Hypernuclear γ-ray spectroscopy at J-PARC

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for the Hyperball-J collaboration

- **Pre J-PARC: Hyperball experiments**
- **At J-PARC: Hyperball-J**
  - **E13 (γ-ray spectroscopy of light hypernulei)**
    - **${}^{4}_{\Lambda}He$, ${}^{7}_{\Lambda}Li$, ${}^{10,11}_{\Lambda}B$, ${}^{19}_{\Lambda}F$**
- **Summary**

E13 experimental setup at J-PARC by K.Shirotori

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KEK: K. Aoki, Y. Kakiguchi, T. Nagae, H. Noumi, Y. Sato, M. Sekimoto, H. Takahashi, T. Takahashi, A. Toyoda

Joint Institute for Nuclear Research, Dubna: P. Evtoukhovitch, V. Kalinnikov, W. Kallies, N. Kravchuk, A. Moiseenko, D. Mzhavia, V. Samoilov, Z. Tsamalaidze, O. Zaimidoroga

China Institute of Atomic Energy: Y.Y. Fu, C.B. Li, X.M. Li, J. Zhou, S.H. Zhou, L.H. Zhu

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University of Torino and INFN Torino: T. Bressani, S. Bufalino, L. Busso, D. Faso, A. Feliciello, S. Marcello

Kyoto University: S. Kamigaito, K. Imai, K. Miwa, K. Tanida

University of Tokyo: H. Fujioka, D. Nakajima, T.N. Takahashi

Florida International University: P. Markowitz, J. Reinhold

Gifu University: K. Nakazawa, T. Watanabe

GSI: S. Minami, T.R. Saito

ITEP, Russia: A. Krutenkova, V. Kulikov

Brookhaven National Laboratory: R.E. Chrien

INAF-IFSI and INFN Torino: O. Morra

Japan Atomic Energy Agency: P.K. Saha

Osaka Electro-Communication University: T. Fukuda

Osaka University: S. Ajimura

Pusan University: J.K. Ahn

Seoul National University: H.C. Bhang

Torino Polytechnic and INFN: M. Agnello

Hyperball-J collaboration

20 institutes, 79 scientists

Hypernuclear γ-ray spectroscopy

Experimental method: particle-γ coincidence

Reaction: (π^+,$K^+\gamma$), (K^-,$\pi^-\gamma$)

Magnetic spectrometer systems (resolution ~3MeV)

- K6-SKS at KEK, D6 at BNL, **K1.8-SksMinus at J-PARC**
- Event by event reaction tagging
- Missing mass →
  - identification of bound hypernuclear states
  - Hyperfragments
    - $^{16}_{\Lambda}O \rightarrow p + ^{15}_{\Lambda}N$, $^{10}_{\Lambda}B \rightarrow p + ^{9}_{\Lambda}Be$, $^{10}_{\Lambda}B \rightarrow ^{3}He + ^{7}_{\Lambda}Li$, $^{12}_{\Lambda}C \rightarrow p + ^{11}_{\Lambda}B$

γ-ray detector array (resolution ~2keV**)**

- superb resolving power → spin-doublet splitting ~100keV
- Hyperball, Hyperball2, **Hyperball-J**

↓

particle-γ-γ coincidence at J-PARC

Spectroscopic information

- **Energy level schemes**

  Energy level spacing → ΛN interaction

  Spin dependent force (spin-spin, spin-orbit, tensor)

