研究会「ハイパー核物理の発展と今後の展望」
2013年7月7，8日 志摩市 和州閣

ストレンジネスでさぐる
核内バリオンの性質変化

東北大学　田村裕和

Contents

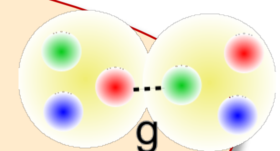
1. ハイパー核物理の意義とガンマ線分光の現状

ストレンジネス核物理の意義

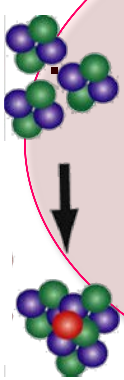
様々なストレンジ核·3次元核図表の拡大

BB(バリオン間)　相互作用

u,d -> u,d,s 拡張によるBB間力の統一的理解、
特に短距離力のクォーク描像での理解
Lattice QCDの検証

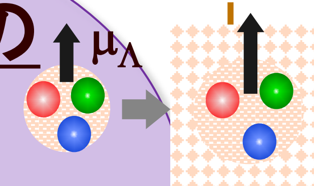


不純物核物理



核の大きさ、変形、クラスター性、
集団運動などの(劇的)変化
新しい対称性の発現
ハイペロンを用いた通常核の
構造解明

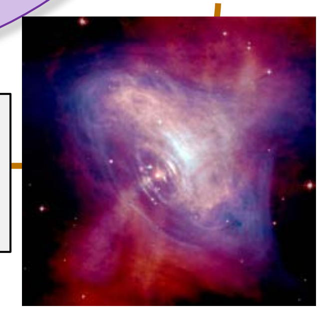
核内バリオンの性質変化



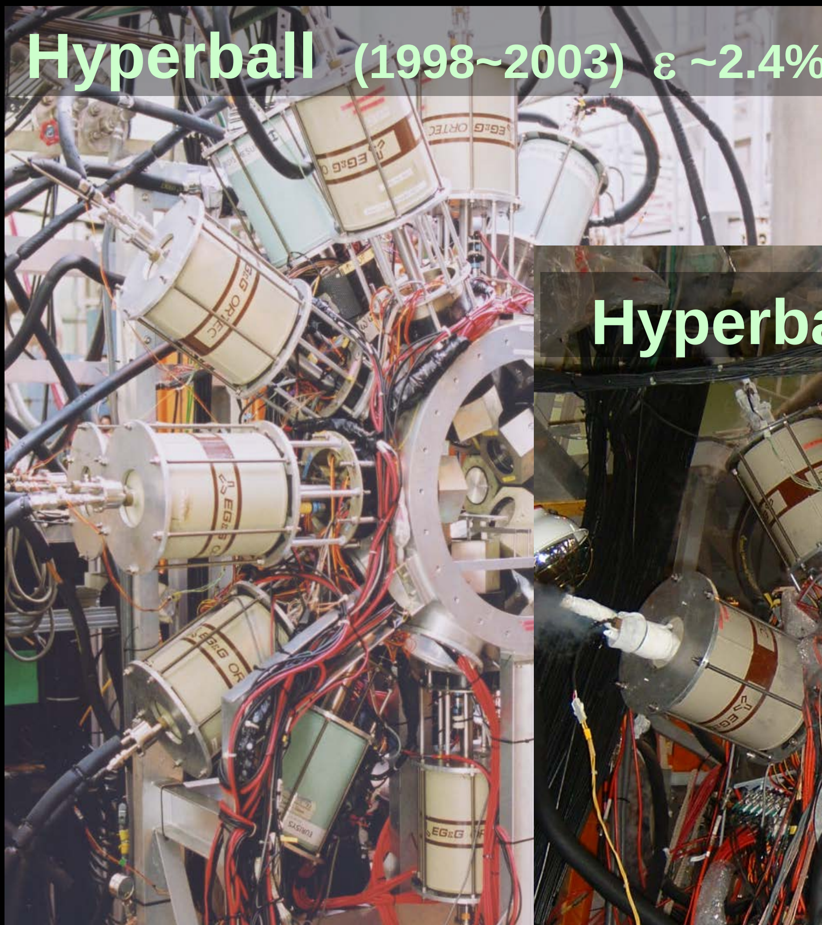
核内μ_Λ や重いΛ核一粒子軌道から
カイラル対称性の破れと
核子スピン·質量の起源の理解へ

