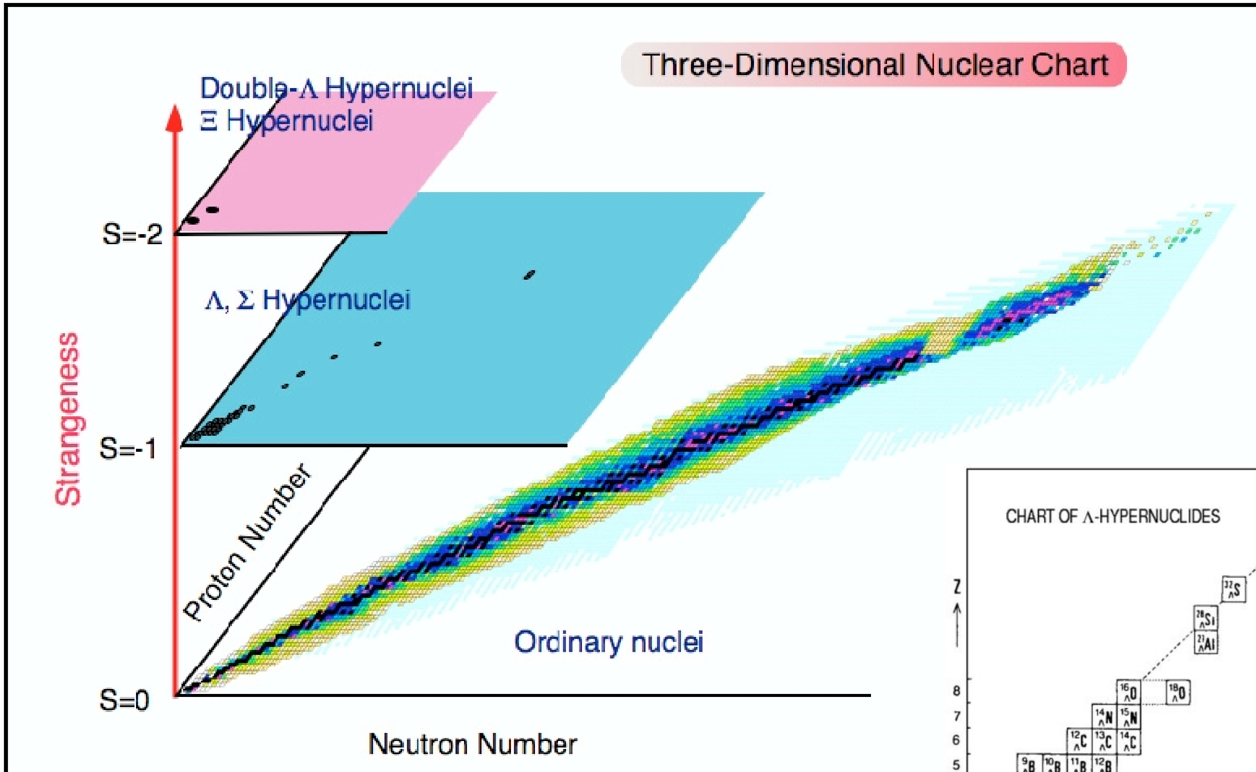
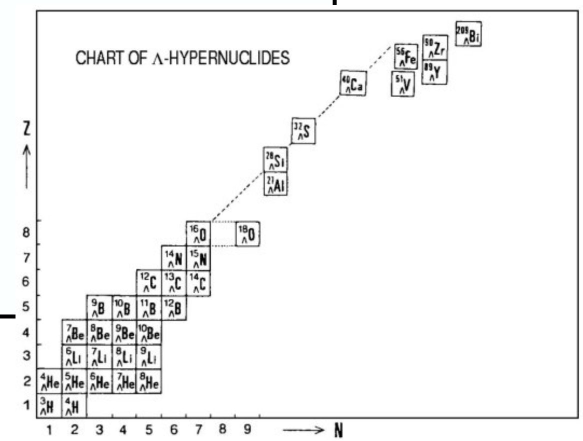
ハイパー核の生成･構造･崩壊

T. Yamada

構　　造：Λ核、Σ核、ΛΛ核、Ξ核、･･･
相互作用：OBEP,　QCM
反　　応：(K^-,π^-), (π^+,K^+), (K^-,K^+), ･･･
崩　　壊：week decay, ･･･





Hypernuclear chart

B_8-B_8 [YN, YY (NN)] int.の統一的理解（Strong+Weak）

ハイペロンを含む核物質の運動様式・存在様式 （生成・構造・崩壊）

: ΛN-ΣN 結合、ΛΛ-ΞN-ΣΣ-ΛΣ-H 結合

中性星におけるハイペロン混在

多重ストレンジネス核物質の可能性

ハイパー核研究の歴史

- **第Ⅰ期:1952ー70年代後半**

  Λ核の基底状態（Emulsionの実験）,($^{6}_{\Lambda\Lambda}$He, $^{10}_{\Lambda\Lambda}$Be)

  基本課題(Dalitz 1960): overbinding of U_Λ, s-shell Λ nuclei,
  weak deacy (mesonic, non-mesonic), CSB ($^{4}_{\Lambda}$H-$^{4}_{\Lambda}$He), ･･･

  1970年代: 殻模型($s^4p^{A-5}s_\Lambda$) Dalitz, Gal , 現実的YN力(Nijmegen)

- **第Ⅱ期:1980ー90年代中頃**

  Λ核の励起状態: (K^-,π^-), (Stopped K^-,π^-), (π^+,K^+)
  クラスター模型、G行列計算、DDHF、sd-fp-殻模型、ATMS、･･･

  $^{4}_{\Sigma}$Heの発見(1989)、E176-ΛΛ核実験(1991)

  中性子星におけるΛΛ超流動、QCMによるYN-YY力

- **第Ⅲ期:90年代後半ー現在**

  γ線分光学の始まり: ΛN spin依存力の議論

  精密計算: Faddeev-Yakubovsky, Gauss-Lobe法, 確率論的変分法, ･･･

  Nagara event ($^{6}_{\Lambda\Lambda}$He)の発見（2001）, 中性子過剰Λ核, ΛΣ coupling

  Non-mesonic weak decay Γ_n/Γ_p比, K^-nuclei

日本のハイパー核研究の始まり（理論）

1980代初頭：坂東グループの結成、坂東、池田、元場、山本、山田（M1)、糸永

Dalitz, Galらの殻模型の牙城に挑む

1985 INSシンポ（坂東）

- **微視的クラスター模型による構造研究**

（背景）日本のクラスター・グループの研究（池田、堀内、・・・）　Ikeda図

p殻核の前半：平均場形成が充分でない

⇒ 基底＋励起状態：微視的クラスター模型「α+x」

構造・散乱・崩壊幅・電磁遷移確率・・・

⇒　ハイパー核へ：坂東・池田・元場の着目点　**α+x+Λ模型**（1982）

- **YN＆YY有効相互作用**

（背景）　永田, 坂東, ・・・ ⇔ Bethe School (1960-70)

Hole-Line expansion in N.M. ⇒ saturation (tensor力、odd-state力、斥力芯）

G行列の核構造への応用、G+ΔG、・・・、成功

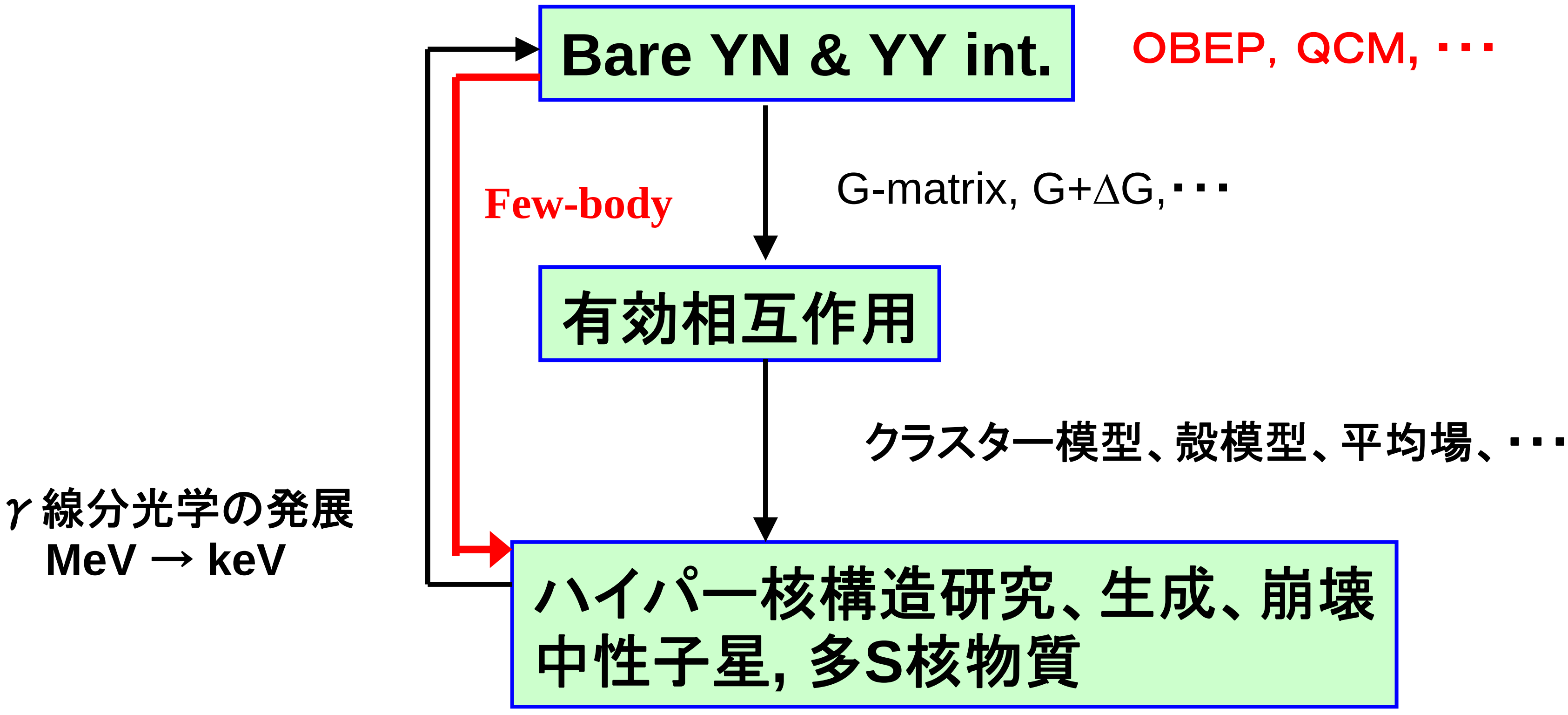
研究の蓄積 ⇒ ハイパー核にG行列理論を応用　（坂東・永田・山本のアイデア）

Nijmegen group (deSwart, Rijken,・・・）

model-D,F ⇒ 有効相互作用　**YNG int.** (1982)

YN&YY力とハイパー核構造

基本的戦略(Bando)：1980－



ハイパー核についての理解が深化・拡大

YN & YY 相互作用

YN & YY 相互作用

- **Boson-exchange model**

  Nijmegen group (1975～): Rijken, de Swart, ･･･

  : NHD(1975-77), NHF(1979), NSC89, NSC97, ESC04

  Jülich pot. (1989)

  Ehime pot. (1999) : 上田, 富永, (山田), (山本), ･･･

  Funabashi-Gifu pot. (2000) : 和田, 有坂, 中川, 新村

- **Quark-cluster model**

  Tokyo, Tübingen, Beijing

  Kyoto-Niigata (1992～) : 藤原･鈴木･仲本,･･･

  : RGM-F, FSS, RGM-H, fss2

SU(3)-invariant YN&YY interaction

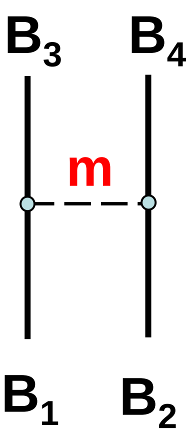
$J^\pi=1/2^+$ Baryon Octet: *B*

$$B=\begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}}+\frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}}+\frac{\Lambda}{\sqrt{6}} & n \\ -\Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}$$

$J^\pi=0^-$ Meson nonet: $P=P_{sin}+P_{oct}$

$$P_{\sin}=\eta_0,\qquad P_{oct}=\begin{pmatrix} \frac{\pi^0}{\sqrt{2}}+\frac{\eta_8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}}+\frac{\eta_8}{\sqrt{6}} & K^0 \\ K^- & \overline{K^0} & -\frac{2\eta_8}{\sqrt{6}} \end{pmatrix}$$

Meson-Baryon coupling constant: SU(3)-invariant Lagrangian:



$$\mathcal{L}=-\sqrt{2}g_8\left\{\alpha Tr\left(\overline{B}P_{oct}B-\overline{B}BP_{oct}\right)+(1-\alpha)Tr\left(\overline{B}P_{oct}B+\overline{B}BP_{oct}\right)\right\} - g_1 Tr\left(\overline{B}B\right)P_1$$

$$g_{NN\pi}=g_8\qquad g_{\Lambda\Sigma\pi}=\frac{2(1-\alpha)}{\sqrt{3}}g_8\qquad g_{NN\eta}=-g_1\sin\theta+\frac{4\alpha-1}{\sqrt{3}}g_8\cos\theta$$

$$g_{\Lambda\Lambda\eta}=-g_1\sin\theta-\frac{2-2\alpha}{\sqrt{3}}g_8\cos\theta$$

Parameters (g_1,g_8,α,θ,･･･): (rich) NN and (scare) YN scattering data

4,000個 40個

Rijken, de Swart, ･･･

Nijmegen potential (1975～)

- **Hard-core model (1975-77,79)**

  model D (ND): S (only singlet)+P+V

  model F (NF): S (nonet)+P+V

ΛN *G*-matrix cal. in NM

Rozynek & Dabrowski (1979), Bando & Nagata (1982)

hard core, Majorana exchange, tensor-force, ΛN-ΣN coupling

⇒ U_Λ (= -30 MeV) 問題の解決へ

有効ΛN相互作用： YNG相互作用、構造計算（クラスター、殻模型）

ハイパー核構造計算での問題点（Bando)

- **Soft-core model, NSC89**

  Nontes of S, P and V, Soft-core: pomeron exchange (2 gluons)

  ΛN spin-spin int, Strong ΛN-ΣN coupling, $^{4}_{\Sigma}$Heのデータと矛盾, ･･･

NSC97 model (1997)

- $\Lambda N\ ^1S_0$-$^3S_1$ phase shifts ： NSC97a-f

  magnetic F/(F+D) ratio α_V^m as a free input ↔ G-matrix cal

- $SU_f(3)$ の破れの導入

  physical mass for *B* and *M*

  meson-mixing within a nonet (η-η’, ω-ϕ, ε-f_0)

  CSB: Λ-Σ^0 mixing ($\Sigma^0 \rightarrow \Lambda + \pi^0$), $g_{\Lambda\Lambda\pi} = -0.0283 g_{\Lambda\Sigma\pi}$

  Coulomb int. (charge-based multi-channel Schrödinger eqs.)

- ハイパー核の構造計算: NSC97e,f

  $^3_\Lambda$H, $^4_\Lambda$H-$^4_\Lambda$He, $^5_\Lambda$He: OK, (but No CSB)

  （問題点）ΛN odd-state int. : 斥力が強すぎる, U_Σ: 引力

  Unrealistic deeply bound statesの存在, Yamada, PRC69 (2004)

Rijken, Stoks, Yamamoto

Partial wave contribution to U_Λ in NM

U_Λ

Model	$^1S_0$	$^3S_1$	$^1P_1$	$^3P_0$	$^3P_1$	$^3P_2$	Sum
(a)	–3.8	–30.7	1.5	–0.2	1.6	–2.2	–33.9
(b)	–5.5	–30.0	1.6	–0.1	1.9	–2.1	–34.1
(c)	–7.8	–29.7	1.7	0.2	2.2	–1.9	–35.3
(d)	–11.0	–27.7	1.9	0.4	2.7	–1.5	–35.1
(e)	–12.8	–26.0	2.1	0.5	3.2	–1.2	–34.3
(f)	–14.4	–22.9	2.4	0.5	4.0	–0.7	–31.1

Partial wave contribution to U_Σ in NM

U_Σ

	Isospin $T=\frac{1}{2}$			Isospin $T=\frac{3}{2}$				
Model	$^1S_0$	$^3S_1$	P	$^1S_0$	$^3S_1$	P	Sum	Γ_Σ
NSC97e	5.2	–7.5	0.0	–6.1	–2.5	–0.9	–11.8	14.6
NSC97f	5.2	–7.6	0.0	–6.2	–2.2	–0.9	–11.6	15.5
NSC89	3.0	–4.2	–0.3	–5.8	3.7	0.1	–3.6	25.0
NHC-F	4.2	–10.9	–1.5	–5.3	18.6	–1.7	3.5	16.3
NHC-D	2.1	–9.6	–2.2	–5.4	9.4	–3.0	–8.7	8.7

Extended Soft-Core Model (ESC04)

- OBE (P,V,S,A)+Meson-pair exchange
- nonlocal

Rijken, Yamamoto

PRC 73, 044008 (2006)

Kyoto-Niigata QCM potentials

- Short-range repulsion and *LS* by quarks
- Medium-attraction and long-rang tensor by S, PS and V meson exchange potentials (fss2)

(*Cf*. FSS, RGM-F, RGM-H without V) Fujiwara, Nakamoto,・・・

Antisymmetrized (RGM) wave function

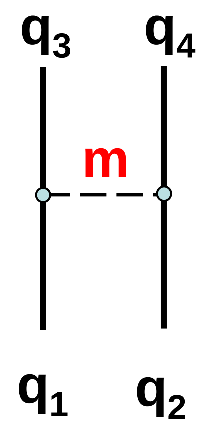
$$\Psi = \mathcal{A}\left\{\phi(3q)\phi(3q)\chi(R)\right\}$$

$\phi(3q)$: **$(0s)^3$ × spin × flavor**

Model Hamiltonian

$$H = \sum_{i=1}^{6}\left(m_i + p_i^{\,2}/m_i\right) + \sum_{i<j}^{6}\left(U_{ij}^{Cf} + U_{ij}^{FB} + U_{ij}^{S} + U_{ij}^{PS} + U_{ij}^{V}\right)$$

$$\left\langle \phi(3q)\phi(3q) \middle| E - H \middle| \mathcal{A}\left\{\phi(3q)\phi(3q)\chi(R)\right\}\right\rangle = 0$$



BB int. $V_{BB}(\varepsilon) = V_D + G + \varepsilon K$; nonlocal, energy-dependent

QCM pot. to Nuclei and Hypernuclei

BB int. $V_{BB}(\varepsilon)=V_D+G+\varepsilon K$; nonlocal, energy-dep.

