「J-PARCで展開される将来の物理」研究会,
2011年6月10-11日, 高エネルギー加速器研究機構,
つくば市

ストレンジネスを持つ原子核

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目次

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

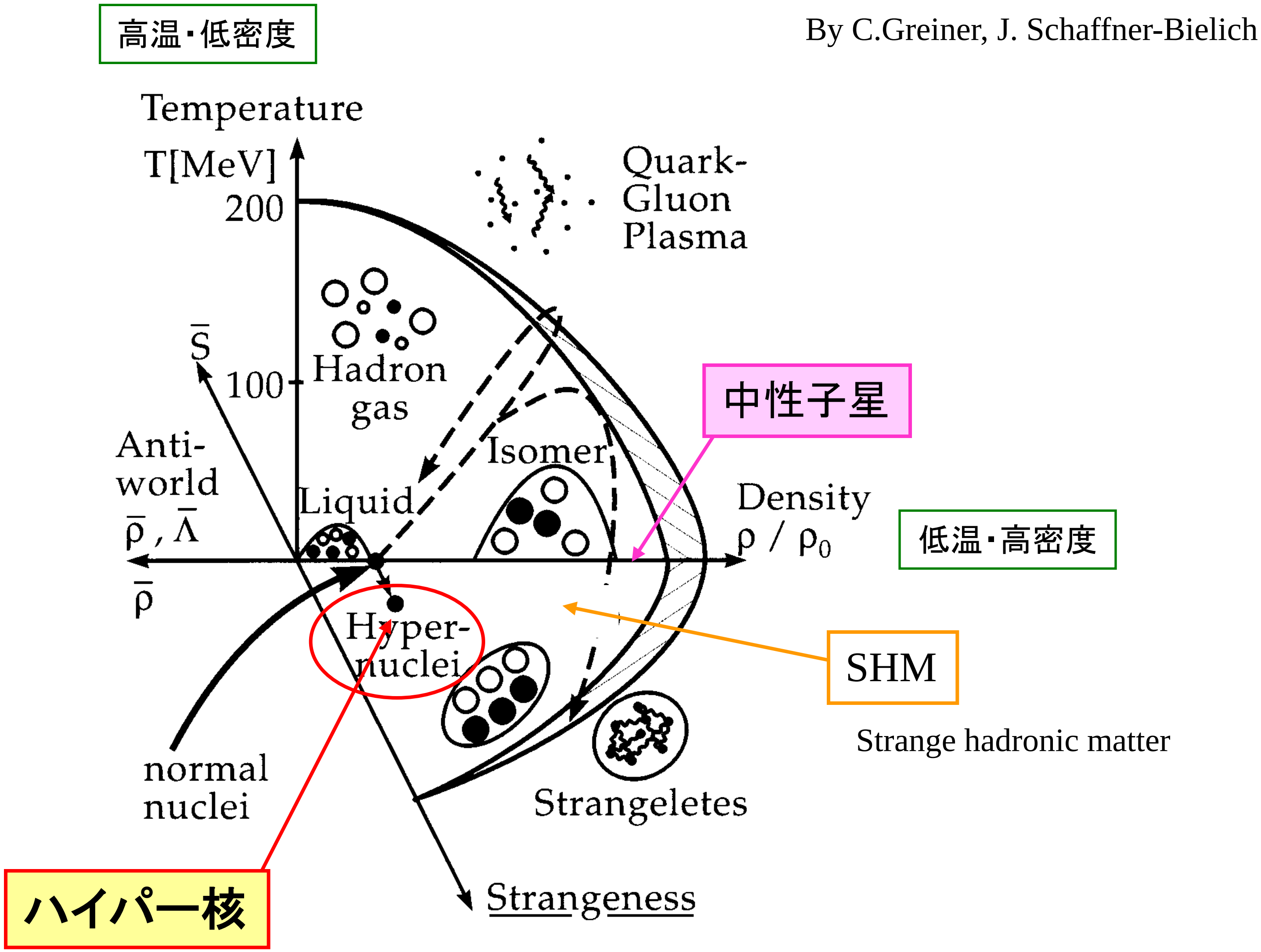
S＝−2

- E03：Measurement of X rays from Ξ^- 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 ^{3}He(K^-,n) reaction/M. Iwasaki (RIKEN), T. Nagae (Kyoto) [Day 1]
- E17: Precision spectroscopy of kaonic ^{3}He 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(π^+,K^+) reaction/T. Nagae (Kyoto)

ハドロン物質の相図



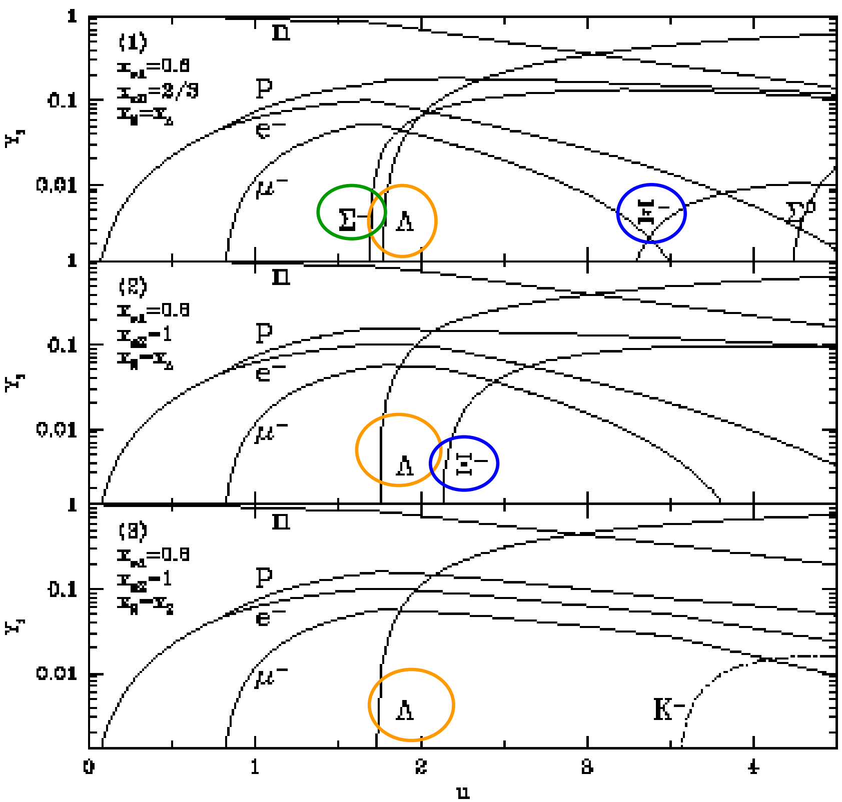
高温・低密度
By C.Greiner, J. Schaffner-Bielich
Temperature
T[MeV]
200
100
Quark-
Gluon
Plasma
Hadron
gas
S̄
Anti-
world
ρ̄ , Λ̄
ρ̄
Liquid
Isomer
中性子星
Density
ρ / ρ0
低温・高密度
Hyper-
nuclei
SHM
Strange hadronic matter
normal
nuclei
Strangeletes
Strangeness
ハイパー核

Neutron star core

"An interesting neutron-rich hypernuclear system"

Hyperon-mixing

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

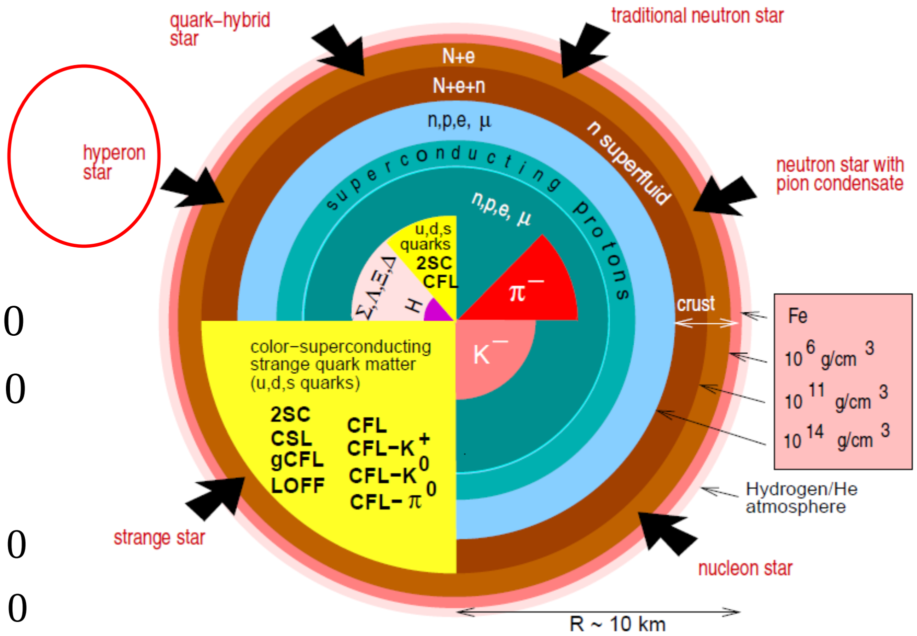


$U_\Sigma < 0$
$U_\Xi < 0$

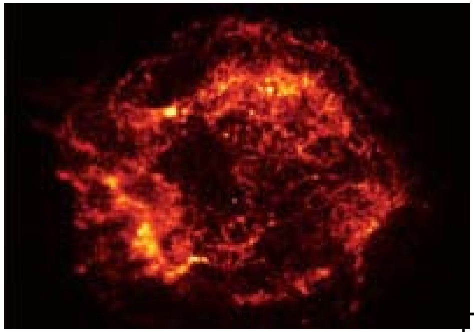
$U_\Sigma > 0$
$U_\Xi < 0$

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

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



F. Weber, Prog. Part. Nucl. Phys. 54 (2005) 193



Cassiopeia A nebula
NASA/CXC/SAO.

ストレンジネス核物理

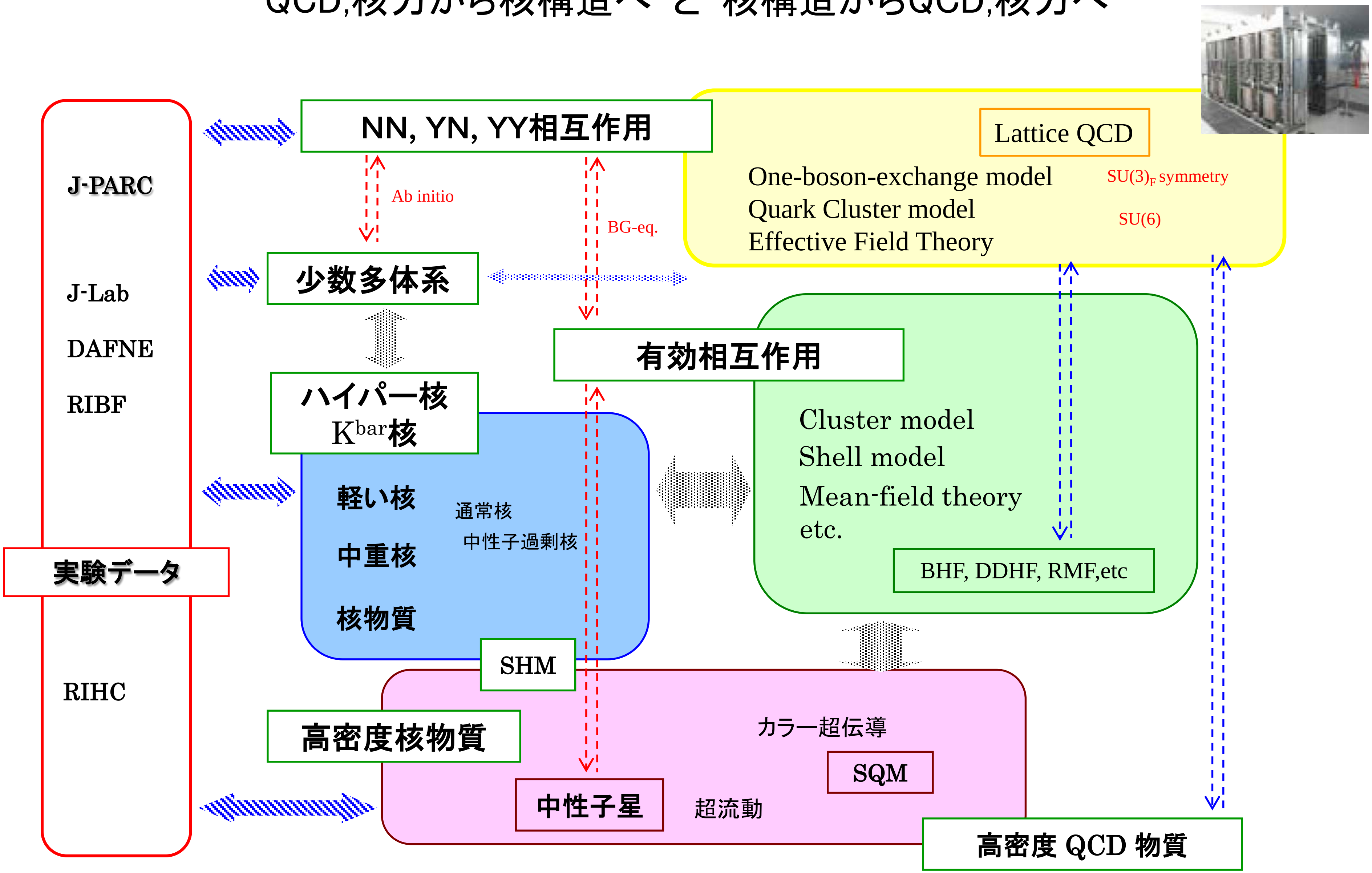
- ストレンジネスは原子核深部を探るプローブ
  - ハイペロンはパウリ排他律を受けない
- Impurity Physics
  - "糊"としての役割
  - 原子核構造の変化
  - 媒質中のハドロンの性質
- Baryon-Baryon Interaction
  - YN, YY Interaction based on SU_f (3)
  - 核力の統一的理解・斥力芯の起源
- Neutron Starの構造と進化
  - 高密度核物質の解明, EOS, ...

"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”



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.

- ■ 核内Λ粒子の働き

- ■ Gamma-ray spectroscopy of light hypernuclei

- ■ Λ粒子の１粒子ポテンシャルとスピン軌道力

- ■ Overbinding Problem on s-Shell Hypernuclei

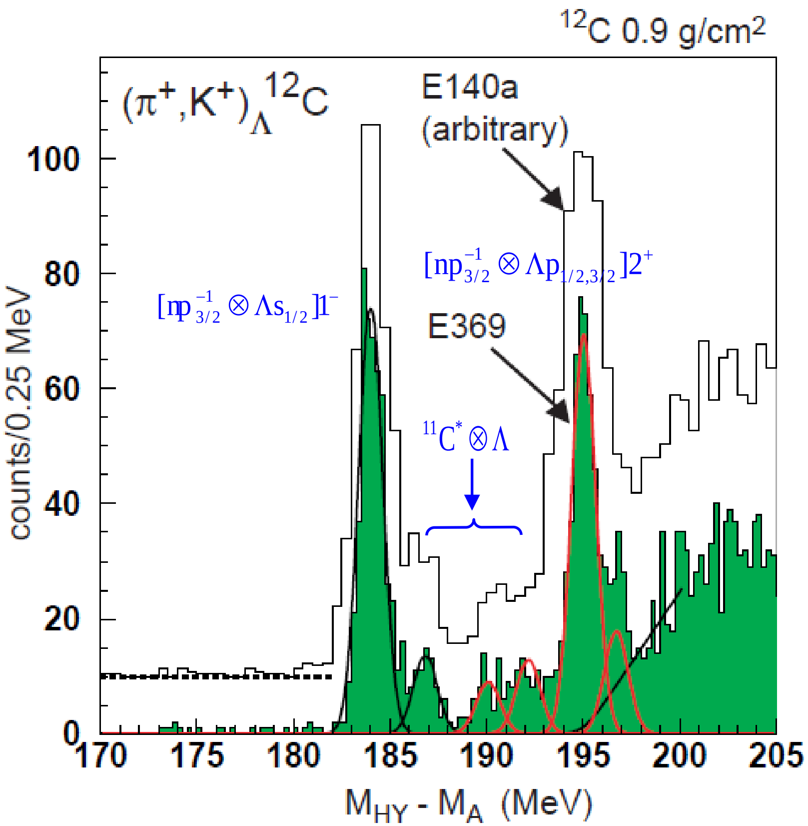
- ■ 中性子過剰ハイパー核

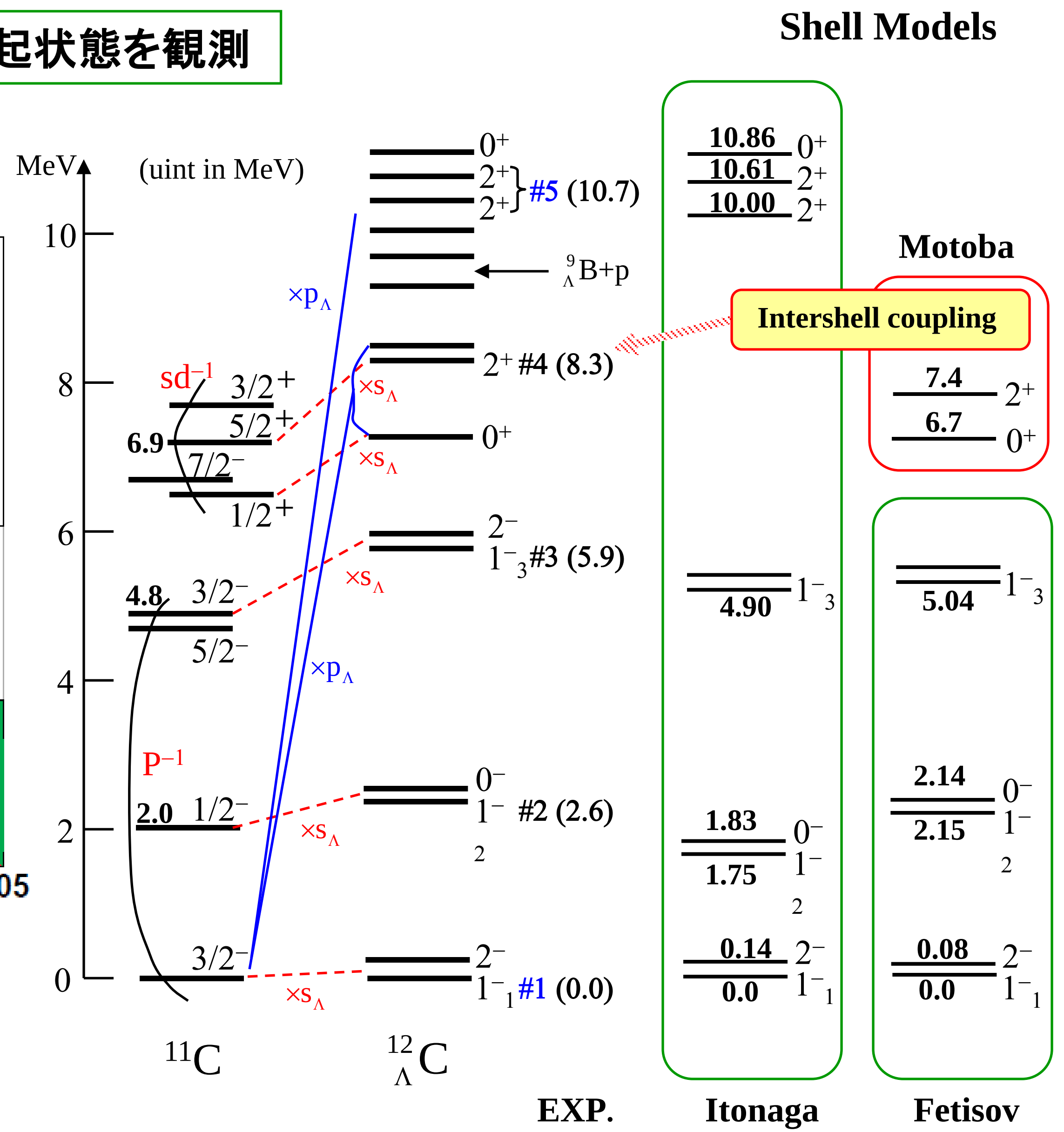
- ■ Λハイパー核の弱崩壊

$^{12}C(\pi^+,K^+)$反応実験 KEK-E369

ハイパー核の励起状態, 芯核の励起状態を観測

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





K. Itonaga, et al.,PTP.Suppl.177(1997)17
V.N.Fetisov, et al., Z.Phys.A339(1991)399
T. Motoba, NPA639(1998)135c

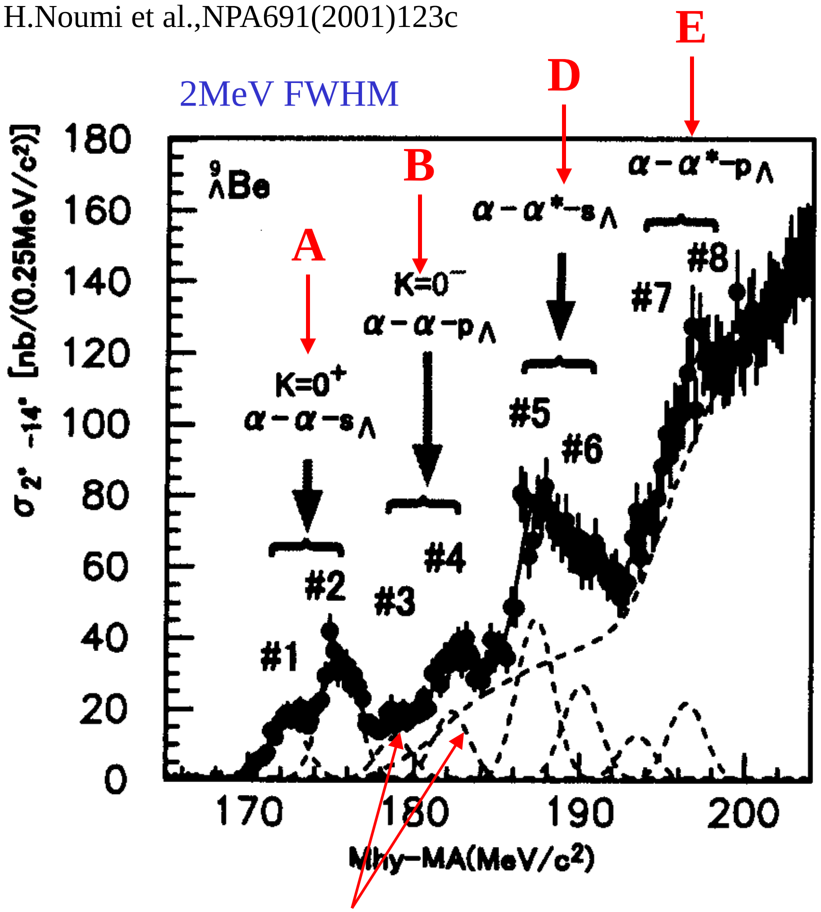
ハイパー核らしい状態の生成

対称性と集団性

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

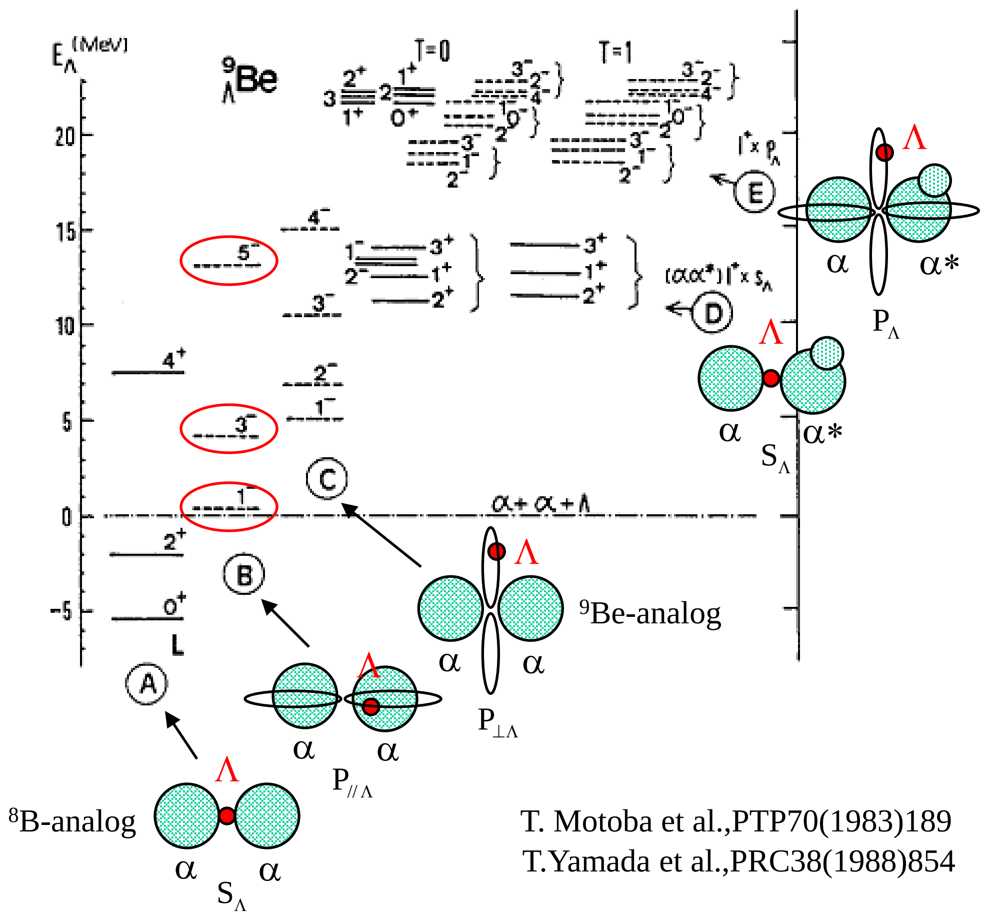
High-resolution, high-statistics

H.Noumi et al.,NPA691(2001)123c



“genuine hypernuclear states”

α+(3N+N)+Λクラスター模型計算



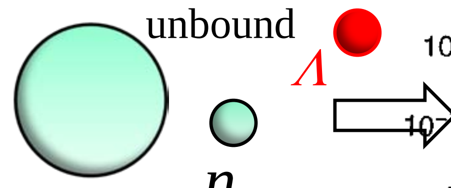
T. Motoba et al.,PTP70(1983)189
T.Yamada et al.,PRC38(1988)854

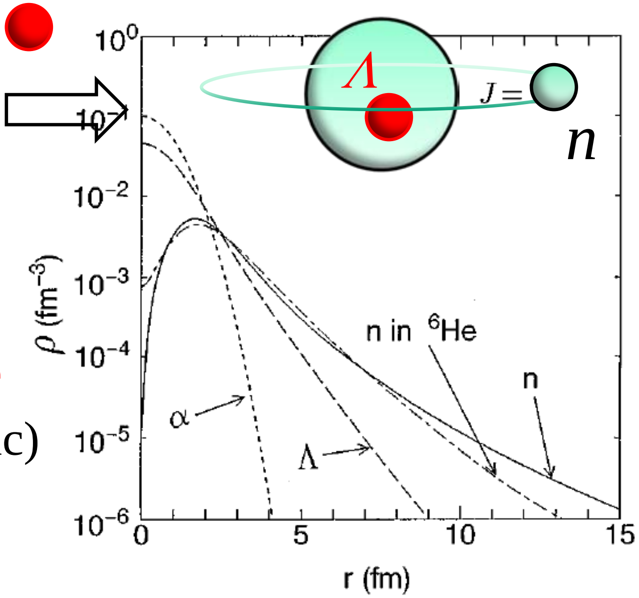
coupling of Λ to rotational bands

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.

