Requests to theorists from experimentalists

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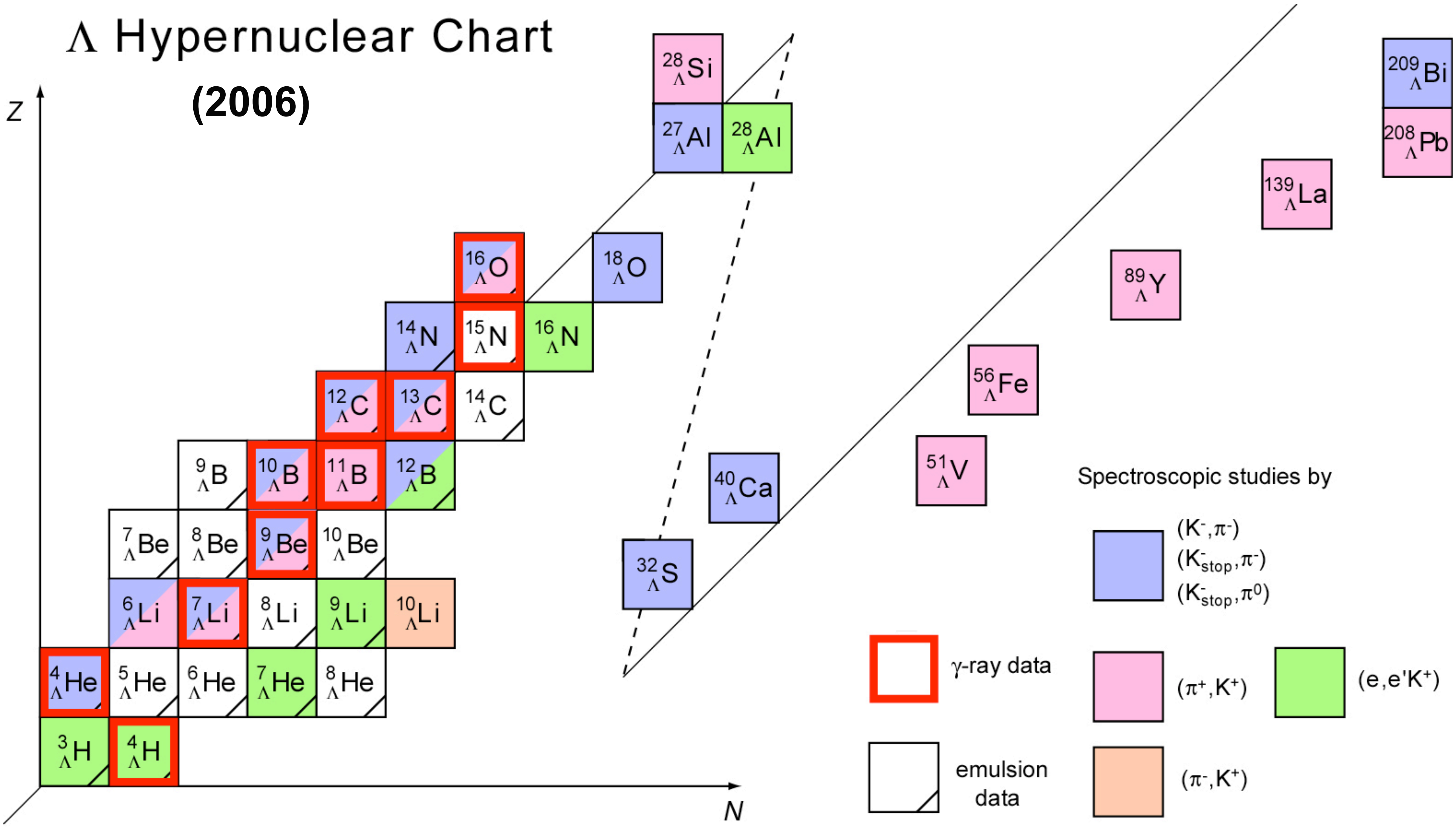
Experimental status and plans

Experimental plans (2009~2019)

- Λ hypernuclear structure
  - (e,e'K$^+$) : A=7~89, ΔE = 400 keV (FWHM)
  - γ spectroscopy: A=4~208, B(M1), B(E2), n-rich,..
  - (π^-,K$^+$) n-rich : $^{6}_{\Lambda}$H, $^{9}_{\Lambda}$He, …
  - High-resolution ($\pi^\pm$,K$^+$)
  - HI induced reaction: p-rich/n-rich
- Ξ hypernuclear spectroscopy: U_Ξ, W_Ξ, ΞN-$\Lambda\Lambda$ mixing
- $\Lambda\Lambda$ hypernuclei: $B_{\Lambda\Lambda}$ and decay
- Ξ atomic X-rays
- Σ hypernuclei/ Σ–nuclear systems
- Weak decays
- ΛN, ΣN, (ΞN) scattering

Present Status of
Λ Hypernuclear Spectroscopy



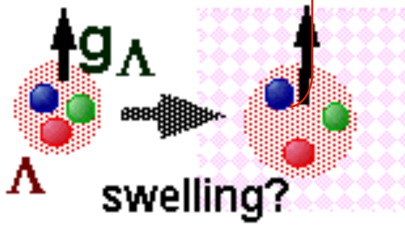
Updated from: O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564.