$\Rightarrow$ nuclei, hypernulcei with Faddeev eq.

Fujiwara, Suzuki, **Nakamoto**, Miyakawa, Kohno

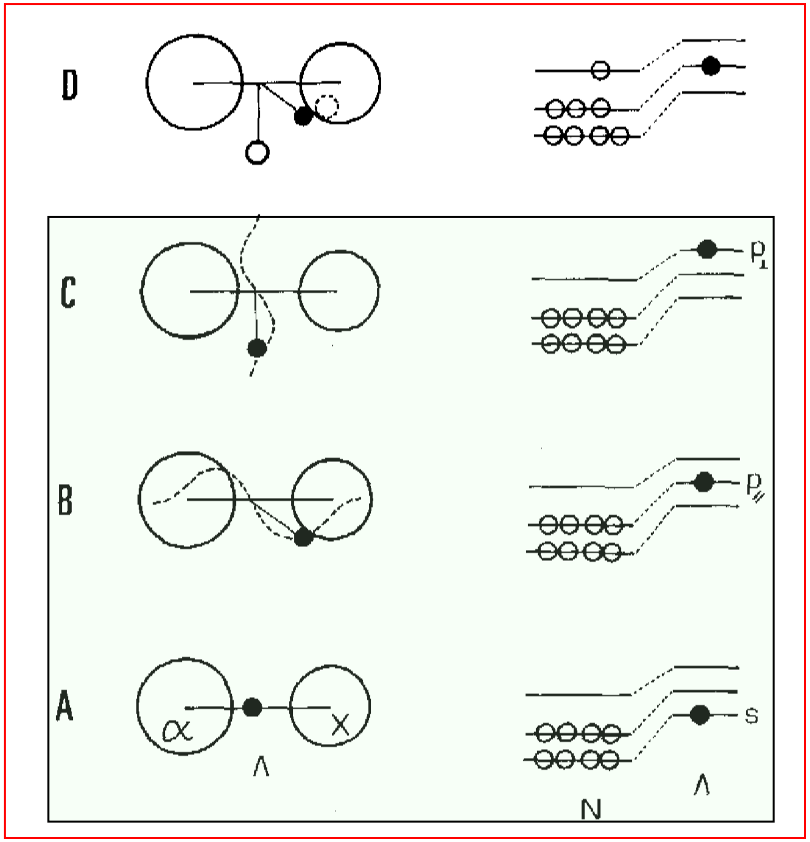
- E/A, U_Λ in nuclear matter (*G*-matrix cal.)
- ^{3}H=N+N+N
- $^3_\Lambda$H=[N+N+Λ]+[N+N+Σ]
- $^9_\Lambda$Be=α+α+Λ

  effective ΛN int. from fss2 $^1S_0$, $^3S_1$ phase shifts; α-Λ folding potential
  5/2+ 3/2+ splittings (LS vs. ALS)
- $^6_{\Lambda\Lambda}$He=α+Λ+Λ

微視的クラスター模型による
Λ核の構造研究

$^{9}_{\Lambda}$Be核の構造研究

p-shell Λ核の典型例



微視的 α+α+Λ 模型

Motoba, Bando, Ikeda PTP70 (1983)

微視的 [α+α+Λ]+[α+α*+Λ] 模型

Yamada, Ikeda, Motoba, Bando, PRC38 (1988)

Λ粒子の役割

- **Pauli-free**

  Genuinely hypernuclear states 出現

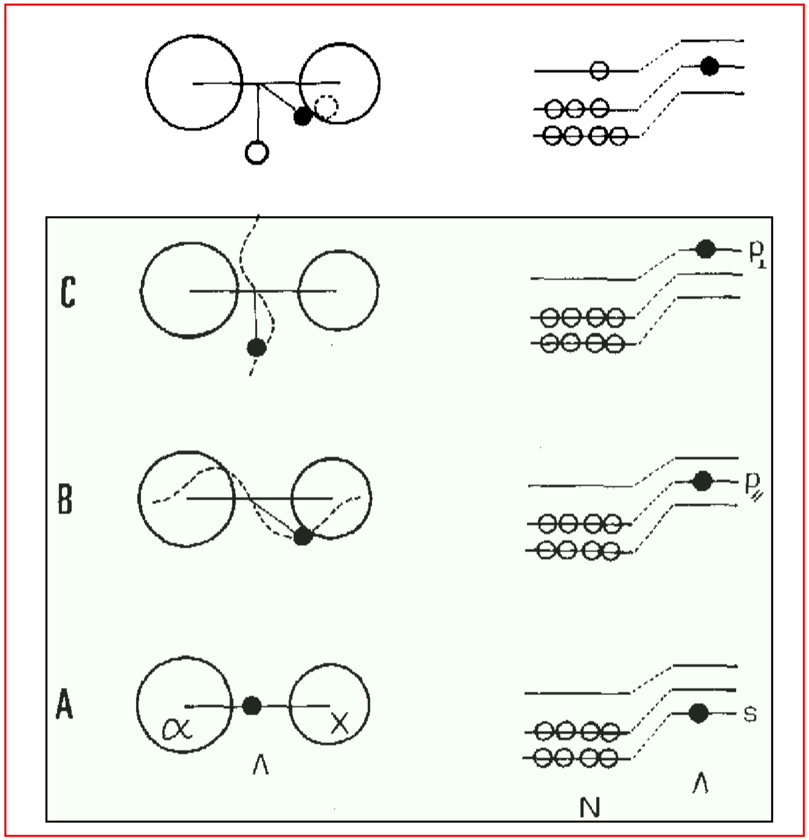
- **エネルギー的に安定化**
- **構造変化: glue-like role**

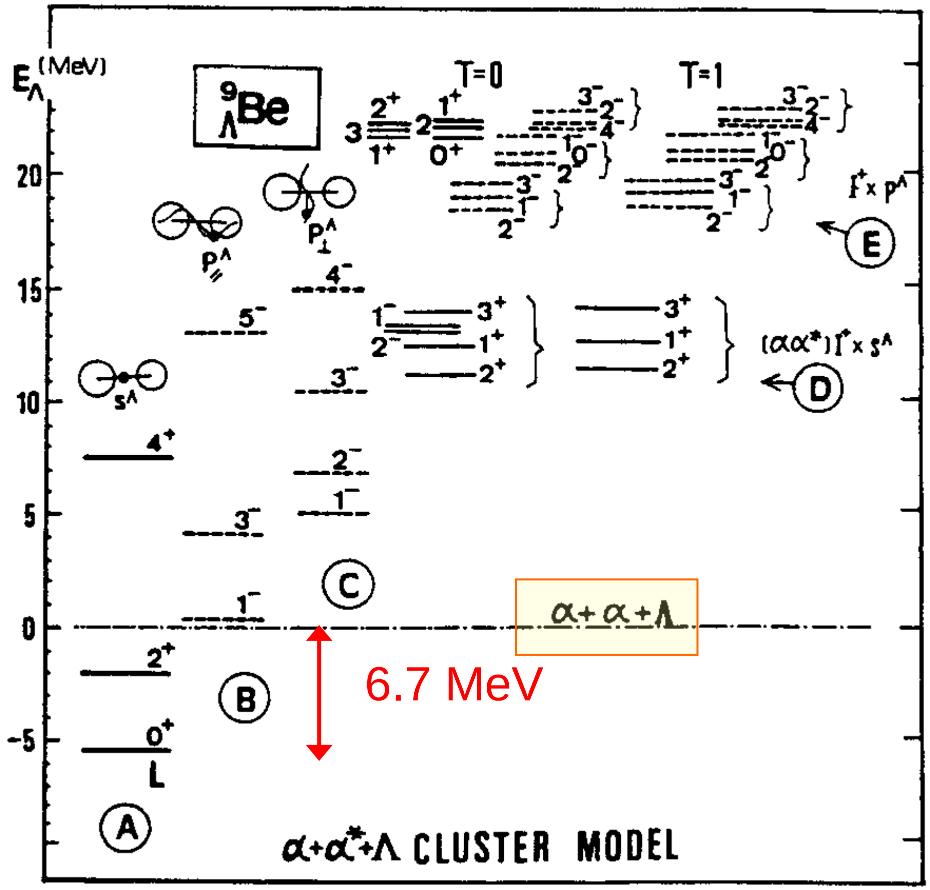
  shrinkage of α-x distance

  reduction of *B*(E2)

$^{9}_{\Lambda}$Be核の構造研究

p-shell Λ核の典型例

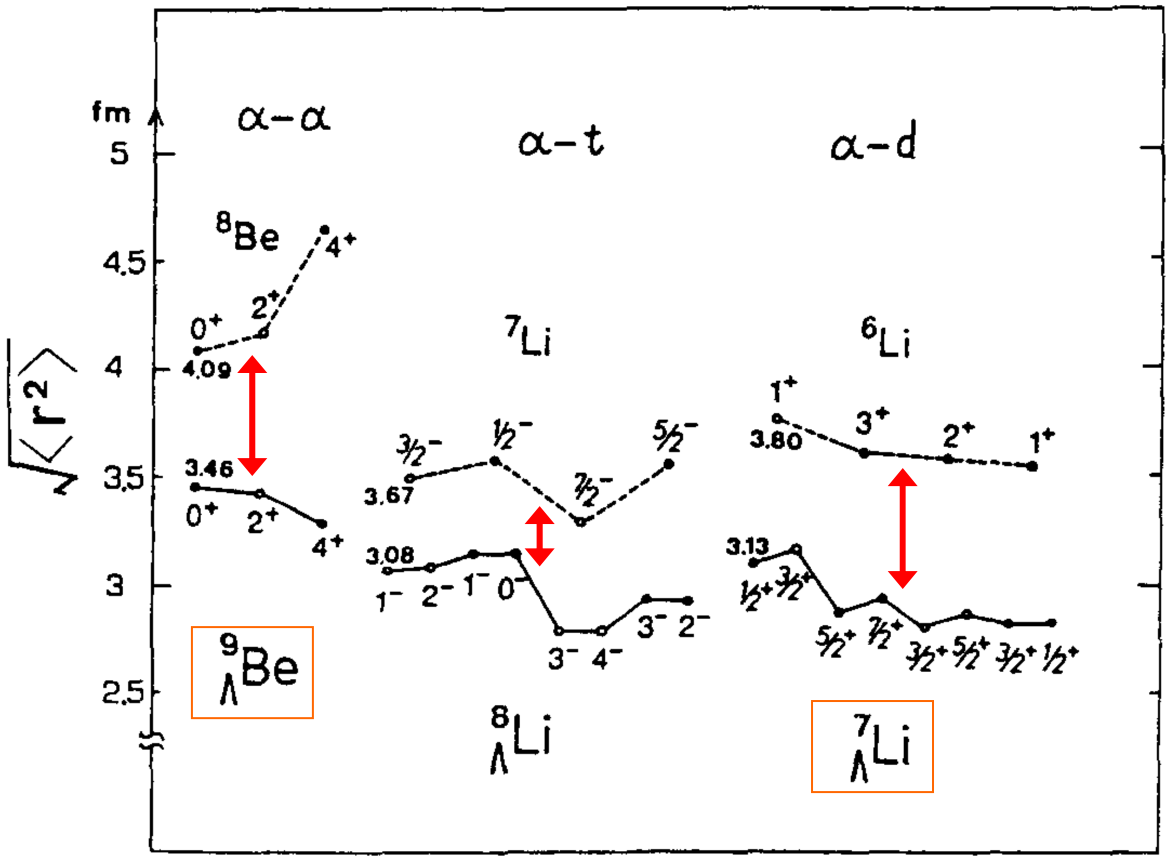




Yamada, Ikeda, Motoba, Bando, PRC38 (1988)

$^{9}_{\Lambda}$Be核の構造研究

Reduction of α-x distance



B(E2)の変化

^{8}Be : $2^{+} \rightarrow 0^{+}$
22.4 $e^{2}fm^{4}$

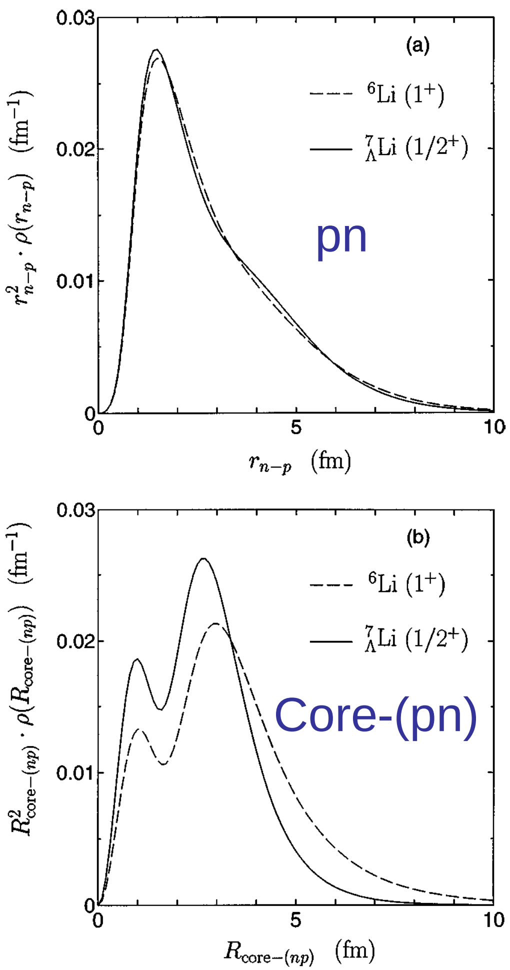
↓

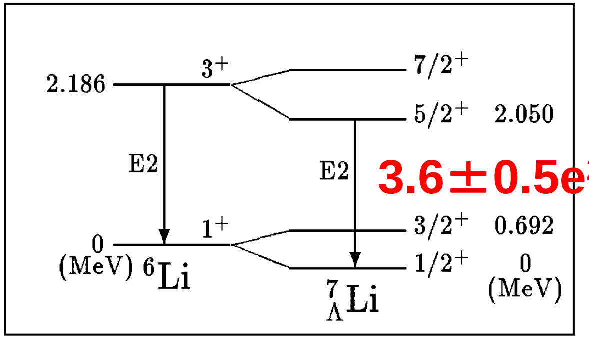
$^{9}_{\Lambda}$Be : $2^{+} \rightarrow 0^{+}$
11.3 $e^{2}fm^{4}$

Motoba, Bando, Ikeda PTP70 (1983)

Possible derivation of hypernuclear size from B(E2) of $^{7}_{\Lambda}$Li

$^{7}_{\Lambda}$Li=$^{5}_{\Lambda}$He+p+n model





KEK-E417

3.6±0.5e²fm⁴

(10.9±0.9 or 9.3±0.9 e²fm⁴)

$$S_{\alpha-d} = \left[\frac{B(E2;\, ^{7}_{\Lambda}\text{Li}, 5/2^{+} \rightarrow 1/2^{+})}{\frac{7}{9} B(E2;\, ^{6}\text{Li}, 3^{+} \rightarrow 1^{+})} \right]^{1/4} \approx \frac{R_{c-d}(^{7}_{\Lambda}\text{Li})}{R_{\alpha-d}(^{6}\text{Li})}$$

S^{exp}=0.81±0.04 or 0.84±0.06

vs. S^{cal}=0.74 Shrinkage !!