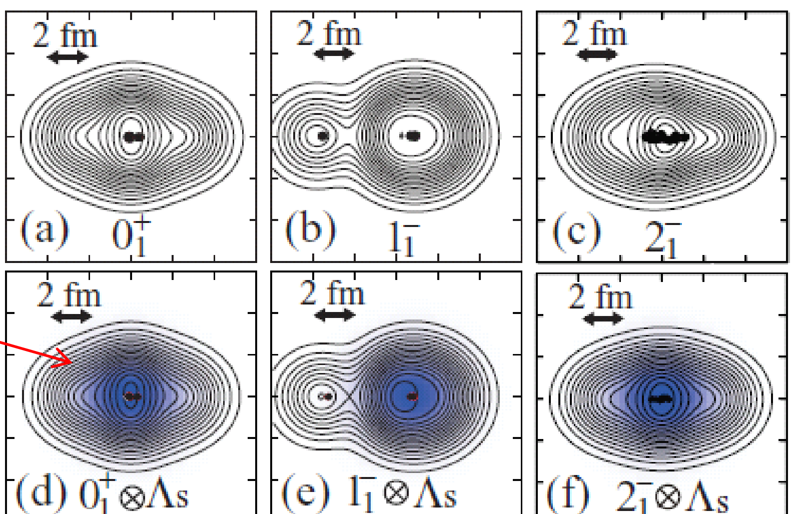
$^{6}{}_{\Lambda}$He
(α+N+Λ calc)

"Stabilizing"

$^{21}{}_{\Lambda}$Ne (AMD calc)

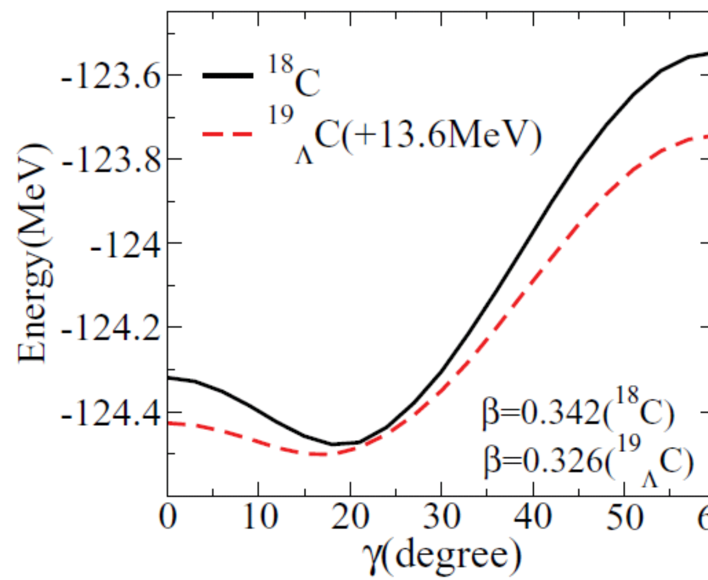
M. Isaka et al, PRC83(2011)054304

g.s.



$^{19}{}_{\Lambda}$C (CSHF+BCS calc)

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

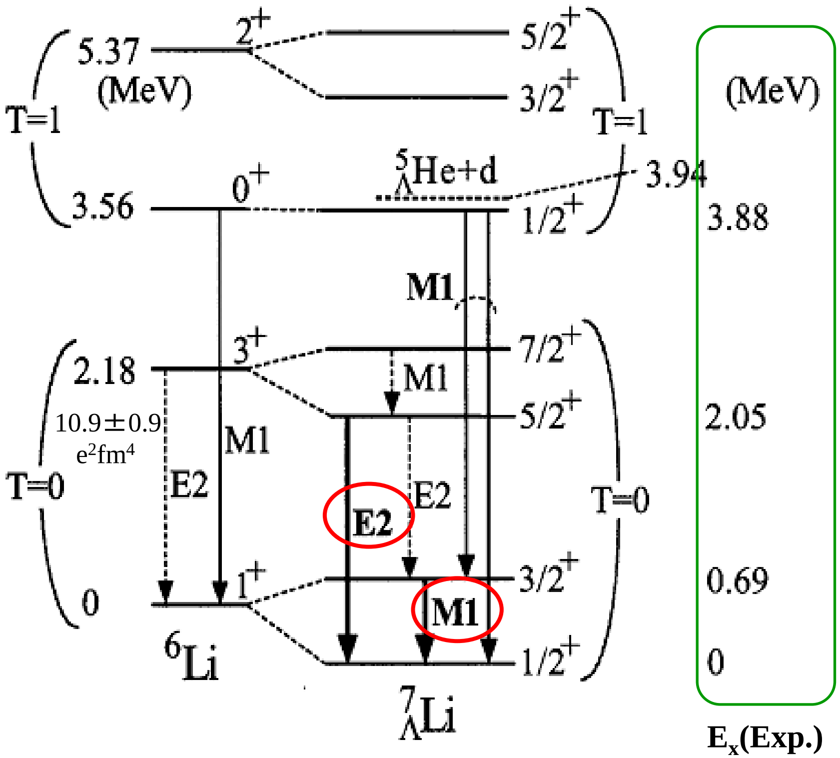


精密γ線分光実験　KEK-E419

Ge detector resolution ～**a few keV**

H. Tamura et al., PRL84(2000)5963
K. Tanida, PRL86(2001)1982

$^{7}_{\Lambda}\mathrm{Li}$



$B(E2;5/2^+\rightarrow 1/2^+) = 3.6\pm0.5 e^2fm^4$ (Exp.)

$8.6 e^2fm^4$ (Shell Model)

$2.5 e^2fm^4$ (Cluster Model)

Spin-flip M1 vs. ΛN spin-spin interaction

Shell Model

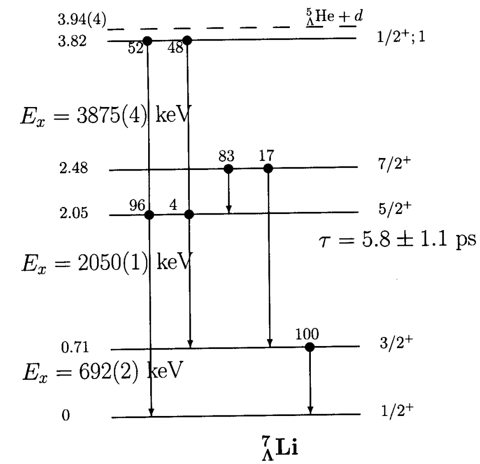
$\Delta=0.50$, $S_\Lambda=-0.04$ $S_N=-0.47$,
$T=0.04$ (No ΛΣ coupling)
[D.J.Millener, NPA691(2001)93c]

$\Delta E(3/2^+-1/2^+) = 0.712$MeV

revised

$\Delta=0.43$, $S_\Lambda=-0.015$ $S_N=-0.39$,
$T=0.30$ (ΛΣ coupling)
[D.J.Millener, NPA835(2010)11]

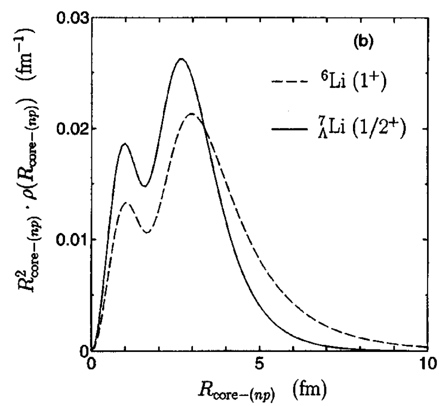
$\Delta E(3/2^+-1/2^+) = 0.693$MeV



B(E2) vs. Shrinking effects

$$\frac{R_{c-d}(^{7}_{\Lambda}\mathrm{Li})}{R_{\alpha-d}(^{6}\mathrm{Li})} = \left[\frac{B(E2;5/2^+\rightarrow 1/2^+)}{B(E2;3^+\rightarrow 1^+)}\right]^{1/4}$$

0.81±0.04	0.84	0.78
(Exp)	**(Motoba83)**	**(Hiyama99)**

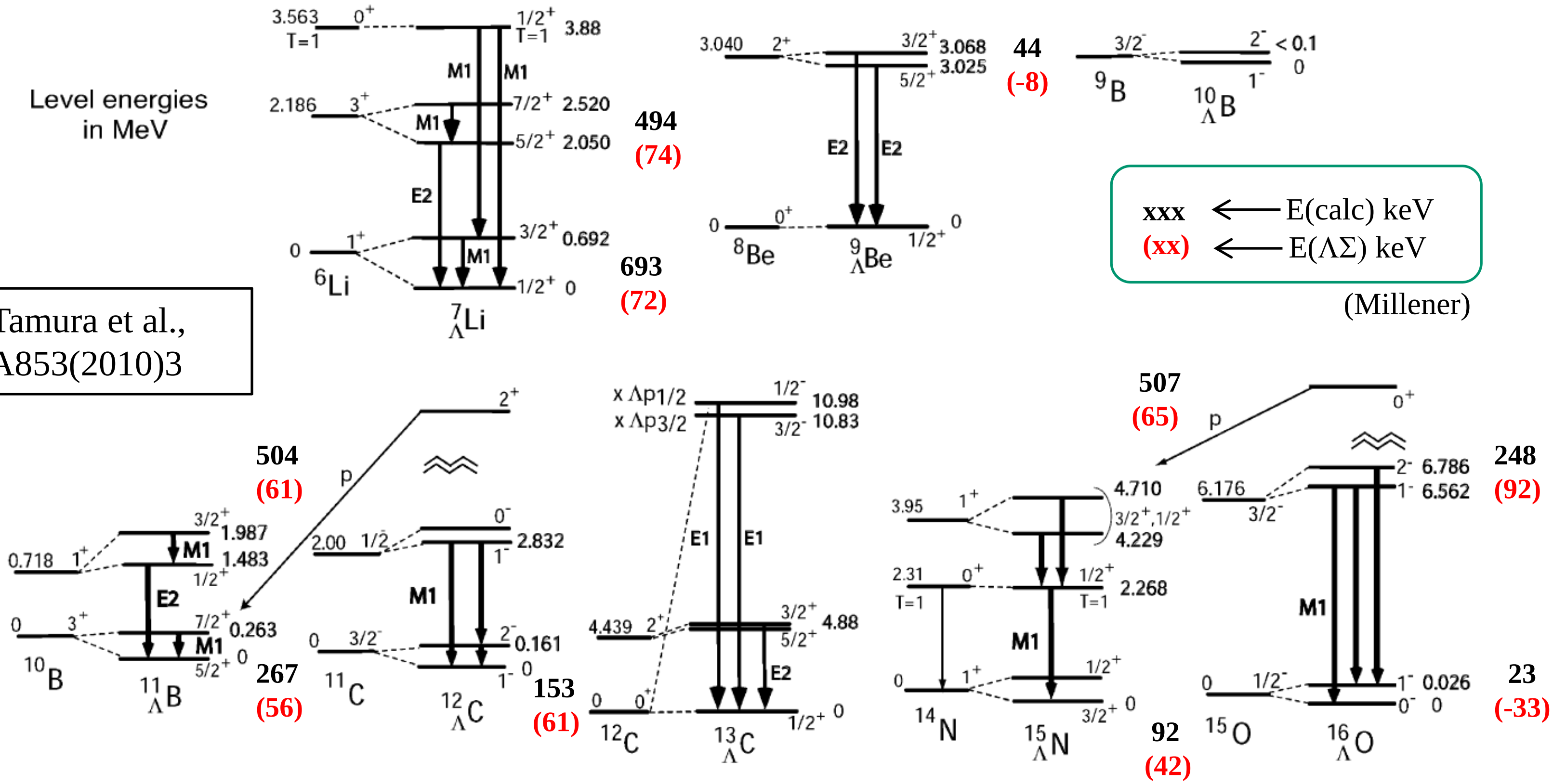


Shrinkage of the ^{6}Li core: 19% !

Cluster Model

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

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]

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

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

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

Microscopic Shell-Model

including **ΛN-ΣN coupling effects**

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

最近の梅谷らの計算に期待

E13@J-PARC

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

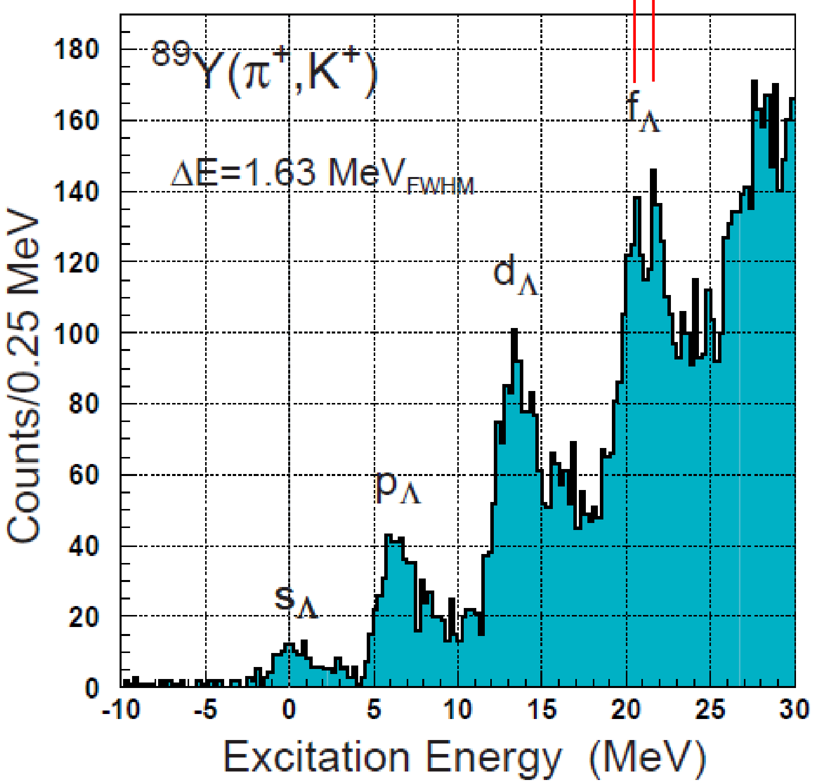
$^{4}_{\Lambda}$He, $^{10}_{\Lambda}$B, $^{11}_{\Lambda}$B, $^{19}_{\Lambda}$F

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

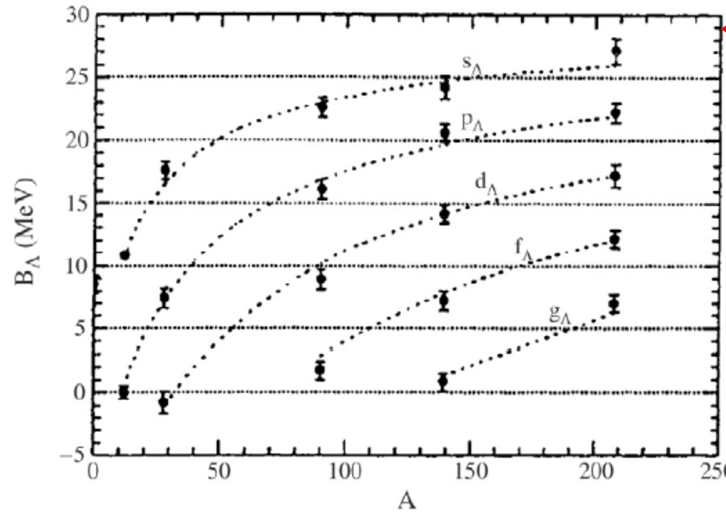
H. Hotchi et al., PRC64(2001)044302

(Exp.) 1.7 MeV

KEK E369



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



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

$a = 0.6$ fm

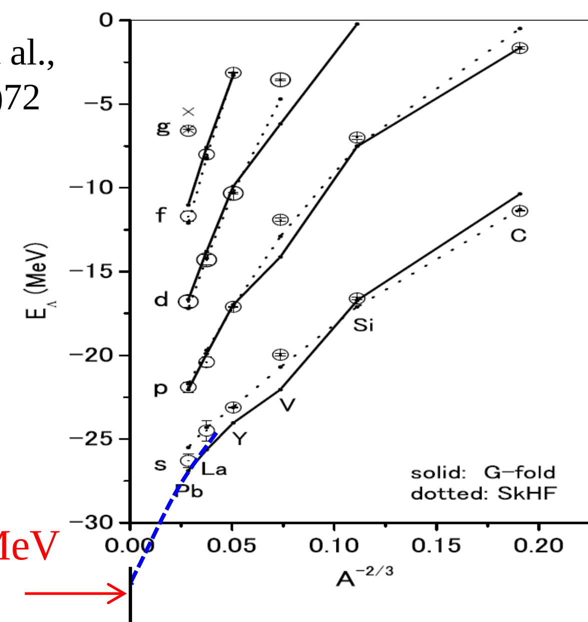
$V_{LS}^\Lambda \simeq 2$ MeV

WS analysis

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

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

G-matrix folding model

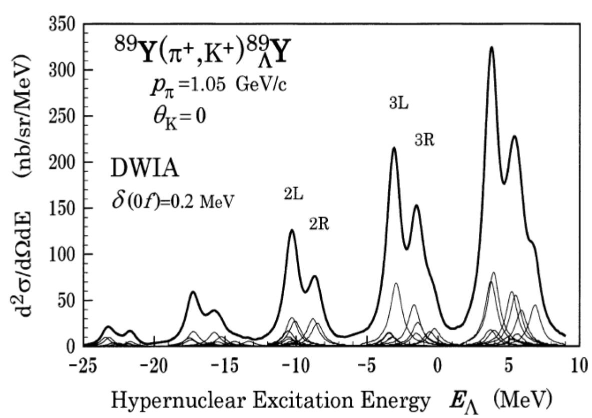


$V_0^\Lambda \simeq -37.2$ MeV ($A \to \infty$)

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

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

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

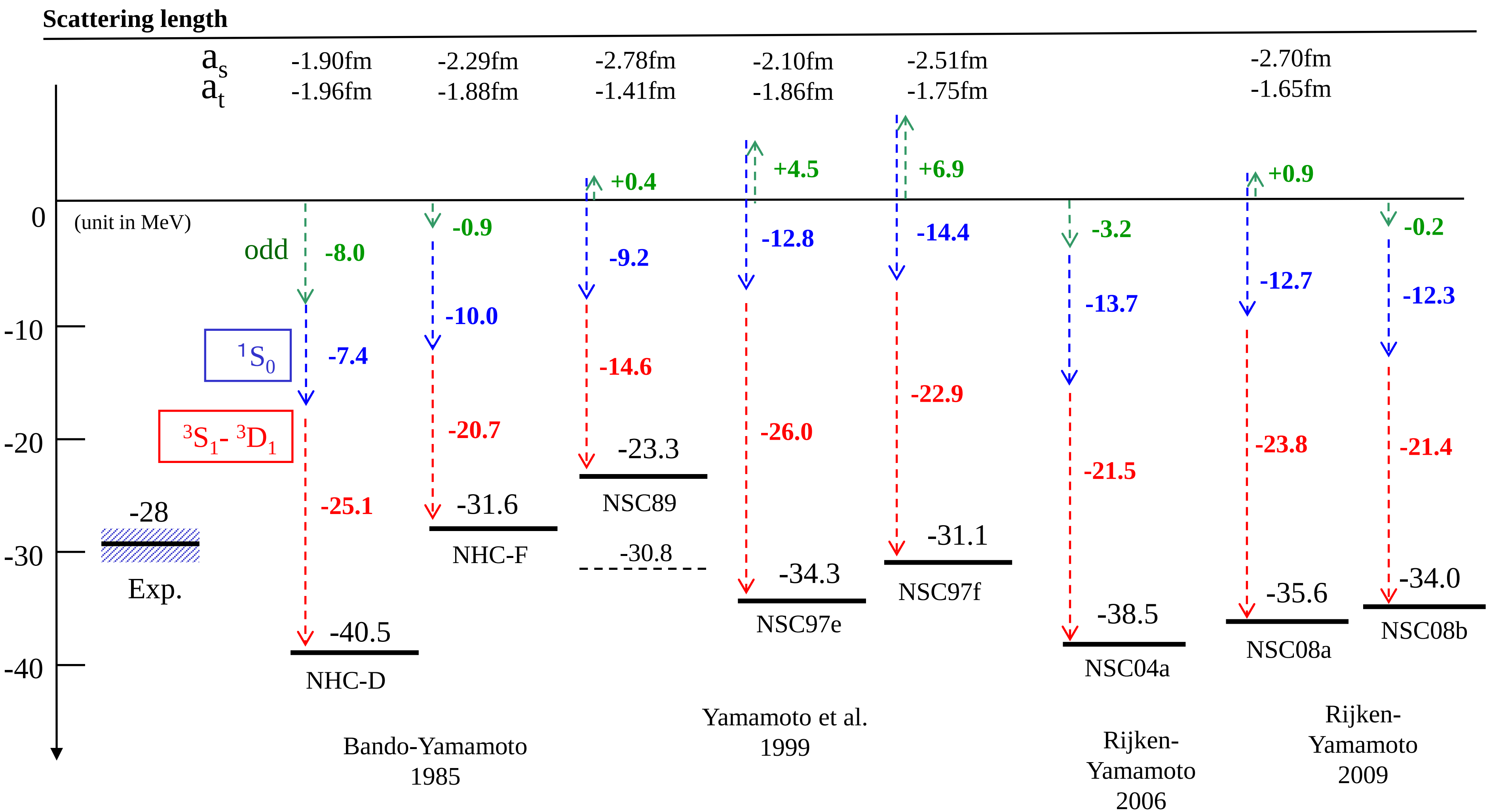


Λ single-particle energies in symmetric nuclear matter

OBEP: Nijmegen YN potential Models

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

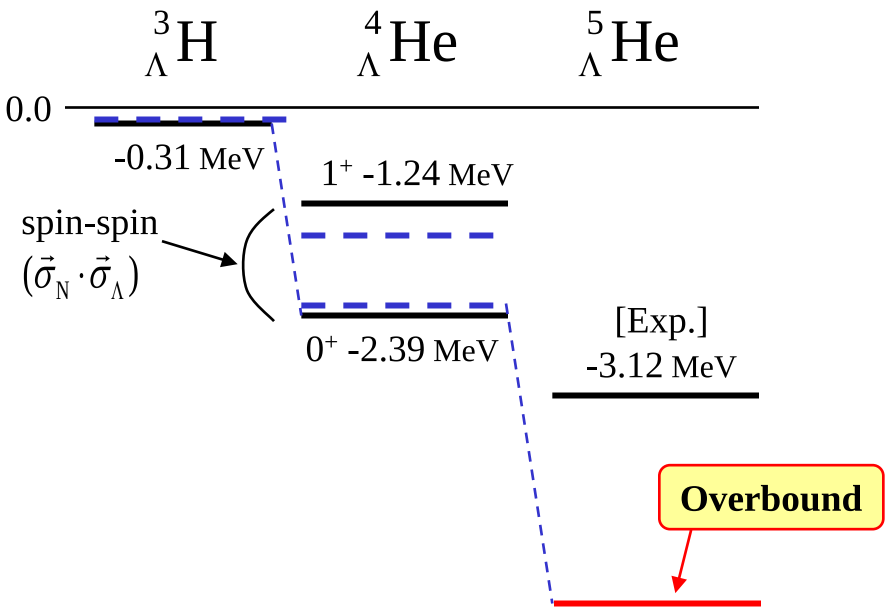
G-matrix calc. QTQ



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

Overbinding Problem on s-Shell Hypernuclei

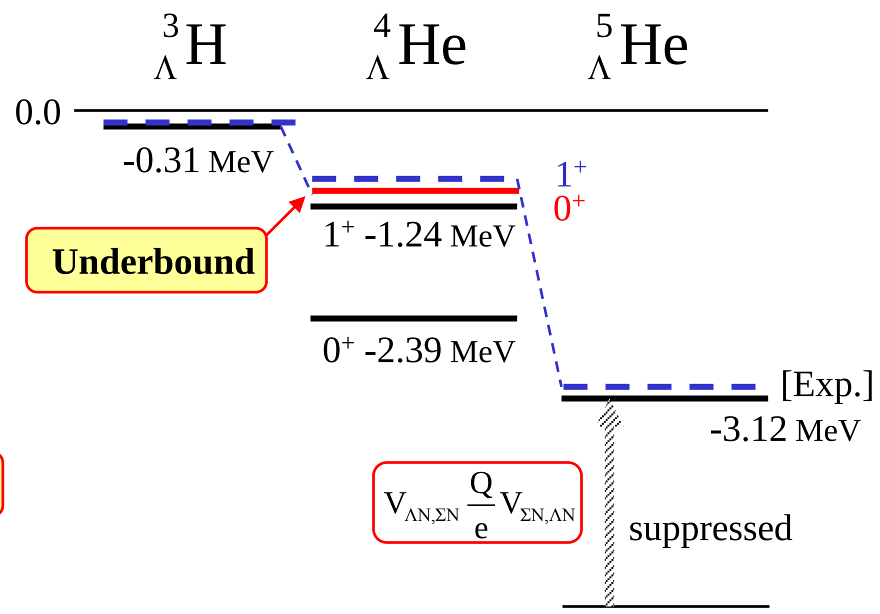
The Overbinding Problem



ΛN single-channel calc.

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

The Underbinding Problem

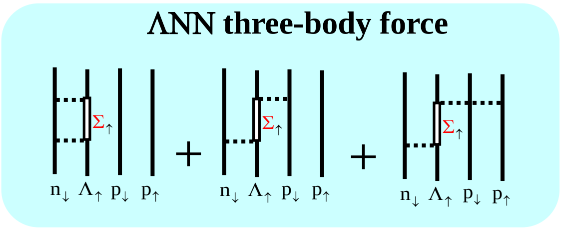


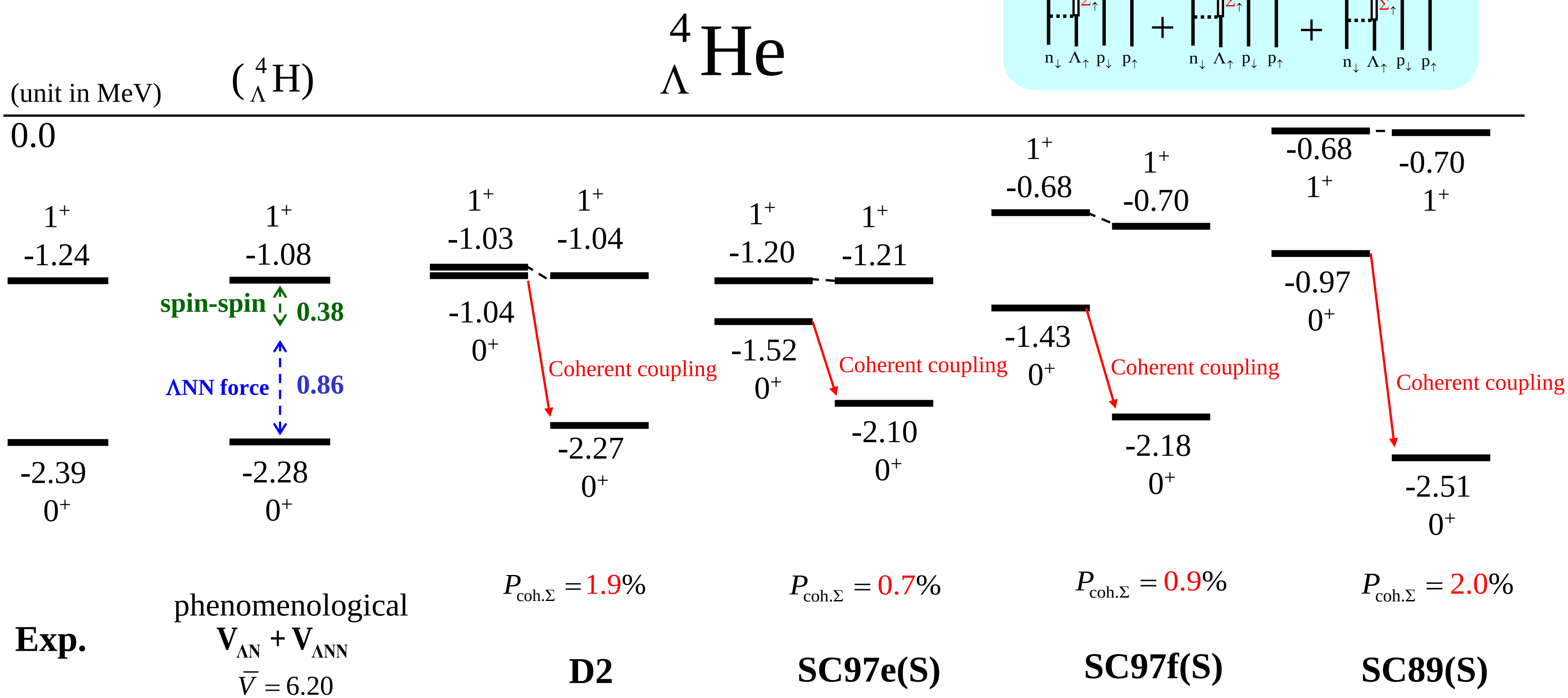
g-matrix calc. with ΛN-ΣN(D2)