J-PARCでのガンマ線分光のテーマ(例)

- ΛN 相互作用の詳細 (E13)
  - Charge symmetry breaking $^{4}_{\Lambda}$He(1^{+}-0^{+})
  - ΛN スピン依存相互作用と ΛNN force $^{10}_{\Lambda}$B and $^{11}_{\Lambda}$B
  - ΛN 相互作用の動径依存性 $^{19}_{\Lambda}$F

J-PARC E13

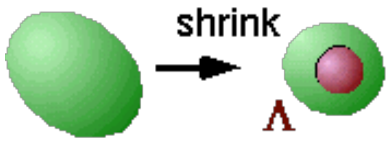
- B(M1) 測定 -> 核内Λのg因子の変化 $^{7}_{\Lambda}$Li



- B(E2) 測定

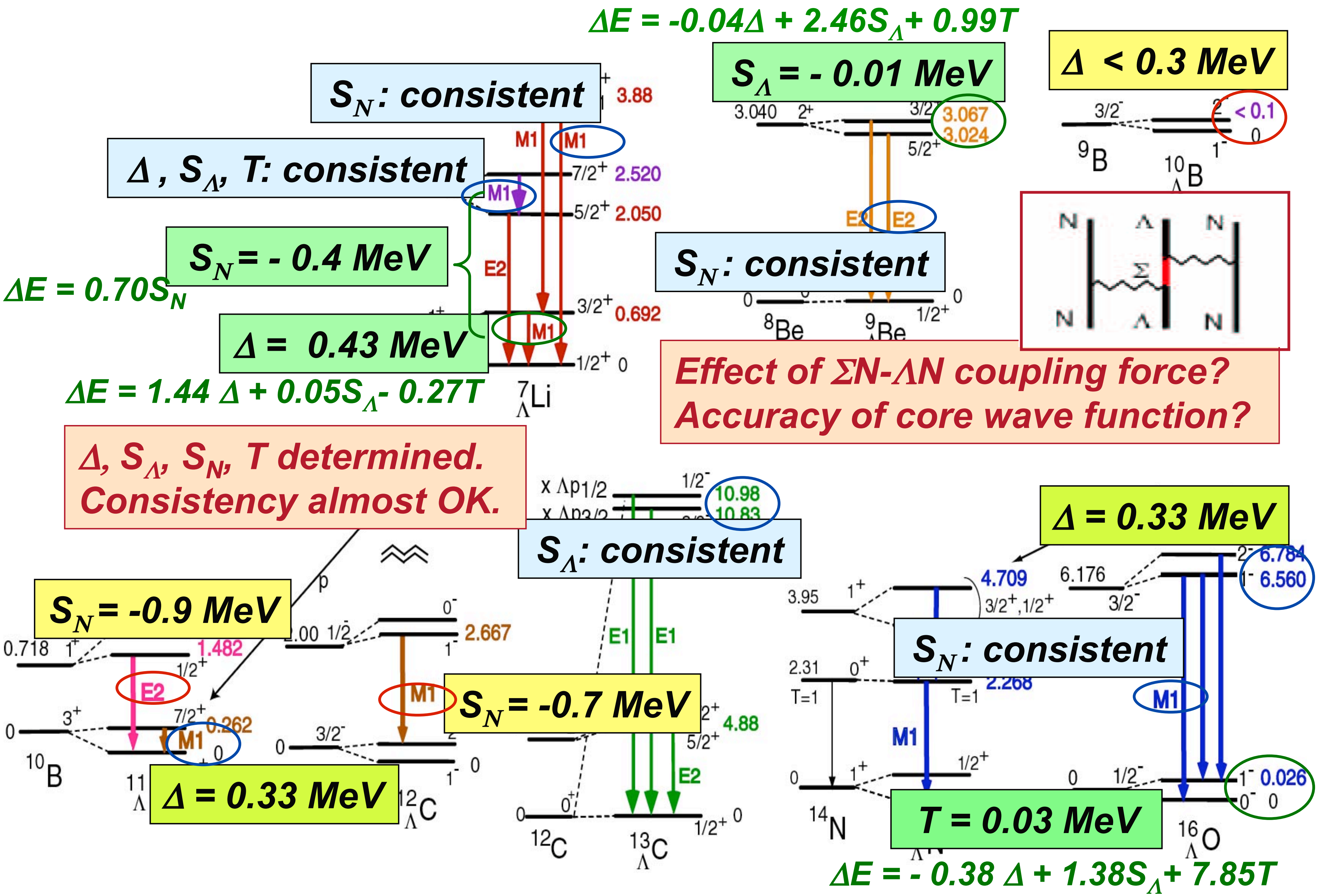
$^{9}_{\Lambda}$Be and $^{13}_{\Lambda}$C → ^{8}Be,^{12}Cのクラスター構造と Λによるその変化
$^{7}_{\Lambda}$He → ^{6}Heの中性子ハローの消失

- sd-殻ハイパー核
  →変形、集団運動の変化



- 重いΛハイパー核 $^{89}_{\Lambda}$Y, $^{208}_{\Lambda}$Pb, etc.
  → Λ核ポテンシャルの詳細、核内深部のバリオンの性質
  (s_{Λ}-p_{Λ} energy, p_{Λ} LS splitting, B(M1))

Interaction Parameters (Millener)