Hiyama, Kamimura, Miyazaki, Motoba, PRC59 (1999)
Tanida et al., PRL86 (2001)

ΛN相互作用のspin依存項

LS力の情報をΛ核から導き出す試み

Spin-orbit splitting in ${}^{9}_{\Lambda}$Be and ${}^{13}_{\Lambda}$C

OBE models, Quark-cluster models

2種類のΛN スピン軌道力: **SLS** vs. **ALS**

SLS (symmetric LS): $\upsilon_{SLS}^{\Lambda N} \propto \vec{\ell}_{N\Lambda} \cdot (\vec{s}_N + \vec{s}_\Lambda)$

ALS (anti-symmetric LS): $\upsilon_{ALS}^{\Lambda N} \propto \vec{\ell}_{N\Lambda} \cdot (\vec{s}_N - \vec{s}_\Lambda)$

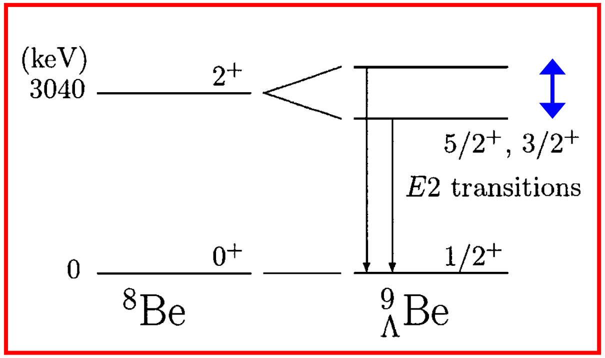
SLS(OBE) ≈ SLS(QC)

ALS(OBE) « ALS(QC) ≈ -SLS(QC)

⇒ OBE: $\upsilon_{LS}^{\Lambda N} = \upsilon_{SLS} + \upsilon_{ALS} \approx 2/3 \times \upsilon_{LS}^{NN}$ **Rijken, Stoks**

QC: $\upsilon_{LS}^{\Lambda N} = \upsilon_{SLS}^{\Lambda N} + \upsilon_{ALS}^{\Lambda N} \approx 0$ **Morimatsu, Yazaki, Shimizu**
Fujiwara, Suzuki, Nakamoto

Spin-orbit splitting in $^{9}_{\Lambda}$Be and $^{13}_{\Lambda}$C



α+α+Λ model

BNL-E930 **Akikawa et al., PRL88 (2002)**

$$\Delta E(5/2^{+} - 3/2^{+}) = 31.4^{+2.5}_{-3.6}\ \text{keV}$$

OBEP: ΔE=80~200 keV
QCM : ΔE=198 keV (fss2), 137 (FSS)

p-wave ΛN-ΣN(QCM) → 1/3-1/5 reduction ?

今後の課題

1) OBEP → YNG int. with SLS+ALS
→ α-Λ folding pot. → α+α+Λ problem

Hiyama, Kamimura, Motoba, Yamada, Yamamoto., PRL85 (2000)

2) QCM: Born kernel of LN LS QM int. (FSS,fss2)
→ α-Λ folding pot. → α+α+Λ problem

Fujiwara, Kohno, Miyagawa, Suzuki, PRC70 (2004)

Spin-orbit splitting in $^{9}_{\Lambda}$Be and $^{13}_{\Lambda}$C

$^{13}_{\Lambda}$C

BNL-E927

$$\Delta E(3/2^- - 1/2^-) = 152 \pm 54 \pm 36 \text{ keV}$$

S.Ajimura et al. Phys. Rev. Lett. 86,(2001) 4255

3α+Λ 模型計算(OBEP)

$$\Delta E(3/2^- - 1/2^-) = 360 - 960 \text{ keV} = \left(2-6\right) \times \Delta E(\text{Exp})$$

Hiyama et al., PRL85 (2000)

⇒ $^{9}_{\Lambda}$Be, $^{13}_{\Lambda}$C 共に ΔE(理論値)/ΔE(実験値)＝２－６

未解決の問題 !!

核内テンソル相関

ΛΣ coupling, ・・・

p殻Λ核の殻模型研究

Tamura

Millener (Dalitz, Dover, Gal: 1971～)

模型空間: $(0s)^4(0p)^{A-5}(0s)_\Lambda$

ΛN int. : $V_{\Lambda N}^{eff} = V_0(r) + V_\sigma(r)\mathbf{s}_\Lambda \cdot \mathbf{s}_N + V_\Lambda(r)\mathbf{l}_{\Lambda N} \cdot \mathbf{s}_\Lambda + V_N(r)\mathbf{l}_{\Lambda N} \cdot \mathbf{s}_N + V_T(r)\hat{S}_{12}$

Integral　Δ　S_Λ　S_N　T

Δ, S_N, S_Λ, T determined by γ-ray spectroscopic Exp. (Tamura et al.)

: $^{7}_{\Lambda}$Li, $^{9}_{\Lambda}$Be, $^{10}_{\Lambda}$B , $^{11}_{\Lambda}$B, $^{13}_{\Lambda}$C, $^{15}_{\Lambda}$N, $^{16}_{\Lambda}$O　keV

Results

1) **Cross check successful for several levels: $^{7}_{\Lambda}$Li, $^{13}_{\Lambda}$C, $^{15}_{\Lambda}$N**

2) **Inconsistent data also exist: $^{10}_{\Lambda}$B, $^{11}_{\Lambda}$B（未解決）**

模型空間の拡張、ΛΣ coupling、･･･

Neutron rich Λ nuclei

n-rich ハイパー核の興味

- 不安定核＋Λ粒子 (glue)

  ⇒ 安定ハイパー核

  新しいハイパー核構造

  ドリップ·ライン の拡大？

- ラムダ·シグマ結合効果

  Coherent ΛΣ coupling（赤石）

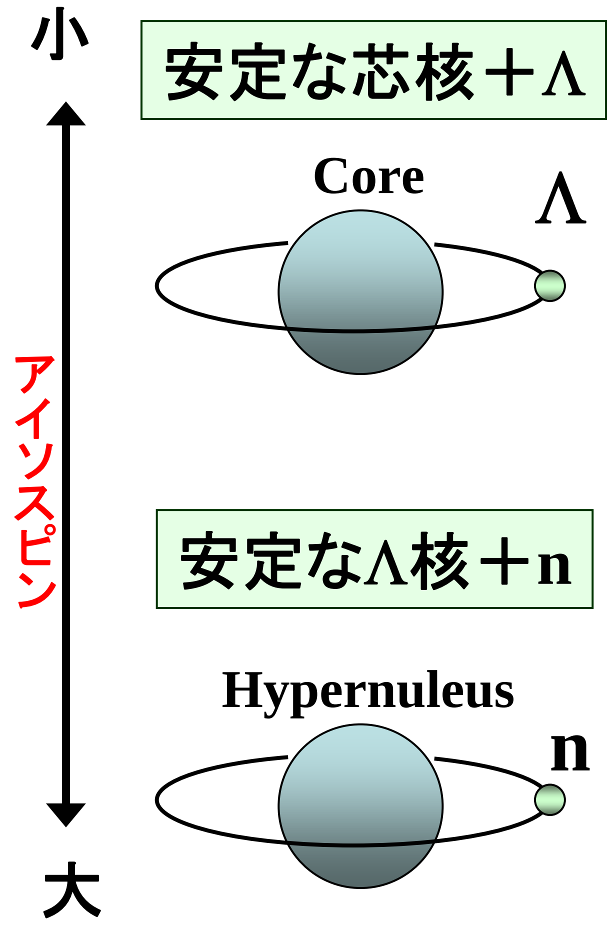
  ⇒ 強く混合（3体効果） cf. $^{6}_{\Lambda}\mathrm{H}$

  binding effect to B_{Λ}

- アイソスピン依存力：中性子星
- 二重荷電交換の反応機構

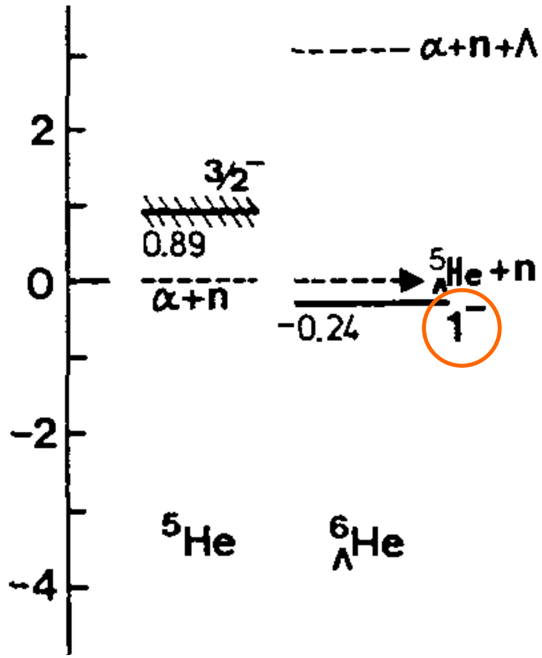
  $^{10}\mathrm{B}(\pi^{-},\mathrm{K}^{+})^{10}_{\Lambda}\mathrm{Li}$反応など

  Saha, Fukuda, et al., PRL94 (2005)

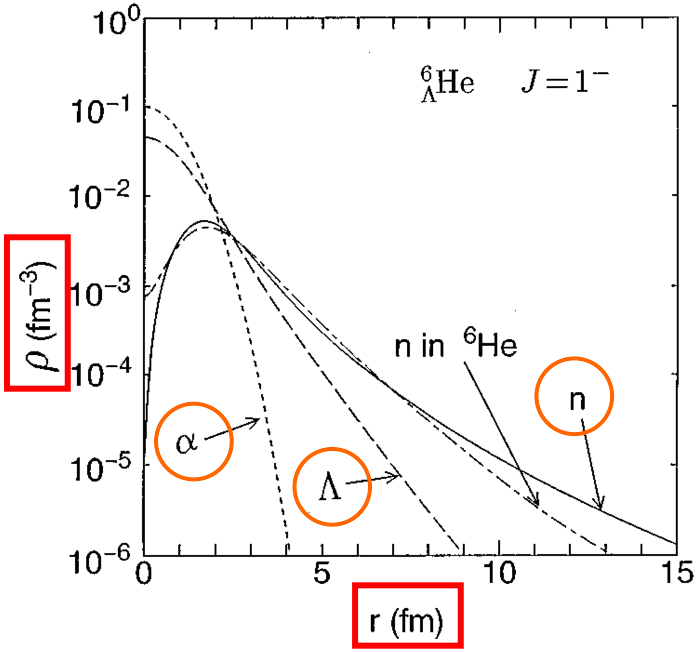


中性子がゆるく束縛（ハロー）

n-halo in $^6_\Lambda$He



$^6_\Lambda$He=α+n+Λ model



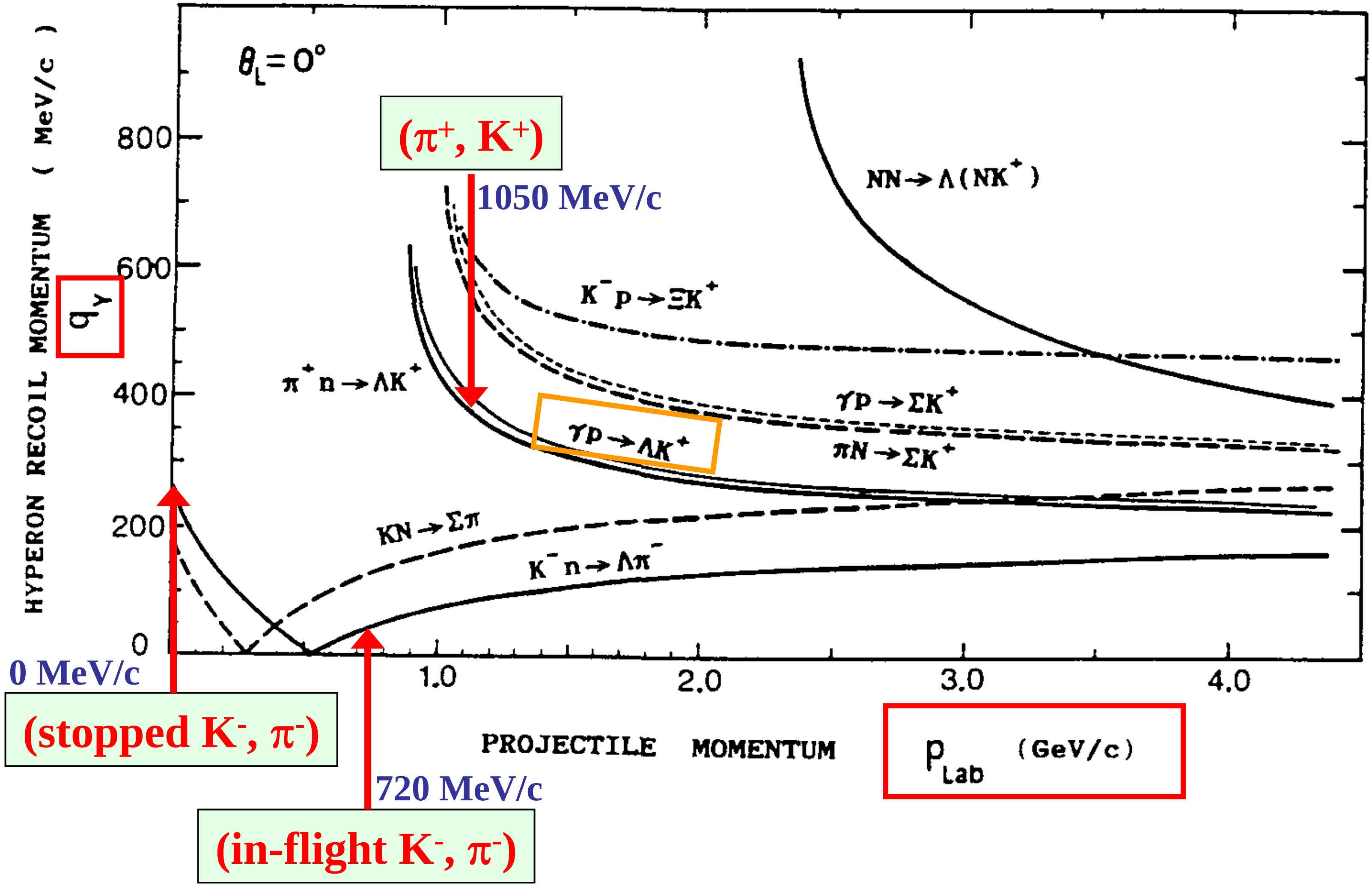
Hiyama, Kamimura, Motoba, Yamada, Yamamoto,PRC53 (1996)

Λ核生成反応

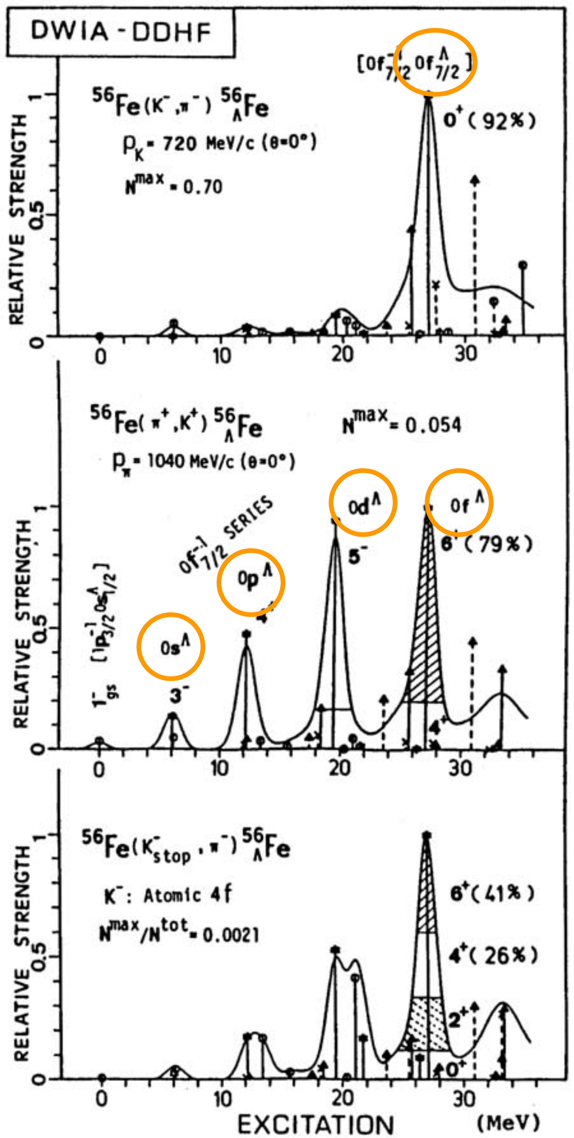
- **(in-flight K^-, π^-), (stopped K^-, π^-)**
- **(π^+, K^+)**
- **(e,e'K^+), (γ, K^+)**
- **double charge exchange (π^-, K^+)**

Neutron-rich Λ nuclei

Hyperon Recoil Momentum



ハイパー核の生成反応



(K⁻,π⁻) 720 MeV/c

$q_\Lambda \sim 60$MeV/c

"Substitutional"

$\Delta\ell \approx 0$

(π⁺,K⁺) 1040 MeV/c

$q_\Lambda \sim 350$MeV/c

"Spin-Stretched"