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

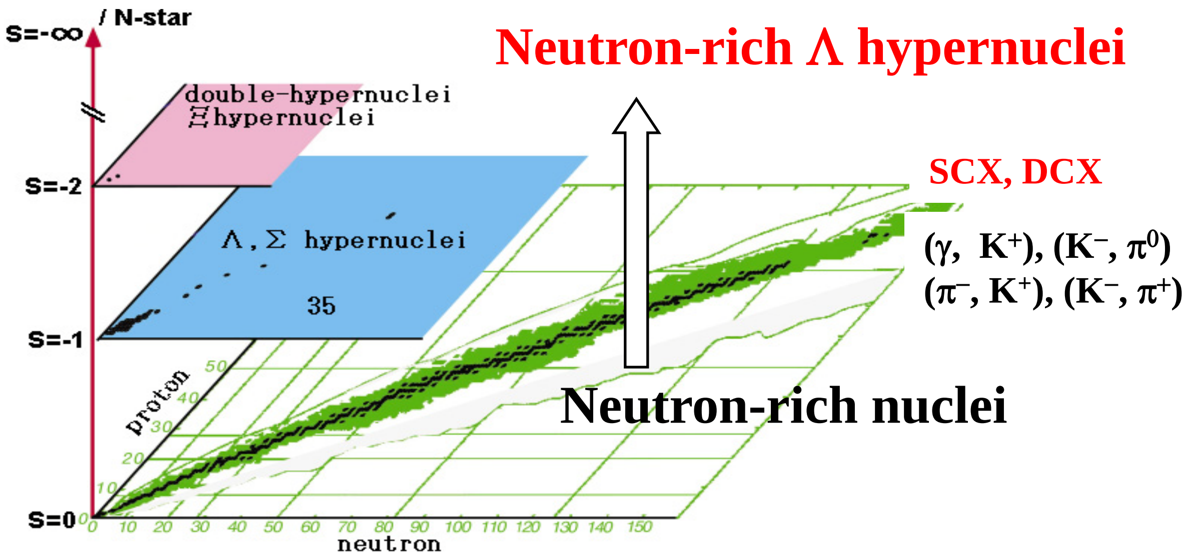
R. Sinha, Q.N.Usmani, NPA684(2001)586c

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

中性子過剰Λハイパー核

E10@J-PARC

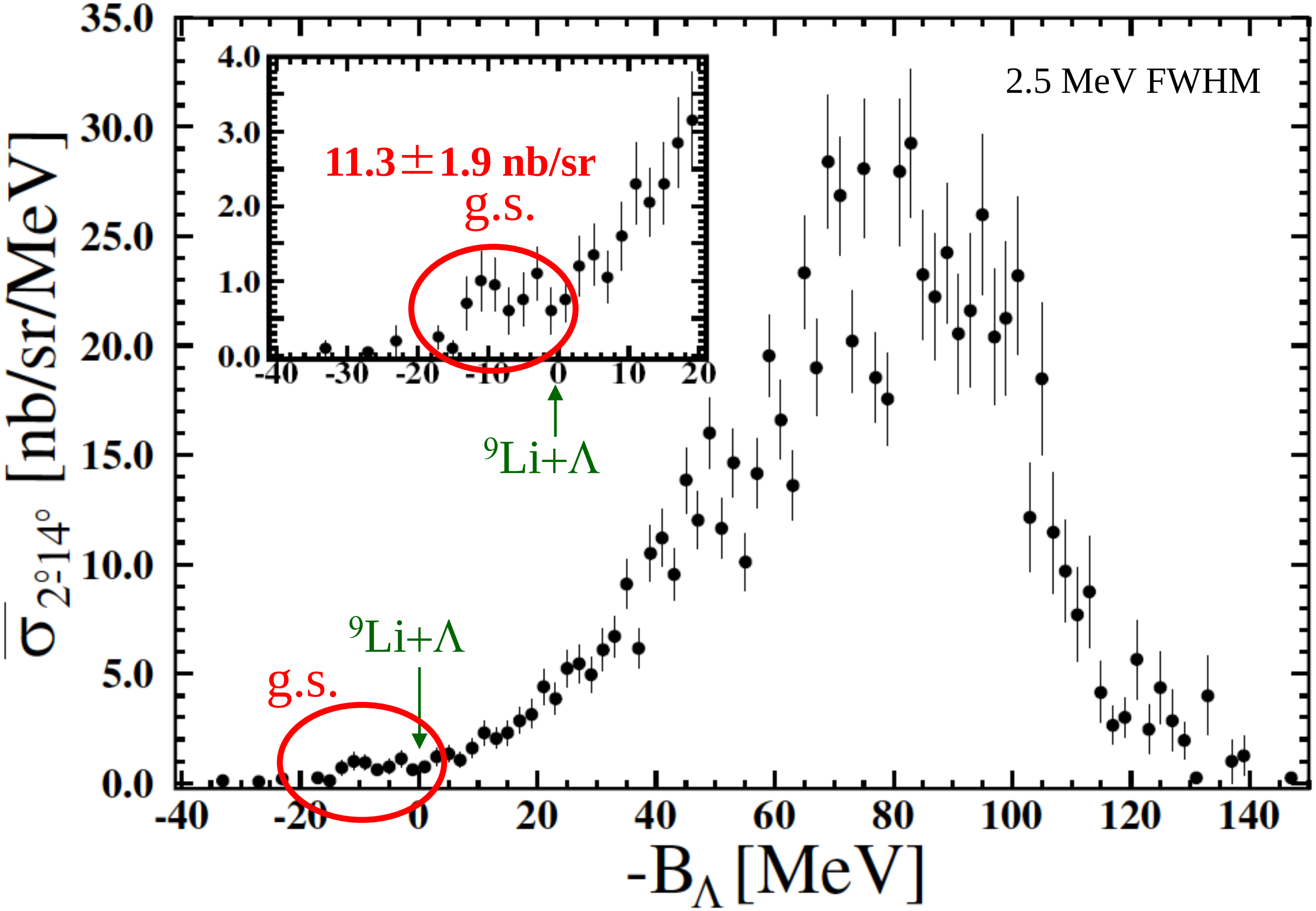
Production of neutron-rich Lambda-hypernuclei with the double charge exchange reaction



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)

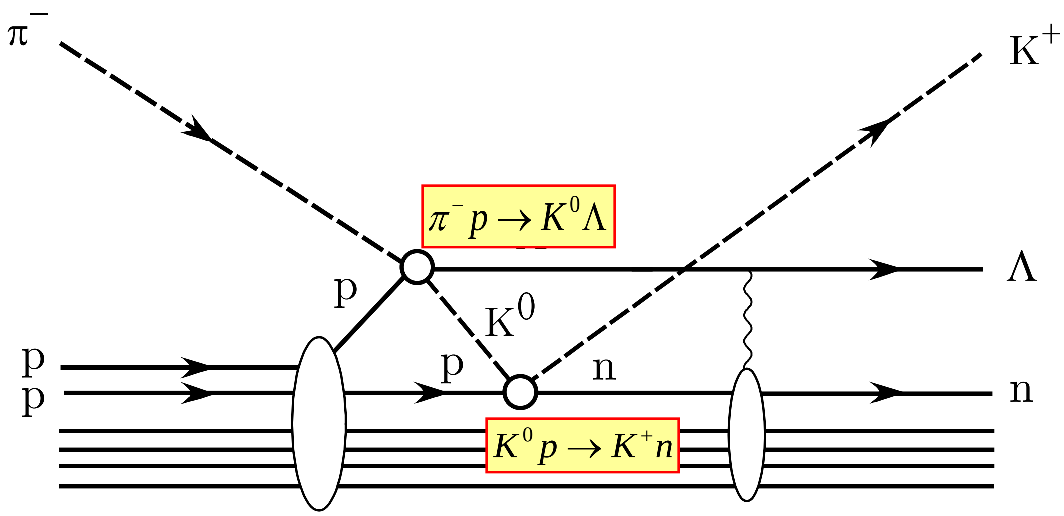
17.5±0.6 μb/sr

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

***Two-step process*:**

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

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

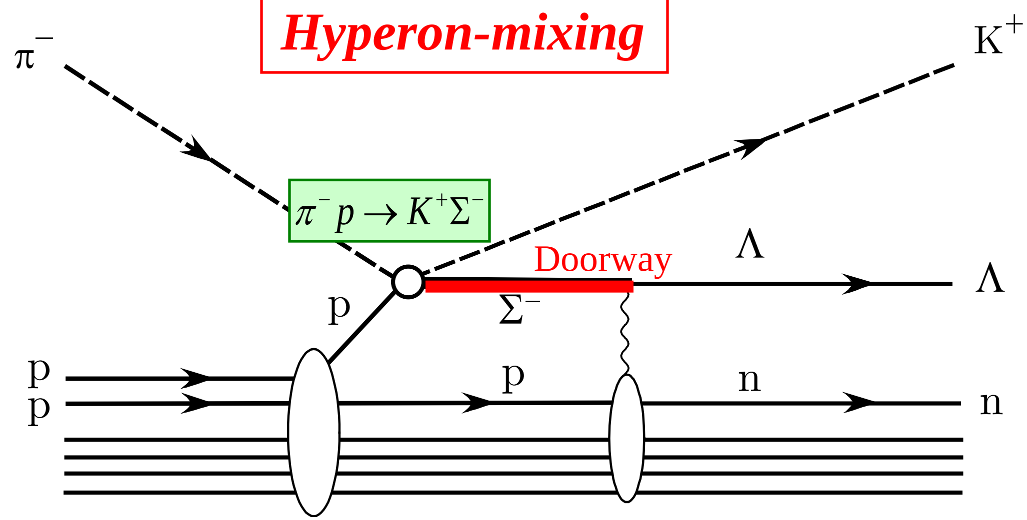


***One-step process*:**

Hyperon-mixing

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

via Σ^- doorways caused by ΛN-ΣN coupling



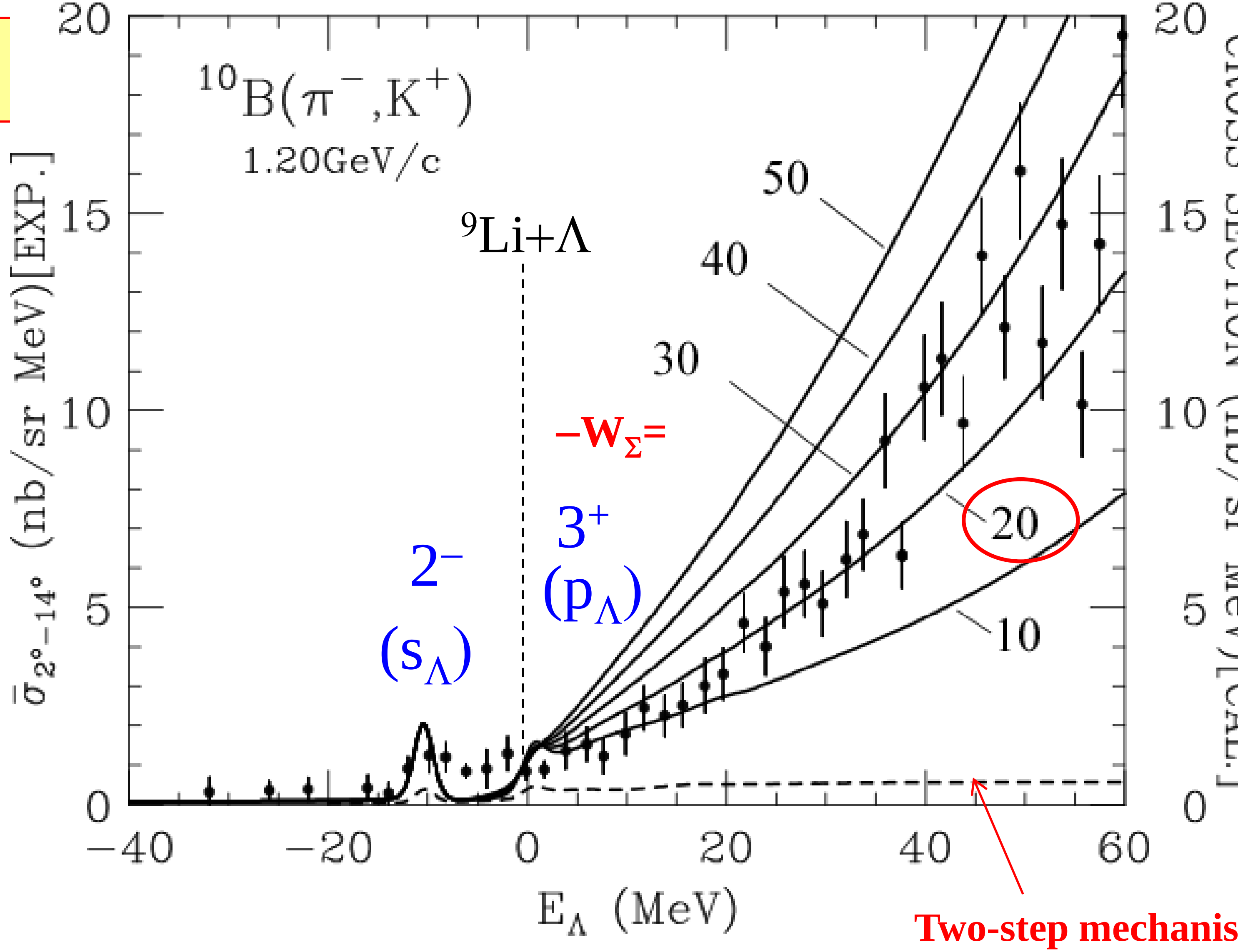
Λ spectrum by DCX (π⁻,K⁺) reactions at 1.2GeV/c

Harada, Umeya, Hirabayashi, PRC79(2009)014603

Spreading potential dep. W_Σ

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

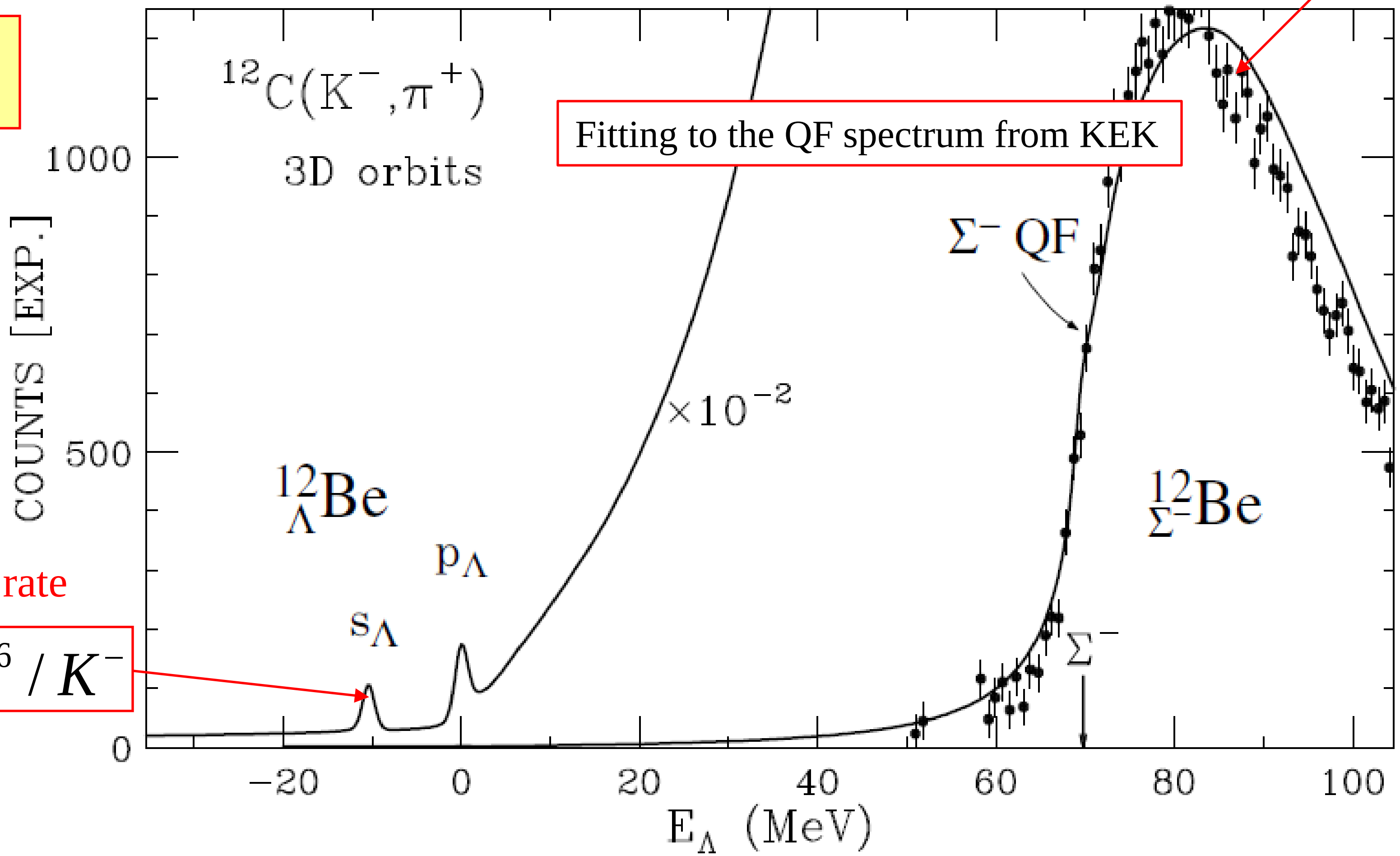
^{10}B



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.

^{12}C



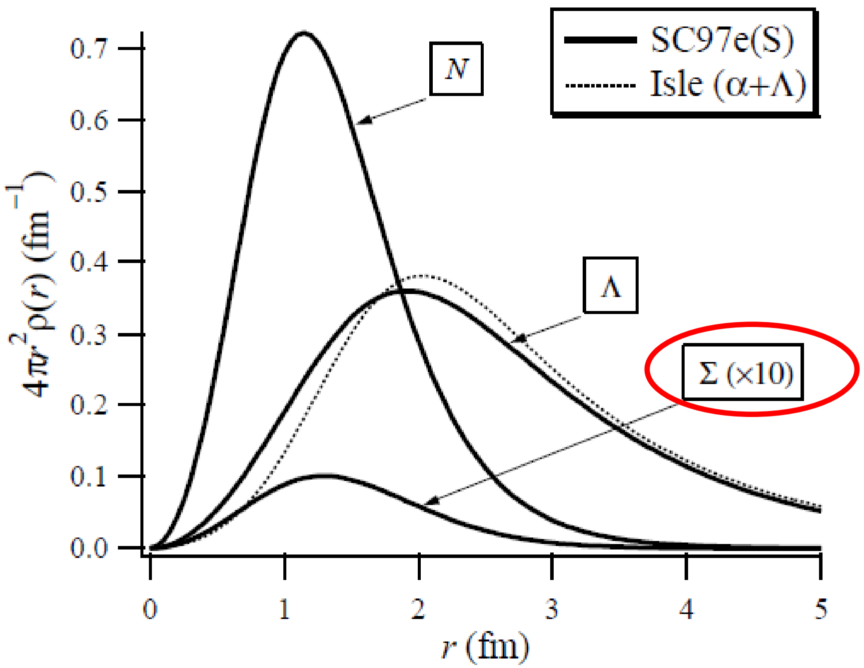
Integrated production rate

$\sim 4\times 10^{-6}\,/\,K^-$

DAΦNE data: U.L. $\sim (2.0\pm 0.4)\times 10^{-5}\,/\,K^-$ M.Agnello, et al.,PLB640(2006)145.

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

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



Better understanding of the Λ-Σ coupling and Tensor force

Hyperon-mixing

α^* $T_C = 1 \otimes \Sigma$ **~ 1.5 % admixture**

"Incoherent Λ-Σ coupling"

α $T_C = 0 \otimes \Lambda$

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

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

-The α-particle is not a rigid core.

The incoherent Σ admixture is also important.

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

E10@J-PARC

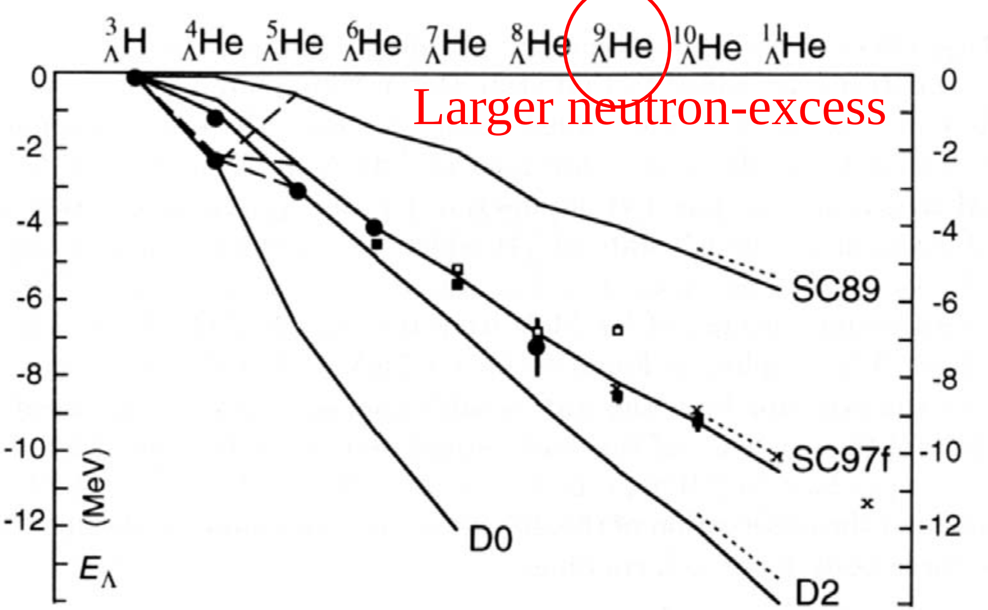
$$^{6}\mathrm{Li}(\pi^-, K^+)\,^{6}_{\Lambda}\mathrm{H}$$

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

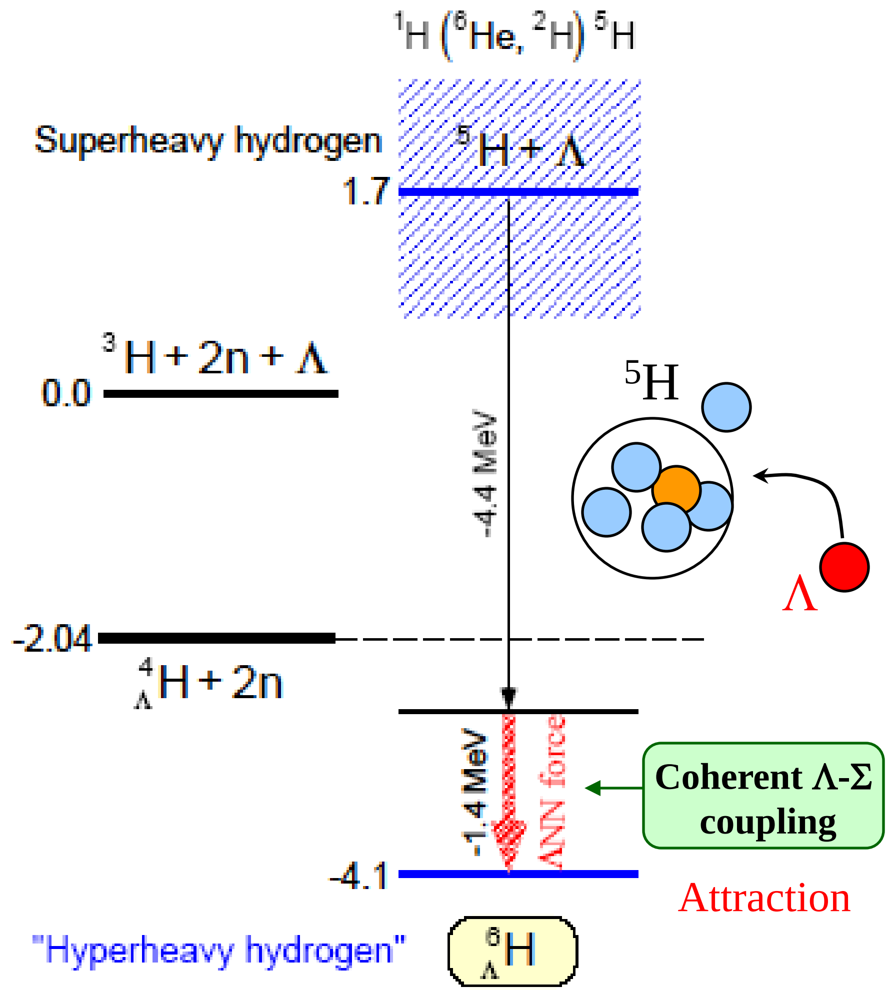
$^{6}_{\Lambda}\mathrm{H}$ **"Hyperheavy hydrogen"**

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

Extremely enhanced

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; FBS.Suppl.12(2000)395]
- **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**

NN, YN, YY interactions

Flavor SU(3)$_f$ symmetry

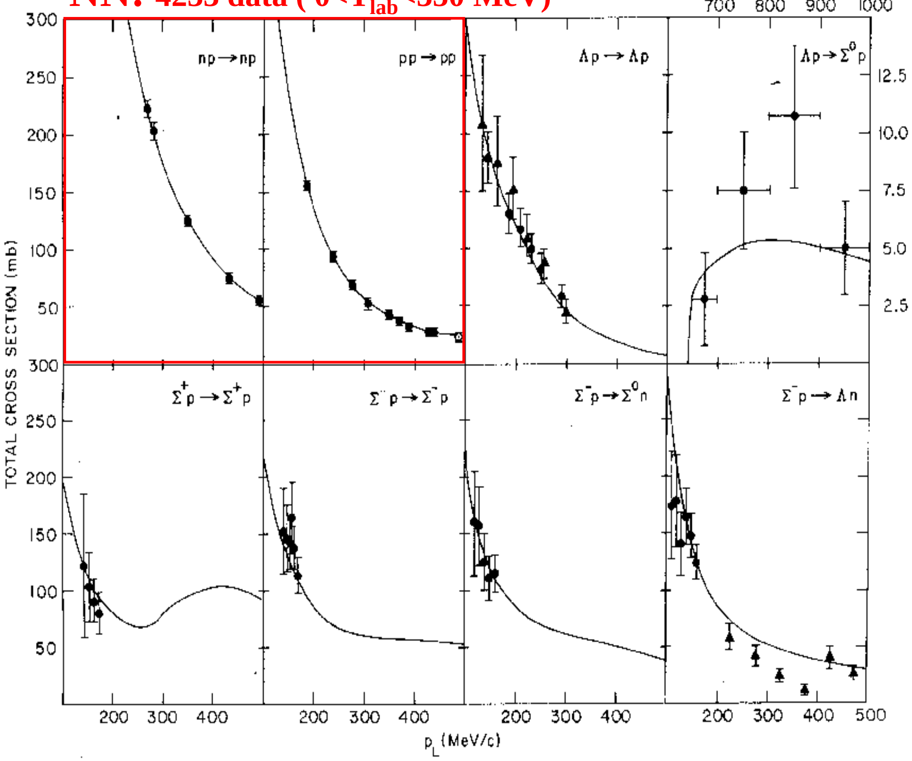
symmetric antisymmetric

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

$^1S_0$ $^3S_1$ ΛΛ

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

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



Total cross section for baryon-baryon scattering

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

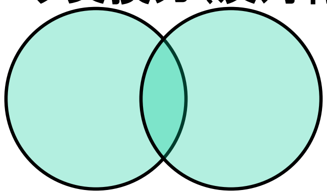
バリオン-バリオン間相互作用の短距離斥力

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

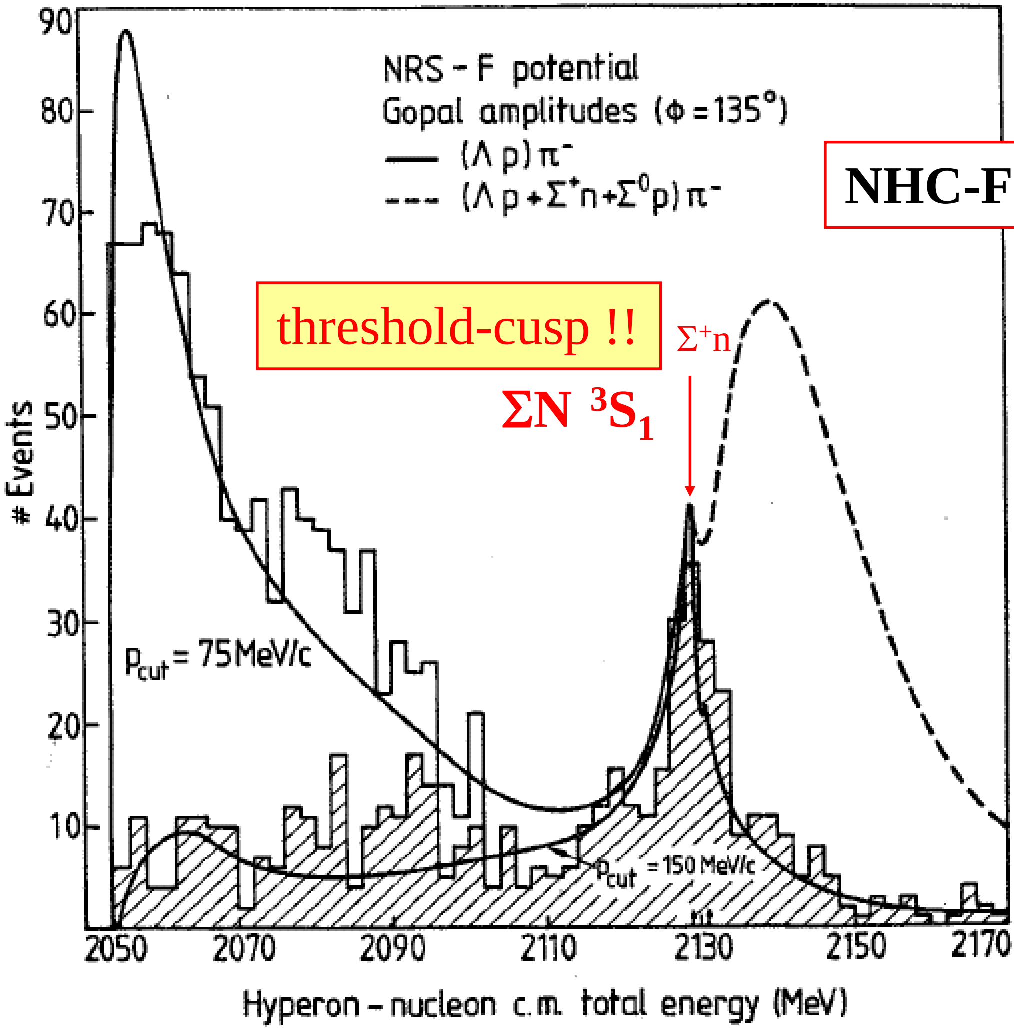
S = 1 state	[51]	[33]	
$\mathbf{8_A}$	5/9	4/9	
10	**8/9**	1/9	ΣN(I=3/2,$^3S_1$) ***almost Pauli forbidden***
10*	4/9	5/9	NN($^3S_1$), ΛN-ΣN(I=1/2, $^3S_1$)