  ΣN-ΛN coupling and the three-body force

  Angular distribution/correlation

  Linear polarization

  transition multipolarity → relative spin and parity

- **Life time measurement of excited states**

  Reduced transition probability → direct information on wave functions

  B(E2) → hypernuclear size, deformation, collectivity

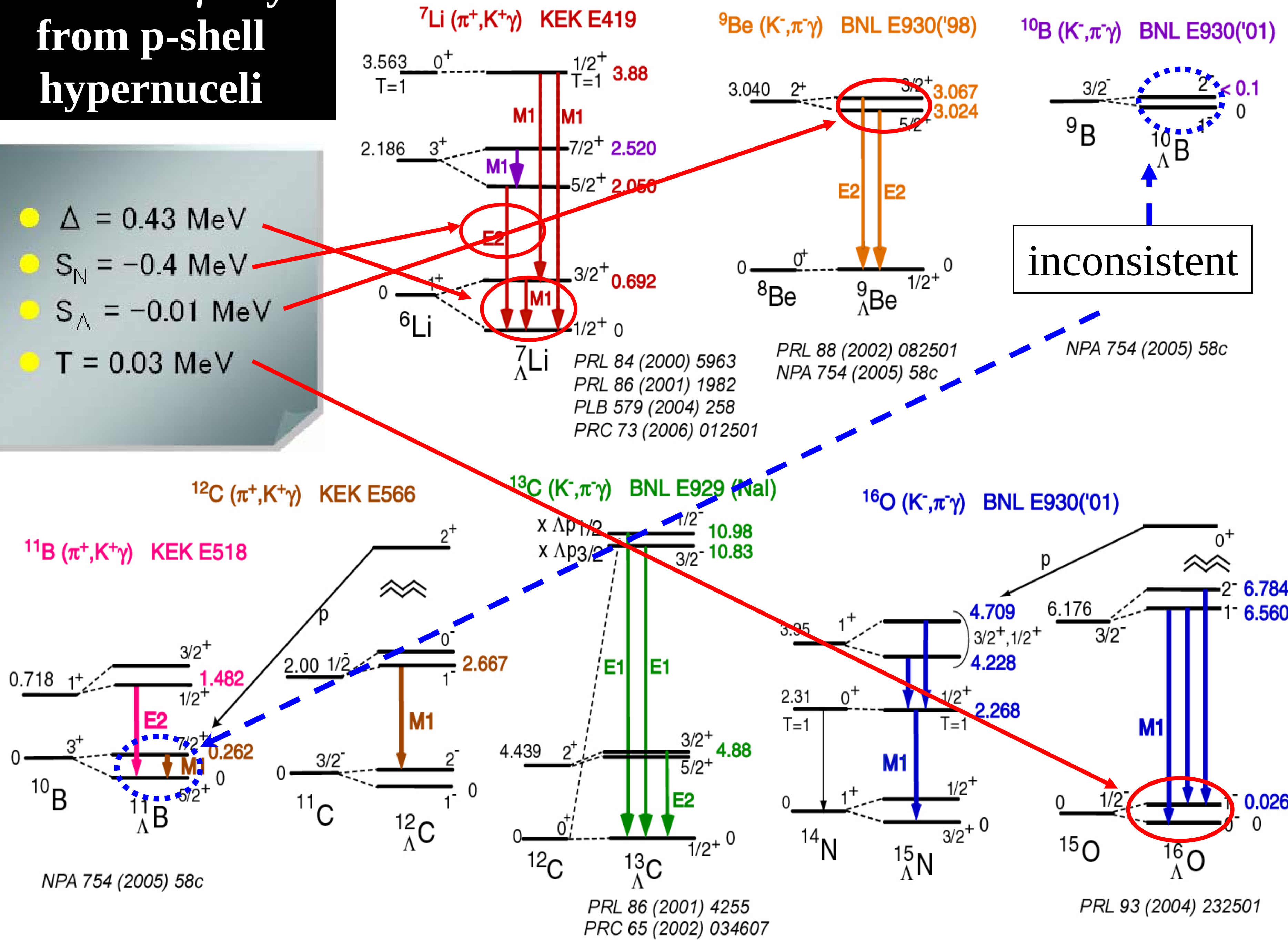
  B(E2;5/2→1/2) in $^{7}_{\Lambda}$Li

  B(M1) → magnetic moment, single particle aspect