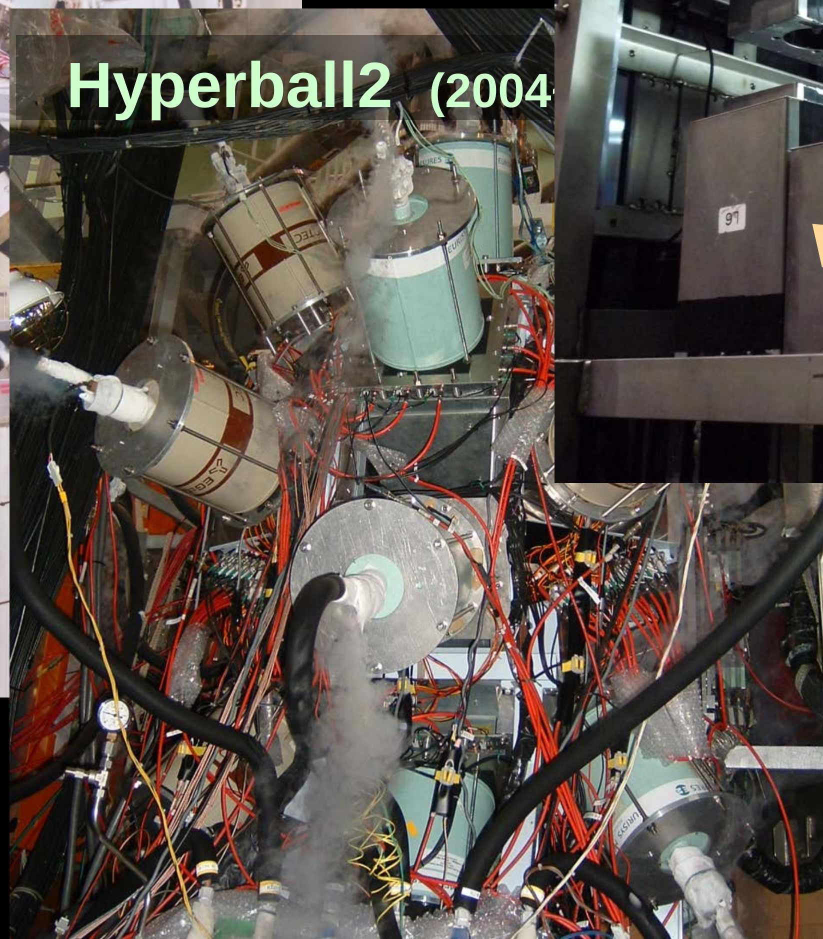
クォーク -> ハドロン -> 原子核
の首尾一貫した真の理解

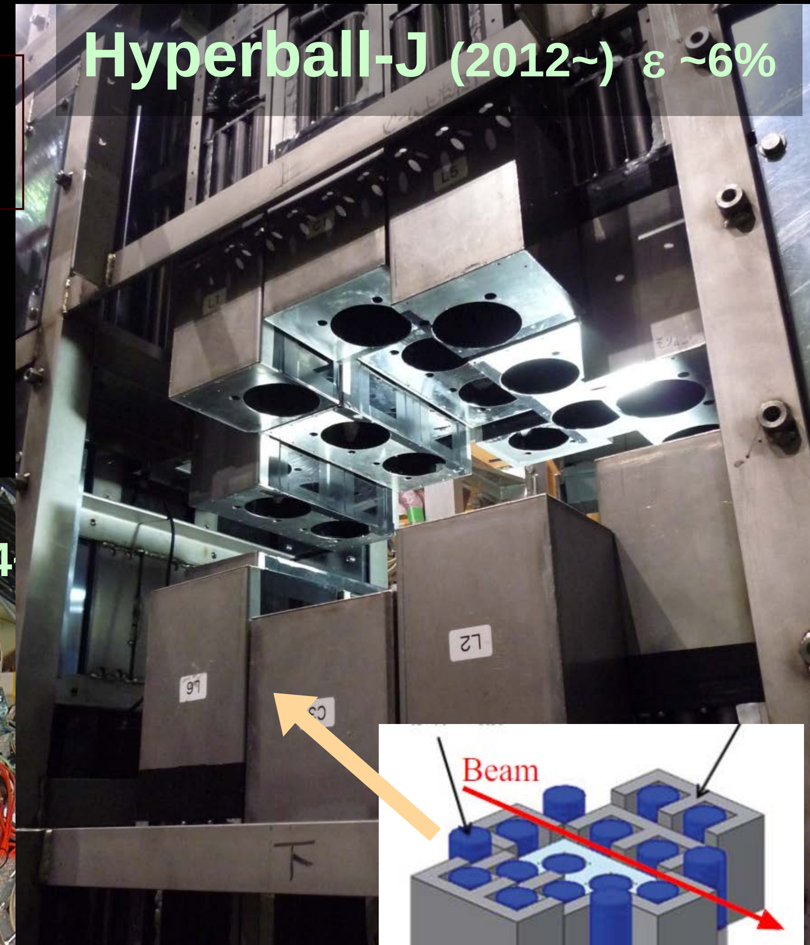
低温高密度核物質の
解明

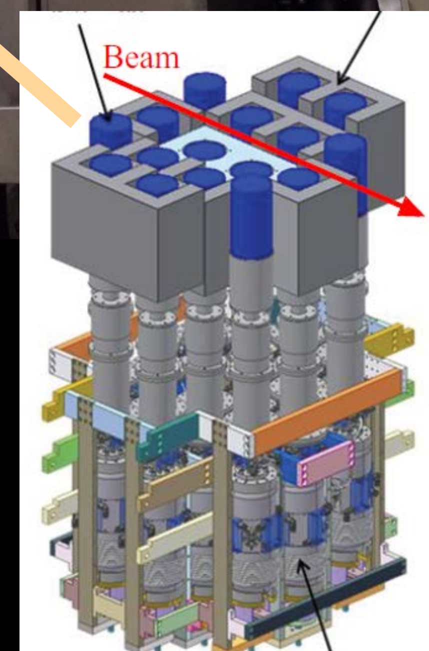


ハイパー核
精密ガンマ線分光
1998~

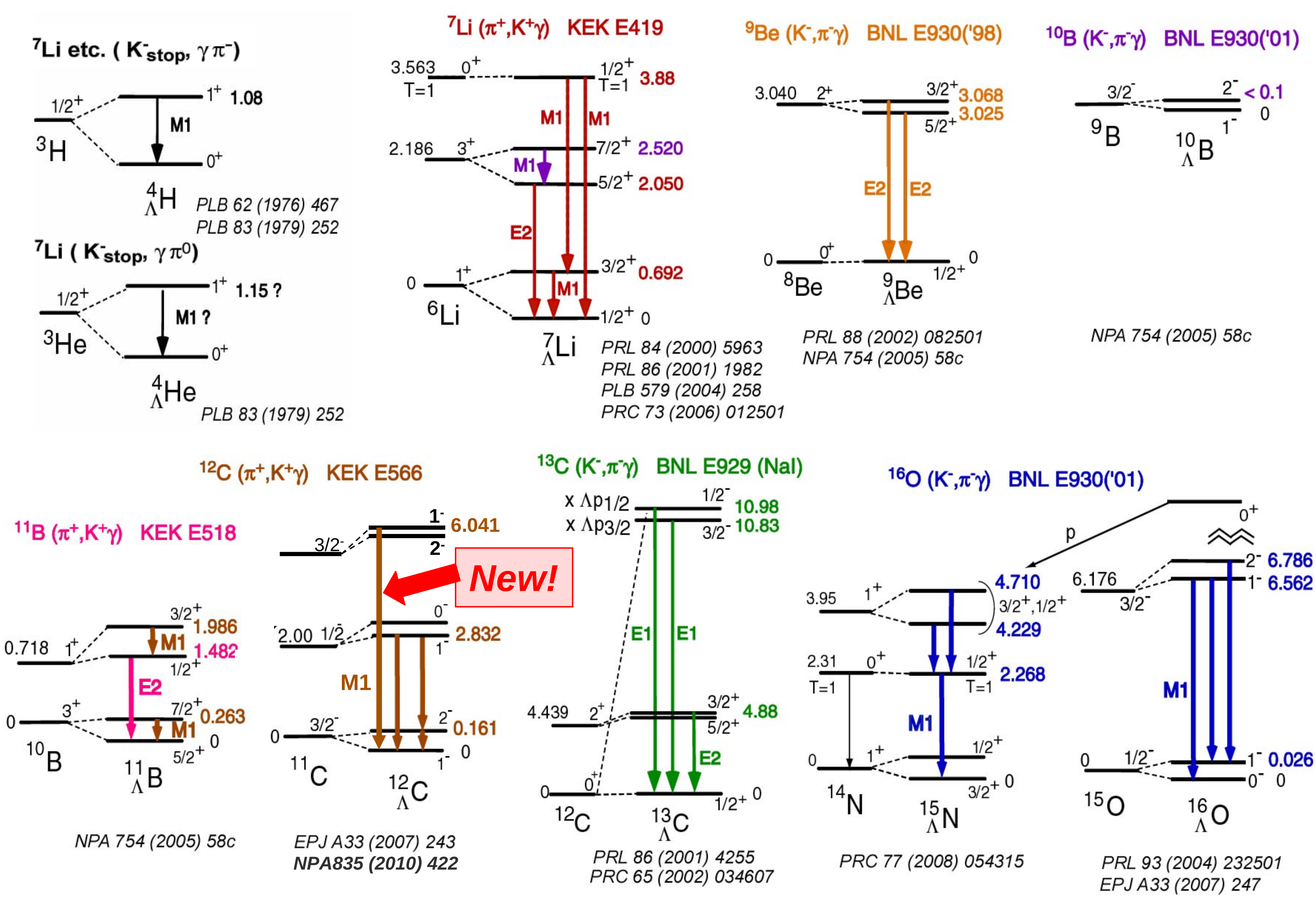




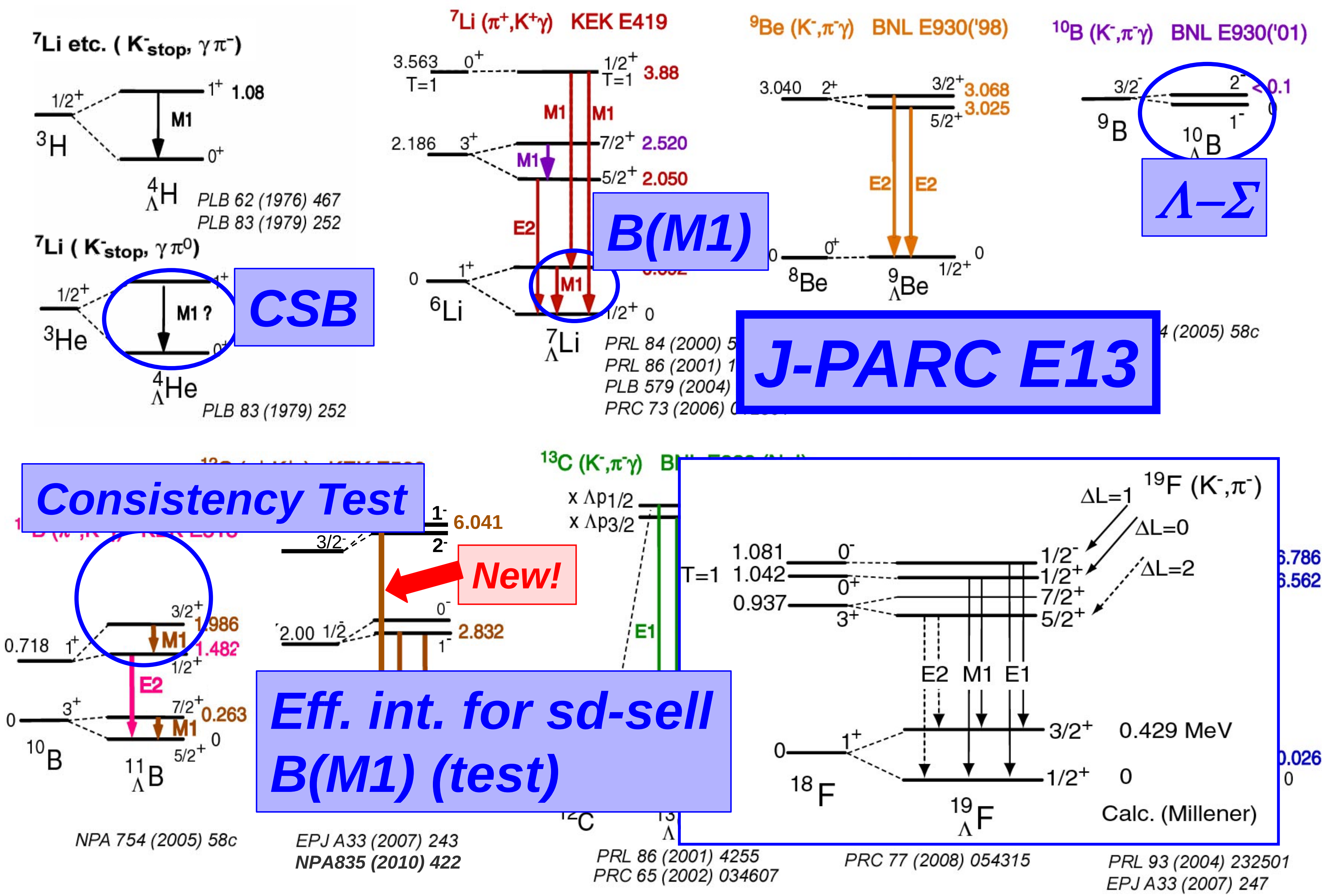




Hypernuclear γ-ray data (2012)



Hypernuclear γ-ray data (2012)



$^{7}_{\Lambda}$Li ground-state spin determined by the yield of γ-rays subsequent to weak decay

J. Sasao [a], D. Abe [a], H. Akikawa [b,1], K. Araki [a], H. Bhang [c], T. Endo [a], Y. Fujii [a], T. Fukuda [d,2], O. Hashimoto [a], K. Imai [b], H. Hotchi [e,1], Y. Kakiguchi [d], J.H. Kim [c], Y.D. Kim [f], T. Miyoshi [a,3], T. Murakami [b], T. Nagae [d], H. Noumi [d], H. Outa [d,4], K. Ozawa [a], T. Saito [g], Y. Sato [a,5], S. Satoh [a], R. Sawafta [h], M. Sekimoto [d], T. Takahashi [a], H. Tamura [a], L. Tang [i], K. Tanida [e,4], H.H. Xia [j], S.H. Zhou [j], L.H. Zhu [b,j]

[a] *Department of Physics, Tohoku University, Sendai 980-8578, Japan*
[b] *Department of Physics, Kyoto University, Kyoto 606-8502, Japan*
[c] *Department of Physics, Seoul National University, Seoul 151-742, South Korea*
[d] *Institute of Particle and Nuclear Studies, KEK, Tsukuba 3*
[e] *Department of Physics, University of Tokyo, Tokyo 113*

KEK E419
PLB 579 (2004) 258

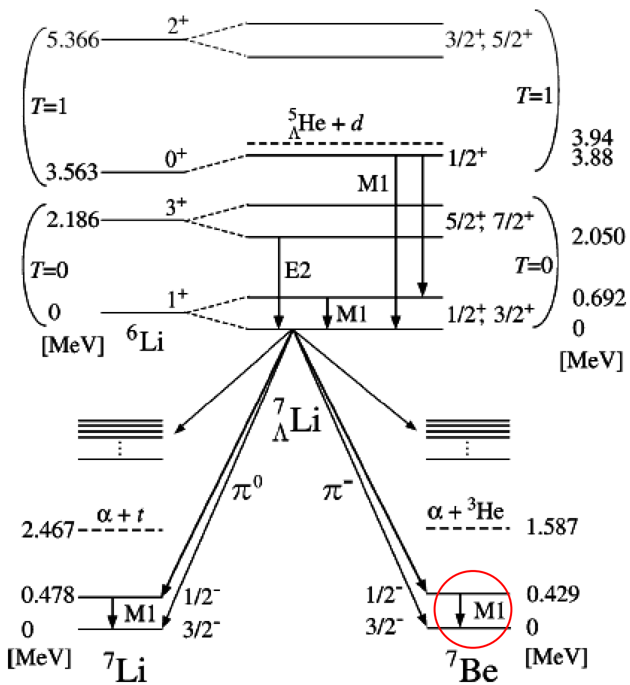


Fig. 3. Scheme of γ transitions and mesonic weak decays of $^{7}_{\Lambda}$Li. The ground state of $^{7}_{\Lambda}$Li decays into ^{7}Be or ^{7}Li through the π^- or π^0 mesonic weak decays, respectively. When $^{7}_{\Lambda}$Li decays into the first excited states of ^{7}Be or ^{7}Li, γ-rays of 429 or 478 keV are emitted, respectively.

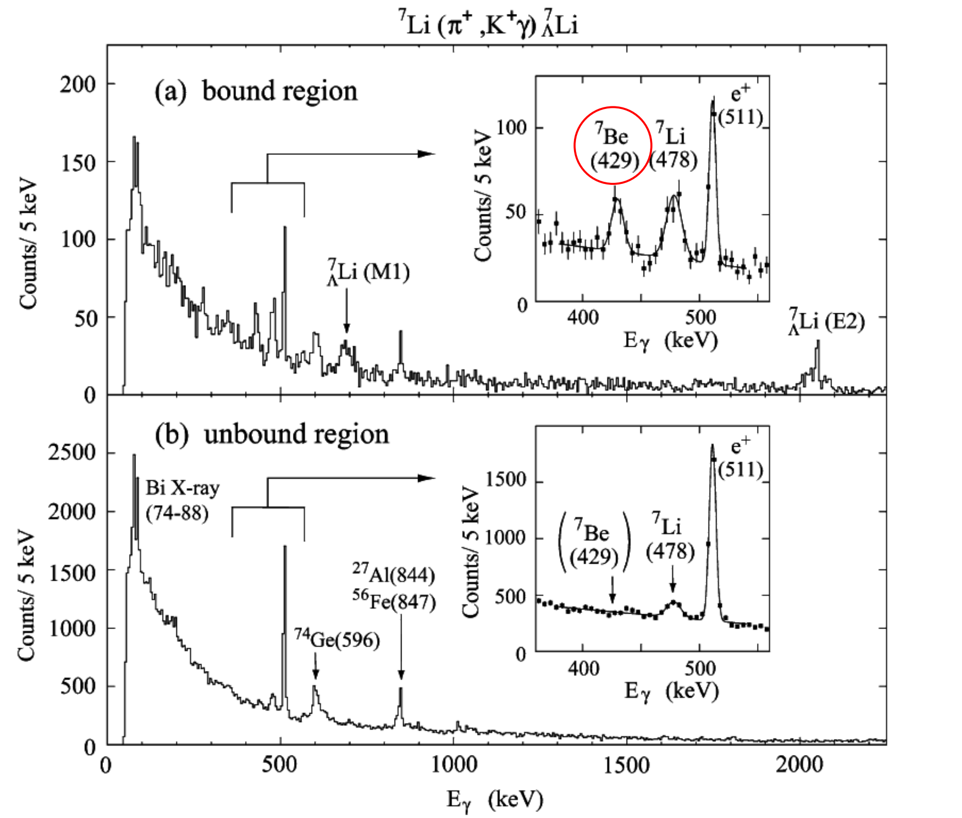


Fig. 2. γ-ray spectra measured in the ^{7}Li(π^+, K^+) reaction (a) for the bound region ($-10 < -B_\Lambda < 2$ MeV) and (b) for the unbound region ($-B_\Lambda > 2$ MeV) of $^{7}_{\Lambda}$Li. The insets show the spectra expanded around 400–500 keV. The two peaks at 429 and 478 keV observed in (a) are attributed to the transitions from the first excited states of ^{7}Be and ^{7}Li, respectively. In (b), only the 478 keV peak was observed. The region around these peaks were fitted with three Gaussians and a linear background.