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

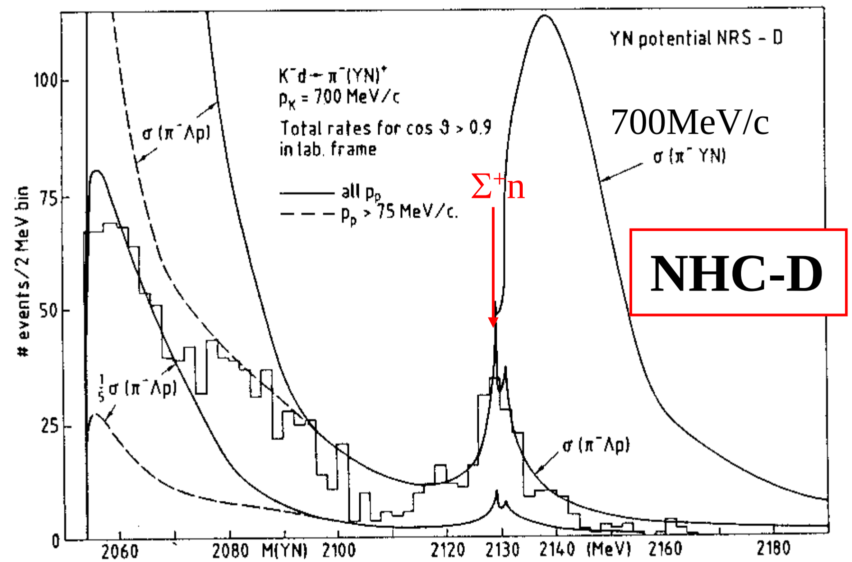
K⁻d→π⁻Λp spectrum in ²H(K⁻, π⁻) Reactions

ΣN ³S₁ [10*]: "Strangeness partner of deuteron"

R.H.Dalitz, Deloff,



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



R.H.Dalitz

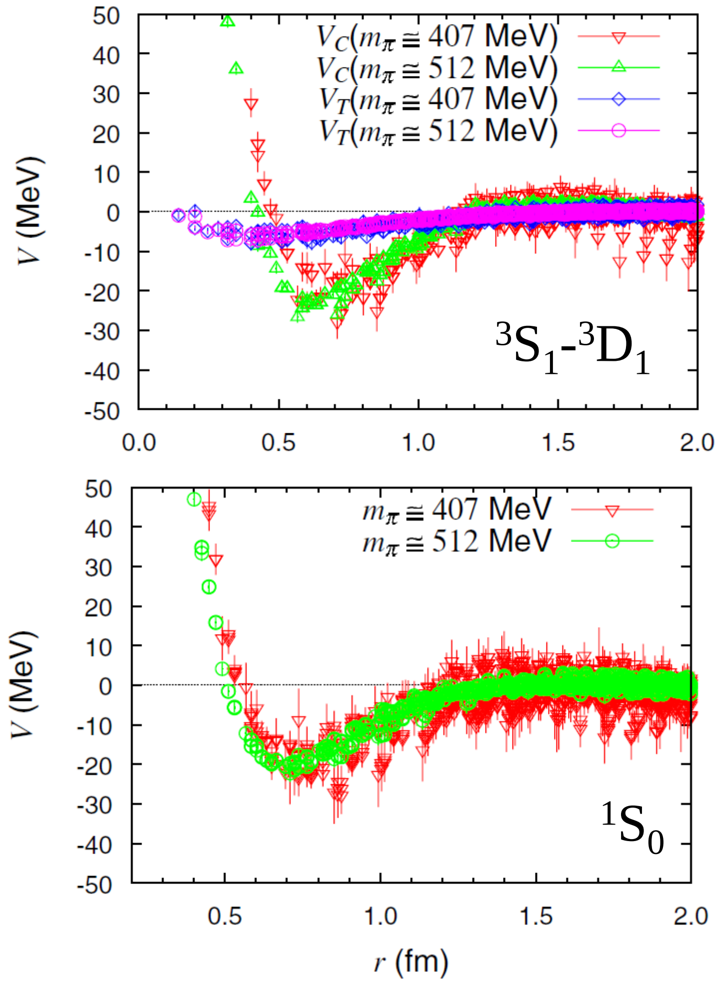
Baryon-Baryon force from lattice QCD

[NN] N. Ishii, S. Aoki, T. Hatsuda, PRL99(2007)022001

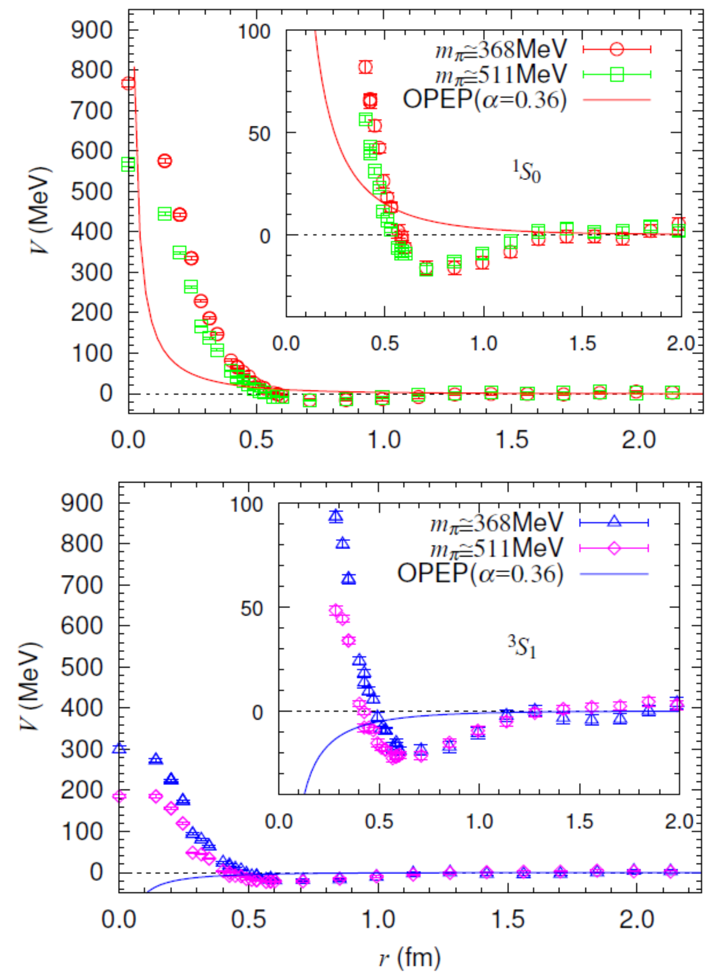
[ΛN,ΞN] H. Nemura et al., PLB673(2009)136; HAL QCD Collaborations, NPA835(2010)176

$$V_{\Lambda N} = V_0(r) + V_\sigma(r)(\vec{\sigma}_\Lambda \cdot \vec{\sigma}_N) + V_T(r)S_{12} + V_{LS}(r)(\vec{L}\cdot\vec{S}_+) + V_{ALS}(r)(\vec{L}\cdot\vec{S}_-) + O(\nabla^2)$$

ΛN



$p\Xi^0$



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

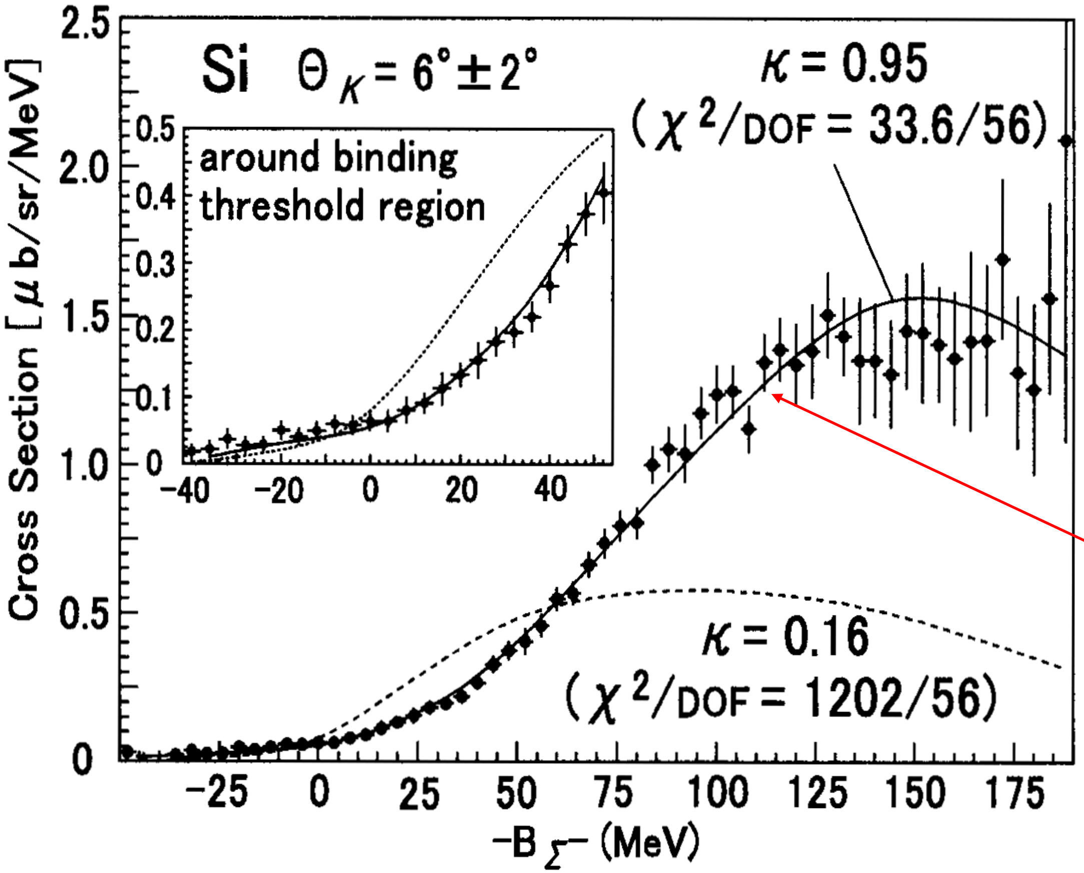
Study of Σ s.p. potential by (π^-,K^+) reactions

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

^{28}Si

Direct Σ production at the nuclear interior

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



Woods-Saxon form

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

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

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

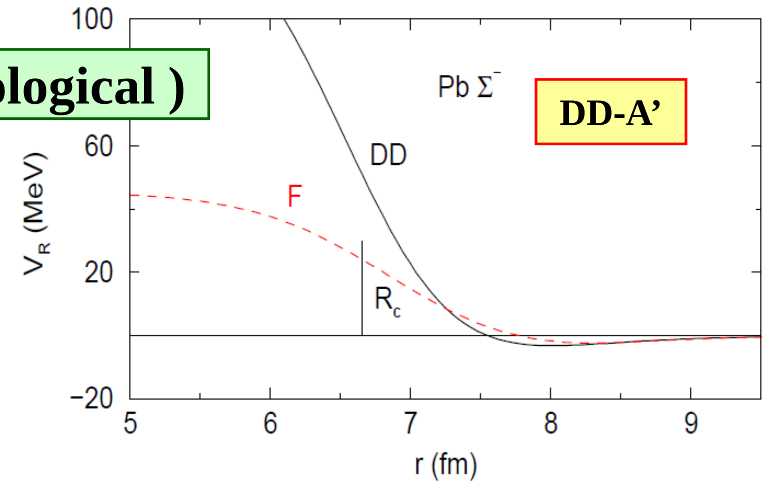
$V_\Sigma = +90$ MeV — Strong repulsion

$W_\Sigma = -40$ MeV — Large imaginary

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

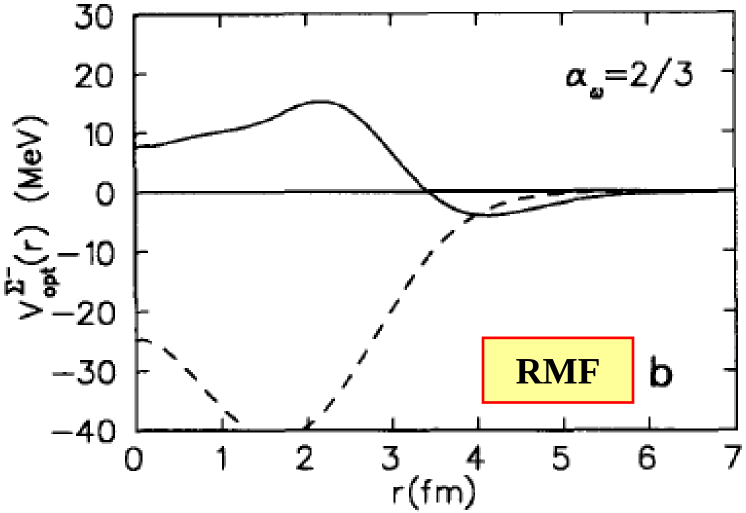
These Σ-nucleus potentials have a repulsion with a sizable imaginary potential.

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



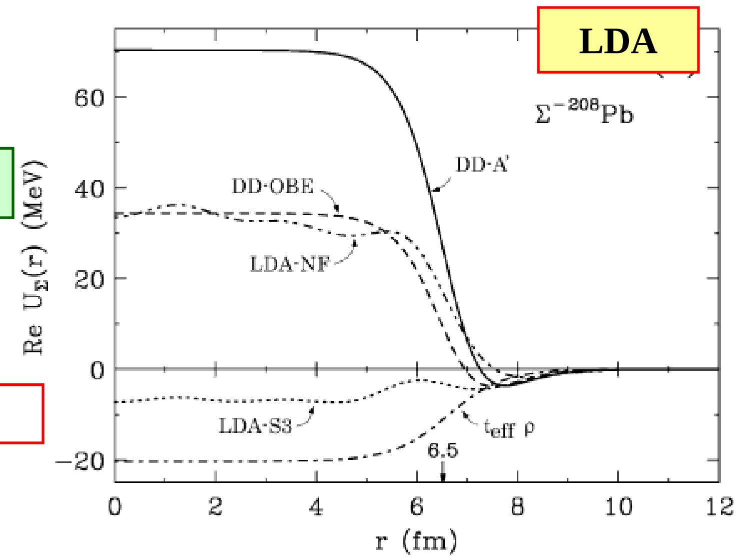
Density-dependent (DD) potential (Phenomenological)

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

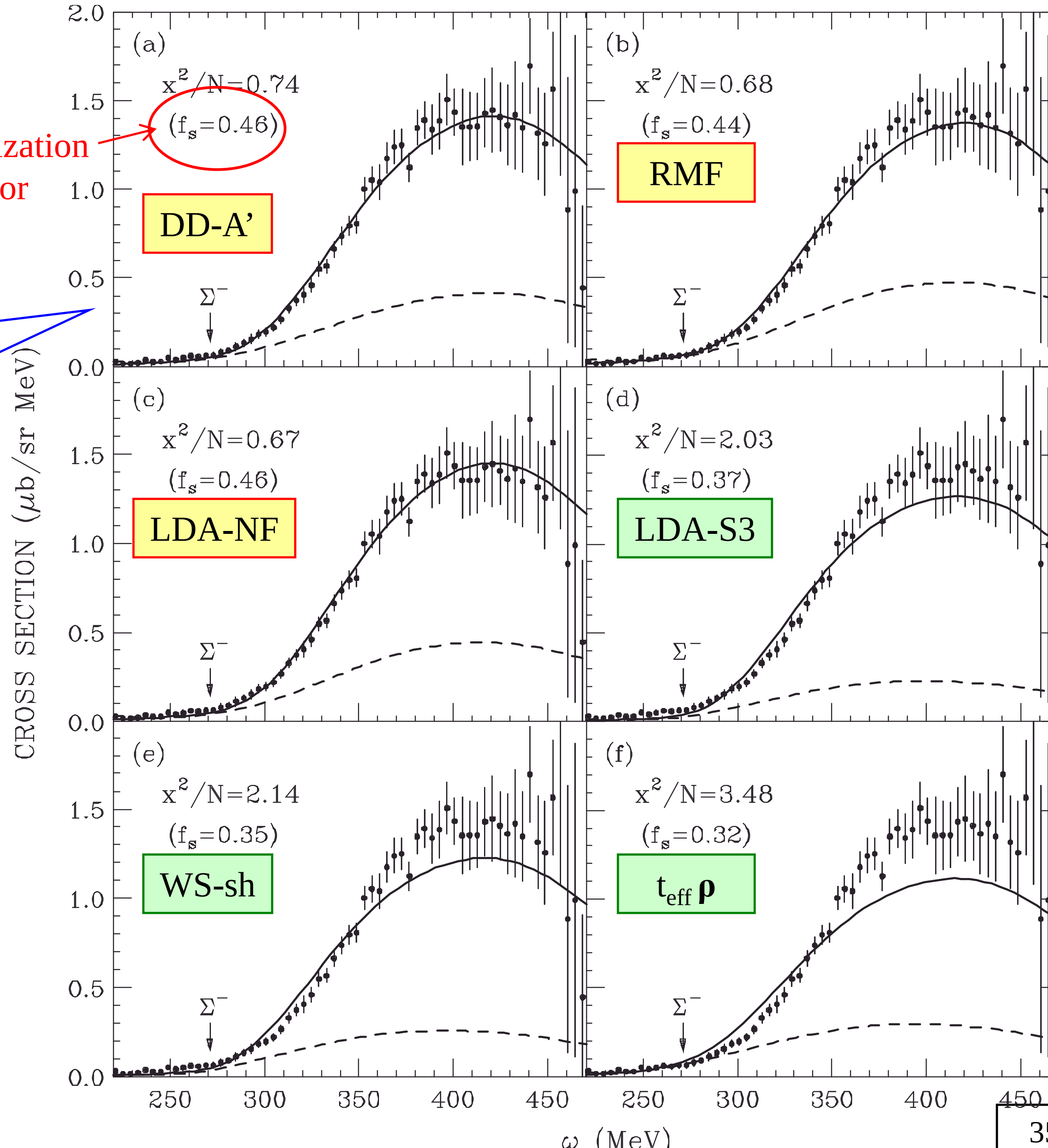
Not so sensitive to the radial behavior of the potential inside the nucleus !!

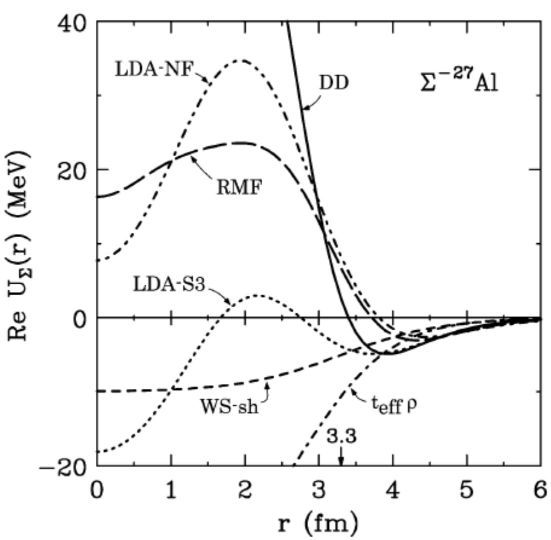
$^{28}Si(\pi^-,K^+)$ reaction at 1.2GeV/c

^{28}Si

Normalization factor

Consistent with the potentials fitted to Σ^- atomic data !!





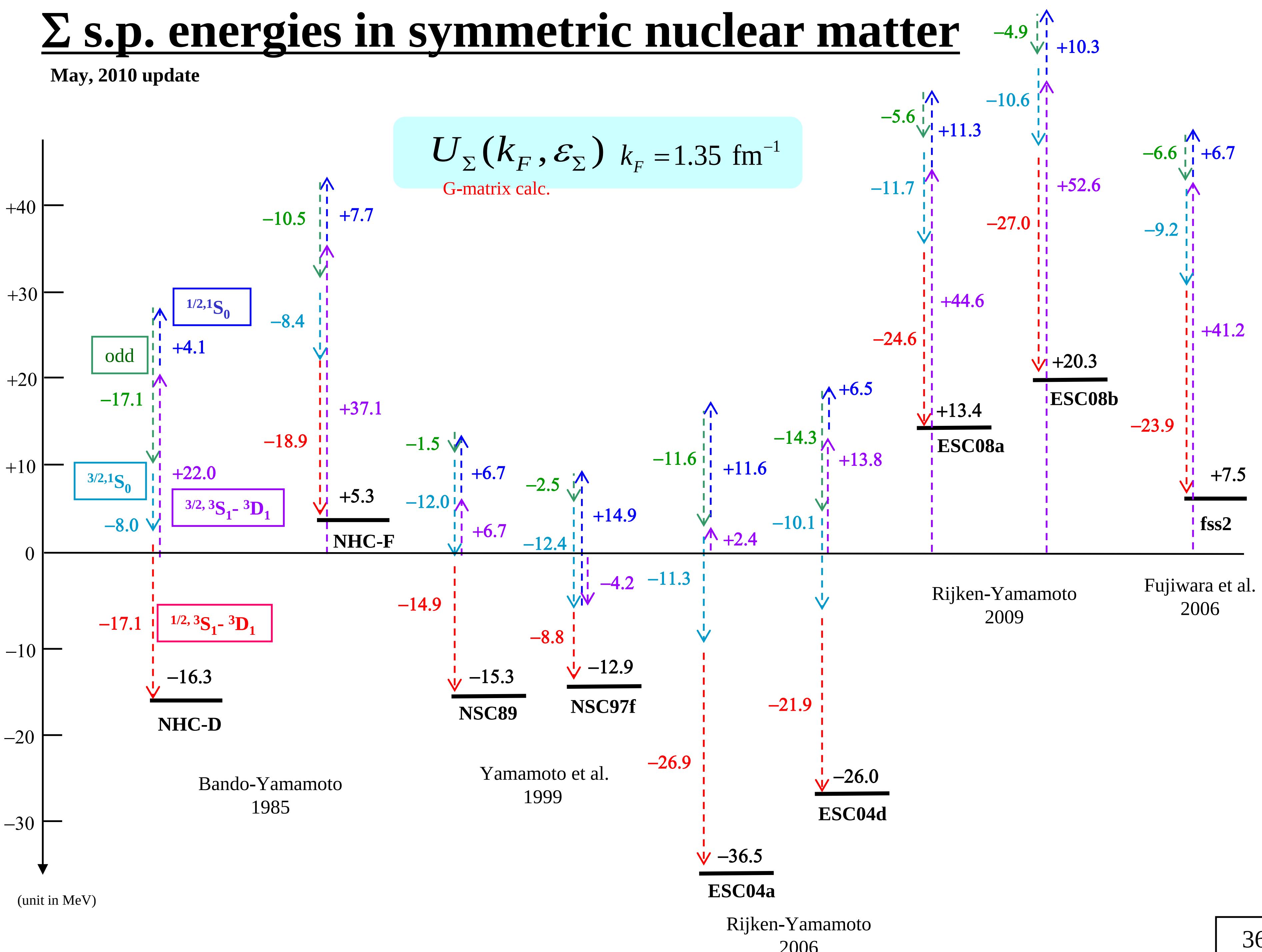
T.Harada, Y.Hirabayashi, NPA759 (2005) 143

Σ s.p. energies in symmetric nuclear matter

May, 2010 update

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

G-matrix calc.

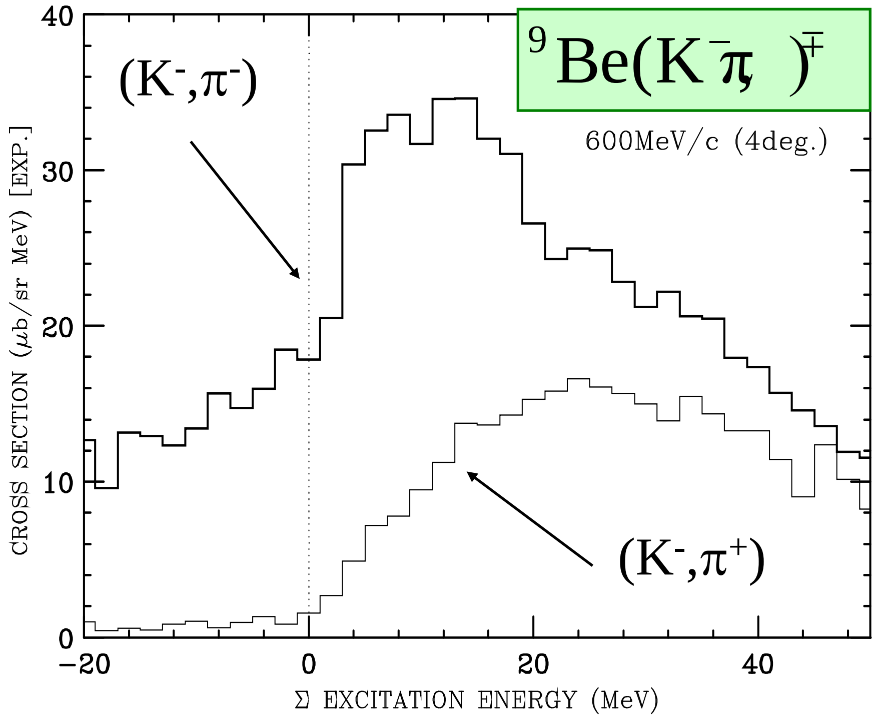


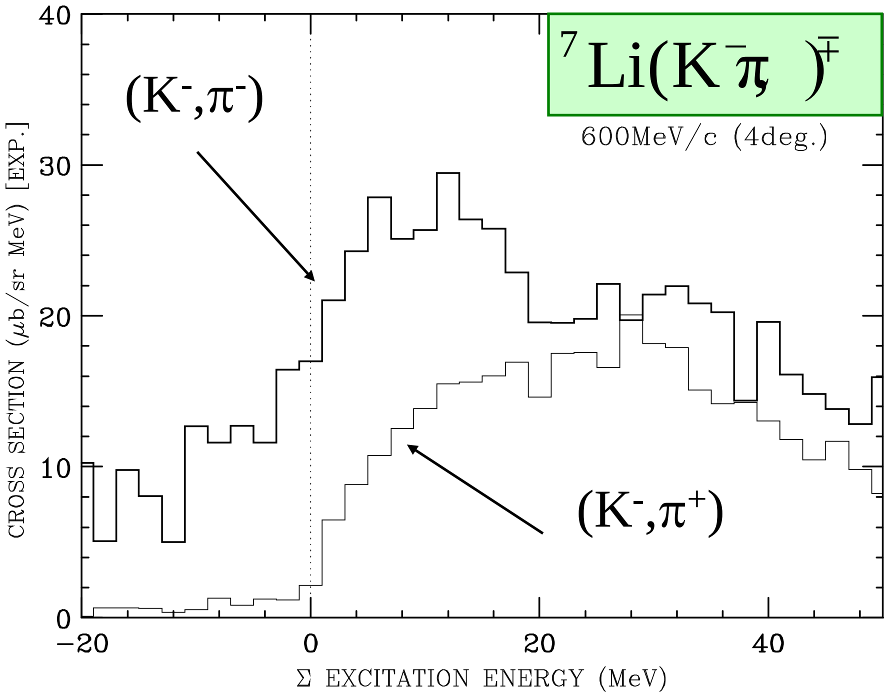
$(K^-,\pi^\pm)$ Experiments at BNL-AGS in 1990-2000

"The Σ narrow width puzzle was disappeared."

by S.Bart et al.,PRL83(1999)5239.