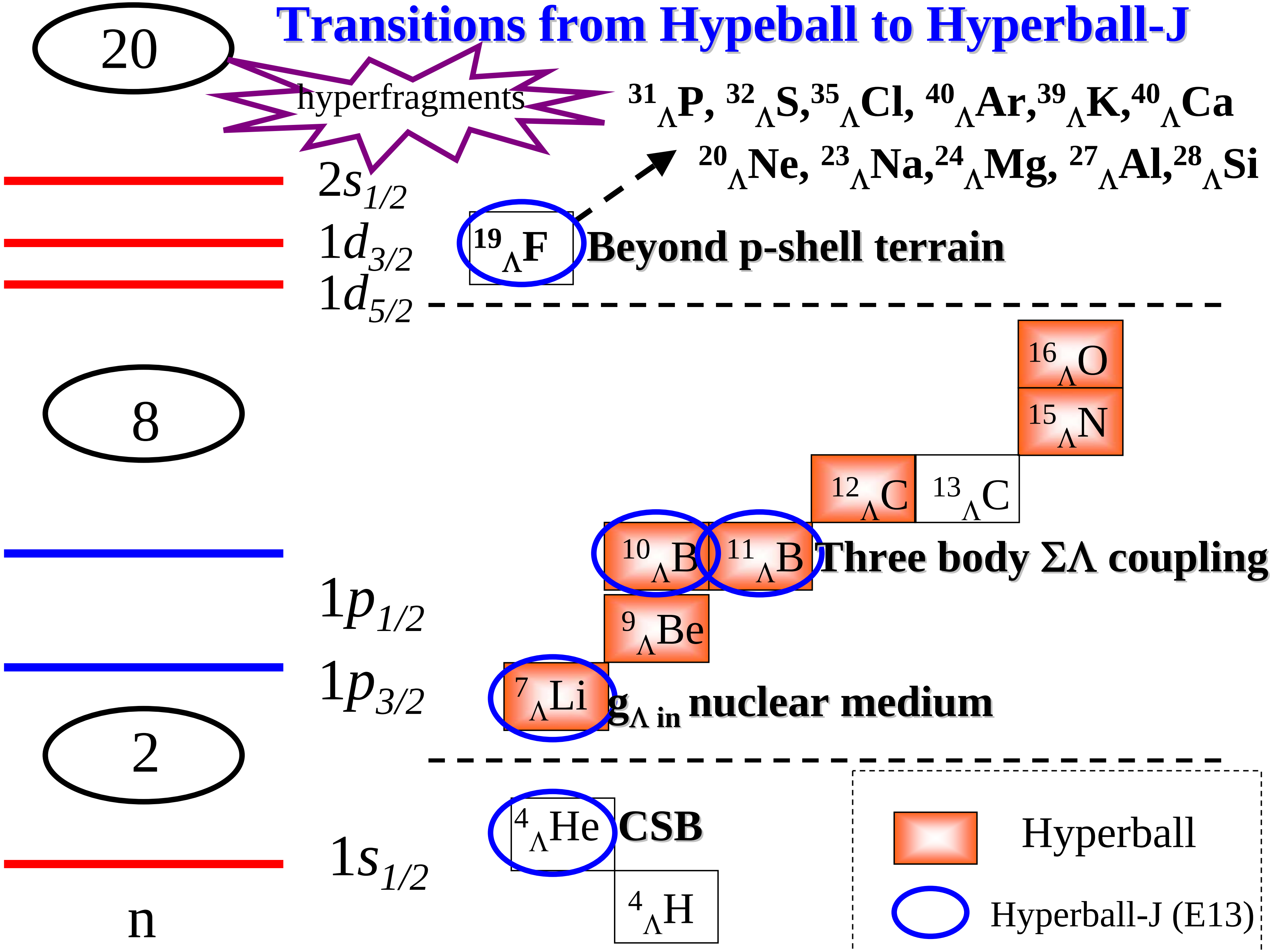
  Attempted, but yet to be measured

Identified γ-rays from p-shell hypernuceli

- Δ = 0.43 MeV
- S_N = −0.4 MeV
- S_Λ = −0.01 MeV
- T = 0.03 MeV



Transitions from Hypeball to Hyperball-J



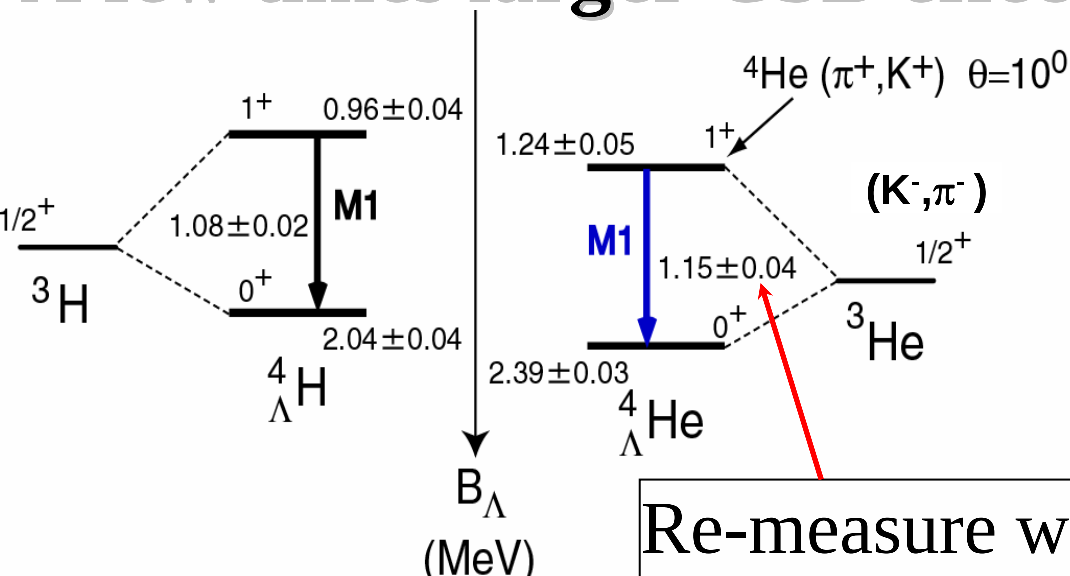
$^{4}_{\Lambda}$He: Spin dependent Charge symmetry breaking (CSB) in ΛN interaction

- Lightest mirror hypernuclei → ΔB_Λ direct measure of $\mathbf{\Delta E_{csb,\Lambda N}}$:
  $\Delta B_\Lambda \approx \mathbf{\Delta E_{csb,\Lambda N}}$

$$\Delta B_\Lambda = B_\Lambda({}^4_\Lambda He) - B({}^4_\Lambda H) = 350 \pm 70 keV$$
$$\Delta E_\Lambda = E({}^4_\Lambda He;1^+) - E({}^4_\Lambda H;1^+) = 270 \pm 160 keV$$

- CSB effect in NN interaction calculated from ^{3}H and ^{3}He
  $\Delta E_{csb,NN} \approx$ 80keV *(Faddeeve calculations, Y.Wu et. al., PRL 64 1875 (1990))*

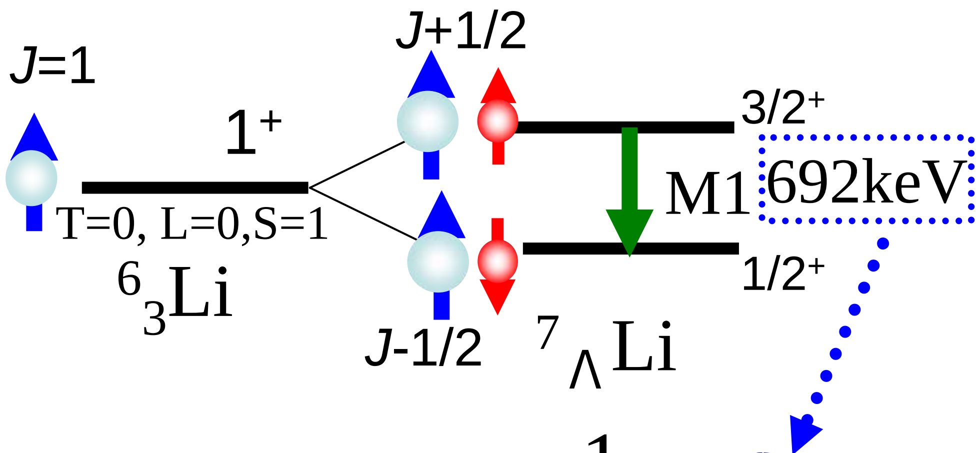
A few times larger CSB effect in ΛN than in NN ??