16年前に詳しく計算されていた
元場さんの先見の明に感銘

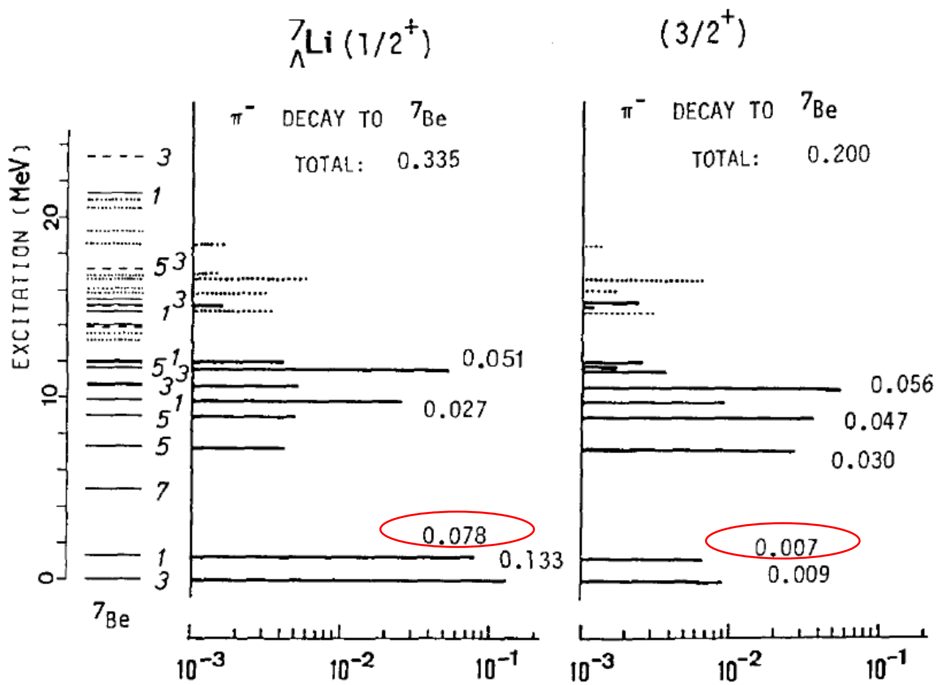
Nuclear Physics A489 (1988) 683–715
North-Holland, Amsterdam

PI-MESONIC DECAY OF LIGHT Λ-HYPERNUCLEI

T. MOTOBA
Laboratory of Physics, Osaka Electro-Communication University, Neyagawa, Osaka 572, Japan
K. ITONAGA
Department of Applied Mathematics, Osaka University, Toyonaka, Osaka 560, Japan
H. BANDŌ
Division of Mathematical Physics, Fukui University, Fukui 910, Japan

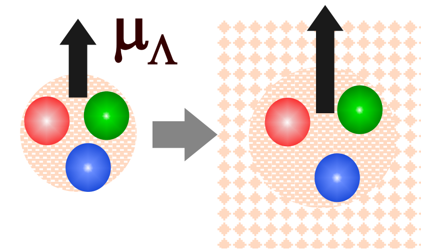
Received 2 June 1987
(Revised 16 June 1988)

The π-mesonic decays of all p-shell Λ hypernuclei are studied using the shell model combined with density-dependent Hartree–Fock wavefunctions. The pion distortion is taken into account by using the optical potential. The summed decay rate of π^0 and π^- decays decreases with the mass number A, while each decay rate (Γ_{π^0}, Γ_{π^-}) exhibits a non-trivial and characteristic variation with A, reflecting the shell-structure effects. Among the π-mesonic decay partial rates some strong transition strengths are seen in, for example, π^- decays of $^{9}_{\Lambda}$Li and $^{9}_{\Lambda}$Be and π^0 decay of $^{12}_{\Lambda}$C. Large-asymmetric pion angular patterns are predicted in π^- decays from the polarized hypernuclei such as $^{8}_{\Lambda}$Li(1^-), $^{8}_{\Lambda}$Be(1^-) and $^{9}_{\Lambda}$Be($\frac{1}{2}^+$).



2. 核内Λのg因子

核内Λ の磁気モーメント



カイラル対称性の部分的回復で変化するか？

$$\mu_q = \frac{e\hbar}{2m_q c}$$

m_q : Const. quark mass

m_q は核内で減少 -> μ は増加?

-> constituent quarkとは？スピンの起源は？の理解の手がかり

Λ-スピン反転 M1 遷移の遷移確率 B(M1)

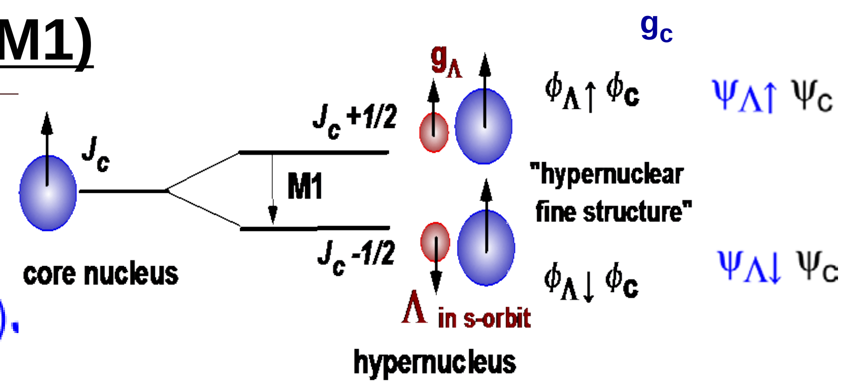
$$B(M1) = (2J_{up}+1)^{-1} |\langle \Psi_{low} \| \mu \| \Psi_{up} \rangle|^2$$

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

$$\mu = g_c J_c + g_\Lambda J_\Lambda = g_c J + (g_\Lambda - g_c),$$

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

: ただし、Λによりg_cが変化しなければ。
–Λスピンによるg_cの変化は小さいのでOK(?)



~100%

Doppler Shift
Attenuation Method

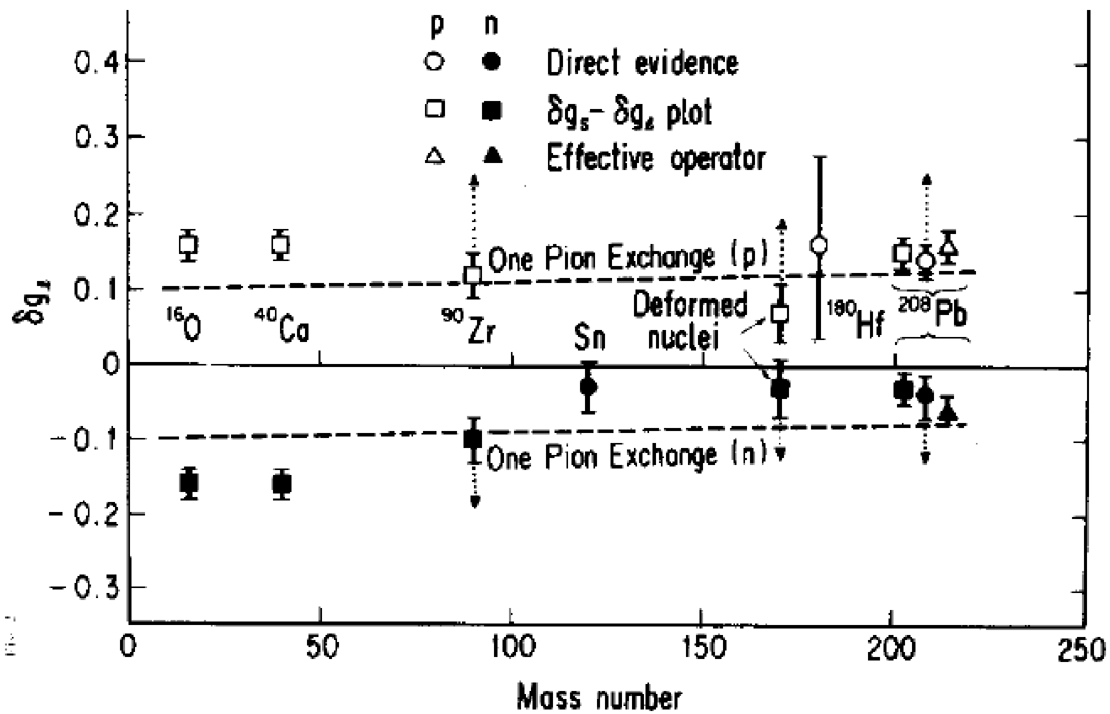
$$\Gamma = BR / \tau = \frac{16\pi}{9} E_\gamma^3 B(M1)$$

J-PARC E13 (Tamura et al.)
γ spectroscopy of light Λ hypernuclei

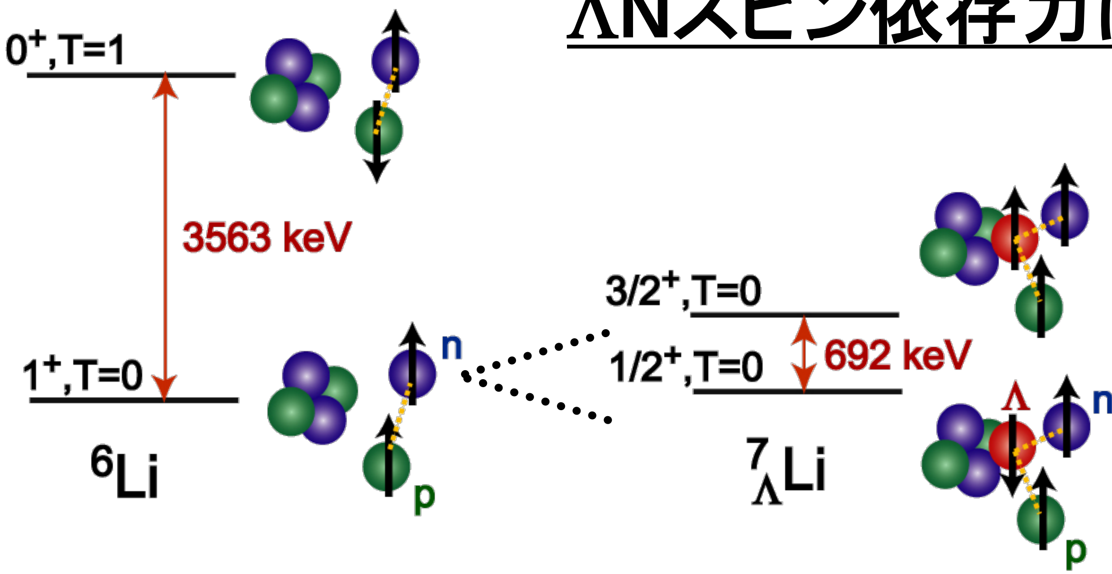
EVIDENCE FOR AN ENHANCED NUCLEAR MAGNETON IN NUCLEI FROM δg_l ANOMALIES; A MODIFICATION OF THE NUCLEON'S PROPERTIES IN NUCLEI

Toshimitsu YAMAZAKI
Physik Department, Technische Universität München, D-8046 Garching, Fed. Rep. Germany
and Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113, Japan

The effective nuclear magneton in nuclei has been found to be (8 + 3)% larger than the free value from a careful analysis of the proton–neutron asymmetric effect of the observed δg_l factors in the $A = 208$ region. This suggests a modification of the nucleon's properties in nuclei.