600MeV/c (4deg.)

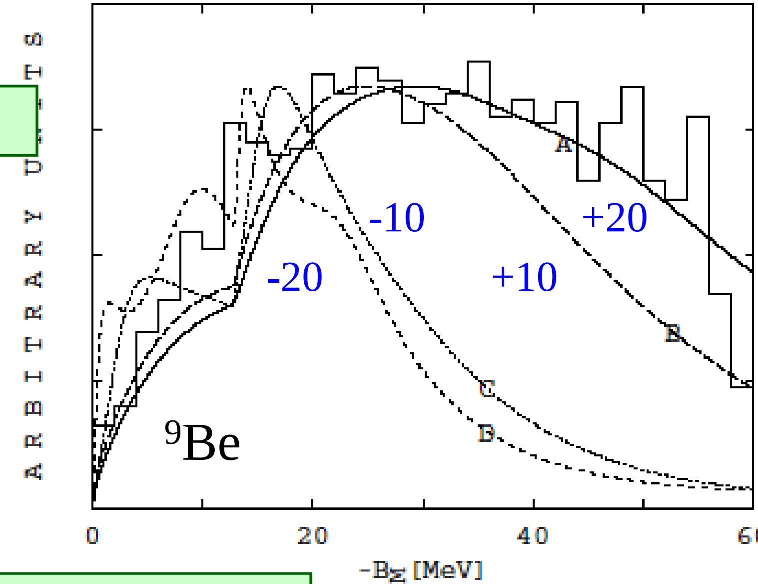




- There is no Σ bound state on both ^6Li and ^9Be.
- The π^- and π^+ spectra are very different each other.

⇒ ***Strong isospin dependence of the Σ-nucleus potentials***

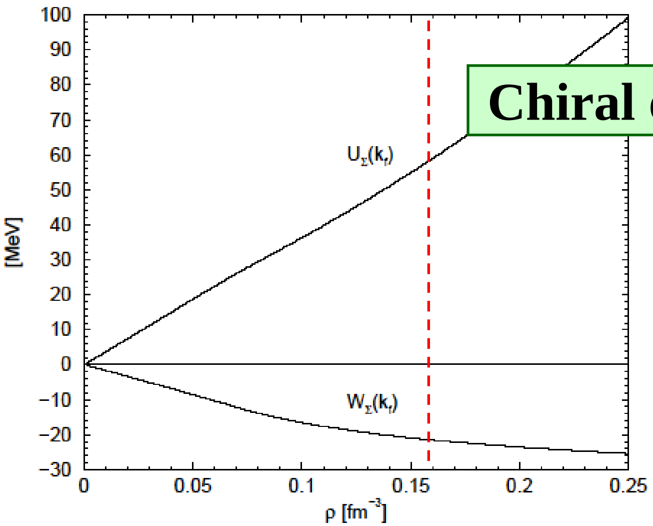
Comparison with resent studies



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."

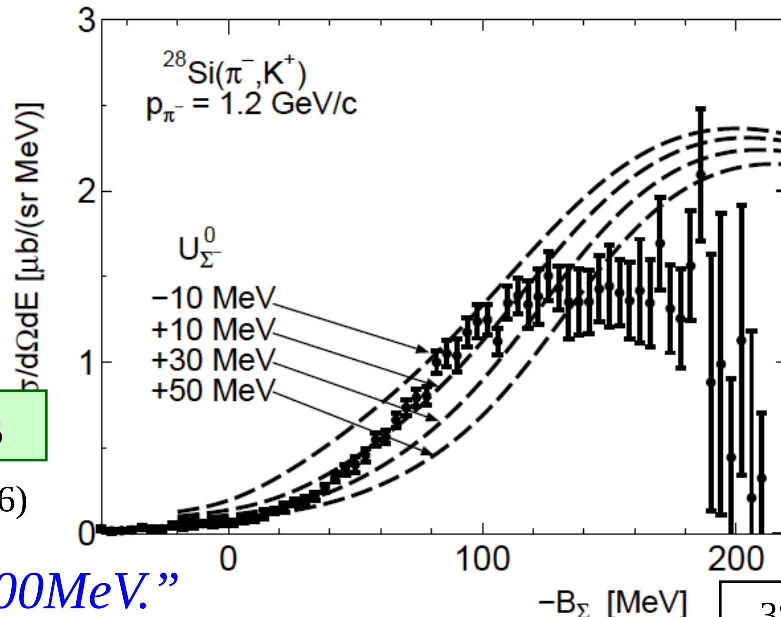


Chiral dynamics in the nuclear medium

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."

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"

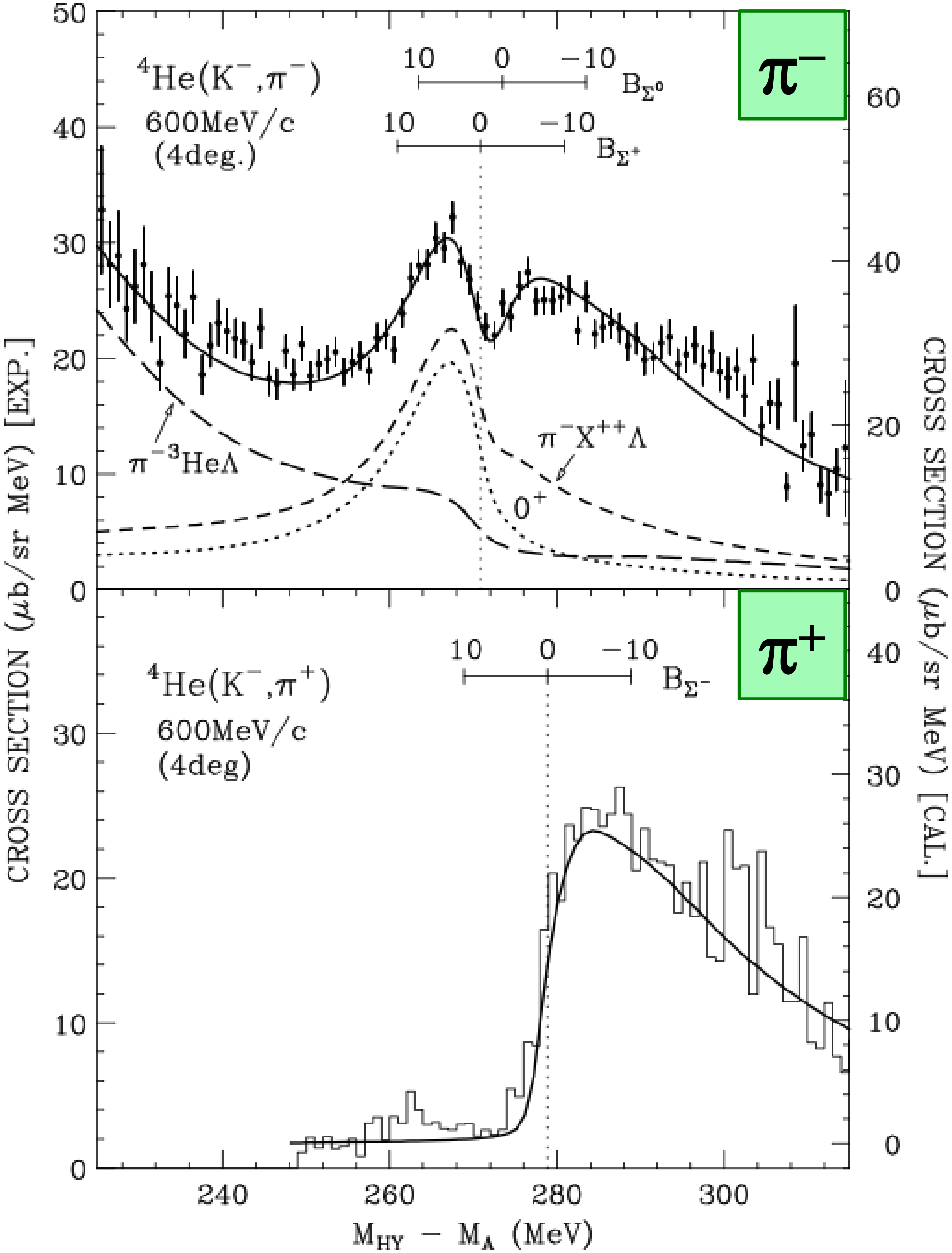
The calculated spectra for ^{4}He(K^-,$\pi^\pm$) reaction can explain consistently the available data from BNL, KEK, and ANL.

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

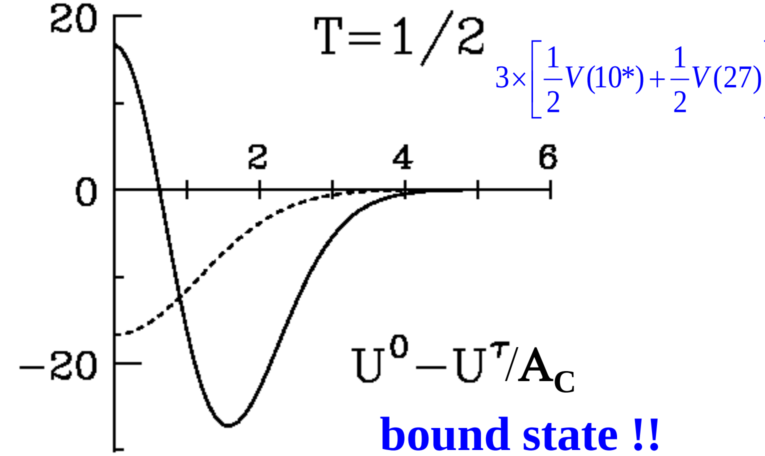
Strong Lane (isospin-dependent) potential and Coherent Λ-Σ coupling

Isospin dependence of the (3N)-Σ potentials

T.Harada, PRL81(1998)5287.

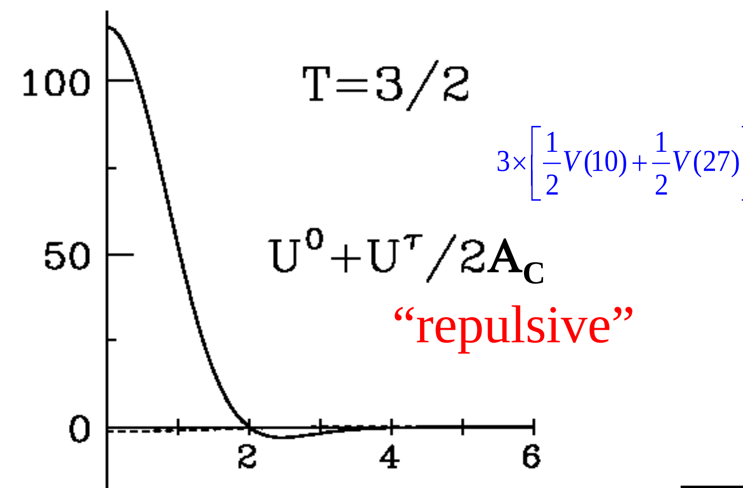


T.Harada, NPA507 (1990) 715.



bound state !!

"repulsive core
+attractive pocket"

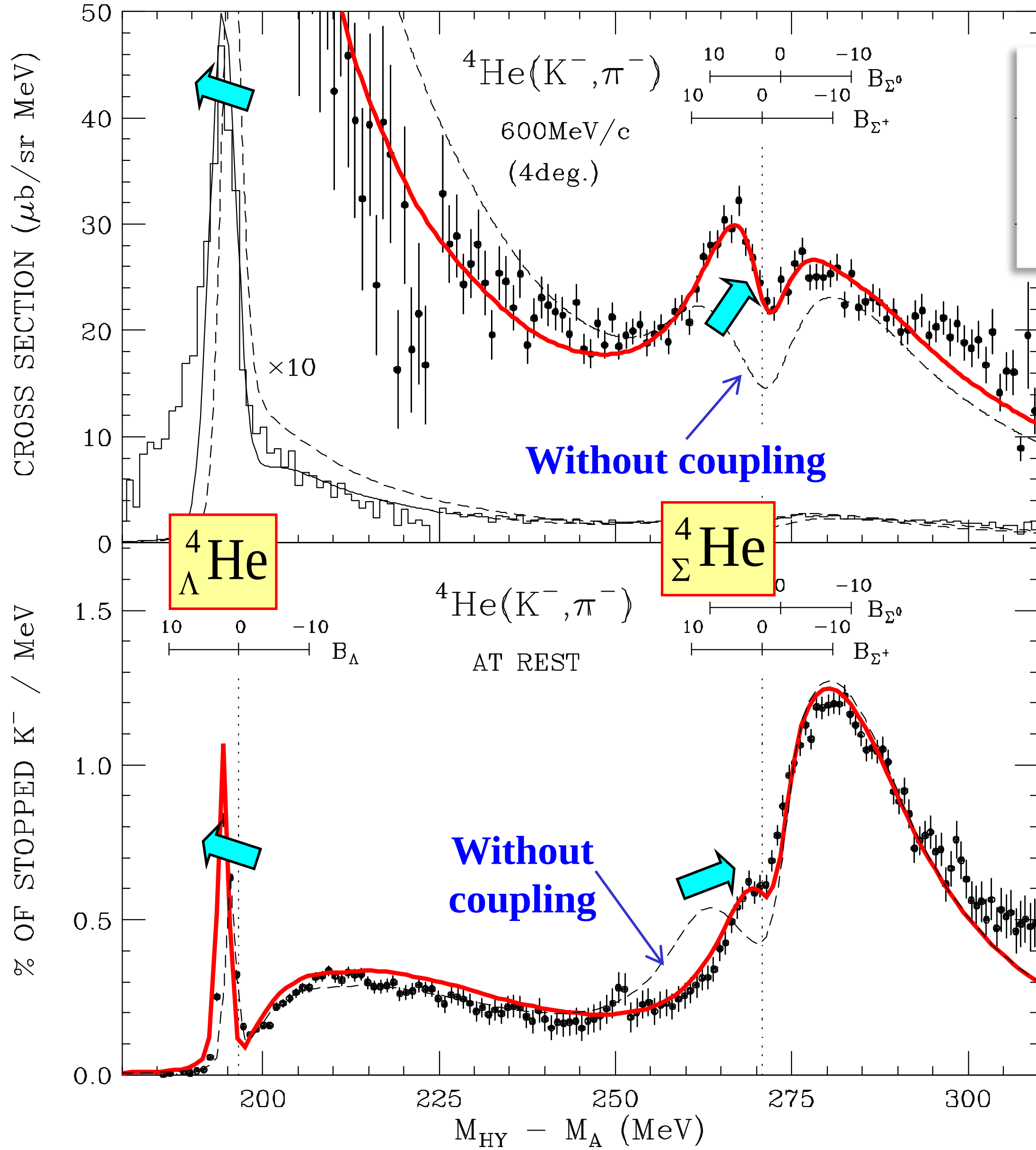


"repulsive"

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

Hyperon-mixing

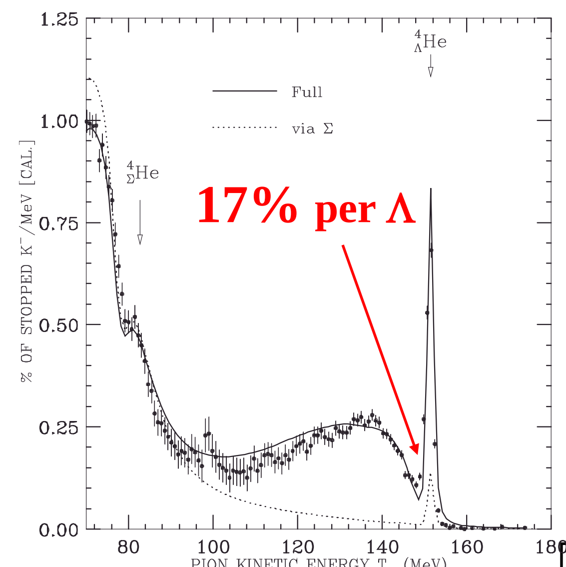
T.Harada, NPA507(1990)715.



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

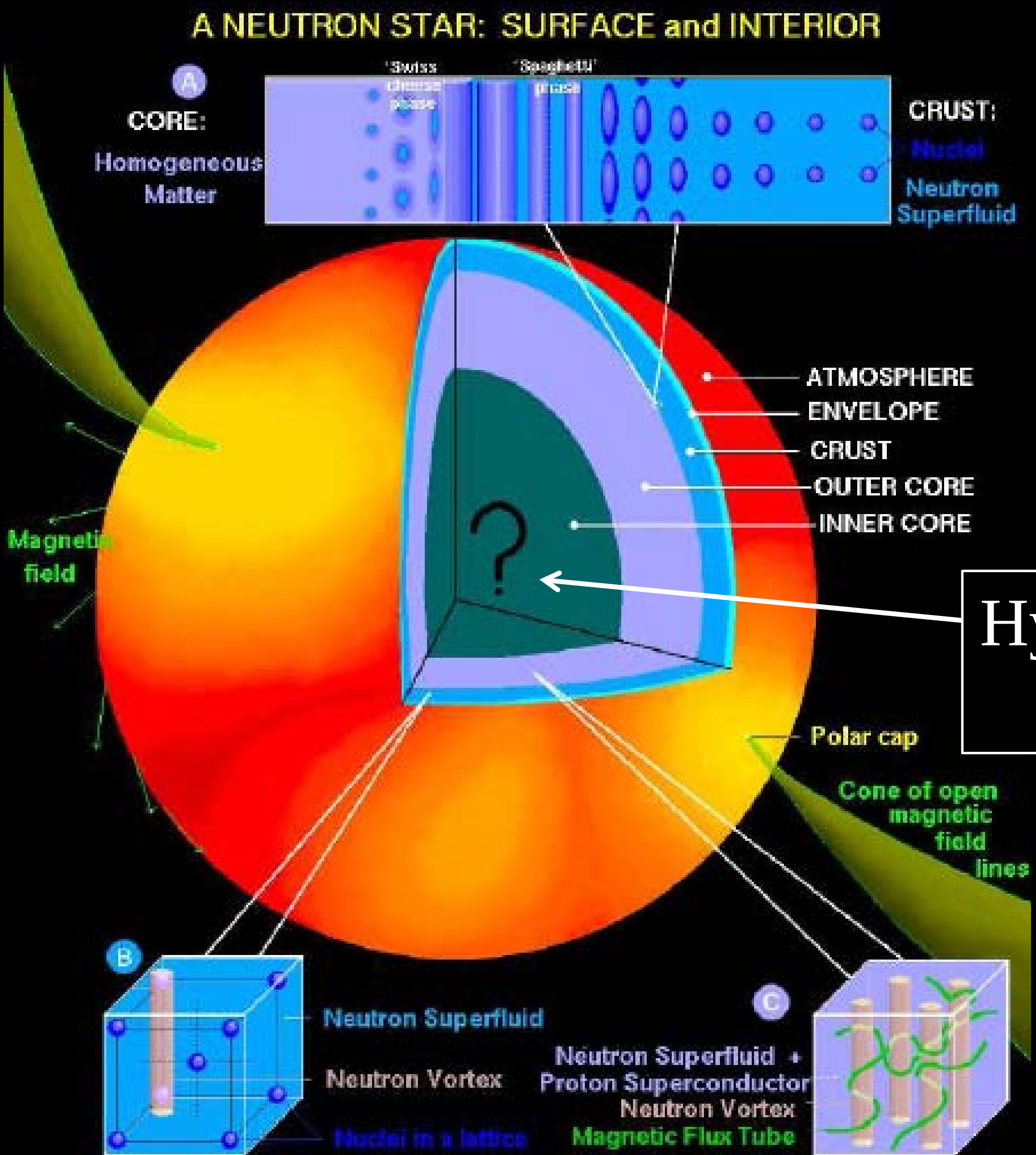
- The Λ state is produced via Σ components in the ground state.

^{4}He(stopped K^-,π^-)$^4_\Lambda$He



3. 中性子星と高密度バリオン物質

by J.M. Lattimer,M. Prakash,

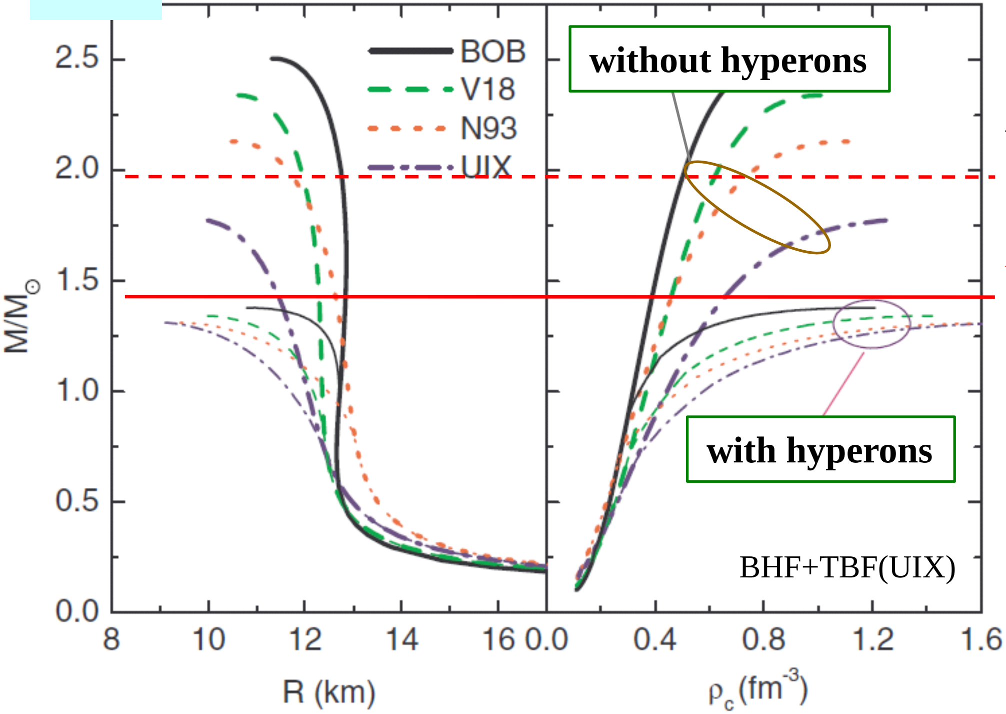


Hyperon mixing

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

中性子星の構造とEOS

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



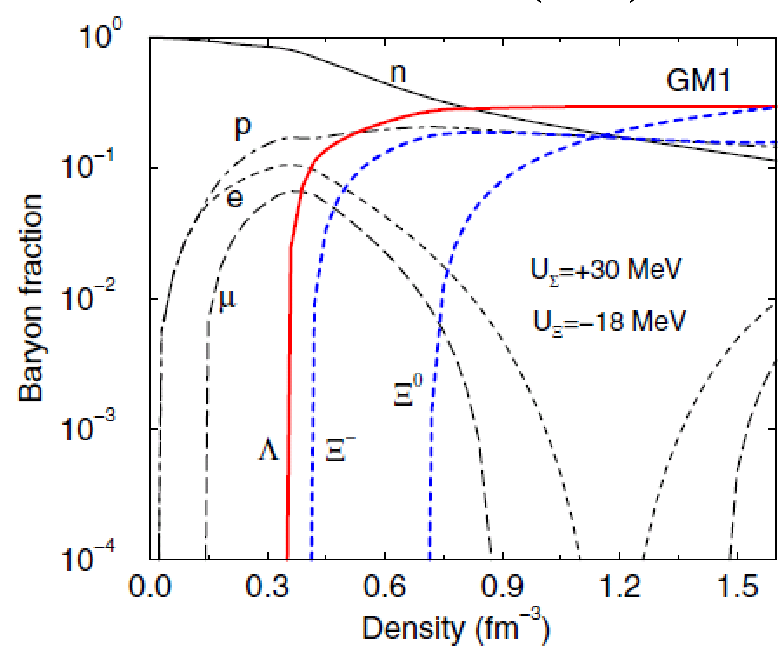
PSR J1614-2230
P. B. Demorest et al., Nature467(2010)1081

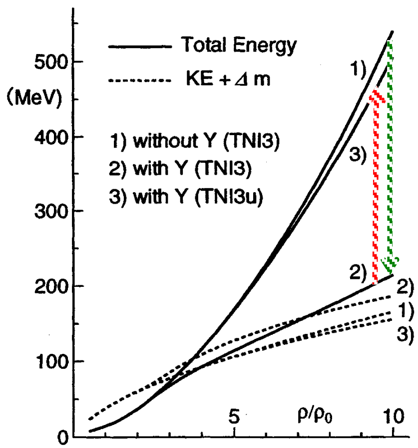
$1.97 M_\odot$

最大質量の下限

$1.44 M_\odot$

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





Softening on the EOS

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

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

ハイペロン混合によって強く影響

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

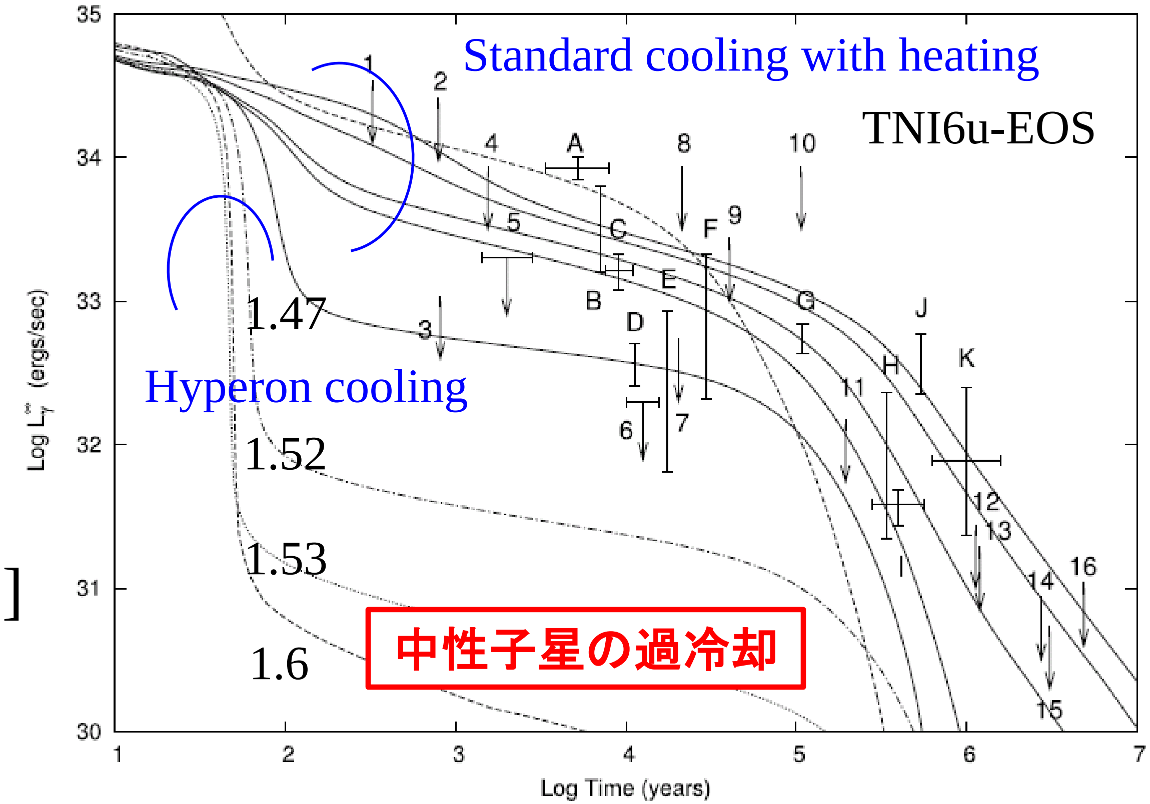
Thermal evolution of hyperon-mixed neutron stars

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

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

YN相互作用の強さによって強く影響

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

Multi-strange hadronic systemの存在可能性

Generalized Bethe-Weizsäcker mass formula

S. Balberg, A. Gal, J. Schaffner, PTP117(1994)325

$$E_B(\{p,n\}) = -a_V^{(0)}A + a_S^{(0)}A^{2/3} + a_C^{(0)}\frac{Z}{A^{1/3}} + a_X^{(0)}\frac{(N-Z)^2}{A}$$