Re-measure with 0.5% accuracy

Charge-asymmetry effects	δE
Static Coulomb ($E_{C,M1}$)	648 ± 4
Magnetic interaction	10 ± 1
Vacuum polarization	4
Orbit-orbit interactions	9 ± 1
Kinetic energy due to *n-p* mass difference	11
δE_{other}	34 ± 2
CIB and CSB forces ($^1S_0$)	75 ± 7
CSB other than $^1S_0$	2
Uncertainty from V_{phe}	1 ± 1
δE_{CSB}	78 ± 8
Total (theory)	760 ± 14
Experiment	764

${}^{7}_{\Lambda}$Li: B(M1) measurement and Λ in nucleus



$$\Gamma = \frac{1}{\tau} \propto E_\gamma^3 B(M1)$$

Doppler **S**hift
Attenuation
Method

Nuclear medium effect

- No Pauli blocking
  →Λ in 0s orbit
- Partial restoration of chiral symmetry?
  reduction of constituent quark mass
  → change of μ_Λ

In the weak coupling limit between Λ and the core nucleus

$$B(M1)\left[\mu_N^2\right] \propto \left\langle J = 3/2 \| \mu \| J = 1/2 \right\rangle^2 \propto (g_\Lambda - g_C)^2$$

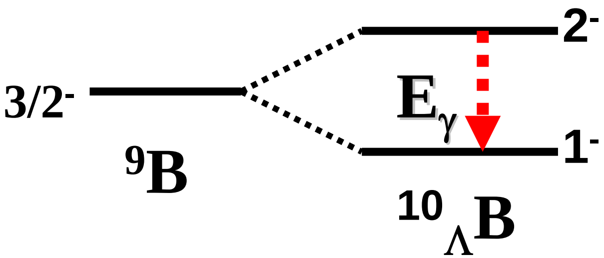
$$\mu = g_\Lambda J_\Lambda + g_C J_C$$

g_Λ,g_c: **Effective** g factor of Λ and core nucleus, respectively
J_Λ, J_c: Total spin of Λ and core nucleus, respectively

${}^{10}_{\Lambda}$B: the puzzle

- Δ = 0.43 MeV
- S_N = −0.4 MeV
- S_Λ = −0.01 MeV
- T = 0.03 MeV

^{10}B (K^-,$\pi^-\gamma$) ${}^{10}_{\Lambda}$B
0.8~0.93GeV/c
(BNL-E930)



Shell model prediction

$$0.578\,\Delta + 1.41\,S_\Lambda + 0.014\,S_N - 1.07\,T + \Lambda\Sigma$$

195keV -15keV

Experimentally not observed:

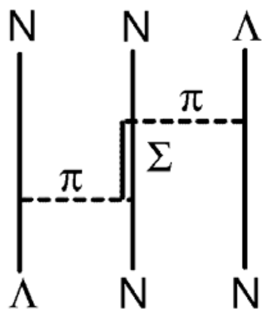
(1) E_γ below experimental sensitivity
→ E_γ<~100keV