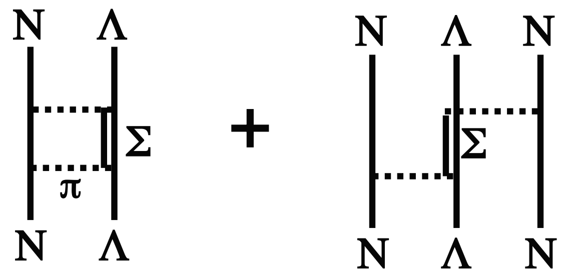
Millener's approach for ΛN-ΣN coupling

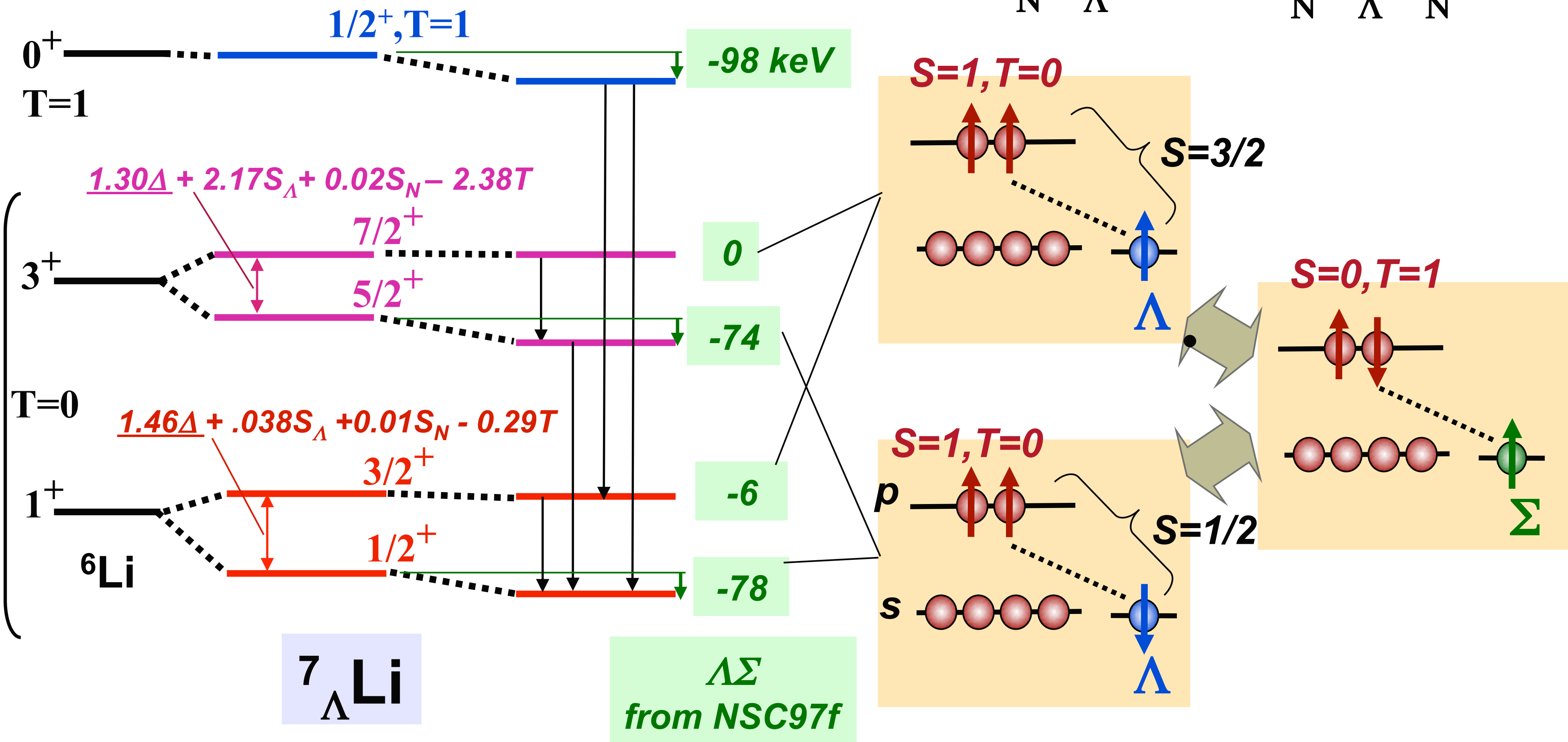
Millener, Lecture Notes in Physics 724, Springer (2007) p.31

$v = \langle p_N^{A-5}\, s_\Sigma(J) \mid V \mid p_N^{A-5}\, s_\Lambda(J) \rangle$ *V: NSC97f through G-matrix (spin-dependent)*

Energy shift $(\Lambda\Sigma) = v^2 / (m_\Sigma - m_\Lambda)$

($s_N^4 s_\Sigma - s_N^4 s_\Lambda$ *coupling has no spin-dependence and can be incorporated in effective 2B ΛN force.)*



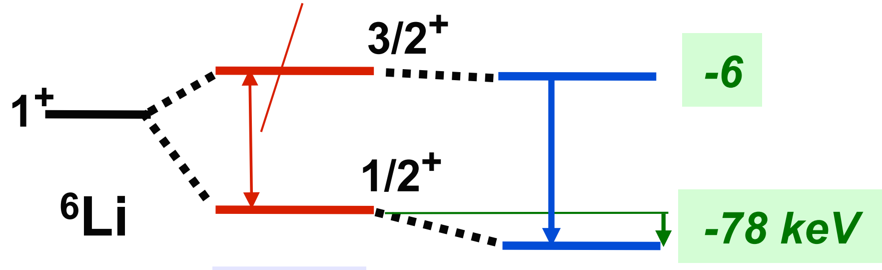


Spin-spin strength (Δ) and Λ-Σ coupling (Millener)

ΛΣ from NSC97f

S_Λ = -0.01 MeV, T = 0.03 MeV from exp.