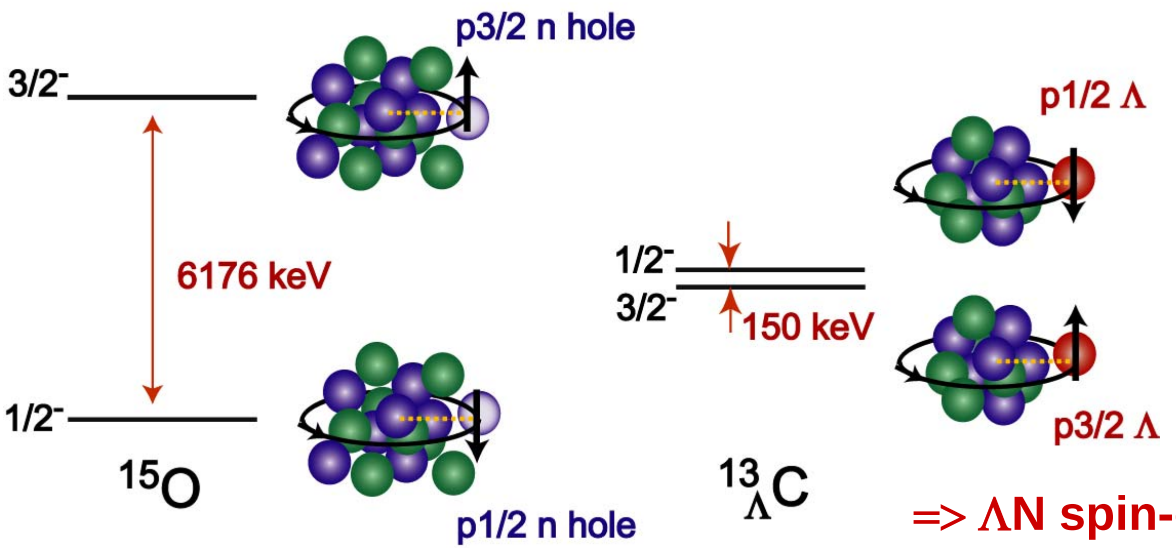
ΛNスピン依存力はこんなに小さい



Tamura et al., PRL 84 (2000) 5963

$\Delta = 0.42$ MeV

=> ΛN spin-spin force
~ 1/10 of NN spin-isospin force



Ajimura et al., PRL 86 (2001) 4255

($S_\Lambda = -0.01$ MeV)

=> ΛN spin-orbit force
~ 1/40 of NN spin-orbit force

Weak coupling assumption is OK?

Theoretical predictions without exotic effects

$^{7}_{\Lambda}$Li ($3/2^+ \to 1/2^+$)

B(M1) $[\mu_N^2]$	method
0.322	$^{5}_{\Lambda}$He+p+n cluster model (Hiyama et al.)
0.309	shell model (Motoba et al.)
0.352	α+d+Λ cluster model (Motoba, old)
0.364	shell model (Gal, old)
0.326	shell model (Gal, old)

The variation gives a rough magnitude of nuclear effect.

Preliminary data on g_Λ

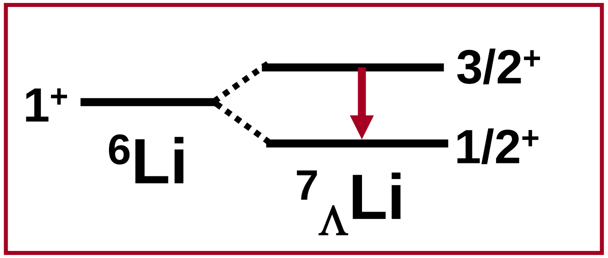
- **BNL E930** (M. Ukai)

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

τ from DSAM

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

$\rightarrow\ ^{7}_{\Lambda}Li^* +\ ^{3}He$



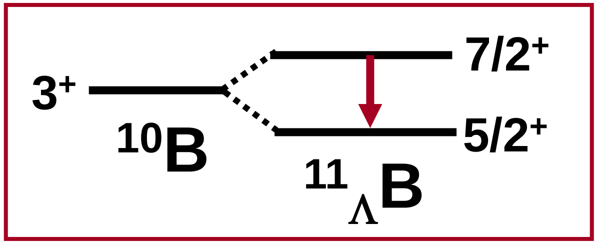
- **KEK E566** (Y. Ma)

$g_\Lambda > -1.76\ \mu_N$

τ from DSAM

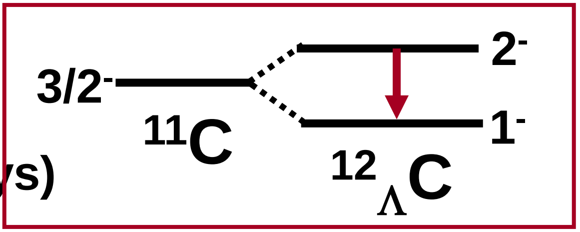
$^{12}C\ (K^-, \pi^-)\ ^{12}_{\Lambda}C^*$

$\rightarrow\ ^{11}_{\Lambda}B^* + p$



$g_\Lambda = -1.04 \pm 0.41\ \mu_N$

$^{12}C\ (K^-, \pi^-)\ ^{12}_{\Lambda}C^*$



- Yield ratio for $[2^- \rightarrow 1^-] / [1^-_2 \rightarrow 2^-]$ γ-rays
  $\rightarrow Br(2^- \rightarrow 1^-) = 0.19 \pm 0.12$ (80% of 2^- weakly decays)
- Weak decay rate of 2^- and 1^- are <u>assumed</u> to be the same, Γ_{weak} = (lifetime 230.7 ± 6.3 ps)$^{-1}$

$\Rightarrow\ \Gamma_{M1} = Br / (1 - Br)\ \Gamma_{weak}$

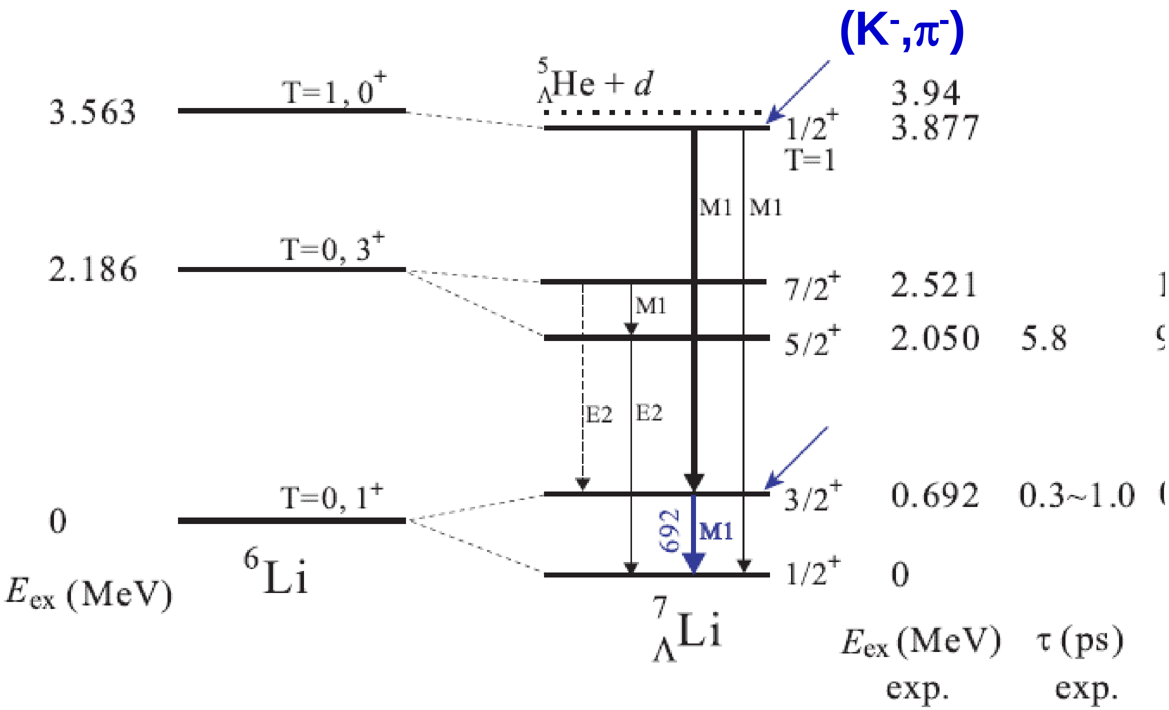
$\Leftrightarrow\ g_\Lambda(\text{free}) = -1.226\ \mu_N$

Proposed B(M1) measurement

To avoid ambiguities, we use the best-known hypernucleus, $^{7}_{\Lambda}$Li.

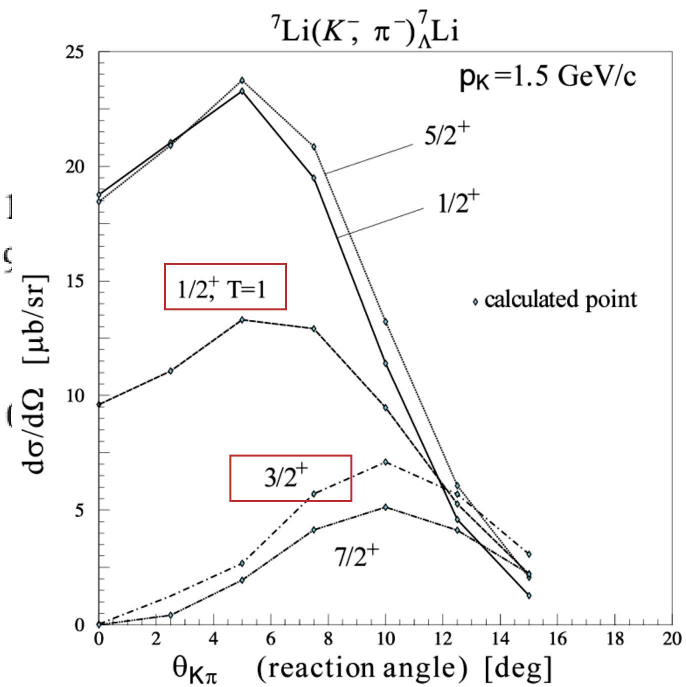
- Energies of all the bound states and γ-ray background were measured.
- Cross sections are reliably calculated.
- τ = 0.5ps, t_{stop} ~2.7 ps for 1.5 GeV/c (K^-,π^-) and Li_2O target
  ~ 2.2 ps for 1.1 GeV/c

(Doppler Shift Attenuation Method works only when $\tau < t_{stop}$)