- Δ < 0.3
- $\Lambda\Sigma$ >> -15keV
- better wave function for ^{9}B

(2) 2^- (non spin-flip) and 1^- (spin-flip) reversed in energy

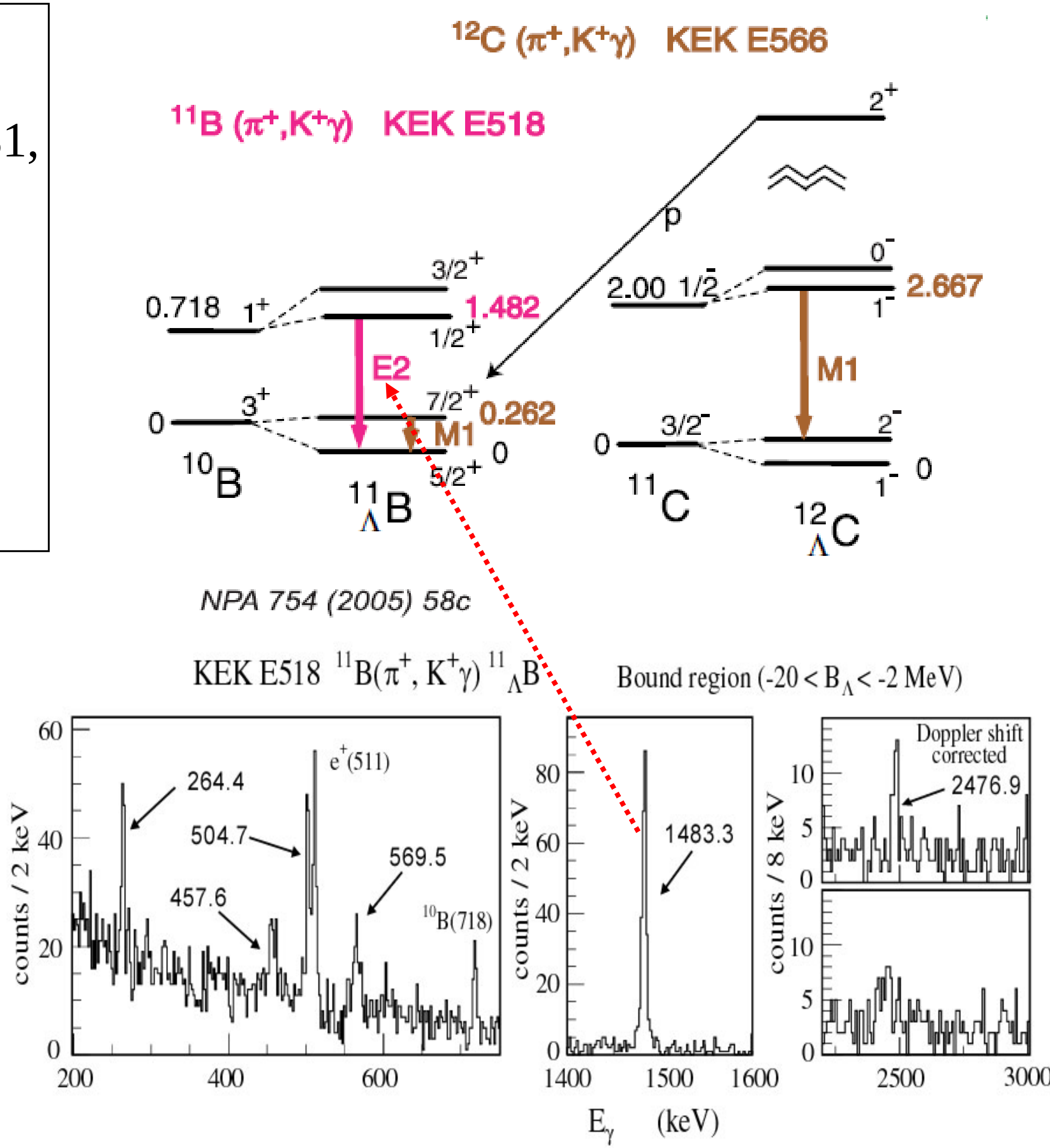
- p_k= 0.8~0.93GeV/c (BNL E930)
  → non spin-flip population
- p_k = 1.8GeV/c (E13 J-PARC)
  → spin flip/non spin flip

