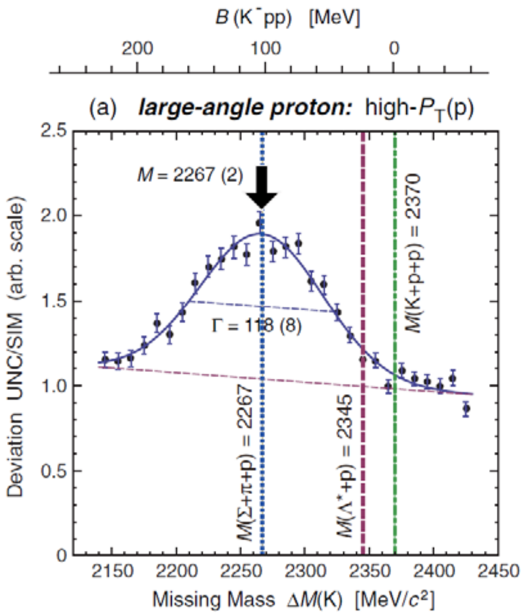
-- Λp invariant mass distrib.



invariant mass spectroscopy



DISTO Collaboration@SATURNE-Saclay



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

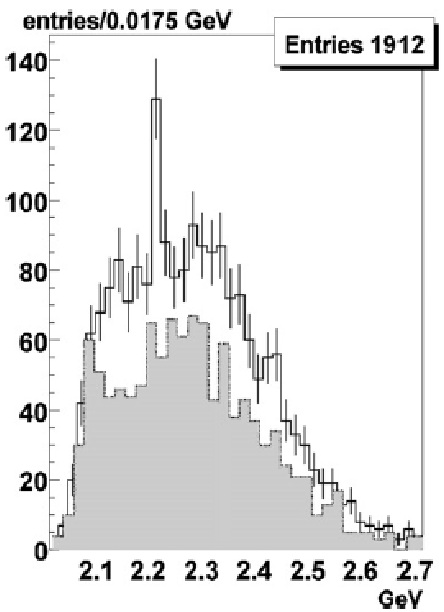
B.E. = 103±3±5 MeV

Γ=118±8±10MeV

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

-- $p\pi^- p$ invariant mass distrib.

$^3He(K^-,n)K$-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

missing mass spectroscopy +invariant mass spectroscopy

Integrated cross section in the bound region

~ 3.5 mb/sr (for YA)