$\underline{1.46\Delta} + .038S_\Lambda + 0.01S_N - 0.29T$



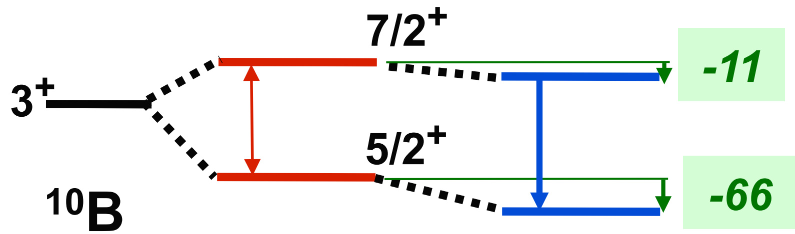
$^{7}_{\Lambda}$Li

Exp. 692 keV

w/o ΛΣ : Δ = 0.50 MeV

➡ w/ ΛΣ : Δ = 0.43 MeV

$\underline{1.03\Delta} + 2.47S_\Lambda + 0.03S_N - 3.36T$



$^{11}_{\Lambda}$B

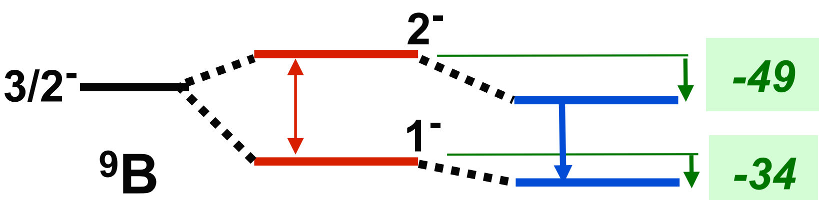
Exp. 264 keV

Size Effect ?

➡ Δ = 0.33 MeV

ΛΣ is correct ?

$\underline{0.58\Delta} + 1.41S_\Lambda - 0.01S_N - 1.07T$



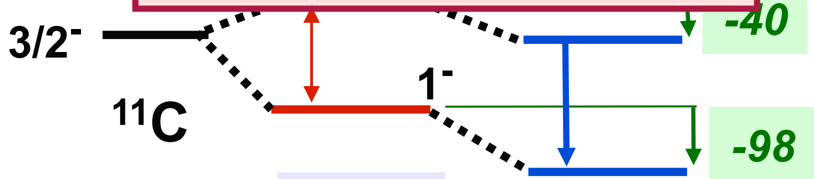
$^{10}_{\Lambda}$B

Exp. < 100 keV

➡ Δ < 0.3 MeV

$0.54\Delta + 1.4S_\Lambda - 0.05S_N - 1.72T$

ΛN p-wave force ?



$^{12}_{\Lambda}$C

E566:under analysis

核内Λのg因子測定

核内バリオンの磁気モーメント

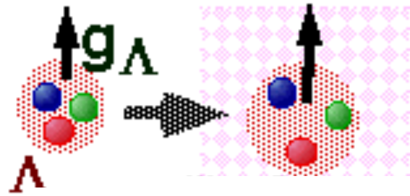
カイラル対称性の部分的回復の影響を受けるか？

→ バリオンのスピンの起源、質量の起源と深く関連

核内 μ_Λ -> バリオンの核媒質効果をみる

$\mu_q = \dfrac{e\hbar}{2m_q c}$ m_q : Const. quark mass

m_q が減少→ μ_q増大？



swelling → μ_q増大？

- 直接測定は極めて困難 (τ ~ 0.1-- 0.2 ns)
- Λ-spin-flip M1 遷移のB(M1) -> g_Λ

g_c

$\psi_{\Lambda\uparrow}\ \psi_c$

$\psi_{\Lambda\downarrow}\ \psi_c$

$$B(M1) = (2J_{up}+1)^{-1}\,|\langle \Psi_{low} \| \mu \| \Psi_{up} \rangle|^2$$

$$= (2J_{up}+1)^{-1}\,|\langle \psi_{\Lambda\downarrow}\psi_c \| \mu \| \psi_{\Lambda\uparrow}\psi_c \rangle|^2$$

$$\mu = g_c \boldsymbol{J}_c + g_\Lambda \boldsymbol{J}_\Lambda = g_c \boldsymbol{J} + (g_\Lambda - g_c)\boldsymbol{J}_\Lambda$$

$$= \frac{3}{8\pi}\,\frac{2J_{low}+1}{2J_c+1}\,(g_\Lambda - g_c)^2 \quad [\mu_N^2]$$