Three-body force by $\Lambda\Sigma$ coupling
-- Not well known



$^{11}_{\Lambda}$B: Most complex p-shell hypernucleus

- 6 γ rays observed
  - 2 transitions assigned (E581, E566 @ KEK)
- ^{10}B: odd-odd core
  - many low-lying energy levels → many hypernuclear bound states

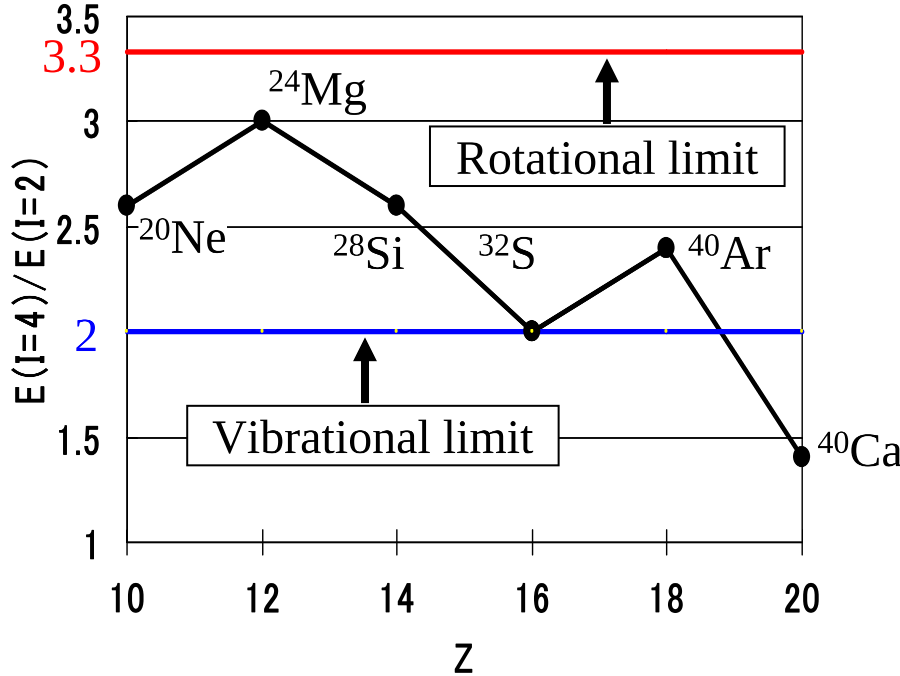


- Consistency check for Δ, S_Λ, S_N, and T parameters
- Test of J-PARC beam intensity & Hyperball-J setup via γ-γ coincidence measurements

γ-ray spectroscopy of sd-shell hypernuclei

- Substitutional states unbound
  - hyperfragments
- Increased complexity away from closed shells
  - large basis space for shell model calculations
  - demography of core nuclei
  - collective degree of freedom
    - core deformation
    - → drastic change by the presence of Λ?

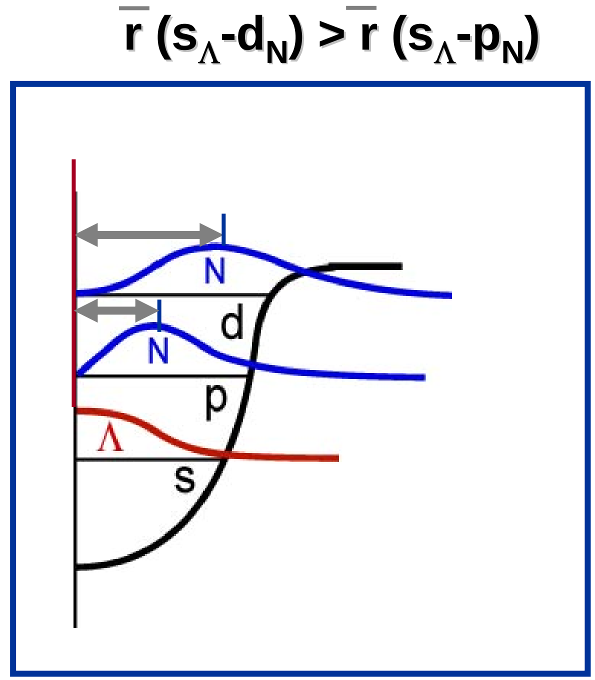
Need for higher sensitivity with γ–γ coincidence