Advantage of the use of ^3He

- Distortion effects

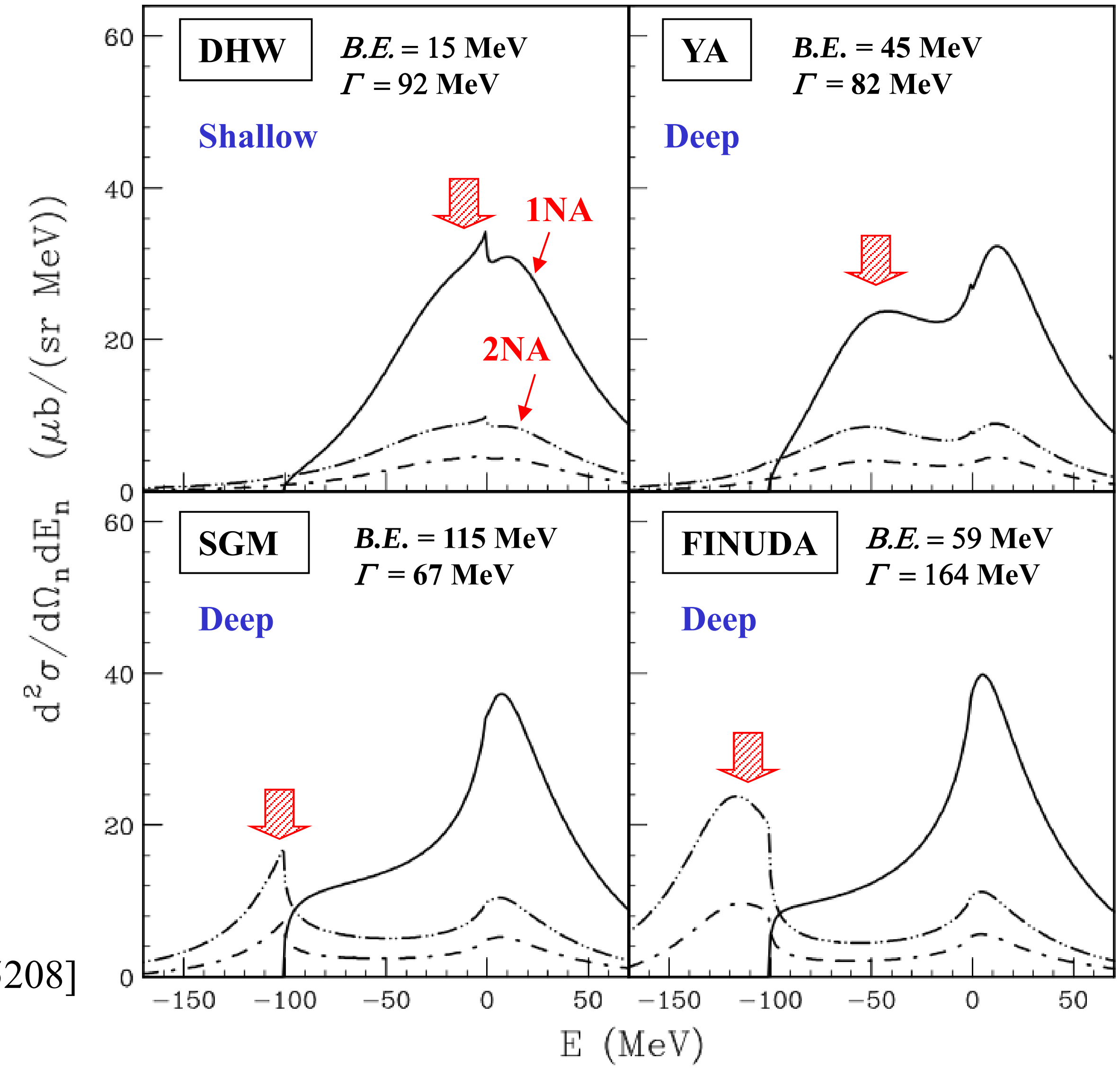
$$\frac{D_{\mathrm{dist}}[^3\mathrm{He}(1s_N \to 1s_K)]}{D_{\mathrm{dist}}[^{12}\mathrm{C}(1p_N \to 1s_K)]} = 0.47/0.095 \rightarrow \text{Factor } 5$$

- Recoil effects

M_C/M_A ~2/3 → Factor 1.8

- Small-size effects

A bound state in L=0



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

中性子星の解明を目指して-ハイペロン相互作用

■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) ? →Σ^+p(=Σ^-n)散乱 E40@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" ?