(unit in MeV) $a_S^{(0)}$: 18 $a_C^{(0)}$: 0.72

$$a_V^{(0)} \to a_V - b_V^{(w)}w - b_V^{(y)}y$$

(Set II) 16   28.7   -5.5   -4.75

$$a_X^{(0)}x^2 \to a_X x^2 + a_U u^2 + a_W w^2 + a_y y^2 + a_{wy} wy$$

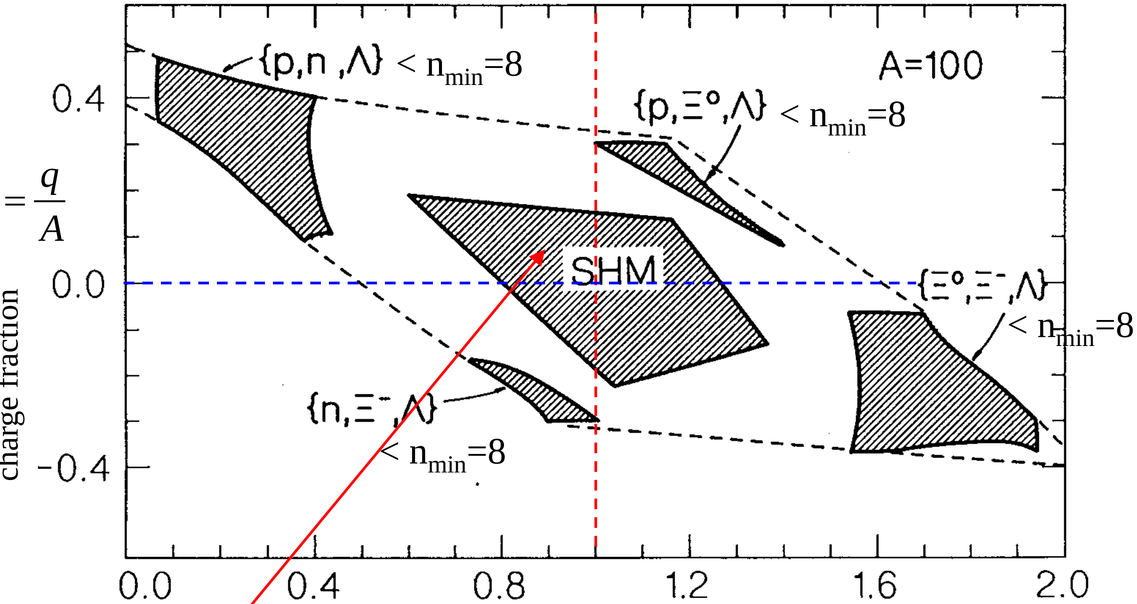
23   43   23.7   57.1   45   7.7

$x = (N-Z)/A$, $y = \left[(N+Z+\Xi^0+\Xi^-)/4-\Lambda\right]/A$

$u = (\Xi^0-\Xi^-)/A$, $w = \left[(N+Z)/2-(\Xi^0+\Xi^-)/2\right]/A$

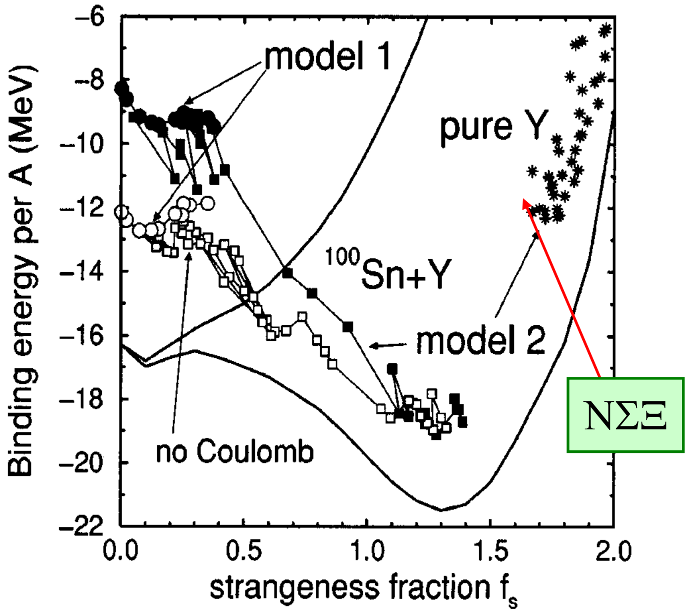
$E_B/A \to -28.3\text{MeV}$, $f_S \to 0.96$, $f_q \to 0$

Σ+N→Λ+N+78 MeV
Ξ+N→Λ+Λ+26 MeV
Ω+N→Λ+Ξ+178 MeV



$f_S \sim 1$, $f_q \sim 0$ strangeness fraction $f_S = -\frac{S}{A}$ $\frac{q}{A}$

RMF   J. Schaffner-Bielich, A. Gal, PRC62(2000)034311



4. 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

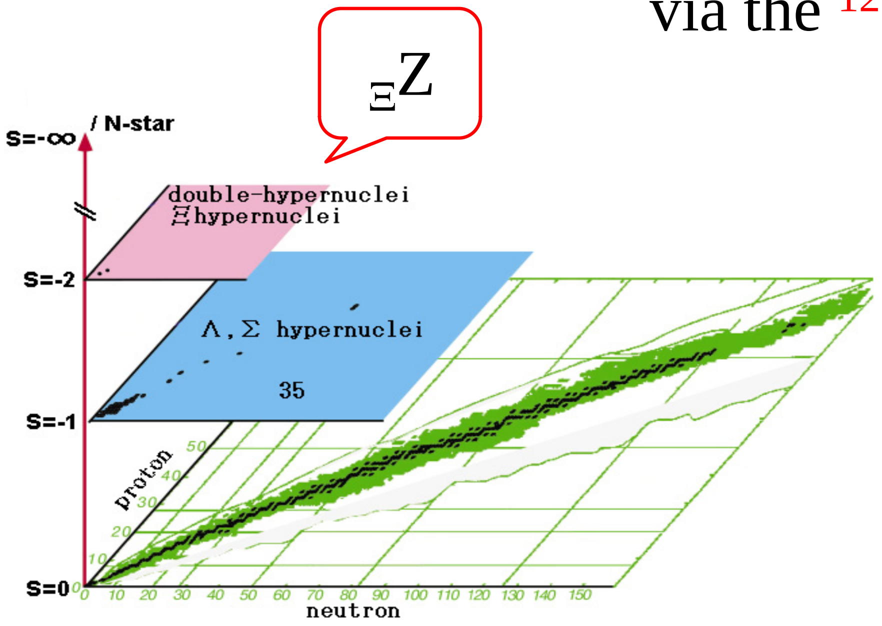
ΞハイパーΞ核

E03,E05@J-PARC

E03 Measurement of X rays from Ξ- atom

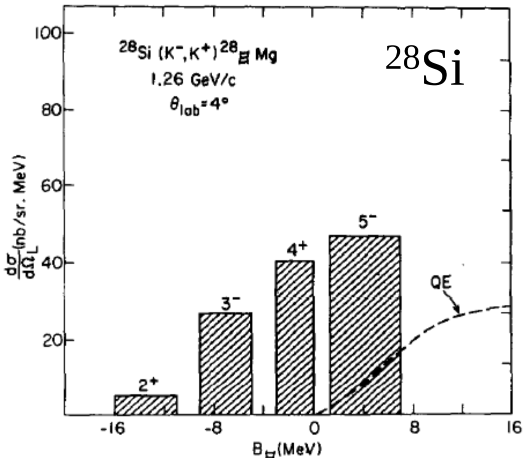
E05: Spectroscopic study of Ξ-hypernucleus, $^{12}_{\Xi}Be$

via the $^{12}C(K^-,K^+)$ reaction (Day-1)



Studies of Ξ^- hyperon interaction with the nucleus

V_Ξ ?



Ξ-hypernuclei via (K-,K+) reactions

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

Analysis of the nuclear $K^-p \rightarrow K^+\Xi^-$ reaction
The potential depth parameters is obtained by

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

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

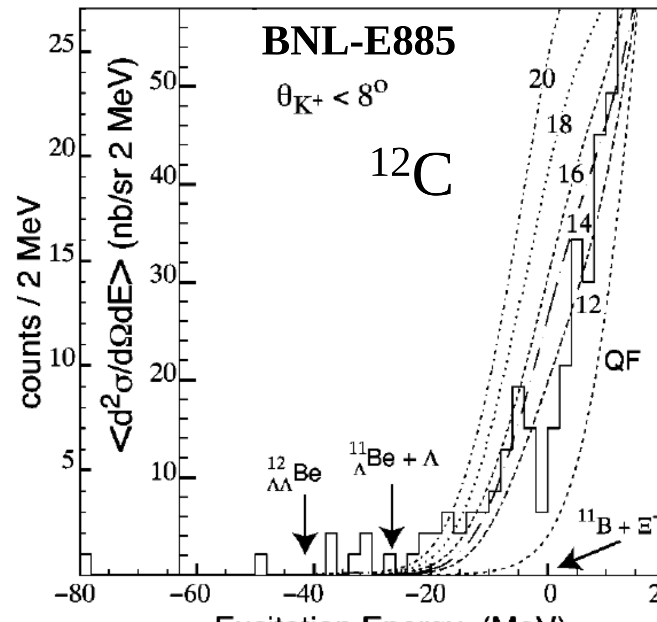
$$V^0_\Xi \simeq -16 \text{ MeV}$$

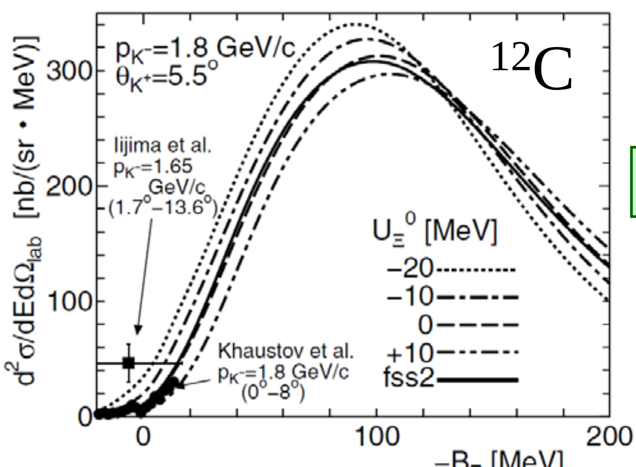
Analysis of 12C(K-,K+) spectrum suggests

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

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

Comparison with the data in the Ξ bound region





Semi-Classical Distorted Wave Model Analysis

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

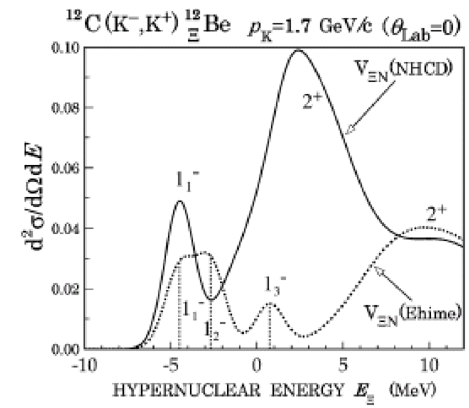
$$V^0_\Xi = -20, -10, \ 0, +10, +20\text{MeV} \quad \longleftrightarrow \quad \textbf{fss2}$$

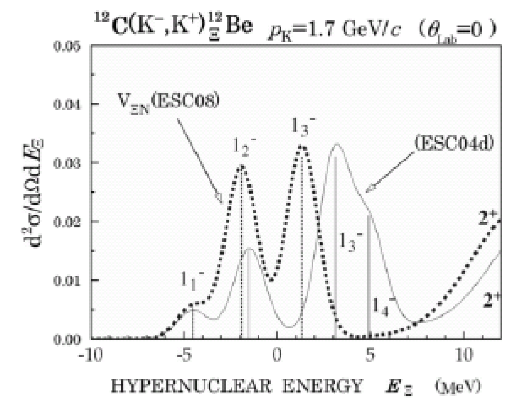
Ξ^- s.p. energies in symmetric nuclear matter

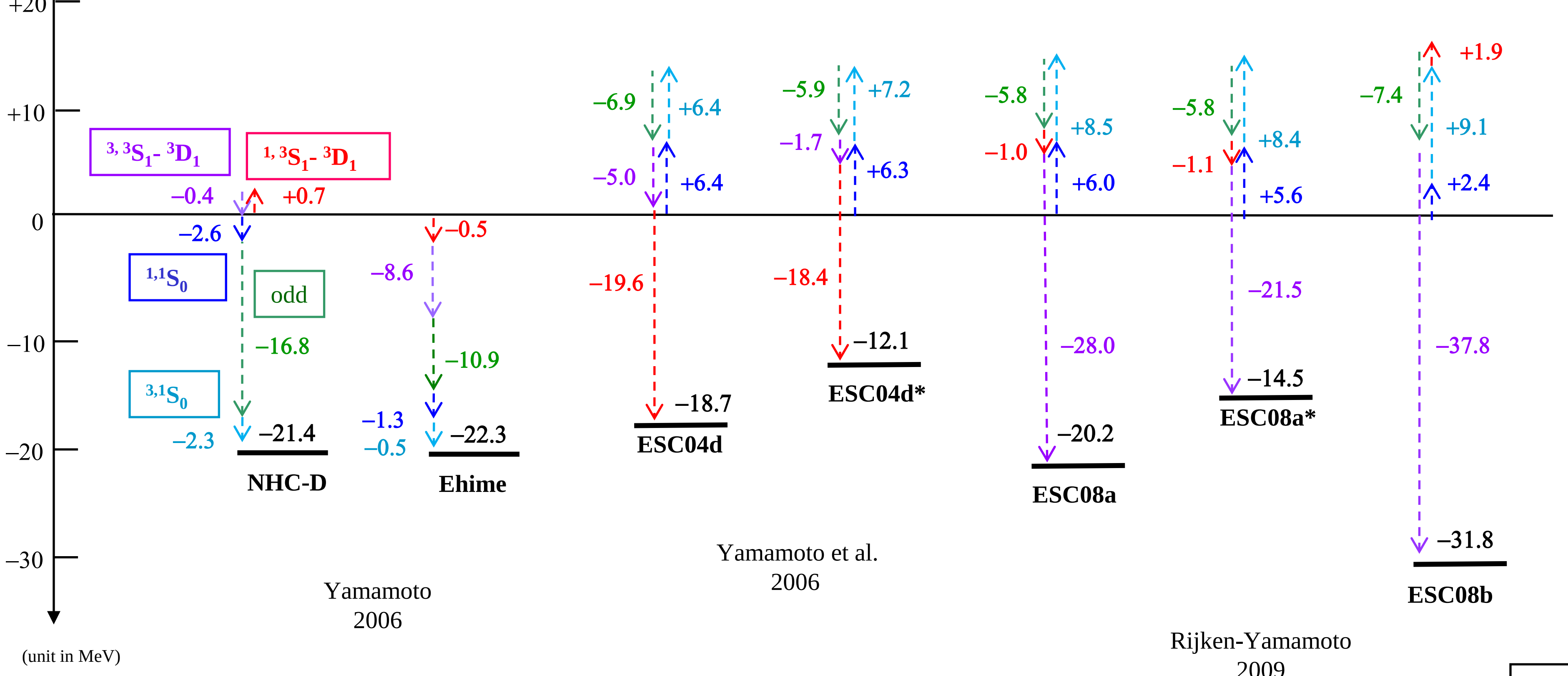
T.Motoba, S.Sugimoto, NPA835(2010)223.

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

G-matrix calc.





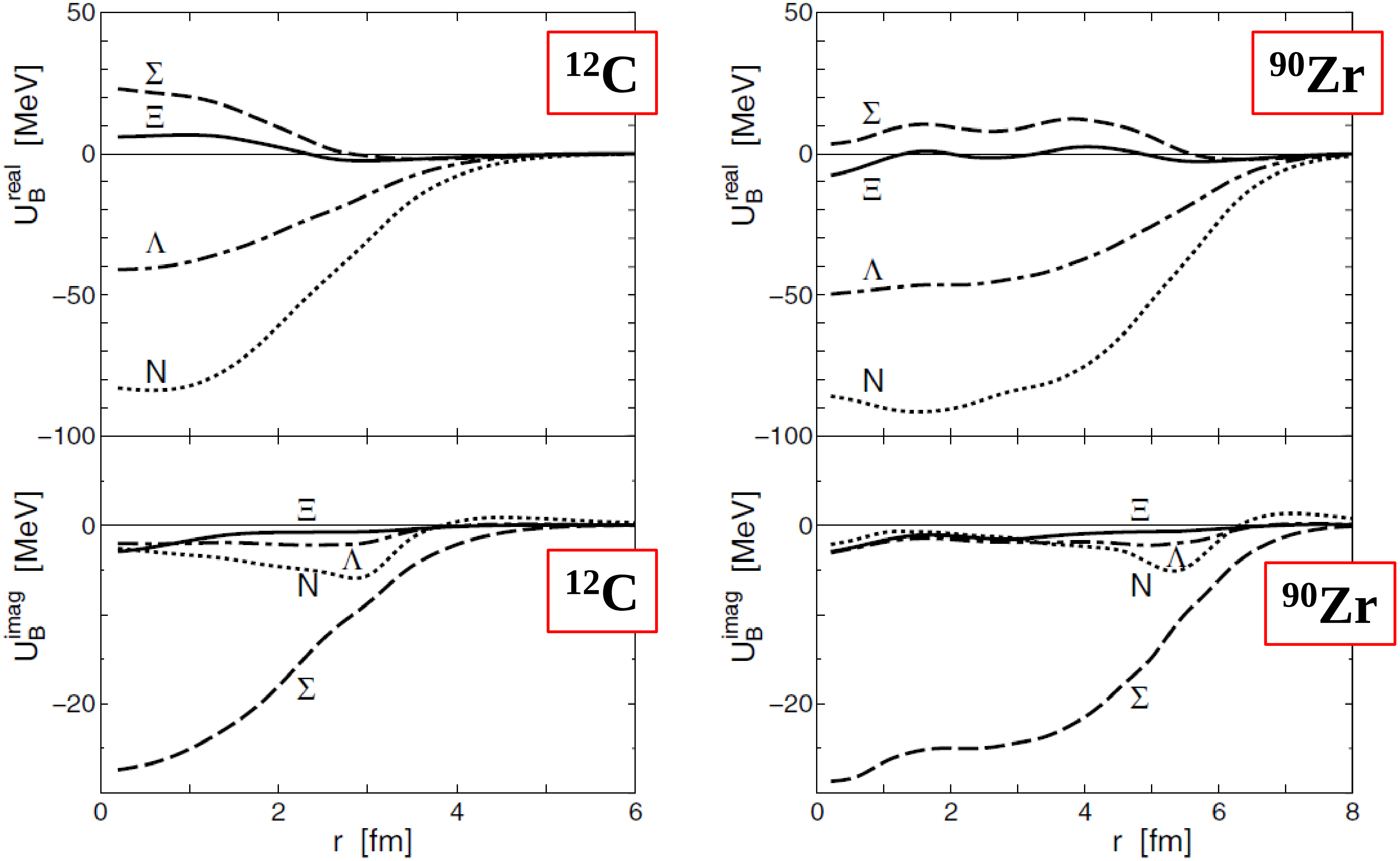


Hyperon s.p. potentials in finite nuclei

G-matrix+local density approximation

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

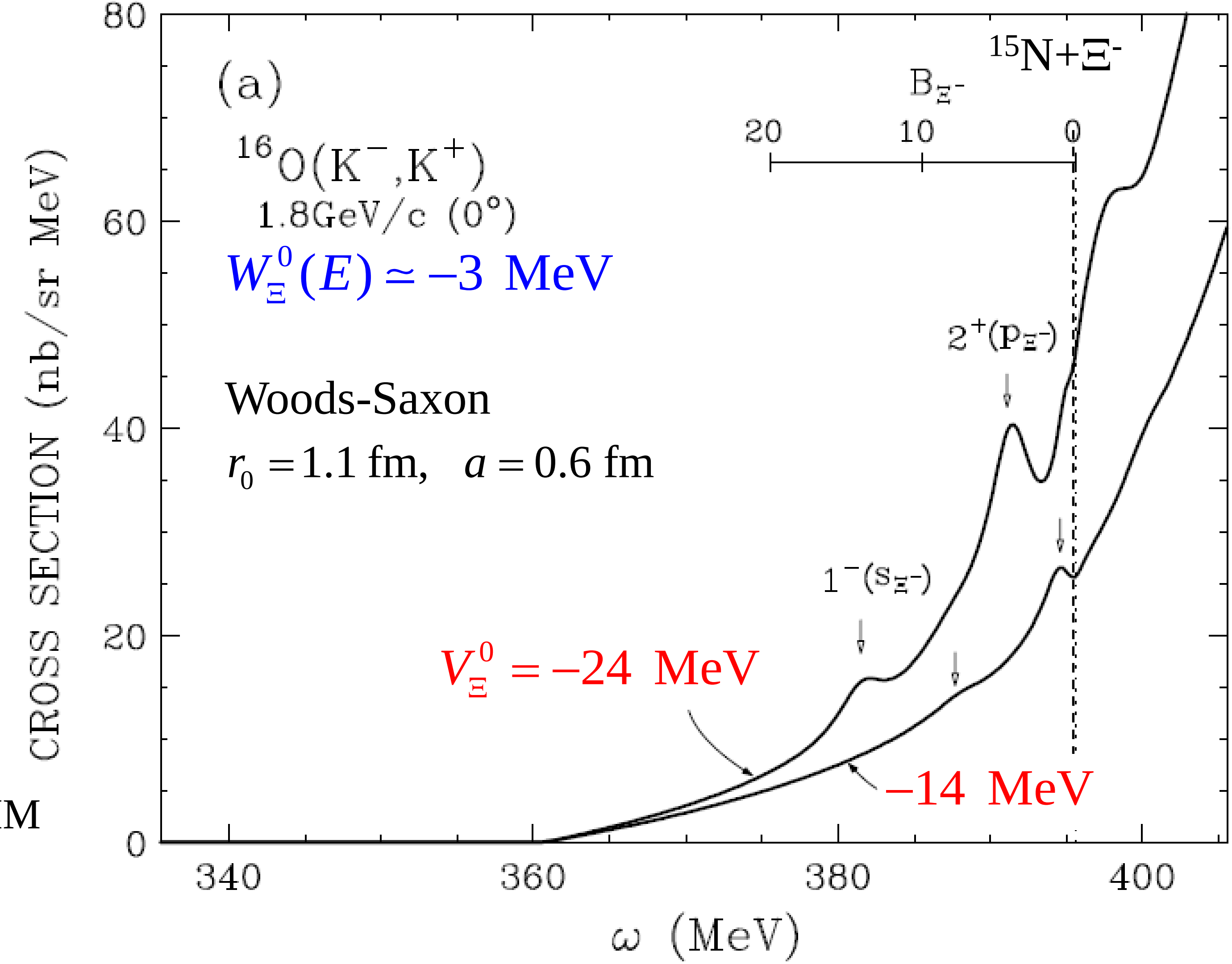
fss2 : SU_6 quark-model BB interaction by Kyoto-Niigata group



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

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

^{16}O

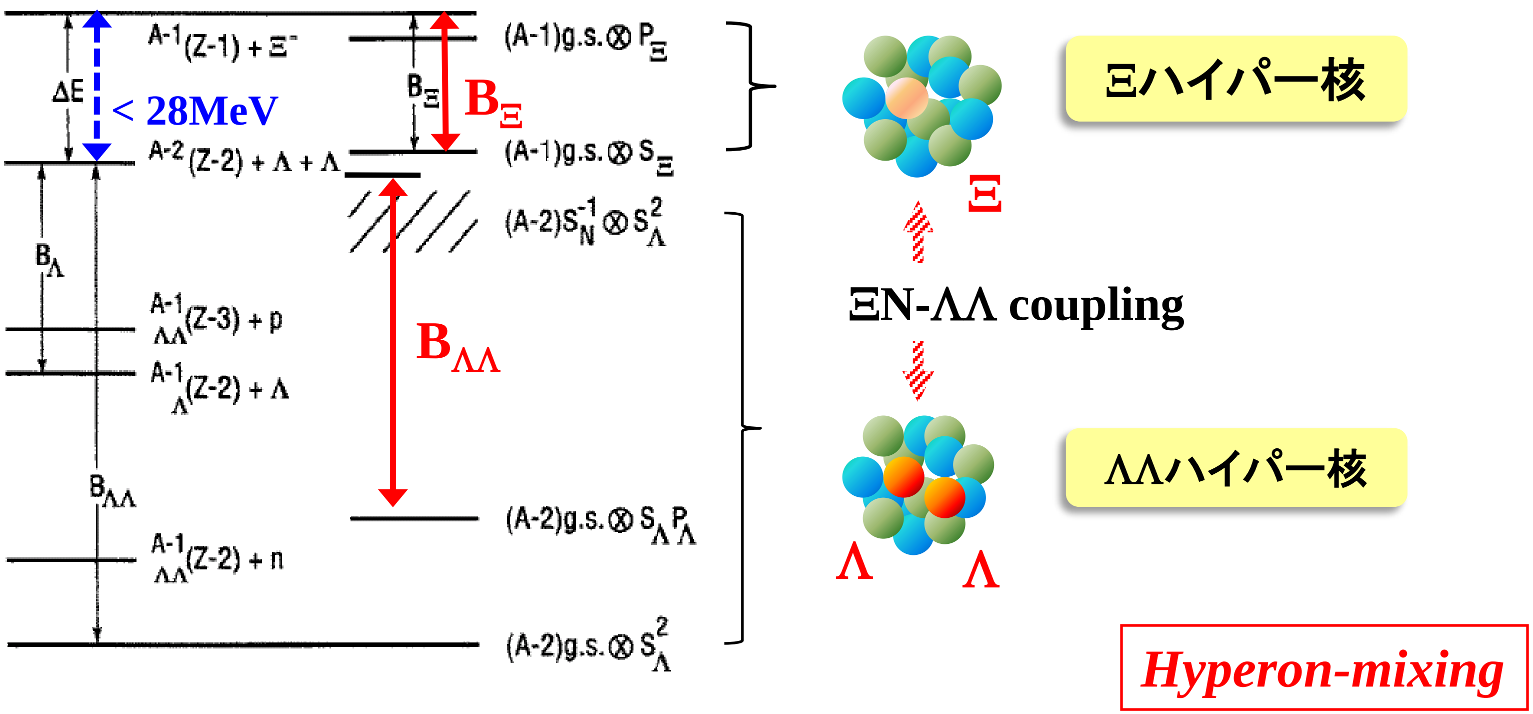


1.5MeV FWHM

- ***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.