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

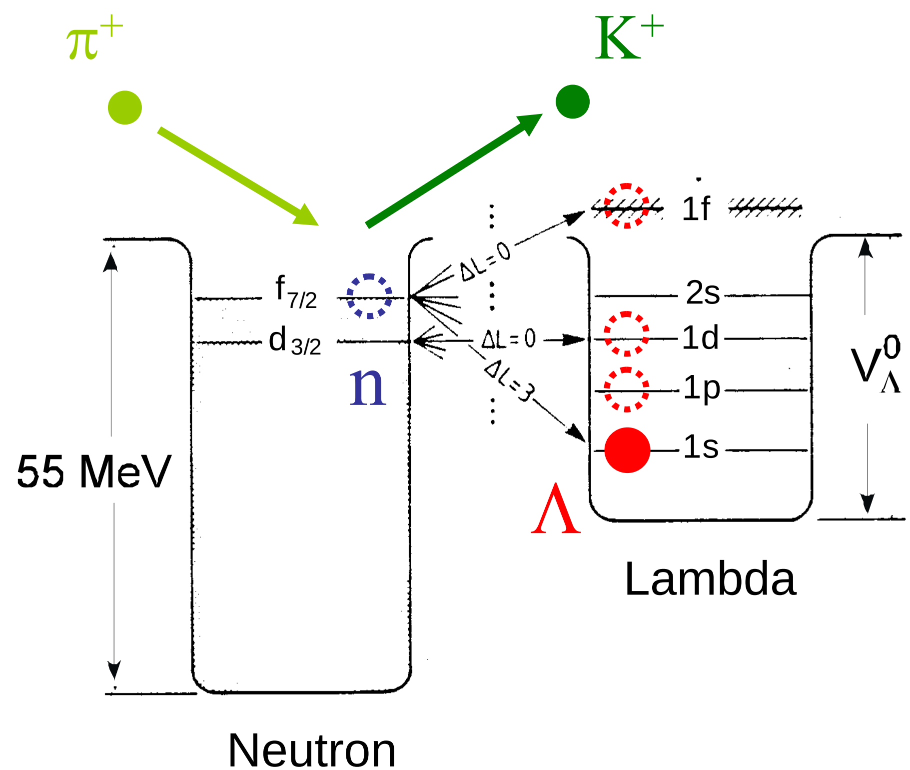
$[j_{N<}^{-1} j_{\Lambda>}]_{J=J\max}$

(K⁻,π⁻) at Rest

$q_\Lambda \sim 300$MeV/c

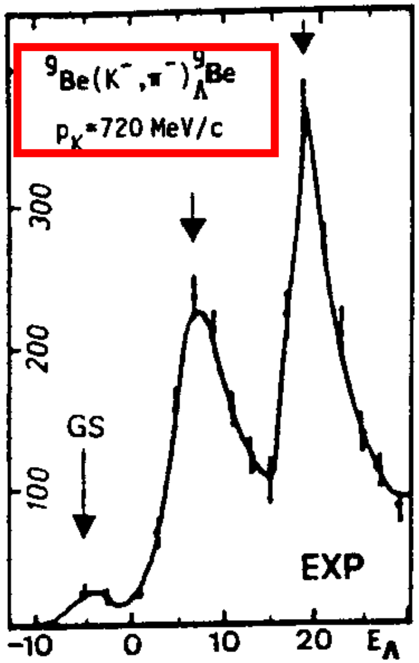
(e,e'K⁺)

(π⁺,K⁺) reactions

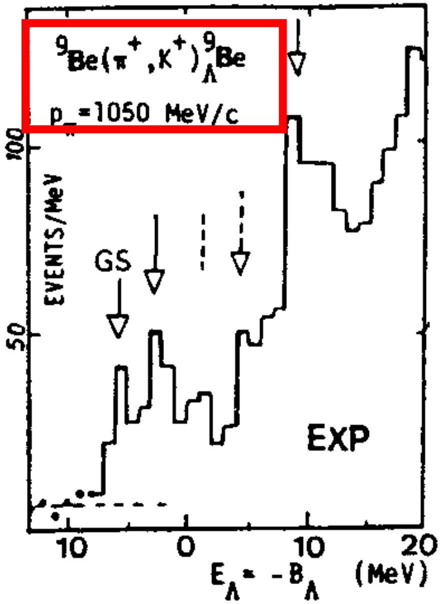


H.Bando, T.Motoba, J.Zofka, Int.J.Mod.Phys. A5(1990)4021

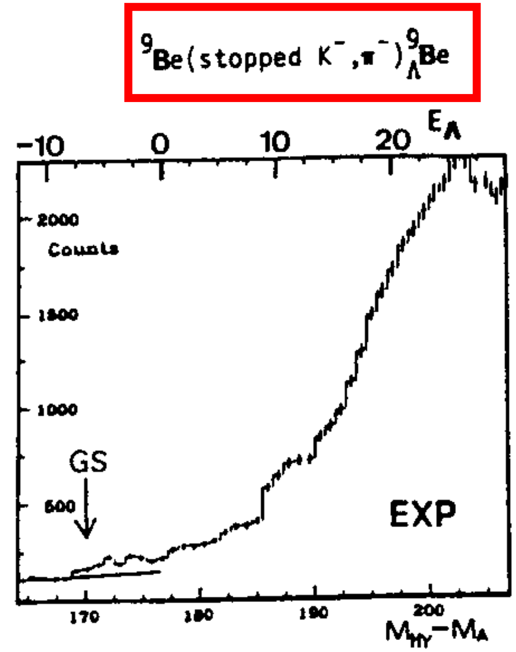
CERN: 1975-78



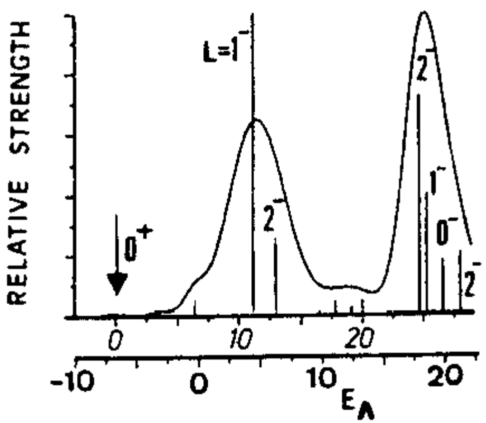
BNL: 1985

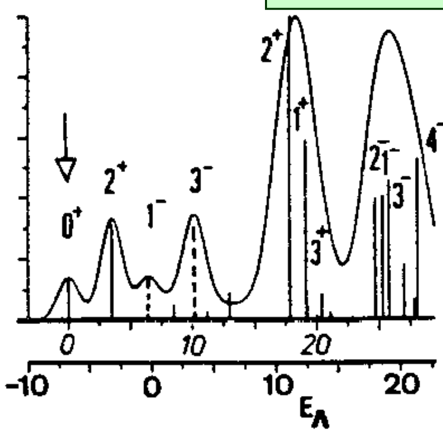


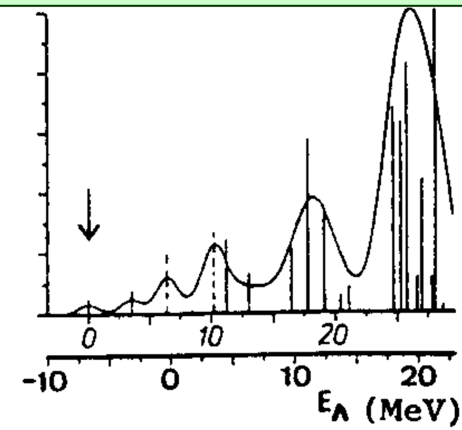
KEK: 1988



[α+α+Λ]+[α+α*+Λ] model



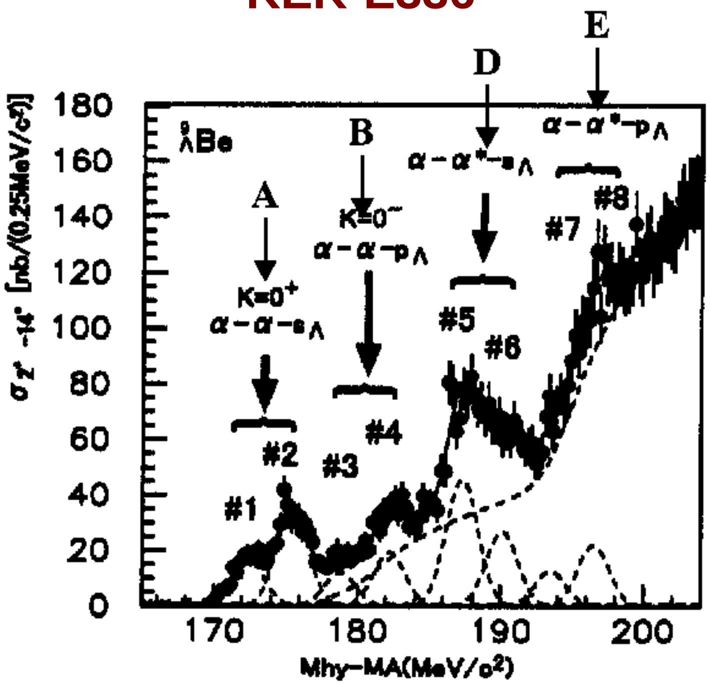




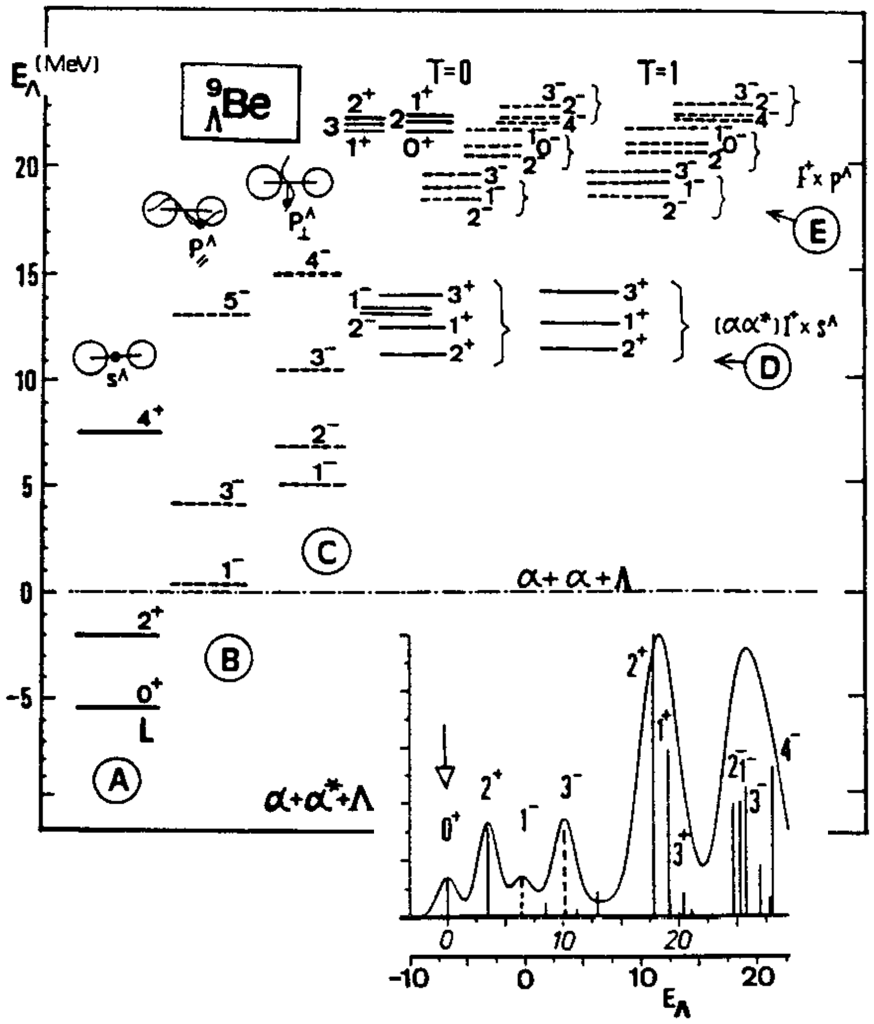
Yamada, Ikeda, Motoba, Bando, PRC38 (1988)

$^9Be(\pi^+,K^+)^9_\Lambda Be$ reaction

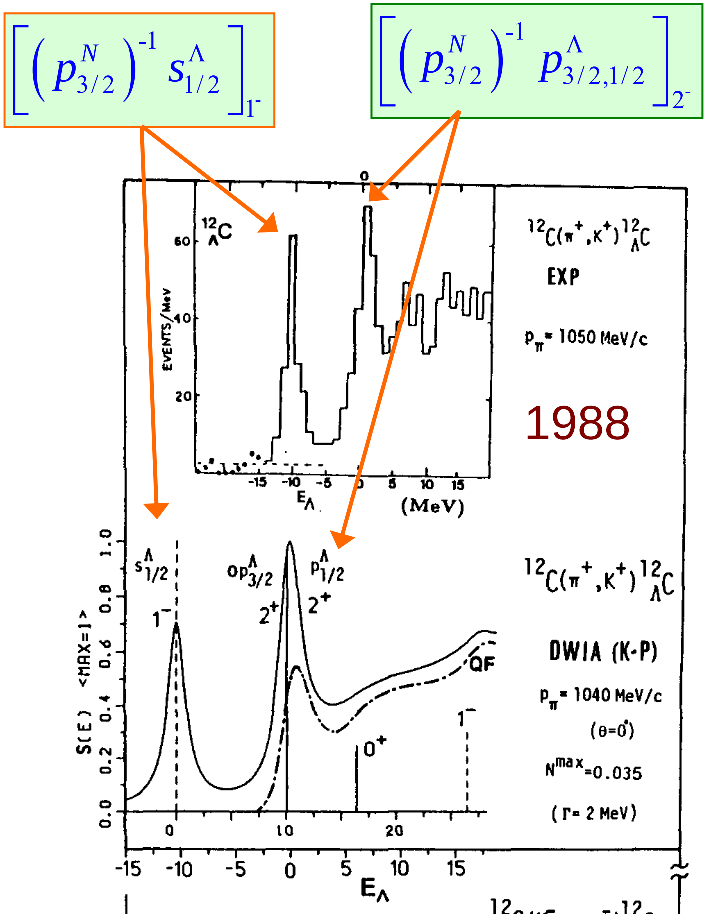
KEK-E336



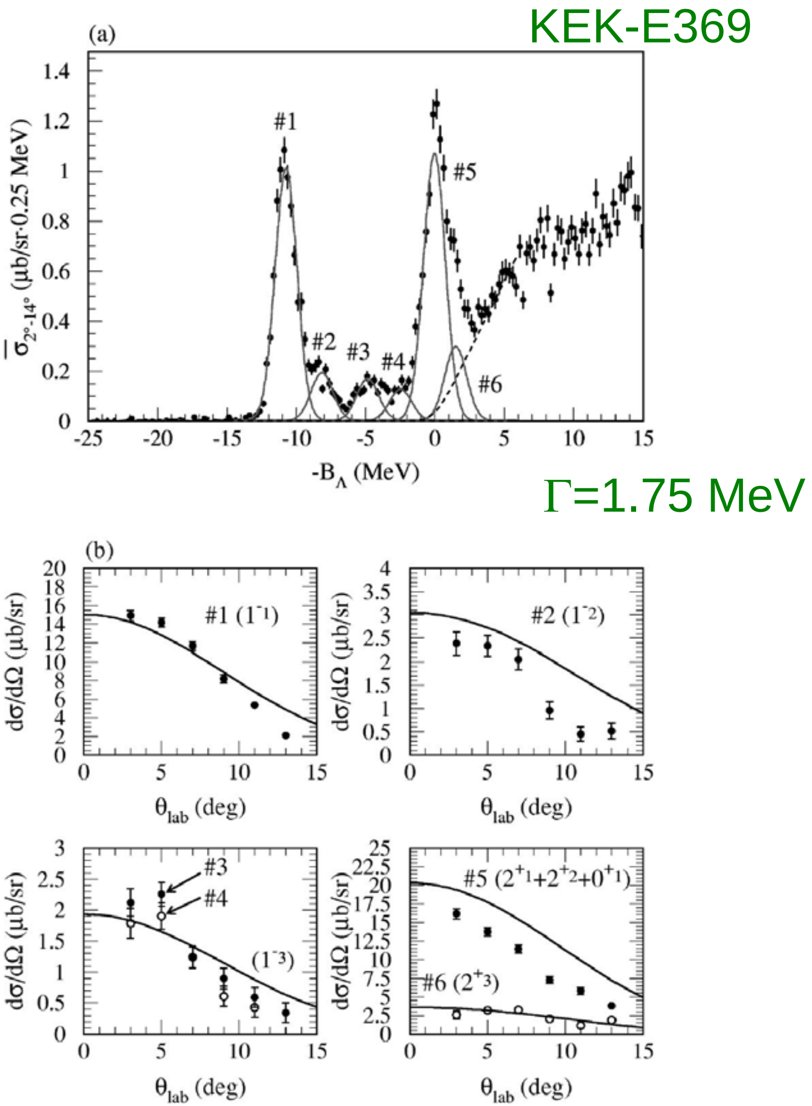
Yamada, Ikeda, Motoba, Bando, PRC38 (1988)



$^{12}C(\pi^+,K^+)\,^{12}_{\Lambda}C$ reaction



Motoba, Bando, Wunsch, Zofka PRC38 (1988)



Hotchi et al., PRC64 (2001)