Tamura et al., PRL 84 (2000) 5963
Ukai et al., PRC 73 (2006) 012501

Calc. by Motoba



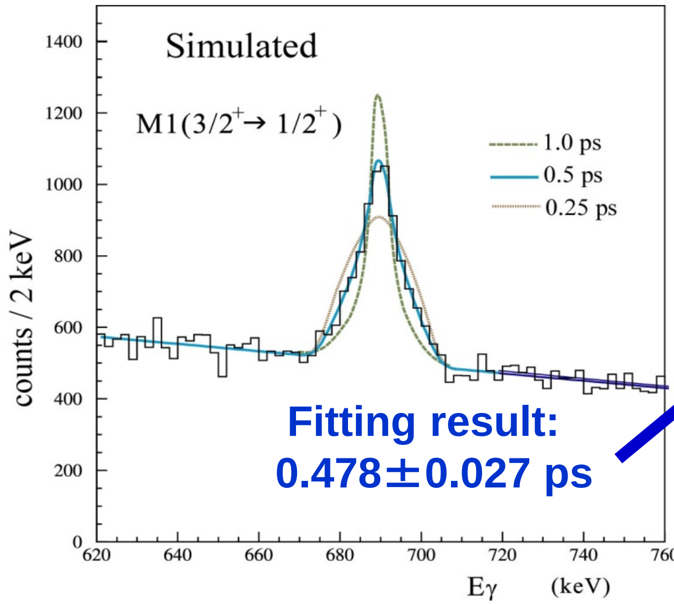
元場さん、いつもありがとうございます。

Expected yield and sensitivity

Original run plan

- p_K = 1.5 GeV/c at K1.8+SKS
- 500 hours
- 270 kW (Ni)

Original proposal



■ Stat. error $\Delta\tau/\tau = 5.4\%$

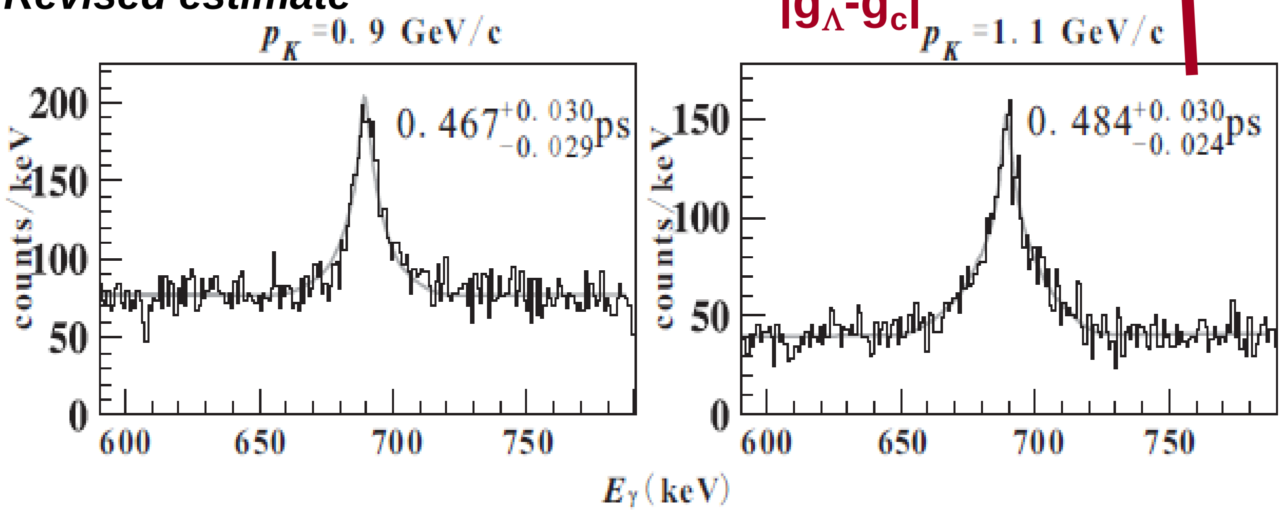
$$\Rightarrow \frac{\Delta|g_\Lambda - g_c|}{|g_\Lambda - g_c|} \sim 3\%$$

■ Syst. error < 5%
mainly from stopping time

■ Stat. error $\Delta\tau/\tau = 5.6\%$

$$\Rightarrow \frac{\Delta|g_\Lambda - g_c|}{|g_\Lambda - g_c|} \sim 3\%$$

Revised estimate



Revised run plan

- p_K = 1.1 GeV/c at K1.1+SKS
- 4 weeks (672 hours)
- 50 kW (Pt)

Future possibility

- **If a large shift of B(M1) is observed,**

  ρ and *T* dependence should be studied from various hypernuclei

  - **Meson-exchange current, $\Sigma-\Lambda$ mixing => *T* dependence**
  - **Restration of chiral symmetry => ρ dependence**

- **τ(M1) ~ t_{stop} (condition for DSAM) cannot be often satisfied.**

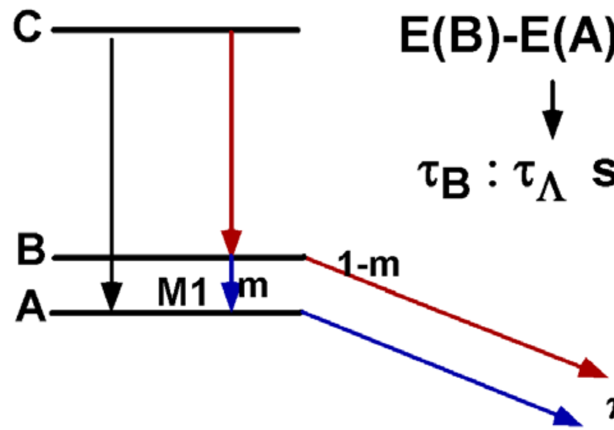
  Heavier hypernuclei -> smaller doublet spacing

  -> longer τ(M1) ~ τ(weak decay)

  Another method for longer τ(M1) is necessary.

B(M1) measurement by γ-weak coincidence

H. Tamura, NPA 754 (2005) 58c

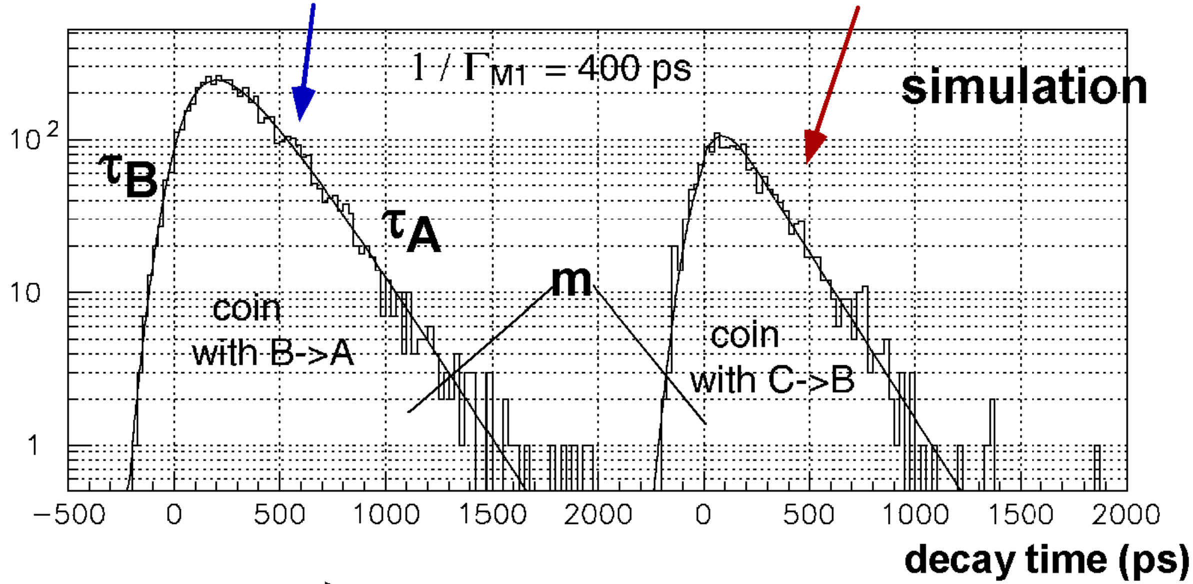


E(B)-E(A) < 0.1 MeV

↓

$\tau_B : \tau_\Lambda$ same order (0.1～0.3ns)

Measure the time spectra of weak decay particles in coincidence with B->A γ ray and with C->B γ ray



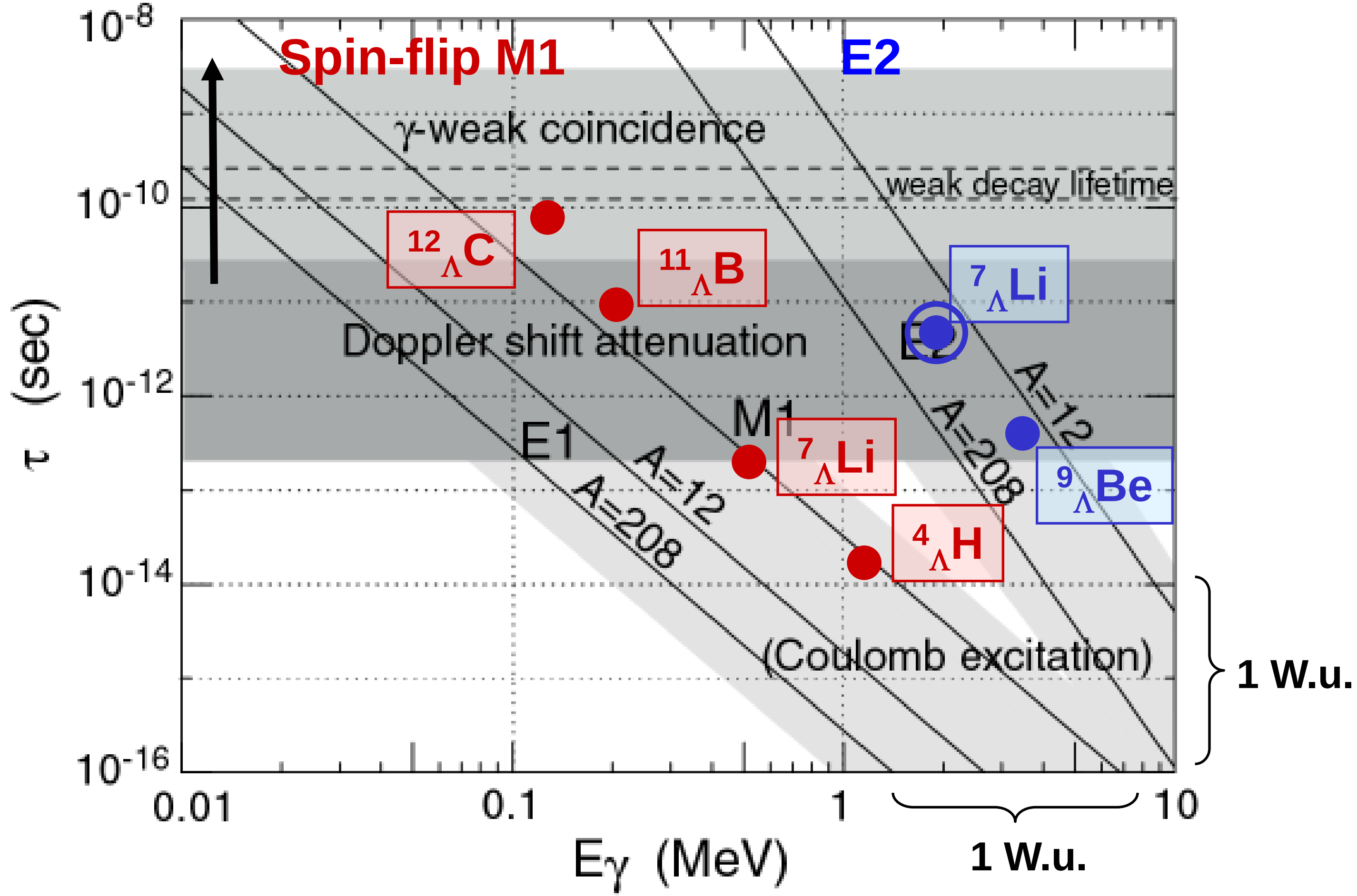
$^{12}{}_{\Lambda}C$ case

900 hours, 9×10^6 K^-/spill at K1.1 (50 GeV full beam) -> 5% stat. error of B(M1)