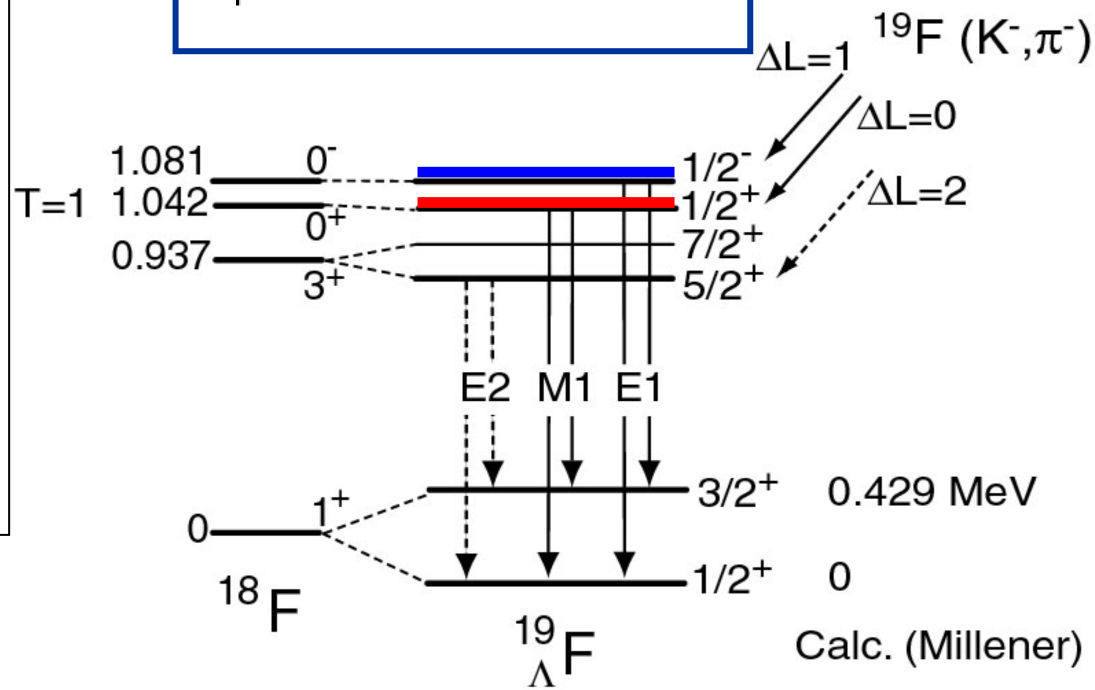


	Direct	Hyper-fragments
Even-even	0	
Odd-A	6	↗
Odd-odd	6	↗

$^{19}_{\Lambda}F$

- Core ^{18}F [^{16}O + p+n]
  - shell model effective
  - simplest to study
  - first *sd*-nucleus to be studied
- Radial dependence of ΛN spin-dependent interaction
  - sensitive to interaction range





Summary

- γ-ray spectroscopy of light hypernucleus at the J-PARC initial phase experiments (E13)
- Towards complete spectroscopic studies of s- and p-shell hypernuclei
  - Re-measurement of $^{4}_{\Lambda}$He $E_{\gamma}(1^{+}\rightarrow 0^{+})$ with ~0.5% accuracy
  - B(M1) measurement in $^{7}_{\Lambda}$Li
  - Energy level schemes for $^{10}_{\Lambda}$B and $^{11}_{\Lambda}$B
- Structural study of *sd*-shell hypernuclei $^{19}_{\Lambda}$F

More complete data for theoretical investigation