^{12}C (π^+、K^+) $^{12}{}_{\Lambda}$C reaction

KEK-E369

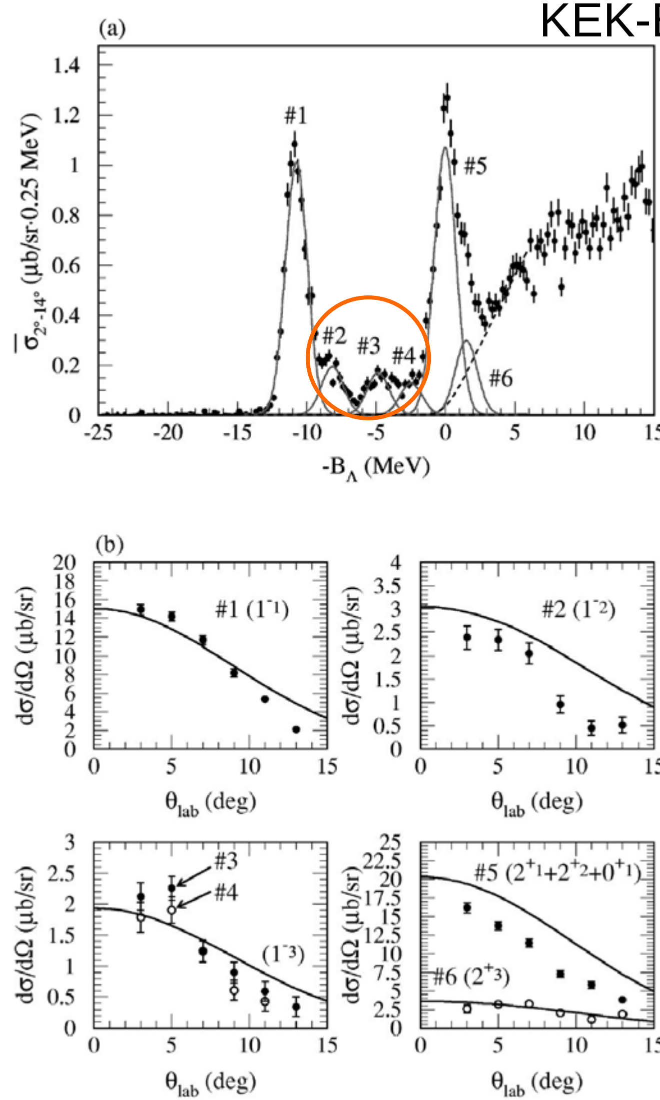
Shell-model analysis

Itonaga, Motoba, Sotona

$$\#2:\ \left[{}^{11}\mathrm{C}(1/2^-_1;2.0\mathrm{MeV})\otimes 0s^{\Lambda}_{1/2}\right]_{1^-_2}$$

$$\#3:\ \left[{}^{11}\mathrm{C}(3/2^-_2;4.8\mathrm{MeV})\otimes 0s^{\Lambda}_{1/2}\right]_{1^-_3}$$

$$\#4:\ \left[{}^{11}\mathrm{C}\left(1/2^-_1:2.0\mathrm{MeV}\right)\otimes 0p^{\Lambda}\right]_{2^+_1}$$



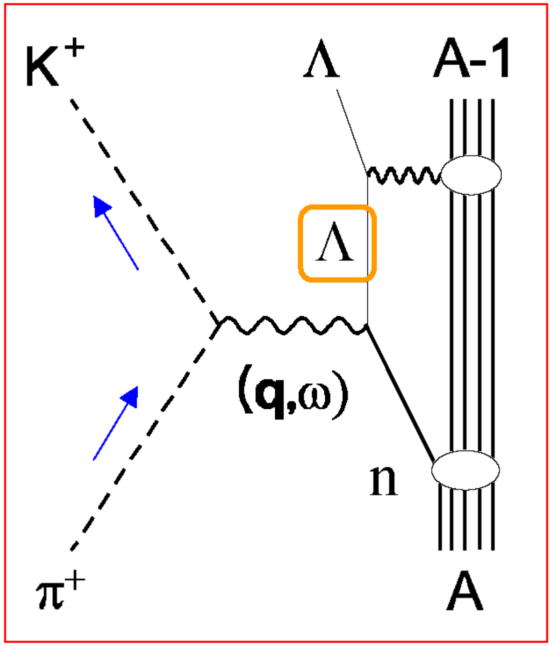
Hotchi et al., PRC64 (2001)

DWIAによる生成断面積の分析

DWIA = Distorted-Wave Impulse Approximation

Differential cross section

$$\frac{d\sigma}{d\Omega_L} = \alpha \left[\frac{d\sigma}{d\Omega_L} \right]^{elem}_{\pi N \to KY} N_{eff}(i \to f; \theta)$$



Effective number of nucleon

$$N_{eff}(i \to f; \theta) = \frac{1}{2J_i + 1} \sum_{M_i M_f} \left| \left\langle J_f M_f T_f \tau_f \left| O \right| J_f M_f T_f \tau_f \right\rangle \right|^2$$

$$O = \int d\mathbf{r} \chi^{(-)*}_{\mathbf{p}_\pi} \left(\frac{M_A}{M_H}\mathbf{r}\right) \chi^{(+)}_{\mathbf{p}_K}(\mathbf{r}) \sum_{j=1}^{A} U_{-}(j) \delta\left(\mathbf{r} - \frac{M_C}{M_H}\mathbf{r}_j\right)$$

Distorted-wave of meson wave functions

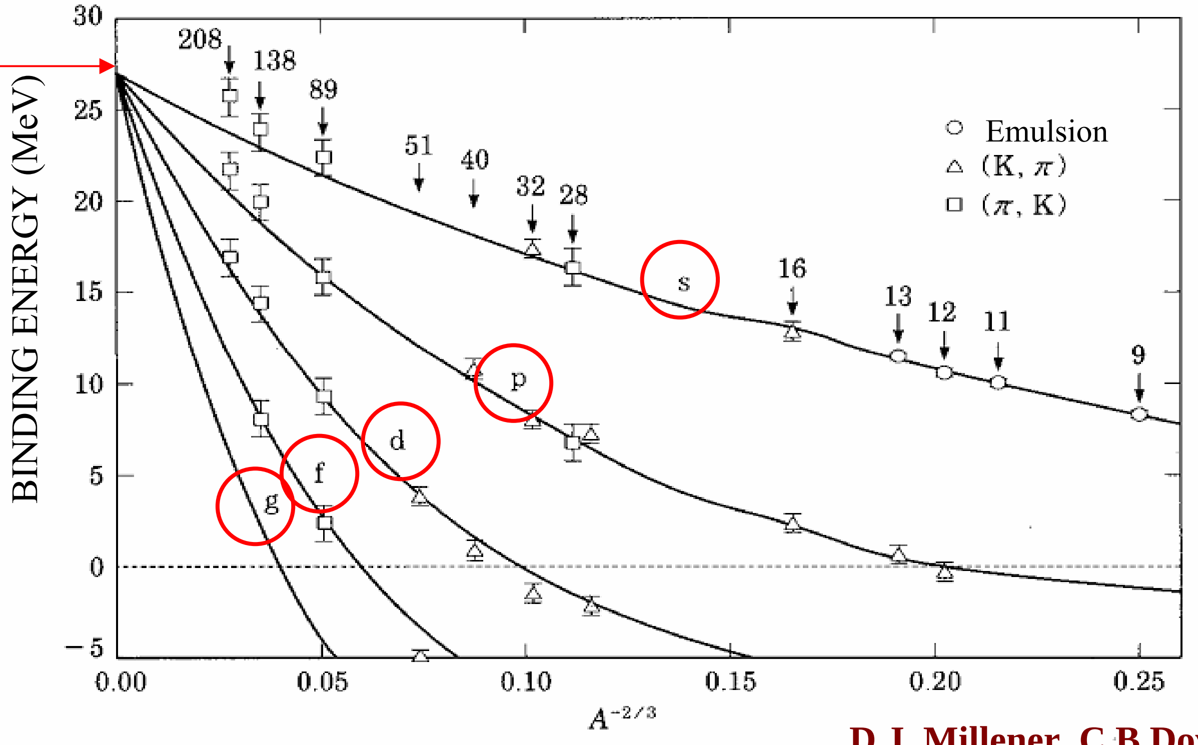
$$\chi^{(-)*}_{\mathbf{p}_\pi}(a\mathbf{r}) \chi^{(+)}_{\mathbf{p}_K}(\mathbf{r}) = \sum_L \sqrt{4\pi(2L+1)} i^L j_{LM}(p_\pi, p_K, \hat{\mathbf{p}}_K; r) Y_{LM}(\hat{\mathbf{r}})$$

Eikonal approximation, Klein-Gordon equation

Binding energies of Λ-Hypernuclear states

28 MeV

$\approx \frac{2}{3} U_N$



Skyrme-HF scheme

D.J. Millener, C.B.Dover, A.Gal, PRC38(1988)

Woods-Saxon form

$$U_\Lambda = -\frac{U_\Lambda^0}{1+\exp[(r-R)/a]} \qquad R = r_0 (A-1)^{1/3} \text{fm}$$

$$U_\Lambda^0 = 28 \ \text{MeV} \qquad a = 0.6 \ \text{fm} \qquad r_0 = 1.128 + 0.439 A^{-2/3} \text{fm}$$

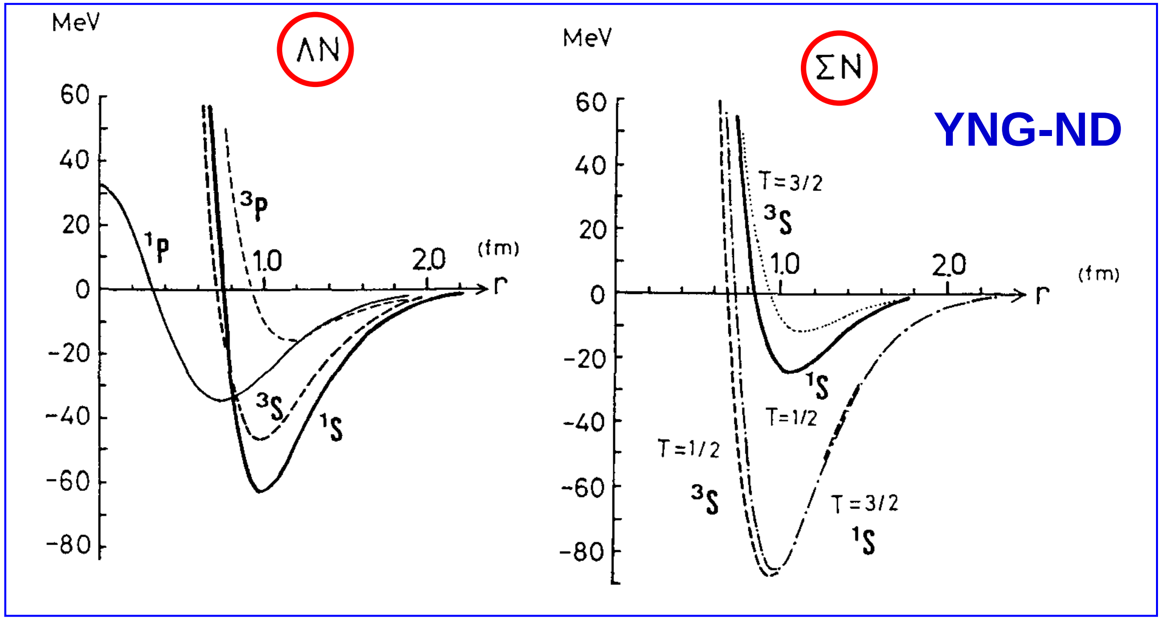
Σ核の生成

[Λ核との違い]

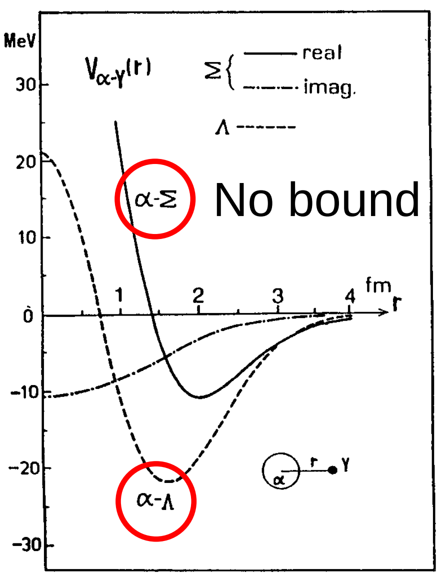
strong ΣN-ΛN coupling

$\Delta M = M_{\Sigma} - M_{\Lambda} = 28$ MeV

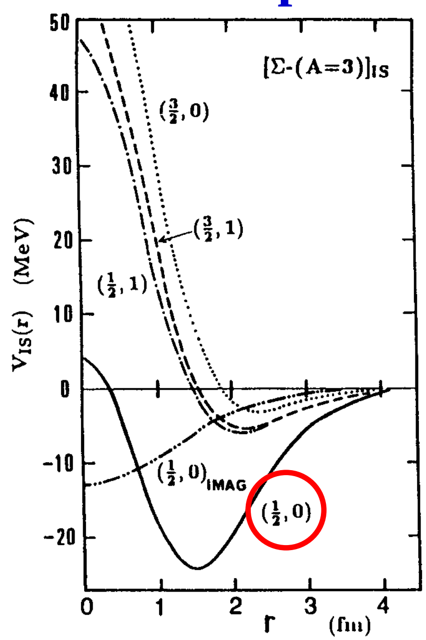
→ 崩壊幅Γの問題



α-Y pot.



"3N"-Σ pot.



Harada, Akaishi et al. 1987

$^4_\Sigma$He: I=1/2, S=0
bound state

ATMS法

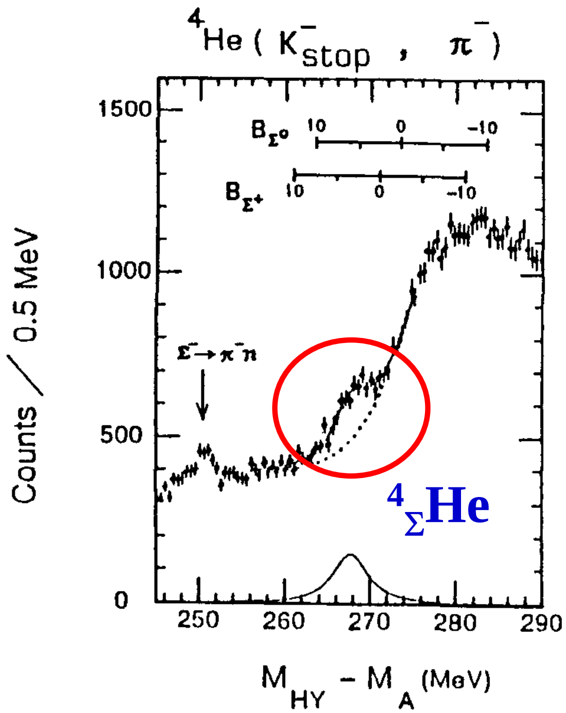
$$V_{\Sigma-\mathrm{nucl}} = V_0 + (\mathbf{t}_\Sigma \cdot \mathbf{T}_{\mathrm{nucl}})V_1$$

Lane term

$h-\Sigma^0$ ↔ $t-\Sigma^+$

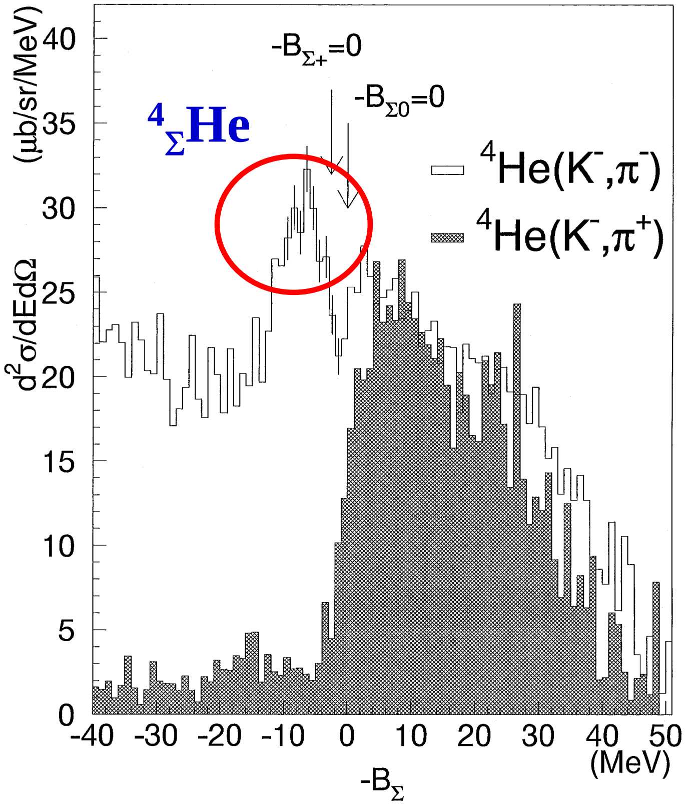
Strong coupling

Observation of a $^4_\Sigma$He bound state



Hayano et al., PLB231 (1989)

$$B_{\Sigma^+} = 4.2 \pm 0.3 \mp 1 \text{ MeV} \qquad \Gamma = 7.0 \pm 0.3^{+1.2}_{-0.0} \text{ MeV}$$