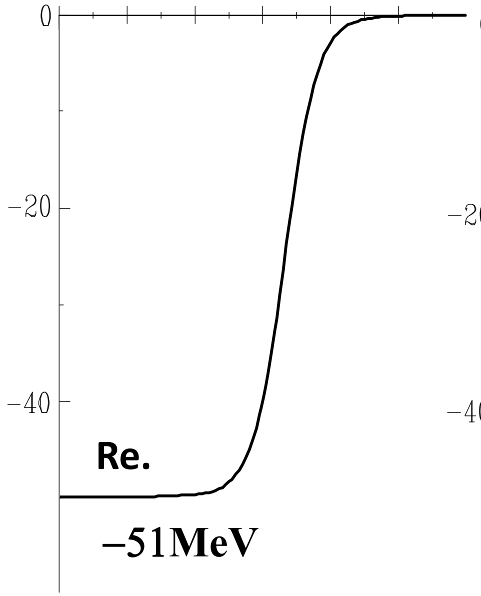
→ (K^-,N), (π^+,K^+)反応

E15,E23@J-PARC

Our understanding of hyperon s.p. potentials

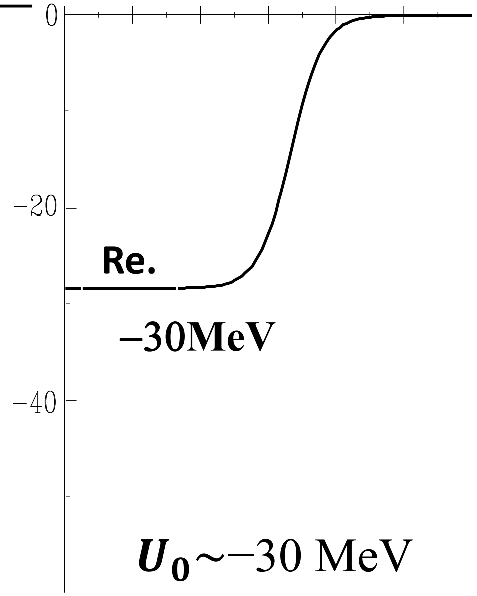
N | **Λ** | **Σ** | **Ξ**

$U_0(\mathrm{N})$



$U_0 \sim -51$ MeV
$U_{LS} \sim 22$ MeV

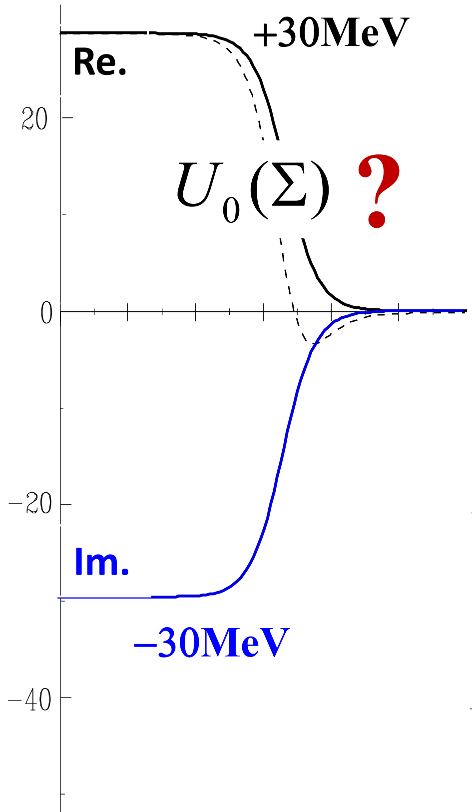
$U_0(\Lambda)$



$U_0 \sim -30$ MeV
$U_{LS} \sim 2$ MeV

ΛΛN 3BF ?
Σ mixing Prob.?

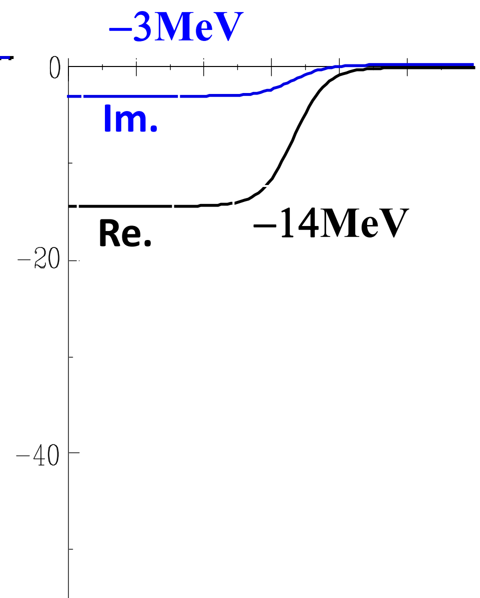
$U_0(\Sigma)$?



Strong repulsive,
Spin-isospin dep.

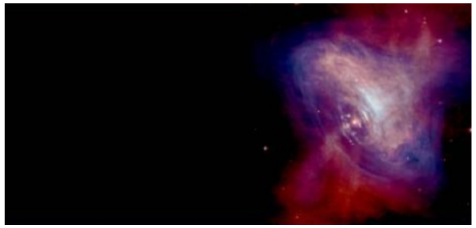
$U_0 \sim +30$ MeV
U_{LS} ?, Σ width ?

$U_0(\Xi)$?



$U_0 \sim$
(−14)□(0)MeV ?
Ξ width ?
ΛΛ-ΞN mixing ?
H-particle ?

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」



D01「中性子星と核物質の理論研究」（代表：大西）

■ 高密度中性子星物質 – 研究計画 –

- 原田　融　　ハイパー核の生成と構造
- 土手昭伸　　K^-中間子を含む原子核と高密度物質
- 木村真明　　中性子過剰ハイパー核の構造
- 山縣関原淳子　媒質中におけるK^-中間子の性質
- 大西　明　　ストレンジネスを含む原子核と核物質