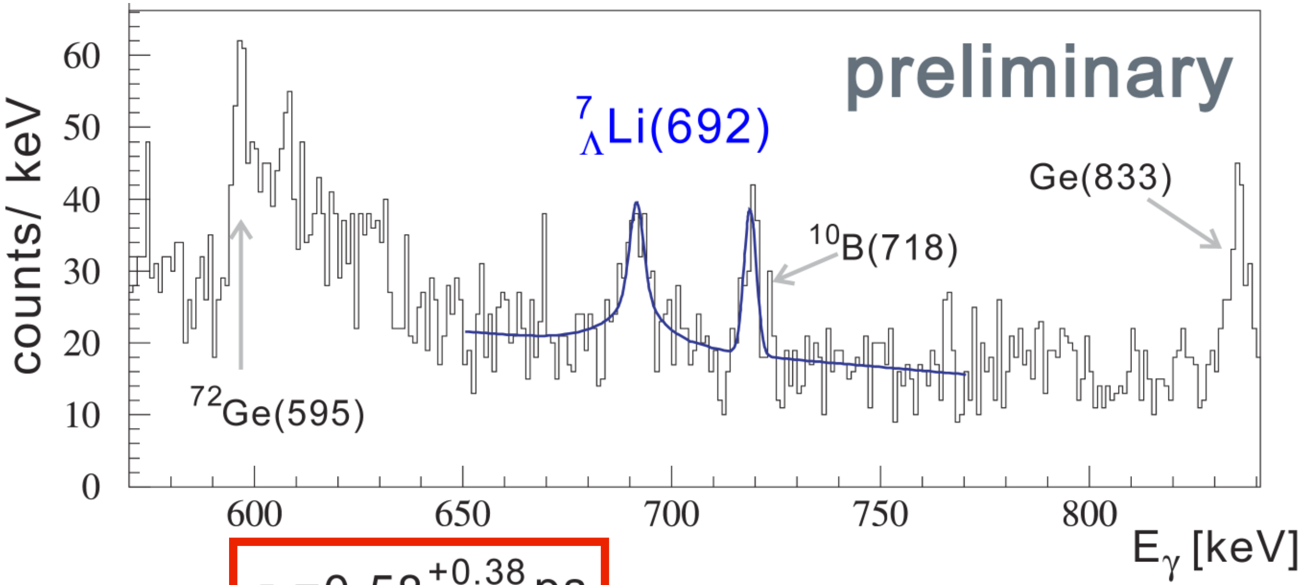
~100% **Doppler Shift Attenuation Method :**

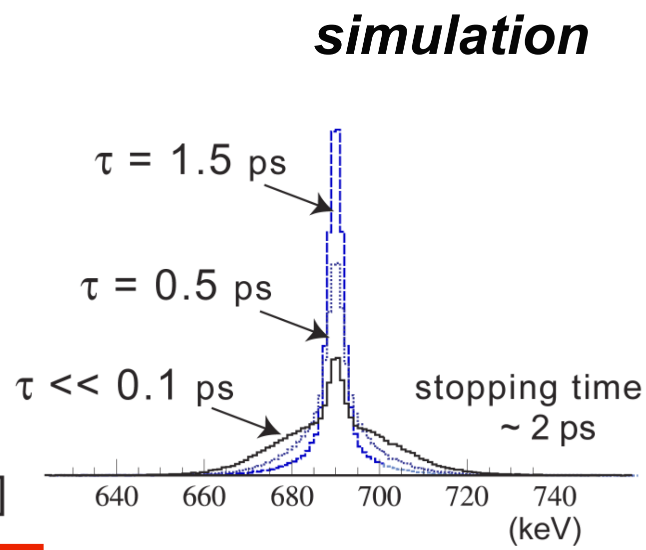
$$\Gamma = BR/\tau = \frac{16\pi}{9} E_\gamma^3\, B(M1)$$

Applied to “hypernuclear shrinkage” in $^7_\Lambda$Li from B(E2) : ***PRL 86 (’01)1982***

Preliminary data on B(M1) in $^{7}_{\Lambda}$Li (BNL E930)

^{10}B (K$^-$, π^-) $^{10}_{\Lambda}$B*, $^{10}_{\Lambda}$B*(3$^+$) -> $^{7}_{\Lambda}$Li*(3/2$^+$) + ^{3}He indirect population





$\tau = 0.58^{+0.38}_{-0.20}$ ps

BR(M1)=100%

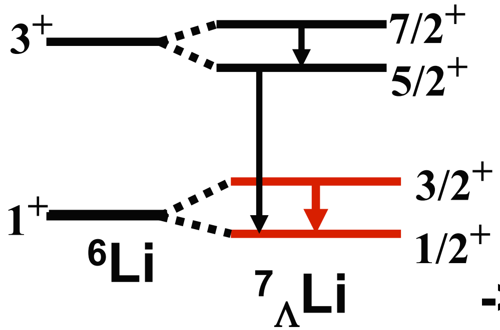
➡ $B(M1) = 0.30^{+0.12}_{-0.16}$ [μ_N^2]

➡ $- g_\Lambda = 1.1^{+0.4}_{-0.6}$ μ_N

preliminary (statistical error only)