Nagae et al., PRL80 (1998)

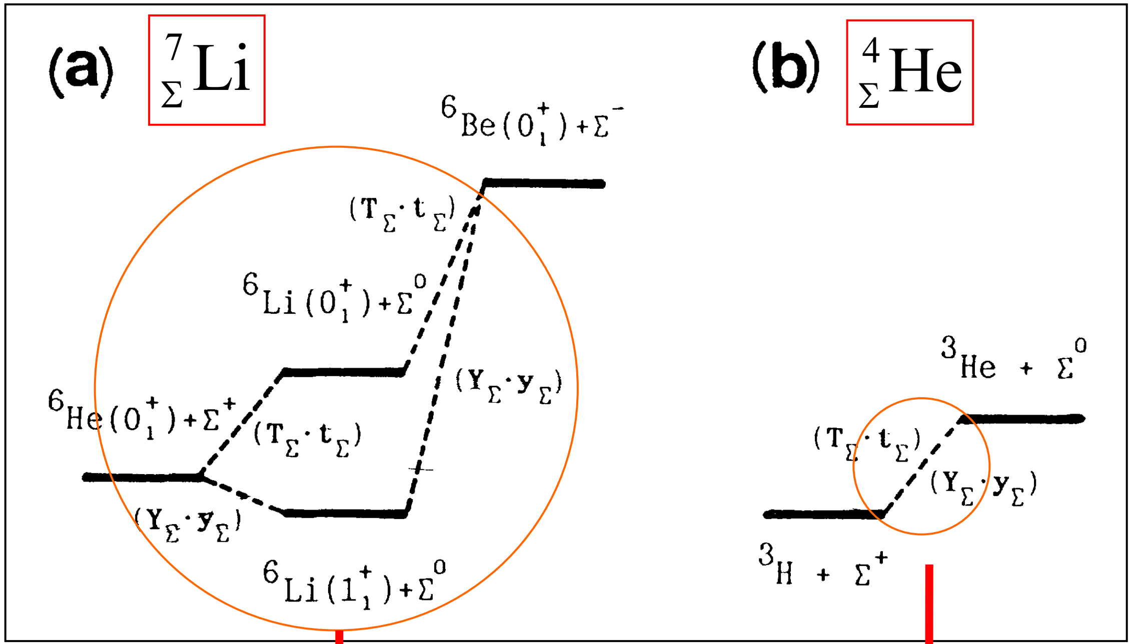
Possible existence of a $^{7}_{\Sigma}$Li bound state

Yamada, Ikeda, PRC46 (1992)

ΣN interaction

$$\upsilon_{\Sigma N} = \upsilon^{0}_{\Sigma N} + (\mathbf{t}_{\Sigma}\cdot\mathbf{t}_{N})\upsilon^{\tau}_{\Sigma N} + (\mathbf{s}_{\Sigma}\cdot\mathbf{s}_{N})\upsilon^{\sigma}_{\Sigma N} + (\mathbf{t}_{\Sigma}\cdot\mathbf{t}_{N})(\mathbf{s}_{\Sigma}\cdot\mathbf{s}_{N})\upsilon^{\tau\sigma}_{\Sigma N}$$

^{6}He-^{6}Li-^{6}Be Super multiplet (I,S)=(0,1),(1,0)



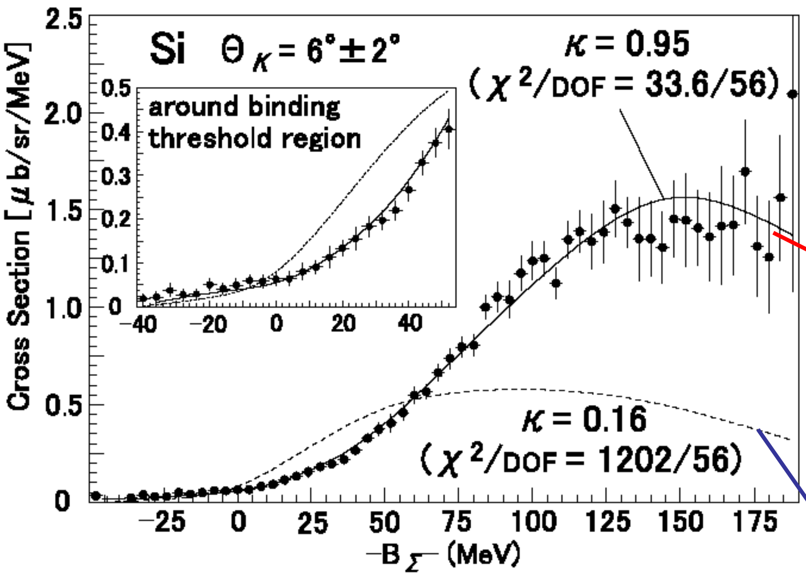
^{3}H-^{3}He I=1/2,S=1/2

prediction Bound state $^{7}_{\Lambda}\mathrm{Li} - ^{7}_{\Sigma}\mathrm{Li}$

Bound state $^{4}_{\Lambda}\mathrm{He} - ^{4}_{\Sigma}\mathrm{He}$

Σ^- spectrum of $^{28}Si(\pi^-,K^+)$ reaction

$^{28}Si(\pi^-,K^+)$ at p_π=1.2 GeV/c



Noumi, et al. PRL89(2002)072301

$V_0 = -10$ MeV, $W_0 = -10$ MeV

DWIA analysis

$$U(r) = \frac{V_0 + iW_0}{1+\exp[(r-R)/a]}$$

$$R = 1.1\times(A-1)^{1/3}, \quad a = 0.67 \text{ fm}$$

$V_0 = +150$ MeV

$W_0 = -15$ MeV

New Data

+90 MeV

–40 MeV

Saha et al., PRC74(2004)

Ni, It, Biでも同様

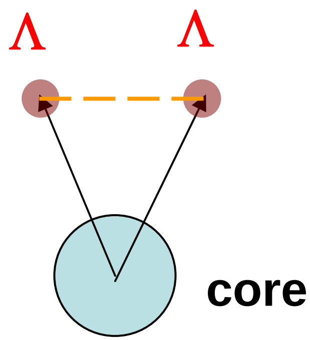
Σ-nucleus pot. : Repulsive !!

Kohno, Fujiwara, et al., PTP112 (2004)

Harada, Hirabayashi, NPA759 (2005)

S=-2核（ΛΛ、Ξ核）

ΛΛ核をめぐって



1962 $^{6}_{\Lambda\Lambda}$**He (emulsion): doubtful**

1963 $^{10}_{\Lambda\Lambda}$**Be (emulsion) ⇒ 再解析: Dalitz (1989)**

1991 $^{13}_{\Lambda\Lambda}$**B (KEK-E176)**

$$\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda} - 2\times B_{\Lambda}$$

Bond energy

$$\Delta B_{\Lambda\Lambda} = 4-5\ \mathrm{MeV} \approx \left|\left\langle \upsilon_{\Lambda\Lambda}({}^{1}S_{0})\right\rangle\right|$$

理論: $\left|\left\langle \upsilon_{\Lambda\Lambda}\right\rangle\right| < \left|\left\langle \upsilon_{\Lambda N}\right\rangle\right| < \left|\left\langle \upsilon_{NN}\right\rangle\right|$ 但し、「model D」のみOK

α+x+Λ+Λ model, [core+Λ+Λ]+[core+Ξ+N]+[core+Σ+Σ] model

Bando, Ikeda, Motoba, Yamamoto, Yamada, Akaishi, ･･･

***H*-dibaryon (QM, QCM):** $|\mathrm{H}\rangle = |\{1\}\rangle = \sqrt{\frac{1}{8}}|\Lambda\ \Lambda\rangle + \sqrt{\frac{4}{8}}|\Xi\ \mathrm{N}\rangle - \sqrt{\frac{3}{8}}|\Sigma\ \Sigma\rangle$ Jaffe

***H*核状態**: Core+(3*q*)+(3*q*) Yamada & Nakamoto, PRC62 (2000)

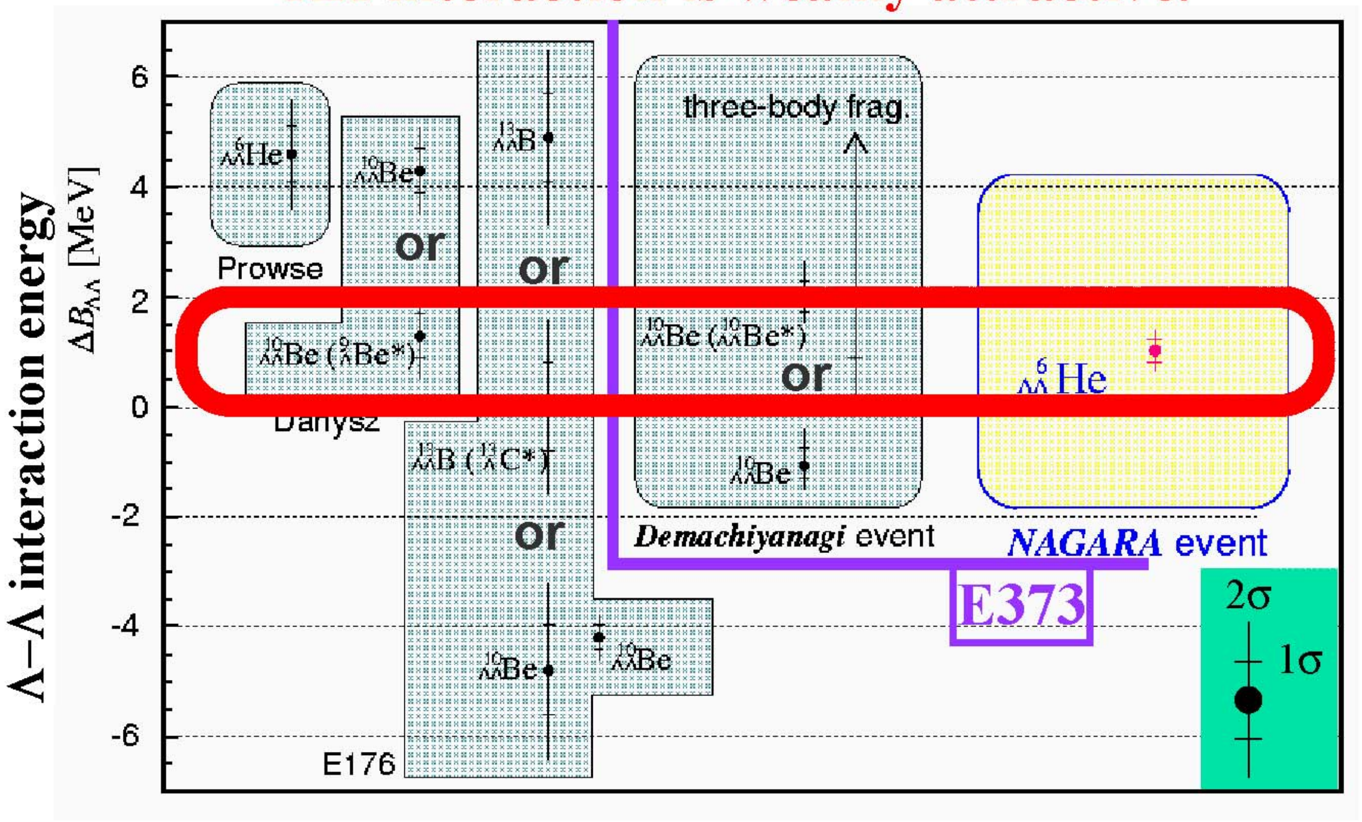
2001 Nagara event: $^{6}_{\Lambda\Lambda}$**He (unique)** $\Delta B_{\Lambda\Lambda} = 1.01 \pm 0.2\ \mathrm{MeV}$

(KEK-E373) weakly attractive

Comparison with past results

<u>Our knowledge for ΛΛ int. until now.</u>

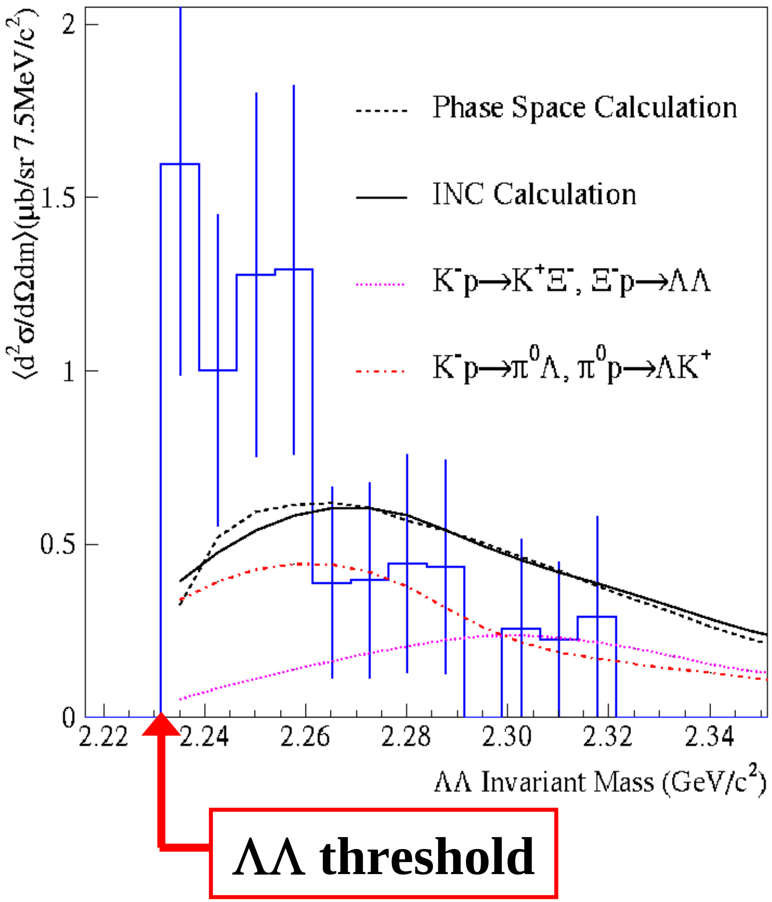
ΛΛ interaction is weakly attractive.



Made by Nakazawa

ΛΛ Enhancement (KEK-E224)

J.K.Ahn et al., Phys. Lett. B444,267(1998)



ΛΛ invariant spectrum of $^{12}C(K^-,K^+)\Lambda\Lambda$

(1) H-dibaryon Resonance?

$K^-p \rightarrow \Xi^-K^+;\ \Xi^-(p) \rightarrow H$

$H \rightarrow \Lambda\Lambda$

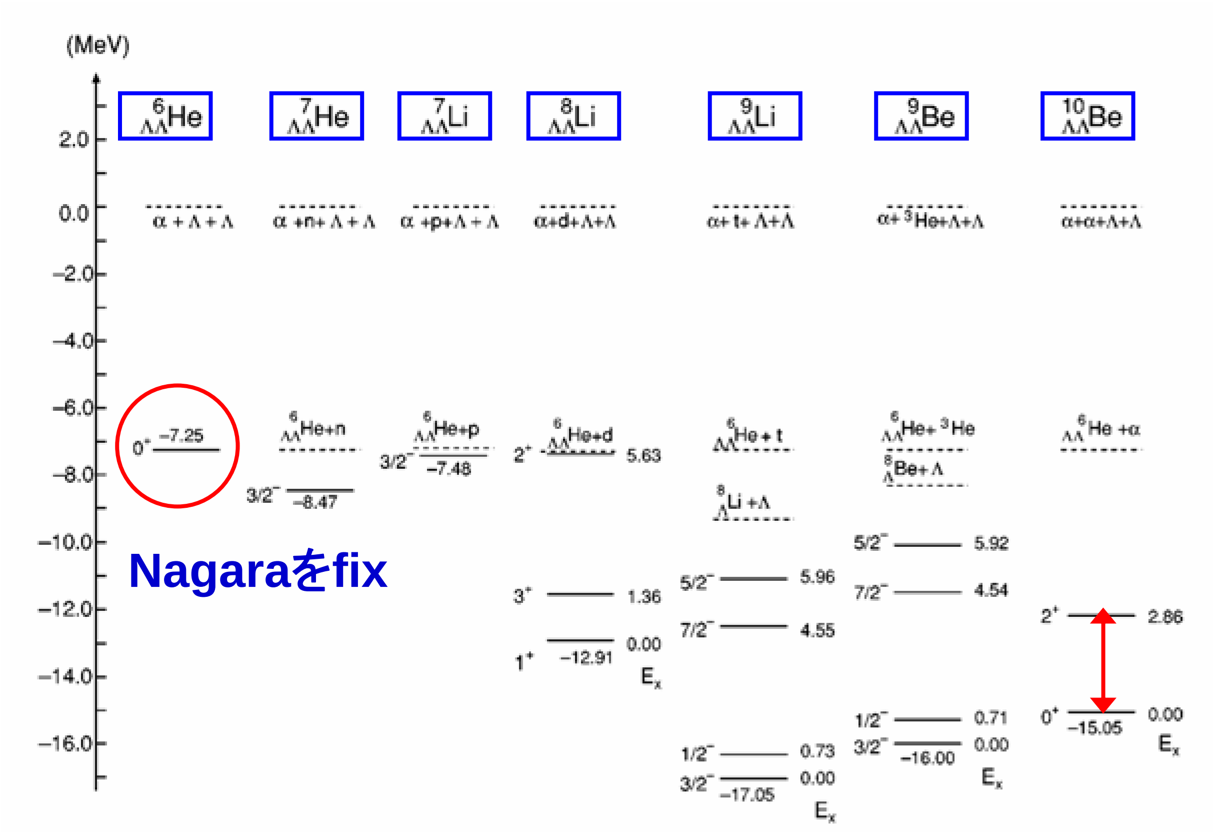
(2) Strong ΛΛ Final State Interaction?