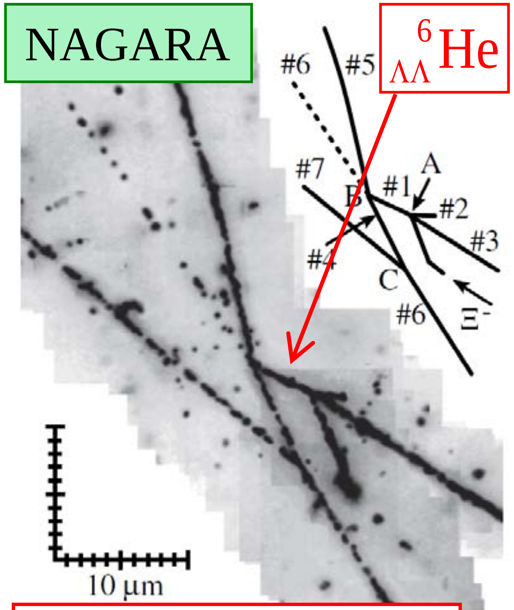
ΛΛハイパー核



E07@J-PARC

E07: Systematic study of double strangeness system with an emulsion-counter hybrid method

Observation of ΛΛ Hypernuclei in E176/E373 Hybrid Emulsion

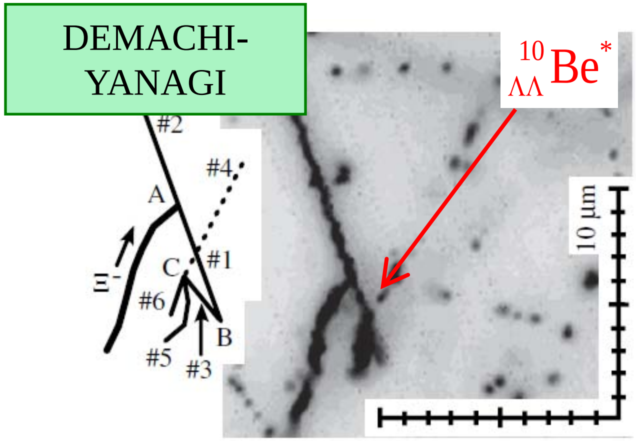


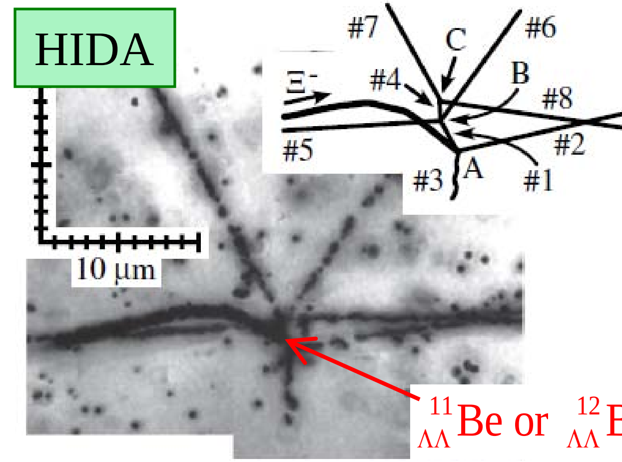
$$^{12}C+\Xi^- \rightarrow {}^{6}_{\Lambda\Lambda}He+{}^{4}He+t$$

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

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

Prowse, 1966 — Nagara,2001 — Ξ mass update

"weak attractive"

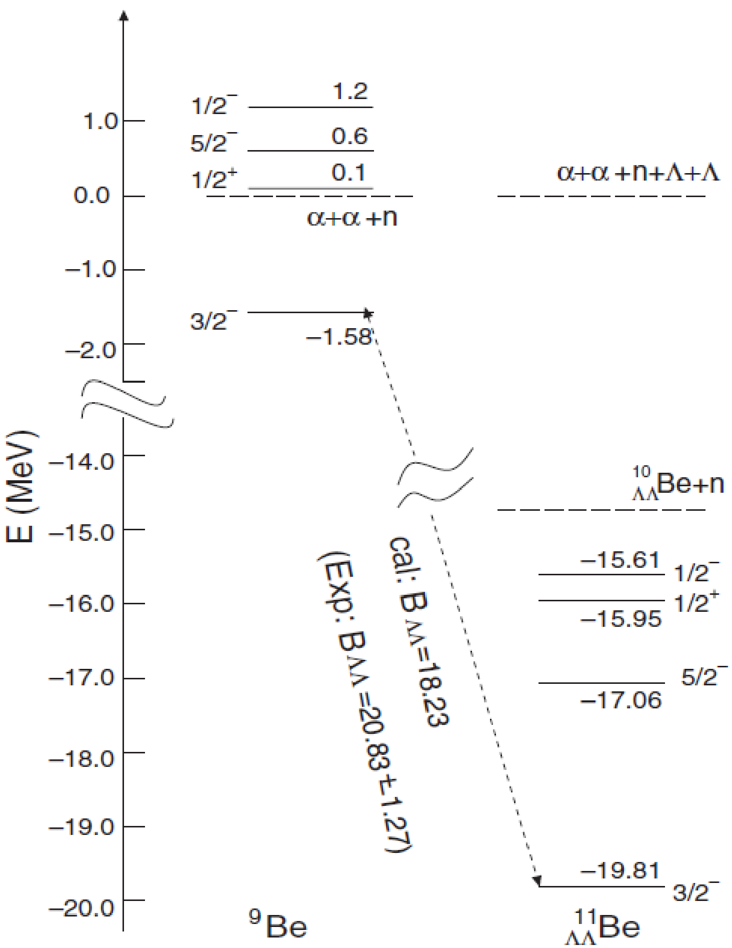
Five-body **Cluster Calculations of the ΛΛ Hypernucleus**

$${}^{11}_{\Lambda\Lambda}\mathrm{Be} = \alpha + \alpha + n + \Lambda + \Lambda$$

E. Hiyama et al., PRL104(2010)212502

OCM + 3BF + ΛN pot. + ΛΛ pot.

HN, KKNN | Pheno. Gaussian | YNG | NF



The subsystems are reproduced:

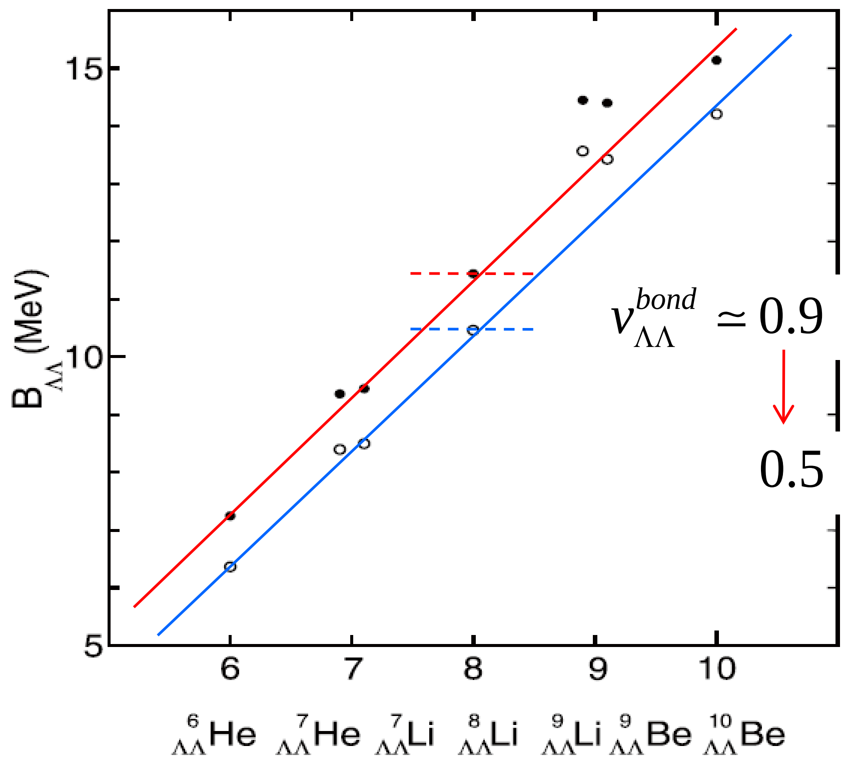
$${}^{6}_{\Lambda\Lambda}\mathrm{He} = \alpha + \Lambda + \Lambda \quad B^{\mathrm{exp.}}_{\Lambda\Lambda}(0^+_{\mathrm{gs}}) = 6.91\ \mathrm{MeV}$$

$${}^{10}_{\Lambda\Lambda}\mathrm{Be} = \alpha + \alpha + \Lambda + \Lambda \quad B^{\mathrm{exp.}}_{\Lambda\Lambda}(2^+_1) = 11.88\ \mathrm{MeV}$$

ΛΛ bound energy

$$V^{\mathrm{bond}}_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}\mathrm{Z}) \equiv B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}\mathrm{Z}) - B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}\mathrm{Z}; V_{\Lambda\Lambda}=0)$$

E. Hiyama et al., PTPS183(2010)152



$$v^{bond}_{\Lambda\Lambda} \simeq 0.9\ \mathrm{MeV}$$

↓

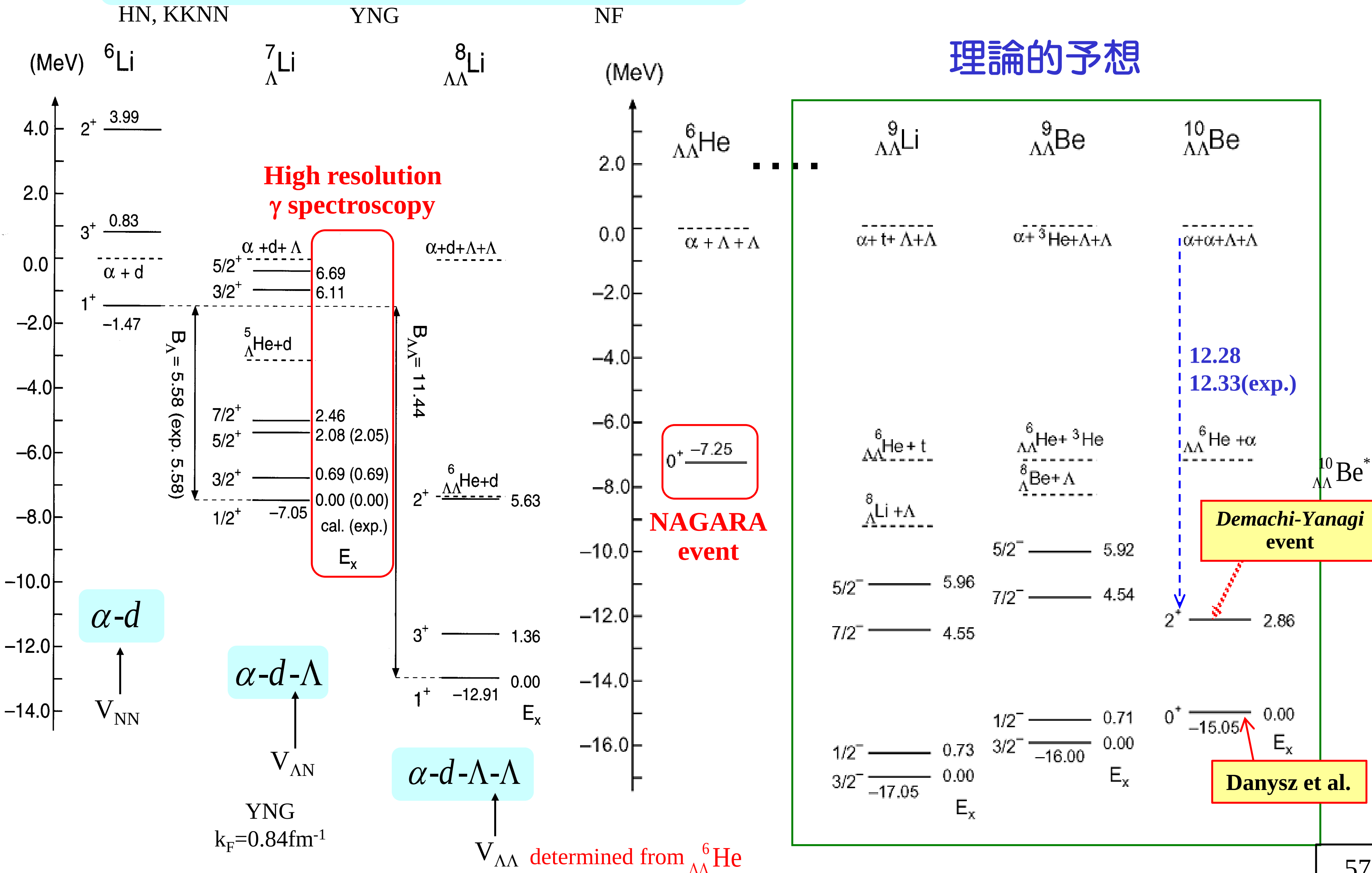
0.5 MeV

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

OCM+ΛN potential+ΛΛ potential

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

理論的予想



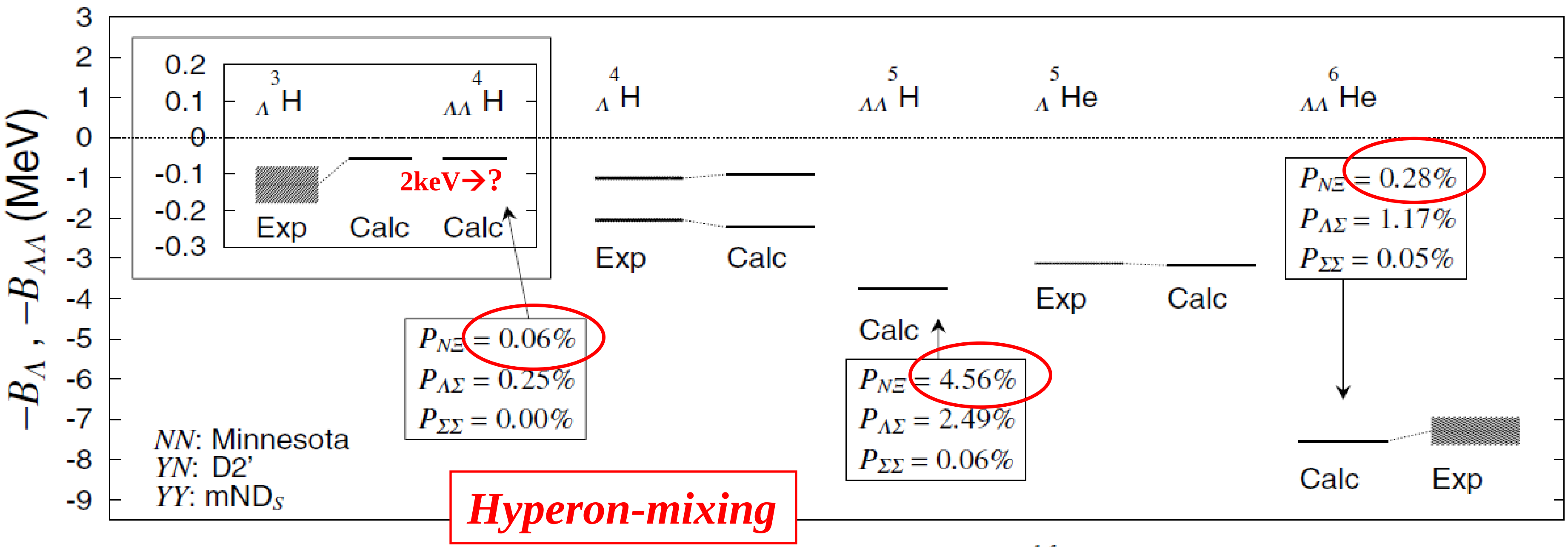
Coupled Channel Approach to Doubly Strange Hypernuclei

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.

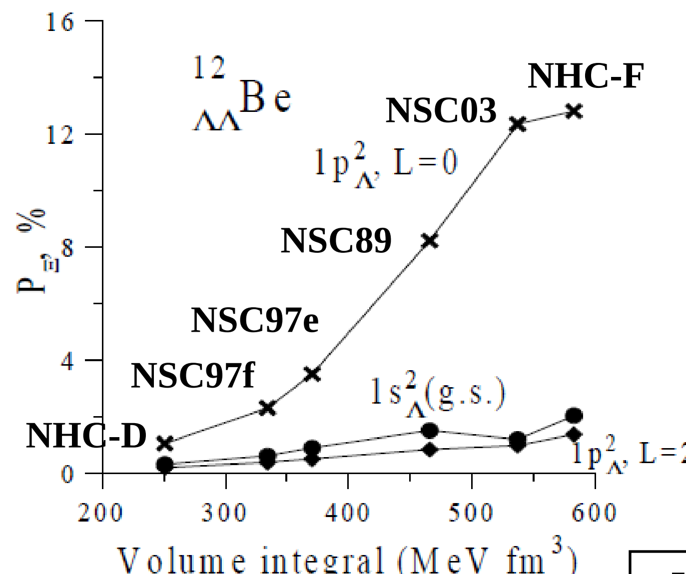
Y. Yamamoto and Th.A. Rijken, PRC69(2004)014303.

ΛΛ-ΞN s-wave: P(Ξ) < 1 %

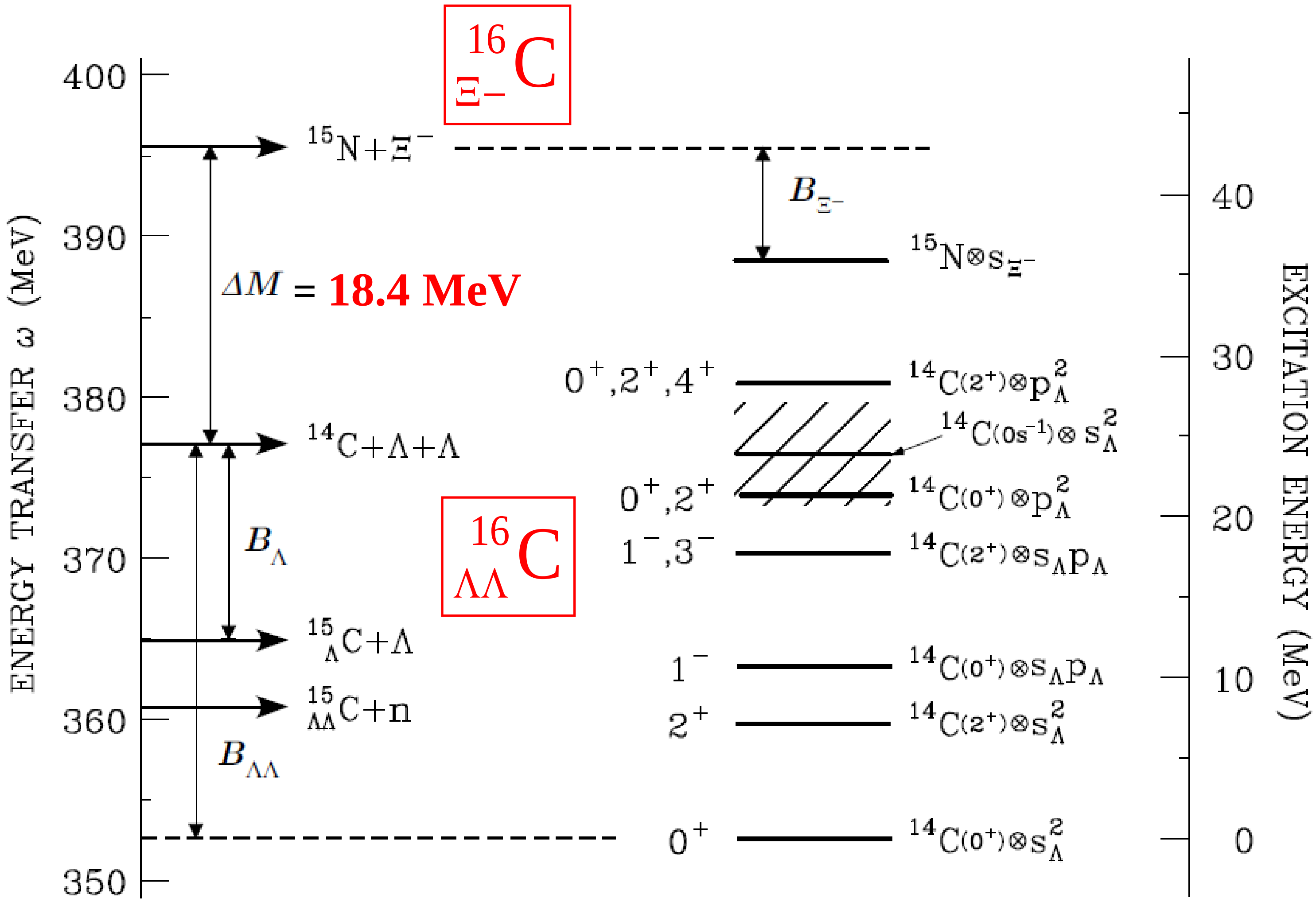
Ξ-ΛΛ coupled-channel calculations

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

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



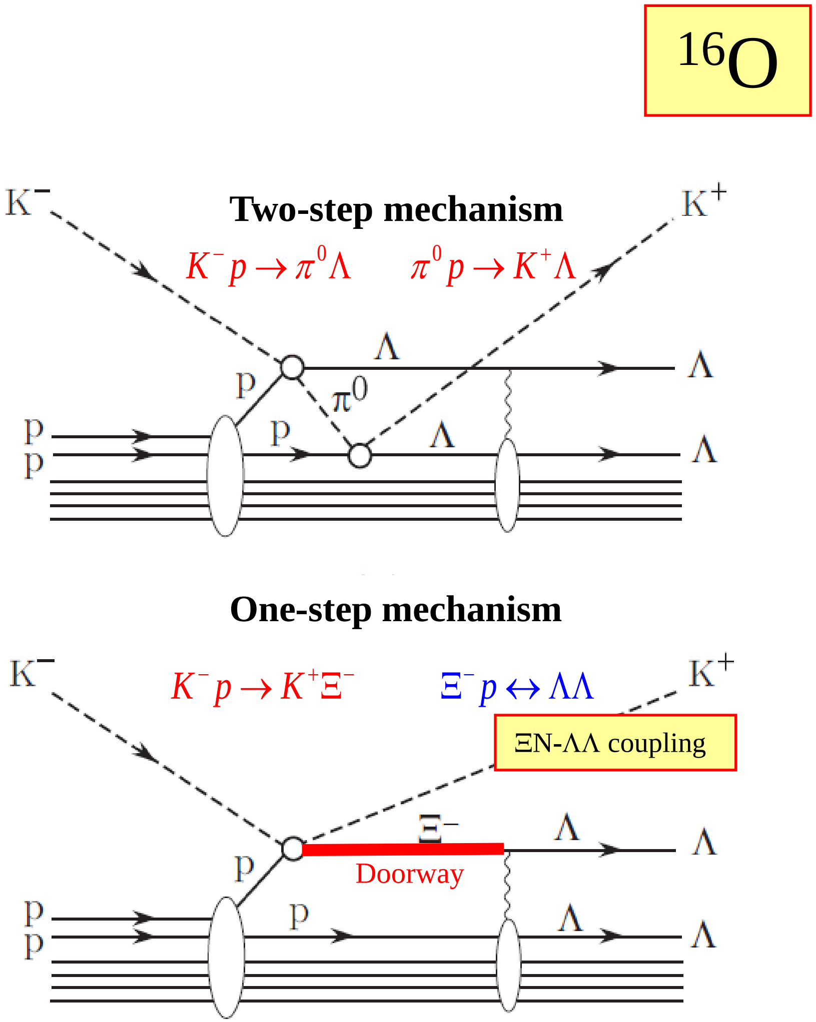
Energy spectrum of Ξ^- and ΛΛ nuclei on a ^{16}O target

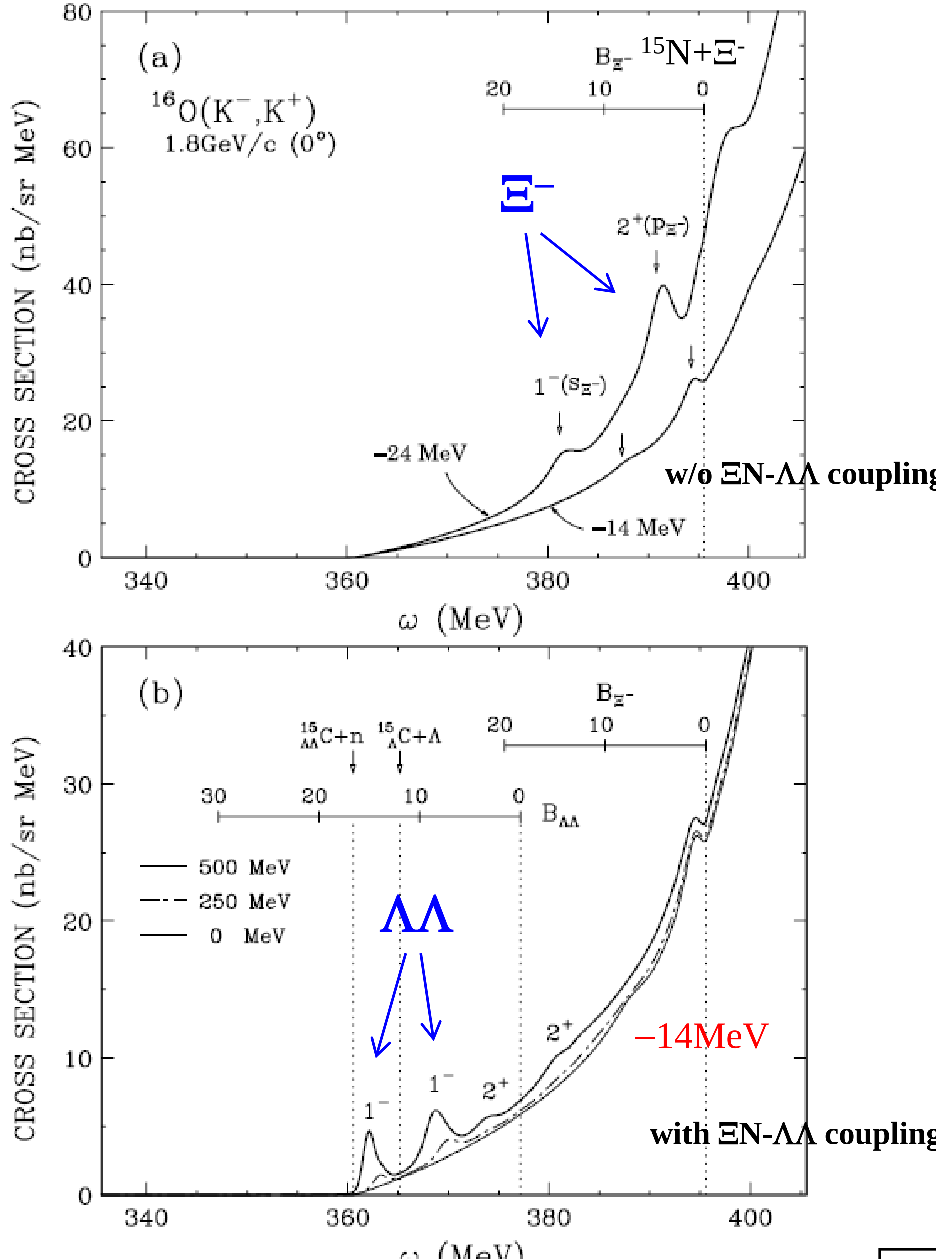


. *The energy shifts $\Delta B_{\Lambda\Lambda}$ are not taken into account.*

See also Dover, Gal and Millener, NPA572(1994) 85.