⬌ $- g_\Lambda$(free) = 1.226 μ_N

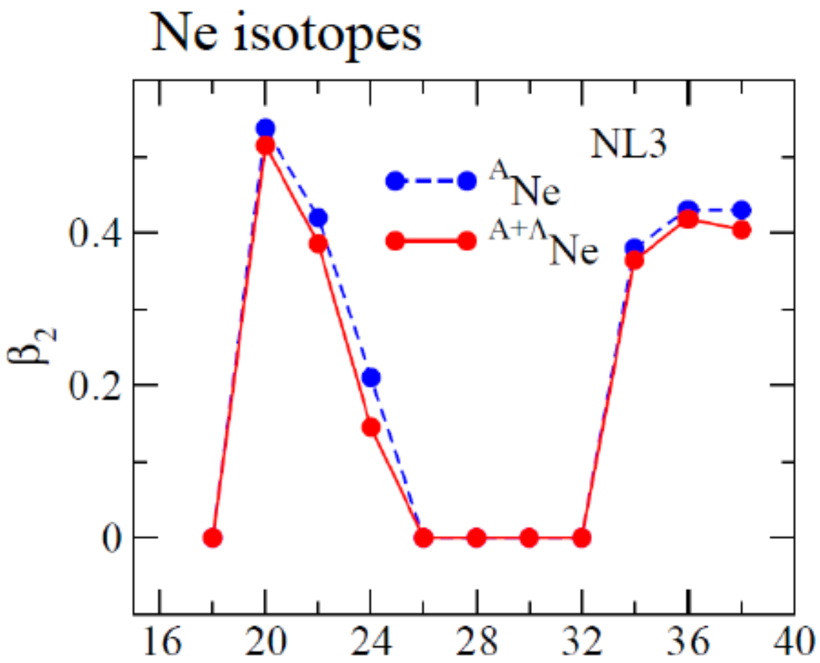
First data of g_Λ in nucleus

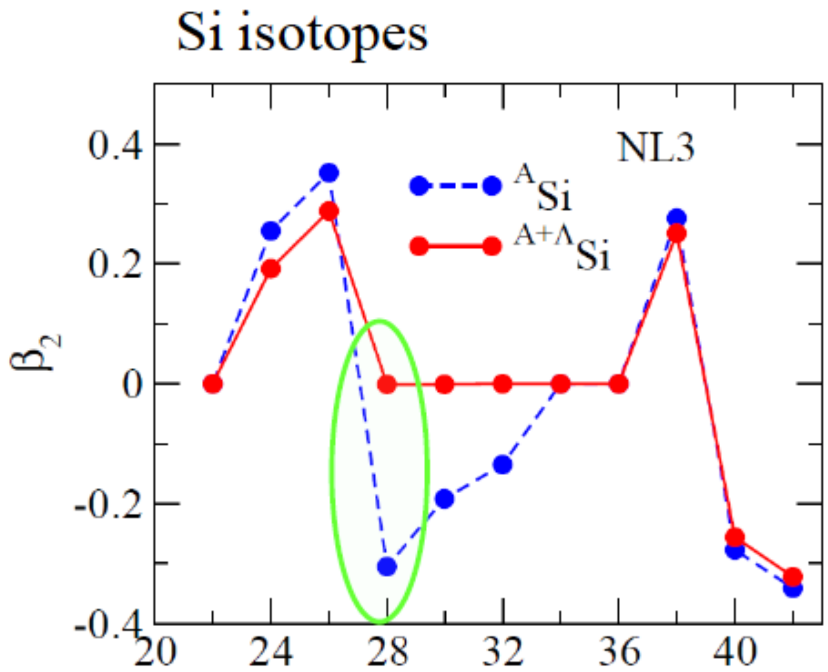


-> Precise B(M1) measurement of $^{7}_{\Lambda}$Li at J-PARC

J-PARC E13 (Tamura et al.)

Impurity effect in deformation (Hagino)

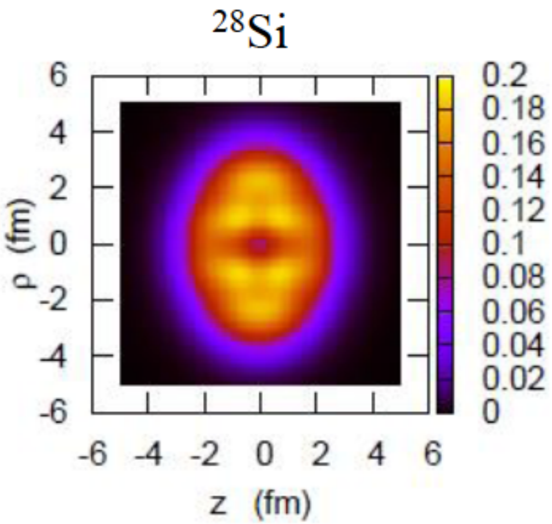




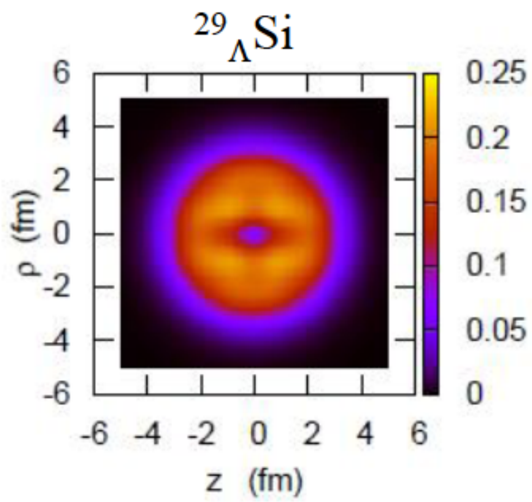
- in most cases, the hypernucle
- hypernuclei: sl

⟶ conc

Exception: $^{29}{}_{\Lambda}$S



Λ ⟶



Myaing Thi Win and K.H., PRC78('08)054311

Requests to theorists

Λ hypernuclear structure

- **Need for shell-model description better than Millener's ($s^4p^{A-5}s_\Lambda$)**
  - Need for larger shell model space and better core wave functions
  - Distinguish effects of 2B and 3B interactions from ΛN-ΣN ?

  (The 2-body ΛN-ΣN coupling force is incorporated in the effective ΛN interaction. Double counting?)
  - Effect of ΛN-ΣN coupling with s^4 nucleons ?
    - Important *(Nemura et al. PRL 89 (2002) 142504)* but incorporated in 2BF?
  - Relation between BB interaction models and the parameters

- **Need for Few-body calc. with $\Lambda\Sigma$ coupling for p-shell ($^{7}_{\Lambda}$Li, $^{10}_{\Lambda}$B , $^{11}_{\Lambda}$B)**
  - Cluster model calculations with ΛN−ΣN coupling
  - Ab initio calculation (Quantum Monte Carlo…) possible?
  - Extract contributions of p-wave force
  - Inclusion of tensor force (for p1/2 shell hypernuclei?)