S=-2核の今後の実験：KEK-E964 (2008)

10倍の統計精度 → ΛΛ核

NAGARA eventを受けて

α+x+Λ+Λ model



Demachiyanagi event

今後の課題:
ΛΛ-ΞN coupling など

Hiyama, Kamimura, Motoba, Yamada, Yamamoto, PRC66 (2002)

ΛΛ核およびΞ核の研究

- B_8-B_8相互作用の統一的理解

  ⇔ *H-dibaryon* : $SU_f(3)$-singlet 状態, Jaffe

- S=ー2核の核種図＋分光学

- 核内でのハイペロン混合の役割 6体問題：Nemura

  [ΛΛ-ΞN-ΣΣ(-ΛΣ)] + [ΛN-ΣN] 結合 + *H*結合 $^{6}_{\Lambda\Lambda}He$

  ⇒ 生成、構造、崩壊

- Ξ原子状態からのΛΛ核生成機構

  $p(K^-,K^+)\Xi^-$, atomic Ξ^- → ΛΛ核生成

- 多重ストレンジネス核物質

- 中性子星におけるハイペロン混在 Takatsuka

  ⇒ 最大質量の問題など

Ξ状態からのΛΛ核生成機構

Observed events in KEK-E176/E373 (hybrid-emulsion method)

$$\Xi^- + {}^{12}\mathrm{C} \to {}^{10}_{\Lambda\Lambda}\mathrm{Be} + \underline{t} \text{ or } {}^{9}_{\Lambda}\mathrm{Be} + \underline{{}^{4}_{\Lambda}\mathrm{H}}$$

$$\text{or } {}^{6}_{\Lambda\Lambda}\mathrm{He} + \alpha + \underline{t}$$

$${}^{4}_{\Lambda}\mathrm{H} = t \otimes \Lambda$$

$$\Xi^- + {}^{12}\mathrm{C} \to {}^{9}_{\Lambda\Lambda}\mathrm{Li} + \alpha : \text{ largest Q - value}$$

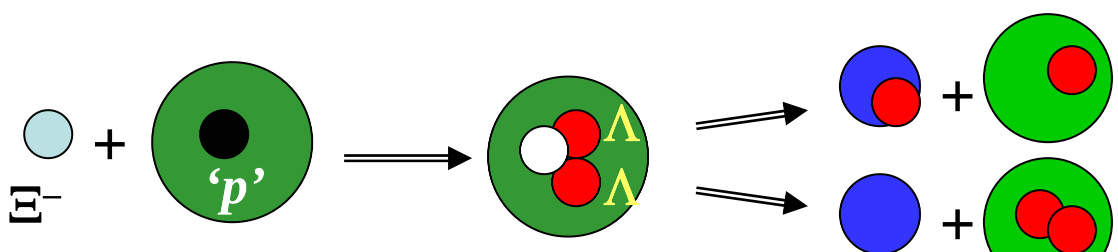
- **Compound double-Λ nuclear picture**

  Yamamoto, Motoba, Wakai, Muraoka, PTP Suppl.117

- **Direct reaction picture:**

  今後の課題

  Yamada, Takahashi, Ikeda, PRC53 (1996), PRC56 (1997)



$$\Xi^- + \text{“}p\text{”} \to \Lambda + \Lambda + 28\ \mathrm{MeV}$$

Ξ状態からのΛΛ核生成機構

Observed events in KEK-E176/E373 (hybrid-emulsion method)

$$\Xi^- + {}^{12}\mathrm{C} \rightarrow {}^{10}_{\Lambda\Lambda}\mathrm{Be} + t \quad \text{or} \quad {}^{9}_{\Lambda}\mathrm{Be} + {}^{4}_{\Lambda}\mathrm{H}$$

$$\text{or} \quad {}^{6}_{\Lambda\Lambda}\mathrm{He} + \alpha + t$$

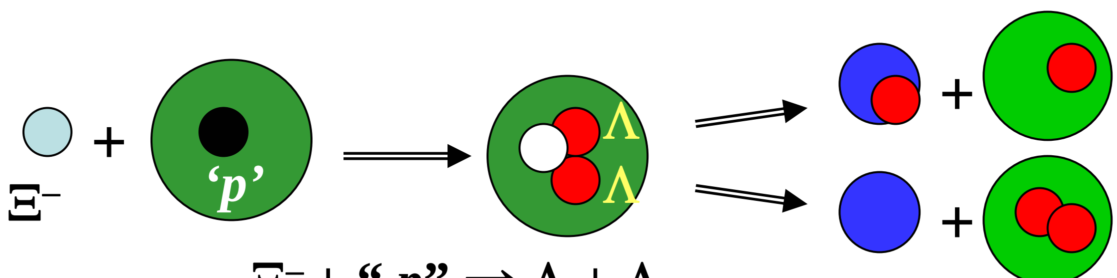
$${}^{4}_{\Lambda}\mathrm{H} = t \otimes \Lambda$$

$$\Xi^- + {}^{12}\mathrm{C} \rightarrow {}^{9}_{\Lambda\Lambda}\mathrm{Li} + \alpha : \text{ largest Q-value}$$

Two Λ's easily stick to the nucleus for the *s*-proton substitutional state

$$\Xi^- + p \rightarrow \Lambda + \Lambda + 28\ \mathrm{MeV} \approx E_{sep}(s\text{-nucleon})$$

T. Yamada et al.,

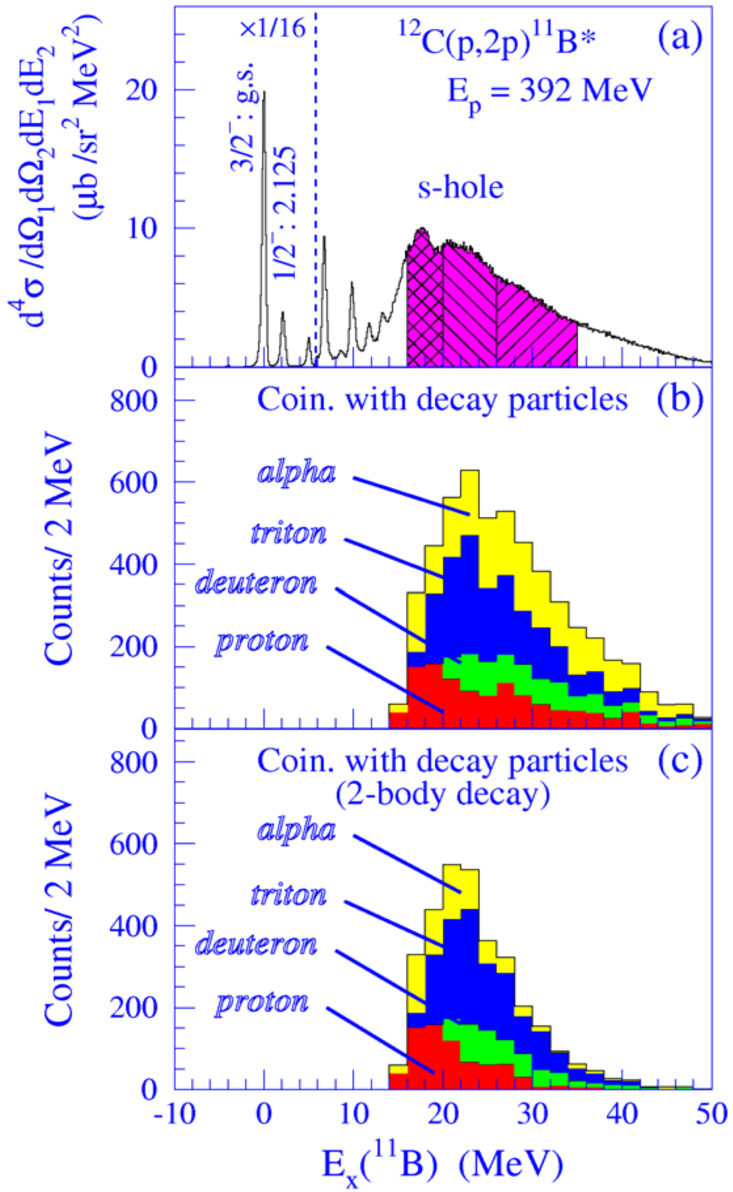


$$\Xi^- + \text{“}p\text{”} \rightarrow \Lambda + \Lambda$$

$$\Xi^- + {}^{12}\mathrm{C} \rightarrow {}^{11}\mathrm{B}^*(s\text{-hole}) \otimes \Lambda \otimes \Lambda \rightarrow$$

Experimental Excitation Spectra of ^{11}B

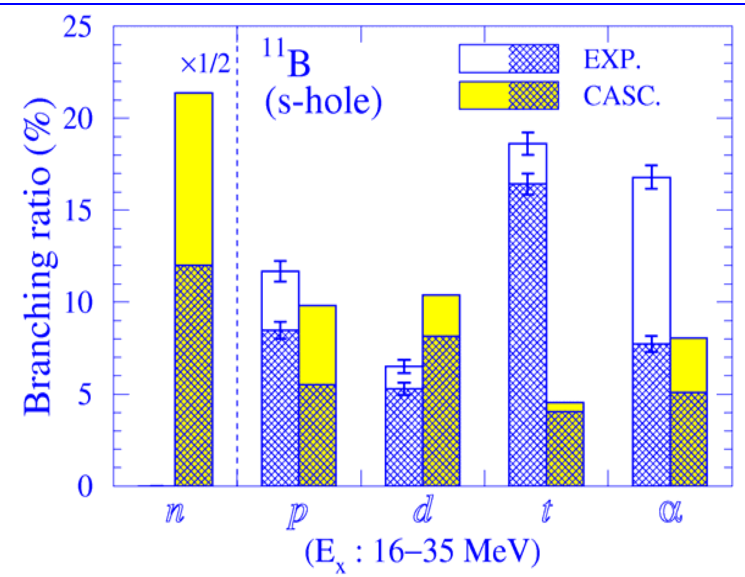
(RCNP-E110 by Yosoi et al.)



Comparison with Statistical Model

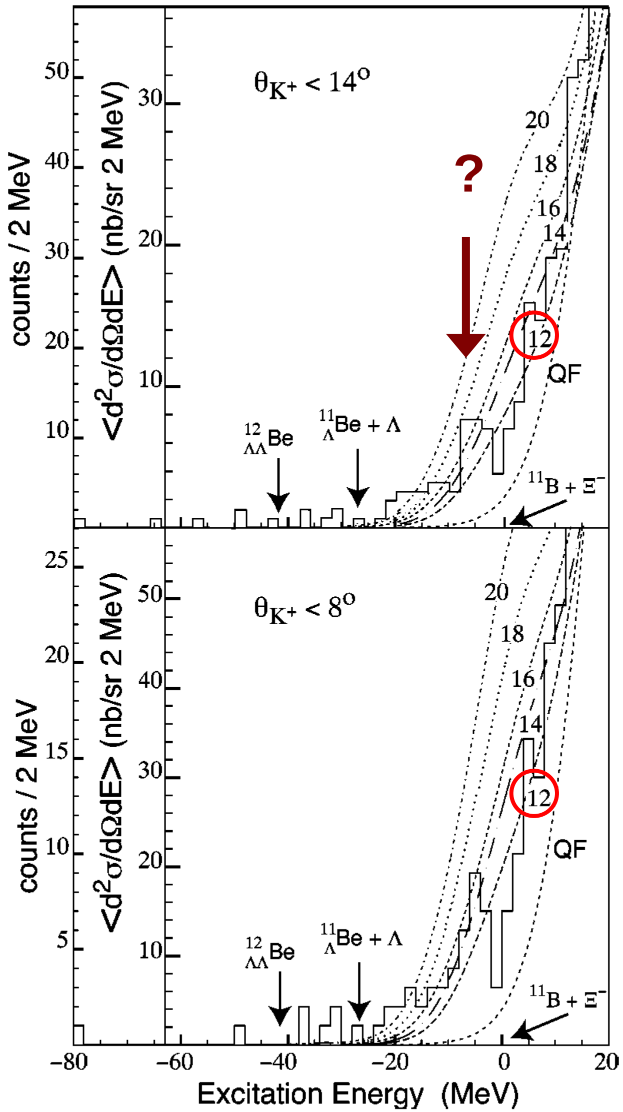
(Cascade cal. by Yosoi)

hatched region : "*2-body decay*" region



- ***t*-decay**: **dominant**
- ***α*-decay**: **large sequential decay or 3-body decay**
- ***p*-decay / *d* -decay**: **opposite between Exp. and Cascade cal.**

Ξ核状態について



BNL-E885 Kaustov et al., PRC61 (2000)