-> m, τ_B

-> $m / \tau_B = \Gamma_{M1} \propto B(M1)$

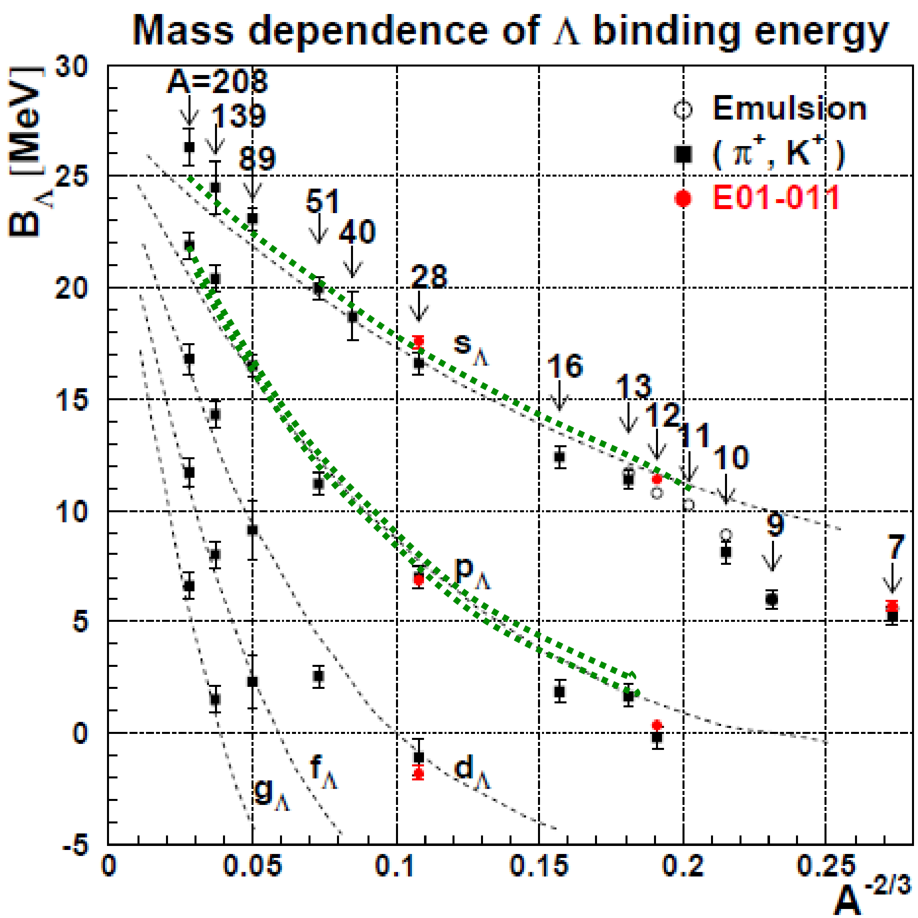
How to measure lifetimes for hypernuclear γ transitions

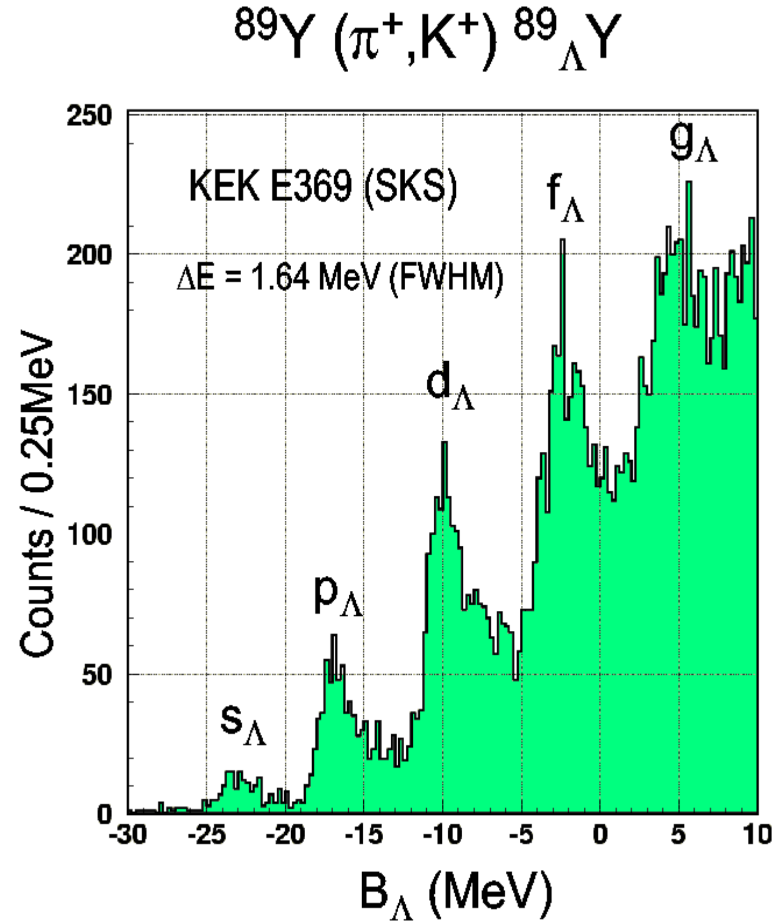


3. 核内Λの単一粒子軌道

Λの単一粒子軌道の測定

大雑把にはconventionalな描像と無矛盾だが





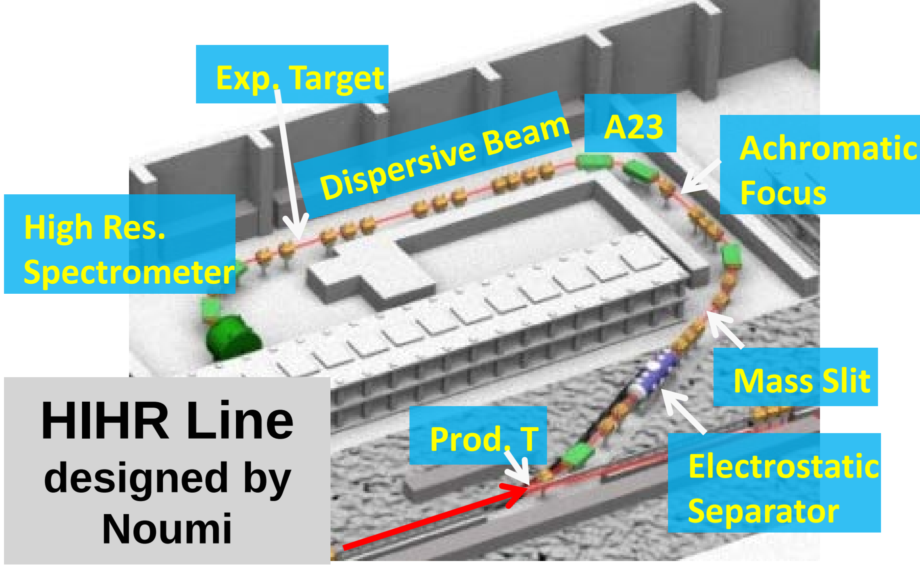
- **E(s_Λ, p_Λ, d_Λ, f_Λ,..) < 0.1 MeV accuracy**

  High resolution (π^+,K^+), (e,e'K^+)

- **E(s_Λ) – E(p_Λ), E($p1/2_{\Lambda 1}$) – E($p3/2_\Lambda$) < 0.01 MeV accuracy**

  γ spectroscopy for E1($p_\Lambda \rightarrow s_\Lambda$)

Λ単一粒子軌道の精密データから何がわかるか

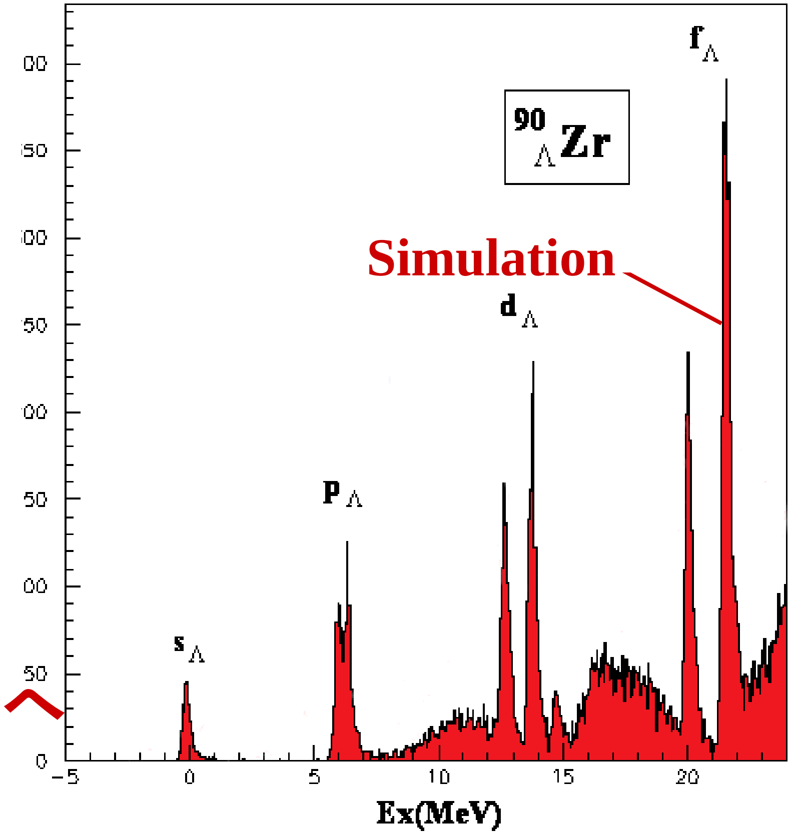


- “単一粒子軌道”の起源の理解
  平均場、有効相互作用、有効質量の微視的・定量的理解

- LS splittingの起源の定量的理解
  2体 LS力、テンソル力、多体相関
  (ΛにはOPEがない)