- **Radial dependence of ΛN int. from sd-shell structure?**

- **How to extract info. on ΛNN force from n-rich hypernuclei?**

- **Collective motion in sd shell hypernuclei (mean-field approach)**

Other issues in Λ hypernuclei

- B(M1) for $^{7}_{\Lambda}$Li
  - Effect of "core polarization"
  - Effects of meson exchange current and Σ mixing
  - Effect of partial restoration of chiral symmetry
  - $^{12}_{\Lambda}$C and other hypernuclei
- Charge Symmetry Breaking（どちらかというと実験待ち）
  - $^{4}_{\Lambda}$H-$^{4}_{\Lambda}$He with recent BB interactions
  - A=7, A=12 ….(e,e'K$^+$) data (will be) available.
- Medium/Heavy hypernuclei
  - B_Λ, m^*_Λ, s_Λ-p_Λ in heavy hypernuclei -> then what can we see?
  - How LS splitting appears in large A ?
  - B(M1) in heavy hypernuclei

Weak decays

- Asymmetry puzzle – solved? μ can be measured?
- ΛNN -> NNN: What is new? (Bhang)
- Direct quark process unnecessary in NMWD?

  What is the unified picture of BB interaction?
- ΔI=1/2 rule ($^4{}_\Lambda$H, $^4{}_\Lambda$He exp.) (Ajimura)
- π^+ decay should be measured?
- $\Lambda\Lambda$ -> ΣN, ΛN decay: How is the relation to H-dibaryon correlation in nucleus?
- Semi-leptonic decay Λ -> p $e^- \nu_{bar}$, Λ -> p $\mu^- \nu_{bar}$ BR~10^{-3}

  -> Possible change of baryon property

  How sensitive to wave function of s/u quark in nucleus?

  (Also sensitive to Pauli effect…)

実験施設充実のために必要な検討

- **K1.1 ライン** （補正でできるかも） for (K^-, π^-)
  - ガンマ線分光（sd-shell, medium-heavy）
    -> 集団運動の不純物効果、核内Λの性質変化

    どれくらいの効果が期待できるか？　ポテンシャルの詳細と核内Λの性質変化の関係は？
  - ΣN, ΛN scattering　測定精度と相互作用模型の判別性は？
  - 少数系Σ核 –> ΣN相互作用の(T,S)ごとの強さ

    どれくらいの精度で強さが決まるのか？
  - Θ核, weak decay, …

- **High-Resolution pion line (Noumi line)**

  20億円　＋ホール拡張（80億円）
  - ($\pi^{\pm}$,K^+) 高分解能(~200 keV FWHM) 分光
    → (中重)Λ核、中性子過剰Λ核、Σ核、(weak decay)

    何がどこまでわかるのか？　インパクトは？

    他に使い道は？

G-matrix results for various interactions

Rijken et al., PRC59 (1999) 21

TABLE XIV. Contributions to U_Σ at $k_F = 1.0\ \mathrm{fm}^{-1}$ in the cases of NSC97e, NSC97f, NSC89, NHC-F, and NHC-D. Conversion widths Γ_Σ are also shown. All entries are in MeV.

	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
ESC04d	**6.5**	**-21.0**	**-3.4**	**-20.2**	**24.0**	**-20.9**	**-26.0**	
fss2(quark)	**6.7**	**-23.9**	**-5.2**	**-9.2**	**41.2**	**-1.4**	**7.5**	

Rijken, Yamamoto PRC73 (2006) 044008

Fujiwara et al., Prog.Part.Nucl.Phys. 58 (2007) 439

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

Lane term $(\sigma_\Sigma\sigma_N)(\tau_\Sigma\tau_N)$ by π/ρ exchange

quark Pauli effect

Previous $^3He(K^-,\pi^-)$ data at BNL E774

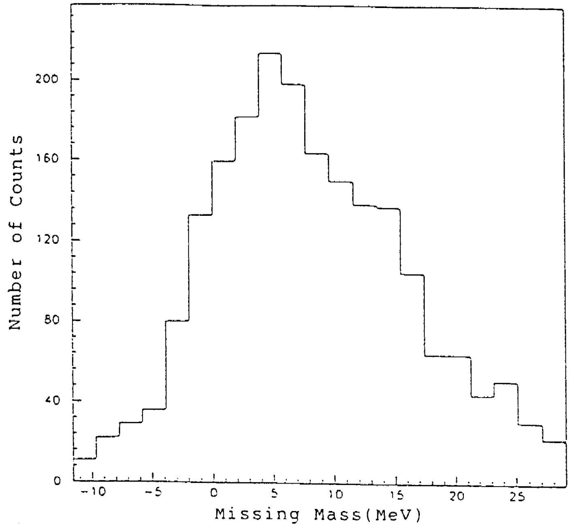


Fig. 1 Missing Mass Spectrum of $^3He(K^-,\pi^+)$ reaction.