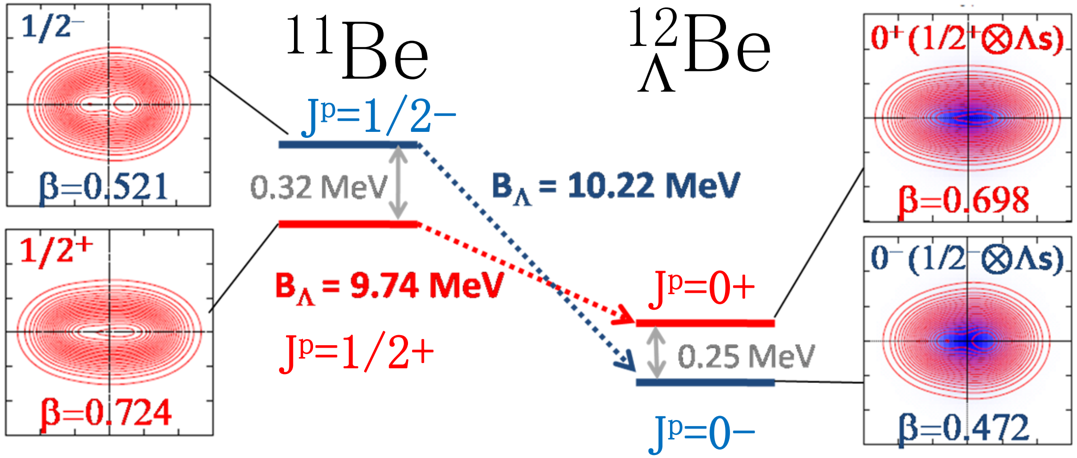
微視的核模型による中性子過剰Λハイパー核の生成反応と構造

(井坂、木村、土手、大西、原田)

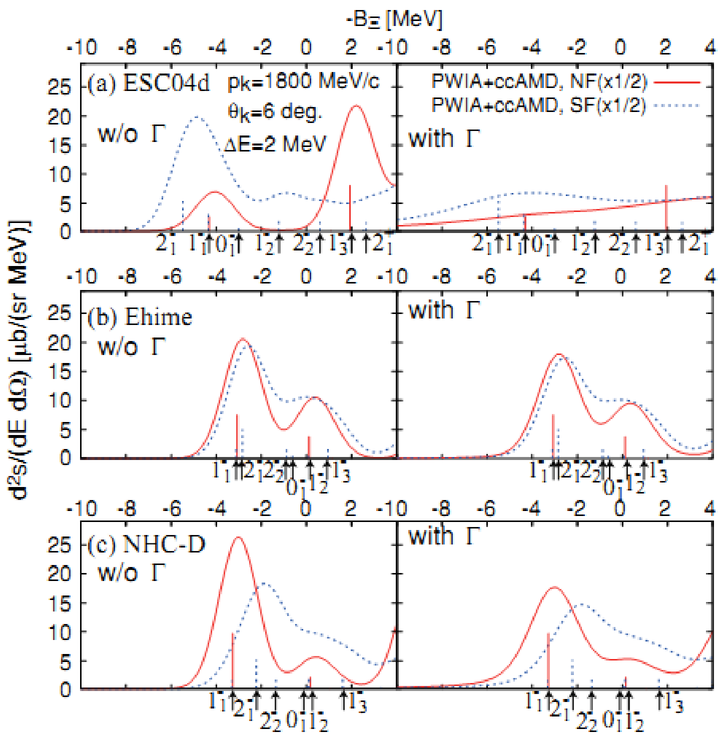
- Impurity effect
- Hyperon as a probe for nuclear structure
- ΛN (−ΣN) interaction in medium
- Evaluation and prediction of production cross section for J−PARC experiments

Research based on a microscopic model
(AMD：Antisymmetrized Molecular Dynamics)

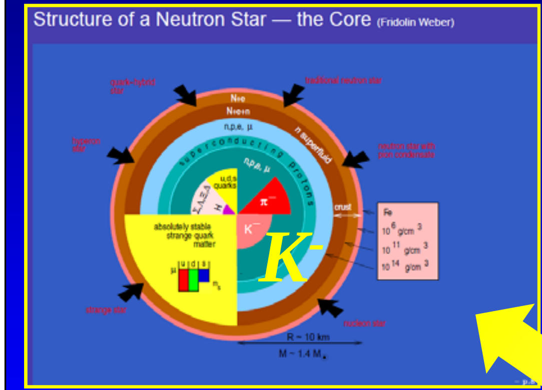
e.g.: Parity inversion and reversion of ^{11}Be and $^{12}_{\Lambda}$Be