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





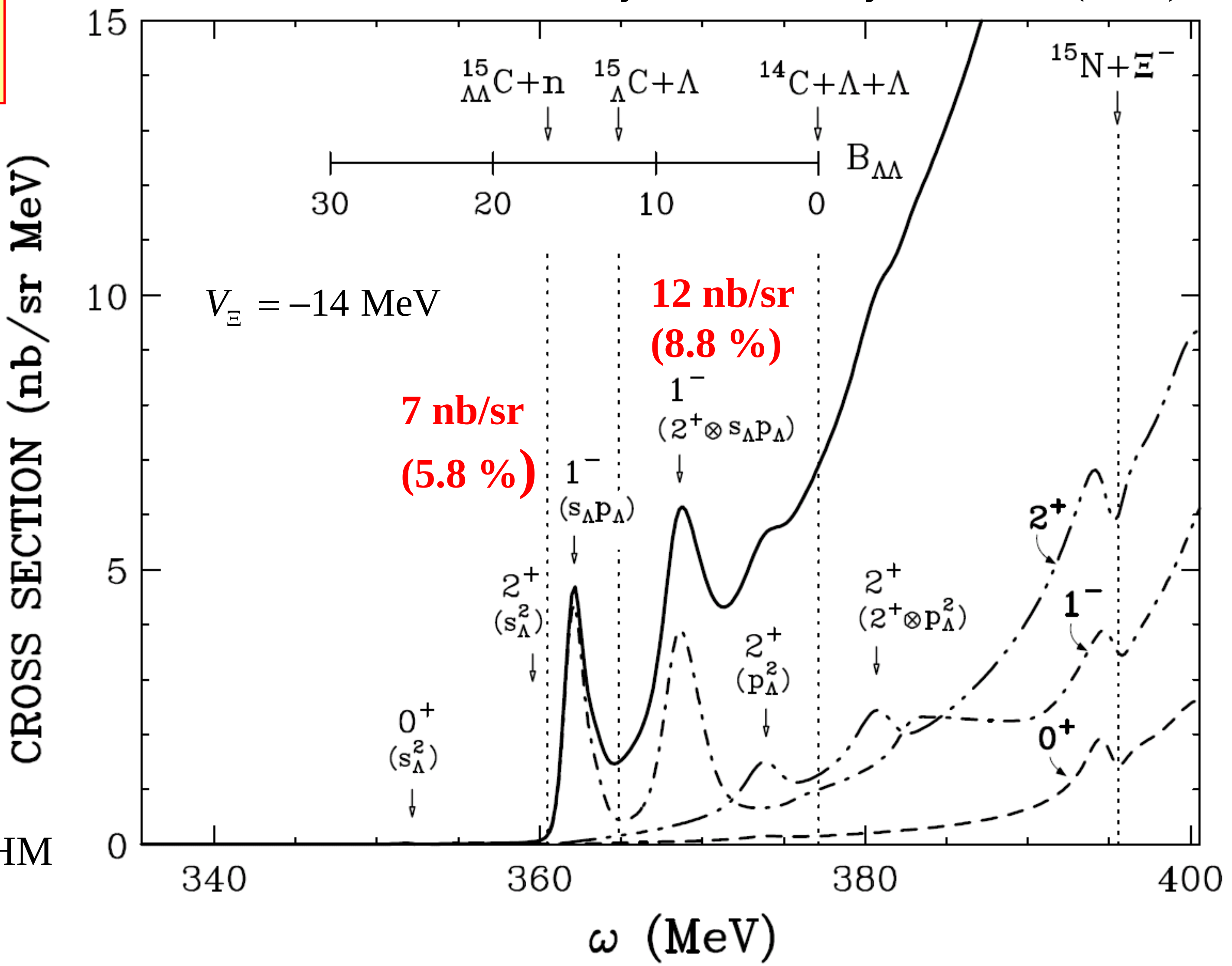
Hyperon-mixing

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

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

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

^{16}O

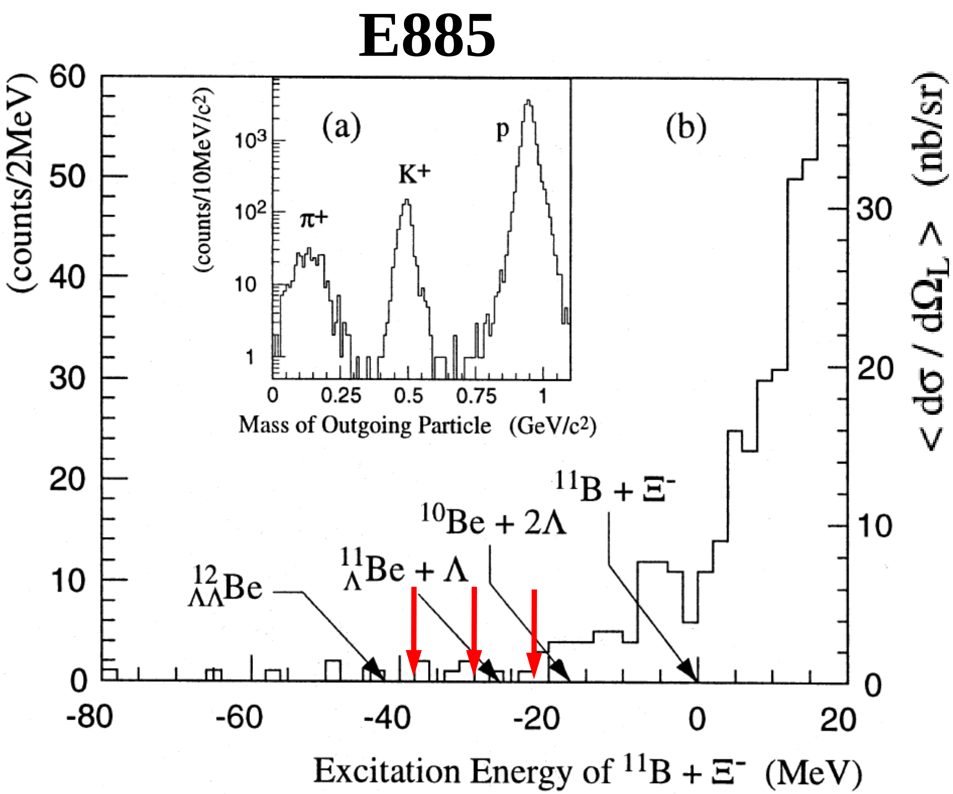


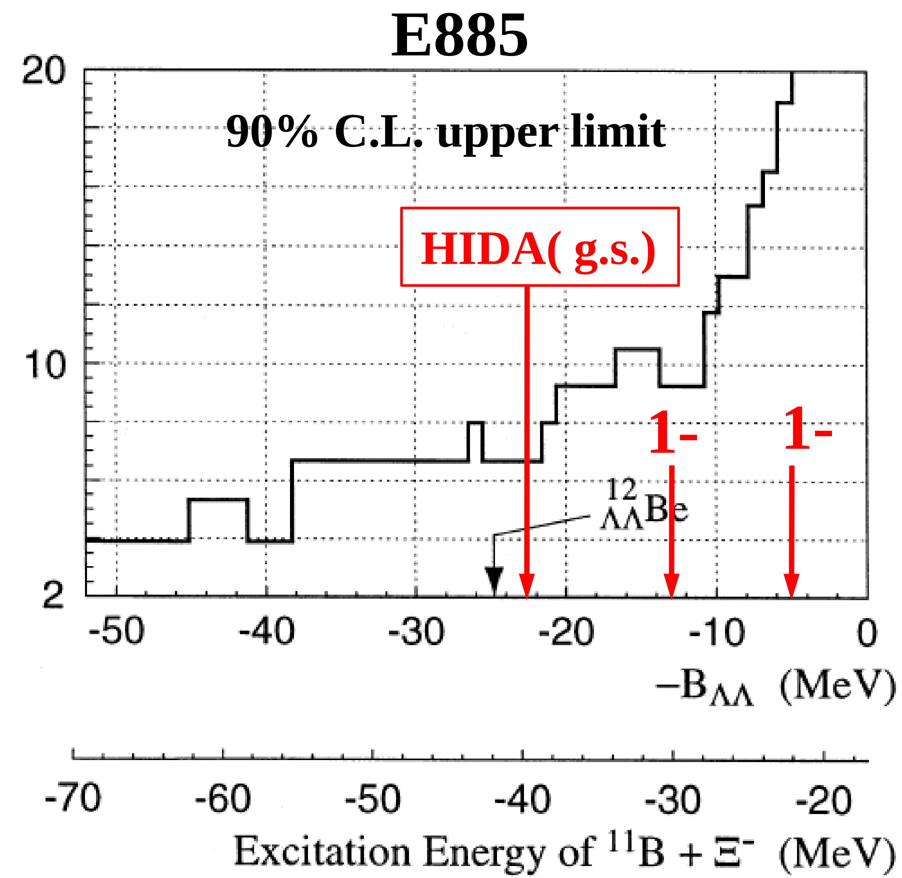
1.5MeV FWHM

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.

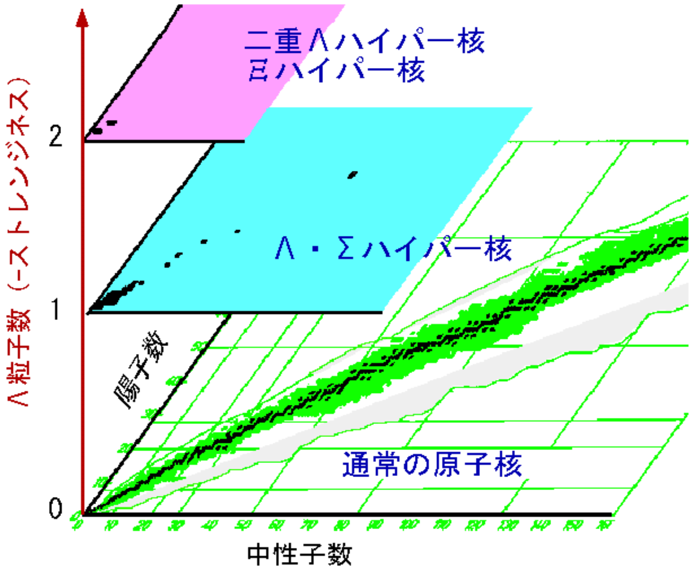




Harada, Hirabayashi, Umeyaの計算値と矛盾しない!!

Remark

Studies of the DCX reactions (π^+,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.

5. K^{bar}中間子原子核

K^{bar}中間子原子核

- Low-energy $K^{bar}N$ interaction and Konic hydrogen

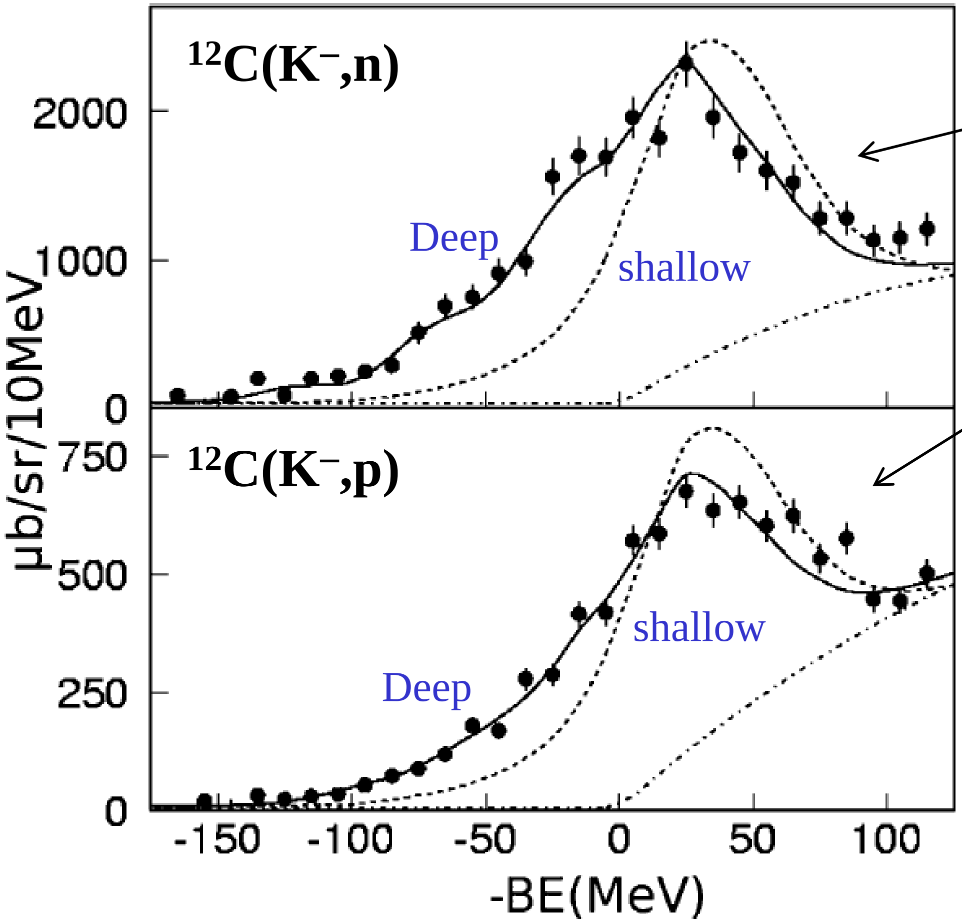
- K^{bar} nuclear potentials: deep or shallow ?
  - Kaonic atoms
  - (K^-,N) reaction on ^{12}C and ^{16}O

- Deeply-bound kaonic state, $K^- pp$
  - Theoretical calculations
  - Experimental candidates

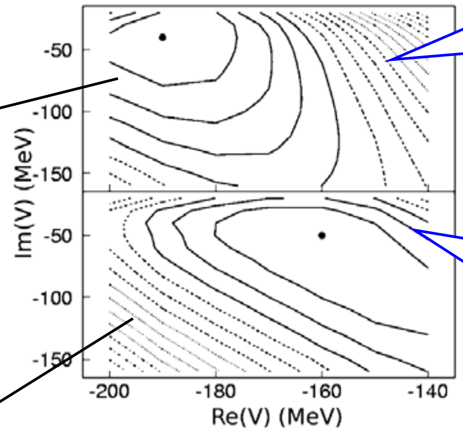
- $^3He(K^-,N)K^- pp$ reaction   E15@J-PARC
- $d(\pi+,K+)K^- pp$ reaction   E23@J-PARC

K^{bar}-Nucleus Interaction studied through in-flight (K-,N) reactions

missing mass spectroscopy



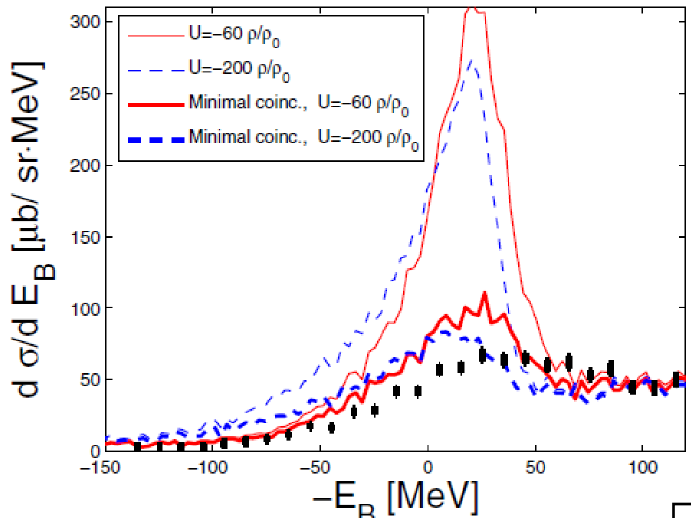
T. Kishimoto et al., PTP118(2007)181



$V_0 = -190$ MeV
$W_0 = -40$ MeV

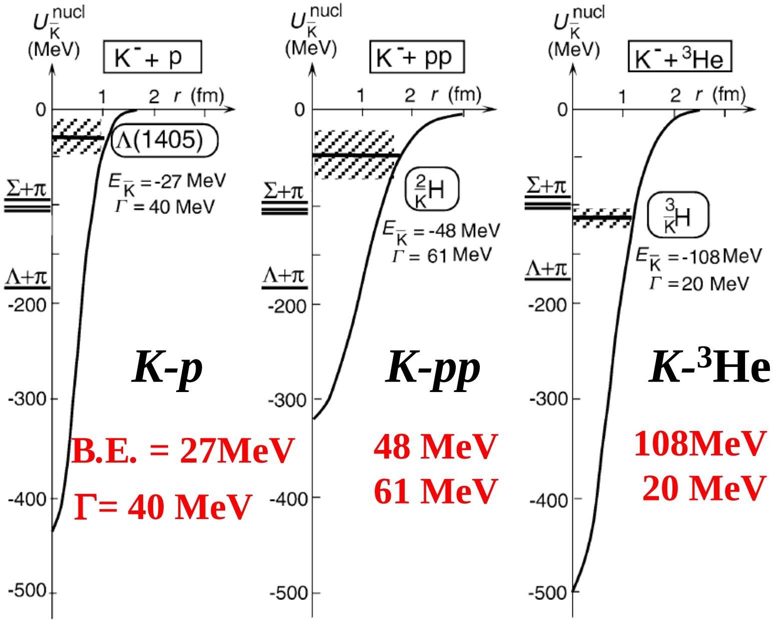
$V_0 = -160$ MeV
$W_0 = -50$ MeV

V. K. Magas et al, PRC81(2010)024609



Deep potentialの方が実験データとの一致がよい？

Theoretical prediction for deeply-bound antiKaonic nuclei



Few-body calculations predicted

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

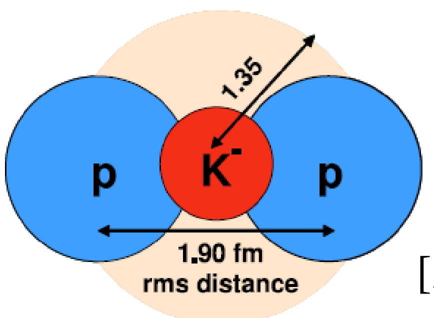
- *K-p* free scattering data
- (1s) level shifts in kaonic hydrogen atoms
- B.E. and Γ of Λ(1405)="*K*-+*p* quasibound state"

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

Strongly attractive

"Super strong nuclear force"

Yamazaki,Akaishi,PJAS. B82(2007)144



K-pp

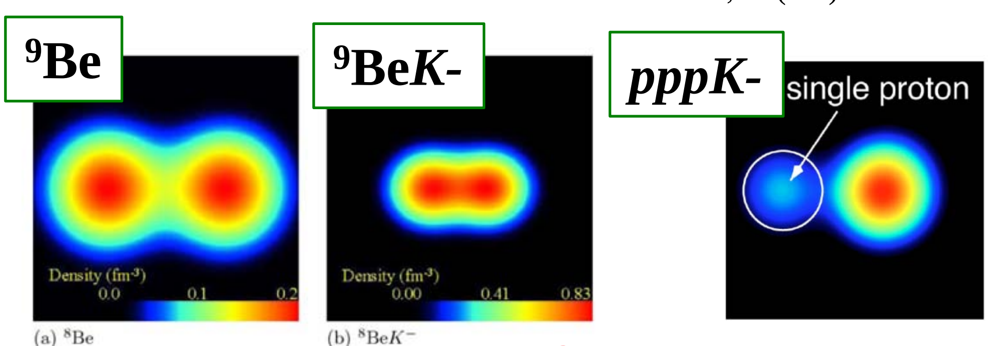
$[\bar{K}_{1/2}^{0^-} \otimes \{N,N\}_1^{0^+}]_{I=1/2}^{J=0^-}$

***Essential* antiKaonic nuclei**

Exotic states of antiKaonic nuclei by AMD

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

AMD+G-matrix NN,KN(AY)



ρ_{AV} = **0.33 fm⁻³** **0.66 fm⁻³**

高密度ハドロン物質

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

2011.6

FINUDA Collaboration@DAΦNE

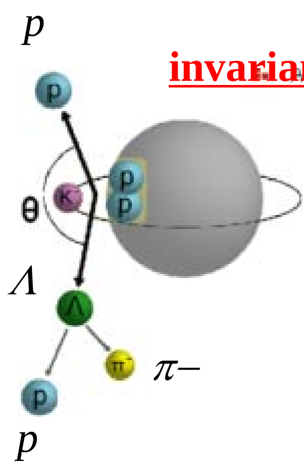
M. Agnello et al.,PRL94(2005)212303

B.E. = 115 ± 9MeV

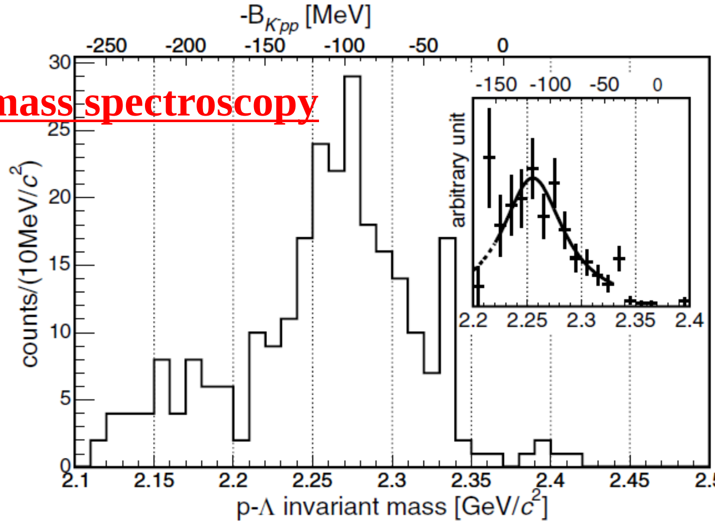
$\Gamma = 67^{+16}_{-14}$ MeV

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

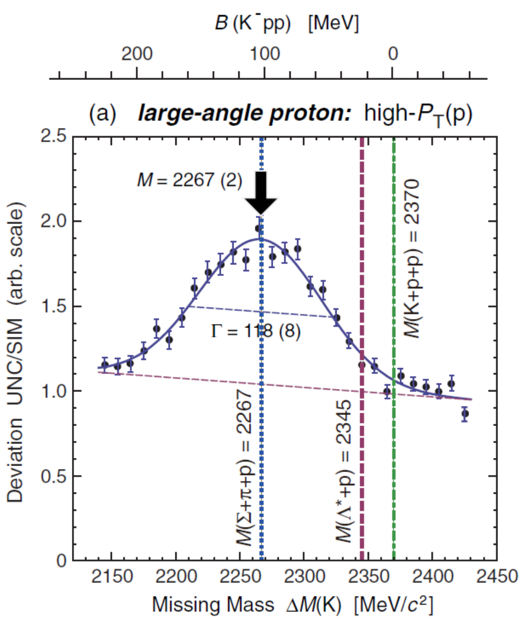
-- *Λp* invariant mass distrib.



invariant mass spectroscopy



DISTO Collaboration@SATURNE-Saclay



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

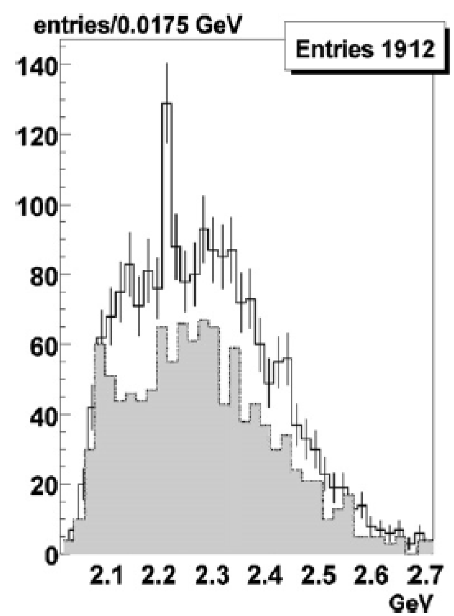
B.E. = 103±3±5 MeV

Γ=118±8±10MeV

-- *p*+*p*→*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

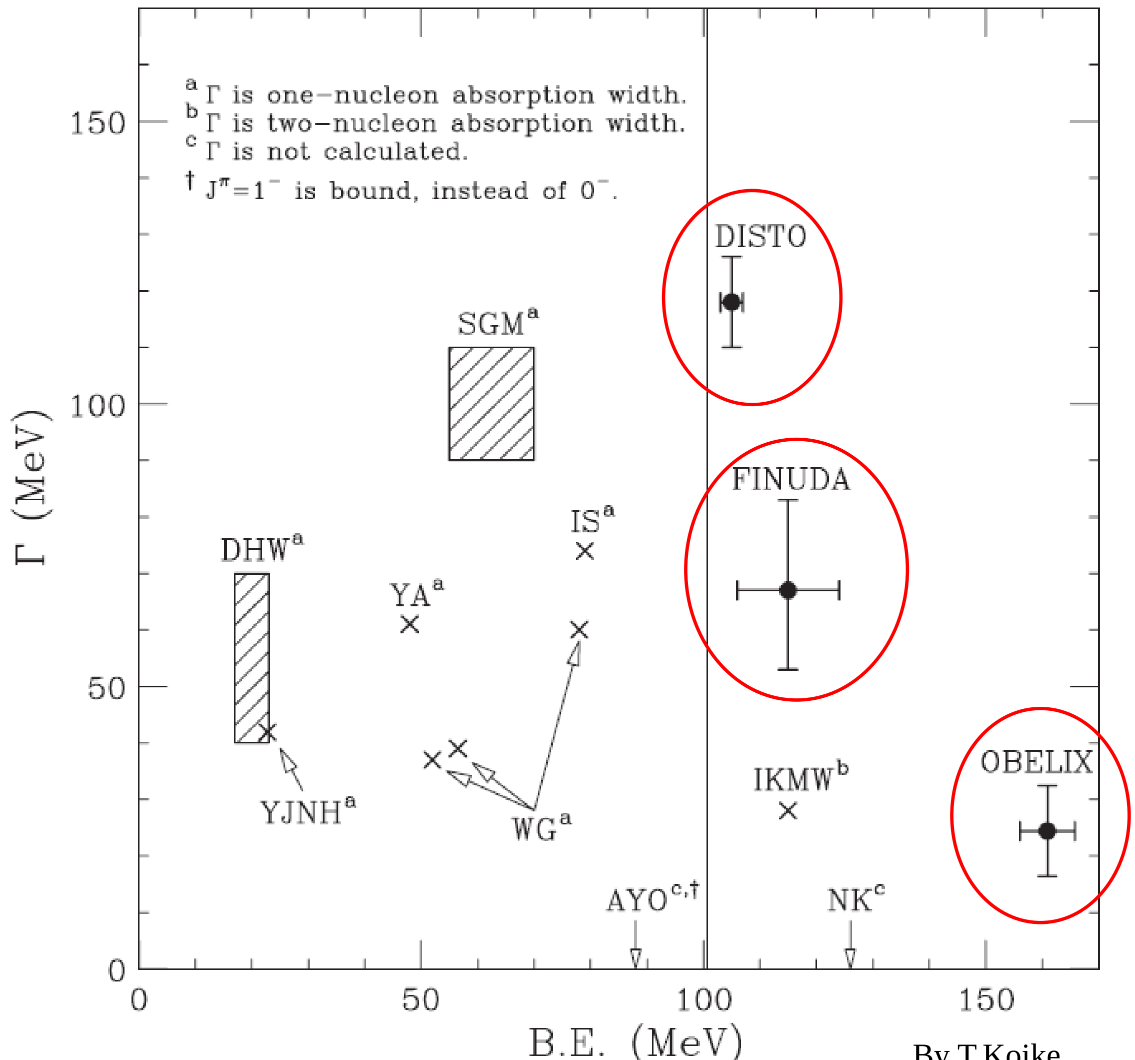
-- anti p+4He at rest

-- *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

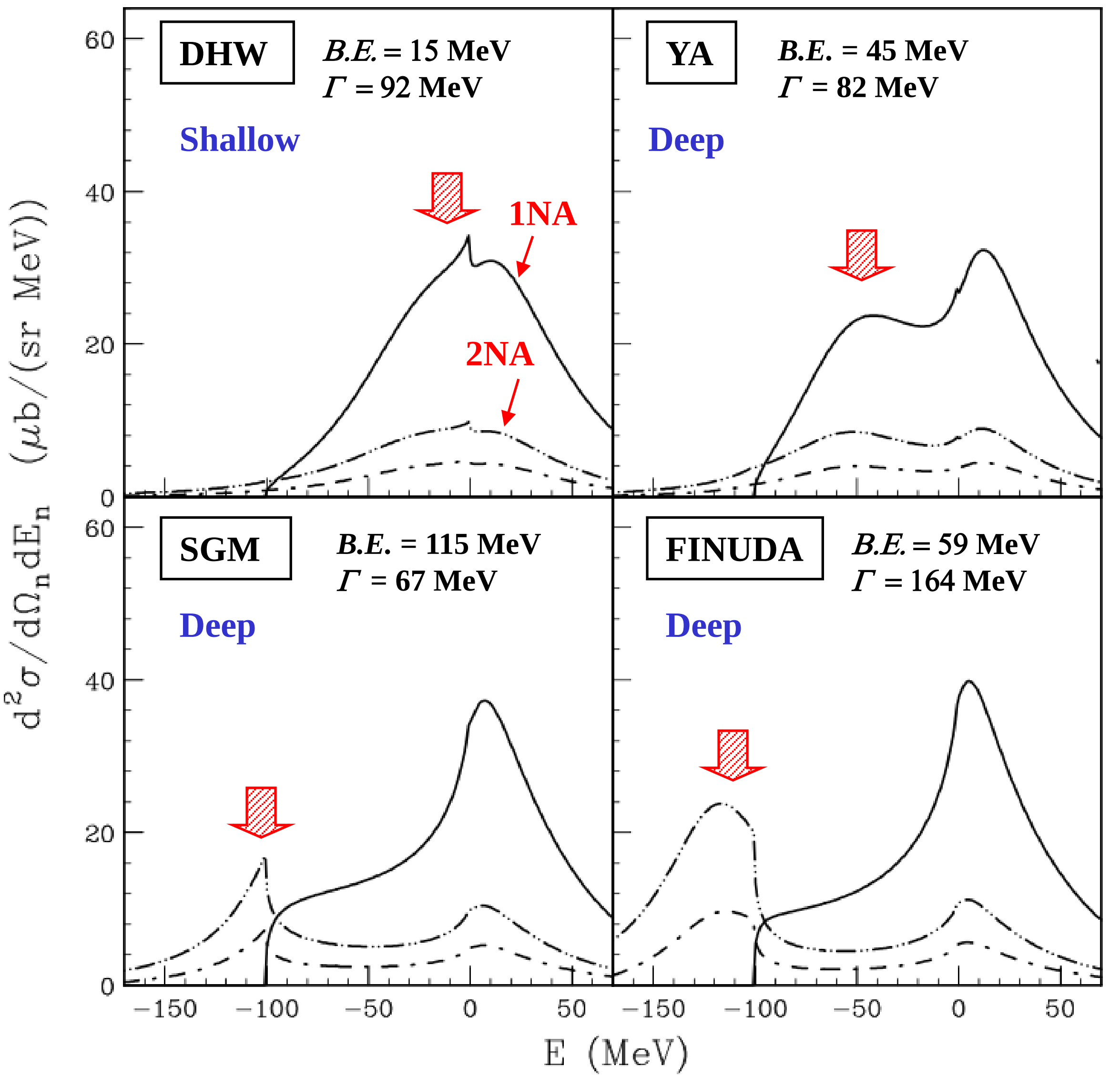
$$\frac{D_{\rm dist}[^3{\rm He}(1s_N \to 1s_K)]}{D_{\rm dist}[^{12}{\rm C}(1p_N \to 1s_K)]} = 0.47/0.095 \to 5倍$$

- 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.

- 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
- 高密度QCD物質の理解 → 中性子星の構造・進化の解明

Keyword

“Hyperon mixing”

Thank you very much.