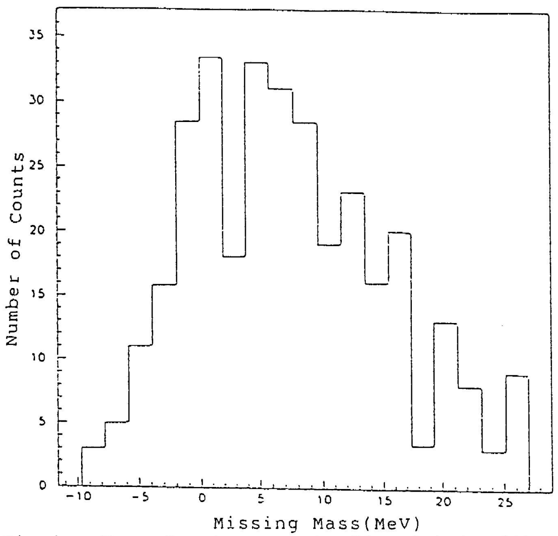
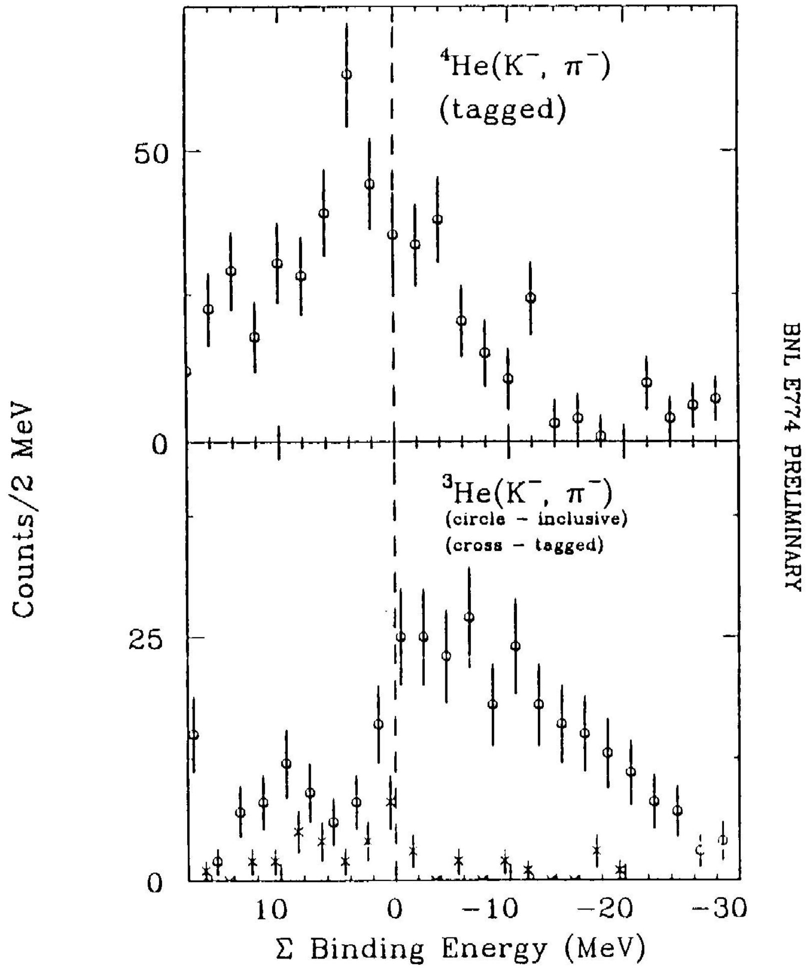


Fig. 2 Missing Mass Spectrum as in fig. 1 but with multiplicity 2 cut.



Top: $^4He(K^-,\pi^-)$ data tagged with the multiplicity ≥ 2 condition (same as ›m-left). Bottom: $^3He(K^-,\pi^-)$ spectra. Inclusive data are in open circles and multiplicity-tagged data are in crosses.

Proposed ^{3}He experiment

- ^{3}He (K^-,$\pi^{\pm,0}$ Λ) at threshold, p_K~0.5~0.6 GeV/c (q < 50 MeV/c)
- $^3_\Sigma$He, $^3_\Sigma$H, $^3_\Sigma$n : different combination of
  ($T_{N\Sigma}$,$S_{N\Sigma}$) = (3/2,1), (3/2,0), (1/2,1), (3/2,0) from $^4_\Sigma$He, $^4_\Sigma$n
- 3-body systems can be accurately calculated
  -> direct comparison with various interactions
  (how sensitive? – theoretical calculations essential)
- Apparatus: Low momentum beam line (K1.1BR)
  + beam spectrometer + SPESII and π^0 spectrometer + Λ tagger (CDS)

Koike-Harada (NPA611(1996)461) "Unstable bound states"

E_Σ (Γ)	SAP-1(ND)	SAP-F(NF)
$^3_\Sigma$He (T=1,S=1/2)	---	+1.77 (7.58) MeV
$^3_{\Sigma 0}$H (T~1,S=1/2)	+0.01 (1.95)	+0.63 (8.2) MeV
$^3_\Sigma$n (T=1,S=1/2)	---	+0.55 (9.05) MeV

Spectral shapes should be calculated.

Experiment

- Beam spectrometer (Δp_{FWHM} <1.5 MeV/c at 600 MeV/c)

  in place of K1.1BR B3
- 3He target
- Λ tagger => CDS
- $\pi^{\pm}$ spectrometer (Δp_{FWHM} <1.5 MeV/c at 500 MeV/c)

  => SPESII
- π^0 spectrometer (Δp_{FWHM} ~ 3 MeV/c at 500 MeV/c)

Yield (K^-, $\pi^{\pm}$): $N_{K^-} \cdot d\sigma/d\Omega \cdot \Delta\Omega \cdot N_{target} \cdot \varepsilon(\Lambda tag) \cdot \varepsilon$

$= 5 \times 10^5$ /spill $\cdot\, 50 \times 10^{-30} cm^2/sr \cdot 0.02 sr \cdot 0.09 g/cm^3 / 3 \cdot 10 cm \cdot 6 \times 10^{23} \cdot 0.3 \cdot 0.5$

=> 1400 counts/100hours ***->Lower beam momentum?***

Yield (K^-, $\pi^{\pm 0}$):

=> ~100 counts/100hours