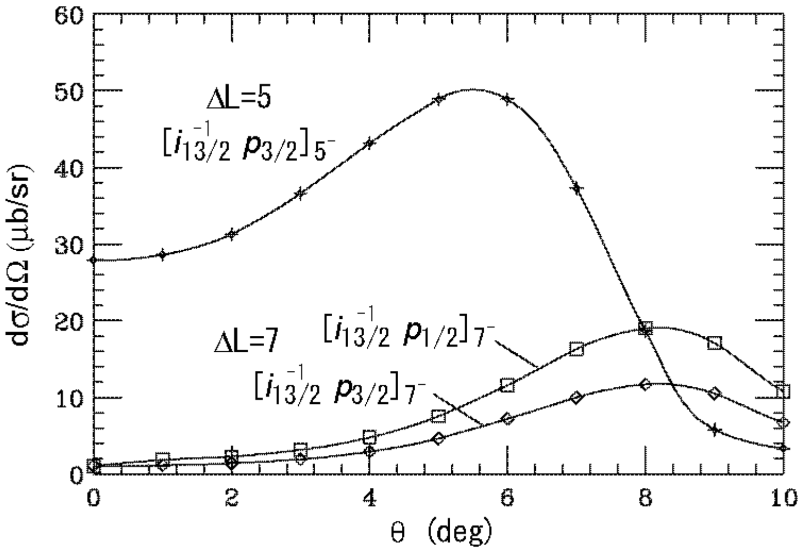
- 物理的理解に基づく正確なEOSの確立
  →高密度核物質の理解

- 核内バリオンと核内バリオン間力の媒質効果の影響？



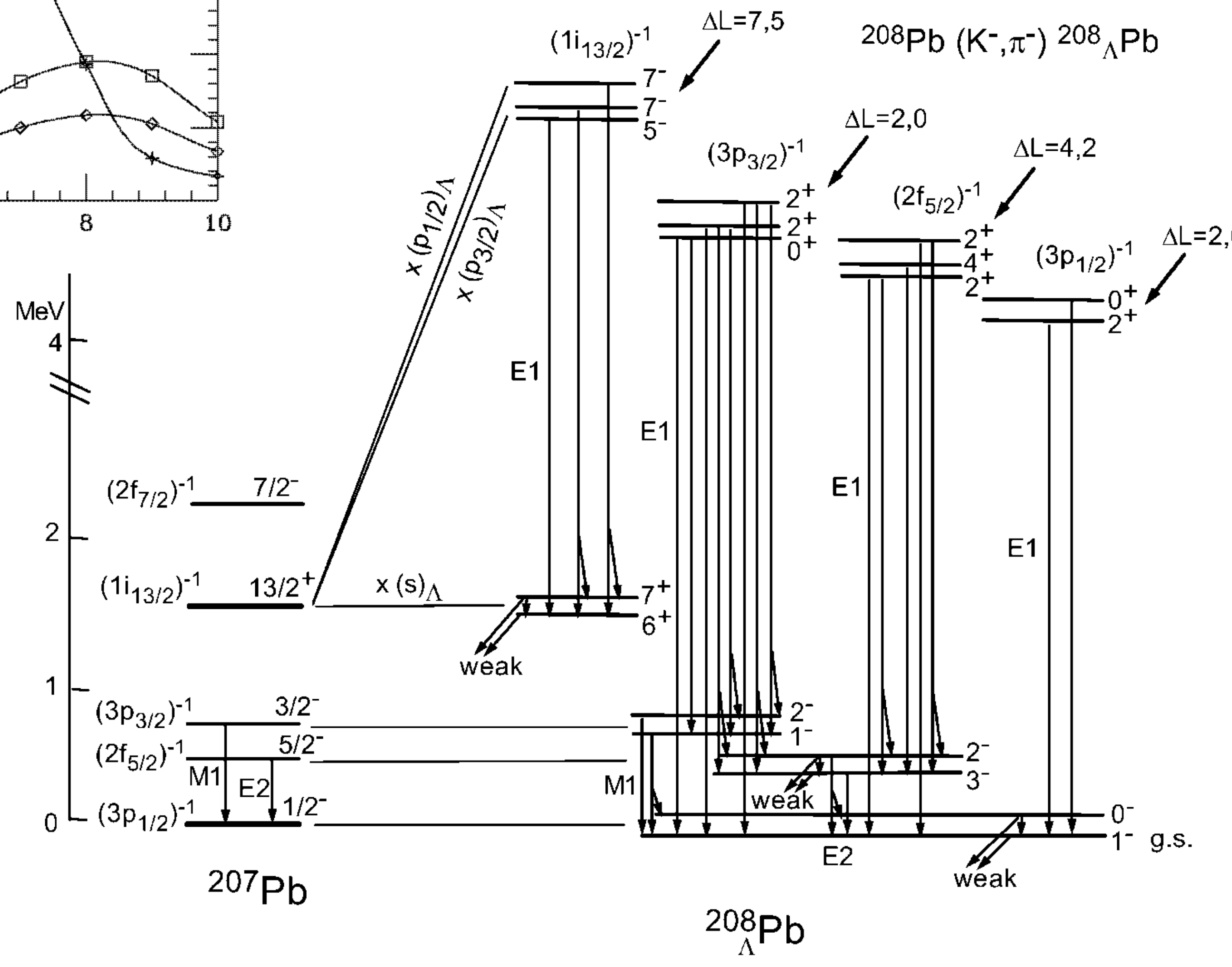
=> 原子核とハドロンのより深い理解へ

ガンマ線による LS splittingの精密測定へ



γ-spectroscopy of $^{208}{}_{\Lambda}$Pb

H.Tamura et al., J-PARC LOI



(K$^-$,π$^-$) at 1.8 GeV/c

10 g target

3x10^{6}K$^-$/4s

500 h

***p*3/2(5-) ~500 events**

***p*1/2(7-) ~200 events**

***p*3/2(7-) ~130 events**

4. 核内 Σ のγ 崩壊

How much does μ_Y change?

- Shift of constituent quark mass in a nucleus
  $\Delta m_{u,d}$ ~ -20%, $\Delta m_s / m_s$ ~ -4%

-> $\Delta\mu(\Sigma)$ ~ 20%, $\Delta\mu(\Lambda)$ ~ 4%
ΔB(M1) for Σ ~ +40%, ΔB(M1) for Λ ~ +8%

- **Quark Cluster Model** **Takeuchi et al., N.P. A481(1988) 639**

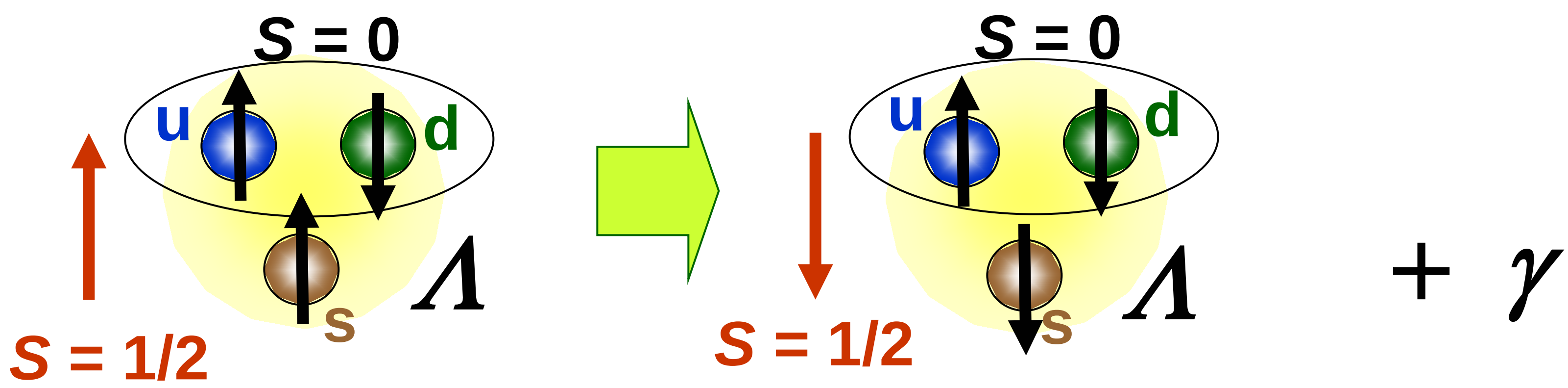
$\delta\mu / \mu$: ${}^4_\Lambda He(1^+)$ -1% ~ -2%, larger by Σ mixing

${}^4_{\Sigma^+}Li(1^+)$ -40% ~ -100%

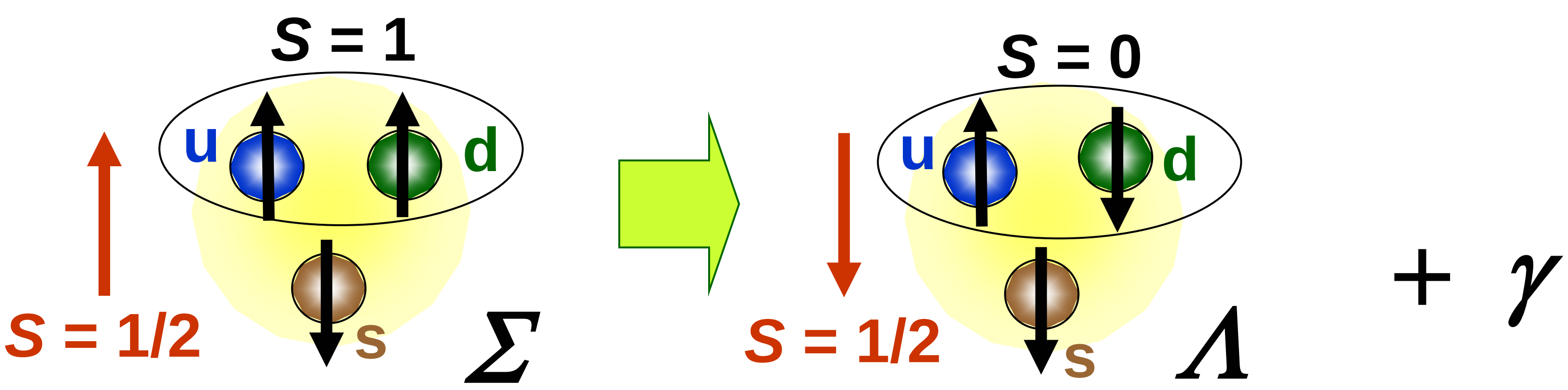
b = 0.6 fm -> 0.8 fm, μ becomes twice large.

Spin-flip M1 transitions

$\Gamma \propto B(M1) \propto |\langle\downarrow|\,\mu\,|\uparrow\rangle|^2$ is sensitive to w.f.



Spin-flip of s quark – small medium effect ?



Spin-flip of u/d quarks – large medium effect ?

Measurement of $\Gamma(\Sigma^0 \to \Lambda\gamma)$ in a nucleus

Σ in nucleus = Σ hypernuclear bound states -> **${}^4_\Sigma$He**

Free $\Sigma^0 \to \Lambda\gamma$ 100%, Eγ = 74 MeV

$\Gamma_{\text{free } \Sigma\to\Lambda\gamma}$ **= 1 / 7.4x10^{-20} sec^{-1} ~ 9x10^{-3} MeV**

$\Gamma_{\Sigma N \to \Lambda N}$ **~ 10 MeV for ${}^4_\Sigma$He**

=> BR($\Sigma^0 \to \Lambda\gamma$ in nucleus) ~ $\Gamma_{\Sigma\to\Lambda\gamma} / \Gamma_{\Sigma N\to\Lambda N}$ ~ 0.001

(K^-,π^-) reaction at 600 MeV/c using K1.1BR

dσ/dΩ (${}^4_\Sigma$He) ~ 100 μb/sr (Nagae et al.)

Yield: $N_{K-} \cdot d\sigma/d\Omega \cdot \Delta\Omega \cdot BR \cdot N_{target} \cdot BR(\Lambda \to n\pi^0) \cdot \varepsilon$

= 5x10^5 /spill·100x10^{-30}·0.02·0.001·0.12g/cm^3/ 4·20cm·6x10^{23} · 0.3·0.5

=> 56 counts/1000hour

Background: QF Σ^0 escape, $\Sigma^0 \to \Lambda\gamma$ (-B_Σ>0 only)

$\pi^0 \to \gamma\gamma$ from $\Lambda \to n\,\pi^0$ (Eγ ~ 50~100 MeV)

=> Tag <u>3 energetic (> 50 MeV) γ rays</u>

=> cover the target region with a calorimeter

A good high-energy γ detector is necessary.