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

DWIA (Motoba) ⇒ $V^0{}_{\Xi}$ ≈ -12 MeV

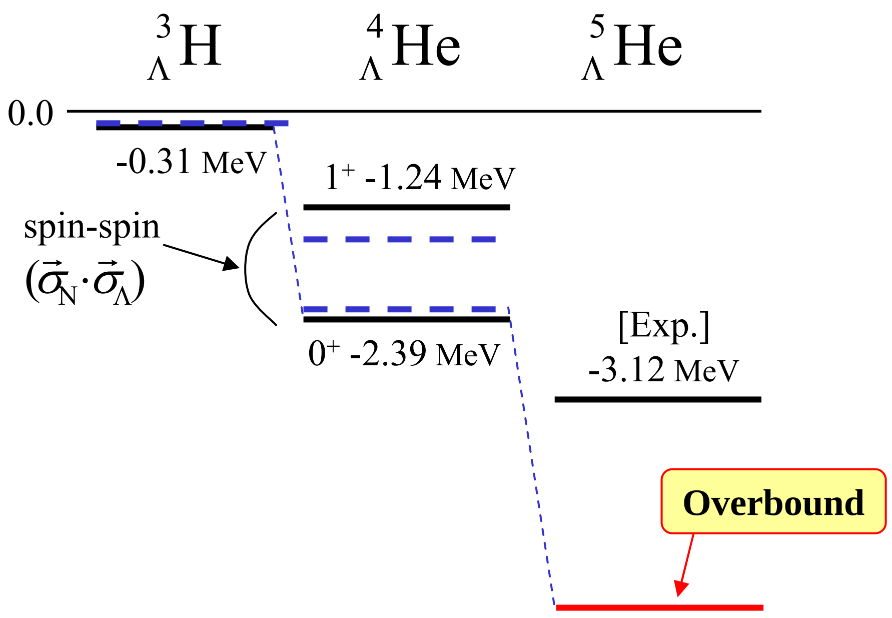
Hiyama, Yamamoto et al.,

Few-body Ξ 核の存在可能性

Few-body hypernuclei

Overbinding Problem of s-Shell Hypernuclei

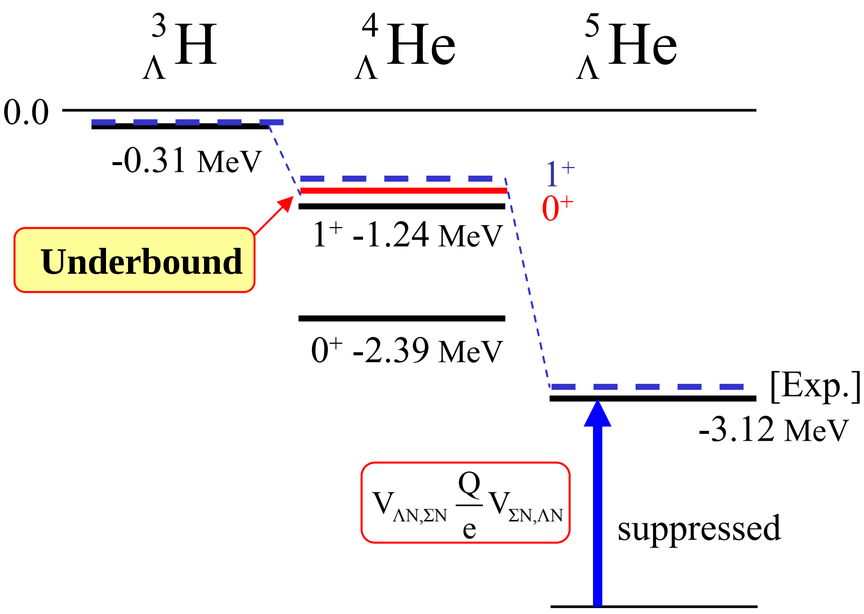
Overbinding Problem



ΛN single-channel calcation

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

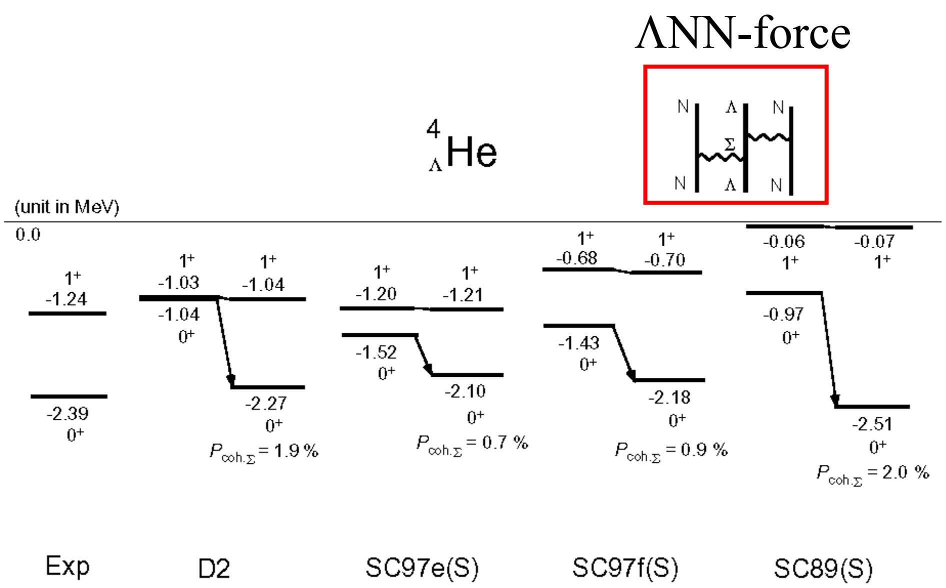
Underbinding Problem



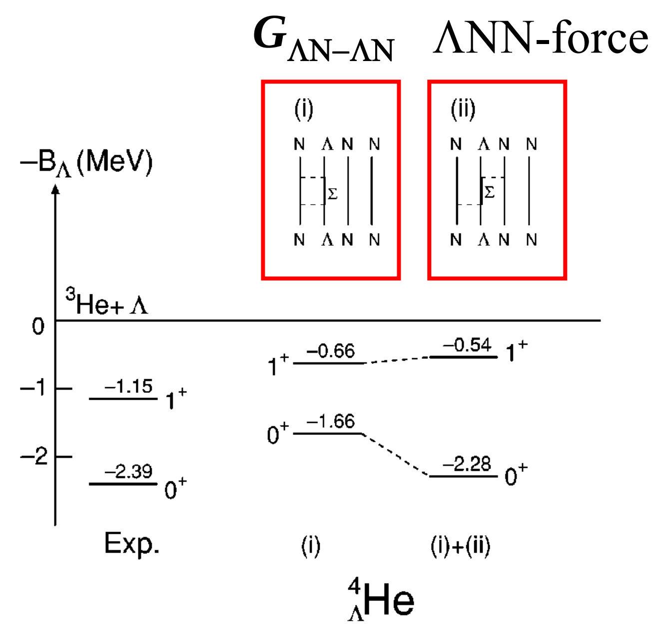
G-matrix calc. with ΛN-ΣN (D2)

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

Coherent ΛΣ coupling

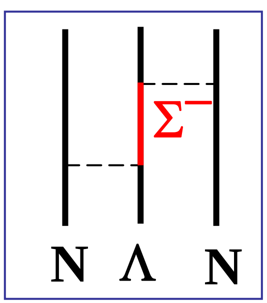


BHF計算: Akaishi et al., PRL84(2000)

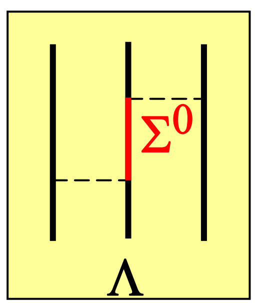


ΛNNN+ΣNNN (GL計算)

Hiyama, Kamimura, Motoba, Yamada, Yamamoto, PRC65 (2001)



incoherent



coherent

Gibson: $\Delta E(1^+\text{-}0^+)=\sigma_\Lambda \cdot \sigma_N + \Lambda\Sigma\text{coupling}$

Other topics

- ${}^{3}_{\Lambda}H$: Faddeev cal. with NSC
- ${}^{4}_{\Lambda}H$: Faddeev-Yakubovsky with NSC

  CSB(荷電対称の破れ）: ${}^{4}_{\Lambda}H$-${}^{4}_{\Lambda}He$

- ${}^{5}_{\Lambda}He$: rearrangement effect

  BHF (Fujiwara et al.,), 5体問題（Nemura et al.)

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

Weak decay of Λ nuclei

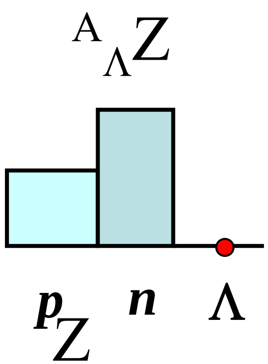
Weak decay modes of Λ hypernuclei

Mesonic decay + Non-mesonic decay

$$1/\tau_{HY} = \Gamma_{tot} \begin{cases} \Gamma_m \begin{cases} \Gamma_{\pi^-} \ (\Lambda \rightarrow p + \pi^-) \\ \Gamma_{\pi^-} \ (\Lambda \rightarrow n + \pi^0) \end{cases} \\ \Gamma_{nm} \begin{cases} \Gamma_p \ (\Lambda + \text{'}p\text{'} \rightarrow n + p) \\ \Gamma_n \ (\Lambda + \text{'}n\text{'} \rightarrow n + n) \end{cases} \end{cases}$$

Mesonic
q **~100 MeV/c**

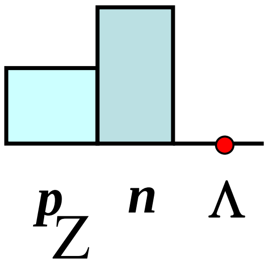
Non-Mesonic
q **~400 MeV/c**



「Baryon-Baryon weak interaction」
の研究と密接な関係

Mesonic Decay of Λ Hypernuclei

$$ {}^{A}_{\Lambda}Z \rightarrow {}^{A}Z' + \pi^{-,0} \qquad \Lambda \rightarrow N + \pi^{-,0} $$



- **Λ粒子**: **s** **軌道、**π崩壊は核内の深部で起こる
- **運動量移行 q~100 MeV/c ＜ k_F**

  A → large, then π decay is suppressed

  due to Pauli-blocking effect

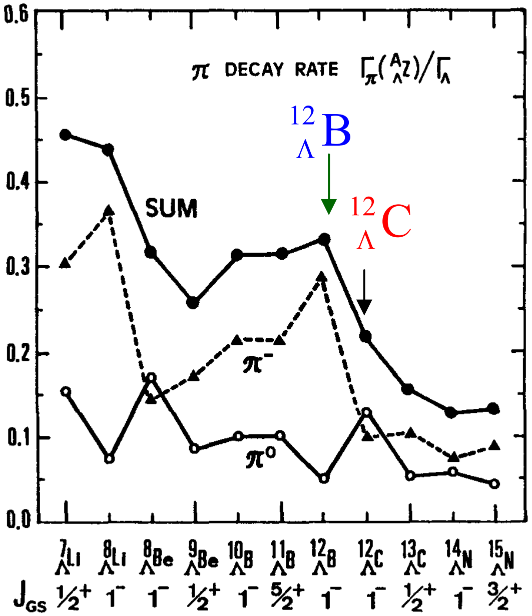
  π-decay rates : sensitive to structure of nuclear interior

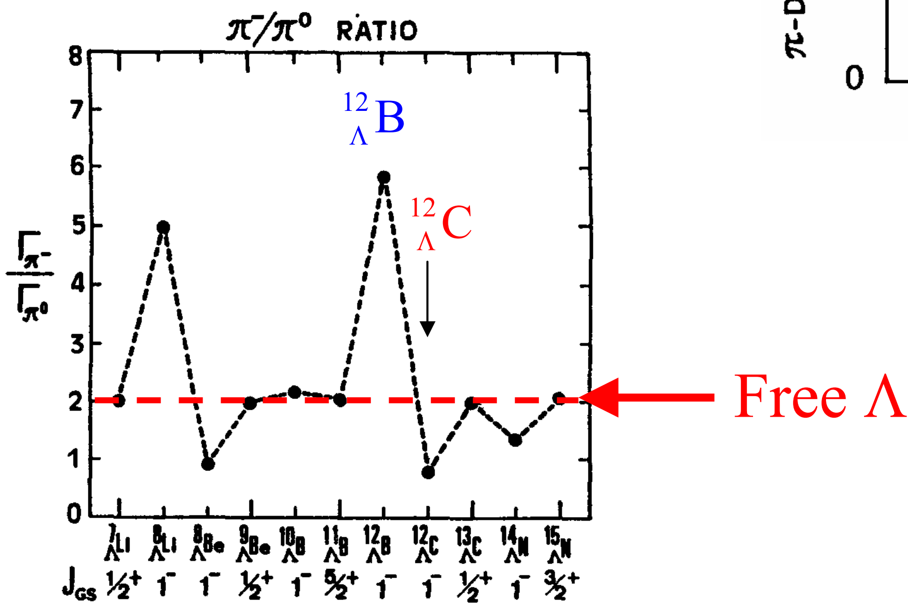
  & π-distortion effect in nucleus

  ⇒ systematic study of p-,sd-shell Λ nuclei

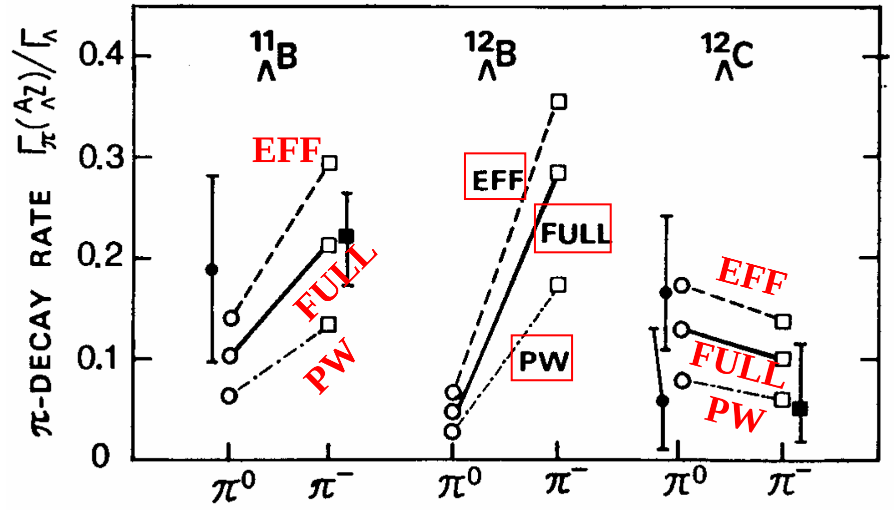
  Λ-nucleus pot. in ${}^{5}_{\Lambda}He$

Effect of nuclear shell structure





π-nucleus pot. dependence



FULL: MSU
EFF : effective pot.
PW : plane wave

Bando, Motoba, Zofka

ハイペロンの非中間子弱崩壊

Λ核

$$\Lambda + N \rightarrow N + N$$

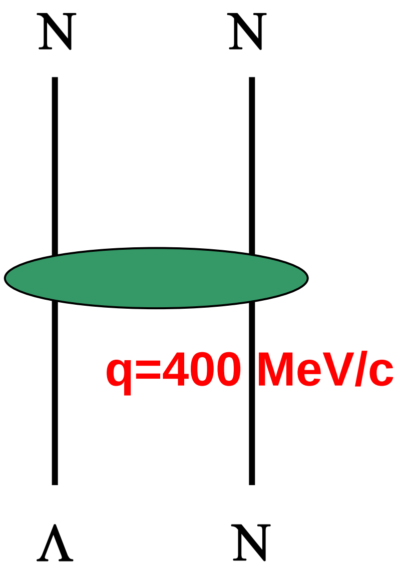
$$\Lambda + p \rightarrow n + p : \Gamma_p$$
$$\Lambda + n \rightarrow n + n : \Gamma_n$$

Double-Λ 核

$$\Lambda + \Lambda \rightarrow Y + N$$

$$\Lambda + \Lambda \rightarrow \Lambda + n$$
$$\Lambda + \Lambda \rightarrow \Sigma^0 + n$$
$$\Lambda + \Lambda \rightarrow \Sigma^- + p$$

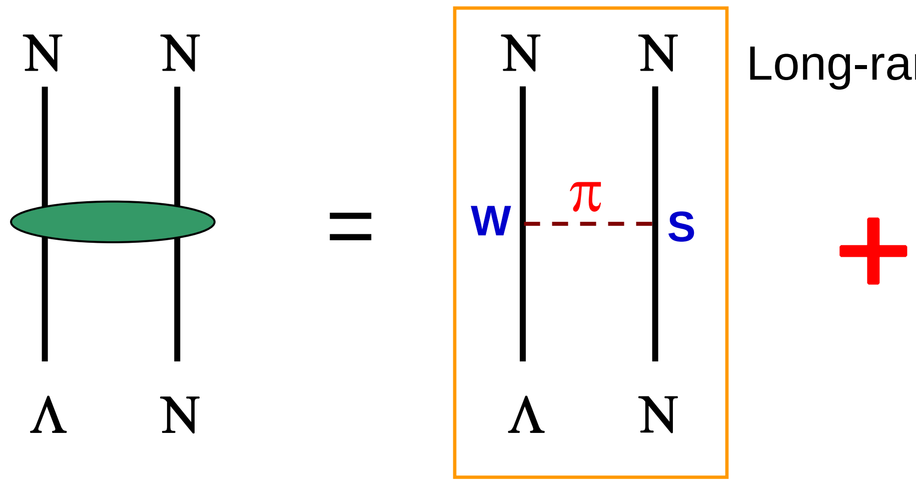
Σ核生成？



現状	理論	実験 $^5_\Lambda He$
1. n/p ratio (Γ_n/Γ_p) puzzle	0.1－0.5	≈ 1 ⇒ ≈ 0.4
2. Asymmetry puzzle	negative	positive
3. ΔI=1/2 rule		

実験：Kang et al. PRL96 (2006)

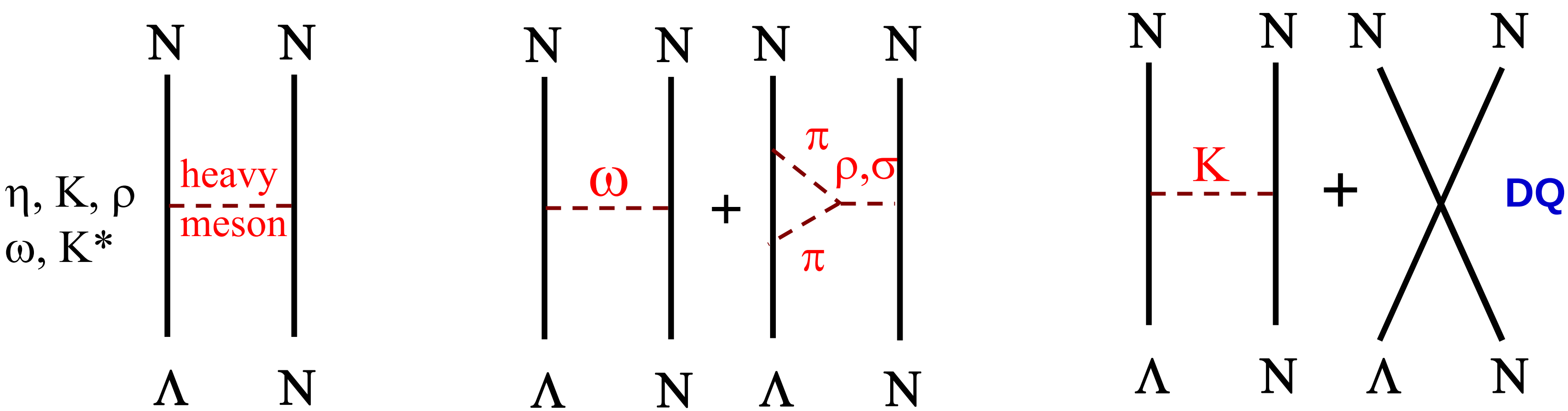
理論のアプローチ



Long-range part

one π exch
: $\Gamma_n/\Gamma_p \approx 0.1$

Middle & Short-range part



Parreno & Ramos
PRC65 (2002)

Itonaga, Ueda, Motoba
PRC65 (2002)

Sakaki, Inoie, Oka
NPA707(2002)

まとめと今後

- ハイパー核の理論的研究の概観

  ハイパー核構造 ⇔ 核力(YN,YY,NN)

  Λ核、Σ核、ΛΛ核、Ξ核、・・・

  少数体系の構造計算(ΛΣ結合の重要性, ・・・)

  γ線分光学, Nagara event, ・・・

- 今後のハイパー核構造研究

  keVの精度

  波動関数の精密化の必要性 ⇔ **γ線の実験(スピン軌道分岐、・・・)**

  NNテンソル相関の効果 + ハイペロン混合の効果

  少数体系の構造計算の成果をうまく取り入れた模型構築

  現実的核力からのp殻ハイパー核構造研究

- **(*p*, *n*, *S*)空間での核物質の存在様式・運動様式**

  J-PARCの成果に期待！