$^{12}C(K^-,K^+)_{\Xi}{}^{12}Be$



中性子星内部でのK⁻中間子（土手、関原−山縣、・・）



中性子星内部でのK⁻中間子の役割？

K⁻ 中間子：ストレンジネスを伴うもう一つのハドロンの存在形態
核子と強い引力的相互作用

高密度下でのK⁻中間子の振る舞い

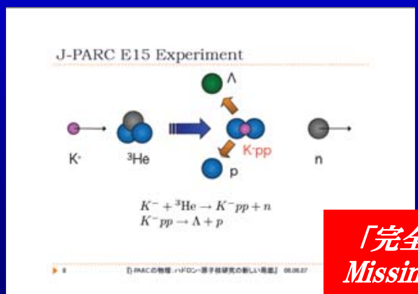
高密度状態方程式へのK中間子の影響

密度依存性
…「カイラル対称性の部分的回復」

中重核領域、多重K原子核の研究
- *near nuclear matter での K⁻ 中間子*
- *複数 K⁻ が存在する場合*

相互作用の規定
- *s-wave K^{bar}N 相互作用*
- *p-wave K^{bar}N相互作用？*
- *K^{bar}NN三体力？？*

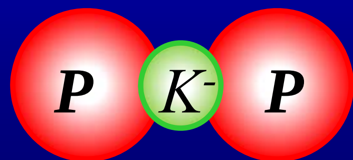
K⁻pp構造計算＆反応研究
- *実験データの解析*
- *観測された状態の正体*



「完全実験」
Missing mass + Inv. mass

今後のK原子核実験
- *K⁻pp　　: J-PARC E15, E27*
- *Λ(1405)　: J-PARC E31*
- *K⁻原子　: SIDDARTA-2,*
(K⁻p, K⁻d)　　J-PARC E17
…

最も基本的なK原子核



媒質中におけるK-中間子の性質

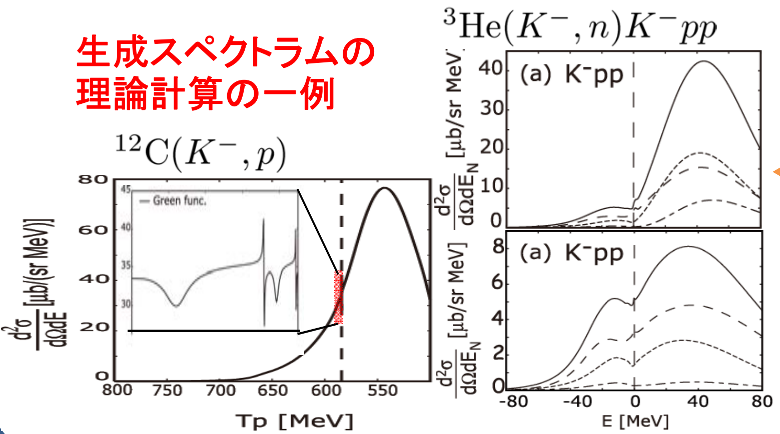
大阪電気通信大学　山縣-関原淳子

現在までの研究

＊K-中間子と原子核の間の相互作用の強さは？
＊K-中間子は原子核に束縛するのか？
＊実験ではどのように観測されるのか？

・浅くても深くてもK-中間子は束縛する!!
・束縛状態の観測のためには、崩壊過程を追うなどの＋αが必要

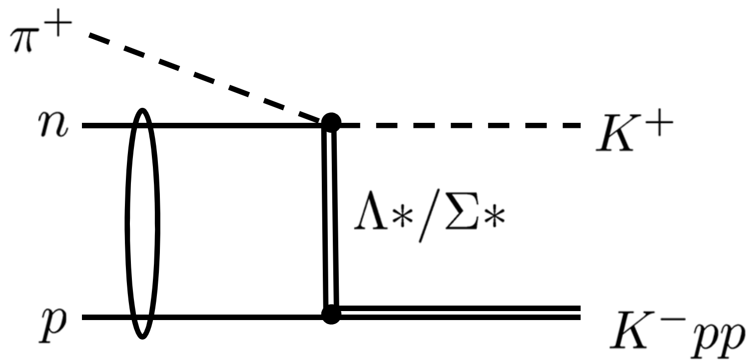
生成スペクトラムの理論計算の一例



今後の研究内容

J-PARC E27

$$\pi^+ + d \rightarrow K^- pp + K^+$$



＊中間状態としてΛ*やΣ*を考慮
＊実験データと直接比較可能な生成スペクトラムの計算

J-PARC E15

$$K^- + {}^3\mathrm{He} \rightarrow K^- pp + n$$

＊少数系の取り扱いを行い update

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.