Theoretical calculation necessary – how large change is expected?

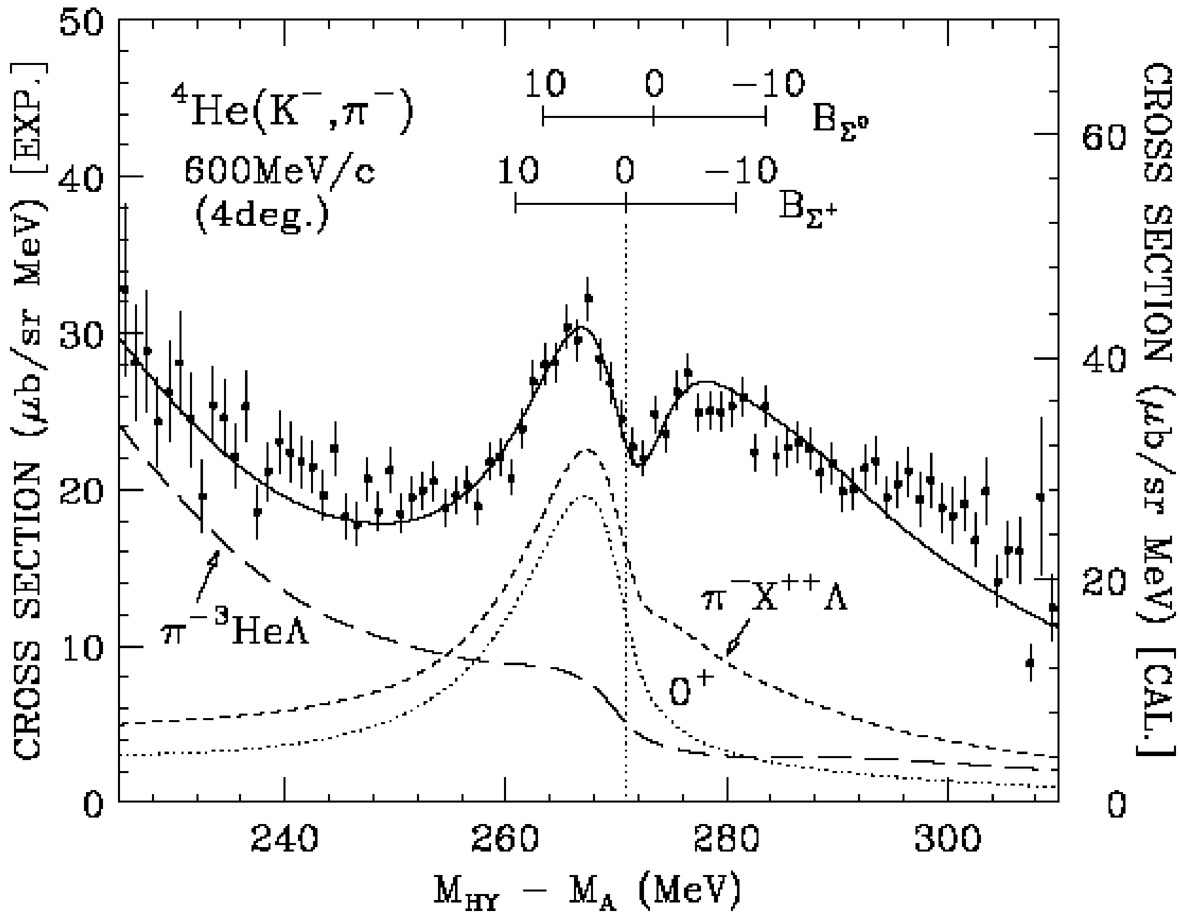


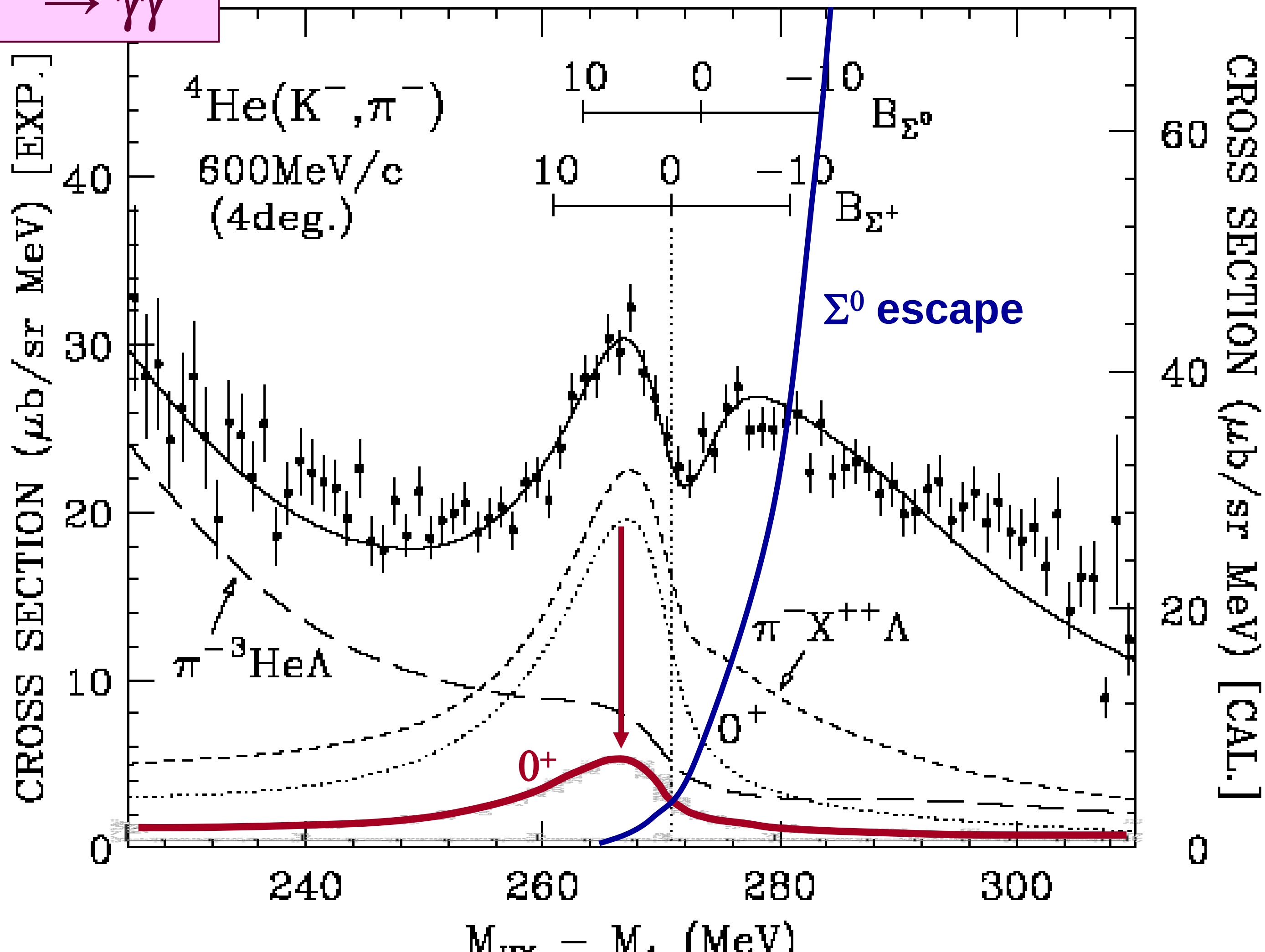
FIG. 3. Contributions to the ^{4}He(K^-, π^-) spectrum near the Σ threshold. The solid, long-dashed, and dashed curves are for the total π^-, $\pi^- + {}^3$He $+ \Lambda$, and $\pi^- + X^{++} + \Lambda$ final states, respectively. The dotted curve denotes the contribution of $J^\pi = 0^+$ in the $\pi^- + X^{++} + \Lambda$ final state.

Harada, PRL 81(1998) 5287

Expected 3γ-tagged spectrum (イメージ)

$\Sigma^0 \to \Lambda\,\gamma$
$\to n\pi^0$
$\to \gamma\gamma$

Assuming that $^3He\Lambda$, $pd\Lambda$, $ppn\Lambda$ never emit 3 energetic γ's

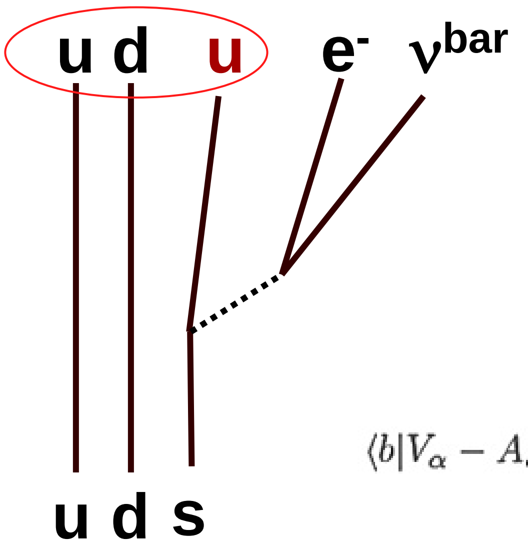


5. 核内Λの
ベータ･ガンマ弱崩壊

Λ のベータ･ガンマ弱崩壊は核内で変わるか？

u-quark distribution may be different between a free proton and a proton in a nucleus

Neutron β-decay takes place on nuclear surface



	BR	p_N
$\Lambda \rightarrow n\,\gamma$	1.8×10^{-3}	162 MeV/c
$p\,e^-\,\nu^{bar}$	8.3×10^{-4}	<163 MeV/c
$p\,\mu^-\,\nu^{bar}$	1.6×10^{-4}	<131 MeV/c

$$\langle b|V_\alpha - A_\alpha|B\rangle = \bar{u}_b(p')[\gamma_\alpha f_1(q^2) + \sigma_{\alpha\beta}q_\beta \frac{f_2(q^2)}{M_B+M_b} + iq_\alpha \frac{f_3(q^2)}{M_B+M_b}$$
$$+\gamma_\alpha\gamma_5 g_1(q^2) + \sigma_{\alpha\beta}q_\beta\gamma_5 \frac{g_2(q^2)}{M_B+M_b} + iq_\alpha\gamma_5 \frac{g_3(q^2)}{M_B+M_b}]u_B(p)$$

How sensitive is it to form factors (in particular, $f_1(0)$, $g_1(0)$)?
Pauli effect should be accurately estimated.

$^{12}{}_{\Lambda}$C gs: 0.3mb/sr at 0.8 GeV/c (K-,π-), K1.1 line:10^6 K^-/4s, SKS: 0.1sr, ^{12}C 10g/cm^2,
γ/e/μ detector eff 10%, Pauli x1/3, 1000 hours
⇒ nγ: 300, peν: <140, pμν: <27 events
A good high-energy γ detector is also useful here.

おわりに

ストレンジネスを使って、核内バリオンの性質を調べられる
と期待している　ーストレンジネス核物理の次の方向性としたい

- 核内Λのg因子
- 単一Λ粒子軌道の精密測定
- 核内Σのγ崩壊によるg因子?
- 核内Λのベータ・ガンマ弱崩壊??

理論とのますますの連携が不可欠

ハドロンホールの高度化・拡張も必要

元場さん、ご退職、お待ち申し上げておりました！
お元気で、ますますストレンジネス核物理を発展させてください。